# NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE (NHERI) 2016-2020: MITIGATING THE IMPACT OF NATURAL HAZARDS ON CIVIL INFRASTRUCTURE AND COMMUNITIES

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# NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE (NHERI) 2016-2020: MITIGATING THE IMPACT OF NATURAL HAZARDS ON CIVIL INFRASTRUCTURE AND COMMUNITIES

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EDITORIAL
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# Editorial: Natural Hazards Engineering Research Infrastructure (NHERI): Mitigating the Impact of Natural Hazards on Civil Infrastructure and Communities

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**Keywords: storm surge, tsunami, earthquakes, windstorms, research infrastructures**

**Editorial on the Research Topic**

**Natural Hazards Engineering Research Infrastructure (NHERI): Mitigating the Impact of Natural Hazards on Civil Infrastructure and Communities**

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Natural hazards in the form of earthquakes, windstorms, and associated events such as tsunami and storm surge can devastate a community's civil infrastructure and severely disrupt the broader society. Communities can take years to recover from widespread damage to, or failures of, civil infrastructure. This is evident from the experiences of the Indian Ocean tsunamis, the Canterbury earthquake sequence in New Zealand, the Tohoku tsunami in Japan, and Hurricanes Katrina, Ike, Sandy, Harvey, and Maria in the United States. With a multi-disciplinary and coordinated research effort, however, it is possible to mitigate costly impacts of natural hazards—and prevent them from becoming societal disasters. Illustrations of the devastation caused by some of these natural hazard events are shown in **Figure 1** (left - Hurricane Ike and right - Haiti earthquake).

*The Natural Hazards Engineering Research Infrastructure (NHERI)* is a shared-use, nationally distributed network that provides key infrastructure for the natural hazards engineering and social science community. NHERI combines state-of-the-art experimental facilities with a computational modeling and simulation center, a convergence-science hub, and post-event reconnaissance and research teams. NHERI's coordination office leads education and community outreach, supports research operations, and manages governance to provide fair and clear access. In addition, NHERI provides a cyberinfrastructure for research and collaboration. NHERI is funded by the National Science Foundation (NSF). The community of NHERI researchers, educators, and students encompasses a large group of universities, industry and federal partners, and research institutions in the United States and abroad.

The research topics covered in the special issue pertain to the unique capabilities of the twelve NHERI components, as well as user satisfaction measures collected by the NHERI User Forum, and examples of community-organized, post-event reconnaissance. Together, the fifteen papers in this collection illustrate the strength and effectiveness of a community of researchers empowered by shared–use facilities and components that encourage multi- and interdisciplinary collaboration. The contributions also highlight how open access to data and high-performance computing resources can advance the state of knowledge. Further, by cutting

**FIGURE 1 |** Bolivar Island, TX, after Hurricane Ike, 2008 (left) and Port au Prince, Haiti, after 2010 earthquake (courtesy of or with permission of M. Eberhard, University of Washington, Seattle, WA, United States) (right).

across disciplinary borders and advancing convergence science to solve grand challenges, NHERI efforts show that it is possible to improve community resilience against the impact of natural hazards. The articles in this collection point to the enabling impact made possible by researchers, students, educators, and practitioners collaborating within the NHERI network.

The NHERI community has fostered the development of students—the earthquake, wind, and coastal engineering researchers of the future. As well, it has provided useful resources for practicing engineers and social science researchers. Since its inception in 2015, NHERI efforts have resulted in a wealth of invaluable experimental data, which are crucial to develop, calibrate and validate high-fidelity computational models of civil infrastructure systems. The community will continue to produce transformational research and outcomes that influence engineering and, increasingly, inform interdisciplinary practice by way of computational simulation models to design guidelines and codes.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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# A Framework for Convergence Research in the Hazards and Disaster Field: The Natural Hazards Engineering Research Infrastructure CONVERGE Facility

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The goal of this article is twofold: to clarify the tenets of convergence research and to motivate such research in the hazards and disaster field. Here, convergence research is defined as an approach to knowledge production and action that involves diverse teams working together in novel ways – transcending disciplinary and organizational boundaries – to address vexing social, economic, environmental, and technical challenges in an effort to reduce disaster losses and promote collective well-being. The increasing frequency and intensity of disasters coupled with the growth of the field suggests an urgent need for a more coherent approach to help guide what we study, who we study, how we conduct studies, and who is involved in the research process itself. This article is written through the lens of the activities of the National Science Foundation-supported CONVERGE facility, which was established in 2018 as the first social science-led component of the Natural Hazards Engineering Research Infrastructure (NHERI). Convergence principles and the Science of Team Science undergird the work of CONVERGE, which brings together networks of researchers from geotechnical engineering, the social sciences, structural engineering, nearshore systems, operations and systems engineering, sustainable material management, and interdisciplinary science and engineering. CONVERGE supports and advances research that is conceptually integrative, and this article describes a convergence framework that includes the following elements: (1) identifying researchers; (2) educating and training researchers; (3) setting a convergence research agenda that is problem-focused and solutions-based; (4) connecting researchers and coordinating functionally and demographically diverse research teams; and (5) supporting and funding convergence research, data collection, data sharing, and solutions implementation.

**Keywords: convergence research, natural hazards, disasters, interdisciplinary, transdisciplinary, training, Science of Team Science, research coordination networks**

## INTRODUCTION

This article offers a definition and framework for bringing *convergence research* to the field of hazards and disasters. Drawing on insights from several foundational publications and extending them to our field, we define convergence research as:

> *An approach to knowledge production and action that involves diverse teams working together in novel ways—transcending disciplinary and organizational boundaries—to address vexing social, economic, environmental, and technical challenges in an effort to reduce disaster losses and promote collective well-being.*

Understanding and managing the convergence of people, supplies, and information has long been of interest to disaster researchers and practitioners (Prince, 1920; Fritz and Mathewson, 1957; Quarantelli and Dynes, 1977). Our focus here, however, is not solely on convergence as a post-disaster phenomenon. Rather, our goal is twofold: (1) to clarify the tenets of convergence research and (2) to motivate such research in the hazards and disaster field.

The hazards and disaster field – which has a well-established history of encouraging inclusive forms of multidisciplinary research (Kendra and Nigg, 2014) as well as of supporting distinctly problem-focused approaches to science and engineering (White and Haas, 1975; Mileti, 1999; Pulwarty et al., 2009) – is poised intellectually and institutionally to advance convergence research. In fact, from the inception of the field, studies have concentrated on issues of great practical and societal concern (White and Haas, 1975; Quarantelli, 1987). This has led to insights – ranging from risk communication to recovery – that have had a meaningful influence on emergency management practice and, in some cases, local, state, and federal policy (Mileti, 1999; Tierney et al., 2001; Birkland, 2006; Olson et al., 2020).

Yet knowing more has not helped to contain disaster-related losses such as property damage, direct and indirect economic costs, population displacement, and other socially and financially harmful disruptions. Burton (2018) offers various explanations for this "knowing more-losing more" paradox, including the settlement and growth of populations in risky areas, the expansion of the global economy, the onset of climate change, inadequate knowledge mobilization frameworks, and, especially, unchecked disaster risk creation in capitalist markets. In addition, social and economic inequality have left more people in harm's way with fewer resources available to prepare for, respond to, and recover from disaster (Fothergill and Peek, 2004; Verchick, 2010). Hazards-related damages and biased disaster policies may further widen wealth inequalities – especially along lines of race, education, and homeownership – rendering already marginalized population groups more vulnerable to future crises (Howell and Elliott, 2018).

Rising risks and losses demand a new approach to extreme events research that focuses on the interconnections between technical, ecological, social, cultural, political, and economic systems. Such an approach must involve researchers from a wide range of disciplines and historically underrepresented groups, such as women and racial and ethnic minorities. This will help ensure that diverse perspectives and paradigms are brought to bear to respond to pressing challenges through elevating research outcomes designed to promote collective well-being. In this context, collective well-being is defined as a community's measured and perceived social and physical health across the domains of vitality, opportunity, connectedness, contribution, and inspiration (Roy et al., 2018).

Convergence, with its focus on *deep integration across disciplines* and *research driven by a specific and compelling problem,* offers a possibility for moving forward as a field (National Science Foundation [NSF], 2019). Convergence requires interdisciplinary or even transdisciplinary approaches. But it also goes beyond these approaches through offering a framework where members of the hazards and disaster research community come together to characterize the mounting threats communities face and, importantly, identify specific actions that will reduce the historical and socio-technical problems, inequalities, and injustices that turn natural hazards into disasters. It is this focus on problem identification and especially solutions implementation that distinguishes convergence research from interdisciplinarity and transdisciplinarity, even though they are each closely interrelated.

For the sake of conceptual and theoretical clarity, we proceed with a brief review of the literature on convergence in disasters. We then offer an overview of the recent turn toward convergence research in other disciplines including those in the life sciences, physical sciences, and engineering. The remainder of the paper is dedicated to describing a novel framework for convergence research through the lens of the activities of the National Science Foundation-supported CONVERGE facility. Convergence research and the Science of Team Science undergird the work of CONVERGE, which is led by a social scientist and brings together networks of researchers from geotechnical engineering, the social sciences, structural engineering, nearshore systems, operations and systems engineering, sustainable material management, and interdisciplinary science and engineering. CONVERGE is the specific component of the Natural Hazards Engineering Research Infrastructure (NHERI) that is dedicated to advancing convergence research. As such, we describe CONVERGE and offer illustrative examples of how its associated activities and research coordination networks are supporting convergent approaches that are ethical, collaborative, holistic, and scientifically rigorous.

## BACKGROUND

Convergence behavior has long been of interest to hazards and disaster researchers. As this section demonstrates, however, the more recent process-oriented and research-based definition of convergence differs from the ways that convergence has historically been conceptualized and studied in disaster research. Both uses of convergence, however, evoke an image of people or things coming together for a common purpose. They also both draw from the same Latin root, *convergere: con-* = together + *vergere* = to incline. In other words, to be inclined toward each other.

## Convergence Behavior in Disasters

Fritz and Mathewson (1957), both pioneers in the social scientific study of disasters, published the first comprehensive report on the topic of convergence behavior in disasters. They defined convergence as the "mass movement of people, messages, and supplies toward the disaster struck area" (p. 1). They distinguished between "external convergence," which involves "movement toward the disaster-struck area from the outside," and "internal convergence," or the "movement toward specific points within a given disaster-related area or zone" (p. 3). They were especially concerned with characterizing and understanding how to control three major types of informal, unofficial, and unauthorized convergence, which they defined as: (1) personal convergence: the actual physical movement of persons on foot, by car, or by other mode of transportation, (2) informational convergence: the movement or transmission of messages, and (3) materiel convergence: the physical movement of supplies and equipment (p. 4).

Although the field was still in its nascent stages, Fritz and Mathewson (1957) asserted that convergence is so common that it should be considered a "virtually universal phenomenon following disasters" (p. 1). Decades of subsequent disaster research has proven these words prescient, as researchers have documented convergence behavior in the aftermath of floods (Neal, 1994; Arnette and Zobe, 2015; Montano, 2015), earthquakes (Subba and Bui, 2010, 2017; Holguín-Veras et al., 2012), hurricanes (Holguín-Veras et al., 2007; Wachtendorf et al., 2013; Schumann and Nelan, 2018), terrorist attacks (Sutton, 2002; Steffen and Fothergill, 2006; Kendra and Wachtendorf, 2016), humanitarian emergencies (Black, 2003), and numerous other disasters across the United States and globally (Tierney et al., 2001; Holguín-Veras et al., 2014). Researchers have also extended Fritz and Mathewson's (1957) classic typology, offering additional categories of convergence behavior in the context of various hazard types (Kendra and Wachtendorf, 2003; Subba and Bui, 2010, 2017).

## Convergence Research

In the early twenty-first century, new approaches to research began to take root. Researchers with backgrounds in engineering, biology, and chemistry started more regularly joining forces to harness technological and scientific advances and accelerate their implementation (Bainbridge and Roco, 2016). The key to this type of progress is *convergence,* a research concept that was introduced and elaborated in a series of foundational publications (Roco, 2002; Roco and Montemagno, 2006; Roco and Bainbridge, 2013). In that literature, convergence has been defined most generally as "an approach to problem solving that cuts across disciplinary boundaries. It integrates knowledge, tools, and ways of thinking from life and health sciences, physical, mathematical, and computational sciences, engineering disciplines, and beyond to form a comprehensive synthetic framework for tackling scientific and societal challenges that exist at the interfaces of multiple fields" (National Research Council [NRC], 2014, p. 1).

In 2016, the National Science Foundation (NSF) named "Growing Convergence Research" as one of its *10 Big Ideas* for prioritizing future investments in science and engineering. In an associated program solicitation, the NSF (2019) identifies convergence research as having the following two primary characteristics (see **Figure 1**).

Examples of the first characteristic – research driven by a specific and compelling problem – abound in a broad array of sectors. In the realm of infectious disease, for instance, the threat of Zika accelerated convergence approaches that brought together immunologists, engineers, chemists, and biologists who developed techniques that can alter the genetic structure of mosquitos. This has introduced the possibility of eliminating the vectors for Zika as well as dengue and perhaps even malaria (Sharp et al., 2016b, p. 31). Researchers with backgrounds in structural engineering, biology, and chemistry are generating new organic materials that would allow buildings to self-heal their own cracks after disaster strikes (Heveran et al., 2020). In biomedical fields, researchers are working on improved disease detection, new drug delivery mechanisms, and new capabilities to modify genetic disorders (MIT Washington Office, 2011, p. 4). Physicians now partner with engineers and computer scientists to use 3D printing technologies to develop customized joint implants for a broader range of body types as well as other medical devices such as hearing aids and dental implants (National Research Council [NRC], 2014, p. 33–34). Rapid advancements in the biomedical sciences have hastened calls for additional convergence investment in the areas of energy,

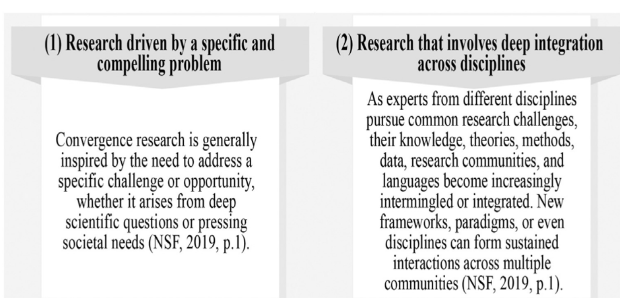


**FIGURE 1 |** Primary characteristics of convergence research.

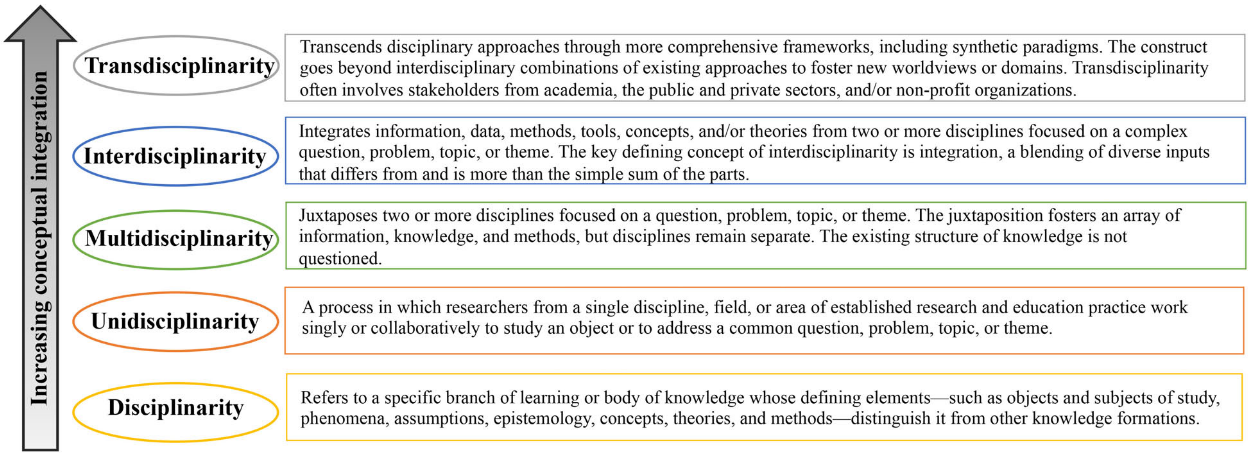


**FIGURE 2 |** Conceptual degrees of disciplinary integration.

food, climate, and water (National Research Council [NRC], 2009), geosciences (McNutt, 2017), health care (Sharp et al., 2016a), psychiatry (Eyre et al., 2016), and, now, hazards and disaster research.

The demand for the second characteristic – deep integration across disciplines – highlights the need for novel approaches to knowledge creation that are relevant to increasingly complex problems. This means that "convergence goes beyond collaboration" and requires the integration of historically distinct areas of inquiry into a "unified whole that creates new pathways and opportunities" (Sharp et al., 2016a, p. 1522). A report from the National Research Council [NRC] (2014, p. 45–46) offers a synthetic typology to represent such increasing degrees of conceptual integration across disciplinary boundaries (see **Figure 2**).

Promoters of convergence acknowledge that the principle of researchers acquiring a depth of knowledge *within* established disciplines remains vital to scientific progress (Sharp and Langer, 2011). But convergence also entails comprehensive integration *across* disciplines. Interdisciplinarity and especially transdisciplinarity, therefore, are most often upheld as the desired states for convergence efforts to thrive (Eyre et al., 2016). Bainbridge and Roco (2006b, p. x) point out that the goal of such integration is not to "create and enforce some kind of new 'orthodoxy' in science and engineering," but, rather, "to nurture all the legitimate connections between fields."

## Convergence Gaps and Barriers

Sharp and Langer (2011, p. 527) identified convergence as the "third revolution" in the biomedical sciences (molecular biology and genomics represent the other two major revolutions). Convergence has clearly transformed the ways that researchers are leveraging computational and technological innovations and merging insights from historically distinct disciplines in the life sciences, physical sciences, and engineering (MIT Washington Office, 2011; Sharp et al., 2016b). The National Research Council [NRC] (2014, p. 14) acknowledges, though, that the "social sciences and humanities are undertapped resources for convergence efforts."

The fact that the social sciences and humanities have received limited attention in the rapidly growing convergence literature represents an important gap (although for exceptions, see: Bainbridge and Roco, 2006a; Roco et al., 2013). Many of the grand challenges that have been identified as of pressing concern – ranging from health care access to environmental degradation – are, at their core, moral, ethical, social, and political problems that require the expertise of those skilled in the study of culture, history, policy, finance, and human behavior. This means that disciplines such as anthropology, philosophy, history, economics, political science, sociology, geography, and psychology could play a central role in advancing the convergence revolution. This will not only broaden the horizons of scientific inquiry and discovery; it could also help to mitigate the unintended consequences of issuing *technical fixes* for what are *fundamentally human problems.*

The convergence revolution has ushered in a fresh vision for how scientific and technological progress can be accelerated through transdisciplinary teams coming together to solve grand challenges for the expressed benefit of society. Bainbridge and Roco even claim that the "future welfare of humanity depends upon mastering... emerging technologies and devoting them to positive applications" (2006b, p. ix). But as Olson et al. (2020, p. 7) convincingly argue, the principal disaster risk reduction (DRR) challenge "is no longer purely the scientific understanding of hazards... nor is it so much the planning, architecture, engineering, or even the social science knowledge required to reduce or at least better manage risk." From their perspective, the principal DRR challenge "now falls primarily in the policy and implementation realms and... in building increased public support for decision-makers and political leaders to champion stronger and more consistently applied DRR policies and programs."

Even when there is political will, identifying solutions to the many problems facing humanity is difficult and could even be potentially harmful. As social scientists who study the intended and unintended consequences of technical interventions have observed, a seemingly brilliant solution for one issue can create an entirely new challenge. For instance, curbing climate emissions through taxation can provide an incentive for behavioral change, but it may further disadvantage poor people, rural citizens, and other marginalized populations. These are not just hypotheticals. Consider the Yellow Vest movement in France, where working-class protesters took to the streets to rally against government-backed emissions reduction standards that caused fuel prices to skyrocket (Kinniburgh, 2019). A recent conflict in Portland, Oregon, also illustrates this point. There, efforts to save lives through the retrofit of unreinforced masonry churches, businesses, and homes for earthquakes simultaneously threatened to disenfranchise and displace African Americans and other communities of color with long histories of dispossession (Njus, 2019).

The aforementioned examples illustrate how fraught "problem-driven" and "solutions-based" approaches to science and engineering can be. This is especially true when there is a lack of diversity within the teams devising the approaches (Hong and Page, 2004; Homan et al., 2007; Horowitz and Horowitz, 2007). This suggests that as the convergence revolution progresses, it must continue to encourage and incentivize diversity in many forms, including *functional diversity* in problem-solving approaches and *identity diversity* in the demographic, cultural, and geographic backgrounds of researchers (National Research Council [NRC], 2014, p. 64). Focusing on inclusion along these varying dimensions can help ensure that existing social injustices and inequalities are not further exacerbated and instead can be addressed in the process of searching for solutions to problems.

In addition to these broader challenges to convergence, there are also structural barriers that threaten to diminish the potential for transformational transdisciplinary research. A report focused on convergence in the biomedical sciences identified two major underlying problems associated with the advancement of convergence research: "(1) a shortage of workers with capabilities in convergence scientific, medical, bioengineering fields, and (2) inadequate [corporate and government] funding for early stage research" (Sharp et al., 2016b, p. 56). The authors cite related challenges associated with siloed agency structures and missions, institutional structures that do not reward cross-disciplinary work, narrow and restrictive grant review processes, and shortcomings in STEM-related education – from grades K-12 through the university-level.

An earlier National Research Council report on convergence identified many similar challenges in advancing convergence research, and advocated for the following correctives: (1) establishing effective organizational cultures, institutional structures, and governance systems; (2) addressing faculty development and promotion needs; (3) creating effective and holistic education and training programs; (4) forming diverse stakeholder partnerships; and (5) obtaining sustainable funding (National Research Council [NRC], 2014, p. 60–62). In each instance, the authors offer specific recommendations and strategies for how institutional resources can be applied to help overcome longstanding challenges, while also acknowledging that the various barriers to convergence echo those described by interdisciplinary and transdisciplinary team members more generally.

### Convergence and the Science of Team Science

Early as well as more recent convergence publications focus heavily on *what* new innovations and trends in science should be pursued and the economic or societal benefits associated with them (Roco, 2002; Bainbridge and Roco, 2006a; Roco and Bainbridge, 2013). The lessons developed by researchers advancing the Science of Team Science (SciTS) can inform the *who* and *how* of convergence research while also helping to overcome some of the identified barriers.

Scholars in the SciTS examine the "processes by which scientific teams organize, communicate, and conduct research" (Börner et al., 2010, p. 1). This emergent field recognizes that teams vary not only in terms of their research goals, but also in their disciplinary composition, size, geographic scope, organizational complexity, levels of intellectual integration, and translational capacity (Stokols et al., 2008a). Ultimately, SciTS helps to understand "*how teams collaborate to achieve scientific breakthroughs that would not be attainable through either individual efforts or a sequence of additive contributions*" (Falk-Krzesinski et al., 2011, p. 146, emphasis added).

Although the term emerged in 2006, SciTS is in many ways a continuation of a body of research on teams that dates back to the well-known Hawthorne studies of the late 1920s and early 1930s (Mathieu et al., 2018). SciTS also builds on the "sociology of science," a research enterprise that began in the 1960s (Merton, 1973) and included studies that illuminated how scientists work together to publish (De Solla Price, 1965) and share knowledge across "invisible colleges" (Crane, 1972). These precursors to SciTS provided foundational insights regarding who was involved in the scientific enterprise and how they collaborated (or not) to conduct research. Since the 1980s, scholars have raised concerns that highly specialized approaches to science and scientific training are insufficient to solve increasingly complex contemporary problems (Hollingsworth, 1984). Pioneers in what would become the field of SciTS spent the next decade researching how to make multidisciplinary, interdisciplinary, and transdisciplinary research a reality so that various problems could be more readily addressed (Klein, 1991, 1996; Committee on Facilitating Interdisciplinary Research, 2004; Epstein, 2005; Hadorn et al., 2008).

Drawing heavily on this body of social and behavioral science research on group dynamics and interpersonal processes, SciTS researchers address both *micro-level team processes* associated with team member familiarity and social cohesiveness, team size, leadership traits and behaviors, goal setting, communication patterns, and task and outcome interdependence, as well as more *macro-level conditions* such as organizational support, institutional reward structures, histories of collaboration, and distributions of power and control across team and institutional boundaries (Hall et al., 2008, 2018; Stokols et al., 2008a). SciTS researchers have also studied many of the challenges that can impede the work of diverse research teams and have offered clear advice for how to overcome them (Cooke and Hilton, 2015).

Convergence researchers can learn from SciTS research how to create inclusive research teams and how team composition affects performance (Guimerà et al., 2005; Contractor, 2013; Zhu et al., 2013; Lungeanu et al., 2014). Managing diverse research teams often requires new forms of leadership, which is another area of inquiry pursued by SciTS researchers (Bammer, 2008; Gray, 2008; Adams et al., 2012). SciTS researchers have also explored how communication processes work in teams and how to develop shared languages and meanings that enable researchers to bridge disciplinary divides (Eigenbrode et al., 2007; Klein, 2014; Hardy, 2018).

While leadership and communication are vital to functioning teams, other elements related to the context in which scientific teams work can also shape project outcomes (Stokols et al., 2008b). As previously noted, institutions can either hamper or cultivate convergence research, and existing SciTS research has illuminated how multi-university research collaboration works and why certain types of universities tend to have higher success rates with this approach (Cummings and Kiesler, 2007; Jones et al., 2008).

Existing SciTS research offers a roadmap for how to measure knowledge integration within convergence research projects (Wagner et al., 2011). Insights from SciTS researchers who have developed evaluation systems for interdisciplinary and transdisciplinary research can assist convergence researchers in developing quantitative and qualitative measures that account for the goals, objectives, and benchmarks of success of teams comprised of researchers with diverse backgrounds (Defila and Di Giulio, 1999; Klein, 2008).

The SciTS has garnered much scholarly attention and momentum over the past decade, in large part because this approach helps to establish not only how and why teams work, but how they can work more effectively together to generate rigorous scholarship (Fiore, 2008). As a case in point, an analysis of more than 17 million publications in the Web of Science found that teams not only produce more research, but also generate higher impact research (Wuchty et al., 2007). Teams are more likely to combine knowledge in atypical ways that lead to scientific breakthroughs that can help address vexing problems (Fiore, 2008; Uzzi et al., 2013). The SciTS is therefore an essential partner to convergence progress.

## A FRAMEWORK FOR CONVERGENCE RESEARCH IN THE HAZARDS AND DISASTER FIELD

Even with the potential challenges and barriers in mind, we believe the hazards and disaster field is poised to advance convergence research while also benefiting from the adoption of its core tenets. Researchers in the field have already employed what McNutt (2017, p. 2) refers to as "convergent-like" approaches. She observes, for example, "the remarkable reduction in earthquake fatalities in nations such as Japan, Chile, and the United States is the result of convergent-like research partnerships between geologists, seismologists, earthquake engineers, architects, social scientists, and public officials. These partnerships have resulted in improved maps of earthquake risk areas, estimates of strong ground motion, engineering designs for earthquake resistant structures, and revised building codes compliant with those designs" (McNutt, 2017, p. 2–3).

Similarly, the reductions in loss of life from weather-related hazards can be attributed to "convergent-like" collaborations between meteorologists, sociologists, psychologists, transportation engineers, urban planners, geographers, wind engineers, architects, and emergency managers. These multidisciplinary and cross-organizational partnerships have led to more timely and accurate weather forecasting, a sustained focus on socially vulnerable populations, more effective risk communication and evacuation strategies, wise land use planning in hazard-prone areas, enhanced engineering designs for wind resistant structures, and more stringent building codes and standards (see Gruntfest, 2018; Lindell et al., 2019; Laska, 2020).

So, have hazards and disaster researchers already been engaging in convergence? To answer that question, we return to the definition that we offered previously for convergence research for the field, now with several key elements underscored:

> *An approach to <u>knowledge production and action</u> that involves <u>diverse teams</u> working together in novel ways—<u>transcending disciplinary and organizational boundaries</u>—to address <u>vexing social, economic, environmental, and technical challenges</u> in an effort to <u>reduce disaster losses and promote collective well-being</u>.*

The aforementioned examples, as well as many others that we could draw on from the field, represent research designed with a compelling challenge in mind – the reduction of loss of life and property and the lessening of societal disruption from natural hazards. An ever-growing number of studies have expanded the evidence base. And although success at actually reducing disaster impacts varies widely at more granular scales, generally speaking, loss of life globally has lessened as economic costs have increased (Wallemacq and House, 2018).

Much of the work in the hazards and disaster field also involves cross-disciplinary and cross-organizational collaborations. But most approaches in the field remain "convergent-like" rather than representative of "true convergence" because they are not advancing solutions nor are they reflective of interdisciplinarity or transdisciplinarity in action. In each of the prior examples, the disciplinary contributions are still readily apparent – it is the urban planners and geographers who lead land use planning efforts, the engineers who develop designs for earthquake- or wind-resistant structures, the psychologists and sociologists who produce the frameworks for risk communication that are then adopted by public officials and analyzed by policy studies experts. These are, of course, laudable efforts that illustrate the powerful contributions of a range of disciplines.

A convergence framework, however, is designed to move beyond additive contributions from distinct disciplines. Again, one of the goals of convergence is to cultivate researchers who have deep disciplinary expertise (depth) and are also well-versed in other disciplines (breadth). Convergence also requires cultures, systems, and institutions that facilitate diverse teams of researchers coming together to learn and conduct integrative studies that are solutions oriented (Nash, 2008; Read et al., 2016). The level of integration that is necessary to achieve interdisciplinarity and transdisciplinarity in research is difficult and time consuming (Kendra and Nigg, 2014; Davidson, 2015), although recent scholarship signals a possibility for a turn toward convergence research. Indeed, a number of contemporary publications focused on interdisciplinarity in the hazards and disaster field detail novel methodological approaches (Reilly et al., 2018; Gharaibeh et al., 2019; Wong-Parodi and Smith, 2019; DeRouen and Smith, 2020), new theoretical frameworks (Sherman-Morris et al., 2018; Subedi et al., 2018; Sutley, 2018; Mostafavi and Ganapati, 2019; Olson et al., 2020), team-based interventions to facilitate the research process itself (Ganapati and Mostafavi, 2018; Morss et al., 2018; Tate et al., 2018; Ge et al., 2019; Gilligan, 2019; Moezzi and Peek, 2019), and advancements in policy implementation and practice (Berke et al., 2018; Sapat, 2018; Johnson, 2019).

The interdisciplinary disaster science degrees offered at the University of Delaware and University of North Texas, for example, are representative of what is possible when social scientists, engineers, policy analysts, emergency managers, and others co-create educational programs that encourage the deep collaboration that convergence calls for. Similarly, the Center for Risk-Based Community Resilience Planning, a National Institute of Standards and Technology Center of Excellence, has methodologically cross-trained well over 100 engineers and social scientists as part of their expansive interdisciplinary program of research (van de Lindt et al., 2020). Over time, if such integrative activities are supported and successful, they can take root and perhaps grow into an entirely new transdisciplinary space (see **Figure 3**). One example of where this has happened is molecular biology, which originated from cell biology and biochemistry but is now recognized as a unified discipline (National Research Council [NRC], 2014, p. 64). Disaster science may be on a similar unifying path (Peek et al., 2020).

Disasters occur at the interface of built, natural, social, and economic environments. Efforts to characterize the range of causes and consequences of extreme events therefore require approaches that draw on multiple disciplines. It is perhaps no surprise, then, that the hazards and disaster field has historically encouraged and incentivized researchers to work together across disciplinary and organizational boundaries. The National Science Foundation Humans, Disasters, and the Built Environment (HDBE) program, for example, supports "fundamental, multidisciplinary research on the interactions between humans and the built environment" in the context of "natural, technological, and other types of hazards and disasters" (National Science Foundation [NSF], 2020). In their analysis of funding for multidisciplinary research between 1982 and 2017, Behrendt et al. (2019) found a positive correlation between award funding and increasingly large multidisciplinary teams in HDBE and other disaster-oriented programs at the National Science Foundation. These multidisciplinary teams, however, only accounted for about one-fifth of funded projects during the study period.

## CONVERGE

*How can the field of hazards and disaster research contribute to the convergence revolution?* The National Science Foundation-supported CONVERGE facility – which was established in 2018 as the first social science-led component of the Natural Hazards Engineering Research Infrastructure (NHERI) – is dedicated to answering that question by bringing a

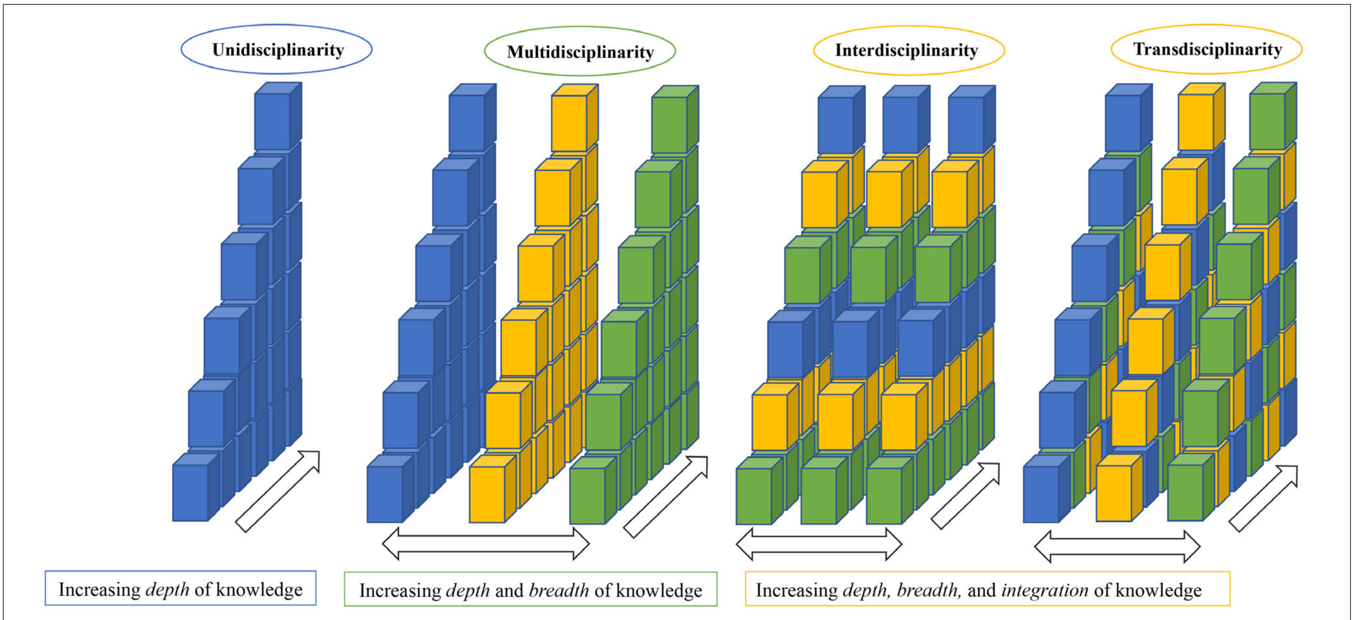


**FIGURE 3 |** Convergence requirements: depth, breadth, and integration of knowledge.

convergence framework to hazards and disaster research (see **Figure 4**). The following sections describe how this framework is being implemented through CONVERGE, which is headquartered at the Natural Hazards Center at the University of Colorado Boulder.

## Identifying Researchers

In 2006, the National Research Council published *Facing Hazards and Disasters: Understanding Human Dimensions*. In that monograph, the Committee on Disaster Research in the Social Sciences dedicated an entire chapter to "The Present and Future Hazards and Disaster Research Workforce." The report raised numerous questions, including: How many hazards and disaster researchers are active in the field? What disciplinary backgrounds and types of methodological expertise do these researchers bring to the study of extreme events? Are these researchers prepared with requisite workforce skills and knowledge to face twenty-first century challenges?

The first step in developing a robust workforce, as the committee acknowledges, is knowing who is part of it already. No precise accounting currently exists, however, of the size or demographic composition of the members of the field (although as a start for the social sciences, see Peek et al., 2020). For this reason, the first step in advancing a research agenda rooted in convergence is to *identify* who counts themselves as a member of the research community. Understanding more about the composition of the hazards and disaster workforce matters because it must be "of adequate size, reflect the diversity of the nation, and include researchers who have both basic and applied research interests and are capable of carrying out disciplinary, multidisciplinary, and interdisciplinary research" (National Research Council [NRC], 2006, p. 319). Identification is also a prerequisite for developing comprehensive educational programs and initiating equitable collaborative efforts that involve a range of researchers – including women and members of historically underrepresented groups – from different disciplines.

Identifying researchers is no simple task, though, and that is why this effort is core to the mission of CONVERGE. The hazards and disaster field is composed, as already noted, of researchers from many different disciplines across multiple scientific and engineering domains and the humanities who are affiliated with academic, private sector, non-profit, and government organizations. While various disciplinary

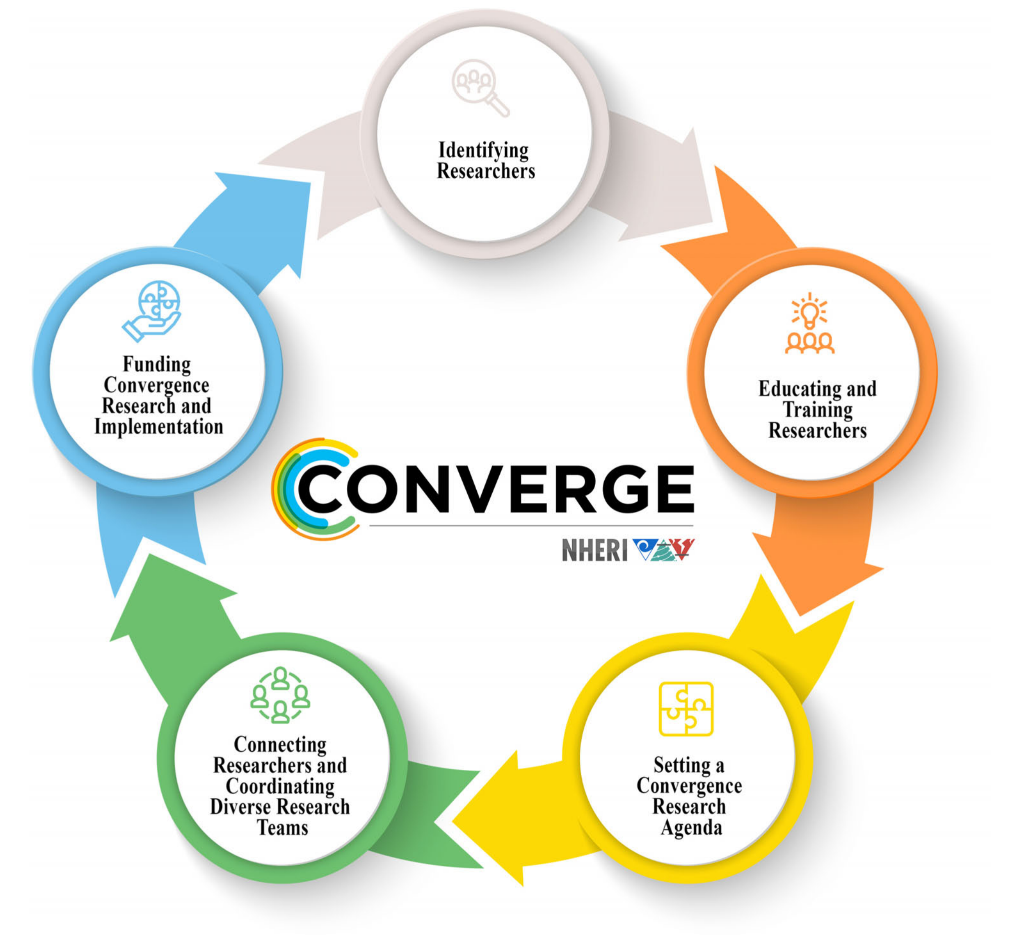


**FIGURE 4** | The CONVERGE framework for supporting convergence research.

and specialty organizations exist that might help to identify some members of the community – such as the Earthquake Engineering Research Institute, the American Society of Civil Engineers, or the American Association of Geographers – these organizations are fee-based and therefore their members are those who can afford to pay.

Due to these and myriad other difficulties with identifying who is a member of the hazards and disaster research community, one approach to finding researchers is to ask them to self-identify with groups or associations that are most aligned with their interests and expertise. This is the idea that has, in part, driven the creation of several NSF-supported Extreme Events Reconnaissance and Research (EER) networks. To date, such networks have been established for geotechnical engineering, social sciences, structural engineering, nearshore systems, operations and systems engineering, sustainable material management, and interdisciplinary science and engineering (see **Figure 5**). These networks are joined together under the auspices of CONVERGE, which is designed to cultivate this type of multi-team research structure working in a much larger hazards and disaster ecosystem (for additional guidance from the SciTS, see Shuffler and Carter, 2018).

Each of the NSF-supported EER networks has taken a different approach to how they identify members. GEER, for example, grew out of an *ad hoc* network of geotechnical engineering reconnaissance teams that responded to the 1989 Loma Prieta earthquake, the 1994 Northridge earthquake, and the 1995 Kobe earthquake. The NSF later awarded a grant to establish GEER to help formalize post-disaster geotechnical reconnaissance efforts (see Bray et al., 2018). SSEER, which was created to identify, support, and coordinate social science researchers, was launched with a formal "Call to Social Scientists," which included an invitation to join the network through completing a brief online membership survey (Peek, 2018). The members were then counted as part of the first census of social science hazards and disaster researchers (Peek et al., 2020) and added to the SSEER map that locates researchers geographically and summarizes their areas of expertise (Mathews et al., 2020). StEER requires that its members have formal training or experience as a structural engineer or in allied fields and that they fill out an online membership application. The point of these examples is that while each of the EER networks has developed membership requirements and generated membership rosters in different ways, they share a common goal in finding and recognizing those who identify themselves as members of a particular research community. CONVERGE, in turn, helps each of the EERs to communicate and share information regarding the size, location, diversity, and range of scientific and technical expertise across the distinct research communities.

## Educating and Training Diverse Researchers

While all established disciplines are continually evolving, the hazards and disaster research field may be especially dynamic (Michaels, 2003; Power, 2018). This is because the field is composed of researchers with varying levels of integration and training. Consider, for instance, that the field is made up of *core researchers*, who are highly committed and spend the most considerable amount of time engaged in hazards- and disaster-specific studies and service activities; *periodic researchers* who do not necessarily see themselves as primary to the field but who focus on related topics from time to time throughout their professional careers; *situational researchers* who become interested in the field because their community is struck by disaster or because a specific opportunity arises to explore new phenomena; and *emerging researchers* who are students, early career scholars, or others new to the field who are still learning about its histories, theories, methods, and approaches (for elaborations on this researcher typology, see: National Research Council [NRC], 2006; Peek et al., 2020).

As the number of disaster events has increased, so too have the number of periodic, situational, and emerging researchers. Because these researchers have the potential to grow and strengthen the field – but may not be fully aware of its contributions over the decades – it is especially important to educate them and encourage them to join the long-standing community of core researchers who are often, although not always, connected to established academic hazards and disaster research centers and institutes. To this end, the 2006 National Research Council report asserts that "specific strategies must be devised (1) to put the next generation of researchers in the pipeline and (2) to recruit new researchers from the existing pool" (p. 320).

The literature on methods and approaches to extreme events research suggests that there is an ethical imperative, in addition to a scientific rationale, for educating and training new generations of researchers (Van Zijll de Jong et al., 2011; Browne and Peek, 2014; Miller et al., 2016; Packenham et al., 2017). Disasters often cause disproportionate harm among marginalized populations and can lead to long-term and shifting vulnerability among people. This recognition has led for calls to increase the number of researchers who are women and racial and ethnic minorities to ensure that the research process itself is sound and that researchers are reflective of the people they study and serve (Anderson, 1990; Peek, 2006; Louis-Charles and Dixon, 2015). Disaster researchers may also witness widespread suffering, damage, and loss, which can cause distress among researchers themselves. For these and many other reasons, not only do researchers need training and mentoring in terms of *how* to do research that is ethical and rigorous, they also need to learn *why* conducting studies in at-risk or disaster-struck communities may be especially challenging (Drabek, 1970; Stallings, 2002).

Core to the mission of CONVERGE is to accelerate the education of a diverse next generation of hazards and disaster researchers. To that end, the CONVERGE team has developed a series of training modules that cover a wide range of topics including, for example, social vulnerability and disasters, disaster mental health, cultural competence, emotionally challenging research, and Institutional Review Board (IRB) procedures for human subjects research. Designed for students, early career scholars, and others new to the field, each module features learning objectives and lesson plans; written content based on a comprehensive review of available literature; examples of past research and links

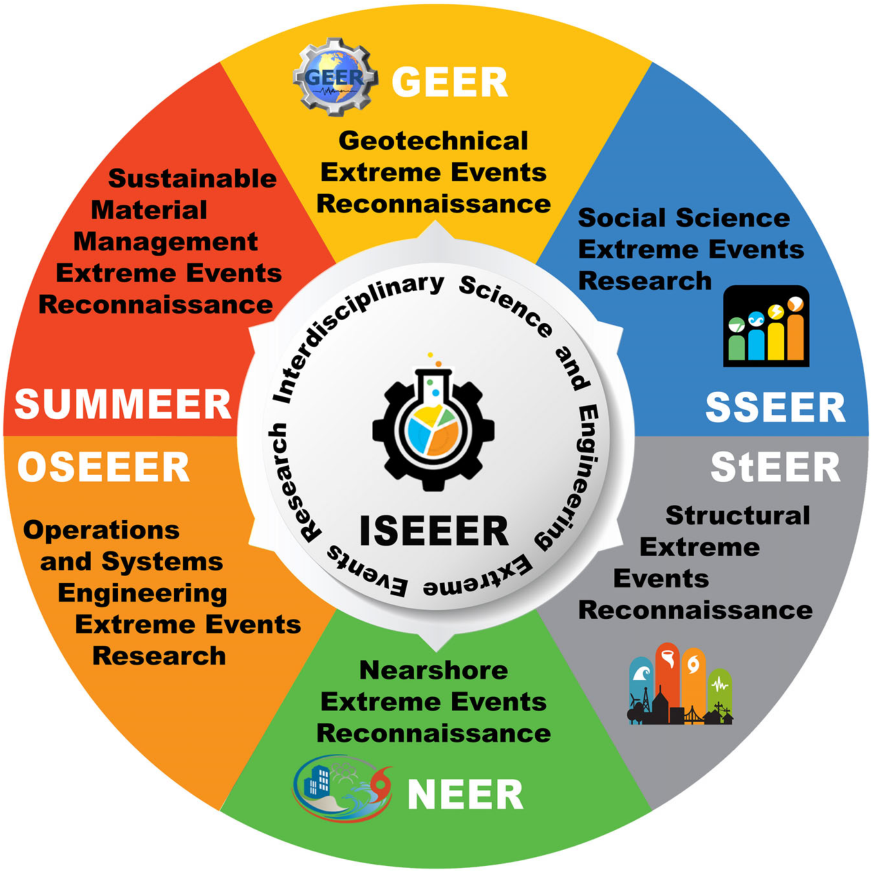


**FIGURE 5 |** NSF-supported extreme events reconnaissance and research networks.

to additional resources; and a final quiz and certificate of completion.

The CONVERGE team has also initiated a series of one- to two-page briefing sheets and check sheets which provide best practice recommendations to help inform the scientific rigor and ethical conduct of extreme events research. The briefing sheets are part of a special peer-reviewed series published in partnership with the journal *Natural Hazards Review* and involving authors from a range of disciplines. As a supplement to the briefing sheets, the CONVERGE team has developed a series of graphical check sheets meant to be used as researchers design their studies, prepare to enter the field, conduct quick response research or other longer-term field studies, and exit the field.

The training materials and guidance documents being developed by CONVERGE are available for free and online as part of a broader effort to democratize access to foundational and recent research in the field (see: https://converge.colorado.edu/resources). While we recognize that researchers will not become experts after completing a training module or reading a briefing sheet, these types of materials can help researchers to quickly background themselves with available knowledge and be prepared for further exploration. Moreover, by compiling these materials in a centralized repository, researchers who are new to the field can more quickly gain a sense of the wealth of available information. As noted by Sharp et al. (2016a), such training efforts have the important benefit of educating a generation of researchers across disciplines to become facile and conversant in a range of fields and ready to take full advantage of convergence research opportunities as they arise.

As demand for disaster-related knowledge grows, a substantial investment in academic training and mentoring programs that educate researchers within and across disciplinary silos is needed to advance convergence research. CONVERGE therefore offers additional opportunities for in-person training and mentoring through hands-on data publication workshops and annual researchers meetings held in Colorado, for example. These and other associated activities are designed to connect next generation scholars to one another and to more senior mentors in the field. CONVERGE also partners with the Bill Anderson Fund and the Minority SURGE Capacity in Disasters project – which are initiatives dedicated to increasing the number of historically underrepresented researchers and practitioners in the field – to ensure that African American, Latinx, Indigenous, and other scholars from communities of color are supported to participate in workshops and other mentoring activities.

### Setting a Convergence Research Agenda That Is Problem-Focused and Solutions-Based

Once researchers are identified and educated, then additional possibilities emerge for deeper levels of disciplinary integration. This is especially true when there is a research agenda designed to help channel and focus the activities of a broader research community. CONVERGE is dedicated to developing such an agenda for cross-site, cross-disciplinary, longitudinal convergence research in the hazards and disaster field.

The increasing frequency and intensity of disasters coupled with the growth of the field suggests that the time is right for a more coherent approach to help guide what we study, who we study, how we conduct studies, and who is involved in the research process itself. While the utility of some quick response post-disaster research has been the source of recent scrutiny (Gaillard and Gomez, 2015; Gaillard and Peek, 2019), we argue that the need for refocusing efforts holds across the disaster lifecycle – including preparedness, response, recovery, and mitigation. Convergence, with its approach to promoting transdisciplinary research that is both problem-focused and solutions-based, offers a framework for moving forward given the enduring and emergent challenges confronting people and regions at risk worldwide.

This raises the following questions, though, which drive the research agenda-setting efforts of CONVERGE: *What are the problems our field is ultimately trying to address? And what solutions can be devised in response to the research that is being produced?*

Reducing disaster losses is one overarching goal that we set forth at the beginning of this article. It is also one that is widely shared across the community of hazards research and practice, but its outcome is nebulous. A convergence research agenda requires more precision, beginning with identifying which type or combination of disaster losses researchers seek to address. The issue of concern for any given team might be reducing disaster-related deaths or injuries, business closures, or educational disruptions (see **Figure 6** for more illustrative examples). The point is, the more precise the problem definition, the more focused the convergence research agenda.

Once the various types of disaster losses have been clarified, then it is important to focus our attention on the root causes of those losses. Disaster impacts emerge not simply from nature, but instead from our histories and cultures, from our technical interventions, and as a result of the ways that our societies are structured and our policies are organized (Wisner et al., 2004; Tierney, 2014; Browne, 2015). This means that the drivers of disaster losses are many, complex, and deeply interconnected. If our ultimate goal as a field, however, is to promote collective well-being in terms of advancing vitality, opportunity, connectedness, contributions, and inspiration for all people, this will require a convergence framework to address the varied drivers of disaster (see **Figure 6**, again, for more illustrative, rather than exhaustive, examples).

Identifying ways to reduce disaster losses represent one of the most vexing problems of our time. Given the number of contributors to this outcome, it will require new processes for teamwork and collaboration that can lead to novel practical interventions. This is where a convergence approach informed by the SciTS can be especially useful, as too often, our field remains in the *problem diagnosis* stage. An untold number of

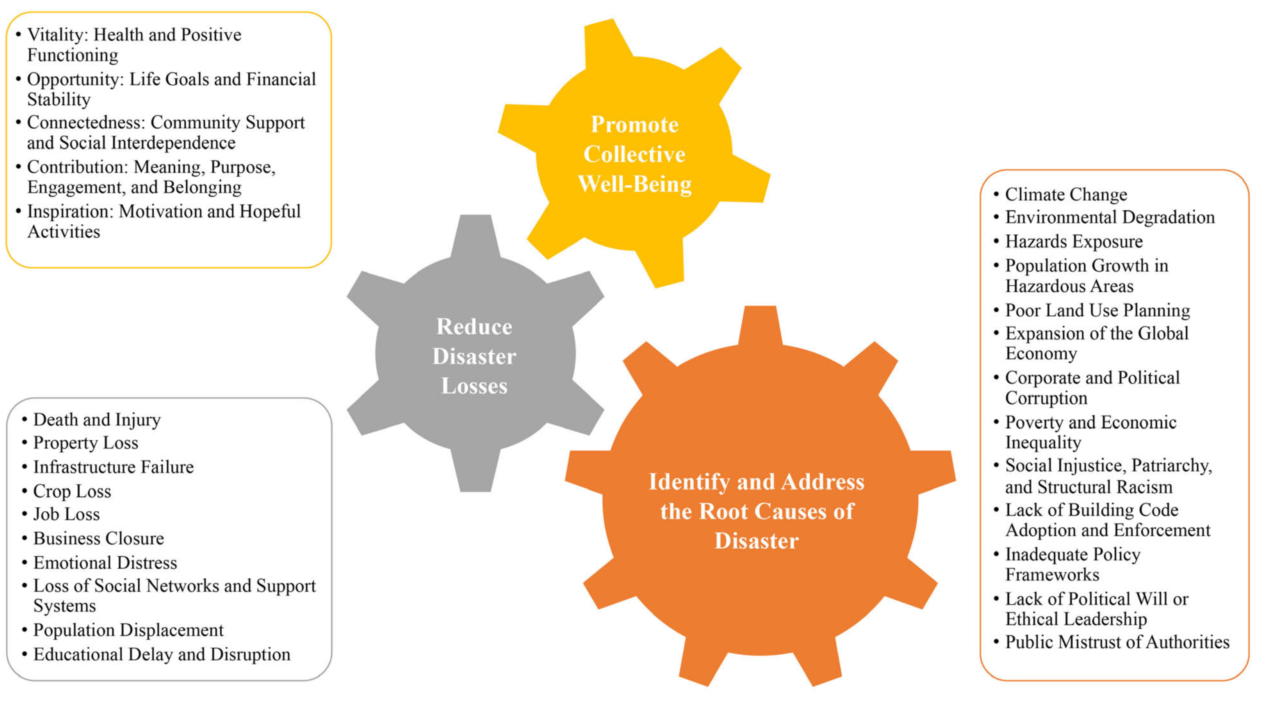


**FIGURE 6 |** Goals for convergence research in the hazards and disaster field.

reports, articles, and books have been published that describe vulnerabilities and failures, often leaving little space to offer a *cure* for the countless consequences of disaster. But when researchers come together with convergence as their guide, it becomes possible to develop more robust interventions. Take for example the groundbreaking work by Sutley et al. (2017a,b,c), which integrated engineering and social science perspectives. Through that collaborative process, her team first discovered that traditional engineering solutions for wood-frame structures may dramatically underestimate mitigation savings by not taking sociodemographic considerations into account. When they are included as part of more conceptually integrative research, it became apparent that mitigation approaches may save even more – in terms of averted deaths, psychological injuries, and dollars lost, especially among marginalized and potentially vulnerable populations – than had previously been considered.

A research agenda rooted in convergence provides a new lens for both examining longstanding problems *and* identifying courses of action to address the root causes of disaster. Convergence is an approach that can help collectively move us toward seeking out solutions for complex social and environmental problems, such as those that culminate in disaster. This is why the CONVERGE facility is invested in establishing convergent processes and supporting diverse interdisciplinary and transdisciplinary teams.

When such teams come together, they have the opportunity to more deeply explore the problem space and therefore can often devise more creative and contextually grounded solutions. For instance, through the combination and extension of engineering and urban planning, Sutley and Hamideh (2017) numerically exposed dynamic and disparate housing recovery processes by incorporating social inequities into traditional mathematical frameworks. Their research not only highlighted the unmet needs of economically marginalized households; it also pointed to sound policy interventions that promote equity through investing in more robust infrastructure in socially vulnerable neighborhoods. Furthermore, their work offers an evidence-based approach for accelerating the equitable distribution of post-disaster shelter and housing. This case is illustrative of the type of research that CONVERGE seeks to champion.

## Connecting Researchers and Coordinating Research Teams

Convergence requires deep disciplinary integration. Yet, the challenge of connecting researchers across disciplinary divides and coordinating research teams is difficult and one that has long been of concern for those interested in participating in and supporting multidisciplinary, interdisciplinary, and transdisciplinary research (Wilson et al., 2015).

The nature of disaster research – which often involves the collection of perishable data and necessitates rapid team formation and deployment – does not always allow for the kind of systematic, measured approach that is required if an area of scholarly inquiry is to make substantial theoretical and conceptual advancements (Tierney, 2007; Börner et al., 2010; Power, 2018). In their report on quick response research, Kendra and Gregory (2015, p. 12) concluded that "field teams [should] coordinate their efforts, both in the earliest days after a disaster, as interest grows in the possibility of quick-response research, and after awards [are] made." Coordinating in the aftermath of the event is certainly desirable, for logistical as well as ethical reasons (Gaillard and Peek, 2019). This can be done most effectively, however, if protocols are established and a coordinating body that performs this function is created *before* disaster strikes (Wilson et al., 2015; Packenham et al., 2017). Furthermore, Tierney (2019, p. 115) argues that the "best way to deal with unacceptable levels of burdensome research is for research teams to communicate and collaborate voluntarily." She adds that "funding agencies have an important role to play in encouraging such coordination but should not mandate it."

The importance of agency-supported, researcher-driven, pre-event coordination drives one of the central tasks of CONVERGE, which is to create and cultivate the first institutionalized Leadership Corps for extreme events reconnaissance and research. The CONVERGE Leadership Corps consists of the principal investigators for the EER networks and the leaders of the four NHERI components that support reconnaissance efforts following natural hazards and other extreme events (this includes the NHERI Network Coordination Office, RAPID facility, DesignSafe cyberinfrastructure, and CONVERGE). As described previously, the EER networks are open to researchers within identified disciplines. The NHERI components, which are described in further detail below, are shared use and therefore meant to make engineering and social sciences resources accessible to the broader hazards and disaster research community.

The CONVERGE Leadership Corps serves a connecting and coordinating function while also advancing the possibility for convergence research in the hazards and disaster field. The members of the Leadership Corps – which includes principal investigators with backgrounds in engineering, social sciences, and natural sciences – meet regularly to share information and to generate opportunities for cross-disciplinary collaborations. For practical purposes, this means that the EER networks have helped to identify researchers *within* particular disciplinary and topical areas, while the Leadership Corps governance structure helps to connect researchers *across* the networks and to the NHERI components that can advance their efforts (see **Figure 7**). While the primary focus of the Leadership Corps is on the academic hazards and disaster research community, we also connect outwards with many other partners from academia, the private sector and local, state, and federal government. As has been observed elsewhere, these types of cross-disciplinary and cross-organizational organizational connections are vital to advancing convergence-oriented research in the hazards and disaster field (Pulwarty et al., 2009; Miller et al., 2016).

The investment that the NSF has made in establishing the CONVERGE Leadership Corps – including the organizational structure and the governance system – is a major step toward moving from "convergent-like" approaches to true convergence. It is now possible for researchers who are

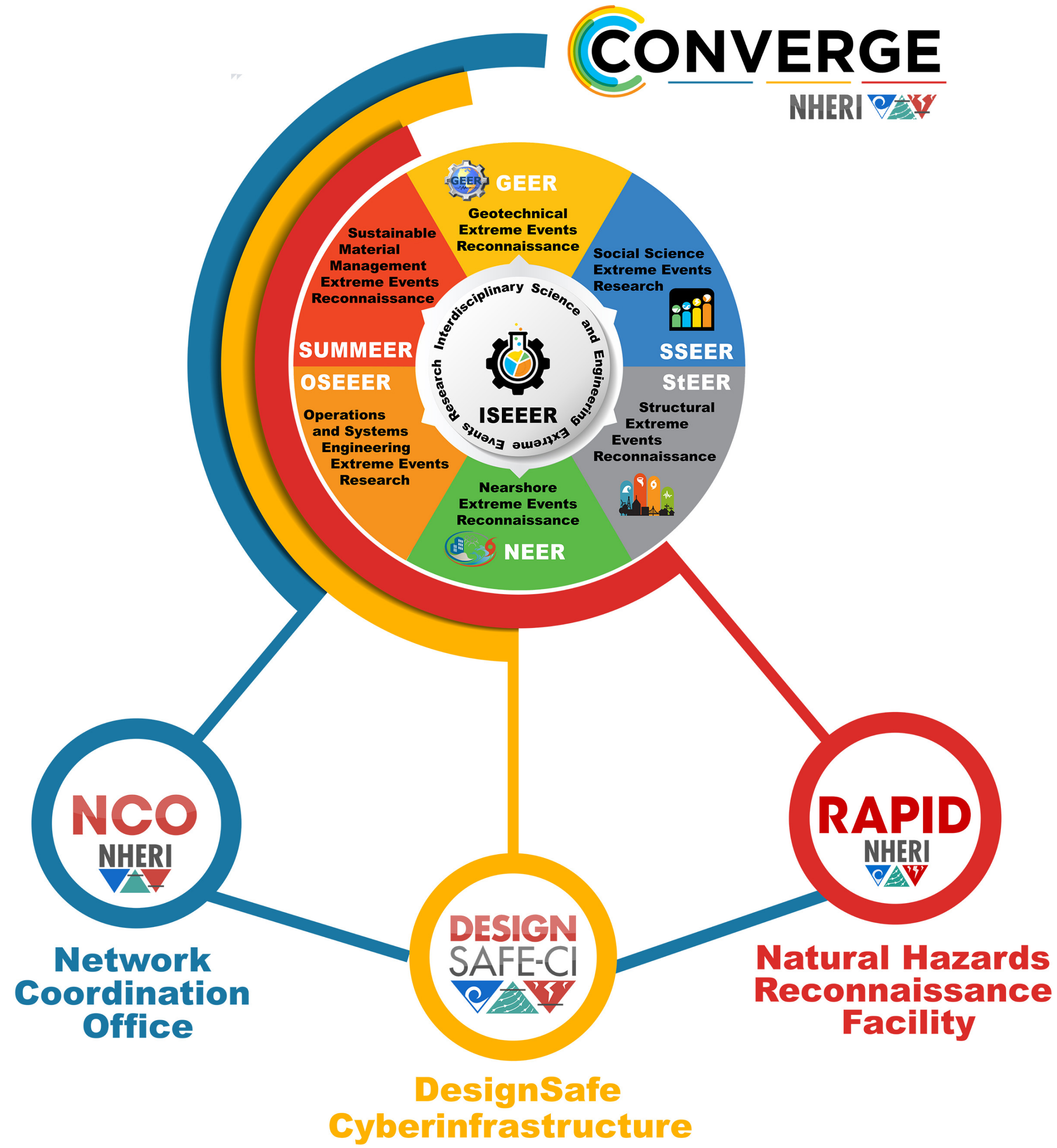


**FIGURE 7 |** NSF-supported CONVERGE leadership corps for extreme events research.

part of the EER networks to communicate, coordinate, and share data and information. The Leadership Corps also encourages researchers to co-design studies that are deeply integrative and explore issues across the disaster lifecycle. Researchers can access key resources through the NHERI shared-use facilities. For example, as researchers initiate projects, they can connect to NHERI and its science plan through the Network Coordination Office, located at Purdue University (Johnson et al., 2020 this issue). They can access tools, technology, and other resources through RAPID – the NHERI facility based at the University of Washington that provides NSF-subsidized equipment and support services to assist with the collection and processing of perishable data from natural hazards events (Berman et al., 2020 this issue; Wartman et al., 2020 this issue). And they can publish reports, protocols, and data through DesignSafe – the cyberinfrastructure platform for the NHERI network, which is based at the Texas Advanced Computing Center at the University of Texas at Austin (Rathje et al., 2017; Rathje et al., 2020 this issue).

These and many other interconnections made possible through the research coordination networks and the NHERI facilities are indicative of how researchers and research teams may begin to move across the conceptual degrees of integration – from unidisciplinarity, to multidisciplinarity, to interdisciplinarity, to, eventually, transdisciplinarity. This shift can reduce the redundancies, delays, and other challenges generated by siloed approaches. With a convergence research framework firmly in place, the focus can also shift toward identifying and working to solve grand challenges (National Research Council [NRC], 2006; Edge et al., 2020).

### Supporting and Funding Convergence Research and Implementation

Many of the most significant advancements in the field would not have occurred without a sustained investment from federal agencies and established academic institutions in hazards and disaster research. Such institutional structures and sustainable funding can also help make convergence research possible (National Research Council [NRC], 2006).

With the National Science Foundation's commitment to "Growing Convergence Research," and its support of the NHERI components and EER networks, the field is now equipped with the coordinating structures and resources to support early stage convergence research. Consider, for example, that when a series of earthquakes rattled Puerto Rico in late 2019 and early 2020, field teams from GEER and StEER were able to deploy nearly simultaneously to conduct reconnaissance research in partnership with locally affected researchers on the island. GEER- and StEER-affiliated researchers shared their virtual and field observations and published their data via the DesignSafe cyberinfrastructure. SSEER leadership, drawing on those preliminary assessments, then called a virtual forum to help establish research priorities and ensure ethical coordination among the social science community.

During the global COVID-19 pandemic, CONVERGE convened hundreds of researchers from dozens of disciplines via successive virtual forums. Spurred by the interest and activity of the research community, CONVERGE then established a global research registry available in multiple languages and funded 90 distinct COVID-19 Working Groups focused on population groups of special concern, impacts and recovery, compound and cascading hazards, and emergent methodological and ethical issues. To catalyze convergence research, the funded Working Groups were required to include members from a minimum of three different disciplines and to submit a research agenda-setting paper that was published on the CONVERGE website.

These examples illustrate how an orientation toward convergence, combined with funding support, can accelerate the development of new research collaborations and innovations. A sub-award between our CONVERGE team and the RAPID facility has led to advancements in engineering, social science, and interdisciplinary capabilities in the RAPID App (RApp), which is a mobile application designed to support the secure collection of engineering damage assessment data as well as quantitative, qualitative, and mixed methods social science hazards and disaster research data.

Another major resource that is now available for the hazards research community is DesignSafe, which is the web-based cyberinfrastructure platform for the NHERI network (Rathje et al., 2020 this issue). DesignSafe provides a secure data repository and the computational tools needed to manage, analyze, and publish critical data for natural hazards research (Rathje et al., 2017). The DesignSafe cyberinfrastructure supports cloud-based research workflows, data analysis, and visualization. Since its launch in 2015, thousands of researchers – predominantly from engineering – have taken advantage of DesignSafe functionalities, publishing several terabytes of data. CONVERGE initiated a subaward with DesignSafe to develop a novel social science, engineering, and interdisciplinary data model for natural hazards research. The data model is available so that social and behavioral scientists, engineers, and members of interdisciplinary teams can publish legacy datasets and recently collected data. Hazards and disaster researchers can have a permanent Digital Object Identifier (DOI) assigned to their datasets and data collection protocols, research instruments, and IRB protocols.

Publishing data and instruments in this way enhances the possibility for richer collaboration and more cross-geographic, cross-disciplinary, and cross-hazards replication in the field. This can ultimately help convergence efforts to take root while also reducing data collection burdens on disaster-affected communities.

Rapid technological change is revolutionizing the ways that hazards and disaster researchers can coordinate, collaborate, and share data and findings. For convergence to truly thrive, however, it is also crucial that government and corporate funding be made available to prototype and test potential solutions to the problems being studied. Convergence, with its focus on addressing grand challenges facing humanity, encourages researchers to develop interventions. The hazards and disaster field, with its applied focus and ethical commitment to returning findings to affected communities, is already advancing new forms of solutions-based thinking. But to do this well, there must be a commitment to and support for working through the entire convergence cycle – from researcher identification to solutions implementation – in multiple iterations. CONVERGE is therefore dedicated to encouraging researchers and their partners to test and evaluate possibilities for reducing disaster losses and promoting collective well-being. These possibilities are nearly limitless, and they span varying geographic and time scales, ecological contexts, social institutions, and policy arenas. Given the scope and urgency of the environmental and social problems that we face, this work is desperately needed. Hazards and disaster researchers are poised to engage in these efforts and to help lead the way toward a more just and sustainable future.

## CONCLUSION

This article has proposed a new definition of *convergence research* for the hazards and disaster field. We have explicated the core tenets of convergence research, identified gaps and barriers to existing approaches, and offered a framework for advancing convergence research in the field. That cyclical framework involves: (1) identifying researchers; (2) educating and training researchers; (3) setting a convergence research agenda that is problem-focused and solutions-based; (4) connecting researchers and coordinating functionally and demographically diverse research teams; and (5) supporting and funding convergence research, data collection, data sharing, and solutions testing and implementation.

The National Academies and the National Science Foundation have both championed growing convergence research across a number of fields, although the social sciences, humanities, and policy studies have been largely underrepresented. The hazards and disaster field, which has long encouraged multidisciplinary collaborations across multiple domains, is poised to contribute to the convergence revolution through recent investments in research coordination networks and shared use facilities to support natural hazards reconnaissance and research. This article has described the efforts of the NSF-supported CONVERGE facility, which is the sole component in the NHERI network that is dedicated to advancing convergence research and involves extensive collaborations across multiple disciplines. The work of CONVERGE and its partners is highlighted throughout to demonstrate current efforts to democratize educational opportunities and the research process through training and fostering interdisciplinary teamwork. These efforts are designed to ready researchers to both assess and address the many pressing social, economic, environmental, and technical challenges that lead to disaster losses. The initiatives described here draw heavily on lessons from the Science of Team Science and are rooted in an ethical commitment to diversity, equity, inclusion, and scientific rigor throughout the disaster research lifecycle.

The various research activities led by the CONVERGE facility exemplify how teams of researchers can apply the steps highlighted in the convergence research framework. To continue to move this work forward, we encourage hazards and disaster researchers to apply these steps to work together to find novel solutions to the mounting threats of extreme events. We call for additional award mechanisms and new opportunities to identify, train, fund, and support the development of interdisciplinary and transdisciplinary teams working to find solutions to complex and deeply rooted social and environmental problems. Focusing these efforts on students, early career faculty, and emerging researchers from historically underrepresented groups is especially important. This will help to grow the number of core researchers in the field, strengthening the hazards and disaster workforce and ensuring that we have the breadth and depth of knowledge to meet twenty-first century demands. As new structures and systems are developed to support interdisciplinary and transdisciplinary research, we envision that our field – with convergence as our guide – can stem the tide of growing disaster losses and promote collective well-being for all people.

## DATA AVAILABILITY STATEMENT

All datasets generated from the CONVERGE facility are available at: https://converge.colorado.edu/. Further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

LP devised the research and manuscript plan, conceived the presented ideas, and wrote the manuscript. JT, RA, HW, and MM read and revised drafts of the manuscript text and figures and helped to develop and advance the CONVERGE initiatives described in the manuscript. All authors contributed to the article and approved the submitted version.

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# Measuring User Satisfaction for the Natural Hazards Engineering Research Infrastructure Consortium

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The User Forum is a Natural Hazards Engineering Research Infrastructure (NHERI)-wide group focused on providing the NHERI Council with independent advice on community user satisfaction, priorities, and needs relating to the use and capabilities of NHERI. The User Forum has representation across NHERI activities, including representatives working directly with the Network Coordination Office (NCO), Education and Community Outreach (ECO), Facilities Scheduling, and Technology Transfer efforts. The User forum also provides feedback on the NHERI Science Plan. As the community voice within the governance of NHERI, the User Forum is composed of members nominated and elected by the NHERI community for a specified term of 1–2 years. User Forum membership spans academia and industry, the full breadth of civil engineering and social science disciplines, and widespread hazard expertise including earthquakes, windstorms, and water events. One of the primary responsibilities of the User Forum is to conduct an annual community user satisfaction survey for NHERI users, and publish a subsequent Annual Community Report. Measuring user satisfaction and providing this feedback to the NHERI Council is critical to supporting the long-term sustainability of NHERI and its mission as a multidisciplinary and multi-hazard network. In this paper, the role and key activities of the User Forum are described, including User Forum member election procedures, User Forum member representation and roles across NHERI activities, and the processes for measuring and reporting user satisfaction. This paper shares the user satisfaction survey distributed to NHERI users, and discusses the challenges to measuring community user satisfaction based on the definition of user. Finally, this paper discusses the evolving approaches of measuring user satisfaction using other methods, including engaging with the twelve NHERI research infrastructures.

**Keywords: user satisfaction, NHERI, evaluation, hazards, experimental facility, consortium**

## INTRODUCTION

The Natural Hazards Engineering Research Infrastructure (NHERI) is a National Science Foundation (NSF) sponsored consortium consisting of physical and simulation infrastructure to support multidisciplinary research broadly focused on natural hazard impacts and resilience. As depicted in **Figure 1**, NHERI consists of (a) a network coordination office (NCO) that offers user support, leads education and outreach activities, develops strategic national and international partnerships, and brings stakeholders together to translate NHERI research into practice and articulates grand challenges for natural hazard engineering research; (b) a community cyberinfrastructure that offers web-based software, and reconnaissance repositories and visualizations open to all NHERI users; (c) a simulation center focused on developing and deploying next-generation computational modeling and simulation tools for infrastructure and regional scale natural hazard simulations; (d) a facility offering diverse state-of-the-art reconnaissance equipment for natural hazard-based measurements; (e) a center focused on convergence across disciplinary-based research communities, specifically bringing together fieldwork-based disciplinary networks; and (f) seven experimental testing facilities that include earthquake, hurricane, tsunami, and other dynamic testing capabilities. The NHERI Council is composed of the principle investigators from each of the eleven NHERI Awards (NCO and ten infrastructures on right side of **Figure 1**). External to and in support of NHERI, the network independent advisory committee (NIAC) consists of representatives from the broad scientific and engineering communities served by NHERI, and the User Forum serves as the community voice in NHERI governance. The User Forum provides independent advice on community user satisfaction, priorities, and needs relating to the use and capabilities of NHERI.

NHERI is a nation-wide consortium with thousands of users. It is critical to measure success of NHERI to promote continued funding and operation. Furthermore, it is essential to measure user satisfaction to promote constant procedural improvements, identify and reduce biases, and promote widespread use of NHERI throughout the natural hazards engineering community. There are many compounding benefits to measuring user satisfaction. First, measuring user satisfaction can inform important changes that may be needed for user retention. User retention ultimately can lead to the sustainability of NHERI, and has its own compounding effects. The continued funding of NHERI with diverse and satisfied users will lead to more use of NHERI, thereby resulting in more scientific advancements in the natural hazards research space. These scientific advances hold tremendous possibility, including the high potential to improve quality of life through more strategic investments and reduced consequences from natural hazards. Such benefits would be felt across the United States, and are often scalable for use around the world.

In measuring user satisfaction, it is always best to be objective rather than subjective. There are a number of metrics that offer a meaningful way to measure user satisfaction across any large consortium. In general, metrics for user satisfaction include user retention, number of users, ways in which users engage or use NHERI, and user-rated experience. Metrics can be measured using different methods, including direct user feedback through interviews or surveys, systematic assessment of the consortium from an external team of evaluators, and through user-data collected in real-time during use (e.g., number of users, tracking how a single user uses NHERI in multiple ways). The User Forum's evaluation follows the "utilization-focused evaluation" approach as developed by Michael Quinn Patton (Patton, 2008). This approach was derived with the intent to focus on the intended use of evaluation data by the intended users and aims to collect data that are meaningful in supporting decision-making processes. The User Forum evaluation also falls into the Rajeshkumar et al. (2013) user experience taxonomy classification of "user-oriented" survey methods collecting both quantitative and qualitative data.

NHERI is one of many major multi-user research facilities funded by the NSF. NHERI is one of two sites in Engineering, where the other is the National Nanotechnology Coordinated Infrastructure (NNCI). These major multi-user research facilities also exist in the geosciences, mathematical and physical sciences, and as research and development centers. NSF-sponsored major multi-user research facilities have a long-supported history of measuring user satisfaction, which proves critically important for the NSF's responsible use of U.S. taxpayer dollars. Despite the long-standing history, there is limited information documenting user satisfaction measurement processes, approaches, challenges, and other decisions, thus providing the most significant impetus for this paper. Given the history of NSF consortiums, NHERI leveraged user satisfaction processes executed for other consortiums. This started with the election of an external committee of users, the User Forum, and continued with member engagement, metric adoption and measurement approaches. The details of each of these are detailed throughout this paper.

## MEMBER ELECTION

As the community voice within the governance of NHERI, up until the time of this submission, the User Forum has been composed of nine representatives who are nominated and elected by the NHERI community. User Forum elections are generally held annually to fill vacant roles as needed. The maximum and minimum number of committee members is not fixed, and can fluctuate based on committee needs. Candidates for vacant roles in the User Forum can be nominated by anyone within the NHERI community, and this opportunity is broadcasted to the NHERI community through NHERI email communications. General User Forum elections are held using the DesignSafe-CI website (https://www.designsafe-ci.org/) to ensure NHERI users have broad access to the elections. Members are elected to the User Forum for a specified term of 1–2 years, with the opportunity to be re-elected.

Members on the User Forum represent the scientific and engineering communities who use NHERI's resources and services for research and/or educational purposes, but who are not directly affiliated with NHERI awardee institutions.

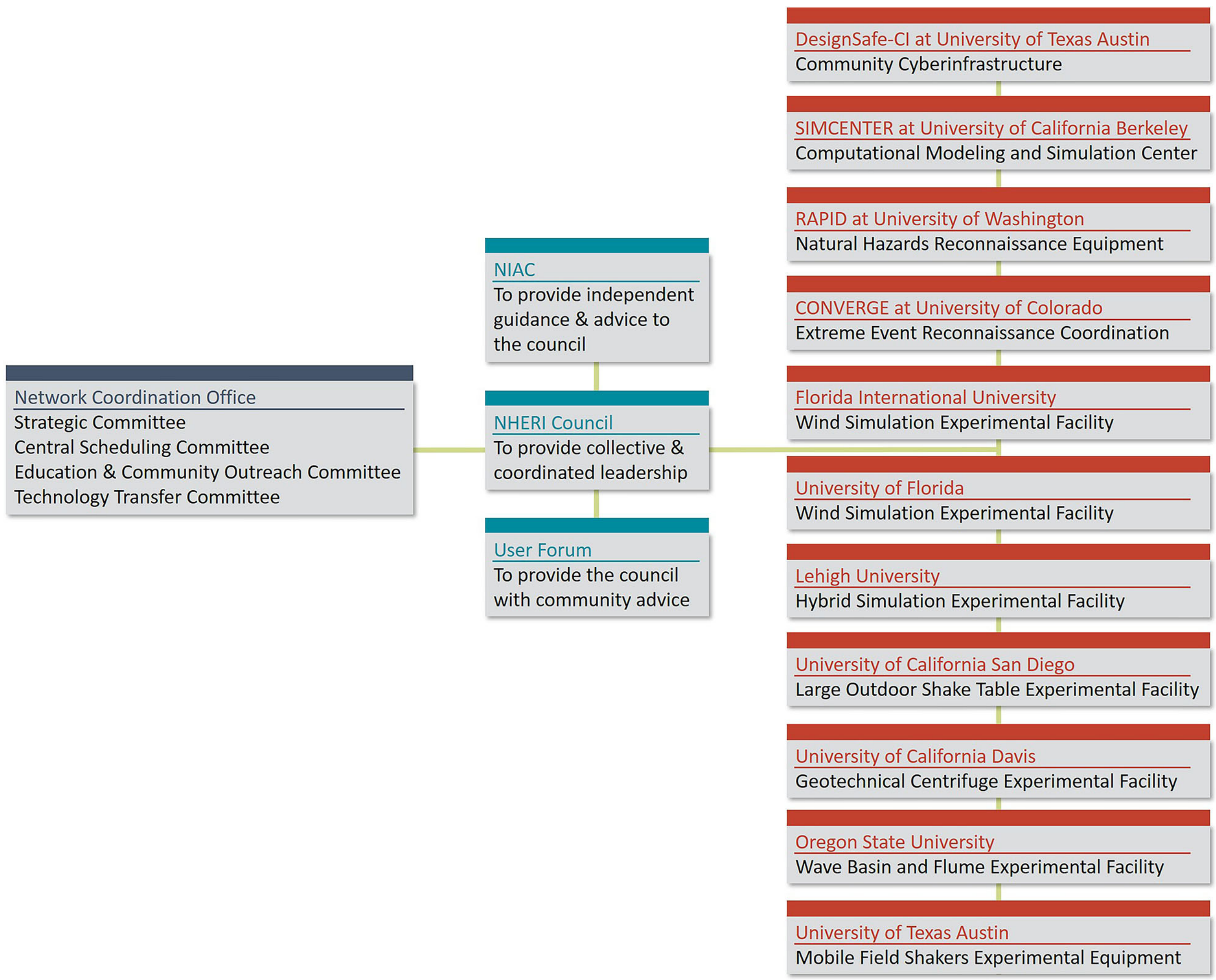


**FIGURE 1 |** Components of NHERI.

User Forum membership spans academia and industry, the full breadth of civil engineering disciplines, the social sciences, and widespread hazard expertise including earthquakes, windstorms, and water events. This broad representation within the User Forum ensures that the needs and concerns of the diverse community of NHERI users are understood by the User Forum and can be accurately expressed to NHERI governance.

## ROLES AND RESPONSIBILITIES

The User Forum provides the NHERI Council with independent advice on community user satisfaction, priorities, and needs relating to the use and capabilities of NHERI. The User Forum, therefore, needs to have a good understanding at a strategic level of the work of the NHERI consortium. This includes an awareness of the vision, values and mission, strategic and operational plans, and evaluation relating to NHERI's work. As depicted in **Figure 2**, the User Forum has historically been comprised of nine members representing the User Forum across NHERI activities, including three User Forum officers (chair, vice chair, and secretary) working directly with the Network Coordination Office (NCO) and participating on monthly NCO meetings, two User Forum representatives working with the Education and Community Outreach (ECO) team, two User Forum representatives working with the Facilities Scheduling committee, and one User Forum representative working with the Technology Transfer committee. Likewise, two members of the NCO participate in User Forum monthly meetings to maintain direct communication between the User Forum and NHERI governance. Additionally, one member leads the User Satisfaction Survey subcommittee, and is joined by the chair, vice chair, and one NCO representative to spearhead the survey work.

Members of the User Forum participate in annual elections of User Forum officers, an annual in-person meeting, and monthly

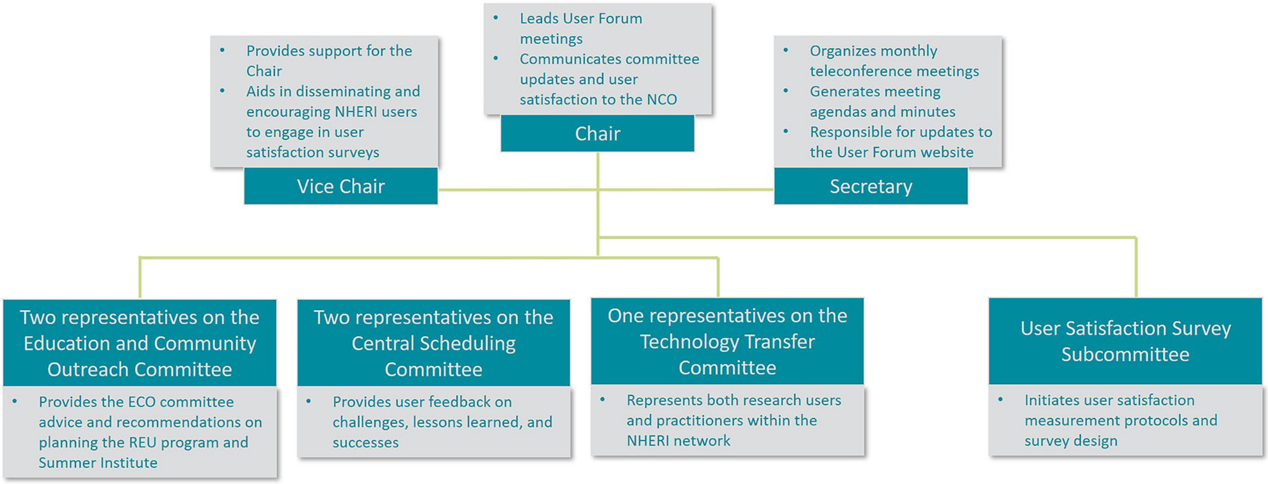


**FIGURE 2 |** User forum member roles and responsibilities.

teleconference meetings. As shown in **Figure 2**, officer roles of the User Forum include Chair, Vice Chair, and Secretary. The Chair is responsible for leading User Forum meetings, assisting in the development of assessment tools of user satisfaction, and communicating committee updates and user satisfaction to the NCO. The Vice Chair serves as support for the Chair, assuming Chair responsibilities when necessary, and also aids in disseminating and encouraging NHERI users to engage in user satisfaction assessment surveys. The Secretary organizes monthly teleconference meetings, generates meeting agendas and minutes, and is responsible for updates to the User Forum website[1]. All officers work directly with the NCO, and all User Forum members are expected to serve as liaisons for the greater NHERI community, providing the NHERI Council with independent advice on user satisfaction, priorities, and needs relating to the use and capabilities of NHERI.

The User Forum holds an annual in-person meeting typically during the ECO's Summer Institute with conference call-in capabilities for members who cannot attend in person. During this day-long meeting, the first part of the day is typically dedicated to discussing user satisfaction survey reports, describing challenges for conducting user satisfaction, identifying areas of improvement to the metrics used to evaluate user satisfaction, and developing strategies on how to best represent NHERI users' feedback and serve the NHERI community. The second part of the day is reserved for meeting with managers from Experimental Facilities, the NCO, the ECO, and the Network Independent Advisory Committee. The focus of those meetings is typically the communication of user satisfaction and feedback to the different entities. **Figure 3** provides a timeline of activities executed by the User Forum since its initiation. As shown, the User Forum initiated in February 2017. To initially engage with the NHERI user community to share the founding and purpose of the User Forum, presentations were given at two major conferences.

Monthly meetings are scheduled using an online scheduler, such as Doodle, that allows selection of several time slots and dates. Monthly meetings are typically scheduled at least 1 month in advance. In the event that more than one User Forum member is unable to attend a single date/time, the choice with at least two Officers and majority of User Forum members is chosen. The meetings are organized via teleconference software, such as Zoom, that allows screen sharing and computer and phone call-in options. At least 1 week in advance, the agenda, the previous meeting's minutes, and call-in information are emailed to User Forum members and representatives of the NCO. Meetings typically last about 1 h and include report-outs and discussion from User Forum members serving on their respective subcommittees as described below. Additional time is utilized to discuss member and officer elections, in-person meeting planning, and for any other specific items, such as the development of this paper. Meeting minutes are emailed to all User Forum members and NCO representatives typically within 1 week of the meeting. Once approved, the meeting minutes are publicly available on the User Forum website.

The most significant responsibility of the User Forum is to provide the Council with community advice. The User Forum provides this advice through administering an annual user satisfaction survey. This process includes survey development, data collection, data analysis, and the finalization of results in a public report. As shown in **Figure 3**, three annual surveys have been conducted and published to date. The duration of the open survey time has expended each year as new challenges and approaches are investigated and taken. The details on these challenges and the user satisfaction measurement process are described in the next section.

A User Forum member (typically one of the User Forum officers) attends the biweekly NCO conference call. During those meetings, a time slot is reserved for the User Forum to

[1] http://www.designsafe-ci.org/community/user-forum/

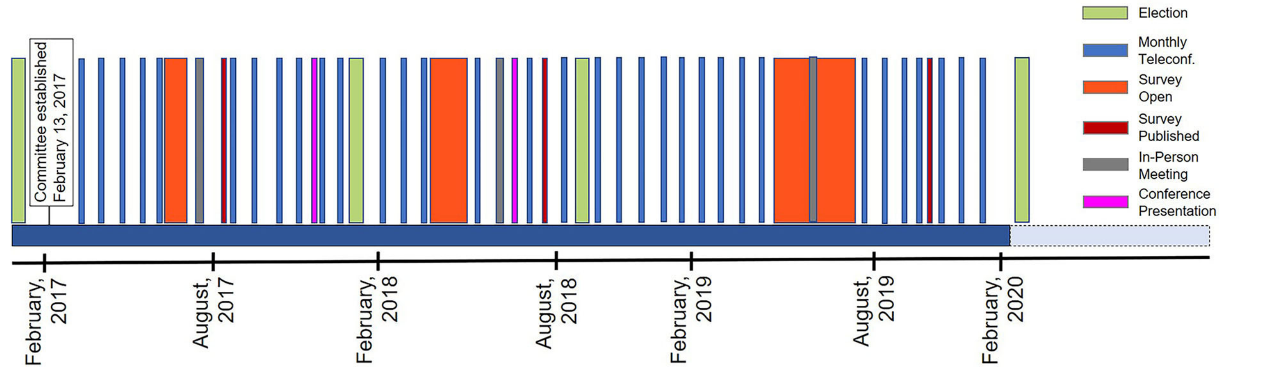


**FIGURE 3 |** User forum timeline of activities in years 1 through 3.

communicate issues and updates of the User Forum without delay to the NCO. This opportunity is also utilized by the NCO to direct requests, questions, or points of discussion to the User Forum. The presence of the User Forum during the NCO calls ensures a direct and sustained communication line between the NCO and the User Forum as well as the integration of the User Forum into the Governance of NHERI.

Two User Forum members serve as representatives on the ECO committee. The ECO committee includes representatives from all of the NHERI Awardees, and plans and executes the NHERI Research Experiences for Undergraduates (REU) program executed at across NHERI facilities, and the NHERI Summer Institute in San Antonio, TX (a multi-day workshop designed for orienting new users to NHERI). The ECO committee also collects and disseminates research and education in progress to the larger natural hazards community, and provides connections between research and education to K-12, community college, and practicing communities. The ECO committee and User Forum representatives meet once per month via teleconference, and once per year in-person, typically during the NHERI Summer Institute. The User Forum specifically provides the ECO committee with advice and recommendations on planning the REU program, Summer Institute, and other matters of concern to the ECO committee, e.g., Research to Practice webinars.

Similarly, two User Forum members serve as representatives on the Facilities Scheduling Committee. This committee is comprised of representatives from each of the Experimental Facilities and the Facility Scheduling and Operations Coordinator and is charged with developing and implementing protocol to standardize the scheduling of NHERI projects. The User Forum members on this committee report on challenges, lessons learned, and feedback from users who have scheduled NHERI projects using the centralized management protocol. This information is used to improve scheduling protocol and improve the online scheduling system.

One User Forum member serves on the Technology Transfer Committee, which consists of practitioners, decision makers, and researchers. This Technology Transfer Committee is focused on strengthening the tie between NHERI researchers and the implementers of NHERI-developed technology. The User Forum member represents both research users and practitioners within the NHERI network.

## MEASURING USER SATISFACTION

The focus of the annual user satisfaction survey is to provide evaluation data to inform decision-making processes among project leads (Patton, 2008). To spearhead this major task, a user satisfaction subcommittee was formed within the User Forum. The user satisfaction subcommittee consists of the chair, vice chair, User Forum awardee institution, and an NCO representative. The remainder of this section explains the User Forum's approach to measuring user satisfaction, executing the annual user survey, reporting survey findings, connecting with facilities, assessing facility surveys, the associated challenges experienced to date, how the process has evolved over time, and a synthesis of the outcomes and relevance of the survey findings. User satisfaction surveys have been completed so far in 2017, 2018, and 2019. The public reports are available at https://www.designsafe-ci.org/community/user-forum/.

### Defining User Experience for NHERI

The NHERI User Forum was unable to find documentation on the user satisfaction evaluation processes for the other NSF consortiums. Generally, such documentation in the literature is rare (Vermeeren et al., 2010), however there are published works on measuring user satisfaction. The literature more broadly refers to user satisfaction as user experience, and has experienced a recent increase in said measurement with the growth in human-centered design (Rajeshkumar et al., 2013). For example, Vermeeren et al. (2010) collected information on 96 different user experience evaluation methods being executed in academia and industry. These methods varied by quantitative vs. qualitative measurements, generalizability vs. application-specific, expert-based vs. broad-user, measurement location (lab, field, online), product development/use phase (beginning, during, after experience), amongst others. The authors concluded that there was widespread interest in measuring user experience, however, there were also widespread systematic development needs, including on (a) methods for early phases of development, (b) validated user experience metrics, (c) methods for social and collaborative evaluation, (d) establishing practicability and scientific quality, (e) multi-method approaches, and (f) generating a deeper understanding of user experience. The interested reader is referred to Vermeeren et al. (2010) to learn more about the various methods they observed through exploration of their online database.

ISO 9241-110 defines user experience as "a person's perceptions and responses that result from the use and/or anticipated use of a product, system or service" (ISO DIS 9241-210, 2010, clause 2.15). This characterization importantly establishes user experience as being subjective (Law et al., 2009). For NHERI, user subjectivity could stem from disciplinary background, how NHERI was used (e.g., workshops, proposals, projects), which part of NHERI was used, and user experience levels in academia, the proposal writing process, with the NSF, and with the NHERI facilities. Furthermore, the characterization of user experience also establishes it as something that occurs through time and not at a single point (Karapanos et al., 2009). For NHERI users, user experience can occur with regular NHERI email communications, intermittent use of the cyber infrastructure, during the proposals writing process, applying to and attending workshops, and during and after funded projects. Thus, clearly defining a NHERI user became an important challenge.

## Defining a NHERI User and Making a Connection

Measuring NHERI user satisfaction is a key task for the User Forum, but has also represented a number of challenges. The first question that arose from this task has been who is the NHERI user. The User Forum has defined the NHERI user as any individuals interacting with NHERI facilities and/or NHERI affiliated data. This includes individuals who have reviewed NHERI information and communicated with NHERI facilities for the preparation of proposals, individuals who actively collect data using the NHERI facilities, as well as individuals who utilize NHERI cyberinfrastructure, existing NHERI data sets, or utilize NHERI data repositories for natural hazard related data storage, amongst others. The User Forum is actively reaching out to different user groups through mailing lists as well as personal contacts to engage the users in providing feedback. The main mechanism for the collection of data on user satisfaction is the annual user satisfaction survey. The User Forum is exploring pathways of most efficient data collection and investigates what information is the most useful information for the NHERI governance.

Three user satisfaction surveys have been carried out at the time of this paper submission. Historically, one questionnaire was initially developed by an external entity and distributed to all users. The external entity was also responsible for developing a summary report of the survey results. After that first year, it was determined that the annual user satisfaction survey was better executed in-house. During the second year of the User Forum, User Forum members took control of developing and executing the survey. This was made possible by an NSF supplement award to a User Forum member institution for student support to incorporate User Forum feedback into survey development, and process findings. Once administered by the User Forum, the survey was sent to all registered users of DesignSafe-CI and investigators of NHERI projects. Across the 3 years of data, user responses were somewhat consistent and allowed preliminary conclusions on positive user satisfaction; however, limiting challenges included low response rates and the fact that, depending on the user group, most respondents encountered questions that did not apply to their user group. In subsequent surveys, the User Forum refined questions based on responses in previous surveys, included different tracks for the respective user groups to ask questions more relevant to the user group, reviewed survey information provided by the individual NHERI facilities, and included in-person surveys of individuals selected based on their survey responses.

## Annual User Survey and Changes to the Survey Over Time

In accordance with requirements set by the National Science Foundation (NSF), the User Forum conducts an annual user satisfaction survey administered using the online survey software, Qualtrics. Potential participants receive an invitation to participate in the user satisfaction survey along with a link to take the survey late spring or early summer. The structure and content of the survey have changed with each iteration of the survey. The most substantial changes to the survey occurred in 2018, based on feedback from the User Forum committee. The committee opted to expand the 2017 survey by refining the questions to obtain more details. Questions featured mixed response options that yielded both qualitative and quantitative data. In 2019, the User Forum conducted the user satisfaction survey for the third time (see the **Appendix** for a copy of the 2019 survey). Rather than make changes to the survey instrument as in previous years, in 2019 the User Forum instead made changes to the data collection strategy. Two separate, but nearly identical surveys were sent out to (1) all registered users of DesignSafe-CI, and (2) to NHERI workshop participants and investigators of NHERI projects. This latter list was provided to the User Forum from the NHERI facilities. Changes in the approach facilitated comparative analysis and allowed the User Forum to garner a clearer picture of user satisfaction. It is anticipated that the 2020 survey will include many identical questions to previous years, preserving the longitudinal nature of the work to date, as well as modifying other questions based on temporal updates.

## Reporting

Each year, an annual report is prepared once data collection and analysis are complete. This report includes an executive summary of all findings, detailed item-level response overviews, and frequencies of response type. The executive report includes information on key findings, response rates, and has details on data collection such as an overview of the sampling strategy and the dates within which data collection occurred. Detailed item-level responses provide an overview of both quantitative and qualitative responses, with qualitative responses reported in full in the appendices.

## Connecting With Facilities and Assessing Facility Surveys

Communication with facilities primarily occurs through online correspondence facilitated by members of the User Forum. For example, in 2019, facilities PIs were contacted before data collection to obtain a list of known facility site users; they were also asked to provide a copy of any site-specific survey instruments. This request was motivated by a desire to assess whether there might be ways to streamline overall data collection regarding user satisfaction. Once all facility surveys were collected, the User Forum conducted a thematic analysis and synthesized findings.

## Associated Challenges

As previously noted, there are a variety of challenges with efforts to measure user satisfaction. The first challenge has been addressing low response rates to the annual user satisfaction survey. This challenge has continued over time, and response rates to the annual satisfaction survey have declined each year. In order to address this challenge, the User Forum has explored adding incentives to participation and more actively involving site PIs in the data collection process. The former method is somewhat problematic given limited resources, but the latter approach holds some potential for the 2020 survey administration. The User Forum has also considered supplementing the annual user satisfaction survey with a module of questions to add to existing facility-administered surveys.

As noted above, the User Forum has also experienced and addressed the challenges of defining NHERI site users. Initially, NHERI made use of an extensive list of associated NHERI site users through a contact list developed in collaboration with DesignSafe-CI. This list, with over two thousand unique potential participants, held no guarantee that each potential participant had used or visited a NHERI site during the evaluation period. To address this challenge, in 2019 the User Forum collaborated

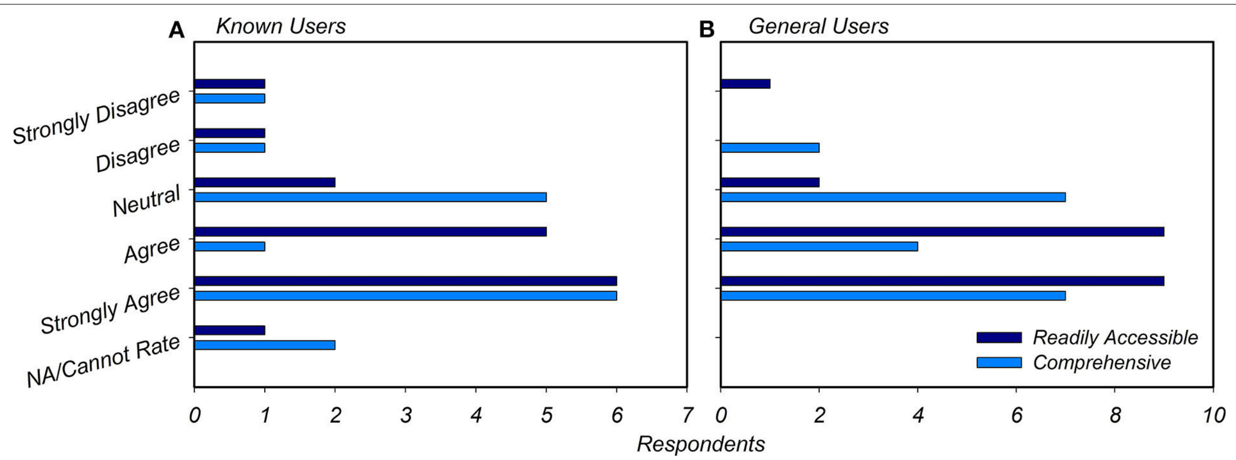


**FIGURE 4 |** Ratings of information of NHERI facilities and resources by user group. **(A)** is the known users, and **(B)** is the general users.

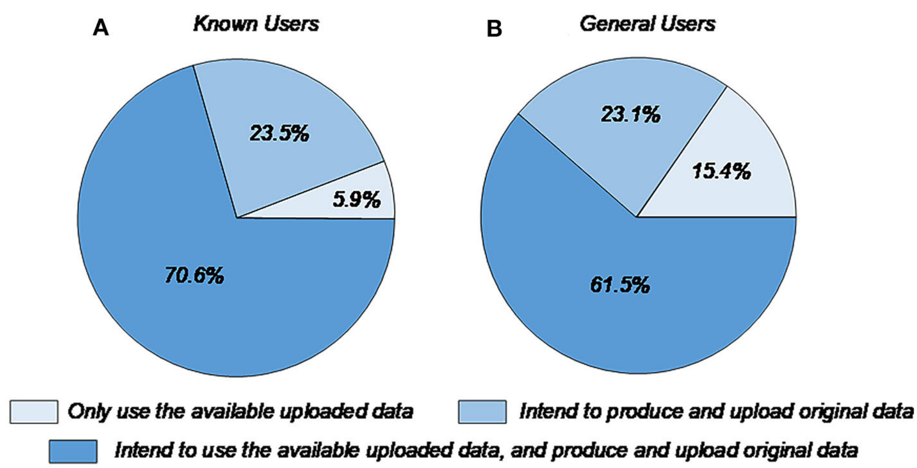


**FIGURE 5 |** Intended use of online NHERI resources by user group. **(A)** is the known users, and **(B)** is the general users.

with NHERI site PIs to develop a separate contact list of potential participants. This list, though much smaller ($N = 108$), only included potential participants that were known to have used or visited an NHERI site in the last calendar year. This allowed for comparative analysis in satisfaction among potential NHERI site users (the extensive list) and known NHERI site users (the smaller, targeted list).

Given that the user satisfaction survey is distributed online via email, the User Forum has experienced typical challenges associated with this method of distribution. During data collection in the summer of 2019, the User Forum discovered that the mass-distributed emails were being flagged by the utilized email server as "potential spam." Concerned that this would negatively affect response rates, the User Forum worked with the team that maintains the email server to address this issue. No workarounds were available, so the User Forum opted to end data collection at that time.

The User Forum has carefully considered each of the associated challenges discussed above. In each case, solutions were co-developed and adaptations were made accordingly.

## Summary of 2019 User Satisfaction Survey Findings

Due to limited changes in user satisfaction results from year to year, this section provides a focused and comparative overview of results from the 2019 NHERI User Satisfaction Survey. Detailed accounting of the 2019 survey and past survey results, as well as item-level descriptions of responses, are provided in the public reports accessible through the User Forum website.

The 2019 NHERI User Satisfaction survey instrument was nearly identical to the 2018 version, including questions that featured mixed response options yielding both qualitative and quantitative data. Building on feedback regarding the 2018 survey, the committee sent the 2019 survey to two targeted populations. As mentioned above, the first population included known NHERI facility users. The second population included a broader NHERI user list, compiled with assistance from NHERI facility PIs and the DesignSafe-CI support staff.

The first notable difference between known NHERI site users and general NHERI users was where respondents were in the proposal writing process. Not surprisingly, most known NHERI site users indicated they were at some point in the proposal writing process and had prepared at least one proposal that used NHERI facilities and resources. On the other hand, more respondents from the general user list indicated they did not plan to submit or prepare a proposal and reported preparing no proposals. Additional differences between these two user groups were how they rated information about NHERI facilities and resources. On the whole, responses from the general NHERI user list rated information about NHERI facilities and resources more positively than known NHERI site users. As shown in **Figure 4**, general users more positively rated information as readily accessible and comprehensive. Even so, known NHERI site users also rated information about NHERI facilities and resources positively but more often indicated they disagreed, strongly disagreed, or could not rate questions regarding the accessibility and comprehensiveness of NHERI information. Substantive responses from the general NHERI user list to questions regarding data were more positive than responses from the known NHERI site user list. Data items referred to the process of uploading data, adding metadata, and accessing data.

Both known NHERI site users and general NHERI users displayed no major differences across a number of measures of user satisfaction such as quality of experience using NHERI facilities, intended utilization of online NHERI resources, and satisfaction with feedback on written proposals. As shown in **Figure 5**, intended utilization of NHERI facilities is similar across both user groups. A majority of both the known NHERI site users (70.6%) and general users (61.5%) indicate they intend to both produce and upload original data and utilize available data,

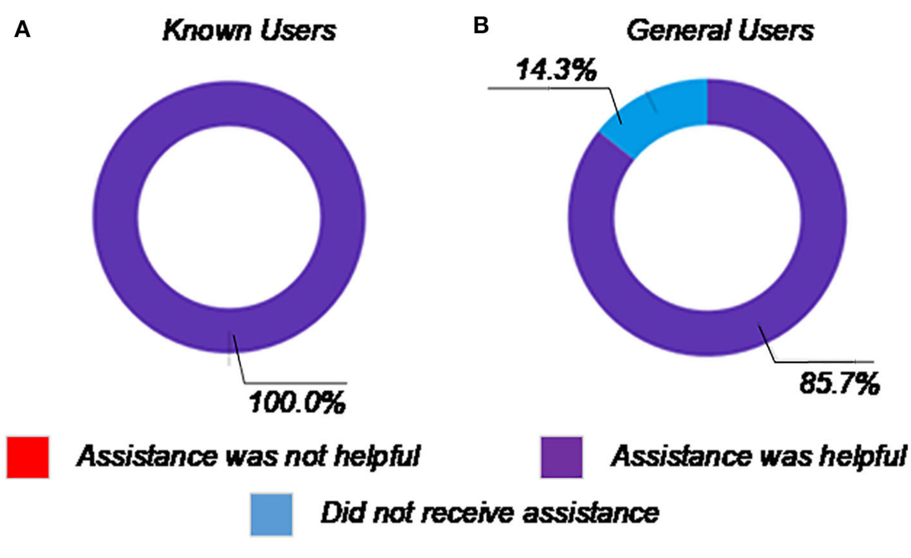


**FIGURE 6 |** Satisfaction with proposal writing feedback by user group. **(A)** is the known users, and **(B)** is the general users.

whereas 23.5% of known users and 23.1% of general users intend to produce and upload original data. The remaining respondents (5.9% of known users and 15.4% of general users) indicate they intend to use only the available uploaded data.

Similarly, known NHERI site users and general NHERI users report similar experiences seeking assistance from NHERI facilities in the proposal writing process. For example, as shown in **Figure 6**, of the six respondents who requested assistance in proposal writing, 100% of them received assistance and found the assistance they received helpful. Satisfaction with online support resources and tools and the available training for these resources and tools were similar, and positive, among both groups. Across both user groups, participants indicated they believe information regarding NHERI and NHERI in DesignSafe-CI are useful, and distributed at a useful rate and quantity. Similarly, responses across both user groups indicated participants intend to use the NHERI Science Plan to learn of major research challenges, to reference how their research fits within the Science Plan in their NSF proposal, and to expand their current research scope.

## CLOSING REMARKS

To help fill a gap in the existing literature on consortium-based user satisfaction measurement processes, this paper provides the roles, responsibilities, approach to and challenges with measuring user satisfaction as experienced by the User Forum for the National Science Foundation NHERI Consortium. The User Forum serves as the community voice in NHERI governance and provides independent advice on community user satisfaction, priorities, and needs relating to the use and capabilities of NHERI. As the community of voice within the governance of NHERI, the User Forum has been composed of nine representatives who are nominated and elected by the NHERI community, and who work directly with NHERI governance. User Forum membership spans academia and industry, and attempts to represent the full spectrum of NHERI user expertise.

A key task of the User Forum is measuring NHERI user satisfaction; three user satisfaction surveys have been carried out to date. Survey questions and data collection strategy have evolved over time, and the User Forum has prepared three final reports that include an executive summary of all findings, detailed item-level response overviews, and frequencies of response type. A significant challenge has been addressing low response rates to the annual user satisfaction survey. The User Forum has explored adding incentives to participation and more actively involving facility PIs in the data collection process. Overall, based on the 2019 survey results, the general NHERI user list rated information about NHERI facilities and resources more positively than known NHERI site users, however satisfaction with online support resources and tools and the available training for these resources and tools were similar, and positive, among both groups. Both groups also intend to use the NHERI Science Plan to learn of major research challenges, to reference how their research fits within the Science Plan in their NSF proposal, and to expand their current research scope.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2020.00101/full#supplementary-material

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# NHERI Centrifuge Facility: Large-Scale Centrifuge Modeling in Geotechnical Research

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The 9-m and 1-m radius geotechnical centrifuges at the Natural Hazards Engineering Research Infrastructure (NHERI) facility at the University of California at Davis provide the national research community with open access to unique and versatile modeling capabilities for advancing methods to predict and improve the performance of soil and soil-structure systems affected by earthquake, wave, wind, and storm surge loadings. Large-scale centrifuge models are particularly effective for the building of basic science knowledge, the validation of advanced computational models from the component to the holistic system level, and the validation of innovative soil remediation strategies. The capabilities and unique role of large-scale centrifuge modeling are illustrated using three example research projects from the shared-use NHERI facility. Education impacts stemming from operations activities and coordination of activities by the center's user base are discussed. Future directions and opportunities for research using the NHERI facilities are discussed.

**Keywords: centrifuge, physical modeling, geotechnical, inverse analyses, natural hazards**

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## INTRODUCTION

Centrifuge modeling addresses a fundamental challenge in the scaled physical modeling of geotechnical structures – the need for proper modeling of stress conditions given that most soil properties are dependent on effective confining stress. Scale models executed at 1 g (i.e., earth's gravitation field) provide only a qualitative evaluation of how full-scale geotechnical structures respond to different loadings because the effective stress conditions and hence soil properties (e.g., stiffness, strength, and dilatancy) are so different. The enhanced gravitational field imposed during a centrifuge test allows for stress similitude between the model and full-scale prototype, such that the response of a scaled centrifuge model to different loadings is more representative of the response expected under field-scale conditions. For example, the profile of vertical effective stress in a 0.6-m thick layer of soil at 50 g is equivalent to those in a 30-m thick layer of soil at 1 g. Centrifuge modeling also offers scaled modeling advantages for other physical processes where self-weight body forces are important, including various porous media, fluid, and gas phenomena (e.g., Taylor, 1995). Scaling laws and questions of similitude have accordingly been developed for a wide range of physical phenomena as they have been examined over the years (Garnier et al., 2007). In this manner, centrifuge modeling has proven invaluable for identifying complex mechanisms and validating computational models across a broader spectrum of conditions than is generally feasible with 1 g field-scale modeling.

Geotechnical centrifuge modeling technology has evolved through several stages over the past century, as described for example in Craig et al. (2015). The earliest reported experiments were in the US and USSR in the 1930s. Early pioneers around the world accomplished notable advances over the next four decades. The 1970s and 1980s brought rapid advances in centrifuge equipment, modeling techniques, and instrumentation, which led to a growth in utilization and increased awareness of centrifuge modeling capabilities in the broader civil engineering discipline. The International Society of Soil Mechanics and Foundation Engineering (now ISSMGE) recognized the growth by establishing an international technical committee on centrifuge modeling in 1981. Centrifuge modeling has continued to see rapid advances in modeling techniques and instrumentation, which has led to higher-resolution data and improved scientific findings, which in turn has fueled expansion in the range of problems that could be explored. Today, centrifuge modeling is firmly established as an essential tool for geotechnical research. This is perhaps best reflected through a recent communication with an NSF program director who noted that reviewers in the 1980s and 1990s asked, "Why would you use centrifuge modeling for this problem," whereas reviewers in the 2000s and 2010s asked, "Why are they not using centrifuge modeling for this problem?"

The centrifuge modeling facilities at UC Davis have similarly evolved over the past four decades. The geotechnical group first acquired a 1-m radius beam centrifuge in 1975. This centrifuge, still in use today, can subject about 50 kg of soil (typical dimensions of 178 mm deep, 560 mm long, and 280 mm wide) to a centrifugal acceleration of about 100 g, which represents a prototype soil layer thickness as great as 18 m. Its servo-hydraulic shaker, commissioned in 1988, was one of the first hydraulically driven shakers to be mounted on a geotechnical centrifuge. In 1983, the Center for Geotechnical Modeling (CGM) was established to develop and manage a 9-m radius "National Geotechnical Centrifuge" in partnership with NASA Ames and with support from the National Science Foundation (NSF awards 7813922 and 7826122). The 9-m centrifuge was constructed at a NASA Ames Research Center before being moved to UC Davis in 1986, where the first experiments were executed with the centrifuge rotating in an unenclosed space. With continuing effort, the 9-m centrifuge and supporting facilities were enhanced by completion of an enclosure rotunda in 1989, commissioning of a servo-hydraulic shaking table in 1995, and over $5 M of major upgrades from 2000 to 2004 with funding from the NSF through the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES). The NEES improvements included upgrades to the centrifuge drivetrain, shaking table upgrades, new model containers, advanced data acquisition systems, high-speed cameras, visualization tools, geophysical tools, and aerodynamic modifications to the enclosure. With those modifications, the large centrifuge was capable of subjecting about 1550 kg of soil (a common container has dimensions of 686 mm deep, 1722 mm long, 686 mm wide) to a centrifugal acceleration of about 75 g, which represents a prototype soil layer thickness as great as 51 m. The CGM has subsequently maintained the 9-m and 1-m radius centrifuges at the state of the art through continuous performance improvements while operating as a national shared-use, open-access facility under NSF funding through NEES from 2004 to 2014 and through the Natural Hazards and Engineering Research Infrastructure (NHERI) program from 2016 to present. Photographs in **Figures 1**, **2** provide a full side view of the 9-m centrifuge, a view of a model container with in-flight cone penetration testing equipment mounted on the end of the 9-m centrifuge arm, and two examples of complex models being constructed for testing on the 9-m centrifuge. Details on the facility history, capabilities, and equipment performance specifications over the years can be found in Wilson et al. (1997, 2010) and Wilson and Allmond (2014) and at the CGM[1] and NHERI DesignSafe-CI[2] websites.

This paper describes the capabilities of the NHERI Centrifuge Facility and the essential role of geotechnical centrifuge modeling for advancing methods to predict and improve the performance of soil and soil-structure systems affected by earthquake, wave, wind and storm surge loadings. Three example projects are used to demonstrate that large-scale models with holistic levels of complexity have produced: (1) uniquely detailed or first-ever measurements of key mechanisms that could not be measured by other means, (2) essential validation for computational models, and (3) major broader impacts for science and society. The three projects are a submerged tunnel surrounded by liquefiable sand backfill, rocking responses of shallow foundations for buildings and bridges subjected to earthquake loading, and liquefiable soil profiles remediated using microbially induced calcite precipitation (MICP). Broader impacts stemming from the NHERI centrifuge facility operations activities and coordination of activities by the center's user base are described. Lastly, potential future directions and opportunities for research using the NHERI facilities are discussed.

## THE CENTRIFUGE AS AN ENHANCED GRAVITY LABORATORY

The centrifuge provides a testing environment with an enhanced gravitational field, in which users execute experiments of their own design. New and novel experimental designs are frequently required to address the scientific needs of the researchers, which leads to ongoing improvements and expansions in the on-arm testing capabilities. New experimental designs can be challenging because the enhanced gravitational field can impose significant demands on structural components, mechanic devices (e.g., actuators, remote tools), model containers, and electronic devices, with the associated challenge that commercially available products may not function adequately on the centrifuge, leading to the need for re-designs and modifications. In many cases, a common interest in an emerging technology across research teams has enabled the pooling/leveraging of research funds to expand capabilities in ways that benefit multiple teams.

The three research studies described in the following sections illustrate a subset of the centrifuge modeling capabilities at the

[1] cgm.engr.ucdavis.edu/
[2] www.designsafe-ci.org

**FIGURE 1 |** NHERI 9-m radius geotechnical centrifuge at UC Davis in 2019 (photo by Gregory Urquiaga).

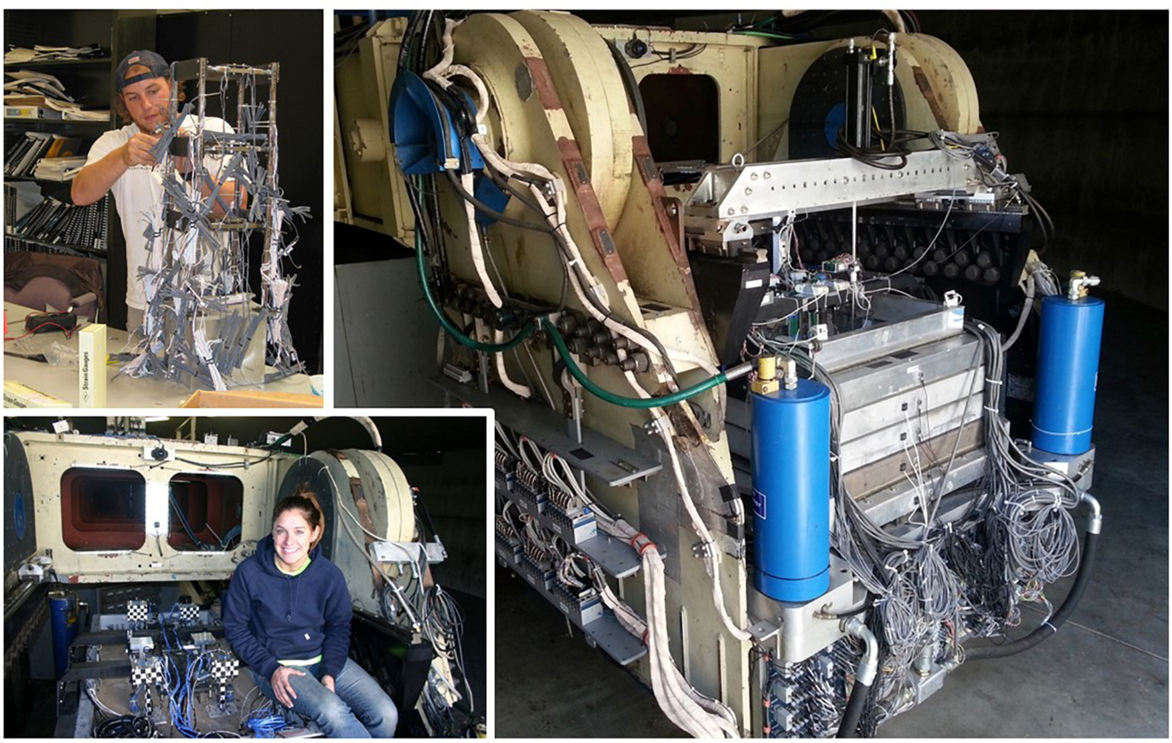

**FIGURE 2 |** Examples of model testing on the 9-m centrifuge: nonlinear multi-story structure-soil-structure interaction **(top left insert)**, multiple rocking foundation systems **(lower left insert)**, and in-flight cone penetration testing actuator mounted on the gantry **(right)**.

CGM facilities. Over eighty research projects, each involving anywhere from a few to dozens of centrifuge experiments, have used the CGM centrifuge facilities. Owing to the uniqueness of the shaking table, most experiments executed to date at UC Davis have focused on seismic applications, including aspects of liquefaction (triggering, lateral spreading, levee/embankment deformations, quay wall deformations), ground improvements (densification, drainage, grouting, soil-cement reinforcements, bio-cementation, bio-desaturation), soil-structure interaction (shallow and deep foundations in soft or liquefiable soils for buildings, bridges, tanks, quay walls), buried structures (lateral pressures and kinematic demands on subway tunnels and stations), seismic site response (sands, soft clays, organic soils), mechanically stabilized earth retaining walls, geo-synthetic liner systems for waste containment, and water-structure-soil interaction for buried reservoirs. Other research projects have examined offshore foundation systems (wave, wind, and seismic loading of jack-up structures, suction caissons, subsea manifolds), *in-situ* characterization of challenging soils (gravelly soils, interbedded soils, fly ash), novel foundation systems (grouted helical anchors), residual strength of clay slickensides in landslides, tsunami effects on coastal stability, bio-inspired stress-state manipulation for soil penetration, and bio-inspired root-type foundations. Regardless of the application, common objectives include the exploration of fundamental mechanisms, the use of sensor arrays with inverse analyses techniques to quantify key mechanisms, and the use of the data for validation of analytical/computational models. Data from past research projects have been archived for public access at the CGM and DesignSafe websites. A review of the literature indicates the available data has been re-used in at least 110 publications by different researchers around the world, recognizing that data re-use is likely under-counted by our current manual processes.

## RESEARCH EXAMPLE: UPLIFT MECHANISMS FOR A BURIED TUNNEL

The Bay Area Rapid Transit (BART) Transbay Tube (TBT) is a 6-km long immersed cut-and-cover subway tunnel that connects Oakland to San Francisco, California. Seismic risk evaluations identified a concern that earthquake-induced liquefaction of the loose sand and gravel backfills surrounding the tunnel (**Figure 3**) could result in tunnel uplift and damage to the tunnel. Predicting the tunnel uplift and extent of damage in an earthquake, however, was hampered by limited scientific understanding of the deformation mechanisms (**Figure 4**) and the lack of data against which the numerical modeling procedures could be validated. Decisions regarding remediation alternatives depended on developing confidence in the analysis methods, and thus the design team recommended physical model testing be performed to quantify deformation mechanisms and validate/evaluate the numerical modeling procedures. The centrifuge and numerical modeling work is described in Chang et al. (2008), Chou et al. (2011), and Kutter et al. (2008), with subsequent reanalysis of the data in Tasiopoulou et al. (2019).

Large-scale centrifuge models were selected as the preferred approach for physical modeling because the large model container (1.8 m long, 0.7 m wide, and 0.6 m deep) facilitated construction of a model with appropriately complex geometric and stratigraphic details to reflect the real design scenarios, as well as the placement of dense instrumentation arrays for quantifying the different deformation mechanisms through inverse analyses. Each physical model was constructed in a rigid container with polycarbonate windows to view the model cross-section, such as is visible in the photograph in **Figure 5**. The model tunnel rested on a thin bedding layer of coarse sand at the bottom of trench within the foundation clay. The trench backfill was coarse sand to about mid-height of the tunnel, and then fine sand to above the tunnel crown. A layer of low-permeability fine-grained soil covered the surface of the model. The test was executed at a centrifugal acceleration of 40 g to simulate the prototype tunnel section of approximately 15-m wide by 7-m high. The instrumentation included dense arrays of accelerometers and pore pressure transducers that would be used to define mechanisms, and novel non-contacting proximity transducers were used to measure tunnel uplift during shaking.

The centrifuge experiments provided quantitative insights on fundamental mechanisms and the basis for validation of nonlinear dynamic analysis procedures. The fundamental mechanisms that could contribute to tunnel uplift were identified as ratcheting, pore water migration, bottom heave, and viscous flow of liquefied soil (**Figure 4**). Inverse analyses of the dense instrumentation array data were used to define the transient seepage volumes in the soil and the lateral and vertical force versus displacement responses of the tunnel. The inverse analyses assume the governing differential equations and then use the discrete sensor data and interpolation functions to numerically compute terms that cannot be measured directly. The centrifuge data and inverse analysis results provided quantitative data on the relative contributions of different mechanisms to tunnel uplift, and provide a basis to evaluate numerical modeling limitations associated with pore pressure diffusion in layered soils, possible formation of water films or blisters at the tunnel-soil interface, localized slip at the tunnel-soil interface, shear deformations in liquefied soils at near zero effective stress, and sedimentation (volumetric) strains in liquefied soils. The design team used the data to evaluate/validate two different numerical modeling procedures, one using the finite element platform OpenSees with the multiple yield surface constitutive models by Elgamal et al. (2002) and another using the finite different platform FLAC (Itasca Consulting Group Inc, 2006) with the UBCSAND constitutive model (Beaty and Byrne, 1998). The same data were later re-used by several members of the design team in evaluating updated modeling procedures using FLAC with the PM4Sand constitutive model (Tasiopoulou et al., 2019). The numerical simulations were found to approximate the dynamic response, tunnel uplift, and sand deformation patterns around the tunnel (**Figure 6**).

This research project, which was an industry-university collaboration, demonstrated immediate broader impacts with the science directly informing the design decisions in an active seismic risk reduction program for a major civil infrastructure

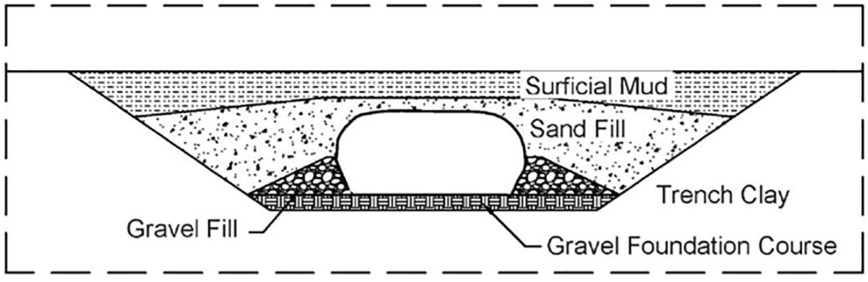


**FIGURE 3 |** Configuration of the BART Transbay tube and backfill materials (Reproduced from Kutter et al., 2008 with permission from ASCE).

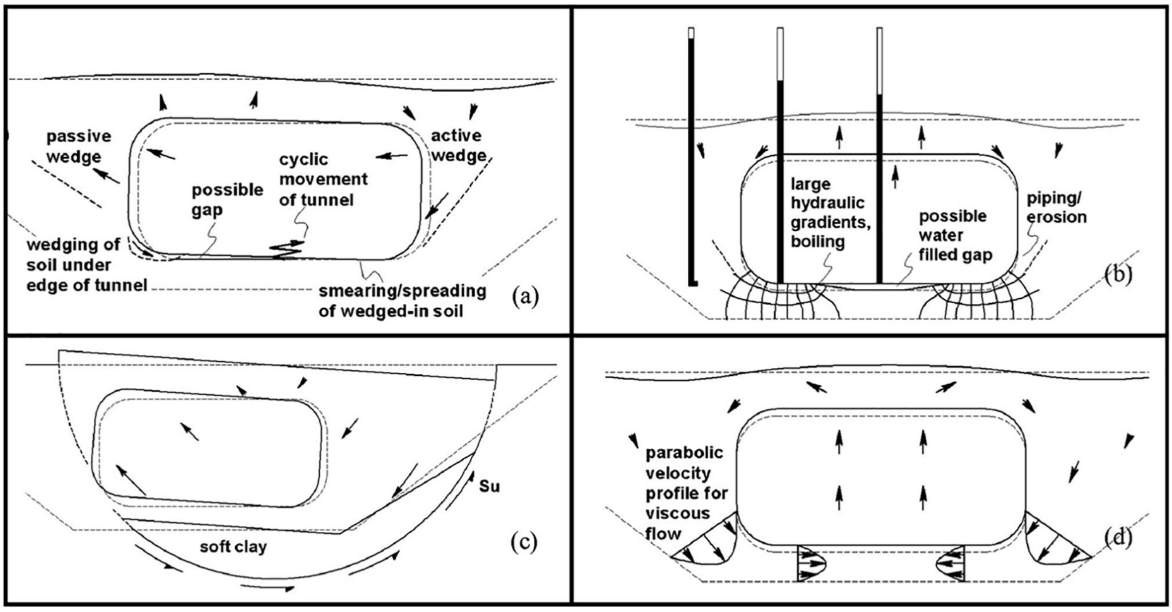


**FIGURE 4 |** Four uplift mechanisms: **(a)** ratcheting, **(b)** pore water migrations, **(c)** bottom heave, and **(d)** viscous flow of liquefied soil (Reproduced from Chou et al., 2011 with permission from ASCE).

system. The findings allowed the authorities to adopt confidently a remediation strategy that minimized construction risks and significantly reduced owner costs by avoiding costly offshore ground improvements. The scientific findings advanced the state of practice for numerical modeling of liquefaction effects. Newly developed inverse analysis techniques using dense sensor arrays were used to quantify the contribution of one of the important deformations mechanisms. The collaboration between students, faculty, and industry researchers provided a uniquely broad experience for the graduate students, faculty and practitioners.

## RESEARCH EXAMPLE: ROCKING FOUNDATIONS

The rocking of shallow foundations for building and bridges during earthquake loading was generally avoided in design practice up through the 2000's, when the potential economic advantages for retrofit projects drove a widespread interest in developing the fundamental understanding and design procedures necessary to accept its occurrence. Prior to that, foundation rocking was recognized to have the appealing characteristics of self-centering tendency and energy dissipation capability, but the fundamental mechanisms and their behaviors for a range of soil and loading conditions was not well understood. In addition, the relative roles of inelasticity in the structural systems and foundation were an additional complicating factor. The ability to design for, and hence allow for, rocking of shallow foundation elements was recognized as having strong economic benefits and performance implications for bridges (Alameddine and Imbsen, 2002) and buildings (Comartin et al., 2000). A concerted research effort in the community over the past 15–20 years led to adoption of code provisions accounting for the benefits and consequences of rocking foundations (e.g., ASCE/SEI 41-17, 2017).

Large-scale centrifuge models were an essential component of the research studies supporting the development of fundamental understanding and validation of analysis methods for estimating

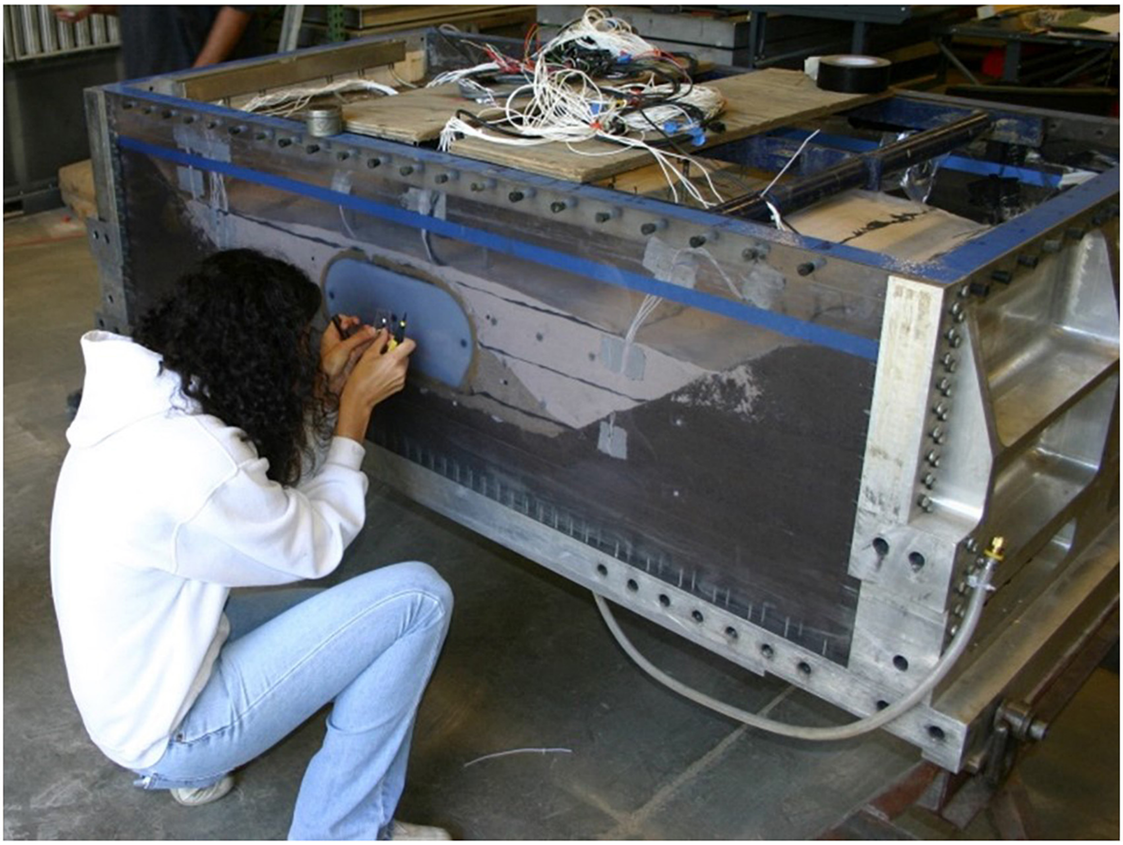

**FIGURE 5 |** Preparation of the BART Transbay tube model in the rigid glass-walled container.

rocking behaviors and the associated foundation settlements, with one example being the work by Liu et al. (2015a,b) described herein. In this study, six different two-story-two-bay frame-wall-foundation building models resting on dense sand were constructed and tested on the 9-m centrifuge (**Figure 7**). The models represented low-rise structures for which the primary seismic lateral resistance was provided by a shear wall supported on a shallow foundation. When predicting the response of models such as this, where the moment capacity of the shear wall foundation is greater than the moment capacity of the shear wall itself, a hinge mechanism develops in the shear wall, which is forced to absorb the large majority of ductility demand (a hinging-dominated system). In cases where the moment capacity of the foundation is less than that of the shear wall, the foundation acts as a fuse, and relatively large ductility demands are absorbed by the foundation rocking on soil (a rocking-dominated system). Foundation rocking can produce large settlements if the static factor of safety against bearing failure is low (e.g., heavily loaded undersized footings), but previous research (e.g., Gajan and Kutter, 2008) has shown that the settlements will be acceptably small if the static factor of safety against bearing failure is sufficient. The six models in Liu et al. (2015a,b) study included two hinging-dominated systems, two rocking-dominated systems, and two balanced systems where the moment capacity of wall and its foundation were similar. The models were subjected to slow cyclic (pseudo-static) loading in one series of tests, and to dynamic earthquake shaking in another series of tests. The individual foundation elements for the shear walls and the frame columns had reasonably well defined moment rotation responses based on a supporting series of tests of single-footing systems on the 1-m radius centrifuge (Hakhamaneshi and Kutter, 2016; Hakhamaneshi et al., 2016). The 1-m centrifuge was well suited for rapid and economical testing of single footings, such that a wide range of footing shapes, sizes, soil types, and loading conditions could be parametrically examined economically. The 9-m centrifuge, however, was required for constructing the holistic models shown in **Figure 7**, wherein small connection-scale details (e.g., beam-column plastic hinges), large building-scale frame action, and realistic nonlinear soil-structure interaction play important roles in the system behavior. The instrumentation in these larger tests consisted of vertical and horizontal accelerometers to define all inertial forces in the structural system, and strain gages to define axial, shear, and moments in the key structural components. The structural models included systems wherein the energy dissipation and yielding were dominated by plastic hinging in the structural components (SHD, **Figure 7A**), foundation rocking (FRD, **Figure 7B**), or a balance of both plastic hinging and foundation rocking (BD, **Figure 7C**).

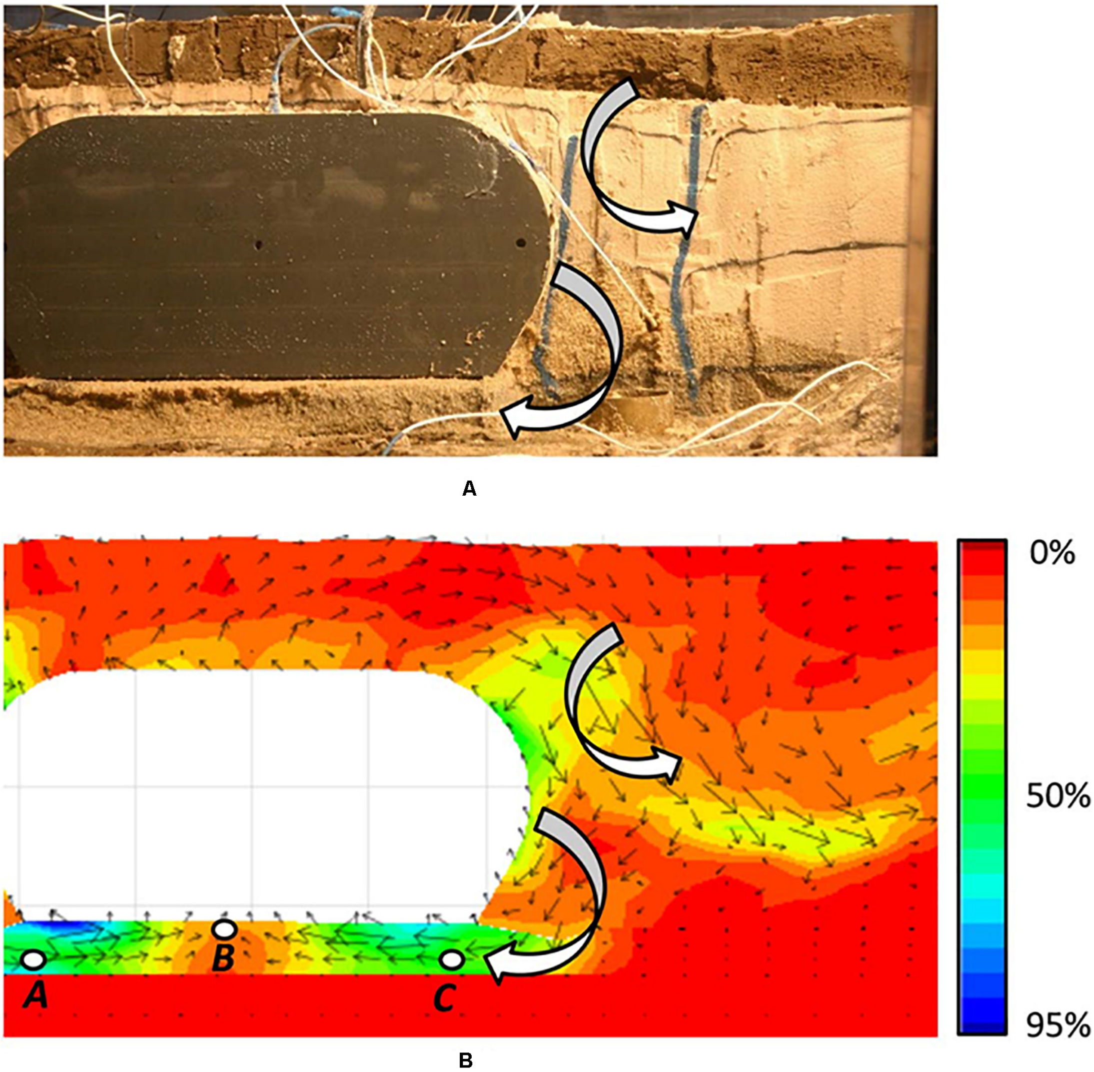


**FIGURE 6 |** Displacement of sand toward and beneath the tunnel from **(A)** experimental observation; and **(B)** numerical analysis. The deformation pattern is illustrated through vertical sand columns for the centrifuge test and displacement vectors and shear strain contours for the numerical analysis (Reproduced from Tasiopoulou et al., 2019 with permission from ASCE).

A common misconception about rocking foundations was that rocking foundations might increase the demand on the structure. The 9-m centrifuge building models showed that rocking foundations, if properly designed, could absorb much of the ductility demand and hence reduce the ductility demand on structural components. The slow cyclic tests on the model buildings demonstrated that the rocking-dominated systems had ductile and stable responses with very little strength degradation, and better re-centering than hinging-dominated systems. The dynamic earthquake shaking tests confirmed that the ductility demand on the shear wall component of the system decreases and system performance improves when demand is shifted from wall hinging to the rocking foundation. Furthermore, systems with rocking foundations sustained a smaller peak roof acceleration, residual drift, and reduced peak base shear despite the relatively larger peak transient drift demand. Consistent with slow cyclic test results, dissipated hysteretic energy was reasonably distributed amongst superstructure and substructure inelastic components if the capacity of the wall and its foundation are balanced; this finding is illustrated in **Figure 8** showing the moment-rotation response in a column fuse (**Figure 8A**), the moment-rotation of the shear wall foundation, (**Figure 8B**), and the moment-rotation response of a single column's spread footing (**Figure 8C**) during slow cyclic loading on a balanced design model. Dynamic shaking tests were then performed on similar structural models that were densely instrumented, after which inverse analyses techniques were used to back-calculate various moment-rotation responses that could not otherwise have been directly measured. The nature and distribution of plastic yielding was similar between

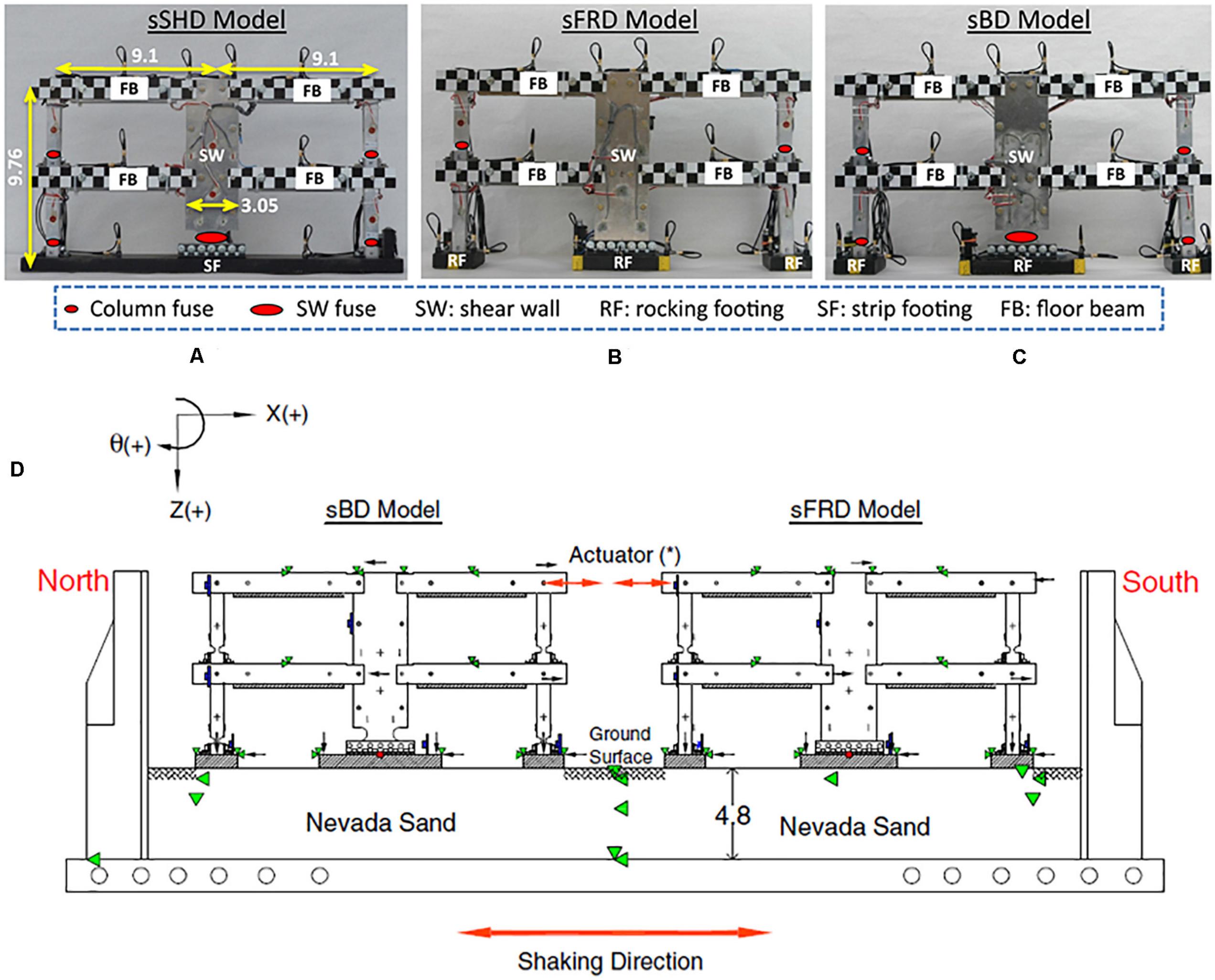


**FIGURE 7 |** Frame wall-foundation models for testing on the 9-m centrifuge (Liu et al., 2015a): **(A)** structural hinging dominated SHD model, **(B)** foundation rocking dominated FRD model, **(C)** balanced design model BD, and **(D)** arrangement of models in the soil container for static and dynamic testing on the centrifuge.

the slow cyclic and dynamic tests, providing confidence in both sets of data. These centrifuge models, with their holistic systems-level details, provided unique experimental data that was the basis for validating the ability of numerical simulation procedures to approximate nonlinearity in the structure and foundation. Numerical simulations demonstrated comparable local and global response to measurements obtained during the experiments, as illustrated by the comparisons of measured and computed moment-rotation responses of the shear wall footings shown in **Figure 9**.

Centrifuge model experiments like those described above, along with centrifuge and shaking table tests performed by others for a broad range of soil conditions and structural systems, provided the basis for rapid broader impact through development and implementation of design procedures for practice. In this regard, projects on rocking foundations using the 1-g shaking table at the UC San Diego NHERI facility and the 9-m centrifuge at UC Davis are illustrative of their complementary roles (Allmond and Kutter, 2014a,b; Antonellis et al., 2015). The 1 g shaking table tests examined rocking responses for two single-degree-of-freedom structures supported on 1.5-m by 1.5-m square spread footings in the same experiment; the large size of the footings enable use of local contact sensors to examine the footing-soil-interface interaction at a high level of detail. The companion tests on the 9-m centrifuge enable simulation of six single-degree-of-freedom structures supported on 7.5-m by 7.5-m square (prototype scale) footings in the same experiment: the enhanced g-field in the centrifuge enabled simulating rocking structures at greater load and stress levels, and to include a greater number of structure/footing configurations at significantly lower cost. This is just one example of how the combination of the 1-m centrifuge, 9-m centrifuge, and large-scale 1-g shaking table facilities in the NHERI network provide flexibility to tackle complex problems across an appropriate and complementary range of scales, depending on the fundamental scientific and engineering issues being explored.

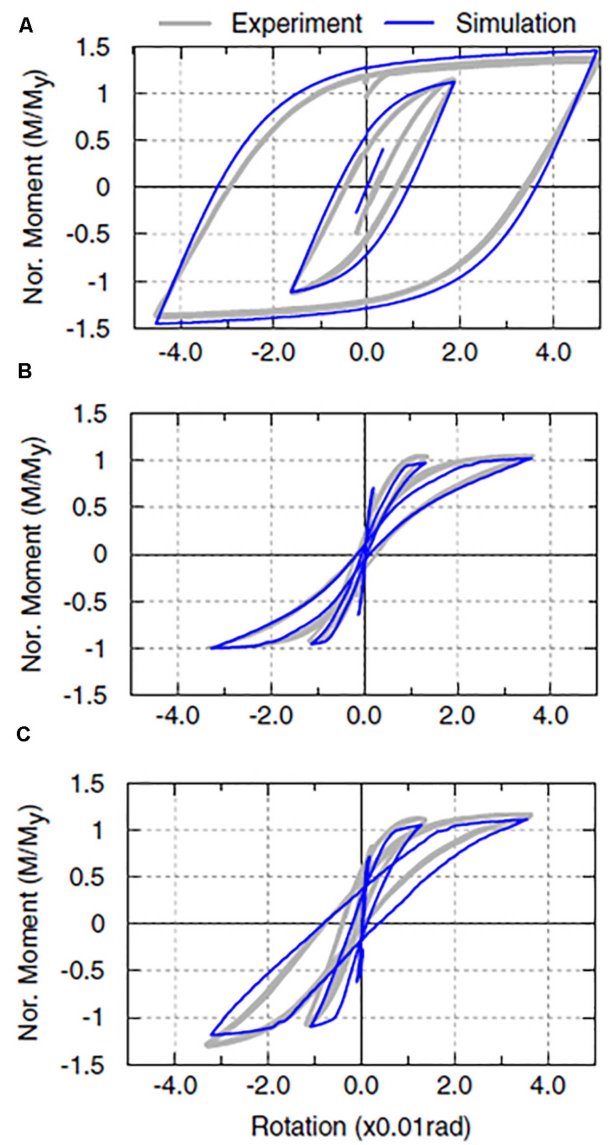


**FIGURE 8 |** Hysteretic response of inelastic elements in the sFRD model: **(A)** column fuse at level 2, **(B)** shear wall rocking footing, and **(C)** column rocking footing (Permission from Liu et al., 2015a with permission from ASCE).

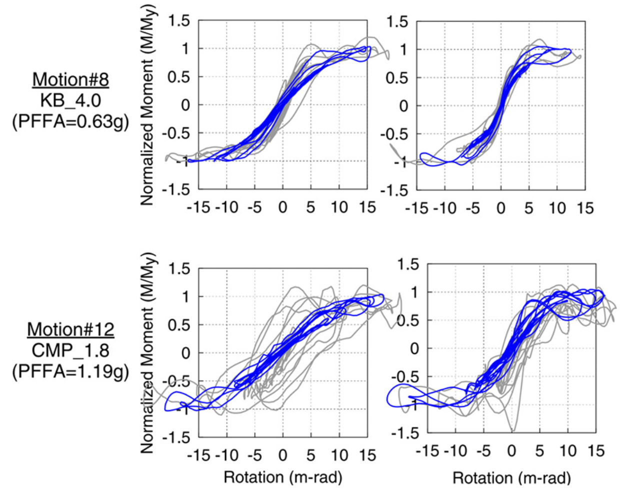


**FIGURE 9 |** Hysteretic rocking response of shear wall footings during shaking with two for two input motions: measured response based on inverse analyses of sensor data (gray lines) and simulated responses from finite element analyses (blue lines) (Reproduced from Liu et al., 2015b with permission from ASCE).

Technology transfer on rocking foundation research was facilitated by the formation of a Technology Transfer Team of practitioners with geotechnical and structural expertise related to buildings and bridges. This group of nominally six people worked over a period of several years, and contributed to guidance for building code provisions that eventually allowed designers to use foundation rocking as an effective mechanism contributing to the seismic performance of buildings per ASCE/SEI 41-17 (2017). The findings advanced the state of practice for design and for numerical modeling of soil-structure systems. The collaboration between students, faculty, and leading practitioners from industry provided a uniquely broad experience for all of the participants – especially the students.

## RESEARCH EXAMPLE: BIO-MEDIATION OF LIQUEFIABLE SOILS

Microbially induced calcite precipitation is a bio-mediation ground improvement method that uses soil microorganisms to induce calcite precipitation within sandy soils (**Figure 10**). MICP bio-cementation can significantly increase the resistance of liquefaction triggering of granular soils through particle bonding (cementation), increased particle angularity, and increased density, which results in stronger dilative tendencies (DeJong et al., 2010; Montoya and DeJong, 2015; Feng and Montoya, 2016). MICP bio-cementation has the potential to be a tunable, noninvasive method for treating liquefiable soils around existing infrastructure where other invasive ground improvement methods are not feasible. Challenges for advancing this technique include optimizing use of native microorganisms, tuning the bio-cementation process, collecting and processing byproducts, upscaling to field scale, establishing *in-situ* quality control measures, and developing the fundamental knowledge base on material behaviors required for engineering design (DeJong et al., 2013). The NSF-sponsored Center for Bio-mediated and Bio-inspired Geotechnics (CBBG) is working to advance MICP ground improvement from the bench scale to field scale in partnership with industry collaborators.

The CBBG selected the NHERI centrifuge facilities at UC Davis for testbed development of MICP bio-cementation, as well as other bio-mediated and bio-inspired processes, because it offered the flexibility for physical modeling at small (**Figure 11A**) and large (**Figure 11B**) scales using the 1-m and 9-m radius centrifuges, respectively. The 1-m radius centrifuge, with its smaller models, provides for high throughput of relatively simple tests that enable rapid and efficient exploration of model

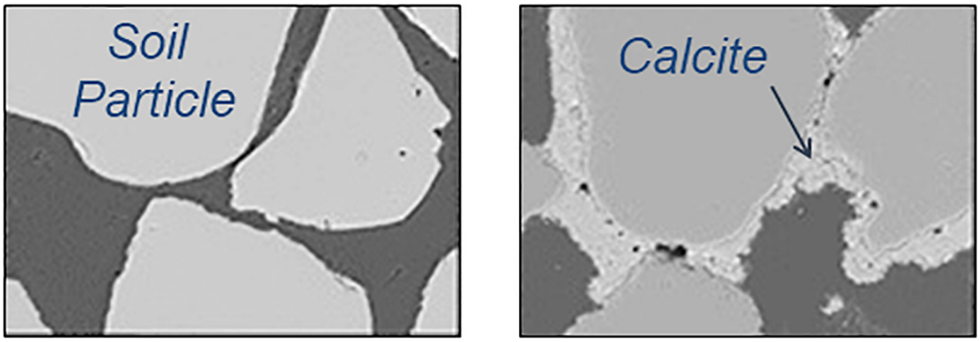


**FIGURE 10 |** Images of sand particles before and after MICP treatment (Reproduced from DeJong et al., 2006 with permission from ASCE).


**FIGURE 11 |** Bio-mediation of sand models for centrifuge testing: **(A)** component level model for testing on the 1-m radius centrifuge, and **(B)** system level model for testing on the 9-m radius centrifuge.

preparation techniques, in-flight characterization techniques (shear wave velocity $V_s$ and cone penetration testing), and degradation of the improved soil in a relatively simple model when subjected to changing static and dynamic loading. In a recent CBBG study (Darby et al., 2019), models were prepared with loose saturated sands having no, light, moderate, and heavy levels of biocementation, and then subjected to multiple shaking events with peak base accelerations of 0.02 to 0.55 g. Arrays of accelerometers and pore pressure transducers were used to compute cyclic stress ratios, shear strains, and excess pore pressure generation. A mini-cone penetrometer was pushed at select times during each test to evaluate the ability of the cone to capture the effects of initial cementation and cementation degradation induced by shaking. Horizontal shear wave ($V_s$) measurements (which give small-strain shear moduli) were obtained prior to each cone push and shaking event using two arrays of bender element (BE) pairs placed with depth. The increase in cone penetration resistance and $V_s$ with the calcium carbonate content produced by the MICP process are shown in **Figures 12A,B**, respectively. Inverse analyses of dynamic response using the instrumentation arrays were used to define cyclic stress ratios (CSRs) imposed on the soil during shaking, up through the triggering of significant shear strains. The inverse-computed CSRs are plotted versus cone penetration and $V_s$ values in **Figure 13**, along with common correlations for estimating liquefaction and non-liquefaction triggering conditions in non-cemented sands (Kayen et al., 2013; Boulanger and Idriss, 2015). Additional details on these tests and their interpretations are provided in Darby et al. (2019). The key observations are that the results of these types of tests, starting on the 1-centrifuge and now moving to the 9-m centrifuge (with its better resolution on details), provide a unique means for evaluating how industry-standard liquefaction triggering procedures may be adapted to MICP treated sands.

In a test recently performed and not yet published, the 9-m radius centrifuge was used to perform a more holistic investigation of system-level performance. The test configuration included multiple surface foundation structures founded on a soil profile with spatially varying relative density, including soil layers susceptible to liquefaction at different depths, and multiple

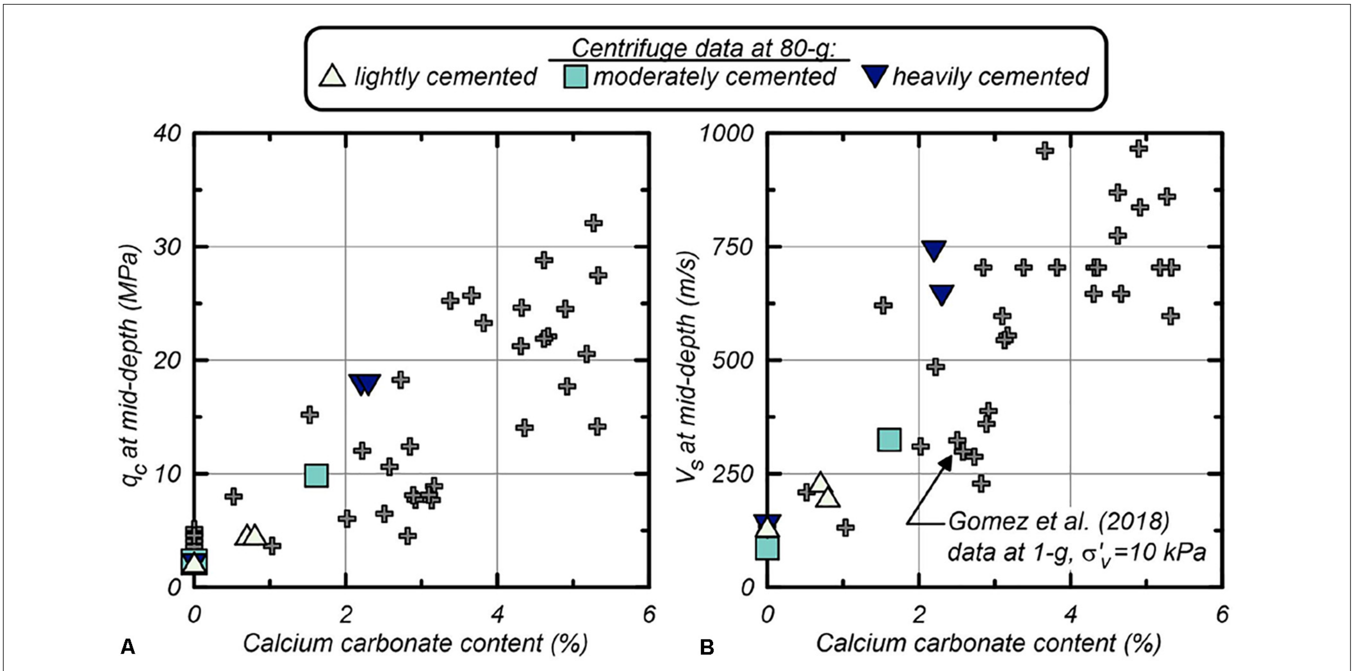


**FIGURE 12 | (A)** Cone penetration resistance and **(B)** shear wave velocity at mid-depth in a model on the 1-m radius centrifuge versus the calcium carbonate content produced by MICP treatment (Permission from Darby et al., 2019 with permission from ASCE).

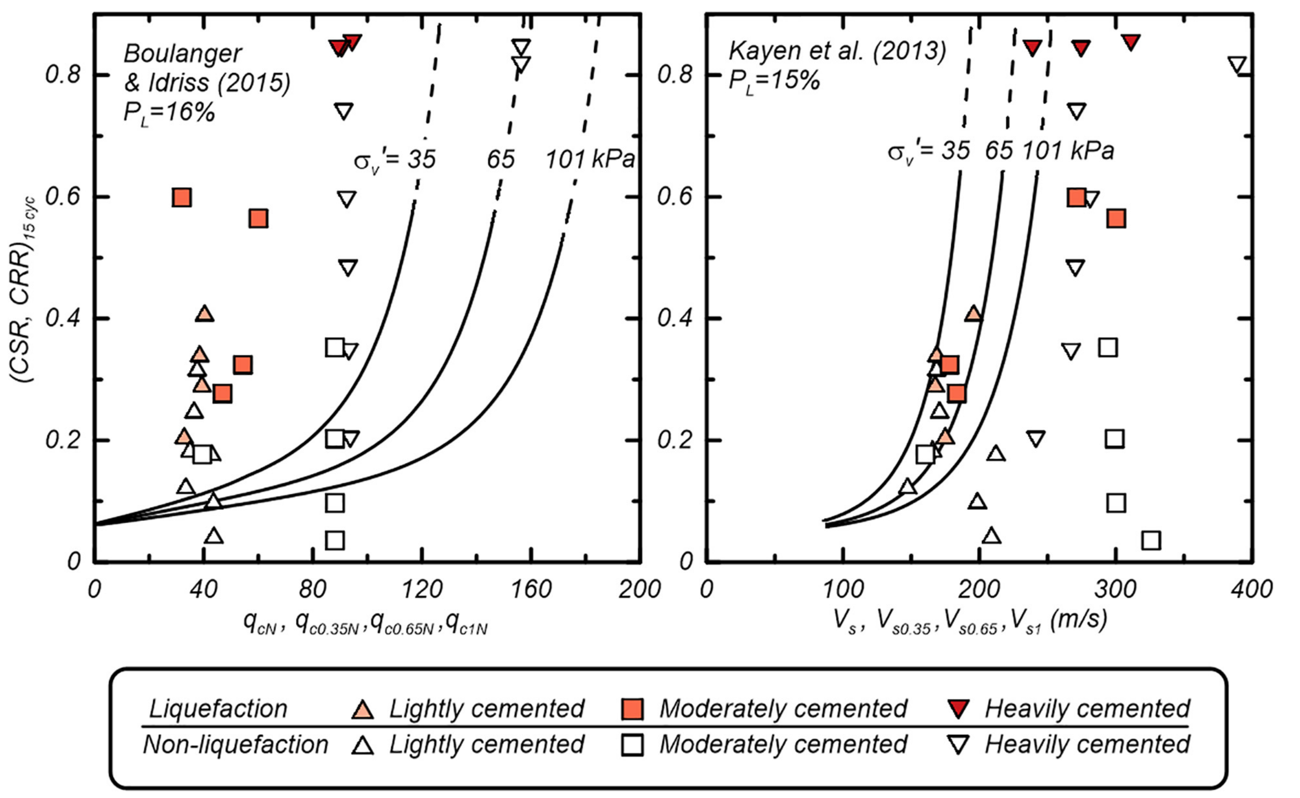


**FIGURE 13 |** Equivalent uniform cyclic stress ratios versus cone penetration resistance and shear wave velocity in a saturated sand model subject to dynamic loading on the 1-m radius centrifuge, along with case-history based liquefaction triggering correlations used in practice (Reproduced from Darby et al., 2019 with permission from ASCE).

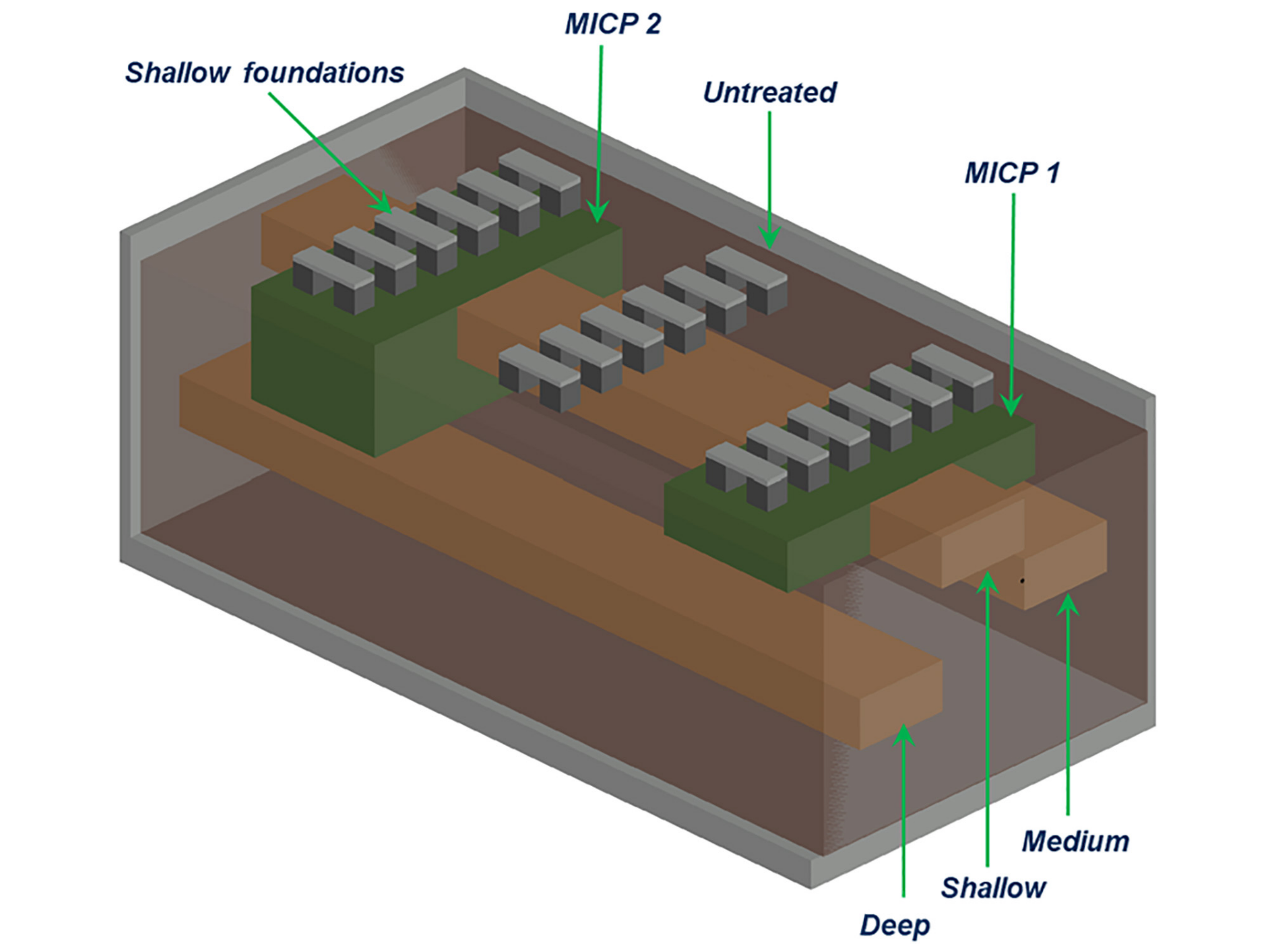


**FIGURE 14 |** Configuration of a centrifuge model for the 9-m centrifuge; multiple shallow foundations arranged over areas that have no, shallow, and deep MICP treatments (labeled as Untreated, MICP 1 and MICP 2) with loose layers of liquefiable sand at shallow, medium, and deep intervals.

MICP treatment strategies, including untreated, shallow, and deep treatments (**Figure 14**). Arrays of accelerometers and pore pressure transducers within the soil, along with displacement and acceleration measurements on the structures, were used to capture the soil and structure responses. Multiple shaking events with peak base accelerations ranging from 0.03 to 0.5 g were applied. Cone penetration resistance, $q_c$, and $V_s$ testing were used to characterize the initial model conditions as well as the change in conditions (i.e., cementation degradation, soil densification) through the course of shaking. Surface settlement measurements and observations (**Figure 15**) provided an evaluation of the degree to which MICP treatment applied to limited depths affected the dynamic site response, triggering of liquefaction at different depths, and surface expression of that liquefaction. A key advantage of these types of large model tests, with multiple variations in conditions across the same container, are that the comparisons of performance are better constrained by the fact the soils throughout the container were prepared by the same researcher at one time and the same shaking motions were imposed throughout the model.

The 9-m and 1-m centrifuge models provided the first insights and essential data on fundamental behaviors of MICP treated sands at a systems level. The 1-m centrifuge tests first demonstrated how changes in liquefaction resistance, $V_s$, and $q_c$ for loose saturated sands treated by light, moderate or heavy levels of bio-cementation, as well as the degradation of cementation, occurs with increasing shaking intensity. Cone penetration resistances at mid-depth increased from 2 to 5, 2 to 10, and 2 to 18 MPa in lightly, moderately, and heavily cemented models, respectively. $V_s$ at mid-depth increased from 140 to 200, 140 to 325, and 140 to 660 m/s in lightly, moderately, and heavily cemented models at 80 g, respectively. Cone penetration resistances and $V_s$ after initial liquefaction decreased significantly in moderately and heavily cemented models, decreased slightly in lightly cemented models, and increased slightly in uncemented models. Cemented models required stronger peak base accelerations (PBAs) and cyclic stress ratios (CSRs) to trigger liquefaction compared to the uncemented model prepared to a similar relative density, even after initial liquefaction in a prior shaking event. The 9-m

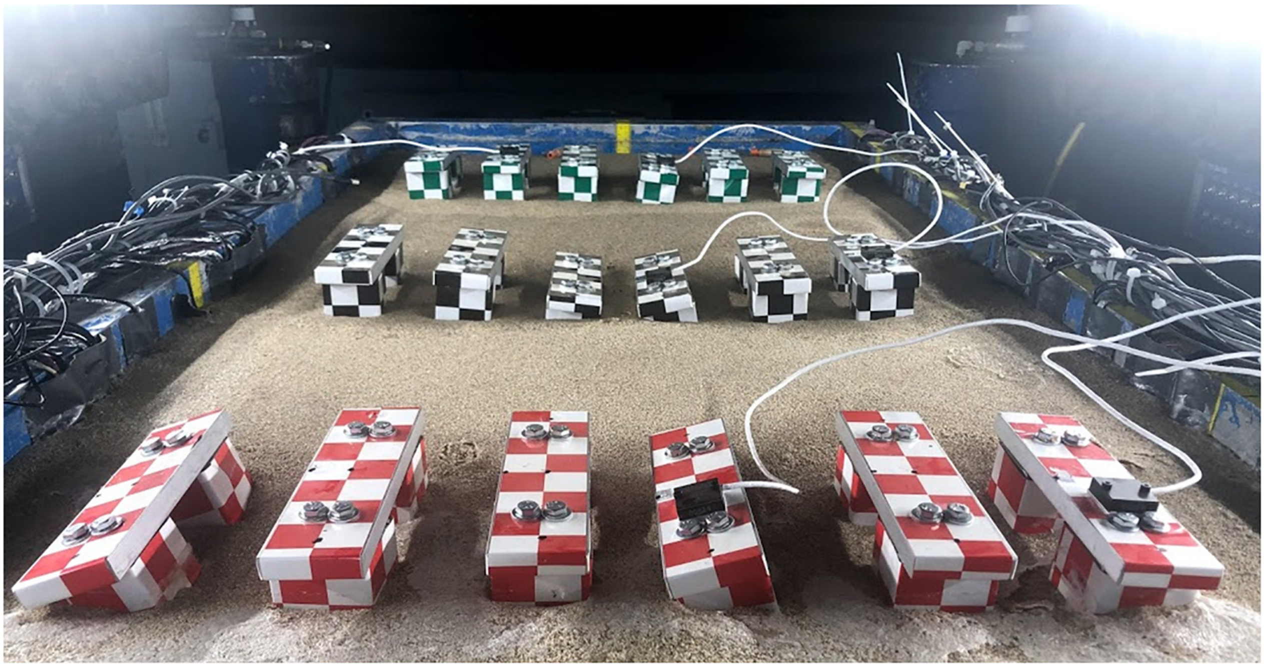

**FIGURE 15 |** Post-shaking photograph showing the variation of foundation settlements and tilting across the untreated, MICP 1 and MICP 2 treatment zones with liquefiable layers at shallow, medium, and deep intervals.

centrifuge tests are still being analyzed, but data analysis to date have shown changes in CPT $q_c$ and $V_s$ that are consistent with the 1 m centrifuge, confirming the scalability of model testing. The performance of the MICP improved zones within a large volume of untreated soil provided new insights with respect to the rate of cementation degradation, how MICP improved zones affected dynamic response, and how MICP improved zones can effectively reduce ground surface distortions due to triggering of liquefaction at different depths. The net practical benefit of MICP treatments was reduced absolute and differential settlement of surface foundations. On average, the absolute settlement of surface foundations due to liquefaction of the underlying layers was reduced by more than 80%, and the differential settlement was reduced by a similar level.

MICP and other bio-mediated remediation methods for liquefiable sands are emerging from being novel, creative, blue-skies ideas to being efficient, sustainable technologies that will likely be implemented at the field scale in the next 5 years. The NSF-sponsored CBBG has enabled the rapid maturation of these technologies by facilitating teams working on the fundamental aspects of the biogeochemical treatment process, evaluating how engineering properties change at the element/constitutive level, and developing how the technology can be up-scaled for field implementation. The NHERI CGM facility provides the critical additional capability of performing simple and complex system model analyses prior to when the technology is ready for field implementation. This has enabled re-evaluation of industry standard liquefaction triggering curves for cemented soils, development of CPT $q_c$ and seismic $V_s$ QA/QC monitoring techniques and target values, and quantified the level of improvement that may be able to be achieved with MICP improvement is applied in both free-field conditions and beneath embankments.

## EDUCATIONAL IMPACTS

The research performed at the NHERI centrifuge facility often have direct broader impacts, such as those described above. The CGM, through its participation as a NHERI facility, pursues broader impacts collectively in addition to the scientific advances discussed in the previous sections. Through its shared use, the facility hosts a range of visiting domestic and international researchers, industry collaborators, graduate students, undergraduate students, visitor tours, and K-12 classes, with the total number of visitors averaging a few hundred each year. Broader impacts include strengthening academic-industry partnerships to bridge science and practice, contributing to the development of codes and guidance documents, producing and sharing large datasets, training practitioners, and educating students through centrifuge activities. As education is critical to the missions of the NHERI centrifuge facility and CBBG, select activities are described in this section.

Students in traditional engineering curriculums often have a simplified concept of what a model is or can do, and have limited ability to use model-based reasoning (Carberry and McKenna, 2014). Wartman (2006) identified four benefits associated with students learning geotechnical engineering through physical modeling: (1) visualization of complex, nonlinear geotechnical mechanisms and phenomena otherwise difficult to visualize;

(2) development of an intuition and physical sense for the fundamental mechanisms that govern the behavior of these systems; (3) observation of failure mechanisms not seen in traditional geotechnical engineering courses, which often focus on element testing; and (4) assessment of the deviation between predicted and actual performance in geotechnical systems.

Through centrifuge modeling, students develop an appreciation of the ability of both physical and numerical models and of model-based reasoning. Student develop professional skills and experience attitudinal shifts as they develop their technical skills (e.g., signal processing, electrical, and mechanical skills). The coordination of their experiments requires strong communication and project management skills, especially in an environment where timelines frequently change due to unexpected circumstances. The physical modeling experience teaches students that engineering projects and the design process are nonlinear and requires they develop adaptive, growth mindsets that allow them to learn from adversity. Dweck (2007) defines a growth mindset as when individuals believe their talents can be developed through hard work, good strategies, and seeking input from others and view failure as a stepping stone to improvement. Successful student centrifuge modelers have or shift to a growth mindset with respect to their modeling skills and knowledge. The process requires students think critically about why a failure occurred and how to learn from it and find a solution. Industry partners have noticed the benefits with a one stating that they "love hiring centrifuge modelers because they already know how to solve problems."

Individuals use mental structures, or schemas, to organize knowledge and guide cognitive processes and behavior. Vygotsky's Social Development Theory notes that our specific mental structures and processes can be related to interactions with others around us (Woolfolk, 2013). The theory notes that learning only occurs when you are teaching at a level in which individuals can accommodate the new knowledge or cognitive skills by adapting their current mental structures. Specifically, the Zone of Proximal Development (ZPD) is as the area between a person's current development level as determined by independent problem solving and the level they could achieve with guidance and collaboration of more capable members of society. The UC Davis geotechnical group's development of a Ladder Mentoring Model (Bronner et al., 2018) for training graduate students in technical knowledge and skills, professional skills, and educational outreach aligns with Vygotsky's ZPD. Individuals starting at the NHERI centrifuge facility work with students with a few years of experience to learn new skills. More experienced staff and faculty provide more direct mentoring to those more experienced students (i.e., those who are one rung up on the ladder). This approach to mentoring graduate students in academic environments enriches graduate student development while minimizing additional demands on center personnel.

The educational thrust described here depends on the technical expertise of the geotechnical graduate students and faculty, educational expertise of a CBBG faculty member focused on engineering education, and expertise and support of NHERI personnel in maintaining the equipment and providing a facility for on-campus outreach activities. By strategically leveraging their resources (funding, equipment, space, time, and expertise), the NHERI centrifuge facility and the CBBG are able to implement sustainable outreach and mentoring programs with the mission of educating future geotechnical engineers and broadening participation from underrepresented groups in engineering.

## FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

The validation of advanced computational models persists as an overarching challenge in hazards engineering due to the variety of multi-scale, multi-physics, coupled nonlinear interactions that come to the forefront in different realizations of natural, extreme hazards. The 9-m centrifuge enables validation of complex mechanisms through physically large and holistic experiments that support inverse analyses of data from dense instrumentation arrays. The 9-m and 1-m centrifuges together enable validation from component to holistic levels of system complexity. The three research examples presented above illustrate how densely instrumented models with inverse analysis techniques can provide multiple levels of data for validating computational models, from local to global features of response. Validation against measurements of complex local mechanisms provides a higher-resolution evaluation of computation models than is possible with conventional tests and can help identify computational modeling limitations that affect simulation accuracy and generalization at a global scale.

The 9-m and 1-m centrifuges also provide unique opportunities for developing and validating engineering procedures for determining, for a range of challenging soil types, the characterizing properties required for advanced computational models (Bray et al., 2017). Determining soil properties for heterogeneous natural deposits or constructed fills across the scale of civil infrastructure systems usually involves a program of *in-situ* testing (destructive or nondestructive) and/or laboratory testing of field samples as well as significant engineering judgment in interpolation and interpretation. All currently available *in-situ* tests, sampling tools, and laboratory tests have known limitations in certain types of soils. Worse yet, there are a broad range of soil types for which no reliable *in-situ* test or sampling procedure has been developed, which makes the estimation of properties a dominant source of uncertainty in the application of advanced computational models. Examples of challenging soils include sensitive clays and silts (e.g., instabilities due to strain softening), gravelly and cobbly soils (e.g., particle size effects for *in-situ* tests and loading responses), carbonate soils (e.g., highly crushable), flyash from coal combustion (e.g., crushable and chemically reactive), intermediate soils (e.g., interpretation of *in-situ* test data in clayey sands to sandy silts), and finely inter-bedded sands and fine-grained soils (e.g., effect of inter-bedding on composite response, and lack of resolution in *in-situ* test data in thin layers).

The paucity of applicable physical data or case histories for many soil types means that their expected behaviors under generalized loading are poorly understood and the procedures for estimating their properties lack appropriate validation (Bray et al., 2017). Centrifuges provide opportunities to obtain inflight characterization tests (e.g., vane shear, T-bar, CPT, $V_s$, $V_p$, and samples for lab testing) and system performance data on the same specimen. The 9-m centrifuge offers the greatest capability for performing these characterization tests in models with realistically holistic levels of system complexity (including geologic complexity, such as inter-bedded sand and silt deposits) and minimizing scale effects (e.g., distorted ratio of penetrometer size to particle or interlayer size). Smaller centrifuges could contribute as well, but their smaller sizes limit model complexity and increases scale effects for some soils and characterization tests. Testing at 1-g in soil boxes can also contribute, but even the largest available 1-g soil boxes have significant limits on model complexity and achievable overburden stresses. Combinations of experiments using the NHERI centrifuge facilities (UC Davis), mobile field dynamic shakers (UT Austin), and large 1-g soil box (UCSD) can provide flexibility and potential synergy for enabling progress across many of the above challenges.

There are numerous other opportunities for technical breakthroughs on issues affecting specific infrastructure systems under loadings from earthquakes, waves, wind, and storms. Examples include the effects of ground deformations or erosion on underground pipelines, effects of tsunamis or storm surge on levees and foundations (e.g., Exton et al., 2018), effects of breaking waves on seashore stability (e.g., Takahashi et al., 2019), effects of storms and earthquakes on foundation systems for near-shore and offshore wind turbines (e.g., Zheng et al., 2019), and development of innovative, low-cost ground improvements for residential homes or levees where society requires a finer balance between costs and performance (e.g., Ishii et al., 2017).

The effective use of centrifuge modeling for geotechnical research requires awareness of several limitations inherent to physical modeling of natural soils as well as the centrifuge environment. The vast majority of physical models, using a centrifuge or shaking table, are constructed using reconstituted soils, which means that numerous environmental factors known to have strong effects on soil properties in the field (e.g., depositional process, over-consolidation, prior seismic loading, age, cementation, pore water chemistry, or thixotropy) are not represented. The large majority of physical models focus on idealized soil profiles with uniform properties within individual soil layers, which means that the influence of stratigraphic complexity and spatial variability remain under-studied experimentally. Centrifuge models are often unable to accurately reproduce complex construction processes, such that certain aspects may be inadequately reflected in the observed responses (e.g., increases in lateral stresses or densification due to vibro-replacement or vibro-installation of piles, drains, and other reinforcing elements), or complex structural systems (e.g., reinforced concrete). Different physical processes (e.g., dynamic shaking and pore pressure diffusion), follow different scaling laws; if these different processes are concurrent and coupled, compromises or special adjustments (e.g., scaling pore fluid viscosity) are required. Model containers impose boundary constraints that may inhibit certain phenomena (e.g., lateral deformations, radiation damping), which means that the selection of the model container requires foresight on the likely responses and interpretations, and that model containers generally need to be included in numerical simulation models. These and other limitations, such as those previously noted regarding scaling limitations with smaller centrifuge models, are generally well-recognized (e.g., Taylor, 1995) and in many cases, represent opportunities for future researchers to overcome.

A combination of NHERI facilities could be particularly effective for addressing some of these problems and more; e.g., the performance of near-shore wind turbines could be examined using model tests at the wind facilities to understand their dynamic responses, model tests at the centrifuge facilities to understand the performance of different foundation systems, and the mobile shakers to characterize the response characteristics of turbines in the field. These and other pressing research needs offer opportunities for partnerships between industry, academia, and public agencies utilizing the centrifuge facilities in combination with other NHERI facilities (wind, tsunami, mobile shaker, 1-g shake table, and RAPID) to contribute to safer and better-managed infrastructure systems.

Enhanced gravity testing also has the potential for increased utilization in scientific disciplines other than geotechnical and hazards engineering, as evidenced by various applications described in the literature. Centrifuge modeling has been used to study a range of geoenvironmental problems, from contaminant transport (Culligan-Hensley and Savvidou, 1995) to site remediation strategies (Marulanda et al., 2000); a number of geologic processes, including intrusions (Dixon and Simpson, 1987), faulting (Koyi and Skelton, 2001), and ice mechanics (Langhorne et al., 1999; Guerin et al., 2016); a number of manufacturing processes, including welding (Aidun and Martin, 1998), casting (Fukui, 1991; Zhang et al., 2018), and powders (Thomas and Beaudoin, 2015); and processes related to gasses and fires (Most et al., 1996). The "Spin your thesis" program by the European Space Agency[3] encourages a wide breadth of potential applications by enabling student researchers to perform research on self-selected topics, with many related to fluids and biological processes, on a centrifuge with centrifugal accelerations up to 20 g.

## CONCLUDING REMARKS

The NHERI facility at UC Davis provides the national research community with open access to 9-m and 1-m radius geotechnical centrifuges, offering unique and versatile modeling capabilities for advancing methods to predict and improve the performance of soil and soil-structure systems affected by earthquake, wave, wind, and storm surge loadings. Three research projects related to seismic hazards – liquefaction effects on a submerged subway tunnel, rocking of shallow foundations, and remediation of liquefaction by MICP – were used to illustrate the facility's capabilities and the complementary roles of the 9-m and 1-m centrifuges. The 9-m centrifuge models with holistic levels of complexity are particularly effective for

[3] https://www.esa.int/Education/Spin_Your_Thesis; accessed April 26, 2020.

the building of basic science knowledge and the validation of advanced computational models from the component to the holistic system level. The NHERI centrifuge facility has helped strengthen academic-industry partnerships to bridge science and practice, contributed to the development of codes and guidance documents, produced and shared large datasets, trained practitioners, and provided uniquely broad educational experiences to a diverse group of researchers.

Some future research opportunities using the NHERI centrifuge facilities were discussed, although the scale and breadth of multi-physics, systems-level challenges that society faces are greater than could be covered in this paper. Opportunities for enhanced gravity testing in technical disciplines other than geotechnical and hazards engineering were briefly discussed to illustrate opportunities for any user to leverage this national shared use facility. The authors expect the coming decades will see continued advances in centrifuge modeling technology and a broadening of its utilization.

## ETHICS STATEMENT

Written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article.

## AUTHOR CONTRIBUTIONS

RB and DW outlined the manuscript. BK, JD, CB, DW, and RB contributed drafts for sections of the manuscript. All authors contributed to manuscript revisions, read, and approved the submitted manuscript.

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# Aeroelastic Testing of Span-Wire Traffic Signal Systems

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Span-wire traffic signals are vulnerable to extreme wind events such as hurricanes and thunderstorms. In past events in the Southeastern Coast of the United States, many failures of span-wire traffic signals were reported. In order to identify their dynamic behavior during extreme wind events and investigate their buffeting response, a large-scale aeroelastic testing was conducted at the NHERI Wall of Wind (WOW) Experimental Facility (EF) at Florida International University (FIU). The WOW is a large-scale open jet wind testing facility, comprised of 12 fans, and capable of simulating winds at speeds up to 70 m/s, corresponding to a Category 5 hurricane. Following the Froude number criterion, a 1:10 aeroelastic model of a span-wire traffic signal system consisting of two 3-section and one 5-section signals was designed and constructed, based on the properties of its full-scale counterpart. In the testing protocol, various wind directions ranging between 0° and 180° were considered at full-scale wind speeds ranging between 21 and 43 m/s. The results of the aeroelastic tests show a similar behavior compared with previous full-scale tests conducted at the WOW. However, an increase in the RMS of accelerations was observed in comparison with those from the full-scale tests. This is attributed to the fact that the aeroelastic model enabled better simulation of low-frequency eddies in the turbulence spectrum compared to the full-scale testing turbulence spectrum.

**Keywords: traffic signals, span-wire, Froude number, aeroelasticity, large-scale, buffeting response, NHERI Wall of Wind**

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## INTRODUCTION

Geographically, Florida and the East Coast of the United States have been very vulnerable to extreme wind events such as hurricanes and thunderstorms. Significant structural damage occurs from such high-intensity winds on an annual basis (Holmes, 2015; Simiu and Yeo, 2019). Of general interest in this paper are civil engineering transportation infrastructure, specifically span-wire traffic signal systems. Such traffic systems are of high importance since a lack of functionality greatly affects traffic flow within a city as well as evacuation plans before or during the passing of such severe events with large geographic footprint. By consequence, the enhancement of traffic signals is of utmost importance to the safety of motorists (Sivarao et al., 2010; Zuo and Letchford, 2010; Irwin et al., 2016; Matus, 2018).

In most cases, traffic conditions and vehicular flow direct the use of certain traffic signal configurations over others. According to the State of Florida Department of Transportation (FDOT), as much as 63% of intersections in the state use span-wire traffic signal systems. Typically, such traffic signal systems consist of the signal units supported by aluminum hangers and two wires (a messenger on the bottom and a catenary on the top) holding the hangers in place and spanning between two poles (typically steel or concrete). Despite their wide use in the state of Florida, there is a lack of design guidelines for span-wire systems subjected to high-intensity wind events (Cook et al., 2012; Irwin et al., 2016; Zisis et al., 2016a, 2017; Azzi et al., 2018, 2019; Matus, 2018). Although mast-arms are preferred to span-wire traffic signals, the use of the latter system remains as the only solution when the installation of a mast-arm is not feasible (Matus, 2018). During the 2004–2005 hurricane season, it was observed that these systems were very susceptible to damages under wind-induced forces, which indicated that a better design was required to enhance their survivability and sustainability (State of Florida Department of Transportation (FDOT), 2005; Cook et al., 2012; Zisis et al., 2016a). More recently, damage assessment studies conducted post-impact of hurricanes Irma and Michael in the state of Florida have showed the vulnerability of traffic signals to strong wind-storms (Pinelli et al., 2018; StEER: Structural Extrement Event Reconnaissance Network, 2018). There have been previous studies on traffic signals, which had found that oscillations, caused by wind-induced forces, can cause structural damages (McDonald et al., 1995). These oscillations were identified as an incipient galloping instability that can produce damages to different components of the traffic signals attached to cantilevered structures (Kaczinski et al., 1998). It is important to enhance the knowledge on the response of the span-wire traffic signal systems as damages may impose life-threatening conditions for motorists during and after extreme wind events (Sivarao et al., 2010). Studies have focused on the effect of wind loads on untethered span-wire signal poles and recommended the consideration of load transfer induced by such forces, which can cause significant deflections to end supports (Alampalli, 1997). Cook et al. (2012) conducted 33 tests of different span-wire traffic signal systems identifying inclination issues as well as hardware failure due to wind-induced forces. Due to the typical span lengths, which can vary from 15 to 60 m length (Irwin et al., 2016), a full-scale test of the traffic signals is difficult and this particular research experiment, conducted by Cook et al. (2012), created hurricane-wind forces (non-ABL) which were applied to 1-signal or 2-signal configurations and not to the entire traffic system. Later investigations carried out in an ABL wind tunnel tested the two most typical span-wire traffic signal configurations used and identified that the most susceptible and/or critical configuration was a 3–3–5 configuration, which consists of two 3-section plus one 5-section signals mounted on a short-span test rig. This investigation also showed that some span-wire traffic signals can undergo aerodynamic instabilities at wind speeds as low as 32 m/s (Irwin et al., 2016; Zisis et al., 2016b). The special short-span rig was designed to produce the same response of a typical 24 m long span-wire traffic signal system by the addition of coil springs at either side of the system cables (Irwin et al., 2016). Other investigations examined the overall response of span-wire traffic signals with different parameters of the signal assembly itself and found out that such changes affect the drag and lift coefficients of the entire system (Matus, 2018). The majority of the previous research has focused on certain components of span-wire traffic signal assemblies due to the difficulty of testing a full-scale span. Zisis et al. (2017) provided valuable validation on the efficacy of a short-span test rig of 6.7 m to represent a 24 m span. It must be noted that as the scale of the model is increased, the ability of the wind tunnel to recreate the full frequency range of the wind turbulence reduces and the aerodynamic buffeting effects may be compromised, failing to provide a full response of the system as well as limiting the length of the span that can be simulated. With the 1:10 aeroelastic model, the full aerodynamic response would be obtained and a study on the effect of different span lengths could be accomplished.

The methodology of this study involves the design and testing of an aeroelastic model of a span-wire traffic system consisting of two 3-section and one 5-section signals subjected to varying wind speeds from various directions. The model is a scaled-down version of an actual span-wire traffic signal assembly previously tested at the NHERI Wall of Wind Experimental Facility (WOW EF) (Irwin et al., 2016; Zisis et al., 2017). Observations pertaining to aerodynamic instabilities were made and the results were compared to those achieved from the earlier full-scale testing. Wind testing of a reduced aeroelastic model representing this particular span-wire configuration allowed a better representation of the wind turbulence spectrum. Such tests also enabled the evaluation of the wind-induced buffeting response of the structure.

# METHODOLOGY

## The Wall of Wind Experimental Facility

The National Science Foundation (NSF) designated FIU's Wall of Wind (WOW) as one of the Experimental Facilities (EFs) under the distributed, multi-user, national Natural Hazards Engineering Research Infrastructure (NHERI). The WOW EF is an open jet testing facility consisting of a 12-fan system. The facility can generate Atmospheric Boundary Layer (ABL) wind speeds and turbulence characteristics, similar to those observed and recorded in hurricanes (up to the intensity of Category 5 in the Saffir-Simpson scale). The test section, which is 6 m wide and 4.3 m high, permits testing of buildings and lifeline infrastructure systems at large scales, as well as full-scale testing of building components, equipment, and rooftop installations, among others. Wind speeds at the WOW are able to reach a maximum of 70 m/s while wind profiles and terrain conditions are simulated by a set of automated roughness elements and spires located in the flow conditioning section. More information about the WOW EF, its capabilities, and enabled research, is available in Chowdhury et al. (2017). **Figures 1A,B** show the intake side and the flow conditioning section at the WOW.

## Prototype Description

The prototype span-wire traffic signal system chosen for this experiment is a typical assembly that can be found on any two- or more lane roadway, particularly in the state of Florida. **Figure 2** illustrates a span-wire traffic signal assembly used in Florida. For the full-scale tests conducted at the WOW, the span-wire traffic signal assembly was composed of the following: (i) two

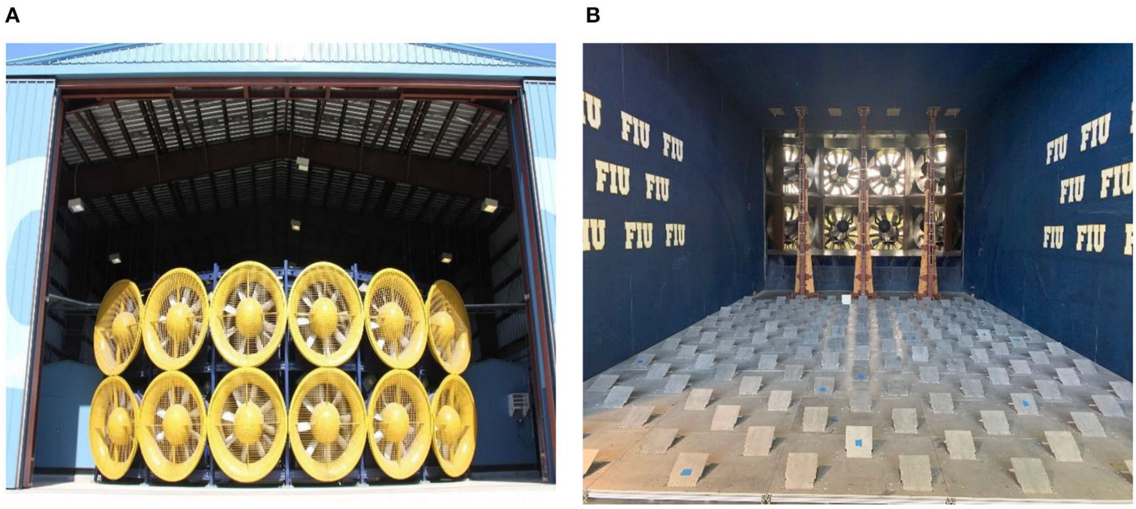


**FIGURE 1 |** WOW facility: **(A)** intake side, **(B)** spires and automated roughness elements [Reproduced from Azzi et al. (2020) under the Creative Commons CC BY license].


**FIGURE 2 |** Typical span-wire traffic signal system.

HSS (ASTM Standard A00/A500M, 2018) Grade B steel columns standing at the end-spans having a height of 8.5 m; (ii) two seven-wire strands steel cables (messenger and catenary cables) having a diameter of 9.5 mm and satisfying the properties specified in (ASTM Standard A475, 2014) for Class A Zinc Coating; (iii) three rigid aluminum alloy hangers holding both cables together, and (iv) three traffic signals hanging from the bottom end of the hangers. The messenger cable is tensioned with a uniform axial force of 240 N and the catenary wire is fixed in a way to provide a 5% sag at mid-span. The traffic signals selected for this study consisted of one 5-section and two 3-section signals. Previous research on span-wire traffic systems by Zisis et al. (2016a,b) has shown the above-described configuration as the most vulnerable, and therefore, was used for this investigation.

Typically, a span-wire traffic signal system spans between 15 and 60 m, depending on the physical properties of the intersections such as the number of lanes and their width (Irwin et al., 2016). For the full-scale specimen, two spans were considered: a short- and long-span. First, a short-span rig of ∼6.7 m was designed and implemented at the WOW. The idea behind the design of the short-span was to be able to fully mount the system on the turntable, thus allowing for multiple wind directions to be tested. Since a span of 6.7 m is not realistic and does not belong to the range mentioned above (between 15 and 60 m), coil-springs were added on both ends of the cables in order to have the same lateral force to deflection properties as the long-span frame (Irwin et al., 2016; Zisis et al., 2017). Both short- and long-span specimens are presented in **Figures 3A,B**, respectively. More information on the validation between both specimens is available in Zisis et al. (2017).

Although full-scale testing provides valuable information on the performance and response of traffic signal components (for instance the focus of the full-scale tests was the detailed evaluation of different hanger connections) mounted on span-wire systems with realistic consideration of structural boundary conditions and system dynamic properties, various limitations are also encountered. Because the tests are conducted at full-scale, and wind tunnels have a limited test section size, it is not feasible to simulate the complete spectrum of wind turbulence as in the real ABL flow (Choi and Kwon, 1998; Mooneghi et al., 2016; Moravej, 2018). Also, in full-scale testing, the exact clearance between the bottom of the traffic signals and the ground, which typically ranges between 4.6 and 6 m, cannot be maintained inside the testing section. On the other hand, scaled aeroelastic testing enables a better simulation of the turbulence spectrum at the natural frequency of the signals. However, at smaller scales, the accuracy of the geometric and mechanical simulation of the components that form the model become quite challenging. Due to the lack of guidelines for the safe design of span-wire traffic signals and because of their wide use, especially in the state of Florida, it is crucial to investigate the dynamic performance of

A　　B

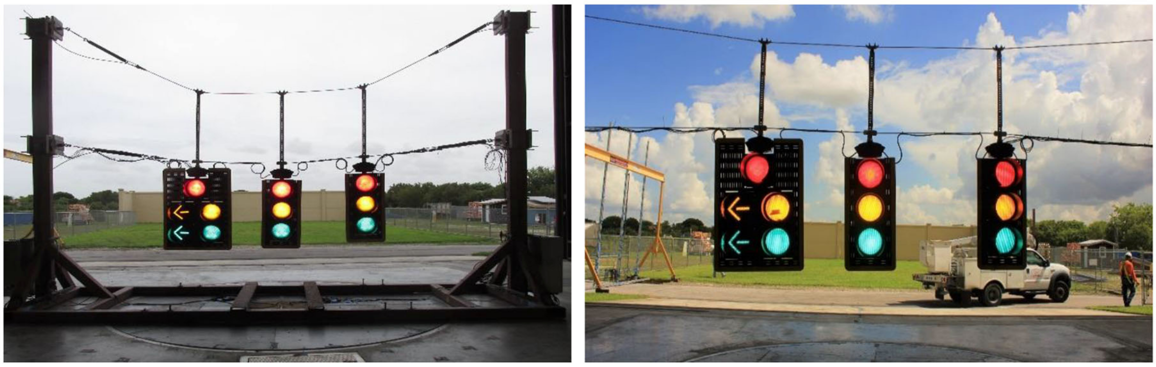

**FIGURE 3 |** Full-scale specimens: **(A)** short-span, **(B)** long-span.

such systems under extreme wind conditions. To the best of the authors' knowledge, no prior studies have been done considering the proper simulation of the dynamic characteristics of the entire system to assess the wind-induced dynamic and aeroelastic response of traffic infrastructure. Such a knowledge gap hinders achieving resilient communities and adverse recovery strategies post hurricane events. Therefore, the main objective of the current study is to perform comparisons between the two wind testing methods (full-scale testing vs. aeroelastic testing) and investigate the adequacy of each individual approach in estimating the overall dynamic response in light of the capacity and limitation of each test. Consequently, it was decided to construct an aeroelastic model with a 1:10 scale of the exact specimen that was tested at full-scale earlier to better investigate the overall dynamic response of the traffic signals and compare its behavior.

**TABLE 1 |** Scaling factors $\lambda_Q$.

| Quantity *Q* | Relationship | Scale factor $\lambda_Q$ |
|---|---|---|
| Length *L* | $\lambda_L = \frac{L_M}{L_P}$ | $\frac{1}{10}$ |
| Velocity *U* | $\lambda_U = \frac{U_M}{U_P} = \sqrt{\lambda_L}$ | $\sqrt{\frac{1}{10}}$ |
| Mass *m* | $\lambda_m = \lambda_P \times \lambda_L{}^3$ | $\frac{1}{1{,}000}$ |
| Mass moment of inertia *I* | $\lambda_I = \lambda_M \times \lambda_L{}^2$ | $\frac{1}{100{,}000}$ |
| Time *t* | $\lambda_t = \frac{t_M}{t_P} = \frac{\lambda_L}{\sqrt{\lambda_L}} = \sqrt{\lambda_L}$ | $\sqrt{\frac{1}{10}}$ |
| Frequency *f* | $\lambda_f = \frac{f_M}{f_P} = \frac{1}{\lambda_T} = \frac{1}{\sqrt{\lambda_L}}$ | $\sqrt{10}$ |
| Acceleration *a* | $\lambda_a = \frac{a_M}{a_P} = \frac{\lambda_U}{\lambda_T} = 1$ | 1 |
| Damping $\zeta$ | $\lambda_\zeta = \frac{\zeta_M}{\zeta_P} = 1$ | 1 |
| Bending elastic stiffness *EI* | $\lambda_{EI} = \frac{EI_M}{EI_P}$ | $\frac{1}{100{,}000}$ |
| Axial elastic stiffness *EA* | $\lambda_{EA} = \frac{EA_M}{EA_P}$ | $\frac{1}{1{,}000}$ |
| Force *F* | $\lambda_F = \frac{F_M}{F_P} = \lambda_U{}^2 \times \lambda_L{}^2 = \lambda_L{}^3$ | $\frac{1}{1{,}000}$ |

# Model Description

## Laws of Similitude

For this set of experiments, which utilizes a relatively large length scale of 1:10, Froude number similitude was preserved. By definition, a Froude number characterizes the ratio of fluid inertial forces to gravitational and elastic forces of the structure itself. For this particular structural aeroelastic modeling, since the gravitational forces (e.g., the wire vibrations) are more dominant than their frictional counterparts and because of the expected significant movement of the traffic signals (as found in the earlier full-scale study), the selection of Froude number *Fr* similarity was adopted. Furthermore, since the gravitational acceleration *g* is kept the same for both prototype and model, then the scaling would be achieved by linking the velocity scale to the square root of the length scale. Note that it is not feasible to satisfy both *Fr* and *Re* scaling simultaneously and because of the scaled model approach, the "full-scale *Re*" simulation was not possible. Lastly, the bluff shapes of the traffic signals are expected to make them less dependent on *Re*. Hence, there is a need to carefully simulate the distribution of masses and elastic stiffnesses along both prototype and model in order to maintain dynamic similarity and structural response. For any general quantity measured on the prototype $Q_P$, Equation (1) can be used to calculate its model counterpart $Q_M$:

$$Q_M = Q_P \times \lambda_Q \tag{1}$$

where $\lambda_Q$ is the physical property scaling factor.

The relationship between the prototype and the model quantities strongly depend on the materials selected for the construction of the latter. To maintain the structural damping of the system components, prototype materials were selected for the construction of the aeroelastic model. However, due to some constraints regarding the satisfaction of other scaling ratios such as the mass and the stiffness, some elements required a change of material type. **Table 1** summarizes the most important scaling factors required for the design of the aeroelastic model.

## Aeroelastic Design of Cables

The dynamic behavior of any cable structure is dominated by three main properties: its distributed weight per unit length, its diameter, and most importantly, its axial elastic stiffness *EA*. Note that *E* is the modulus of elasticity and *A* is the cross section. The prototype axial elastic stiffness *EA* was scaled down using the appropriate factor from **Table 1** and a diameter of 0.25 mm was selected. Equation (2) states the drag coefficient requirements that need to be satisfied for aeroelastic modeling:

$$C_{DM} \times D_M = C_{DP} \times D_P \times \lambda_L \quad (2)$$

where $C_{DM}$, $C_{DP}$, $D_M$, and $D_P$ are the drag coefficients of the model and the prototype cables and their diameters, respectively, and $\lambda_L$ is the length scale factor. Although the previously chosen diameter of 0.25 mm satisfies the axial stiffness scaling requirements, yet, it partially fulfills the drag and weight requirements. This explains the need to add non-structural elements in the form of foam rods along the span of the wires in order to fulfill that purpose. The rods were 9.5 mm thick and 2.3 cm long. By carefully meeting all three requirements related to axial stiffness, diameter, and distributed weight, the frequency and mode shapes of the prototype span-wire system are reproduced at the reduced scale. More details about the design validation are discussed later on in the paper. The actual shape and location of the foam elements can be seen in **Figure 4**.

### Aeroelastic Design of Column, Hangers, and Traffic Signals

The column rigs used for the supports of the aeroelastic span-wire traffic signal model were made of aluminum having a solid rectangular cross-section of 2.54 by 1.9 cm. The column section was chosen so that the columns are sufficiently rigid. As for the hangers, thin aluminum sheets with cross-sectional dimensions of 3 by 0.5 mm are selected. Both structural elements are designed according to their bending elastic stiffness *EI* and their weight *W*.

For the traffic signals, three units were used: two 3-section and one 5-section. The full-scale signals were weighed and measured at the WOW and then scaled down according to the appropriate factors from **Table 1**. Consequently, the units were carefully drawn on a CAD software using the scaled-down measurements and considering all the important geometry details (e.g., openings, chamfering of edges, etc.). Moreover, an in-house 3D printer was used to reproduce the small-scale traffic signals using a resin. Since the 3D printed elements are lighter than their aluminum counterparts, their masses were adjusted by installing steel sheets on the inner walls of the signals. This procedure made the signals heavier in order to reach the target mass. **Figure 4** shows the small-scale aeroelastic model mounted on the WOW turntable.

## Numerical Modeling and Validation

Modal analyses were performed for both full- and small-scale specimens using the Finite Element Methods (FEM) commercial software SAP2000® (CSI, 2018). All the previously described sectional properties and dimensions (full- and small-scale) were used to reproduce the prototype and the model. The subsequent mode shapes along with their respective frequencies were identified and summarized in **Table 2**.

The columns were modeled as straight rigid frame elements with fixed supports at the ground level. The hangers were also modeled as rigid frame elements and were clamped to both cables at the desired locations. The wires were represented using cable elements and the traffic signals were drawn as solid sections and their shapes were accurately simulated.

**Table 2** shows the two most dominant mode shapes in the behavior of both models. Note that the target frequency is equal to the prototype frequency times the appropriate scaling factor ($\lambda_f = \sqrt{10}$, **Table 1**). As can be seen, the target and model frequencies are very close with a maximum percentage difference of about 5.8%. This indicates that the materials and sections chosen for generating the FEM aeroelastic model were appropriate, which gave confidence to proceed with the construction of the model at the WOW.

Moreover, the prototype frequency $f_p$ obtained for mode 1 (0.37 Hz) is very close to the experimentally obtained one using a free vibration test for the full-scale specimen. **Figure 5** shows the power spectral density (PSD) of the acceleration of the traffic signals in the short-span full-scale prototype, in the direction normal to the span. The PSD plot was obtained from the response of the accelerometers during wind testing. The percentage difference obtained between the theoretical (0.37 Hz) and experimental values (0.39 Hz) for the prototype is ∼5.4%. This indicates once again that the modeling of the prototype was conducted properly, and it was representative of the actual specimen tested at the WOW.

## Instrumentation and Testing Protocol

The aeroelastic model was instrumented with three 3-axis accelerometers. One accelerometer was installed on the lower backend of each traffic signal. Additionally, and to record the time histories of the velocities, two Cobra probes (Cheung et al., 2003; Cochrane, 2004; McAuliffe and Larose, 2012) were mounted on a rig behind the model at a height of 0.61 m. Data were sampled at a rate of 2,500 Hz for the Cobra probes. Two load cells were installed at the bottom end of each column support. This enabled the recording of the change in tension experienced by the messenger cable.

Open terrain exposure was adopted for this set of tests and the aeroelastic model was exposed to the following wind speeds: 6.5, 9, 11, and 13.5 m/s (corresponding to a full-scale speeds of 21, 28, 35, and 43 m/s at a reference height of 3.2 m). The previous velocities yielded Reynolds number *Re* values of $1.76 \times 10^5$, $2.43 \times 10^5$, $2.97 \times 10^5$, and $3.65 \times 10^5$, respectively. Note that *Re* values were calculated at a mean signal height of 0.4 m. Also note that, in the full-scale tests, the *Re* values ranged between $2.2 \times 10^6$ and $3.7 \times 10^6$ for the different tested wind speeds. Using the automated WOW turntable, several wind directions were investigated, ranging between 0° and 180° at increments of 15°. Note that a wind direction of 0° represents wind approaching normal to the frontend of the traffic signals. Accelerometer and load cell data were sampled at 100 Hz and for a duration of 1 min per exposure angle.

## Surface Roughness

Both full-scale and small-scale specimens were tested with the same spires and automated roughness elements that are installed in the flow control box downwind of the fans at the WOW (**Figure 1B**). Due to the large difference in specimen heights, the surface roughness $z_o$

**FIGURE 4 |** Aeroelastic model on the WOW turntable.

**TABLE 2 |** Modal analyses results.

| Modal number | Mode description | Full-scale frequency $f_p$ (Hz) | Target frequency $f$ (Hz) | Scaled model frequency $f_m$ (Hz) | Percentage difference (%) |
|---|---|---|---|---|---|
| 1 | Displacement in the longitudinal direction (normal to traffic signals) | 0.37 | 1.17 | 1.11 | 5.1 |
| 2 | Rotation of traffic signals about their vertical support | 0.49 | 1.56 | 1.65 | 5.8 |

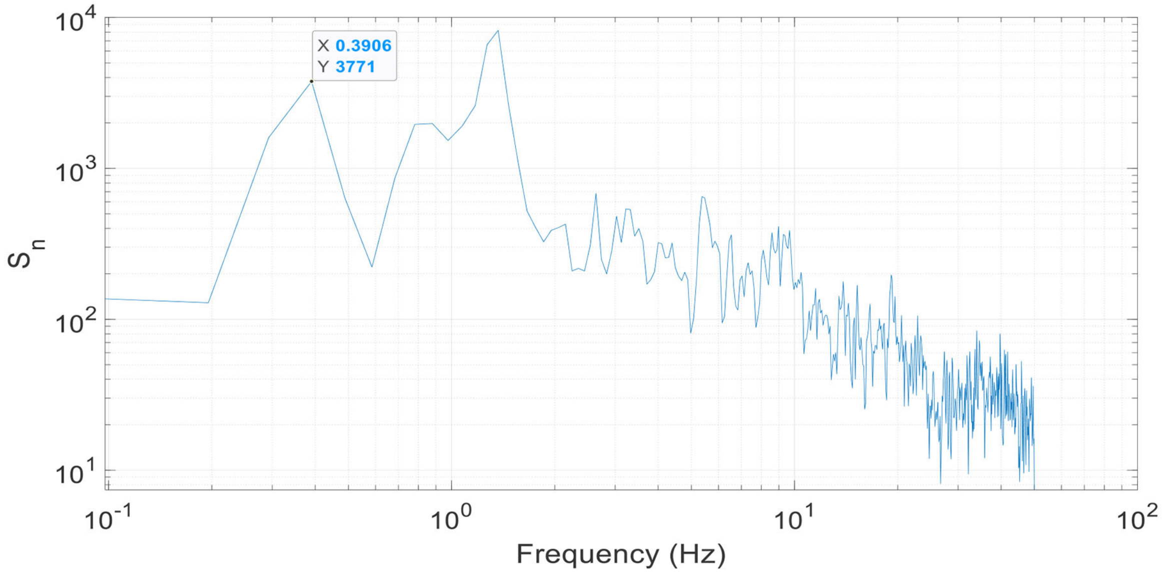


**FIGURE 5 |** PSD of acceleration for short-span prototype in the direction normal to the span.

at the mean height of the traffic signals might have been rougher for the aeroelastic model. **Figure 6** portrays the normalized PSD of longitudinal turbulence fluctuations for the aeroelastic model.

Because of the high speeds at which the full-scale tests were run, and so as not to damage the instruments, no cobra probes were used. However, based on previous full-scale tests at the WOW having a similar roughness and spire configuration in

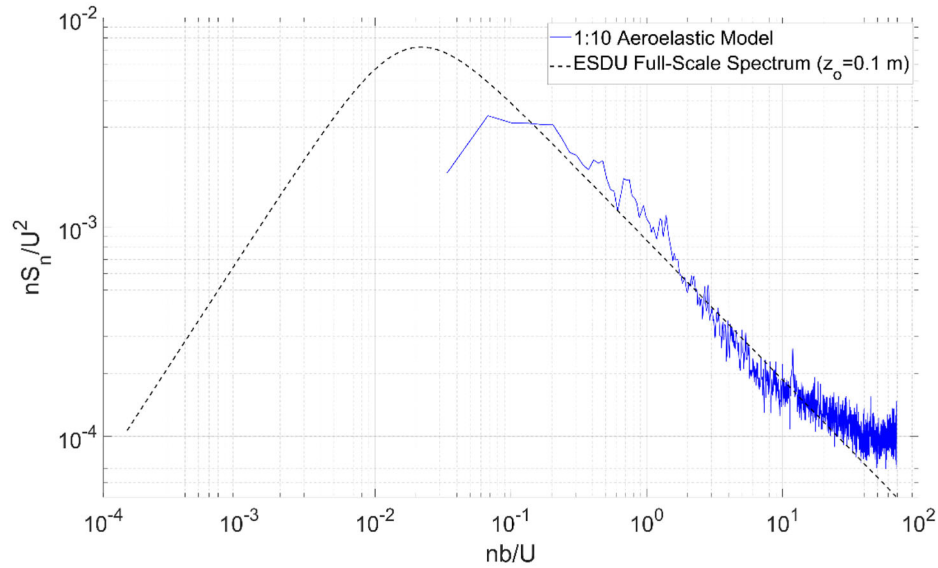


**FIGURE 6 |** PSD of longitudinal turbulence fluctuations.

the flow chamber, the surface roughness $z_o$ ranged between 0.02 and 0.06 m (Moravej, 2018; Moravej et al., 2019). On the other hand, and according to ESDU (2001), the surface roughness of the aeroelastic tests were about 0.1 m (full-scale). This difference in surface roughness between both specimens might lead to slight divergences in peaks, which could affect the dynamic response comparisons that will follow. Note that in the aeroelastic tests, the turbulence intensity $I_u$ ranged between 10.2 and 12.4% and the integral length scale $^xL_u$ varied between 0.43 and 0.48 m.

## RESULTS AND DISCUSSION

In the following section, free vibration test results are reported prior to the actual wind testing findings. Then, the aerodynamic instabilities observed during the entirety of the tests are noted down. In addition, the surface roughness of both full-scale and small-scale specimens are calculated and compared. Furthermore, root-mean-square (RMS) of accelerations are presented and compared to their full-scale counterparts. Last but not least, dynamic amplification factors are calculated for both models. Such a factor allows the investigation of the dynamic response of the system. Furthermore, a buffeting analysis is conducted and theoretical values of RMS of accelerations are calculated and compared with their experimental counterparts.

### Free Vibration Tests

A free vibration test prior to the actual start of wind testing was conducted. The purpose of such a test is to compare the recorded natural frequency of the constructed model in the wind tunnel with design values. The test consisted of using a straight wooden rod to manually push back all three traffic signals and let them oscillate freely until reaching their initial rest position while measuring their instantaneous accelerations. This practice allows the recreation of mode shape 1, described in **Table 2**.

From the captured acceleration time histories, the fluctuating response and the corresponding frequencies can be obtained using a Fast Fourier Transform (FFT) application. **Figure 7** depicts the PSD of the acceleration time history of the 5-section traffic signal. Note that the PSD plot has been adjusted to show the full-scale frequency, i.e., the frequency was divided by its respective scaling factor $\lambda_f$ from **Table 1**.

From **Figure 7**, the frequency of the first mode of vibration, which is defined by the first spike in the curve, occurs around 0.4 Hz (seen in the data box, **Figure 7**). By comparing the obtained value to the target frequency for mode shape 1 given in **Table 2** (0.37 Hz), it can be concluded that the tension in the messenger is nearly equal to the target one and that the model was correctly designed and constructed to mimic the behavior of its full-scale counterpart. Since the reproduction of mode shape 2 (**Table 2**) was challenging as the traffic signals were rotating around their vertical supports in different patterns, it was decided that matching mode shape 1 was sufficient for the model construction validation.

### Observed Instabilities

The aeroelastic model was subjected to wind speeds ranging between 21 and 43 m/s (full-scale) and at angles ranging between 0° and 180° at 15° increments. During the entirety of the test time, some aerodynamic instabilities and natural modes of vibrations were observed, especially from oncoming cornering winds. **Figures 8A,B** show the aerodynamic instabilities that were most visible during the tests. These instabilities included the appearance of mode shape 1 and some twisting of the 5-section signal around its vertical axis.

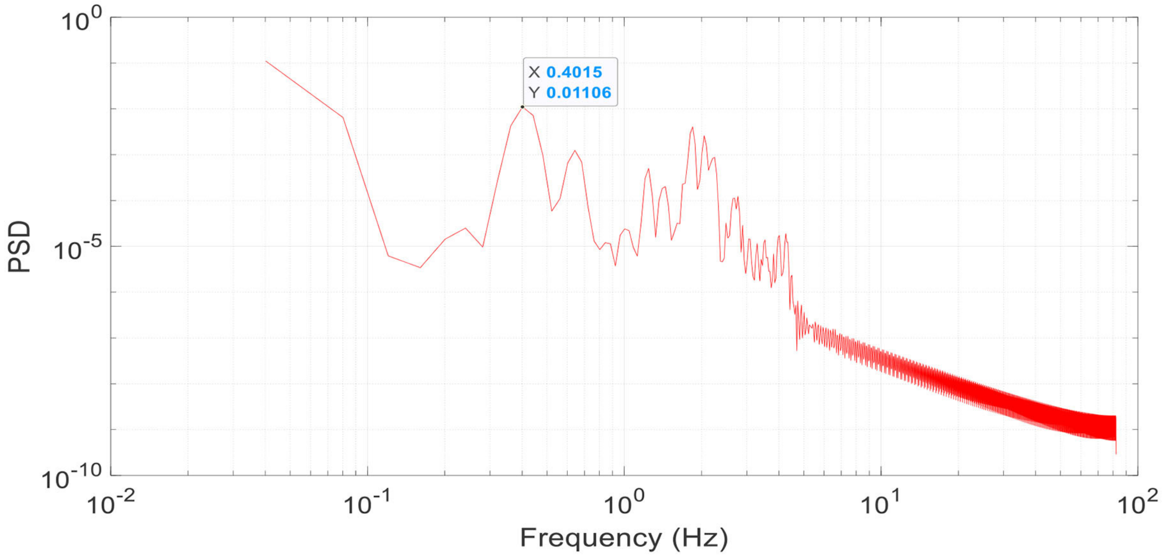


**FIGURE 7 |** PSD of acceleration of 5-section signal during a free vibration test.

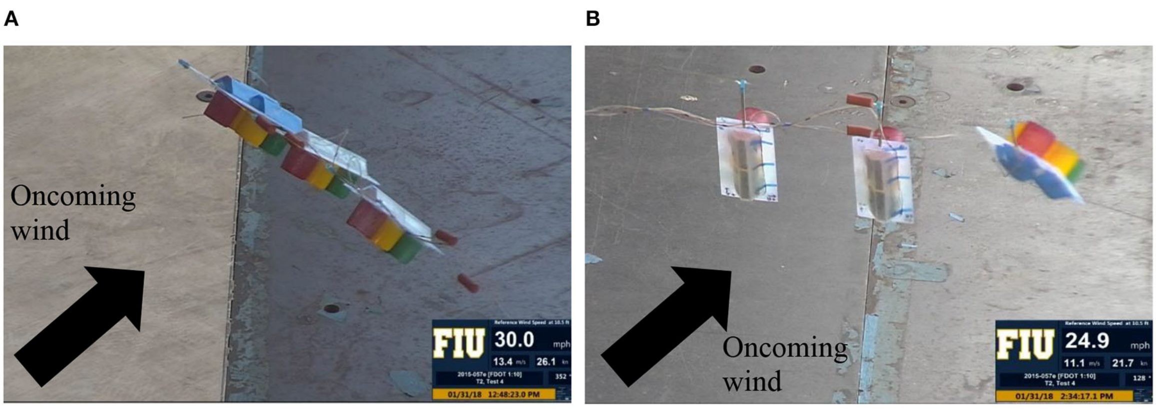


**FIGURE 8 |** Observed instabilities: **(A)** backward tilting of all three signals at 0° angle of attack, **(B)** twisting of 5-section signal at 135° angle of attack.

**Figure 8A** shows that, at 0° angle of attack and 13.4 m/s, all three traffic signals rotated and tilted backward due to the oncoming wind, illustrating the first natural mode of vibration of the specimen (**Table 2**). At 135° angle of attack and 11.2 m/s (**Figure 8B**), and at 45° and 13.4 m/s, more aerodynamic instabilities were observed. Such instabilities included the twisting of the 5-section signal about its vertical axis among others. In other brief instances, the WOW team noticed the appearance of mode shape 2 during the wind testing.

## RMS of Accelerations

This section discusses the RMS of the accelerations experienced by the aeroelastic model. As previously mentioned in section Instrumentation and Testing Protocol, three accelerometers were installed on the model, one on the bottom of each of the backplates of the traffic signals. **Figure 9A** portrays the change in root-mean-square (RMS) of the accelerations experienced by the signals with respect to the increase in oncoming wind speeds at 0° angle of attack, for both models. Note that "A" stands for the RMS of the 5-section signal whereas "B" and "C" belong to each of the 3-section signals. Also, note that the wind speed used is the one at the mean signal height for both specimens and represents the full-scale parameter. In addition, "FS" stands for full-scale and "SS" represents small-scale. More results on the full-scale study for both long-span and short-span specimens is available in Irwin et al. (2016) and Zisis et al. (2017).

As it can be observed, the results obtained for the aeroelastic model are higher than the full-scale ones for the same approaching speed at the mean height of the traffic signals. The RMS values of the aeroelastic model are around 30–40% higher than the ones experienced by the prototype. However, all values show an approximately linear increasing proportionality

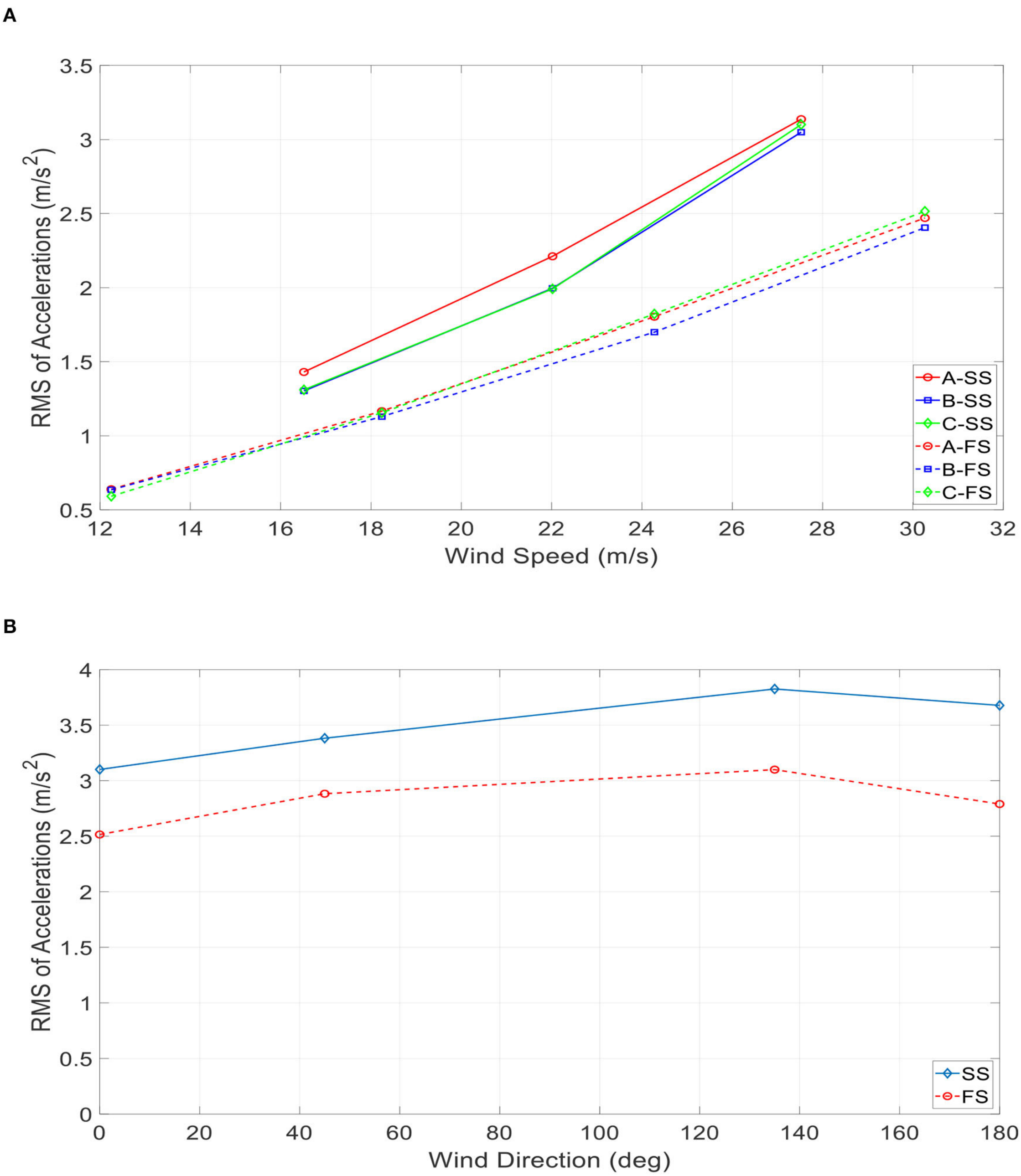


**FIGURE 9 |** RMS of accelerations at: **(A)** 0° wind direction, and **(B)** a wind speed of 27 m/s and different wind directions.

relationship between RMS of accelerations and oncoming wind speeds. The same observation was also seen at different wind directions at a wind speed of 27 m/s (this is corresponding to the "full-scale" wind speed at the center of the traffic signals for the full-scale short-span rig and the aeroelastic model) (**Figure 9B**).

The higher values obtained for the aeroelastic model could be attributed to the better representation of the turbulence spectrum that could be achieved at the small-scale (**Figure 6**). In addition, the power spectrum value of the response at the model natural frequency in the aeroelastic model was much higher than in the full-scale tests, and at a level that gave a good indication of the resonant response caused by turbulence buffeting from the approaching turbulence. However, in the full-scale tests, the effects of signature turbulence from the signals themselves tended to dominate the entirety of the testing.

## Dynamic Amplification Factors

One step in assessing the buffeting response of the traffic signals is to try and decompose the dynamic response of the system into peak, mean, background and resonance. This section introduces the concept of a dynamic amplification factor (DAF). According to Elawady et al. (2017), the DAF is defined as the ratio of the maximum peak response over the maximum quasi-static response, as shown in Equation (3):

$$DAF = \frac{Maximum\ peak\ response}{Maximum\ quasi-static\ response} \tag{3}$$

where the maximum quasi-static response is the summation of the mean and absolute maximum of the background responses. Note that the resonant response is associated with resonant amplification due to components (accelerations, forces, moments, etc.) with frequencies close or equal to the fundamental natural frequency of the structure. On the other hand, the background response involves no resonant amplification (Simiu and Yeo, 2019).

In brief, the concept of the DAF revolves around to the need to distinguish between the resonant and background components of response fluctuations. The procedure adopted in this study requires calculating and plotting the PSD of the fluctuating response (without the mean) and the corresponding frequencies with the application of a Fast Fourier Transform (FFT). Then, the cumulative PSD of the fluctuating response at each identified frequency is calculated and then normalized to the variance of the fluctuating response PSD. Using the PSD and cumulative PSD of the fluctuating response, the average slope of the common logarithmic values of two successive data points in the PSD of the fluctuating response is divided by the same variable pertaining to two successive data points in the cumulative PSD. At resonance, it is expected that this ratio will be noticeably high, and thus, the detected frequency is marked as resonance frequency. Consequently, once all the resonance frequencies have been identified, a Bandstop filter is adopted to separate the resonance frequencies from the fluctuating responses. The result of that process is the background response. For more details on the procedure, it is advised to refer to Elawady et al. (2017).

Once more, it is expected that the 1:10 aeroelastic model will experience a higher dynamic response compared to its full-scale counterpart due to a better representation of the turbulence spectrum, especially at the low-frequency range (large eddies). The role of analyzing the DAF of the accelerations experienced by both specimens is to separate the resonance from the fluctuating response. The calculation of the DAF of the acceleration will help in better estimating the response of the traffic signals to dynamic loading. Consequently, this will give a better insight into the design of span-wire traffic signals. **Figure 10** shows one sample of the processed PSD plot obtained when decomposing the resonance of the acceleration of one traffic signal (Signal “A”) at one wind speed (16.5 m/s at mean signal height) and for one wind direction (0°). The process adopted for this study followed the dynamic response decomposition recommendations described by Elawady et al. (2017). Consequently, the maximum DAF values for accelerations at different wind speeds and for different angles of attacks are calculated and presented in **Table 3**, for both full- and small-scale specimens. Note that only two accelerometers were installed in the full-scale tests, one on signal “A” and one on signal “C,” hence, there are no available values for DAF of signal “B.”

By observing **Table 3**, it can be noted that the DAF values calculated from the aeroelastic model data are generally higher than the ones obtained from the full-scale prototype by around 20–30%. As previously mentioned, a higher dynamic response exhibited by the aeroelastic model can be justified by the presence of more low-frequency turbulence, i.e., a better representation of the low-frequency part of the turbulence spectrum. Recommendations regarding the design of span-wire traffic signals could be formulated using the obtained DAF values. Static design values of accelerations could be multiplied by a uniform DAF value in order to account for dynamic effects.

## Buffeting Analysis for RMS of Accelerations

This last subsection discusses the theoretical buffeting of a flexible line-like structure such as the case of span-wire traffic signal systems. By conducting a buffeting analysis on the response of the traffic signals in the longitudinal direction, one can determine the theoretical variance and RMS of acceleration fluctuations and compare the values with experimentally obtained ones. To perform the buffeting analysis, some assumptions need to be made:

- While the instantaneous turbulence velocities at different points are different, the turbulence is homogeneous along the span.
- Using a quasi-steady approach, the fluctuating wind loads can be determined from the aerodynamic force coefficients measured in a steady flow.
- The motions involved in the natural modes of vibration are purely in the along-wind direction or 0° (wind normal to front-end of traffic signals).
- All three traffic signals are treated as one single unit. The single unit has a mass and frontal area equal to the combined masses and frontal areas of all three traffic signals.

Consequently, in its simplified form, the power spectrum of deflection $S_q$ at the mean height of the signals is given by Equation (4) (Davenport, 1962a,b; Irwin, 1977, 1979, 1996):

$$S_q(n) = \frac{(\rho.U.C_{x0}.A)^2}{M_G^2\omega_0^4}.\left|H\left(\frac{n}{n_0},\zeta_{tot}\right)\right|^2.\left|\chi_y(n)\right|^2.\left|\chi_{2D}(n)\right|^2 .S_u(n) \tag{4}$$

where $\rho$ is the density of air in kg/m$^3$, $U$ is the wind speed at mean signal height in m/s, $C_{xo}$ is the drag coefficient of the traffic signal, $A$ is the frontal area of the traffic signal in m$^2$, $M_G$ is the mass of the signal in kg and $\omega_o$ is the natural angular frequency of the system in rad/s. In addition, $n$ *and* $n_o$ are the forcing and natural frequencies in Hz, $\zeta_{tot}$ is the total damping of the structure (mechanical + aerodynamic), $H(n/n_o, \zeta_{tot})$ is the mechanical admittance function, $\chi_y(n)$ and $\chi_{2D}(n)$ are the lateral aerodynamic admittance function and two-dimensional admittance function, respectively. Furthermore, $S_u(n)$ is the power spectrum of the longitudinal wind speed time history. To obtain the variance of the deflection fluctuations $\sigma_q^2$ from the

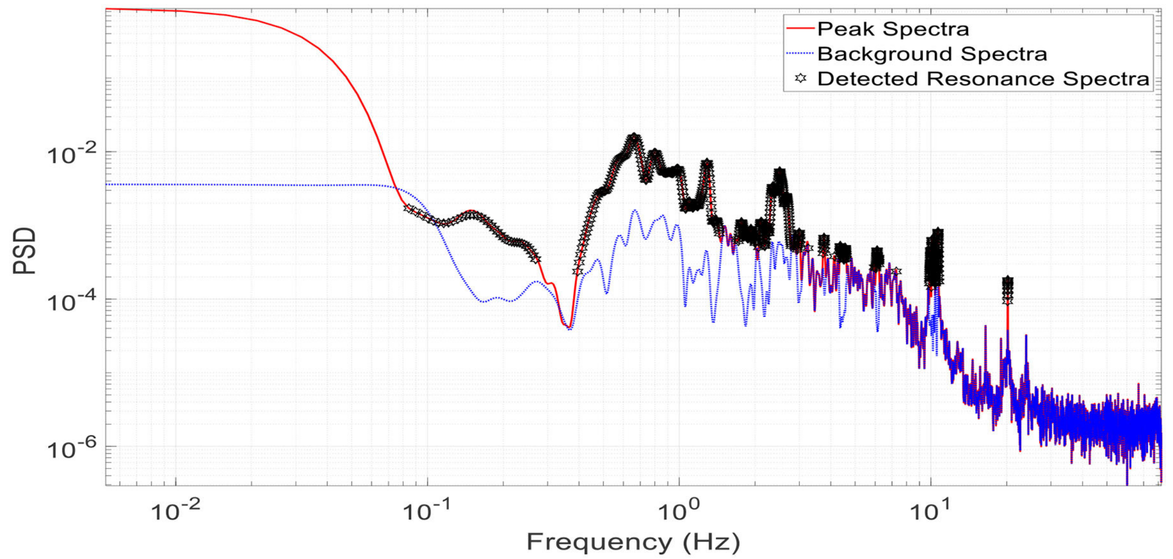


**FIGURE 10 |** Decomposition of resonance for the acceleration time history of signal "A" (16.5 m/s at 0° wind direction).

**TABLE 3 |** DAF results for both specimens in the along-wind direction (wind speeds are converted to full-scale).

| Wind direction | Signal | Aeroelastic model | | | Full-scale short-span model | | |
|---|---|---|---|---|---|---|---|
| | | 16.5 m/s | 22 m/s | 27.52 m/s | 16.5 m/s | 22 m/s | 27.52 m/s |
| 0° | "A" | 1.24 | 1.30 | 1.32 | 1.04 | 1.03 | 1.04 |
| | "B" | 2.68 | 1.77 | 1.45 | – | – | – |
| | "C" | 1.34 | 1.35 | 1.36 | 1.03 | 1.03 | 1.03 |
| 45° | "A" | 1.40 | 1.41 | 1.51 | 1.08 | 1.12 | 1.12 |
| | "B" | 2.57 | 2.75 | 2.01 | – | – | – |
| | "C" | 2.03 | 1.65 | 1.68 | 1.05 | 1.05 | 1.05 |
| 135° | "A" | 1.18 | 1.39 | 1.51 | 1.31 | 1.25 | 1.19 |
| | "B" | 1.05 | 1.17 | 1.26 | – | – | – |
| | "C" | 1.08 | 1.19 | 1.29 | 1.12 | 1.08 | 1.06 |
| 180° | "A" | 1.12 | 1.17 | 1.26 | 1.05 | 1.04 | 1.03 |
| | "B" | 1.03 | 1.09 | 1.15 | – | – | – |
| | "C" | 1.05 | 1.12 | 1.24 | 1.03 | 1.02 | 1.04 |

power spectrum, Equation (4) is integrated over all frequencies and the RMS of the deflection $\sigma_q$ can then be expressed in terms of background and resonant terms using Equation (5):

$$\sigma_q = \frac{\rho.U^2.C_{x0}.A.I_u}{M_G.\omega_0^2}.\sqrt{B+R} \tag{5}$$

where $I_u$ is the turbulence intensity and B and R are the background and resonant terms, defined in Equations (6) and (7), respectively:

$$B = \int_0^\infty \left|\chi_y(n)\right|^2.\left|\chi_{2D}(n)\right|^2.\frac{S_u(n)}{\sigma_u^2}dn \tag{6}$$

$$R = \left|\chi_y(n)\right|^2.\left|\chi_{2D}(n)\right|^2.\frac{n_0.S_u(n_0)}{\sigma_u^2}.\frac{\pi}{4.\zeta_{tot}} \tag{7}$$

where $\sigma_u^2$ is the variance of the wind speed time history. The rest of the parameters of Equation (7) are defined in Equations (8–10):

$$\left|\chi_y(n)\right|^2.\left|\chi_{2D}(n)\right|^2 = \frac{4}{\eta_b^2.\eta_d^2}.\left(\eta_b - 1 + e^{-\eta_b}\right).\left(\eta_d - 1 + e^{-\eta_d}\right).\frac{2}{\eta_L^2}.(\eta_L - 1 + e^{-\eta_l}) \tag{8}$$

$$\frac{n_0.S_u(n_0)}{\sigma_u^2} = \frac{4.\frac{n_0.^xL_u}{U}}{(1+70.78.(\frac{n_0.^xL_u}{U})^2)^{5/6}} \tag{9}$$

$$\zeta_{tot} = \zeta_s + \zeta_a = \zeta_s + \frac{\rho.U.C_{x0}.d}{2.\omega_0.M_G} \tag{10}$$

In the previous equations, $\eta_b$, $\eta_d$, and $\eta_L$ are parameters linked to the width, depth, and length of the structure and defined in Equations (11–13). $^xL_u$ is the integral length scale of longitudinal

**TABLE 4 |** Buffeting analysis conducted on the aeroelastic model for a wind speed of 27 m/s and at a wind direction of 0°.

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| $\rho$ (kgs/m$^3$) | 1.225 | $^xL_u$ (m) | 0.5 | $\zeta_a$ | 0.202 |
| $C_{xo}$ | 1.1 | $^yL_u$ (m) | 0.125 | $\zeta_{tot}$ | 0.232 |
| $A$ (m$^2$) | 0.026 | $^zL_u$ (m) | 0.125 | $\frac{n_0.S_u(n_0)}{\sigma_u^2}$ | 0.217 |
| $I_u$ | 0.12 | $n_o$ (Hz) (Mode 1) | 1.17 | $\left\|\chi_y(n)\right\|^2 . \left\|\chi_{2D}(n)\right\|^2$ | 0.575 |
| $M_G$ (kgs) | 0.103 | $\zeta_s$ (assumed) | 0.03 | $\theta$ (assumed) | 0.75 |
| $b$ (m) | 0.033 | $\eta_b$ | 0.057 | $U$ (m/s) | 27 |
| $d$ (m) | 0.152 | $\eta_d$ | 0.513 | Resonant response $R$ | 0.423 |
| $L$ (m) | 0.366 | $\eta_L$ | 1.230 | $\sigma_a$ (m/s$^2$) (Equation 14) | 2.31 |

component of turbulence in the $x$-direction (normal to the traffic signal) in $m$, $\zeta_s$ is the damping ratio of the structure, $\zeta_a$ is the aerodynamic damping and $d$ is the depth of the traffic signal. In Equations (12) and (13), $^yL_u$ and $^zL_u$ are the integral length scales of the longitudinal component of turbulence in the $y$- (lateral) and $z$-direction (vertical), respectively, in $m$. Moreover, $\theta$ is taken as 0.75 and $b$ along with $L$ are the width and length of the traffic signal in $m$:

$$\eta_b = 0.95.\theta.\frac{b}{^xL_u}.(1+70.78.(\frac{n.^xL_u}{U})^2)^{1/2} \quad (11)$$

$$\eta_d = 0.475.\theta.\frac{d}{^zL_u}.(1+70.78.(\frac{2.n.^zL_u}{U})^2)^{1/2} \quad (12)$$

$$\eta_L = 0.475.\theta.\frac{L}{^yL_u}.(1+70.78.(\frac{2.n.^yL_u}{U})^2)^{1/2} \quad (13)$$

Subsequently, the acceleration spectrum may be obtained by multiplying the deflection spectrum (Equation 5) by circular frequency to power 4. Typically, the resonant portion of the spectrum is the dominant one and the background response can be taken as zero. Therefore, the RMS of the acceleration $\sigma_a$ reduces to the relatively straightforward expression, given in Equation (14):

$$\sigma_a = \frac{\rho.U^2.C_{x0}.A.I_u}{M_G}.\sqrt{R} \quad (14)$$

By using Equation (14), the RMS of acceleration values at different wind speeds for both full- and small-scale specimens can be calculated and compared with their experimental counterparts, presented in **Figure 9A** at 0° wind direction. In order to apply some of the previous equations, more assumptions must be made. First, the three traffic signals are treated as a single unit having the following full-scale dimensions: a frontal area of about 2.6 m$^2$ and a mass of 103 kgs. Concerning turbulence correlation effects, it is assumed that they happen for a total length of 3.66 m, a total height of 1.52 m and a total width of 0.33 m (full-scale). The remaining values obtained for all the parameters listed in Equations (7–14) for the aeroelastic model for a wind speed of 27 m/s are summarized in **Table 4**.

From **Table 4**, the obtained RMS of acceleration $\sigma_{a,th}$ value using the theoretical buffeting analysis approach yielded a value of about 2.31 m/s$^2$. By inspecting **Figure 9A**, $\sigma_{a,ex}$ obtained from the recorded time histories of the accelerometers for the aeroelastic model is about 3 m/s$^2$ at a wind speed of 27 m/s. The obtained value from the buffeting analysis is lower than that observed in **Figure 9A**. However, it is worthwhile noting that the buffeting analysis does not take into account any excitation of the model due to self-generated wake turbulence. If we assume such excitation to be around 1.8 m/s$^2$ for both aeroelastic and full-scale specimens and using the root sum square (RSS) method to combine both values, we obtain a $\sigma_a$ equal to about 2.93 m/s$^2$. This is very close to the value obtained from the time histories of accelerations recorded at the WOW. For the same wind speed of 27 m/s and applying the buffeting analysis to the full-scale specimen using its own prototype parameters, Equation (14) yields a $\sigma_a$ of about 0.46 m/s$^2$. Combining the previously obtained value with the self-excitation from wake turbulence using the RSS method, we obtain a value of about 1.86 m/s$^2$. The result is also well in line with the observed value of 2.05 m/s$^2$ obtained from **Figure 9A** at a wind speed of 27 m/s. This exercise can be repeated with a different combination of wind speeds $U$, integral length scales of longitudinal turbulence $^xL_u$ and turbulence intensities $I_u$ to compare the obtained theoretical results from the buffeting analysis with the experimentally recorded ones. Note that the scaling factor for accelerations $\lambda_a$ from **Table 1** is equal to 1. Therefore, it is reasonable to assume one value for the excitation due to self-generated wake turbulence for both full- and small-scale specimens. More studies are needed to assess the assumptions made in the current study. In particular, more dedicated studies are encouraged to quantify the structural excitation due to self-generated wake turbulence.

## CONCLUSION

This paper summarized the results of an aeroelastic test conducted at the WOW for a span-wire traffic signal assembly consisting of a 5-section and two 3-section traffic signals. The model was designed based on previous experiments of the same model at full-scale and was first calibrated using a Finite Element software SAP2000® (CSI, 2018). The small-scale aeroelastic model enabled better representation of the full spectrum of the turbulence and the dynamic response of the system. The aeroelastic model started experiencing aerodynamic instabilities such as twisting at wind speeds as low as 27 m/s (full-scale) at cornering winds, mainly 45° and 135°. The RMS values of the recorded accelerations for the aeroelastic model were higher compared to their full-scale counterparts. This was justified due to the difference in model heights and turbulence spectra. Last but not least, a resonance decomposition was attempted on both models and a Dynamic Amplification Factor (DAF) was calculated. DAF results showed that the aeroelastic model exhibited higher numbers (20–30%) than the full-scale prototype in terms of accelerations. More aeroelastic testing on scaled models of span-wire traffic signal systems is required to better understand the dynamic behavior of such systems under hurricane winds. As such, future tests should address the aerodynamic damping along with force (drag and lift) and moment coefficients in order to formulate some design recommendations to span-wire traffic signal systems.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

IZ and AE supervised the experiments and data analyses and revised the manuscript. ZA and MM have carried out most of the data analyses and have written sections of this manuscript in collaboration with all the co-authors. PI and AG helped in reviewing and interpreting results and providing input for enhancing the scientific value of the manuscript. All authors contributed to the article and approved the submitted version.

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# The Network Coordination Office of NHERI (Natural Hazards Engineering Research Infrastructure)

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Since 2015, NHERI, or the Natural Hazards Engineering Research Infrastructure, began research operations supported by the United States National Science Foundation (NSF) as a distributed, multi-user national facility that provides the natural hazards research community with access to a powerful research infrastructure. NHERI is comprised of separate research infrastructure awards for a Network Coordination Office (NCO), Cyberinfrastructure, a Computational Modeling and Simulation Center, eight Experimental Facilities, and CONVERGE (an initiative to advance social sciences and interdisciplinary research). Awards made for NHERI contribute to NSF's role in the National Earthquake Hazards Reduction Program and the National Windstorm Impact Reduction Program of the United States. The mission of NHERI is to provide the earthquake, wind, coastal engineering, and social sciences communities with access to research infrastructure, education, and community outreach activities focused on improving the resilience and sustainability of the civil infrastructure against earthquakes, windstorms, and associated natural events such as tsunami and coastal storm surge. In this paper, the role and key NHERI activities are described for the NCO, which is led by Purdue University, along with partner institutions—the University of Texas at San Antonio, North Carolina State University, Texas Tech University, the U.S. Naval Research Laboratory, and the University of Hawaii at Manoa. The NHERI NCO serves as a focal point and leader of a multi-hazards research community, and maintains a community-based NHERI science plan. It manages scheduling for partner NHERI Experimental Facilities and coordinates all components to ensure effective and fair governance, efficient testing, and user support within a safe environment. Another important role of the NCO is to lead NHERI-wide educational and outreach activities: the network facilitates educational experiences ranging from summer programs for undergraduates to workshops for post-docs and early-career faculty that also both involve development of K-12 lesson plans. The NCO works to develop strategic national and international partnerships and to coordinate NHERI activities with other awardee components to form a cohesive and fully-integrated global natural hazards engineering research infrastructure that fosters collaboration in new ways.

**Keywords: natural hazards, network coordination, NHERI, earthquake, storm surge, tsunami, wind**

## INTRODUCTION

Around the globe, the vulnerability of civil infrastructure to natural hazards presents one of the greatest risks to life, safety, and property damage. It also impairs the resiliency and sustainability of communities. In the United States, the frequency and scale of disasters has grown in recent decades. The U.S. has experienced 10 or more billion-dollar weather and climate-related disasters in 9 years since 1980; 7 of them occurred in the last decade (National Oceanic Atmospheric Administration, 2020). Recent experiences with multiple hazards, such as Hurricane Katrina, the Tohoku tsunami in Japan, earthquakes in New Zealand, and tornados in Joplin, Missouri, have shown the long timescales associated with recovery from damage to civil infrastructure (Edge et al., 2020). The scientific community has recognized the need for interdisciplinary collaboration in order to reduce the loss of life, economic damage, and community disruption caused by these hazards (National Research Council, 2006).

Established to combat these risks, the Natural Hazards Engineering Research Infrastructure (NHERI) is a shared-use, distributed national facility that provides the natural hazards engineering and social science research community with a network of state-of-the-art laboratories, computational modeling and simulation capabilities, convergence-science and research network support, and cyberinfrastructure. The community of NHERI researchers, educators, and students encompasses a large group of universities, industry partners, and research institutions in the United States and abroad.

NHERI is a multi-hazard expansion of the United States National Science Foundation's (NSF) first-generation natural hazards research network focused on earthquake events, the George E. Brown, Jr., Network for Earthquake Engineering Simulation (NEES, 1999–2014). In November 1998, the National Science Board approved NEES for construction with funds totaling $82 million from the NSF Major Research Equipment and Facilities Construction appropriation. Construction occurred during the period 2000–2004. Over a decade of operations, NEES provided a vibrant collaboratory consisting of unique experimental facilities and a collaboration platform that served tens of thousands of users from over 210 nations with more than 400 multi-year, multi-investigator projects. NHERI builds upon that legacy by supporting research on earthquakes, windstorms, tsunami, and storm surge.

The objectives of NHERI are to more effectively generate, collect, and publish data; and to educate the next generation of leaders in the field of natural hazards research, particularly including a multi-hazards focus in efforts to improve the resilience of civil infrastructure. Funded by the United States National Science Foundation (NSF), NHERI's various geographically distributed components (see **Figure 1** and **Table 1**) facilitate physical tests and numerical simulation of groundbreaking concepts to protect people and communities, including their homes, businesses, and civil and lifeline infrastructure. This work enables engineering and scientific innovations to help prevent natural hazards from becoming societal disasters. In its first 4 years (2015–2018), research utilizing NHERI facilities and/or data have produced over 300 research publications, including over 160 peer-reviewed journal articles, as tracked by DesignSafe Cyberinfrastructure (Rathje et al., under review); it has also led to numerous other positive advances in the natural hazards community outlined in this paper.

The leadership of NHERI is its Network Coordination Office (NCO), whose mission is (i) to serve as a focal point and leader of a multi-hazards research community focused on mitigating the impact of future earthquakes and windstorms, including the natural hazards caused by these events such as tsunamis and storm surge, respectively; and (ii) to support the NHERI governance and coordinate NHERI laboratory scheduling, education and community outreach activities with the other awardee components to form a cohesive and fully-integrated global natural hazards engineering research infrastructure that results in a collaborative effort greater than the sum of its individual components.

In its fourth year of activities as of early 2020, this complex organization is a collaborative effort for multi-hazards research. The process of awarding the various components started in July 2015 with the establishment of the cyberinfrastructure at the University of Texas at Austin. The various experimental facilities, with the exception of the RAPID facility, were awarded throughout the period from September 2015 to January 2016. The Network Coordination Office was awarded to Purdue University in July 2016, followed by the Computational Modeling and Simulation Facility at the University of California-Berkeley and the RAPID facility to the University of Washington. As of October 2016, NHERI—supported by NSF as a distributed, multi-user national facility that provides the natural hazards research community with access to research infrastructure—was fully in place. CONVERGE, an initiative to advance social sciences and interdisciplinary research, was later awarded to University of Colorado-Boulder in September 2018 under

**TABLE 1 |** List of NHERI components.

| Institution | Component | Location | Principal investigator | NSF award number |
|---|---|---|---|---|
| Florida International University | Wall of Wind International Hurricane Research Center | Miami, FL | Arindam Chowdhury | 1520853 |
| Lehigh University | Large-Scale Multi-Directional Hybrid Simulation Testing | Bethlehem, PA | Jim Ricles | 1520765 |
| Purdue University | Network Coordination Office | West Lafayette, IN | Julio Ramirez | 1612144 |
| Oregon State University | O.H. Hinsdale Wave Research Laboratory | Corvallis, OR | Dan Cox | 1519679 |
| University of California at Berkeley | SimCenter | Berkeley, CA | Sanjay Govindjee | 1612843 |
| University of California at Davis | Centrifuge Facility | Davis, CA | Ross Boulanger | 1520581 |
| University of California at San Diego | Large High-Performance Outdoor Shake Table | La Jolla, CA | Joel Conte | 1520904 |
| University of Colorado-Boulder | CONVERGE | Boulder, CO | Lori Peek | 1841338 |
| University of Florida | Wind Experimental Facility | Gainesville, FL | Forrest Masters | 1520843 |
| University of Texas at Austin | DesignSafe Cyberinfrastructure | Austin, TX | Ellen Rathje | 1520817 |
| University of Texas at Austin | Large Mobile Shakers | Austin, TX | Kenneth Stokoe | 1520808 |
| University of Washington | RAPID Natural Hazards Reconnaissance | Seattle, WA | Joseph Wartman | 1611820 |

the NHERI umbrella. CONVERGE also coordinates several networks for sub-communities, such as the Social Science Extreme Events Research (SSEER), Interdisciplinary Science and Engineering Extreme Events Research (ISEER), and Structural Extreme Events Reconnaissance (StEER) networks, which complement a long-established research network Geotechnical Extreme Events Reconnaissance (GEER) (Peek et al., 2020). More information about each of the NHERI components is provided in **Table 1**, and the other papers comprising this special issue provide detailed descriptions of other facilities' and components' activities.

Information about the unique capabilities of each NHERI component can be found at the NHERI website[1], and more information about the 5-year award is provided on NSF's website[2]. Awards made for NHERI contribute to NSF's role in the National Earthquake Hazards Reduction Program and the National Windstorm Impact Reduction Program.

This paper describes the governance structure of the NHERI NCO and the many functions and activities it provides to support the community of NHERI stakeholders. These include the creation, maintenance, and promotion of a 5-year Science Plan; education and outreach through various intensive programs and regular communications; centralized scheduling of NHERI's facility resources; strategic promotion of technology transfer; and collaboration with likeminded natural hazards engineering facilities outside of the United States.

[1]https://www.designsafe-ci.org/facilities/experimental
[2]https://www.nsf.gov/news/news_summ.jsp?cntn_id=189975

## GOVERNANCE

The governance of NHERI consists of the Council of Principal Investigators (PIs), the User Forum, and the Network Independent Advisory Committee. These three components of the governance work together to ensure that the users of NHERI have clear and transparent access to all NHERI resources.

The Council is composed of the PIs of each NHERI Awardee or a designated substitute member, as chosen by any PI not present at the monthly Council meetings. The role of the Council is to provide collective and coordinated leadership for NHERI through the development of network-wide policies and annual work plans.

The User Forum (UF) is a NHERI-wide committee elected by the user community. The focus of the UF is to provide the NHERI NCO and Council with specific input on community user satisfaction as well as priorities and needs relating to the use and capabilities of NHERI components. The UF was established in February 2017 after a call for nominations for UF members and subsequent vote from the user community. Currently, the UF is composed of 9 members who represent the broad scientific and engineering communities served by NHERI, including representatives with expertise in coastal, earthquake, wind, and geotechnical engineering; lifeline infrastructure;

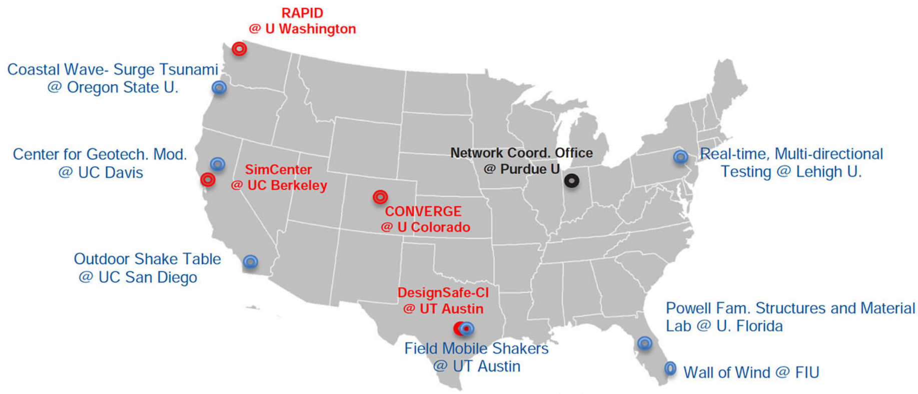


**FIGURE 1 |** Components of the Natural Hazards Engineering Research Infrastructure, a geographically distributed resource (experimental facilities in blue, NCO in black, and other components in red).

social sciences, and policy. Appointment for the committee members is for 2 years, which can be extended. Two *ex officio* members from the NHERI NCO are appointed to the committee to keep the NCO leadership apprised of committee progress and to coordinate any needs of the committee with the rest of the natural hazards community. There are three officers: chair, vice-chair, and secretary, all of whom are elected by the UF and serve 2-year, renewable terms.

The UF holds monthly meetings, conducted remotely, and a face-to-face meeting once a year during the Summer Institute, which is organized and hosted by the NCO. The UF oversees the annual community user satisfaction surveys for NHERI. Members of the committee also serve as representatives to the NCO, as well as to the Education and Community Outreach, Facility Scheduling Protocol, and Technology Transfer committees.

The Network Independent Advisory Committee is composed of representatives from the broader scientific and engineering communities served by NHERI. Its primary roles are to provide independent guidance and advice to the NHERI Council and to keep the community informed of NHERI activities via the publication of an annual report. To keep the community informed on NHERI activities, the committee produces an annual report which is published and publicly available on the DesignSafe-CI website hosted by the NHERI Cyberinfrastructure, NHERI's online presence.

The committee provides independent guidance and advice to the NCO on (i) progress, plans, and performance of the NHERI Awardees and annual Council work plan; (ii) an assessment of the level of community engagement and user satisfaction across NHERI, with input from the User Forum survey results; (iii) an assessment of NHERI's continuing value added and impact on research and educational advancements; and (iv) an assessment of the transparency and efficiency of the NCO's Facility Scheduling Protocol.

## NHERI SCIENCE PLAN

The NHERI NCO is charged with leading the nation's multi-hazards community in the development of a 5-year research agenda that will elucidate grand challenges, key questions, and research objectives for the engineering and social science communities that study earthquake, wind, and coastal hazards. That research agenda is the basic roadmap used to develop the NHERI Five-Year Science Plan. It provides the earthquake, tsunami, wind, and coastal hazards research community, including NSF and other funding agencies, a path to high-impact, high-reward, hazards engineering and interdisciplinary research using NHERI's various facilities and components. The research results are intended to prevent loss of life, mitigate damage, and reduce the social vulnerability of populations to natural hazards.

The Science Plan is grounded on three Grand Challenges with five Key Research Questions to guide NHERI research. The research will deliver technical breakthroughs to fundamentally transform the resilience and sustainability of existing and future civil infrastructure, also known as the built environment. High-priority research subject areas are provided for each of the key research questions to assist future researchers in responding to the Grand Challenges. The Science Plan illustrates how powerful new technologies can empower researchers to accelerate the pace of innovation to achieve NHERI's goals.

### Development of the Science Plan

The Science Plan Task Group was assembled to guide the development of the first Five-Year NHERI Science Plan, which was released in July 2017 (Smith et al., 2017). The plan was generated with review and input from the NHERI facility leadership, the NCO, and broad community-based participation of earthquake, wind, tsunami, and coastal engineering professionals, social scientists, and engineering education experts. Stakeholders and leaders in various fields of natural hazards research reviewed the Science Plan before it was published via DesignSafe and widely distributed through email and newsletter campaigns. It was also highlighted as a resource for the broader natural hazards research community during several professional science and engineering meetings.

The Science Plan Task Group, along with the Network Independent Advisory Committee and User Forum, sought additional input from the professional and research communities to advance the original Science Plan through an NSF-sponsored international workshop held in March 2019. Participants gathered in interdisciplinary teams, discussed disruptive technologies, and developed research campaigns to advance the NHERI Five-Year Science Plan. The presentations and findings of the workshop are summarized in a report available on DesignSafe-CI (Natural Hazards Engineering Research Infrastructure, 2019), and they ultimately led to a new version of the NHERI Science Plan, published in January 2020 (Edge et al., 2020), also available on DesignSafe-CI.

The inclusion of the CONVERGE initiative as an integral part of NHERI seamlessly advances disciplinary and interdisciplinary hazards and disaster research (Peek et al., 2020). With CONVERGE, NHERI's mission has been expanded to identify and coordinate social science, engineering and interdisciplinary research teams before, during and after disasters. The latest version of the Science Plan reflects this broader mission.

## Three Grand Challenges

The Five-Year Science Plan focuses on the process and scope of conducting multi-hazard research for more resilient and sustainable civil infrastructure and stable communities. The three grand challenges identified by the plan are as follows:

1. Identify and quantify the characteristics of earthquake, windstorm, and associated hazards—including tsunamis, storm surge, and waves—that are damaging to civil infrastructure and disruptive to communities.
2. Assess the physical vulnerability of civil infrastructure and the social vulnerability of populations in communities exposed to earthquakes, windstorms, and associated hazards.
3. Create the technologies and engineering tools to design, construct, retrofit, and operate a multi-hazard resilient and sustainable infrastructure for the nation.

As noted above, these three grand challenges are further developed into five key research questions paired with high-priority research subject areas.

## Key Research Questions

The five key NHERI research questions for earthquake, wind, and coastal hazards engineering that the community believes will lead to transformative discoveries are listed below:

1. How do researchers characterize the transient and variable nature of the loading actions imposed on the nation's civil infrastructure from earthquakes, windstorms, and associated hazards?
2. How can the scientific community enable robust simulation of the behavior of civil infrastructure to loading from earthquakes, windstorms, tsunamis, and associated coastal hazards, while also considering the effects of these hazards on individuals, households, and communities?
3. What are the key physical responses, vulnerabilities, and factors influencing post-event recovery of civil infrastructure and communities?
4. What are effective and potentially transformative mitigation actions to achieve community resilience, especially when considering different hazards, shifting vulnerabilities, emerging technologies, and sustainability goals?
5. How can the scientific community more effectively collect and share data and information to enable and foster ethical, collaborative, and transformative research and outcomes?

## Example of Specific Research for Key Research Question #3

Determining the key physical factors influencing the post-event recovery of civil infrastructure is crucial to reestablishing the physical and social fabric of impacted communities. Characterizing the response and performance of buildings and other structures using "vulnerability" enables the identification of threats to resilience and prioritization of research. **Figure 2** shows a large-scale earthquake simulation on a large, multistory structure which is used to identify better designs for improved building performance. Below are examples of similar research thrusts necessary to answer this question:

- Identify vulnerability indicators and metrics to be employed in resiliency analyses. Vulnerability is used here in both the physical sense of the built environment, as well as in the social sense of the well-being of community inhabitants.
- Systematically investigate interrelationships between components in systems to identify key vulnerabilities affecting resilience at all levels.
- Systematically investigate civil infrastructure and community interrelationships to identify the most efficient balance between improved mitigation and improved response and recovery.
- Enhance performance-based design procedures for tsunamis, storm surge and waves, and wind effects parallel to those available for earthquakes, particularly considering debris impact and performance of the building envelope. These procedures should enable economical designs for improved performance and life-cycle analysis with defined uncertainty. Eventually, these procedures should be integrated to produce consistent multi-hazard analysis.
- Improve system and component fragilities for use in performance-based design and loss estimation.

Specific research for other Key Research Questions can be found in the 2020 NHERI Science Plan on DesignSafe-CI (Edge et al., 2020). The 2020 NHERI Science Plan also identifies research needs that can be conducted and supported by the NHERI components. These research needs are not intended to be exhaustive but rather to encourage use of the unique NHERI research infrastructure in traditional and innovative ways.


**FIGURE 2 |** Large-scale hybrid simulation of a self-centering steel moment-resisting frame building under simulated earthquake loading. (Photo: Jim Ricles).

## The NHERI Science Plan as a Living Document

The Five-Year NHERI Science Plan is intended to provide information for constituents, including practitioners, as well as guidance for members of the broad research community. The Science Plan will continue to be updated as feedback is received from NHERI researchers, practitioners, and collaborative communities of technology and social science. Researchers and other members of the stakeholder NHERI community are encouraged to reference the Grand Challenges and Key Research Questions when submitting proposals to NSF and other agencies that support natural hazard research for earthquake, tsunamis, wind and coastal engineers and scientists.

# CENTRAL SCHEDULING

The NCO developed, with input from the Experimental Facility (EF) sites and the UF, a protocol to standardize the scheduling of NHERI projects. This protocol prioritizes NSF-funded research projects and facilities, which can be accessed by these research teams at heavily discounted rates. It is composed of six phases through which each approved NHERI project will progress. The first two phases involve training of researchers in the utilization of a facility's equipment and the development of a detailed experimental plan for how the facility's equipment will be used. These phases are scheduled at the discretion of the researchers and EF site staff. Phases 3–6 involve the real-time use of the facility; the scheduling of these portions of a project are managed centrally by the NCO's dedicated Facility Scheduler and Operations Coordinator to fairly and efficiently share the facility resources among all. **Figure 3** summarizes the scheduling process, while the following sections describe each phase in more detail.

## Phase 1: User Training

During the first phase, EF sites coordinate with researchers to ensure that every participant in the project is properly trained for safety within the facility and near the test equipment.

## Phase 2: Planning and Experimental Design

The second phase of each project is to produce a detailed document, called the experimental test plan, of the experiments to be performed. This important document ensures that researchers and site personnel each have a full understanding of the work to be performed on the site equipment during the scheduled time within the facility, as researchers will not be directly operating the test equipment. The researchers and site personnel work together to ensure the test plan is realistic to the site's equipment capabilities and that an adequate amount of time within the facility has been allotted to the project.

## Phase 3: Specimen Construction and Instrumentation

This phase marks the beginning of the project time inside the EF site work area and the first phase to be strictly scheduled by the NCO. At this point, test specimens will be constructed for the experiments to be performed. Some EF sites have an area where this construction can be performed away from the actual test equipment, but it may be necessary that test specimens be constructed directly on the testing area due to the layout of the EF site or the specifications of certain experiments.

## Phase 4: Testing

This phase is when the actual experimentation is executed. Each facility offers researchers a different level of access to operate the equipment based upon local policies for safety and liability. Some facilities allow researchers to operate test equipment after appropriate training, while other sites restrict researchers to directing how site personnel should operate the equipment to perform the experiments. These details are established for each project during the development of the experimental test plan in Phase 2, which ensures the role of each participant is clear.

## Phase 5: Transferring Raw Data

This phase marks a milestone where ownership of the experimental data transfers from the facility to the researchers for analysis. Raw data from the test equipment is uploaded to NHERI data storage servers, operated by the DesignSafe Cyberinfrastructure team. Each experimental facility has local procedures in place for performing this file transfer from their unique equipment setup to the NHERI servers. Some sites perform this data transfer during the testing phase while other sites allow the data transfer to happen simultaneously with the following demolition phase. Any analysis and results of the experiments are not captured within the scheduling protocol, as they do not require any use of the EF site and fall outside the scope of the management of facility equipment utilization.

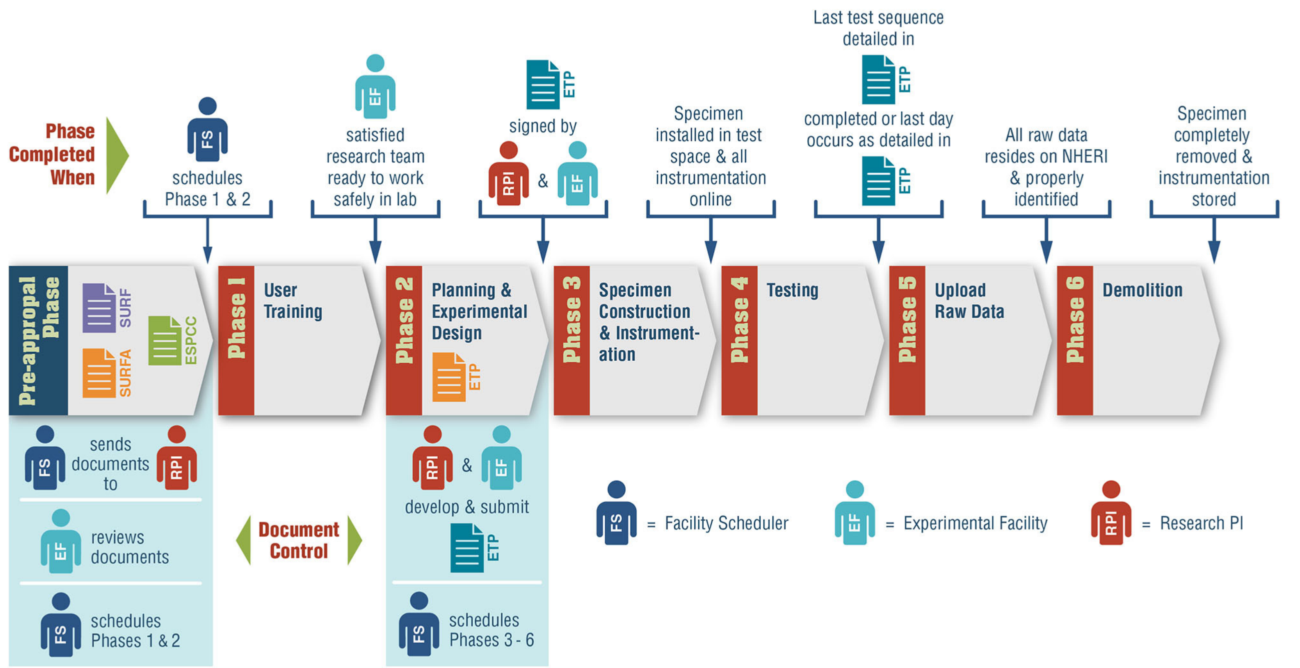


**FIGURE 3 |** Conceptual diagram of the NHERI central scheduling process.

## Phase 6: Demolition

The final stage of each NHERI project is to remove any leftover test equipment from the EF site equipment so it can be prepared for the next project entering the space. If multiple rounds of testing are prescribed by the experimental test plan, some demolition may have occurred previously at the discretion of the EF site personnel once the use of each test specimen has ended. By the end of this phase, however, all test rigging from all experimental rounds is demolished and removed from the work area.

Using the above protocol for the experimental facilities has allowed the NCO to facilitate and support the scientific mission of each facility and support the research community with clear, equitable access to the resources needed to complete their funded projects.

## NHERI Network Metrics

The Facility Scheduler and Operations Coordinator is also charged with recording and updating the metrics of the NHERI network. The current metrics for the network include: Number of NSF Awards, Days of Utilization, results from User Satisfaction Surveys, Number of Safety Recordable Incidents, and Duration Variance. Within our cooperative agreements, NSF defines utilization as the ratio of actual days of equipment utilization by NSF-supported projects to total planned days of utilization, as included in the approved final Annual Work Plan and accounting for days planned for routine equipment maintenance and calibration.

The NCO and the experimental facilities are in the process of adopting a uniform set of metrics to demonstrate throughput at the EFs that can be used to reflect level of engagement or research impact. These include metrics defined using days of use, similar to the structure reported by the NSF-sponsored Academic Research Fleet. For example, a large number of science days would intuitively reflect that the equipment facility is being commonly used in science applications and would be a useful evaluation. The metric could not be used to demonstrate utilization as a percentage of capacity, and would not reflect the efficiency of use.

Furthermore, NHERI plans to adopt a uniform practice of reporting utilization as throughput divided by capacity using local definitions of throughput and capacity. A uniform set of categories may be possible, so, for example, equipment facilities could report X% supporting the science of project A, Y% in maintenance, Z% administration, etc. The utilization percentage would be comparable across sites by category, but the raw throughput and capacity numbers likely would not be.

# EDUCATION AND COMMUNITY OUTREACH

The Network Coordination Office's Education and Community Outreach (ECO) component extends the impact of the natural hazards engineering research community by engaging NHERI sites in educational and outreach activities. The main goal of the ECO is to broaden participation in natural hazards engineering research, especially within diverse groups of individuals in K-12 education, undergraduate and graduate school, and early career faculty members. To facilitate activities relevant to multiple hazards, the ECO Committee includes representatives from all NHERI sites. The committee plans, and also strategically assesses, two flagship programs: the Research Experiences for Undergraduates program and the Summer Institute. Both are described later in this section. The committee also collects, analyzes, and reviews information from each program to understand and improve the educational and outreach experiences, and to improve the overall impact associated with broadening participation in the NHERI community.

In order to engage a diverse team of multi-hazards researchers, the ECO Committee established a common vision and related goals around educational objectives within the first grant year. The team considered research-based educational best practices as well as innovative ways to engage and leverage the various networks available to each hazard group. Team science research helped build a cohesive team within the ECO Committee (Bennett et al., 2018). Throughout the first year, continuous communication and transparency of decision-making and challenging issues helped build trust among representatives in the group. Members were encouraged to provide feedback throughout the planning and evaluation phases, and complete participation was key for the success of all educational activities.

From the start of NHERI, a committee of members representing each of the components was selected by each awardee to serve on the ECO Committee. As more awards were announced, new members to the ECO Committee were added. These individuals serve on the ECO Committee throughout the life of the grant, which helps to build rapport and establish and maintain expectations. The ECO representatives are a steering committee that strategically decides important elements of the education and community outreach components for the entire NHERI network and maintains a dynamic evaluation process.

## ECO Strategic Activities

The ECO Committee plans strategic, research-based educational programs that help to connect the NHERI network with young scholars. The Research Experiences for Undergraduates (REU) summer program brings together cohorts of diverse undergraduates to conduct scholarly research, while the Summer Institute focuses on preparing early-career faculty and senior-level doctoral students to collaborate on proposals for federal funding that utilize NHERI resources in multi-disciplinary ways. Meanwhile, lesson plans for K-12 education aim to enlarge the next generation of natural hazards scholars and practitioners.

### Research Experiences for Undergraduates

The NCO, through the ECO Committee, organizes a summer REU program that places talented undergraduates with senior research faculty and staff at each of the NHERI components. Starting with recruitment, the NCO through the ECO leads the dissemination of best practices in recruiting diverse students to the NHERI REU program, with the secret to success being personal communications from faculty members teaching relevant undergraduate coursework. Webinars are held to guide students through the application process, as well as to help them learn more about expectations for the summer research program. Because a large part of the mission of the ECO is to broaden participation among women, as well as racial and ethnic minority students, recruitment also involves connecting to minority-serving institutions, especially those with civil engineering, environmental engineering, and computer science degree programs. The ECO Committee has established a list of high-leverage recruitment groups to disseminate information, such as Pathways to Science, where students can learn more about NHERI and the REU program.

Because several universities operate on a quarter system while others are on a semester academic calendar, the ECO coordinates two REU blocks that intersect for a maximum number of weeks during the blocks' 10-week durations; this ensures that students across the two REU blocks can interact and build working relationships across the sites. Students in different locations use videoconferencing to learn about each other's work. They attend guided research meetings across the distributed NHERI sites to discuss individual components of peer-reviewed publications. These meetings, held on a weekly basis, allow students to share details of their research, challenges they are confronting, and successes worth celebrating.

Mentorship is a big part of the REU student experience (**Figure 4**). All students are assigned a faculty mentor, and others working at each site serve as informal mentors and guides for the students. Educational best practices are used to help guide mentors (Handelsman et al., 2005), and student researchers are also encouraged to engage with mentors in meaningful ways throughout the summer.

In order to record work produced by NHERI-REU undergraduate students, the NCO serves as a central place for deliverables to be submitted. Through the DesignSafe-CI website, the NHERI cyberinfrastructure facility archives recruitment communication, participant information, and published papers. The site serves as a focal point to easily access data, publish student-authored manuscripts, and quickly disseminate information to other stakeholders.

### Summer Institute

The second flagship educational program, the NHERI Summer Institute, helps prepare early career faculty for writing collaborative research proposals within an interdisciplinary, multi-hazards research community. Each year, ~20 participants from multiple disciplines—tenure-track assistant professors, post-doctoral fellows, and senior-level graduate students—are offered travel awards to participate in the 2.5-day Summer Institute.

During the Summer Institute workshop, participants learn about the NHERI Science Plan and also provide feedback on it. Speakers from each of the NHERI components present an overview of the various facilities and resources available for early-career professionals' research use. An NSF Program Director also typically presents a workshop geared toward providing valuable information about submitting grant proposals to NSF. A separate workshop speaker presents information about the NSF CAREER program[3]. Successful NSF and CAREER awardees also share their experiences in a panel, answering participants' questions and providing useful perspectives on the proposal process.

[3]https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503214

**FIGURE 4 |** NHERI REU students form close relationships with peers and mentors.

Throughout the Summer Institute, funded participants work in interdisciplinary teams to propose solutions to the Grand Challenges posed by the NHERI Science Plan (**Figure 5**). These groups are challenged with building a collaborative proposal concept, taking into account multiple hazards and innovative research methods. Additionally, the teams of attendees have valuable opportunities to network in formal and informal ways; the workshop agenda includes networking luncheons, time to interact with the NHERI Program Director and presenters, and an excursion to the city's most popular tourist sites.

### K-12 Lesson Plan Development

Through both flagship activities, participants in the REU summer program as well as the Summer Institute also develop K-12 lesson plans, which are tested by teachers with their students and submitted to TeachEngineering for publication. Guided by a K-12 educational specialist, participants in both programs learn about engaging young scholars to build their experiences in providing broader impacts to the community. These valuable experiences give researchers an important perspective on the significance of developing working relationships with educators. Both educators and researchers gain valuable perspective about the importance of motivating young learners into natural hazards engineering careers.

## Strategic Activity Outcomes

The ECO Committee engages in formative evaluation of the strategic programs; pre- and post-assessments collected for both the REU and the Summer Institute inform changes to the programs. Analyses are compared on a yearly basis and give the ECO Committee information about the successes and challenges of the intended goals for each program. Additionally, the committee collects longitudinal data to review the success of the programs after participants complete the program. From this initiative, the entire NHERI community has learned about the impact of the network's educational objectives. At the time of this publication, 22% of senior-level graduate students and post-doctoral fellows who attended the Summer Institute have secured tenure-track appointments, and 23% of early-career faculty have secured competitive federal grant funding as Principal Investigators (PI) or co-PIs, with an average award of $263K, including two CAREER award winners. Undergraduate students who complete the NHERI REU program ($N = 45$) reported exceptional retention in their engineering and science majors: All REU alumni respondents ($N = 42$) remain in their major or have graduated from their STEM degree program. Of those who graduated, 39% are continuing on to graduate studies immediately after completing their undergraduate degree, with five students (11% of NHERI REU alumni) already continuing for PhD work.

## INTERNATIONAL PARTNERSHIPS

As evidenced by events such as New Zealand's Canterbury earthquake swarm; Japan's Tohoku tsunami; hurricanes Katrina, Sandy and Maria; and the 2011 Joplin tornado in the United States, communities can take years to recover from widespread infrastructure failure and damage associated with natural hazards. To mitigate the consequences of these kinds of events, many nations have put forth significant efforts toward improving the resilience of their infrastructure. The NHERI network, and similar networks around the globe, significantly enhance natural hazards research, facilitating studies previously presumed impossible (e.g., large-scale hybrid simulations of earthquake effects on structures). These natural hazards networks—recognizing complementary resources—have also formed bi-lateral partnerships with counterparts in other nations to enable access to facilities and data. For instance, the United States' Network for Earthquake Engineering Simulation (NEES, 1999–2014) established strong ties with the European Union's Seismic Engineering Research Infrastructures for European Synergies (SERIES) network through joint activities. This led to the CELESTINA project for shared access to a wealth of experimental data by NEES and EU researchers (Taucer and Apostolska, 2015). NEES' partnership with Japan's National Institute for Earth Science and Disaster Resilience (NIED), specifically the Miki City laboratory Hyogo Earthquake Engineering Research Center (best known as "E-Defense"), enabled several bi-national capstone experiments. These include Controlled Rocking of Steel-Framed Buildings with Replaceable Energy Dissipating Fuses (PI Deierlein, NSF 05-30756) to confirm the viability of combining conventional

**FIGURE 5 |** Summer Institute early career faculty work in interdisciplinary teams with NHERI researcher mentors.

steel-braced framing with rocking-mobilized energy-dissipating shear fuses; Tools to Facilitate Widespread Use of Isolation and Protective Systems, a NEES/E-Defense Collaboration (PI Ryan, NSF 07-24208/11-13275) to evaluate knowledge gaps and design assumptions in base isolation technology with special attention to non-structural content protection; and NEESWood: Development of a Performance-Based Seismic Design Philosophy for Mid-Rise Woodframe Construction (PI van de Lindt, NSF 05-29903) to develop a performance-based seismic design approach to enable mid-rise wood frame construction.

NHERI was established by NSF to inform the broader global vision of earthquake, wind, and coastal inundation risk mitigation. As such, the NCO has worked to secure similar commitments from leading earthquake, wind, and coastal engineering organizations in Japan, Korea, China, and Europe for the purposes of research collaboration, access to facilities, data exchanges, assessment of post-event damage to civil infrastructure, and to conduct educational and outreach activities. The NCO also explores new collaborations with partners in Europe, Central and South America, and Asia on topics such as elaborating a research roadmap to promote collaboration of research infrastructures in multi-hazard engineering, post-disaster data collection, and new instrumentation and sensor techniques. These partnerships will identify priority topics for transnational access to large-scale research infrastructures. They will also facilitate development of innovative technologies for efficient use of research infrastructures, including robotics and real-time hybrid simulation.

In July 2017, a new phase of research collaboration on earthquake engineering between the US and Japan broke ground with the signing of a Letter of Agreement between NHERI and the National Research Institute for Earth Science and Disaster Resilience (NIED) on earthquake engineering research, using E-Defense and NHERI facilities. The First Planning Meeting discussed the details of a new research collaboration, identifying both the scope of the first research collaboration under the framework of NHERI and NIED agreement, and the process for research collaboration over the coming years. Reports from collaborative planning meetings between the organizations are hosted on DesignSafe-CI[4], with the most recent meeting held in December 2019. In February 2018, with support from the RAPID facility, Texas A&M professor Maria Koliou and her team collected data on two full-scale, three-story wood-frame buildings (NSF project #1829433, funded under the NHERI-NIED/E-Defense research collaboration) (**Figure 6**).

The National Center for Research on Earthquake Engineering (NCREE) was officially established in 1990 through a joint effort of the Ministry of Science and Technology and the National Taiwan University. NCREE became a non-profit organization under the supervision of the National Applied Research Laboratories in 2003. NCREE currently operates two laboratories (Taipei and Tainan) and is able to conduct long-stroke, high-velocity shake-table tests, and cyclic quasi-static tests under extreme high axial loads. NCREE and NHERI signed a Letter of Agreement in August 2017 during a tour by NHERI representatives of the NCREE Tainan facility. The mission of NCREE is aligned with NHERI and includes the promotion of international research on earthquake hazard mitigation and emergency responses to pre-quake preparation and post-quake recovery.

The third NHERI international agreement, signed in July 2018, is with the EUCENTRE Foundation. The European Centre for Training and Research in Earthquake Engineering of Pavia, Italy (EUCENTRE), has developed and constructed an array of experimental laboratories focused on seismic simulation of earthquake effects on full-scale structures and non-structural elements, which include a high-performance uniaxial shake table, a multiaxial shake table, a bearing tester system for full-scale testing of isolation devices, a damper tester system for tests

[4]https://www.designsafe-ci.org/facilities/nco/partnerships/nied

**FIGURE 6 |** Full-scale test of two wooden houses at E-Defense.

on dissipative devices, and a system for hybrid simulation and pseudo-static tests.

## TECHNOLOGY TRANSFER

The NHERI NCO sponsors a Technology Transfer Committee (TTC) composed of a group of ∼20 volunteer practitioners and decision makers. The committee works to strengthen ties between NHERI researchers and the implementers of NHERI–developed technology. Members are experienced in contributing to the development of design guidelines, technical briefs, building/infrastructure codes and standards and technical seminars regarding earthquake, wind, tsunami and storm surge, and geotechnical issues. Although code committees and other implementation groups are often generally aware of ongoing applicable research, it is less common to see a coordinated, systematic review of all natural hazards risk-reduction research for the potential for practical implementation.

The TTC's primary task is to review the results of NHERI research projects in order to identify findings that could immediately lead to improvements in the design process resulting in mitigation of risk due to natural hazards. Another task is to educate researchers, particularly young researchers, regarding the many ways in which research in natural hazard risk reduction is implemented and the characteristics of research results that are most often implemented.

In the first 3 years of the NHERI program, over fifty NSF awards in various stages of completion have been reviewed. Several awards have been identified as having potentially implementable results. Members of the TTC have contacted the researchers in these cases and offered suggestions about implementation of the results moving forward.

The committee has published instructional material and guidelines for researchers aiming to promulgate their work into building codes and standards or to influence regulation. The document, "Mechanisms for Implementation of NHERI Research Results," is a resource to the NHERI research community (Holmes et al., 2020). It describes not only building code applications, but also other paths that can lead to improvements in design practices as a result of research. The paper is available on the DesignSafe-CI website as well as at user workshops held for potential researchers at NHERI Experimental Facilities.

In the third year of the NHERI NCO award, a one-and-one-half day meeting was held that included all members of the TTC and a representative of each NHERI facility. The meeting was both for the TTC to further discuss research awards that have been reviewed and to develop a closer relationship between the TTC and NHERI researchers. Importantly, the group defined activities that would improve the effectiveness of the TTC in future years. These improvements include wide dissemination of the "Mechanisms" paper, more direct communication with researchers, and making TTC members available to researchers interested in implementation of their research.

Based on the first few years of activity of the Technology Transfer Committee, the committee should greatly increase the practical impact of the NHERI network.

## COMMUNICATIONS AND ENGAGEMENT

The primary mission of the communications and outreach arm of the NCO is to position NHERI as the nation's top source for natural hazards expertise and information. This involves promoting NHERI—its activities and accomplishments—to the external community while also unifying and informing NHERI's own network of 11 diverse, distributed facilities. The communication and outreach challenges are met through a combination of traditional digital formats, such as email and newsletters, as well as through a more dynamic social media campaign and website.

### Tools of Engagement

The backbone of the network's communications tools is the NHERI cyberinfrastructure, known as the DesignSafe Cyberinfrastructure (DesignSafe-CI). DesignSafe-CI is physically based at the University of Texas-Austin, as part of the Texas Advanced Computing Center (TACC). DesignSafe-CI not only serves as the high-performance computing resource for natural hazards researchers and home to the NHERI network's data center; it also provides an ideal communications hub for the entire NHERI network. Via DesignSafe-CI, the NCO's communications and outreach activities provide a website and real-time communications for researchers and practitioners.

### Online Communications

The NHERI DesignSafe-CI website holds key documents and information for NHERI network users, as well as anyone interested in the subject of natural hazards research. NCO communications have focused on establishing a dynamic newsroom which regularly issues feature stories, news releases, and research highlights that capture ongoing output from the NHERI facilities and their researchers. This also includes DesignSafe Radio[5], a podcast series that interviews researchers about their experiences and provides topical coverage of natural hazards news. The newsroom serves as a resource for NHERI-branded logos and a launch pad for external communications on social media platforms. The DesignSafe-CI website also enables a location for educational webinars and event registration.

All experimental facilities have template websites on DesignSafe, enabling them to showcase their products and expert personnel. Because the NCO does not control or maintain the DesignSafe-CI website, close coordination and collaboration with the Cyberinfrastructure facility within the NHERI network has been needed to add network-wide communication functionality (e.g., the newsroom, a calendar, and network logos). Furthermore, not all NHERI facilities have trained communicators who can readily update and manage their NHERI website presence, so the NCO works to coordinate and encourage this.

The NHERI community also has access to real-time communications through an open-access Slack server hosted by DesignSafe-CI. Slack enables users to discuss their work within one of nearly 100 topical channels from anywhere around the world. The channel-specific nature of communications ensures a focused exchange of information. Consequently, heavy users have been engineering researchers involved in computational simulations and people soliciting volunteers and posting details of field work during post-disaster reconnaissance efforts.

### Newsletters

For the NCO, newsletters sent via email are the primary mode of internal communications, within the NHERI network. The NCO solicits news from individual facilities to disseminate across the network in a monthly email newsletter, the "Monthly Recap." The newsletter broadcasts media coverage, new grant awards, student activities, upcoming workshops, recent successes, and any other network-wide relevant information. A second publication, "The Quarterly Newsletter," contains longer stories focused on research projects hosted at the NHERI sites. To address the challenge of convincing busy faculty researchers of the benefits of promoting their work beyond a narrow publishing community, the NCO maintains monthly person-to-person communication between an NCO member and each component's principal investigator. This often provides the inspiration for upcoming stories. NCO communications staff minimize time requirements for researchers by providing initial story copy for revision and review.

### Calendar

The NCO communications staff also provide a calendar on the DesignSafe-CI webpage that tracks webinars, conferences, training, and other relevant network-wide activities. The calendar provides quick access to a centralized information source where all activities across the NHERI network can be easily found.

### Branding

To be recognized as the go-to source for natural hazards engineering, a unified branding across the NHERI network is a necessity. Led by the NHERI NCO, a series of NHERI site-specific logos with a common color scheme and graphical representation were created and adopted by each NHERI site. Additionally, the NCO developed presentation templates containing proper logo branding as well as introductory slides of the NHERI network to be used by the NHERI components whenever NHERI research is presented to outside communities. Lastly, inclusion of the NSF logo has also been an important part of the branding and results in exposure to a wider community of research.

### Email Subscriptions

The NCO employs external mailing lists to create and send messages and to monitor the success of our external campaigns. It disseminates information about NHERI activities to national media entities, to engineering and social science researchers and practitioners, to college students, and to government agencies involved with natural hazards engineering and social science research.

External messages take two general forms: news releases, which go out on an *ad hoc* basis to over 500 subscribers, and a curated Natural Hazards newsletter, published weekly to over 250 subscribers. News releases announce major findings and activities, while the Natural Hazards newsletter is a roundup of research papers and news stories of interest to natural hazards researchers. The biggest challenge is communicating specific research information to a broad natural hazards research audience. For example, many earthquake engineers may be uninterested in learning about successes in hurricane storm surge mitigation. Nonetheless, NHERI email communications typically generate a very high open rate of 40% or higher. By design, the NHERI network, composed of researchers studying a wide range of natural hazards, is tackling collaborative research which has led more and more researchers to see the tremendous value of sharing data, experiences, and tools across multiple natural hazards. It is anticipated that this content will continue to grow in popularity as researchers recognize the importance of interdisciplinarity and connections between best practices in different hazards.

### Social Media

Once more traditional digital forms of communication were established, the NCO communications turned to establishing a robust social media presence. The platforms selected are two of the most commonly recognized across the research community: Facebook and Twitter, with over 1,500 combined followers as of

[5]https://www.designsafe-ci.org/podcast

May 2020. NHERI tweets reach over 400 impressions per day. NCO communications outreach goals outlined for the NHERI network participants are specified as follows: (i) NHERI posts and tweets should encourage followers to learn more about NHERI and consider using NHERI facilities for their research purposes, and (ii) NHERI research sites should actively engage with other components, faculty, and students. NHERI site participation involves tagging other known NHERI sites, faculty, and/or student handles in their posts. NHERI's social media campaign has seen substantial growth since becoming a major focus in the middle of 2018.

## SUMMARY

As described in this article, the NHERI Network Coordination Office provides leadership and multiple services to the greater community of natural hazards researchers, practitioners, and students within the United States and internationally. Through its efforts to lead the research agenda, coordinate experimental and post-event field research, disseminate research findings, partner with international facilities, and educate and inspire the next generations of natural hazards engineers and social scientists, the NCO is an effective team to reduce risk and ensure community resilience to natural hazards for years to come.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

## ETHICS STATEMENT

Written informed consent was obtained from the individuals and minors' legal guardian for the publication of any potentially identifiable images or data included in this article.

## AUTHOR CONTRIBUTIONS

All authors are affiliated with the NHERI NCO and listed alphabetically by surname. Each section of the manuscript was led by a particular author, with additional contributions from others. DJ compiled and edited the manuscript, with helpful revisions provided by all.

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# NHERI Lehigh Experimental Facility With Large-Scale Multi-Directional Hybrid Simulation Testing Capabilities

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The NHERI Lehigh Experimental Facility, as part of the NSF-funded Natural Hazards Engineering Research Infrastructure (NHERI) program, was established in 2016 as an open-access facility. This facility enables researchers to conduct state-of-art research on natural hazard mitigation in civil infrastructure systems, including high-performance numerical and physical testing to improve the resilience and sustainability of the civil infrastructure against natural hazards. The facility has the unique ability to conduct real-time multi-directional hybrid simulation (RTHS) on large-scale structural systems using 3D non-linear numerical models combined with large-scale physical models of structural and non-structural components. The Lehigh Experimental Facility possesses testbeds that include a lateral load-resisting system characterization testbed, a non-structural component multi-directional dynamic loading simulator, full-scale and reduced-scale damper testbeds, a tsunami and storm surge debris impact force testbed, and a soil-foundation structure interaction testbed. This paper describes the infrastructure and capabilities of the NHERI Lehigh Experimental Facility. Developments by the facility in advancing large-scale RTHS are detailed. Examples of research projects performed by users of the facility are then provided, including large-scale RTHS of steel frame buildings with magneto-rheological (MR) dampers and non-linear viscous dampers subject to strong earthquake ground motions; 3D multi-hazard large-scale RTHS of tall steel buildings subject to multi-directional wind and earthquake ground motions; characterization of a novel semi-active friction device based on band brake technology; and testing of cross-laminated timber self-centering coupled wall-floor diaphragm-gravity systems involving multi-directional loading.

**Keywords: large-scale experiments, real-time hybrid simulation, multi-directional, structural control, multi-hazard**



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## 1. INTRODUCTION

The Natural Hazards Engineering Research Infrastructure (NHERI) is a National Science Foundation (NSF)-supported distributed, multi-user, open-access national research infrastructure. It consists of twelve components, including the Network Coordination Office (NCO), the Computational Modeling and Simulation Center (SimCenter), the DesignSafe-Cyberinfrastructure

(DesignSafe-CI), the Natural Hazards Reconnaissance (RAPID) Facility, CONVERGE, and seven Experimental Facilities (EF). The NHERI Experimental Facilities provide research tools that allow researchers to test natural hazard mitigation concepts and is located at various universities around the United States, including (1) Lehigh University, (2) the University of Texas at Austin (UTexas), (3) the University of California, Davis (UC Davis), (4) the University of Florida (UF), (5) Florida International University (FIU), (6) the University of California, San Diego (UCSD), and (7) Oregon State University (OSU). Researchers can utilize multiple facilities for a single research project. For example, wind pressures imposed on a structural system by a wind storm can be measured at a wind tunnel facility (i.e., FIU or UF) and subsequently used to define the wind loading for a real-time hybrid simulation performed at the Lehigh EF.

The NHERI Lehigh EF is an open-access facility that provides experimental resources for state-of-art research on natural hazard mitigation in civil infrastructure systems. The NHERI Lehigh EF provides a unique portfolio of experimental equipment, instrumentation, testbeds, and simulation protocols for large-scale multi-directional testing. The facility's experimental resources include a strong floor, multi-directional reaction wall, static and dynamic actuators, and test algorithms to enable researchers to conduct large-scale multi-directional dynamic testing and real-time hybrid simulation. Various testbeds are available at the NHERI Lehigh EF, including: (1) a lateral load resisting system characterization testbed; (2) full-scale damper testbeds; (3) a tsunami debris impact force testbed; (4) Lehigh Real-Time Cyber-Physical Structural Systems Laboratory; (5) a non-structural component multi-directional dynamic loading simulator; and (6) a soil-foundation structure interaction testbed. The types of testing and simulations that the NHERI Lehigh EF can perform include: (1) large-scale hybrid simulation (HS), which combines large-scale physical models with computer-based numerical simulations (Lin et al., 2013); (2) large-scale real-time hybrid simulation (RTHS), which is a HS conducted at the actual time scale of the physical models and excitations (Chen et al., 2009; Karavasilis et al., 2011; Chae et al., 2014; Dong et al., 2015); (3) large-scale real-time hybrid simulation with multiple experimental substructures, where several experimental specimens are used in an RTHS (Chen and Ricles, 2012; Al-Subaihawi et al., 2020); (4) geographically distributed hybrid simulation (DHS), which is an HS with physical models and/or numerical simulation models located in different laboratories and connected through the internet (Ricles et al., 2007); (5) geographically distributed real-time hybrid earthquake simulation (DRTHS), which combines DHS and RTHS (Kim et al., 2012); (6) dynamic testing (DT), which use high speed servo-controlled hydraulic actuators at real-time scales to impose predefined force or displacement histories (Ricles et al., 2002a; Chae et al., 2013b; Riggs et al., 2014); and (7) quasi-static testing (QS) of physical models using predefined force or displacement histories (Ricles et al., 2002b; Zhang and Ricles, 2006; Perez et al., 2013). A broad array of instrumentation, large-scale data acquisition systems, and advanced sensors is available to acquire the system-level data needed to support the goal of advancing computational modeling and simulation. All test results and research data are shared through the NHERI DesignSafe-Cyberinfrastructure using the Data Depot, a multi-purpose data repository for experimental, simulation, and field data (https://www.designsafe-ci.org/data/browser/public/).

The unique ability of the NHERI Lehigh EF is the real-time hybrid simulation (RTHS) methodology. RTHS is a cost-effective and efficient experimental tool that divides a structural system into experimental and analytical substructures where, in the former, components of the system not well-understood and for which accurate computational models do not exist are modeled physically in the laboratory. The latter (i.e., the analytical substructure) includes components with well-understood dynamic behavior that are modeled numerically in the computer. The natural hazard mitigation performance of load-rate-dependent devices, such as rotary friction dampers (Cao et al., 2015) and viscoelastic dampers (Lee et al., 2005) can be experimentally investigated using RTHS methodology. The RTHS performed at the NHERI Lehigh EF uses the unconditionally stable parametrically dissipative MKR-$\alpha$ integration algorithm developed by the authors (Kolay and Ricles, 2019). For the analytical substructures, the numerical modelings and state-determination process use explicit-formulated elements and material state determination functions that are embedded in finite element programs developed by the authors (Kolay et al., 2018; Ricles et al., 2020b) on a real-time workstation. For the experimental substructure, an adaptive servo-hydraulic control law developed by the authors (Chae et al., 2013a), called the adaptive time series (ATS) compensator, is used to provide accurate servo-hydraulic actuator tracking capability. The algorithm and adaptive control scheme have been successfully implemented and used at Lehigh to conduct over 2000 RTHS on structures with elastomeric, viscous, and semi-active controlled dampers subjected to seismic (Chen et al., 2009; Karavasilis et al., 2012; Dong et al., 2016, 2018a,b) and wind loadings (Al-Subaihawi et al., 2020; Kolay et al., in press).

The NHERI Lehigh EF has a staff dedicated to supporting the operations of the facility (**Figure 1**). The facility is directed by Dr. James Ricles, who provides overall leadership and accountability for completing the mission of the facility. Dr. Richard Sause, Associate Director, provides facility technical support leadership and assistance to the Director. Thomas Marullo, Research Scientist, oversees the facility's IT systems in addition to the development and implementation of software and algorithms to support experimental protocols. Dr. Liang Cao, Research Scientist, oversees the experimental protocol configurations, user training, and site enhancements. Dr. Chad Kusko manages the facility's operations and oversees the education community outreach program. Darrick Fritchman manages the laboratory technicians who provide laboratory staff support to research projects. Dr. Shamim Pakzad provides technical capacity building support in the areas of advanced sensors and structural health monitoring. Dr. Muhannad Suleiman provides technical capacity building support in soil-structure interaction and geotechnical engineering.

The large laboratory space, staff of skilled laboratory technicians, and multitude of equipment at the NHERI Lehigh

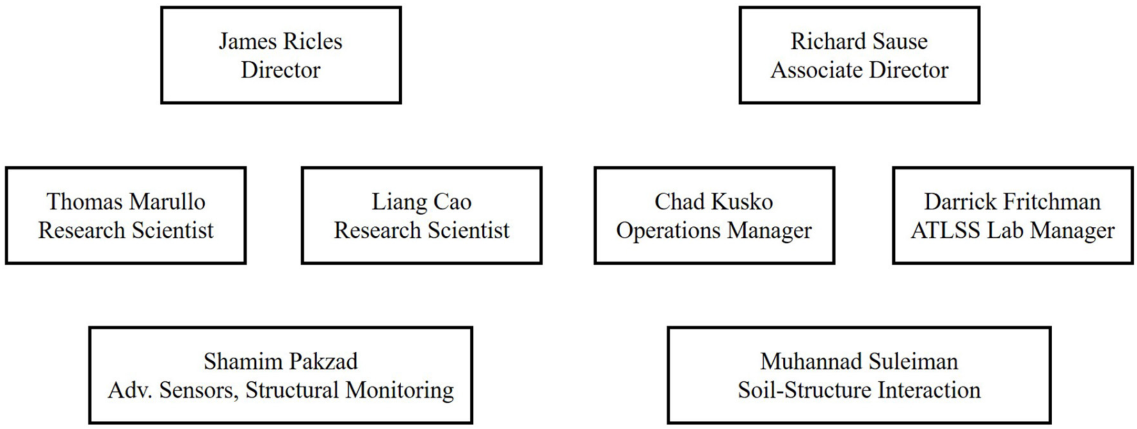


**FIGURE 1 |** NHERI Lehigh experimental facility staff.

EF enable multiple large-scale simulations and tests to be conducted simultaneously. Several experimental tests have been performed recently using the equipment and algorithms at the NHERI Lehigh EF, including (1) large-scale RTHS of a three-story steel frame building equipped with magneto-rheological (MR) dampers subject to strong earthquake ground motions; (2) large-scale RTHS of a reduced-strength steel building with non-linear viscous dampers subject to strong earthquake ground motions; (3) 3D multi-hazard large-scale RTHS of a tall steel frame building with non-linear viscous dampers subject to multi-directional wind and earthquake ground motions; (4) characterization of a novel semi-active friction device based on band brake technology; and (5) performance testing of cross-laminated timber self-centering coupled wall-floor diaphragm-gravity systems subjected to multi-directional seismic loading.

This paper is organized into five remaining sections. Section 2 presents an overview of the NHERI Lehigh EF, including the infrastructure, equipment, and various testbeds. Section 3 introduces the real-time integrated control system. Section 4 presents experimental protocols. Section 5 provides examples of research projects conducted at the NHERI Lehigh EF. Section 6 summarizes and concludes the paper.

## 2. OVERVIEW OF THE NHERI LEHIGH EF

### 2.1. NHERI Lehigh EF Infrastructure and Equipment

The NHERI Lehigh EF is housed in the multi-directional experimental laboratory at the Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center, Lehigh University. The ATLSS Laboratory has a strong floor that measures 31.1 × 15.2 m in plan and a 30.4 m long multi-directional reaction wall that measures up to 15.2 m in height. Anchor points are spaced on a 1.5 m grid along the strong floor and walls. Each anchor point can resist 1.33 MN of tension force and 2.22 MN of shear force. Additional steel reaction frames can be used in combination with the strong floor and reaction walls to create a wide variety of test configurations. A 178-kN capacity overhead crane services the test area and an adjacent fabrication area. Additional smaller cranes with capacities of 45 and 27 kN also serve this area. The ATLSS Laboratory includes a machine shop and material testing facilities.

The NHERI Lehigh EF equipment portfolio includes the following:

1. Five large-capacity hydraulic actuators manufactured by Servotest Systems and five smaller-capacity MTS hydraulic actuators. Details will be presented in the next subsection.
2. Two high-force, heavy-duty RSA electric rod actuators manufactured by Tolomatic with an 89-mm stroke and 22.2-kN force capacity.
3. Ten three-stage 2,080 lpm high-flow-rate servo-valves. Ten service manifolds with low-pressure and high-pressure settings that operate at 24.1 MPa.
4. Five 454-lpm hydraulic pumps with an oil reservoir and two banks of accumulators that enable strong seismic ground motion effects to be sustained for up to 30 s. The accumulators supply a total accumulated oil volume of 3,030 L connected to the hydraulic pressure line. Dedicated connections exist for accessing the high-flow hydraulic supply and return lines to the pumps.
5. Two Servotest Pulsar distributed high-performance, real-time digital servo-control systems with fiber-optic-based actuator and analog node modules for use in servo-drive PID control command generation and feedback signal conditioning.
6. A high-speed 384-channel data acquisition system manufactured by Pacific Instruments, capable of acquiring data up to 4,096 Hz (4,096 samples per second) per channel.
7. A Synology network attached storage system with dual-redundancy data protection and daily mirroring to Designsafe-CI.
8. Conventional sensors, including 12 temposonic displacement sensors with 1,500 and 2,240 mm stroke, 5 triaxial and 5 uniaxial ± 10 g accelerometers, 8 bi-axis dynamic 360° inclinometers, and other sensors including LVDTs, string potentiometers, linear potentiometers, etc.

9. Two Blue Iris web camera systems capable of streaming and recording 4K HD video and time-lapse images from IP web cameras, including 22 Amcrest 8MP 4K/30 FPS IP PoE cameras and 4 Sony SNC-EP550 720p/30 FPS PTZ IP PoE cameras.
10. Auxiliary equipment including forklifts and man lifts.

In addition to the above equipment, there are 27 additional servo-hydraulic actuators that can be used for static load applications (e.g., to apply gravitational load to test specimens). These actuators range in capacity from 130 to 2,680 kN, with strokes from 250 to 1,500 mm.

Advanced sensors are also available, including two digital image correlation (DIC) systems that can perform non-contact 3-D full-field strain measurements under dynamic loading. The measurement area range is from 23 × 18 to 5000 × 3800 mm with a strain measurement resolution range of 0.05–100%. The maximum sampling rate is 500 frames/s.

## 2.2. NHERI Lehigh EF Testbeds

Various testbeds are available for NHERI Lehigh EF, and photographs of these testbeds are shown in **Figure 2**.

### 2.2.1. Lateral Load-Resisting System Testbed

Tests, including RTHS of large-scale structural systems, can be performed using the lateral load-resisting system characterization testbed, as shown in **Figure 2A**. The testbed consists of a bracing frame for testing lateral load systems and has a width of 11 m and a height of 13.7 m. **Figure 2A** shows a photograph of a two-thirds-scale 5-story moment-resisting frame test specimen placed in the lateral load-resisting system characterization testbed.

### 2.2.2. Full-Scale Damper Testbed

The full-scale damper testbed in the NHERI Lehigh EF provides the ability to perform damper characterization tests and real-time hybrid simulations using full-scale dampers. Five servo-hydraulic actuators, two with a 2,300-kN capacity and three with a 1,700-kN capacity, are available. The actuator specifications are listed in **Table 1**. An example of a real-time hybrid simulation of a building equipped with four full-scale dampers is shown in **Figure 2B**, where the experimental substructure is comprised of these four dampers.

### 2.2.3. Tsunami Debris Impact Force Testbed

The tsunami debris impact force testbed is used to study water-borne debris impact forces on structures (Riggs et al., 2014). The testbed is shown in **Figure 2C**, where impact forces from a cargo shipping container are being investigated. Full-scale in-air impact tests were also conducted. The utility pole and shipping container were used as the debris object, suspended in a pendulum system and swung in free-fall to generate impact forces against a fixed load cell. A winch system is used to pull back the debris to the desired height. Data from all instrumentation are recorded during debris impact tests using a high-speed camera at 5,000 frames/s.

### 2.2.4. Lehigh Real-Time Cyber-Physical Structural Systems Laboratory

The Lehigh Real-Time Cyber-Physical Structural Systems (RCPSS) Laboratory is a multidisciplinary research facility that is focusing on small-scale dynamic testing for mitigating the effects of natural hazards on civil infrastructures. Five servo-hydraulic actuators designed and manufactured by MTS Systems Corporation are available for small-scale multi-directional dynamic tests and real-time hybrid simulations. The specifications for the actuators are listed in **Table 1**.

The characterization test setup of a 29-kN capacity non-linear viscous damper is shown in **Figure 2D**. The MTS actuator is installed on a foundation beam, and a reaction support (identified as column support in **Figure 2D**) and the damper are shown placed. Characterization tests are conducted using pre-defined displacement inputs.

### 2.2.5. Non-structural Component Multi-Directional Dynamic Loading Testbed

Large-scale dynamic tests of non-structural components can be performed using the non-structural component multi-directional dynamic loading testbed. **Figures 2E,F** show the experimental substructure for a real-time multi-directional seismic hybrid simulation of a building piping system using this testbed (Chen et al., 2008). The testbed consists of a 3-m wide by 12-m long rigid horizontal truss suspended from an overhead frame via four hanger rods. The non-structural components (e.g., the piping system) are attached to the horizontal truss and the laboratory's strong floor. The horizontal truss serves as a rigid floor diaphragm, and controlled bi-directional displacements are imposed on the truss using three hydraulic actuators to investigate the multi-directional dynamic performance of the non-structural components.

### 2.2.6. Soil-Foundation Structure Interaction Testbed

The soil-foundation structure interaction testbed consists of a vertical reaction frame and two stacked soil boxes and is shown in **Figures 2G,H**. The two soil boxes, each with dimensions of 1.5 × 1.5 × 1.5 m and 1.5 × 1.5 × 0.75 m were designed to allow for flexible assembly. The advanced sensors in the testbed include tactile pressure sheet sensors, in-soil null pressure sensors, customized flexible shape acceleration arrays (SAAs), and deformation sensors. The testbed also has a soil storage and moving system, vibrating table to characterize granular material compaction properties, nuclear density gauge, and web-broadcasting capability (Suleiman et al., 2014).

# 3. NHERI LEHIGH INTEGRATED CONTROL SYSTEM

## 3.1. Real-Time Integrated Control System Components

A schematic of the real-time testing architecture for the NHERI Lehigh EF is shown in **Figure 3** and includes the Real-Time Integrated Control System. The Real-Time Integrated Control System consists of several workstations linked by SCRAMNet and is configured with the experimental protocols required by

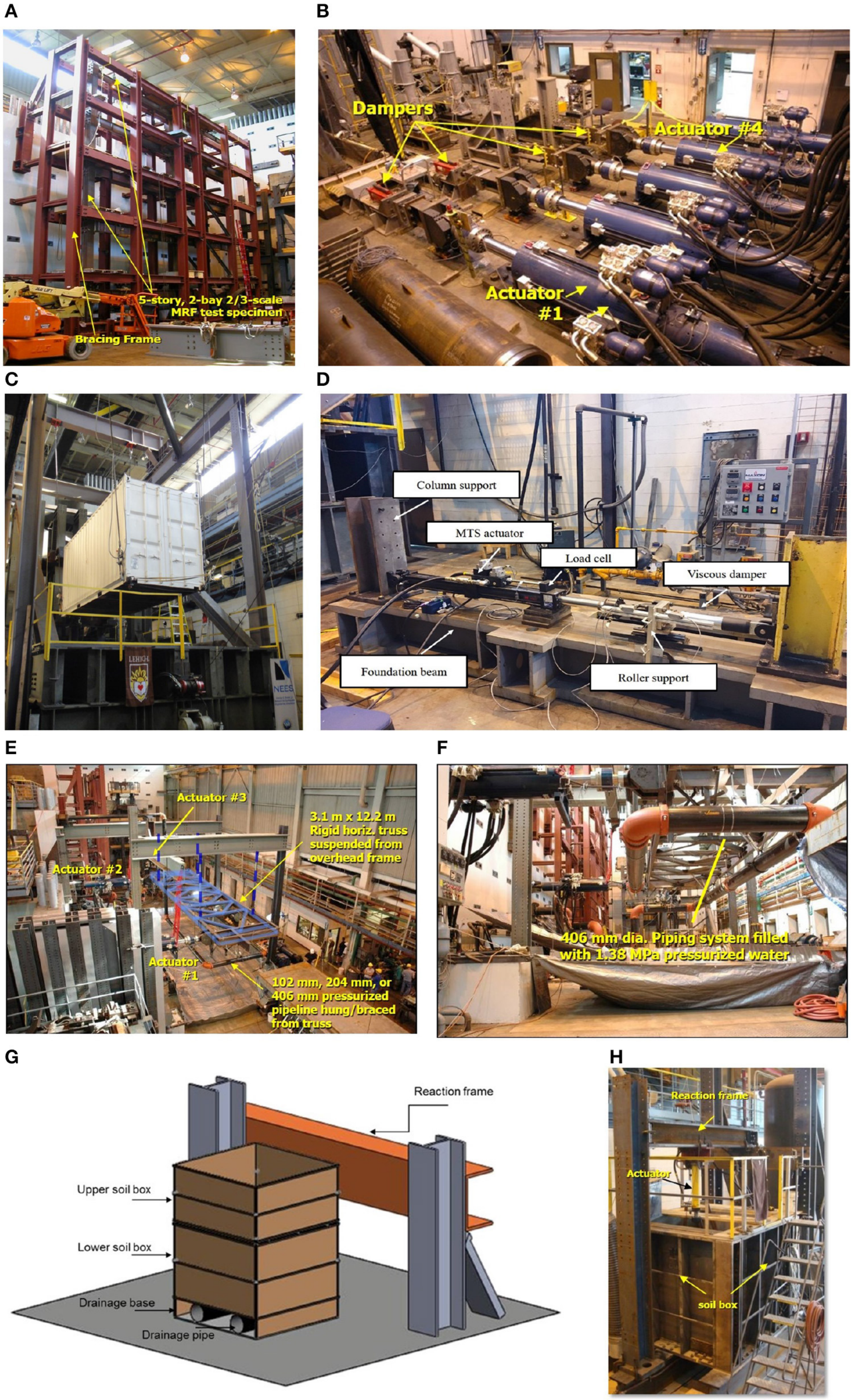


**FIGURE 2 |** NHERI Lehigh EF testbeds: **(A)** lateral force-resisting system characterization testbed; **(B)** full-scale damper testbed; **(C)** tsunami debris impact force testbed; **(D)** Lehigh Real-Time Cyber-Physical Structural Systems Laboratory testbed; **(E)** non-structural component multi-directional dynamic loading testbed being used for real-time multi-directional hybrid simulation of a building piping system; **(F)** piping system details; and soil-foundation structure interaction testbed; **(G)** schematic; and **(H)** photograph.

**TABLE 1 |** Dynamic actuator specifications.

| Number | Force capacity (kN) | Stroke length (mm) | Max velocity (mm/s) | Servo valve (lpm) | Comments |
|---|---|---|---|---|---|
| 1 | 1,700 | 1,000 | 1,140 | 2,082 | Large-scale dynamic actuator |
| 2 | 1,700 | 1,000 | 1,140 | 2,082 | |
| 3 | 1,700 | 1,000 | 1,140 | 2,082 | |
| 4 | 2,300 | 1,000 | 840 | 2,082 | |
| 5 | 2,300 | 1,000 | 840 | 2,082 | |
| 6 | 80 | 356 | 1,295 | 342 | RCPSS laboratory dynamic actuator |
| 7 | 49 | 508 | 736 | 114 | |
| 8 | 49 | 508 | 736 | 114 | |
| 9 | 98 | 152 | 381 | 114 | |
| 10 | 98 | 152 | 381 | 114 | |

the user to perform their test. The protocols and specifications are published in the NHERI Lehigh EF User's Manual (available at https://lehigh.designsafe-ci.org/resources/). The experimental protocols and specifications are presented to potential users at the biannual NHERI Lehigh EF researcher workshops and to users with research awards at training workshops to assist them in planning their research.

The Real-Time Integrated Control System uses reflective memory, SCRAMNet GT, to enable communication among the telepresence server (RTMDtele), simulation coordinator (RTMDsim), real-time targets (RTMDxPC), servo-hydraulic controllers (RTMDctl), and data acquisition system (RTMDdaq). The data exchange across SCRAMNet GT occurs within 90 ns, enabling shared memory among the workstations and real-time testing capabilities. Synchronization is maintained on SCRAMNet GT at the real-time control rate of 1,024 Hz. Experiments can be run in real time (e.g., real-time hybrid simulations, distributed real-time hybrid simulations, dynamic testing) or at an expanded time scale (e.g., hybrid simulations, distributed hybrid simulations, quasi-static testing). When the Real-Time Integrated Control System is operated in distributed hybrid simulation mode, Matlab provides functions for creating TCP/IP sockets across the Internet with another client computer and is used as the interface to the Internet. The Integrated Control System is robust and has a flexible design, enabling software and middleware packages developed by the community to be adopted and utilized for conducting tests.

The algorithms necessary to control the test are implemented on the RTMDsim workstation and compiled on the RTMDxPC workstation. The algorithms are tailored specifically for each test and are programmed primarily with MathWorks (Mathworks, 1992). Simulink is used to design a model-in-the-loop system that is compiled and loaded on the RTMDxPC workstation. If an RTHS requires a large computational model with many degrees of freedom (DOFs) to create the analytical substructure, then the executable code is parallelized and placed onto two RTMDxPC workstations and run in a synchronous manner. For each time step of an RTHS, all of the calculations must be completed within the time step, which affects the size of the model and the maximum number of DOFs that can be used in the simulation. The maximum possible number of DOFs for an RTHS depends on the characteristics of the analytical substructure (e.g., type of elements, degree of non-linearity that occurs in the simulation and elements, complexities of the material model), the integration algorithm, the size of the time step for the simulation, and physical memory limitations of the software and hardware. In general, Simulink and Simulink Real-time can support up to 8,000 DOFs before running out of physical memory when performing a traditional matrix multiplication.

The RTMDctl workstations operate tunable closed-loop PID control algorithms for each actuator and have I/O controls for managing the hydraulic power system. The servo controller utilizes both software programmable limit states and physical limit switches on equipment to ensure the safety of personnel and equipment during operation. Emergency stops are located at each workstation and at various locations in the laboratory for quick access in case an emergency arises.

The integrated control system has a hydraulics-off simulation mode for use in validation of testing methods, training, and education. In the hydraulics-off simulation mode, the servo-hydraulic equipment (e.g., servo-actuators, servo-valves) and test structure are analytically modeled. Models of the servo-hydraulic equipment have been developed in Simulink for this purpose and have been calibrated based on system identification tests of the equipment.

The RTMDtele, RTMDws, and RTMDcam workstations provide a multimedia perspective into an experiment. Data located on SCRAMNet GT are presentable locally and remotely through the RTMDtele workstation Data Turbine application as a web interface via the RTMDws workstation, allowing for real-time plots and time seeking of data at any point of the experiment. Data can be analyzed and exported either during or after a test. The RTMDcam workstation organizes and synchronizes all of the video channels and provides a grid-based system for video observation to local and remote users. Video recording and image capture can be triggered by various methods depending on the user's requirements.

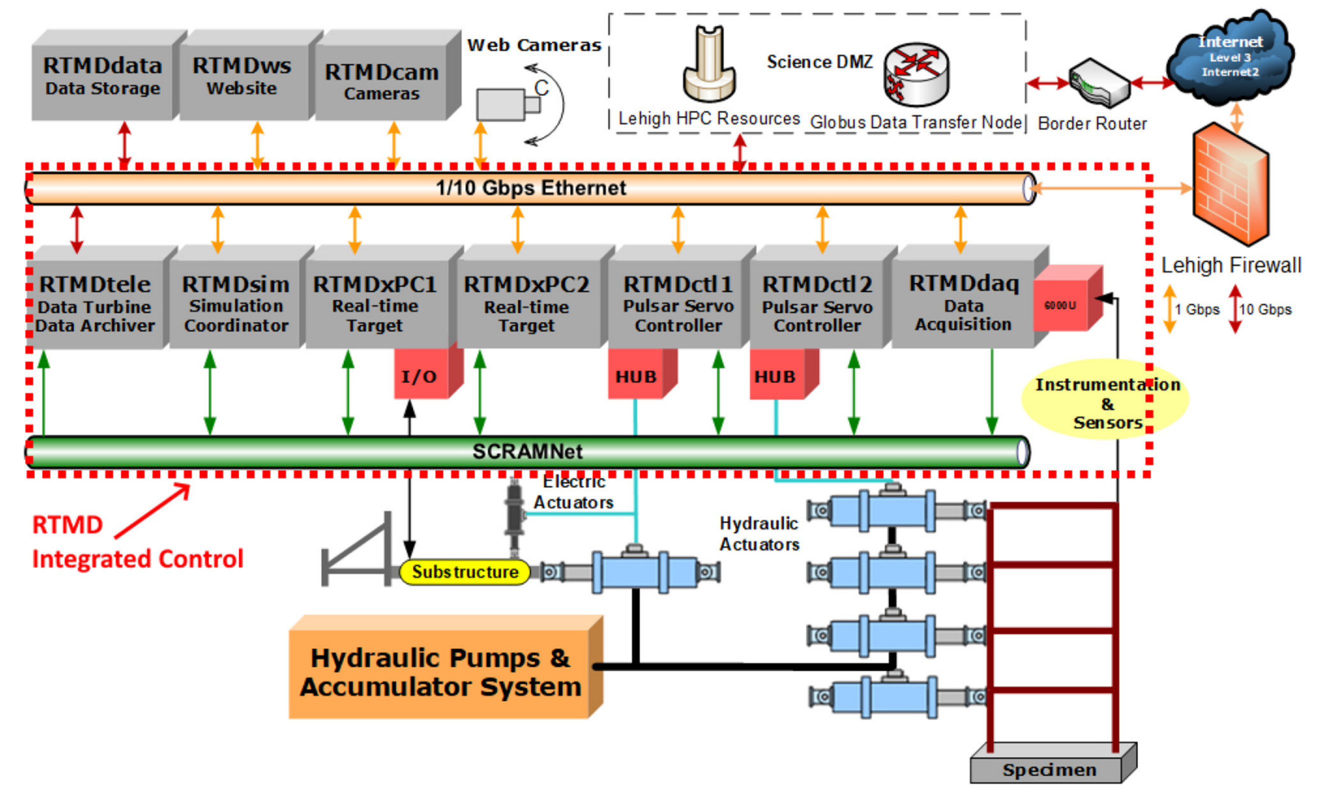


**FIGURE 3 |** NHERI Lehigh EF real-time integrated control system.

All data generated and captured is archived on the RTMDdata Synology system. Dual-redundancy data safeguards are implemented to ensure the reliability and security of the data. Data are organized for each experiment, and user permissions are designated per the requirements of the project team. Data related to NHERI projects are automatically synchronized daily with project space in the DesignSafe-CI project warehouse through https://www.globus.org/.

## 3.2. Real-Time Telepresence

Real-time telepresence is available for remote users. Teleobservation and teleoperation equipment (RTMDtele) are connected to an experiment using discrete and global sensors. The real-time visualization of the response of the complete system, including analytical and experimental substructures that exist in a hybrid simulation, is achieved using real-time structural system animation software. The experimental protocol includes the use of the Lehigh Data Model (Lee et al., 2008), which enables post-testing use of archived data from a hybrid simulation.

# 4. NHERI LEHIGH EF RTHS PROTOCOLS

Real-time hybrid simulation (RTHS) is a cost-effective method for performing experimental validation of natural hazard mitigation strategies for civil infrastructure systems. Typically, a structural system in an RTHS is divided into two different substructures: (1) an analytical substructure where structural components with well-understood behavior are numerically modeled on the computer; and (2) an experimental substructure where complex components in the structural system for which there are no accurate numerical models are physically modeled in the laboratory. The two substructures are kinematically linked together via a simulation coordinator in order that the demand imposed on the structural system is correctly represented by that imposed on the two substructures. The overall concept is demonstrated in **Figure 4** by using the example of a tall building equipped with passive dampers. Non-linear passive viscous dampers are installed in outrigger trusses of a 40-story steel frame building to improve its performance against wind and earthquake excitations. The structural components, which include the steel frames, associated seismic mass, and inherent damping, are modeled numerically as part of the analytical substructure, and the non-linear viscous dampers are physically modeled in the laboratory as the experimental substructure. Earthquake loads are determined from the accelerograms of ground motions. If an RTHS were to be performed where the building is instead subjected to a wind hazard, the wind load could be obtained from a wind tunnel test (e.g., at the NHERI FIU or UF EF). The equations of motion for the system are written:

$$\mathbf{M}\ddot{\mathbf{X}}_{i+1} + \mathbf{C}\dot{\mathbf{X}}_{i+1} + \mathbf{R}^{a}_{i+1} + \mathbf{R}^{e}_{i+1} = \mathbf{F}^{a}_{i+1} \quad (1)$$

where $\ddot{\mathbf{X}}_{i+1}$ and $\dot{\mathbf{X}}_{i+1}$ are the acceleration and velocity vectors of the system at time $t_{i+1}$, respectively, $\mathbf{R}^a_{i+1}$ and $\mathbf{R}^e_{i+1}$ are the restoring forces of the analytical and experimental substructures, respectively, at time $t_{i+1}$, $\mathbf{F}^a_{i+1}$ is the excitation force vector at time $t_{i+1}$, and **M** and **C** are the analytically defined mass and inherent damping matrices of the system, respectively.

For a given time step $t_{i+1}$, the simulation coordinator in **Figure 4** solves Equation (1) using an explicit integration algorithm in real time. For the applied loading $\mathbf{F}^a_{i+1}$, the algorithm generates command displacements $\mathbf{X}^a_{i+1}$ and $\mathbf{X}^e_{i+1}$ for the analytical and experimental substructures, respectively. The command displacements $\mathbf{X}^e_{i+1}$ are imposed on the experimental substructure (e.g., non-linear viscous dampers) in real time using servo-hydraulic actuators, while, simultaneously, the command displacements $\mathbf{X}^a_{i+1}$ are applied to the analytical substructure. The restoring forces $\mathbf{R}^a_{i+1}$ and $\mathbf{R}^e_{i+1}$ from the analytical and experimental substructures are obtained, sent back to the simulation coordinator, and subsequently used to obtain the acceleration $\ddot{\mathbf{X}}_{i+1}$ to complete the tasks for the time step. The simulation coordinator then advances to the next time step, and the process is repeated. Upon reaching the end of the loading history, the simulation is completed, and the real-time response obtained.

RTHS is performed at the NHERI Lehigh EF using explicit model-based dissipative integration algorithms developed by the authors (Chen and Ricles, 2008; Kolay and Ricles, 2014, 2019; Kolay et al., 2015). These algorithms are explicit and unconditionally stable. They do not require iteration to satisfy the equilibrium of Equation (1) and are ideal for conducting RTHS. The integration algorithm used in the examples described herein is the MKR-$\alpha$ integration algorithm (Kolay and Ricles, 2019). The MKR-$\alpha$ method features controlled numerical energy dissipation and controlled overshoot.

The analytical substructure for an RTHS is created using a suite of finite element programs developed by the authors (Kolay et al., 2018; Ricles et al., 2020b), termed HybridFEM-MH and HyCoM-3D. HybridFEM-MH and HyCoM-3D are similar, where the former is a multi-hazard 2D non-linear structural system response simulation program for assessing the performance of civil infrastructure systems, while the latter a 3D simulation program. Both programs are MATLAB- and Simulink-based. The source code is compiled and run in real time. The explicit-formulated element library in the programs includes non-linear fiber elements, non-linear truss elements, non-linear geometric elements to model P-$\Delta$ effects, non-linear hysteretic connection elements, non-linear panel zone elements, and zero-length elements, along with a material library that enables the hysteretic stress-strain behavior of steel, concrete, steel reinforcement, and zero-tension, zero-compression materials to be modeled. The programs also feature reduced-order elements, real-time model updating, and multi-point constraint options. User-defined elements can also be readily added to both programs. The programs have been successfully used to conduct non-linear time history analysis and RTHS of complex non-linear structural systems (Chen et al., 2008, 2009; Karavasilis et al., 2011, 2012; Chen and Ricles, 2012; Chae et al., 2014; Dong et al., 2015, 2016, 2018a,b; Kolay et al., 2015, in press; Al-Subaihawi et al., 2020).

An advanced adaptive delay compensation algorithm developed by the author (Chae et al., 2013a), termed the adaptive time series (ATS) compensator, is used to accurately achieve the target displacements associated with the command displacements of the experimental substructure in real time. The algorithm uses feedback signals from the measured state of the experimental specimen and minimizes displacement errors in an adaptive manner to ensure that the experimental substructure target displacements are accurately achieved.

For multi-directional experiments, a kinematic compensation testing protocol based on an algorithm developed by the authors (Mercan et al., 2009) is used to avoid kinematic errors during a test. The algorithm accounts for the displaced configuration of the test structure and the actuators, and the non-linear relationship between the target displacements, displaced configuration of the test structure, and the actuators, in determining the actuator command displacement signals issued to the servo-controller (RTMDctrl).

## 5. EXAMPLE RESEARCH PROJECTS

In this section, five selected example projects performed by researchers that have utilized the NHERI Lehigh EF are presented.

### 5.1. Large-Scale RTHS of a Three-Story Steel Frame Building Equipped With Magneto-Rheological Dampers

The seismic response of a 3-story, 6-bay by 6-bay office building located in Southern California, equipped with magneto-rheological (MR) dampers was investigated by Chae et al. (2014) using the RTHS method. The building's lateral force-resisting system consists of steel moment-resisting frames (MRFs) with reduced beam section (RBS) beam-to-column connections and damped braced frames (DBF) with MR dampers, as shown in **Figure 5**.

A 0.6-scale three-story DBF installed with two MR dampers was fabricated at the NHERI Lehigh EF and represented the experimental substructure for the RTHS. The DBF was braced out of plane by the lateral load-resisting system testbed at each floor, and the floor beams in the DBF were connected to the columns by a bolted T-section connection, as shown in **Figure 6A**. Two MR dampers were installed in the first and second stories through clevises and diagonal bracing. Each MR damper has a 200-kN capacity, a stroke of 558 mm, and a maximum piston velocity of 100 mm/s under a current input of 2.5 A. To conduct the RTHS test, 2,300 kN servo-hydraulic actuators were attached to the first and second floors of the DBF, and a 1,700-kN servo-hydraulic actuator was attached to the third floor (**Figure 6B**). The remaining parts of the building, including the MRF, gravity load system, and the tributary seismic floor

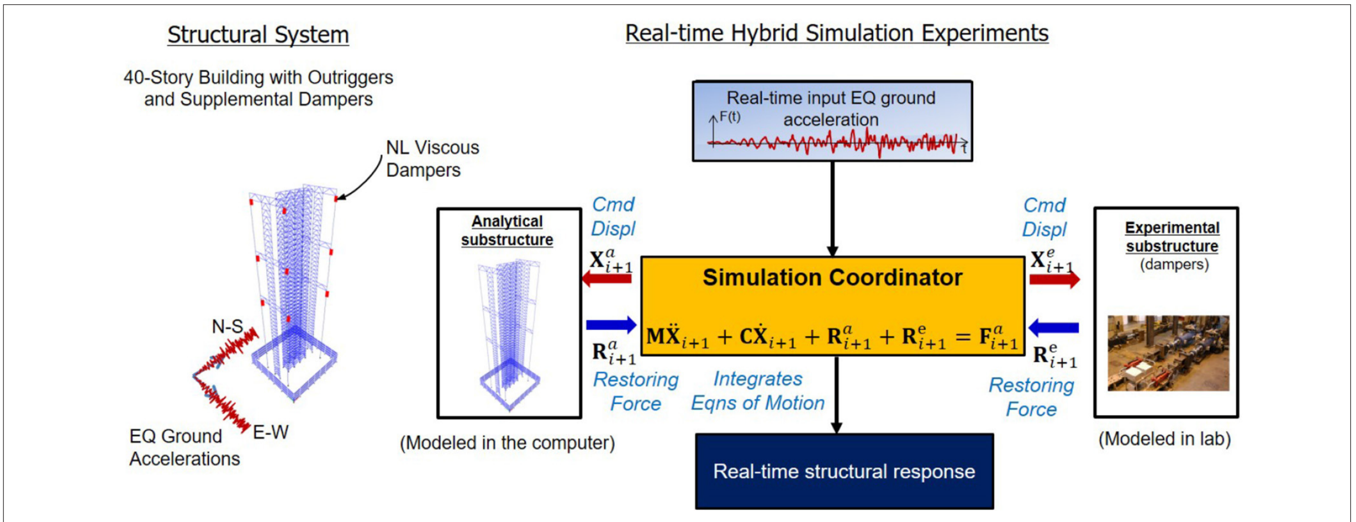


**FIGURE 4 |** Overall concept of real-time hybrid simulation: structural system subject to seismic ground motions.

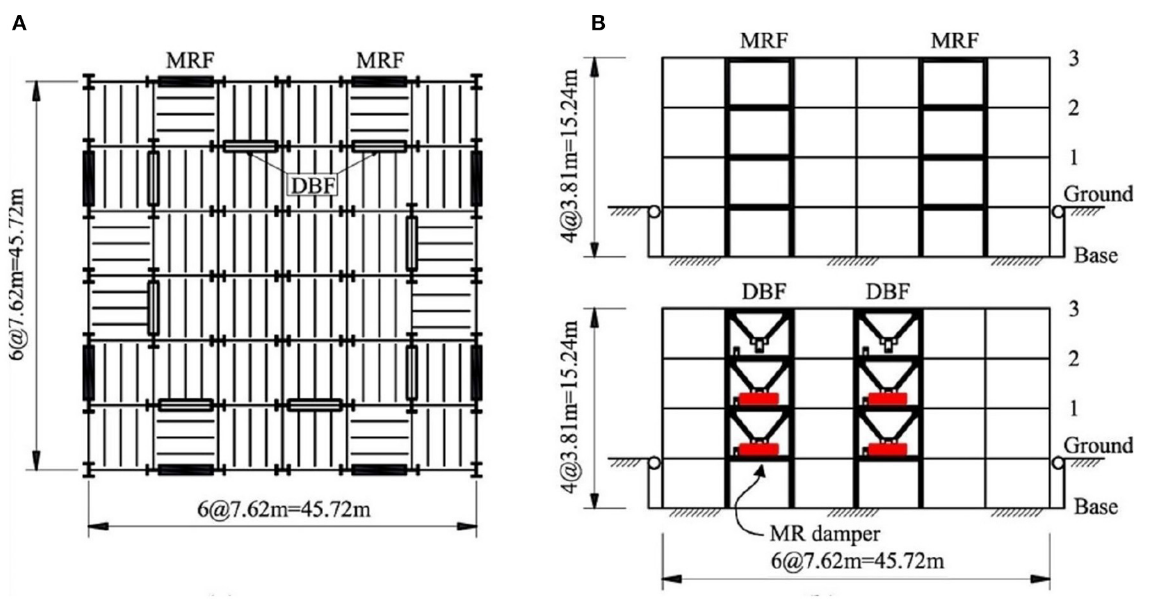


**FIGURE 5 |** Three-story building: **(A)** plan view and **(B)** elevation (reprinted from Chae et al., 2014 with permission).

masses, were modeled via the analytical substructure, as shown in **Figure 6C**.

The RTHS study focused on evaluating the seismic performance of the building when using the MR dampers in semi-active control mode. Two ground motions, namely, the 1992 Landers earthquake and the 1994 Northridge earthquake, were used and scaled to 60 and 80% of the design basis earthquake (DBE) level. The RTHS results show that maximum story drifts are reduced by 44 and 14% under the 1992 Landers earthquake and the 1994 Northridge earthquake, respectively, when using MR dampers with an LQR control law. Data from the RTHS were used to develop a computational model for an MR damper (Chae et al., 2013c). Comparisons between numerical simulations using the MR damper model and RTHS results under the 80% DBE hazard level of the 1994 Northridge earthquake show good agreement, as shown in **Figure 7**.

## 5.2. Large-Scale RTHS of a Reduced-Strength Steel Building With Non-linear Viscous Dampers Subject to Strong Ground Motions

The performance of the three-story steel frame building equipped with non-linear viscous dampers subjected to strong ground

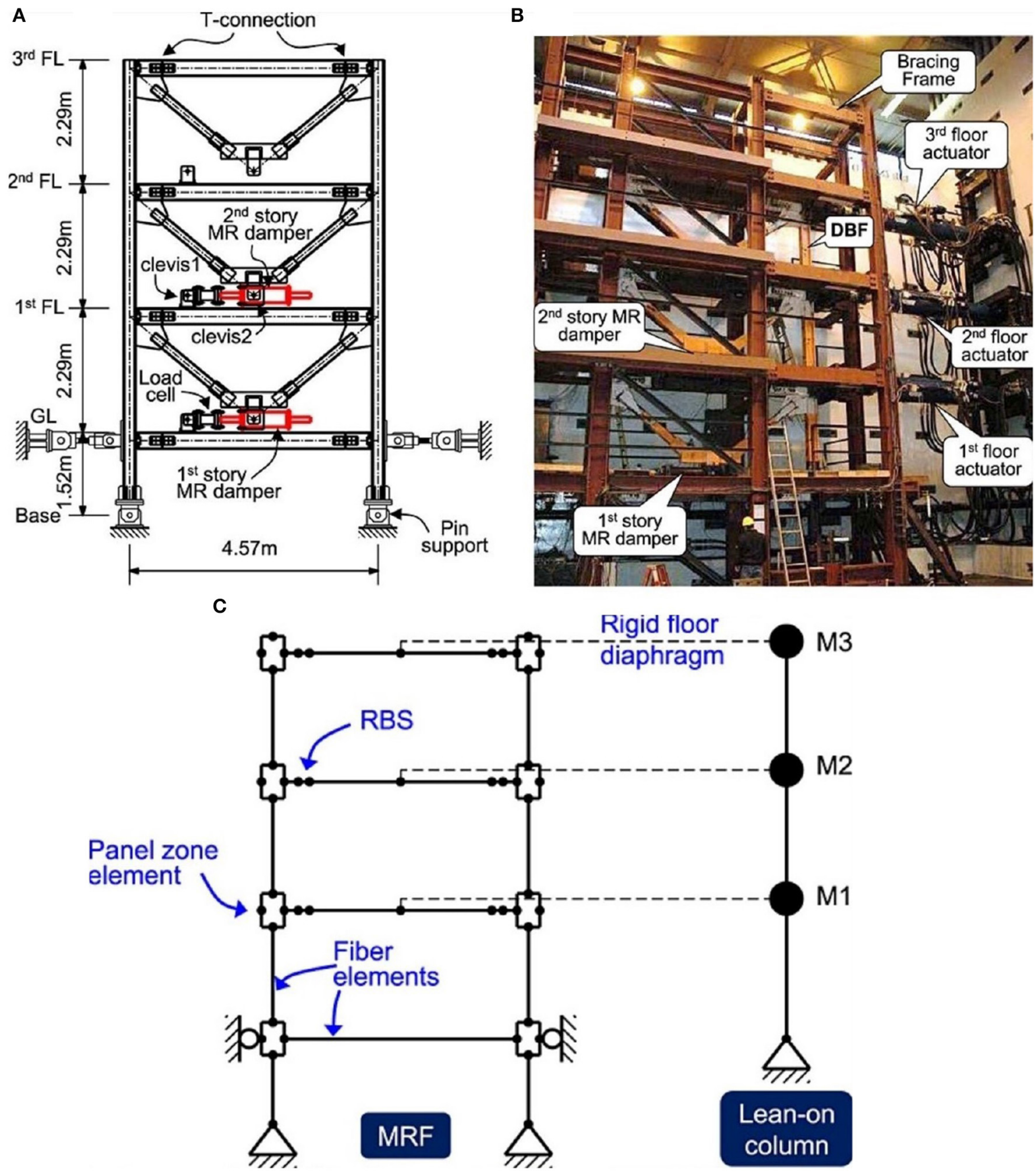


**FIGURE 6 |** RTHS of a three-story building with MR dampers: **(A)** schematic of the experimental substructure, **(B)** photograph of the experimental test setup, and **(C)** analytical substructure (reprinted from Chae et al., 2014 with permission).

motions was investigated by Dong et al. (2018b) using real-time hybrid simulations. The same building's lateral force-resisting system from the previous subsection (**Figure 5**) was used except that the damped braced frames (DBF) were equipped with non-linear viscous dampers at three floors. Unlike the previous RTHS substructure, the analytical substructure used in this study included only the seismic mass and gravity load system (**Figure 8A**). The MRF and DBF with non-linear viscous dampers were physically modeled via the experimental substructure; see **Figure 8B**. The test setup for the experimental substructure is shown in **Figure 8C**.

Three MRF designs were studied, where the MRF was designed for 100, 75, and 60% of the required design base shear according to ASCE 7-10 (ASCE, 2010). The objective was to assess the seismic performance of MRFs designed with reduced strength and added supplemental damping. Four hazard levels were considered for the RTHS, specifically DBE, maximum considered earthquake (MCE), and two earthquakes scaled to

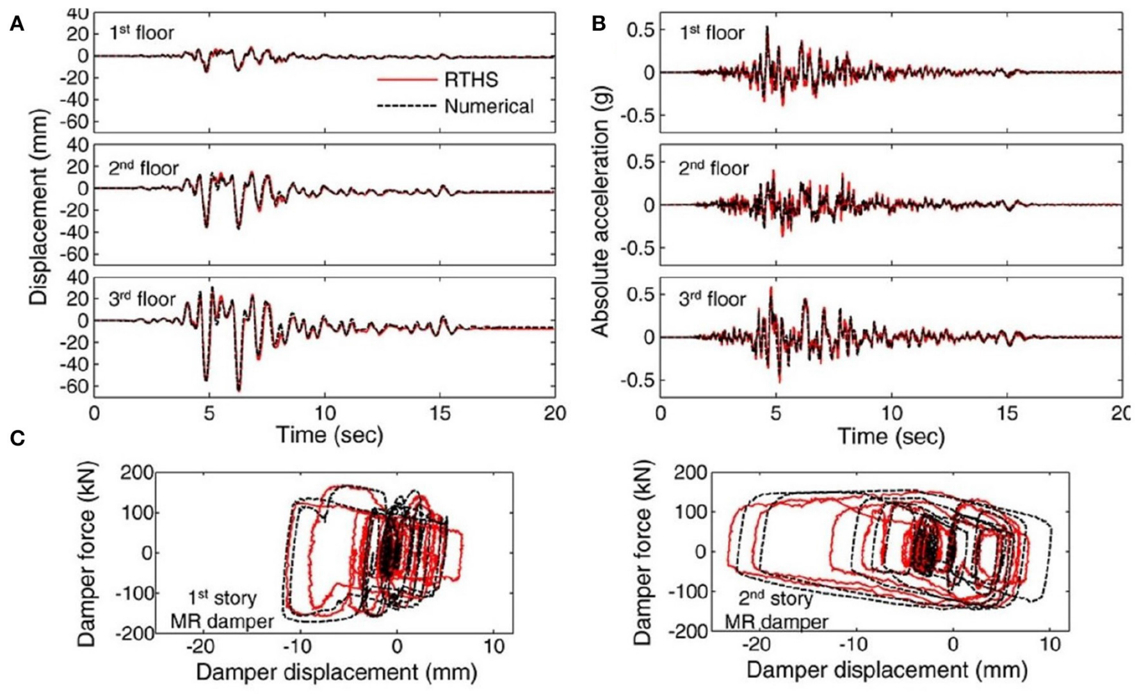


**FIGURE 7 |** Comparison between numerical simulation and RTHS results under the 80% DBE level 1994 Northridge earthquake: **(A)** floor displacement, **(B)** floor absolute acceleration, and **(C)** force-displacement response of MR dampers (reprinted from Chae et al., 2014 with permission).

hazard levels beyond the MCE level (1.2 and 1.4 MCE). The peak story drift results of the building with the 60% design base shear strength MRF under the 1979 Imperial Valley earthquake were found to be <1.4% under the DBE and to satisfy the "Life Safety" performance level of 2.5% under the MCE and the "Collapse Prevention" performance level of 5% for both 1.2 and 1.4 MCE. The RTHS results demonstrated good performance of the prototype building with a 60% design base shear strength when subjected to strong ground motions, including intensity levels beyond the MCE level. The researcher concluded that buildings can be designed using supplemental dampers with a reduced strength that is lower than that which the code permits for seismic hazards (Dong et al., 2018b).

## 5.3. 3D RTHS of Tall Buildings Equipped With Non-linear Viscous Dampers Subject to Multi-Natural Hazards

The damped outriggers system for tall buildings aims at placing dampers vertically between the outrigger truss and the perimeter columns as a means of increasing the equivalent damping of the building (Smith and Willford, 2007). When the outrigger truss ends move relative to the perimeter columns, the dampers develop forces that suppress vibrations caused by lateral loading.

The building is shown in **Figure 9** and is assumed to be located in Los Angeles, California. It was designed by Simpson Gumpertz & Heger Inc. as part of the PEER Tall Building Initiative (Moehle et al., 2011). The building is 166-m tall measured from the ground level, with 40 stories above grade and four basement levels. Six buckling restrained braced frames (BRBFs) provide the lateral force-resisting systems in each of the North-South and East-West directions. Outrigger trusses are located at the 20th, 30th, and 40th stories. The original design of the building was modified by Kolay et al. (in press) to include non-linear viscous dampers (NLVDs) between the outriggers and the perimeter columns, as shown in **Figure 9**. Real-time hybrid simulations were used by Kolay et al. (in press) and Ricles et al. (2020a) to understand the behavior of the modified system when subjected to wind and earthquake hazards.

The analytical substructure for the RTHS included a total of 2,411 elastic beam-column elements to model the beams and columns and 552 non-linear truss elements to model the buckling restrained braces (BRBs). The total number of degrees of freedom in the model for the RTHS is 3974, allowing the equations of motion to be integrated in real time with an integration time step of 11/1,024 s. The analytical model is developed using HyCoM-3D (Ricles et al., 2020b) to perform 3D RTHS with bi-directional loading.

Four non-linear dampers are placed between each outrigger truss and perimeter column, coming to a total of 48 dampers. One full-scale non-linear damper was considered as the experimental substructure for the RTHS and was placed at the South-East side of the 40th story outrigger, while the other dampers were modeled numerically using on-line model updating. The combined system (analytical and experimental) was subjected to natural hazards consisting of an earthquake scaled to the

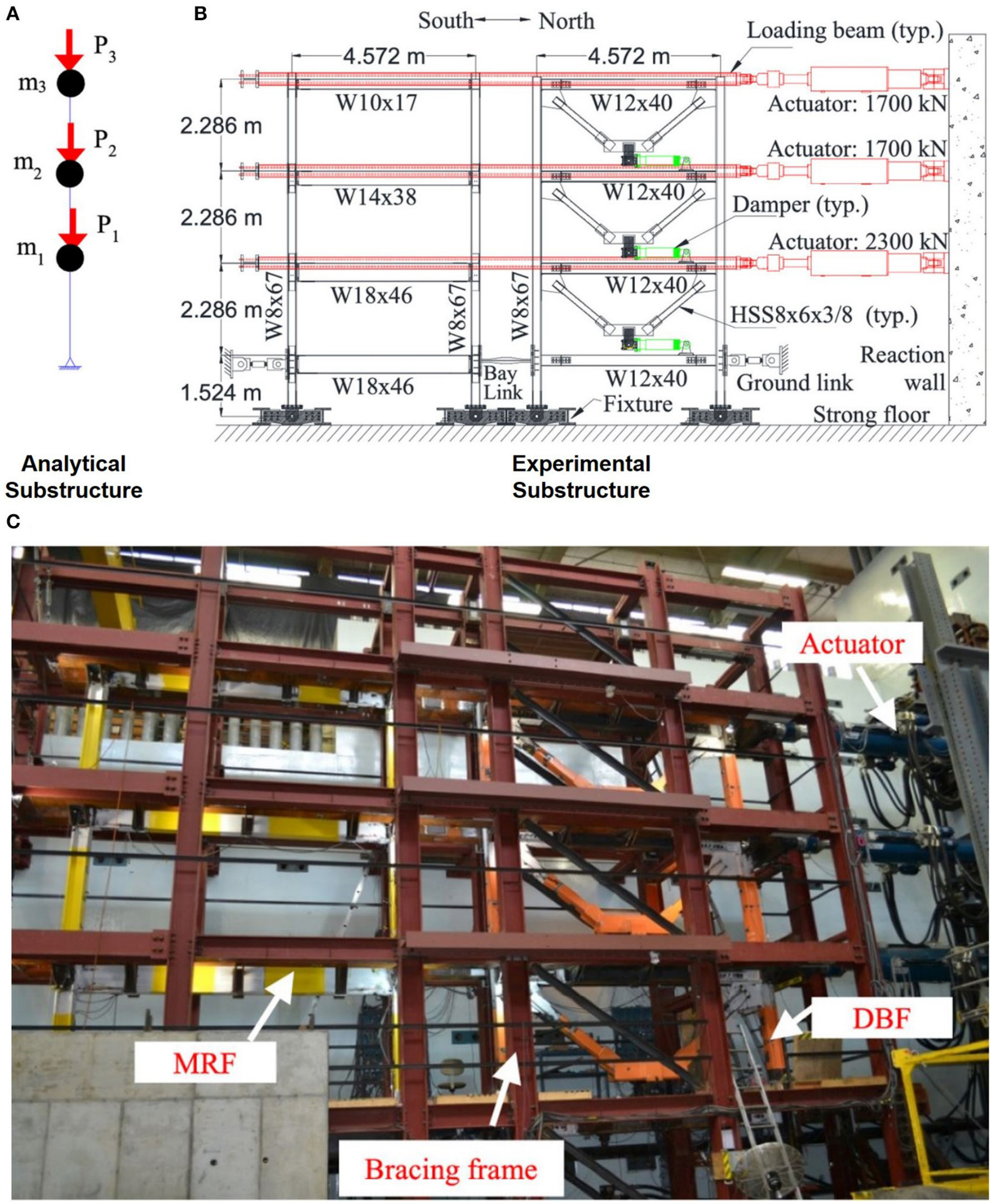


**FIGURE 8 |** RTHS substructures of a three-story building equipped with non-linear viscous dampers: **(A)** analytical substructure, **(B)** experimental substructure, and **(C)** experimental test setup (reprinted from Dong et al., 2018b with permission).

Maximum Considered Earthquake hazard level and a windstorm with a 177 km/hr windspeed acting in the East-West direction and associated cross-wind effects acting in the North-South direction. The windstorm forces are obtained from wind tunnel tests performed in the wind tunnel facility at Tokyo Polytechnic University (Tokyo Polytechnic University, 2017).

**Figures 10**, **11** show the response of the building under the two natural hazards. Building response was non-linear under earthquake, as characterized by inelastic deformations in the BRBs at several story levels. The period of the first translational mode in the North-South direction was 6.3 s, while that in the East-West direction was 4.3 s (obtained via an eigenvalue analysis using a linearized damper model). More damage in the building is observed in the East-West direction (**Figure 10D**) despite its higher stiffness compared to the North-South direction (**Figure 10C**) because of the characteristics of the ground motion, which impose higher spectral accelerations and correspondingly higher inertial forces in the East-West

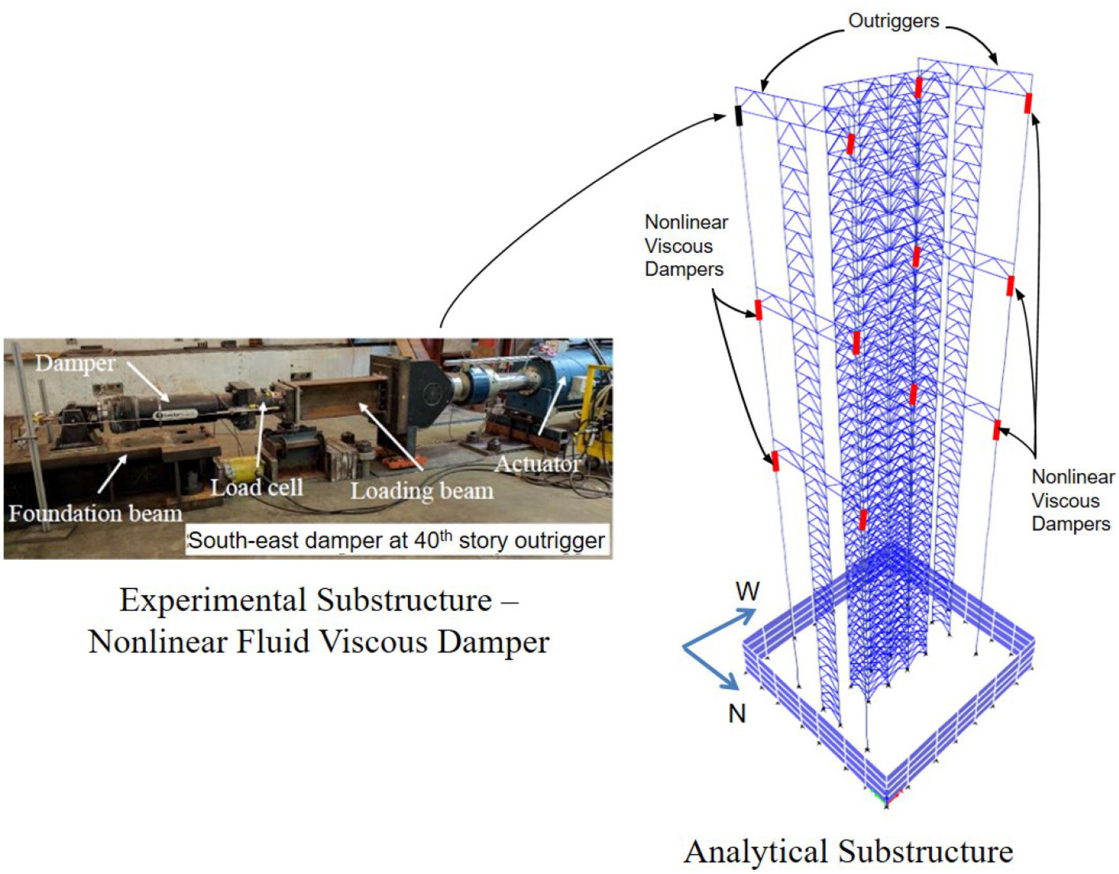


**FIGURE 9 |** RTHS of a tall building equipped with a damped outriggers system; numerically and physically modeled dampers are marked in red and black, respectively.

direction. The response of the experimental substructure in **Figure 10E** is characterized by a wide hysteresis loop because of the non-linear response of the damper at high velocities, which limits the rate at which the damping force increases as the damper force becomes capped and limited in magnitude (Lin and Chopra, 2002).

The building response was linear under the windstorm. As described earlier, the building is less stiff in the North-South direction, so it undergoes a higher peak roof displacement in that direction (**Figure 11B**) despite the fact that vortex shedding is imposing peak floor forces in the North-South direction that are comparable to wind forces in the East-West direction (**Figures 11H,I**). The flexibility of the building in the North-South direction makes it more susceptible to wind-induced vibrations, and thus adding dampers in the North-South direction helps control the floor accelerations in that direction. The damper response under wind differs from that under earthquake loading, which is characterized by elliptically shaped hysteresis in the damper force-displacement plot (see **Figure 11E**). The results of this study show that for large complex structures, the RTHS can capture the rate dependency of the experimental substructure depending on the natural hazard imposed.

## 5.4. Characterization of a Novel Semi-active Friction Device Based on Band Brake Technology

A new semi-active friction damper using band brake technology, termed the Banded Rotary Friction Damper (BRFD), has been developed by Downey et al. (2016). The damping mechanism is based on band brake technology and leverages the self-energizing mechanism to produce large damping forces using low input force. It consists of three flexible braking bands lined with friction material that tightens concentrically around a cylindrical drum to slow or stop its rotation. One inner band is attached to a screw-type actuation mechanism consisting of a threaded rod for the purpose of varying the force applied ($F_{\text{applied}}$) to the band brake, and two outer bands are anchored to a rigid frame. The BRFD produces a variable braking torque as a linear function of the input force.

The dynamic behavior of the BRFD was investigated through characterization tests performed at the NHERI Lehigh Real-Time

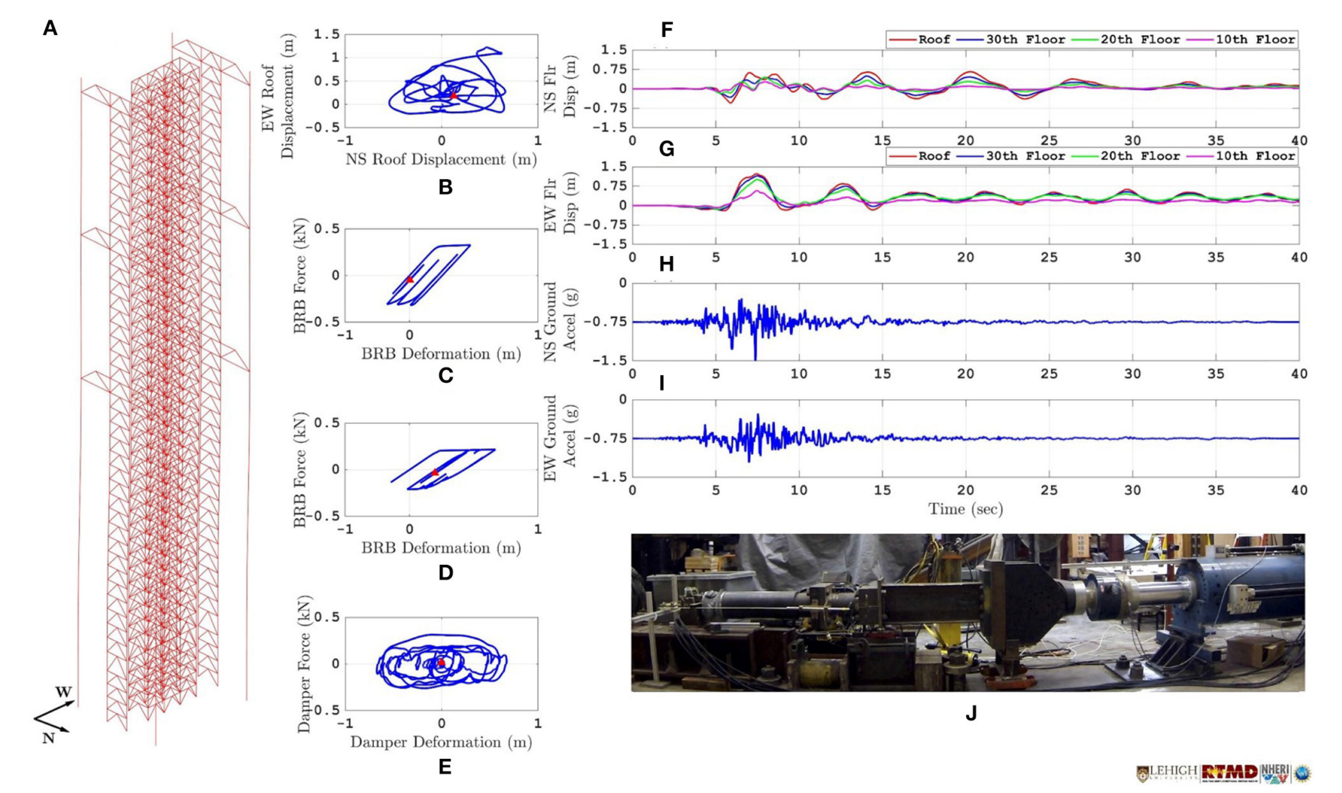


**FIGURE 10 |** The 3D RTHS of a tall building equipped with non-linear viscous dampers under seismic excitation: **(A)** isometric view of structure, **(B)** bi-directional roof displacement orbits, **(C,D)** 1st story brace hysteresis in the NS and EW directions, **(E)** force-displacement hysteresis of the NLVD experimental substructure, **(F,G)** floor displacement time histories of selected floor levels, **(H,I)** bi-directional ground accelerations, and **(J)** experimental substructure (full-scale NLVD).

Cyber-Physical Structural Systems Laboratory. A one-third-scale BRFD was connected to an MTS actuator via a clevis, and the damping force was recorded by the actuator load cell. The applied input force $F_{\text{applied}}$ was achieved using force feedback signals from a load cell placed in the BRFD.

The prototype was subjected to a displacement-controlled harmonic excitation of a 25.4-mm amplitude with a frequency of 0.5 Hz. Three different values of constant $F_{\text{applied}}$ were investigated: 222, 267, and 311 N. The BRFD force-displacement and force-velocity responses are plotted in **Figure 12**, where the results show that the prototype BRFD is capable of obtaining a damping force of 22.2 kN using an input force of $F_{\text{applied}} = 311$ N, resulting in a force amplification ratio (FAR) of 72. The FAR is defined as the ratio of BRFD force output to actuator force input.

## 5.5. Multi-Directional Dynamic Testing of Cross-Laminated Timber Self-Centering Coupled Walls-Floor Diaphragm-Gravity System

Cross-laminated timber (CLT) is an engineered-wood structural component fabricated by laminating layers of timber boards in an orthogonal pattern glued together on their wide face. A self-centering (SC) rocking post-tensioned CLT structural wall (SC-CLT walls) has been proposed recently and its experimental response under unidirectional cyclic loadings was studied by Akbas et al. (2017). However, the dynamic behavior of SC-CLT rocking walls under bidirectional loading and its performance coupled with wood structures have not been investigated.

To fill this knowledge gap, Sause et al. (2020) recently conducted multi-directional quasi-static testing with predefined displacement at the NHERI Lehigh EF on a CLT-floor diaphragm-gravity system with an SC-CLT rocking wall. **Figure 13A** shows the schematic of the CLT-floor diaphragm-gravity system, and **Figure 13B** shows a photograph of the shear wall and CLT test setup. The system consists of a 0.625-scale subassembly of a self-centering coupled CLT floor diaphragm, three glulam gravity beams, two glulam collector beams, and five glulam gravity columns. The glulam collector beams transfer the lateral force from the CLT floor diaphragm to the SC-CLT walls through a slotted connection, and two U-shaped flexural plates (UFP) are embedded between the SC-CLT rocking wall to dissipate energy. Four servo-hydraulic actuators are used to impose the bi-directional motion on the system subassembly (two in the in-plane direction and two in the out-of-plane direction). A kinematic compensation algorithm developed by the authors (Mercan et al., 2009) was used to perform the multi-directional test. A structure-physical node (SPN) located at the center of the

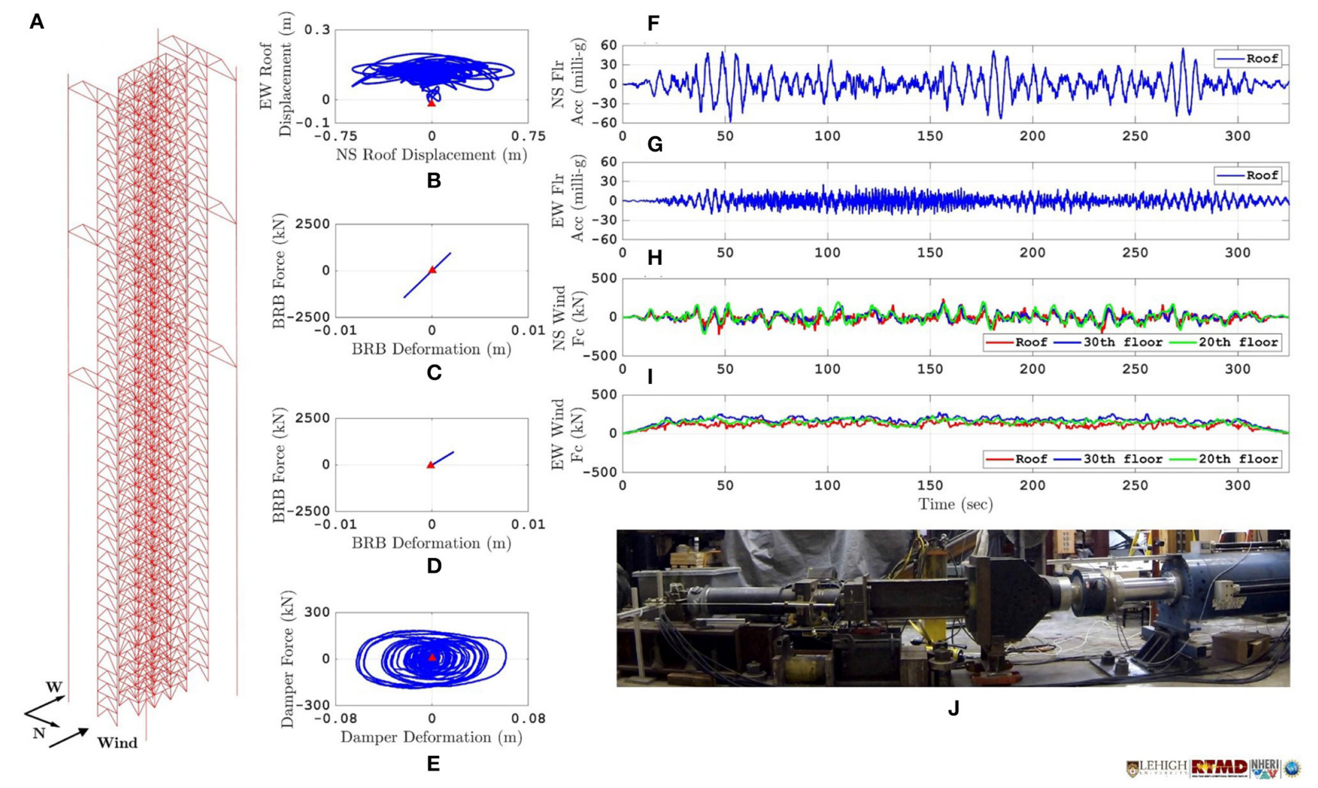


**FIGURE 11 |** The 3D RTHS of a tall building equipped with non-linear viscous dampers under wind excitation: **(A)** isometric view of structure, **(B)** bi-directional roof displacement orbits, **(C,D)** 1st story brace hysteresis in the NS and EW directions, **(E)** force-displacement hysteresis of the NLVD experimental substructure, **(F,G)** floor displacement time histories of selected floor levels, **(H,I)** bi-directional wind loading at selected floor levels, and **(J)** experimental substructure (full-scale NLVD).

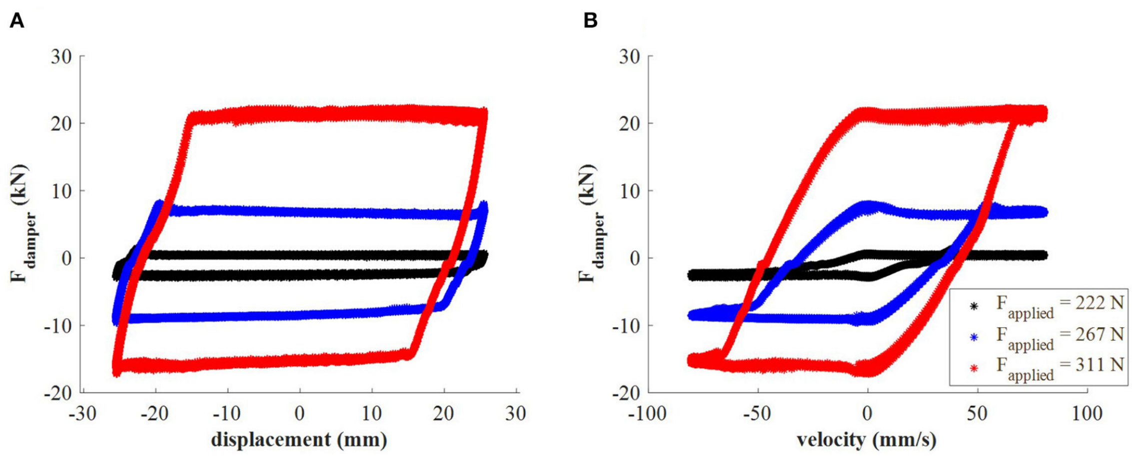


**FIGURE 12 |** Characterization tests of BRFD under harmonic testing at 0.5 Hz: **(A)** damper force-displacement response and **(B)** damper force-velocity response.

SC-CLT wall was used as the test specimen control node associated with the subassembly degrees of freedom. Two measurement-structural nodes (MSN) located on the CLT floor diaphragm were used to measure the floor displacement. The degrees of freedom relationship between the SPN and MSN was established via the compensation algorithm, and the SPN displacement is controlled using real-time continuous displacement feedback from the two MSNs. The multi-directional quasi-static cyclic test was performed, and the bi-directional target and measured subassembly drifts of the SPN are compared in **Figure 14A**. Comparing the targeted and measured SPN drift, the normalized root mean square error (NRMSE)

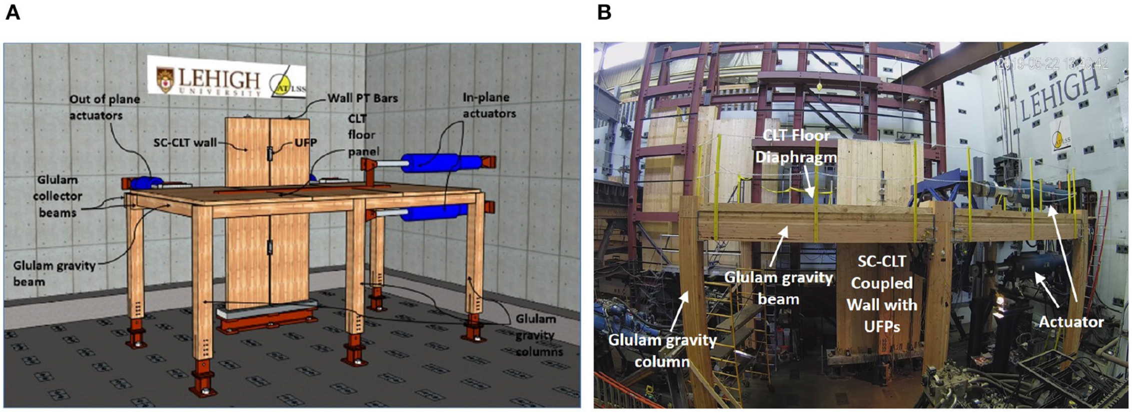


**FIGURE 13 |** Multi-directional test of cross-laminated timber self-centering coupled walls-floor diaphragm-gravity system: **(A)** schematic and **(B)** test setup (courtesy of Amer, 2021).

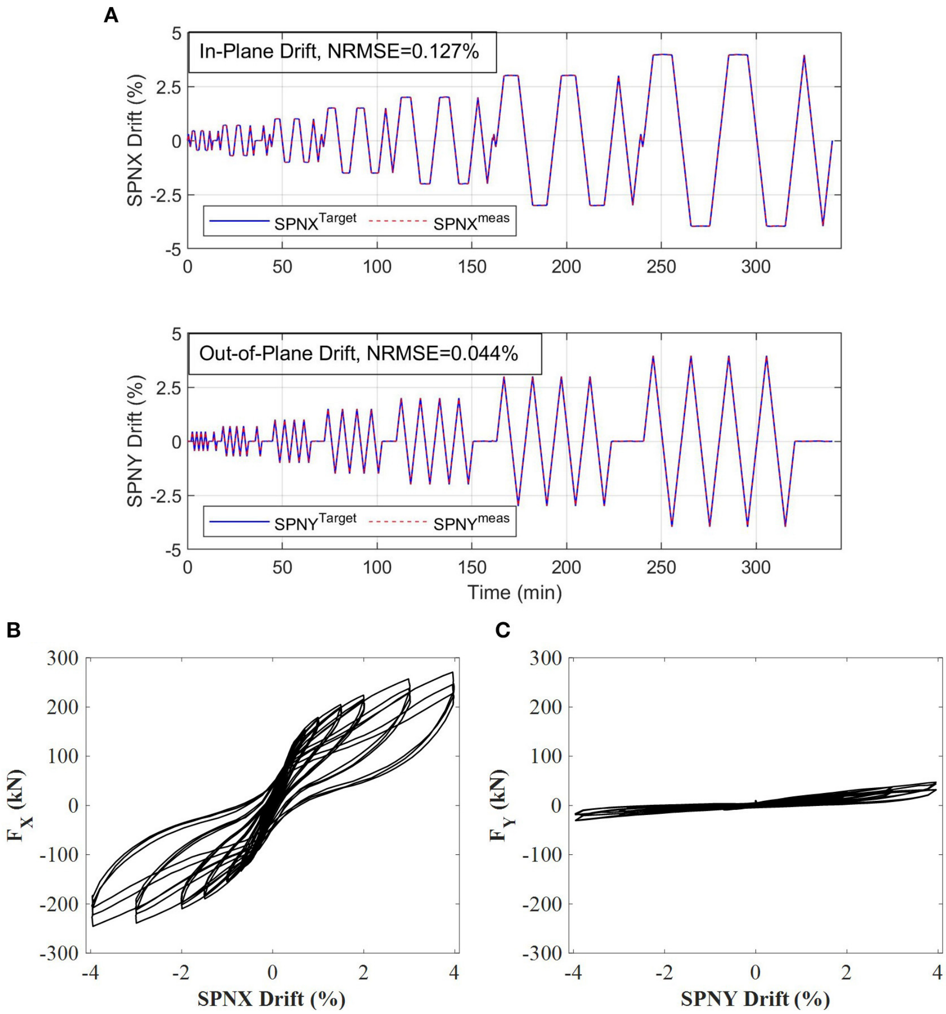


**FIGURE 14 |** Multi-directional test of cross-laminated timber self-centering coupled walls-floor diaphragm gravity system: **(A)** comparison of target drift and measured subassembly drift, **(B)** in-plan lateral load-story drift response, and **(C)** out-of-plane lateral load-story drift response (courtesy of Amer, 2021).

of drifts for the in-plane (SPNX) and out-of-plane directions (SPNY) were calculated and were equal to 0.127 and 0.044%, indicating that a high degree of accuracy was achieved for specimen displacement.

The in-plane and out-of-plane lateral load-story drift response are shown in **Figures 14B,C**. $F_X$ and $F_Y$ represent the in-plane and out-of-plane applied lateral loads, respectively. The results show that energy dissipation occurs from the UFPs. In addition, the in-plane capacity is greater than the out-of-plane capacity due to the wall geometry, and the walls exhibit a self-centering behavior. Some deterioration is observed to occur under the cyclic loading, which is exacerbated by damage caused to the CLT outer plies by the out-of-plane imposed drift. This work is still in progress, with more testing planned by Amer (2021).

## 6. SUMMARY AND CONCLUSIONS

The infrastructure and capabilities of the Natural Hazards Engineering Research Infrastructure Lehigh Experimental Facility were presented. The facility is an open-access facility that enables researchers to conduct state-of-art research on natural hazard mitigation for civil infrastructure systems. The facility has the unique ability to conduct 3D large-scale multi-directional real-time hybrid simulations and testing involving large-scale physical structural and non-structural components. Several testing protocols are enabled at the facility, including (1) large-scale hybrid simulation, (2) large-scale real-time hybrid simulation, (3) large-scale RTHS with multiple experimental substructures, (4) geographically distributed hybrid simulation, (5) geographically distributed real-time hybrid earthquake simulation, (6) dynamic testing, and (7) quasi-static testing. The unique portfolio of experimental equipment, instrumentation, testbeds, and testing protocols that exist at the NHERI Lehigh EF was presented. Various testbeds including a lateral load-resisting system testbed, a non-structural component multi-directional dynamic loading simulator, full-scale and reduced-scale damper testbeds, a tsunami and storm surge debris impact force testbed, and a soil-foundation structure interaction testbed were described and are available for a wide range of research.

Several selected example research projects recently performed at the NHERI Lehigh EF were introduced to illustrate the facility's capabilities. These projects included (1) large-scale RTHS of a three-story steel frame building equipped with magneto-rheological (MR) dampers subject to strong earthquake ground motions, (2) large-scale RTHS of a reduced-strength steel frame building with non-linear viscous dampers subject to strong earthquake ground motions, (3) 3D multi-hazard large-scale RTHS of tall steel buildings subject to multi-directional wind and earthquake ground motions, (4) characterization testing of a novel friction device based on band brake technology, and (5) testing of a cross-laminated timber self-centering coupled walls-floor diaphragm-gravity system involving multi-directional loading. All test results and research data are shared through the NHERI DesignSafe (https://www.designsafe-ci.org/data/browser/public/).

More information about the NHERI Lehigh EF can be found at the facility's website at https://lehigh.designsafe-ci.org/facility/overview/. This information includes the facility overview, equipment portfolio, experimental protocols, projects, resources, facility outreach, and contact information.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.


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METHODS
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# Automation and New Capabilities in the University of Florida NHERI Boundary Layer Wind Tunnel

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The Natural Hazards Engineering Research Infrastructure (NHERI) experimental facility at the University of Florida provides a diverse suite of experimental resources to support wind hazard research. The 40-m long Boundary Layer Wind Tunnel (BLWT) simulates boundary layer flows to characterize wind loading on rigid structural models and assess the response of aeroelastic structures. The use of experimental automation tools provides researchers unparalleled flexibility in their test configurations while supporting high throughput testing and data collection. The Terraformer, an array of 1116 roughness elements, can be rapidly reconfigured to generate terrain conditions in less than 90 s, the test section turntable can move automatically through a range of wind approach angles, and the instrumentation gantry can traverse preset paths to collect wind field measurements anywhere in the tunnel cross-section. These test automation tools, along with mechatronic structural models and real-time data transfer and processing, provide new opportunities in experimental wind tunnel testing. Recent cyber-physical wind tunnel testing projects highlight the benefits of these experimental automation tools. This paper will also discuss the most recent addition to the BLWT, the Flow Field Modulator (FFM). It consists of a 2D array of 319 individually controlled ducted fans driven by electronic speed controllers. The FFM expands the BLWT capabilities by supporting the simulation of non-monotonic profiles and non-stationary events such as gust fronts and downbursts, where mean velocity and turbulence distributions change over short spatial scales. The ability to simulate these flow conditions in a wind tunnel enables the investigation of a wide range of damaging conditions and the solutions for mitigating their impact on structures.

**Keywords: NHERI, boundary layer wind tunnel, experimental wind engineering, structural optimization, automation**



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## INTRODUCTION

The Natural Hazards Engineering Research Infrastructure, funded by the National Science Foundation (NSF), provides a geographically distributed network of shared use experimental resources for conducting natural hazards research. NSF's investment in the experimental facilities (EFs) that house these resources enables their use by researchers that may not otherwise have access to such facilities, thereby broadening participation in natural hazards experimental research. The University of Florida (UF) NHERI EF offers experimental resources that support a range of wind hazard research activities. These resources provide unique testing capabilities and represent the state-of-the-art in experimental wind engineering. The UF EF is intended to facilitate research that provides a better understanding of how meteorological phenomena translate to loads on buildings and other infrastructure and how these loads may be best mitigated to improve the performance and enhance the safety of the built environment. The data generated by the NSF-supported researchers that use the UF EF are published and may be reused by the research community to further the NHERI mission and extend the outcomes of the research beyond the initial experiments. Beyond research outcomes, the UF EF is also dedicated to inspiring the next generation of wind hazard researchers through education and outreach activities that engage K-12 students and their educators, undergraduate and graduate students, and underrepresented members of the natural hazard research community.

This paper provides an overview of the experimental resources and services offered by the UF EF; however, the focus is on the enhanced experimental capabilities of the BLWT that are enabled by advances in automation and control. Two research projects are described that highlight the BLWT capabilities.

## UF EXPERIMENTAL FACILITY OVERVIEW

The UF EF broadly supports researchers in the natural hazards community. Users have access to a diverse suite of wind engineering experimental research infrastructure; enhanced testing capabilities afforded by integrated high-performance computing; skilled and resourceful personnel that promote organization, productivity, and a culture of safety and collegiality; and effective and easy-to-use technologies to collaborate, document and share findings.

The UF EF is housed in the Powell Family Structures and Material Laboratory at the University of Florida. The EF offers five experimental resources for wind engineering research. Investigators can characterize loading on and dynamic response of a wide range of infrastructure in a large, reconfigurable boundary layer wind tunnel (BLWT) and conduct full-scale tests on large building systems with equipment capable of ultimate/collapse loads associated with a Saffir-Simpson Hurricane Wind Scale Category 5 hurricane or an Enhanced Fujita Scale 5 tornado.

### Experimental Resources

The Self-Configuring Hybrid Boundary Layer Wind Tunnel (BLWT) offers a unique automated terrain roughness element system (Terraformer) which can reconfigure within minutes to achieve desired approach flow conditions over a large range of geometric scales. Furthermore, the Flow Field Modulator adds non-stationary capabilities to the BLWT. Detailed descriptions of the BLWT, the Terraformer, and the Flow Field Modulator, are provided in section "Boundary Layer Wind Tunnel."

The remaining four experimental resources offered by the UF EF are the Multi-Axis Wind Load Simulator (MAWLS), the Dynamic Flow Simulator (DFS), the High Airflow Pressure Loading Actuator (HAPLA), and Spatiotemporal Pressure Loading Actuator (SPLA). The MAWLS is a pressure loading actuator that accommodates full size wall and cladding specimens for destructive testing. It applies time-varying out-of-plane pressure to simulate loads associated with buffeting or separated flow, while simultaneously applying static in-plane uplift or shear. The DFS is a high-speed wind tunnel that recreates building surface flows. The HAPLA accommodates moderately sized specimens that can be quickly interchanged and can impart dynamic wind pressure and simulate impinging rain conditions. The SPLA can rotate into a horizontal or vertical position and has the ability to simulate spatially varying pressure conditions by applying synchronized pressure loading to four reconfigurable chambers that span the specimen. All EF apparatus are interconnected in the lab through a high-speed network; thus, making it possible to characterize wind loading or velocity in the BLWT and instantly converting and applying those measurements as full-scale inputs to MAWLS, DFS, HAPLA, or SPLA.

### Science Plan

Current policymaking and research trends signal that design, construction, and operation of civil infrastructure and lifelines will rapidly advance through the next few decades. Reliability-based design approaches that underpin current codes, regulations and engineering standards will mature into a resilience-based decision framework that establishes new performance goals for community functioning pre- and post-disaster. Hazard-centric design approaches will further homogenize (e.g., ASCE 7–10 shifting wind loading provisioning into alignment with its seismic counterpart) and collectively evolve into multihazard engineering guidelines that optimize the lifecycle cost of infrastructure. Concurrent adoption of sustainable design practices will influence this process, leading to long-term performance expectations for infrastructure as it physically ages and undergoes changes caused by operation and exposure to weather. Design tools will rapidly advance, shifting toward automation with an increasing reliance on machine learning and other AI-based agents to reduce cost, construction time, and environmental impact. Robotics, prefabrication, and additive manufacturing will become more widespread. Humans and machines will work with lighter, stronger, and greener materials, while application of conventional materials continue to be honed to overcome the technical limitations of today. The future of civil infrastructure presents multiple grand challenges and informs the science plan that guides the resources and services offered by the UF EF.

The UF EF science plan identified seven broad objectives, each of which embodies a grand challenge: (1) Reduce uncertainties in the wind loading chain, especially those related to predicting peak loads and structural response, (2) Advance computational wind engineering and reduce reliance on physical testing, (3) Develop methodologies that reliably predict performance as a function of building age and use, (4) Advance the state of knowledge regarding collapse limit state fragilities, (5) Advance automation and design of hazard resistant infrastructure, (6) Introduce high-performance and greener material, and (7) Find innovative and cost-effective solutions to retrofit existing infrastructure.

## User Services

The UF EF offers users a range of services to support the development, execution, and dissemination of their research. The EF PIs and staff are available to discuss experimental ideas, address the feasibility and refinement of experimental plans, identify appropriate co-PIs and assist in the preparation of proposals and budgets for submission to NSF. Once projects are funded, the EF PIs and staff work with users to refine and schedule their test plans, assess instrumentation needs, design a data collection and transfer plan, provide project oversight, ensure safety compliance, and implement risk management. The UF EF has staff dedicated to the various aspects of experimental planning and execution with expertise in: wind engineering testing and analysis, instrumentation and controls, civil/mechanical design and fabrication, and cyberinfrastructure and information technology. Multiple 3D printers, a 3-axis CNC router and a fully staffed machine shop are available at the EF to assist in the design and fabrication of models and customized test rigs. The facility manages the construction, staging, transport, and disposition of test specimens.

# BOUNDARY LAYER WIND TUNNEL

## Background and Overview

BLWTs have served as important experimental tools in wind engineering research since the early 1960s (Cermak, 2003) and currently provide insight into the complex fluid motions observed around bluff bodies immersed in turbulent boundary layers – phenomena that are, in many cases, poorly captured by theoretical and computational fluid dynamics. Conventional BLWTs simulate natural winds in the first few hundred meters of the earth's atmospheric boundary layer (ABL) at reduced geometric scales on the order of 1:50–1:400. To achieve similarity with full-scale ABL flows, air is forced through a large duct with a floor-mounted roughness element array to generate mechanical turbulence similar to the kind produced by buildings, trees, and other elements in the earth's landscape (Cermak, 1982; Cook, 1982). This process naturally grows a boundary layer along the length of the tunnel's development section to produce the desired mean velocity, turbulence intensity, power spectral density, and integral length scales at a downwind test section. The geometric dimensions, density and configuration of roughness elements in the development section are traditionally manually arranged to produce target approach flow conditions. Trips, spires, turbulence grids, and strakes are installed upwind of the roughness elements to artificially introduce large-scale motions and to promote mixing when required. A geometrically scaled model of the test subject installed on a turntable in the downwind test section is instrumented to record pressure, acceleration, displacement or base reaction data.

The UF EF BLWT infrastructure incorporates many features of traditional facilities and several key innovations. It is a long-fetch low-speed open circuit tunnel with dimensions of 6 m W × 3 m H × 38 m L (see **Figure 1**). Eight Aerovent 54D5 VJ vaneaxial fans driven by 75 hp (56 kW) AC induction motors – configured in a 2 × 4 array – generate axial flow, which is pre-conditioned by a nested honeycomb system to reduce fan-generated turbulence and ensure horizontal homogeneity of the velocity profile before entering the development section. A set of removable Irwin spires (Irwin, 1981) – i.e., vortex generators – are situated at the beginning of the development section to induce large scale mixing. The wind tunnel ceiling pitch is adjustable to produce approximately zero static pressure gradient flows ($\partial p/\partial x \cong 0$) along the length of the development and test sections – measured by an array of wall-mounted static tube and differential pressure transducer assemblies. Test section air temperature, humidity, and barometric pressure are monitored using a ceiling-mounted Omega iBTHX sensor centrally located above a mechanized turntable that can be rotated through 360 degrees to achieve user-specified wind directions. On this location, scale models are installed, instrumented, and tested. All tunnel systems are integrated into a command and control center with data collection and tunnel control computers.

Turbulent flow fields in the tunnel are measured using an automated multi-degree-of-freedom instrument gantry capable of traversing longitudinally, laterally, and vertically nearly the entire length, height, and width of the test section. The system is equipped with several fast-response four-hole Turbulent Flow Instrumentation (TFI) Series 100 Cobra Velocity Probes to capture discrete point measurements of $u$, $v$, and $w$ fluctuating velocity components and static pressure within a ±45° acceptance cone (Tfi Catalogue, 2015). The gantry is also fitted with a Dantec Dynamics stereoscopic particle image velocimetry (PIV) system – a high-energy laser and high-speed camera assembly – that is actuated on linear guides for positioning over user-defined near-surface measurement locations. The gantry system is designed to minimize test section blockage at 4.63%. A bank of 10 fluid atomizers (i.e., seeders) is installed upwind of the test section to entrain 1–2 micron oil particles in the flow. Double frame images from two high-speed cameras – one on each side of an emitted laser light sheet – capture particle motion to produce time-resolved 3-D flow field measurements. Rigid body surface pressure monitoring is achieved through a 512 channel Scanivalve pressure scanning system. Rigid body base shears and overturning moment are measured using one of two ATI Industrial Automation six-axis load cells.

Data collected at the UF EF are stored at the High Performance Computing Center (HiPerGator supercomputer), which serves as the primary working storage for projects. Data are automatically transmitted to the DesignSafe CyberInfrastructure in the NHERI network. All hardware is connected through a 1 Gb/s dedicated high-volume data transfer network exclusively operated to support experimental and computational research. Data are curated using DesignSafe's curation features including built-in support for the extraction and tagging of technical metadata from data files, aiding in the creation of well-documented datasets.

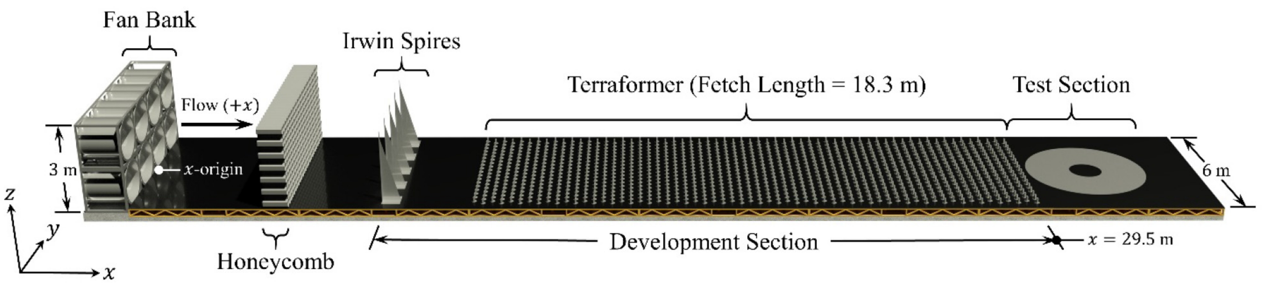


**FIGURE 1 |** Diagram of the BLWT at the UF EF.

## Terraformer

Unique to the UF EF, the Terraformer (**Figures 1**, **2**) automates the roughness grid arrangement process by replacing hand-built terrains with a computer controlled terrain generator that can quickly change its configuration. The fully integrated system is an array of 1116 electronically actuated roughness element assemblies that independently rotate and translate to precisely control height and aspect ratio as shown in **Figure 2C**. Hardware for the assemblies include the Nanotec Linear Actuator LS4118S1404-T6 × 1–230, Motor Controller SMCI12, rectangular aluminum element, rotating disk, baseplate, supporting rods, slide, nylon sleeves, and endcaps. This system can configure the frontal projected area of each element over a continuous range between a minimum of 0 $mm^2$ to a maximum of 16,256 $mm^2$ in under 2 min. The individual elements have nominal lateral dimensions of 102 mm × 51 mm and a maximum actuated height of 160 mm yielding a range of drag coefficients from ∼0.97 to 1.21. The Terraformer is intended to represent approach terrain in the general sense of achieving desired flow parameters (e.g., profile, roughness coefficient, scale). The representation of particular landscape features such as individual buildings or trees surround the test subject can be achieved using the on-site fabrication facilities described in section "User Services."

Uniform actuation of the system (**Figure 2A**) – for the production of traditional homogeneous obstacle arrays – was calibrated using a predictive model that relates the morphometric properties of the roughness element grid to the aerodynamic roughness parameters (Catarelli et al., 2020). This provides a deterministic solution enabling the tunnel to accurately produce user-specified upwind target exposures for a range of model scales with minimal configuration time. The independently actuating roughness elements are also capable of configuring discrete random fields to simulate heterogeneous upwind terrain conditions as shown in **Figure 2B**. Control software was developed to model terrain based on stochastic simulation techniques from prescribed Fourier-based models and probabilistic targets.

Validation studies of the wind field and pressure monitoring system have recently been published. These include floor to freestream mean and turbulence profiles for 33 homogeneous terrain configurations (Fernández-Cabán and Masters, 2018a; Catarelli et al., 2020), ESDU target and measured longitudinal velocity spectra (Fernández-Cabán and Masters, 2018a, 2020; Fernández-Cabán et al., 2018), comparisons of measured bluff body pressure coefficients with NIST database benchmarks (Ho et al., 2003; Fernández-Cabán et al., 2018; Fernández-Cabán and Masters, 2020), and the sensitivity of pressure coefficients on a NIST benchmark building to fine changes in approach terrain (Fernández-Cabán and Masters, 2018a).

## Flow Field Modulator

Modern wind tunnels have a limited ability to precisely and rapidly recreate complex wind fields associated with extreme weather, e.g., gust fronts and downbursts that exhibit non-monotonic mean velocity profiles and non-stationary amplitude and frequency components (Kwon and Kareem, 2009). These departures from traditional stationary straight-line wind models may alter the spatial distribution of instantaneous loads over the surface of a structure and thus impact structural vulnerability and habitability (Kijewski-Correa and Bentz, 2011; Nguyen and Manuel, 2013). Physical simulation techniques have been developed in proof-of-concept studies for turbulent flow control (e.g., Cao et al., 2002; Smith et al., 2012), which differ from standard BLWT simulations in that multi-fan arrays are used to generate user-specified mean velocity and turbulence characteristics downwind of a mixing region.

Building upon this prior work, the multi-fan Flow Field Modulator (**Figure 3**) was developed as a high resolution flow control device and integrated into the upwind portion of the tunnel to simulate complex extreme wind phenomena including non-monotonic mean velocity profiles, non-stationary flow properties, and transient flows. It is designed to operate in series with the existing vaneaxial fan bank (i.e., primary fan system) and consists of a computer controlled 2D array of 319 modular hexagonal aluminum cells containing shrouded three-blade corotating propeller pairs with high-performance 800 Watt brushless DC motors driven by electronic speed controllers (**Figure 3**). This hardware configuration permits a maximum frequency response of approximately 3 Hz, a maximum free discharge velocity of 23 m/s with the primary fan system running at full power, and a peak instantaneous flow acceleration of 100 $m/s^2$. Individual cell assemblies incorporate pitot-static tube velocity monitoring and open-loop control. Closed-loop control of the individual cells is under development. The FFM 319 fan bank is located immediately upwind of the dimensionally

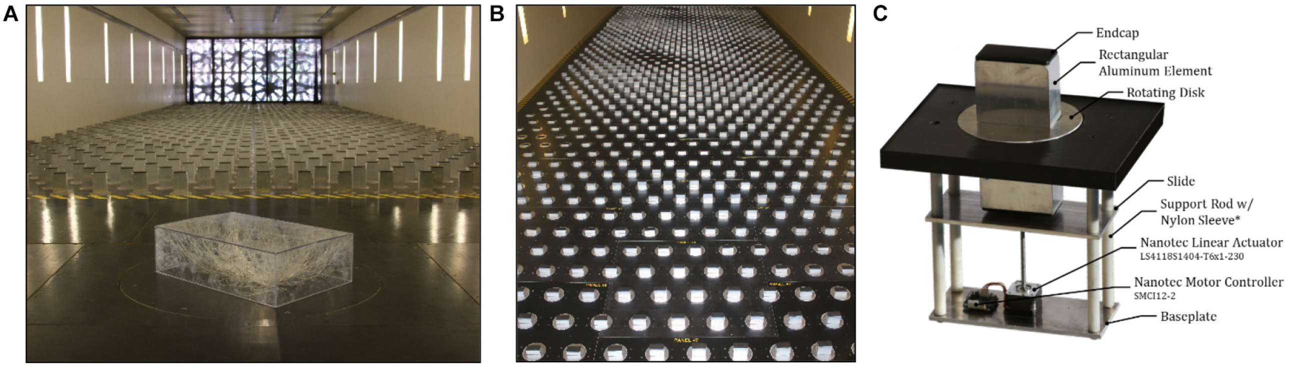


**FIGURE 2 |** The Terraformer: **(A)** test subject installed in the foreground and roughness element field with elements uniformly actuated in the background; **(B)** heterogeneous terrain; and **(C)** annotated individual element assembly.

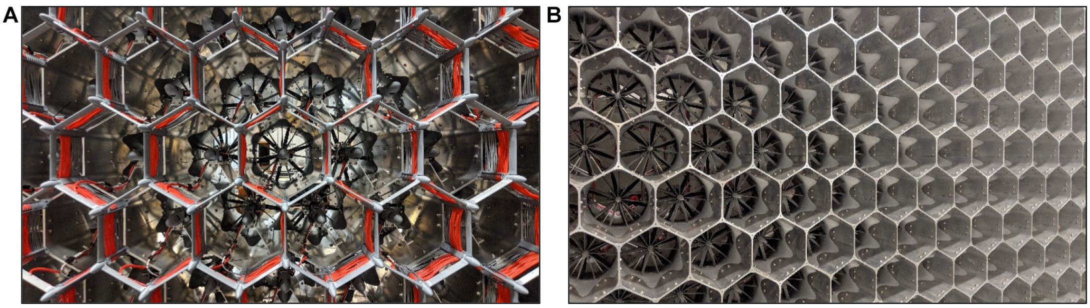


**FIGURE 3 |** The Flow Field Modulator. Array of 319 modular hexagonal aluminum cells: **(A)** upwind face; **(B)** downwind face.

identical 319 cell honeycomb shown in **Figure 1**. The FFM is mounted on a track system, allowing easy installation in or removal from the BLWT as needed.

Variations in mean fan speeds of cell rows impart vertically stratified steady flows – mean velocity profiles – along the height of the tunnel, accounting for free shear layer interactions, as well as frictional and orifice losses. Individual instantaneous fan speeds are capable of fluctuating according to stochastic simulations (e.g., reproduced velocity time histories) based on target vertical, across, and along-wind integral length scales to achieve desired turbulence properties at the end of a mixing region downwind. Additional lateral and vertical turbulence can be introduced by shifting the phases of adjacent cells, decorrelating the gust structure.

The current status of validation and performance of the FFM for simulation of non-monotonic profiles (Vicroy, 1992) and non-stationary gusts (Balderrama et al., 2011) can be found in Catarelli (2019).

## Limitations

The previous sections describe unique capabilities that facilitate high throughput and expand the breadth of wind phenomena that can be simulated. We now round out the facility description with a discussion of current known limitations of the UF EF.

The strength of this wind tunnel facility is the precise control and measurement of the flow field. For this reason, the BLWT is not a destructive testing apparatus (e.g., Chowdhury et al., 2017). The windspeed is nominally limited to 20 m/s freestream. Typical tests include rigid pressure-tapped models, rigid high-frequency base balance models, and aeroelastic models. Other equipment at UF, including the multi-axis wind load simulator, dynamic flow simulator, high airflow pressure loading actuator, and spatiotemporal pressure loading actuator, provide destructive testing capabilities. The flow limits on the FFM include a maximum frequency response is approximately 3 Hz, maximum instantaneous velocity is 23 m/s, and maximum instantaneous flow acceleration is 100 m/s$^2$.

The Terraformer is limited to the representation of homogeneous or heterogeneous upwind terrain in a general sense. If needed, detailed proximity models can be added to capture the impact of discrete near-field terrain features. Based on the range of possible roughness element frontal areas, the Terraformer can create upwind terrain conditions for model scales ranging from approximately 1:20 (e.g., a low-rise building) to 1:3100 (e.g., a topographic model). At the larger model scales, additional flow conditioning devices (or the FFM) may be required to create the appropriate low-frequency turbulence.

The PIV provides time-correlated 3D flow measurements within the viewing window, however it comes with some limitations. The PIV viewing window is limited to 150 mm in the x-axis and 215 mm in the z-axis, so multiple sample windows may be required to cover larger areas. Measurements will not be time correlated across windows. The window can be positioned at any x-position in the test section and at any y-position within ±50 mm of the center of the test section (coordinate system shown in **Figure 1**). The BLWT is open circuit, requiring a baffle at the exit for safety when running the PIV laser. This baffle increases the static pressure in the tunnel and has a small impact on other flow characteristics, all of which can be characterized. Additionally, special model preparations may be needed to avoid damage under the high-power laser.

## EXAMPLE RESEARCH PROJECTS

Two recent projects are highlighted to demonstrate the automated, high throughput capabilities of the UF EF BLWT.

### Cyber-Physical Design and Optimization in the Wind Tunnel

Cyber-physical systems link the real world to the cyber-world by leveraging the ability of computers to monitor and control physical systems. Components include sensors, actuators, data communication, computers for executing numerical models or algorithms, and a physical phenomenon of interest. In wind engineering, advances in cyber-physical systems coupled with UF EF's push for automated and high-throughput testing offer the unprecedented opportunity to integrate BLWT modeling into the engineering design process.

Researchers at the University of Maryland (UMD) and UF pioneered the first cyber-physical systems approach to the optimal design of structures subjected to wind hazards. This approach combines the accuracy of physical wind tunnel testing with the efficient exploration of the design space using numerical optimization algorithms. The approach is fully automated, with experiments executed in the BLWT, sensor feedback monitored by a computer, and actuators used to bring about changes to a mechatronic building model as dictated by the optimization algorithm. The model undergoes physical changes in dynamics or aerodynamics as it approaches the optimal solution, accurately capturing the impacts of these changes on its response. As part of the project, cyber-infrastructure was developed to seamlessly connect the BLWT operations (e.g., turntable angle, metadata collection), instrumentation (triggering and data transfer), specimen actuation, data post-processing, finite element modeling, and optimization algorithms. The interconnectivity was critical to creating an automated high-throughput system that, once set up, would drive the specimen to the optimal design given user-specified objectives and constraints.

Proof-of-concept was demonstrated for a low-rise building model with a parapet wall of variable height (Whiteman et al., 2018a,b). Parapet walls alter the location of the roof corner vortices, reducing suction loads on the windward facing roof corners and edges and setting up an interesting optimal design problem. In the BLWT, the parapet height was actuated using servo-motors (see **Figure 4**). Exploration of the design space was conducted using multi-objective heuristic optimization algorithms to achieve a design that minimized loads on both components and cladding and the main wind force resisting system. The optimal design repeatedly and quickly converged, and the influence of the objectives and constraints were clearly seen in the results.

Further studies focused on tall building design, for which a 1.5 m 1:200 scale multi-degree-of-freedom aeroelastic model was created (Fernández-Cabán et al., 2020; see **Figure 5**). Aeroelastic models directly simulate the scaled dynamic behavior of the building including effects of aerodynamic damping, vortex shedding, coupling within modes, and higher modes. The model's responses were monitored using accelerometers and displacement transducers. The model was equipped with a series of variable stiffness devices (adjustable leaf springs) in the base connected to internal steel tendons to enable quick and automated adjustments to the model's dynamics. Additionally, the model had a set of mechanized corner fins to tune the aerodynamic shape. The fins were designed to reduce vortex-induced vibration and can be adjusted based on windspeed and direction to keep occupants safe and comfortable. Multiple design problems were explored where the model's dynamics and aerodynamics were refined using heuristic optimization algorithms to minimize costs while satisfying acceleration and drift limits.

This project advances the capacity to build stronger, lighter, and more resilient structures in the face of wind hazards. The traditional design process requires a lengthy collaboration between designers and wind tunnel operators. This process may include the construction of a very limited set of building models, leading to a non-exhaustive exploration of potential designs. The use of scaled building models with physically adjustable properties (e.g., geometry, stiffness, damping, etc.) allows optimum designs to be attained faster than conventional methods and eliminates the need to reconstruct new models and perform additional wind tunnel tests. Mechatronic specimens connected to cyber-infrastructure greatly enhances the capacity of BLWT facilities. In wind engineering, cyber-physical design enables engineers to more exhaustively explore a range of candidate designs and replace trial-and-error approaches with automation.

### Characterization and Prediction of Upstream Terrain Effects on Wind Pressure Loading

Previous research in wind tunnels (e.g., Gartshore, 1973; Hillier and Cherry, 1981; Saathoff and Melbourne, 1997) have revealed a strong linkage between the surface pressure field acting on sharp-edged bluff bodies (e.g., low-rise buildings) and the turbulent characteristics of freestream approach flows. In particular, the intensity and distribution of wind-induced loads developed in regions experiencing extreme suction pressures, such as roof edges/corners of buildings, are highly sensitive to mechanical turbulence largely driven by the morphometric features of the upstream terrain. The Terraformer provides unique capabilities to rapidly and accurately control upstream turbulent flow conditions in the BLWT, enabling prompt quantification of pressure loading

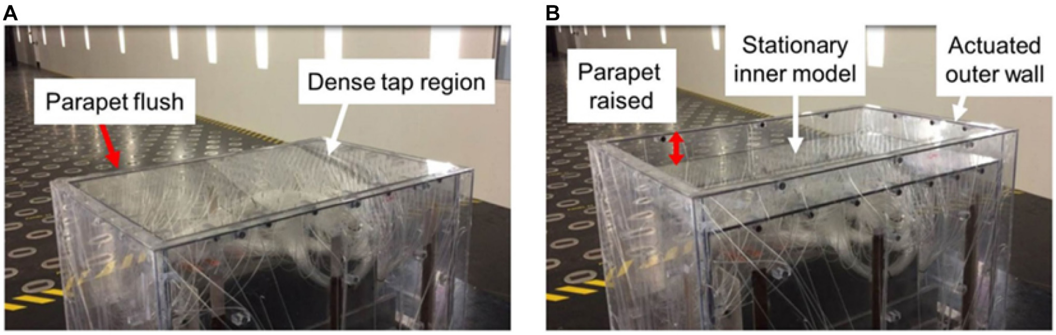


**FIGURE 4 | (A)** Building model with a flush parapet wall and **(B)** a raised parapet wall (from Whiteman et al., 2018a under the Creative Commons CC BY license).

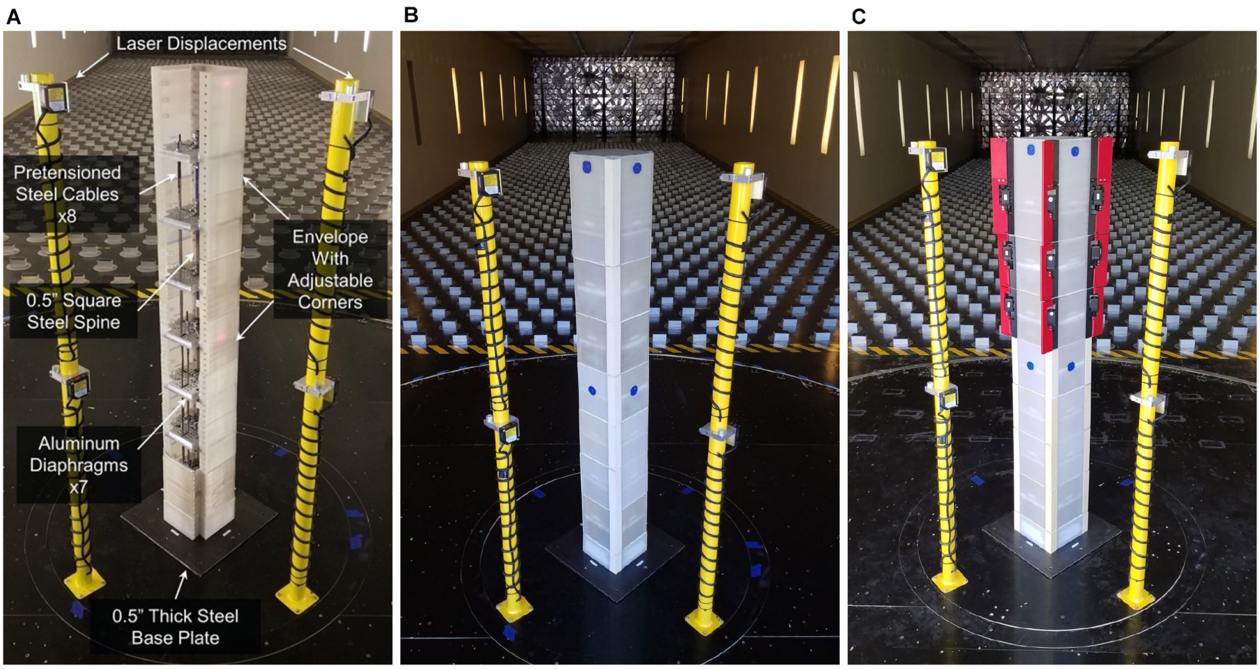


**FIGURE 5 |** 1.5 m tall multi-degree-of-freedom aeroelastic model: **(A)** inner mechanics exposed, **(B)** enclosed model without fins, and **(C)** enclosed model with fins.

on civil infrastructure for a wide range of upwind terrain conditions (e.g., a continuum between marine to dense suburban exposures).

A holistic assessment of upstream terrain effects was performed at the UF NHERI EF through a series of aerodynamic BLWT experiments on three scaled (1:20, 1:30, and 1:50) low-rise building models. Geometric building properties (i.e., plan dimensions, roof eave height, and roof slope) for the three models were based on full-scale dimensions of the Wind Engineering Research Field Laboratory (WERFL) experimental building, which is located at Texas Tech University (Levitan and Mehta, 1992). The three WERFL models were tested under 33 unique turbulent boundary layer flows through fine adjustment of the Terraformer roughness element grid. The initial series of baseline aerodynamic tests only employ homogeneous (i.e., uniform) roughness element arrays. That is, in each test, all 1116 roughness elements were set to the same height and orientation. Homogeneous terrains consisted of the bare floor (i.e., "flush," $h$ = 0 mm) case, 16 element heights ($h$ = 10–160 mm using 10 mm increments) and two element orientations namely wide and narrow edge windward. For each upwind terrain configuration, surface pressures were recorded by 266 pressure taps located on the roof and walls of the low-rise models. **Figure 6** includes pressure coefficient contours of standard deviation for the 1:20 WERFL model for three representative roughness element heights ($h$ = 10, 80, and 160 mm).

Clear distinctions are observed in both the magnitude and distribution of the wind pressure field for the three cases shown in **Figure 6**, particularly near the leading windward edge of the roof. Similar pressure distributions were obtained for the

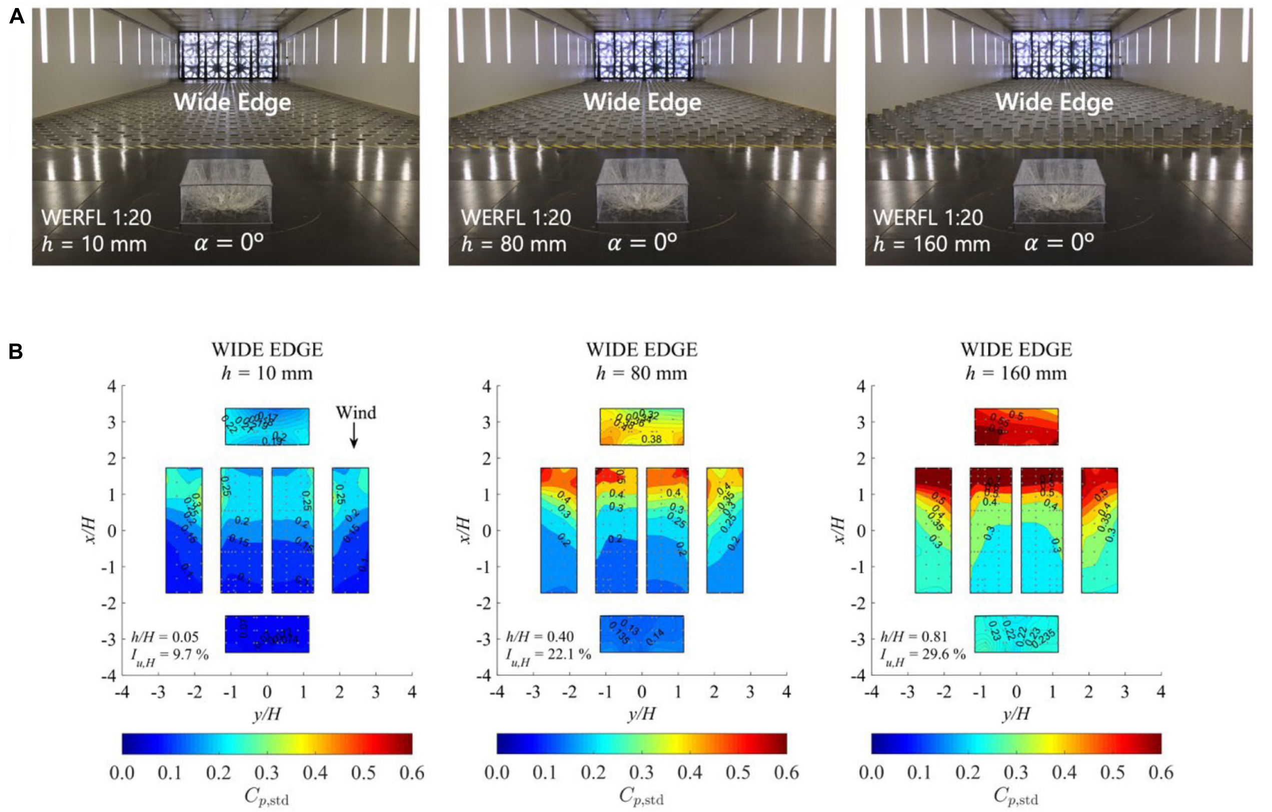


**FIGURE 6 | (A)** Aerodynamic BLWT tests on the 1:20 WERFL model for three homogeneous Terraformer configurations ($h$ = 10, 80, and 160 mm); **(B)** pressure coefficient contours of standard deviation (from Fernández-Cabán and Masters, 2018a under the Creative Commons CC BY license).

1:50 and 1:30 WERFL models. However, scale dependencies were detected when comparing the magnitude of the pressures under similar freestream turbulence flow conditions, which may be attributed to Reynolds number discrepancies in the BLWT (Lim et al., 2007). Therefore, the data are well suited for further examination of scaling effects in the BLWT when testing low building models (Stathopoulos and Surry, 1983). The complete aerodynamic BLWT dataset is publicly accessible in the DesignSafe-CI repository (Fernández-Cabán and Masters, 2018b, 2020). The data can be re-used to validate computational fluid dynamic models (e.g., LES) and train machine learning algorithms such as artificial neural networks (ANN; see **Figure 7**) to develop analytical tools for predicting wind-induced loads on low-rise structures (Fernández-Cabán et al., 2018; Tian et al., 2020).

Both the holistic quantification of the influence of upwind terrain and the development of the ANN model required a large dataset enabled by high-throughput testing. The three BLWT models were each evaluated under 33 unique turbulent boundary layer flows at three angles of attack for a total of almost 300 experiments. Automation in the Terraformer, turntable, and data transfer made it possible to complete all tests within four working days. It is estimated that without the Terraformer, it would take an order of magnitude longer to complete the same test matrix.

## SUMMARY AND CONCLUSION

As part of the NSF NHERI network, the UF EF offers five shared use resources that support a range of wind hazard research activities. The research supported by the UF EF provides a better understanding of how meteorological phenomena translate to loads on buildings and other infrastructure and how these loads may be best mitigated to improve the performance and enhance the safety of the built environment. The focus of this paper is on the enhanced experimental capabilities of the Self-Configuring Hybrid BLWT, which simulates boundary layer flows to characterize wind loading on rigid structural models and assess the response of aeroelastic structures. The development of unique automation tools provides researchers unparalleled flexibility in their test configurations while supporting high throughput testing and data collection. Terrain roughness can be rapidly reconfigured to alter approach flow turbulence, and the instrumentation gantry can traverse preset paths to collect wind field measurements anywhere in the tunnel cross-section. The Flow Field Modulator adds non-stationary and non-monotonic boundary layer capabilities to the BLWT. These test automation tools, along with mechatronic structural models and real-time data transfer and processing, provide new opportunities in experimental wind tunnel testing.

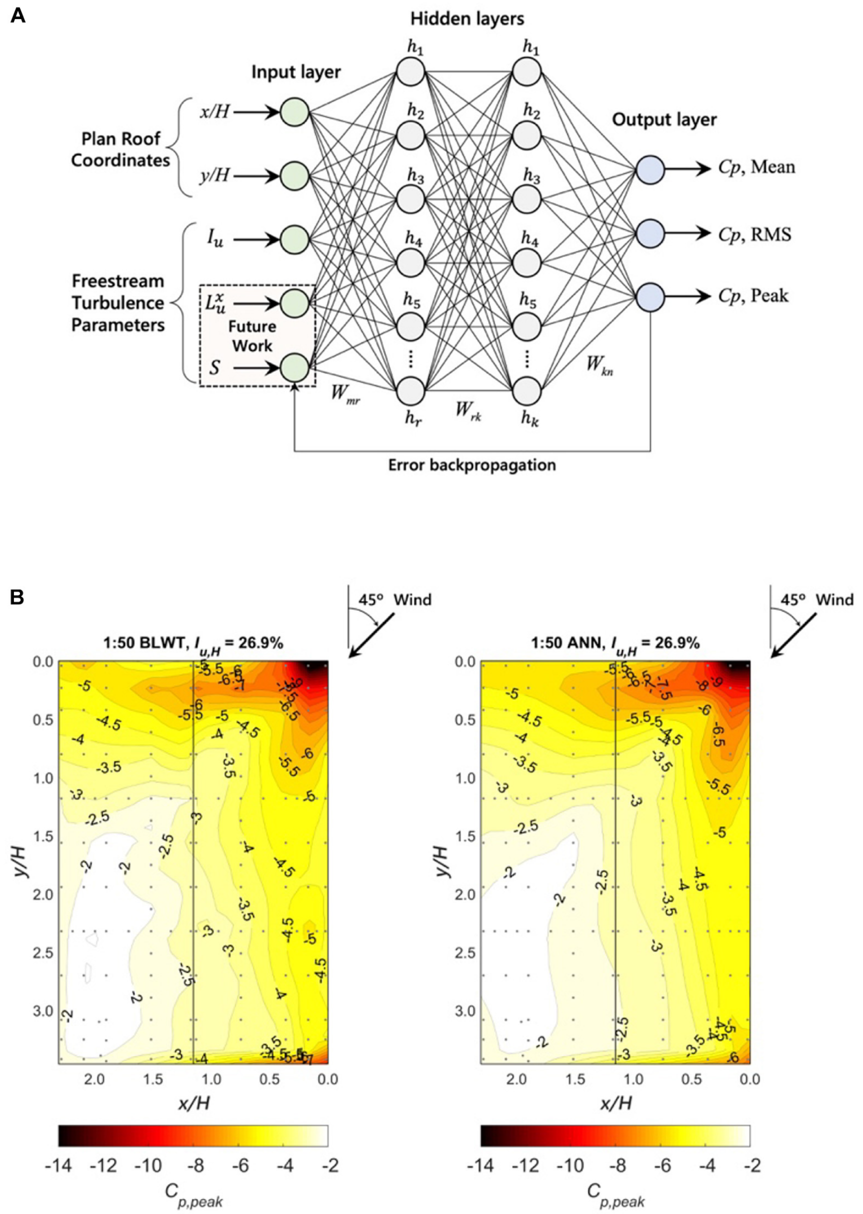


**FIGURE 7 | (A)** Architecture of an artificial neural network (ANN) for wind pressure prediction accounting for turbulence parameters. **(B)** Peak pressure contours of the 1:50 WERFL model: BLWT experimental data (left) and ANN model prediction (right) (from Fernández-Cabán et al., 2018 under the Creative Commons CC BY license).

Two recent projects are highlighted to demonstrate the automated, high throughput capabilities of the UF EF BLWT. In wind engineering, advances in cyber-physical systems coupled with UF EF's push for automated and high-throughput testing offer the unprecedented opportunity to integrate BLWT modeling into the engineering design process. Cyber-infrastructure was developed to seamlessly connect the BLWT operations (e.g., turntable angle, metadata collection), instrumentation (triggering and data transfer), specimen actuation, data post-processing, finite element modeling, and optimization algorithms. The interconnectivity was critical to creating an automated high-throughput system that would drive the specimen to the optimal design given user specified objectives and constraints. The rapidly reconfigurable and automated Terraformer facilitated a study of pressure sensitivity to approach flow with unprecedented resolution, illuminating the limitations of the current standard of coarsely discretized terrain characterization.

More information about the NHERI UF EF can be found at https://ufl.designsafe-ci.org/ and through contact with the corresponding author.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: doi: 10.17603/DS2W670.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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REVIEW
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# Building Resilient Coastal Communities: The NHERI Experimental Facility for Surge, Wave, and Tsunami Hazards

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Through the Natural Hazards Engineering Research Infrastructure program (NHERI) established by the National Science Foundation in the United States, a suite of experimental facilities has been made available to the research community to advance the resilience of civil infrastructure and communities to coastal storm and earthquake hazards. A NHERI Experimental Facility, hosted at the O.H. Hinsdale Wave Research Laboratory at Oregon State University (HWRL EF), was created through this program that serves as a state-of-the-art engineering research, education, and outreach center related to tsunamis caused by earthquakes and coastal waves and surge caused by windstorms. HWRL EF includes two specialized large-scale resources for physical model testing of coastal systems: a large wave flume (LWF) and a directional wave basin (DWB). These facilities are available to the research community to address grand challenges relating to tsunami and coastal windstorm surge and wave hazards impacting the built and natural environments. This paper describes the capabilities of the HWRL EF and presents 10 example projects conducted under NHERI since 2016. The research projects highlight the broad scientific interest and potential application of physical model testing in multi-hazard mitigation and resilience in coastal communities.

**Keywords: coastal structures, waves, surge, tsunami, experimentation (laboratory tests), resilience, natural hazards and disasters**



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## INTRODUCTION

The Natural Hazards Engineering Research Infrastructure (NHERI) program is supported by the US National Science Foundation (NSF) since 2016 to enable a distributed, multi-user, national facility that will provide the natural hazards engineering community with access to research infrastructure coupled with education and community outreach activities. NHERI enables research and educational advances that can contribute knowledge and innovation for the nation's civil infrastructure and communities to prevent natural hazard events from becoming societal disasters. NHERI consists of 12 components: the Network Coordination Office (NCO), cyberinfrastructure for collaboration and data archival (DesignSafe-CI), seven Experimental Facilities (EFs) for seismic and windstorm disasters, a disaster reconnaissance equipment facility (RAPID), a CONVERGE facility to coordinate reconnaissance research, and a computer modeling facility (SimCenter).

The purpose of this paper is to describe the NHERI Experimental Facility hosted at the O.H. Hinsdale Wave Research Laboratory at Oregon State University (HWRL EF for brevity). The HWRL EF supports the broader vision of NHERI to increase the resilience of civil infrastructure and communities to coastal windstorms and tsunamis (NHERI Science Plan, 2020) along the lines of these three grand challenges:

1. Identify and quantify the characteristics of tsunamis, storm surge, and waves hazards due to earthquakes and windstorm that are damaging to civil infrastructure and disruptive to communities.
2. Assess the physical vulnerability of civil infrastructure and the social vulnerability of populations in communities exposed to earthquakes, windstorms, and associated hazards.
3. Create the technologies and engineering tools to design, construct, retrofit, and operate a multi-hazard resilient and sustainable infrastructure for the nation.

The science drivers for HWRL EF can be found in the NHERI Science Plan (2020), and more detailed information is contained in a number of guidance documents for research related to hurricanes and tsunamis (NSTC, 2006; NSB, 2007; NIST, 2014; NRC, 2011, 2012, 2014).

The research gaps for surge, wave and tsunamis in the NHERI Science Plan was initially drafted by the first and second authors of this paper. Therefore, much of the text in this section is included verbatim from the NHERI Science Plan:

**Surge, Wave, and Tsunami Inundation Hazards:** A grand challenge for overland flow is to model the hazard intensity over scales ranging from entire regions (several hundred kilometers) to subassemblies of structures (several meters). The current state of the practice assumes "bare earth" models, meaning that the effect of the built environment is not modeled in detail even though it is known that the built environment has significant influence on the local flow field. Other key research questions include how to account for the time-varying conditions—for example, the changing bathymetry and topography due to coastal erosion and roughness due to damage/failure of buildings and other infrastructure. Additional challenges related to overland hazard include the quantification of flood-borne debris hazards that are related to debris impact, debris damming, and debris removal challenges. The inundation and subsequent return flow also generate significant currents and other navigational hazards. It is generally accepted that velocity is more difficult to quantify than the water level, so the generation of current hazards remains an open area of research. The generation of tsunamis from landslides is also an open area of research (NHERI Science Plan, 2020).

**Surge, Wave, and Tsunami Loads:** Estimating surge, wave and tsunami loads on coastal infrastructure, including buildings, water, power, transportation, and communication lifelines, remains an engineering grand challenge. Although significant progress has been made for offshore and coastal structures which regularly experience extreme wave loads, similar progress has not been made for near-coast structures for which these conditions are rare but have high consequence. Our ability to predict the pressure distributions for both horizontal and uplift loads accurately remains a challenge. Moreover, because the wave climate is random in nature, the wave loading will follow a statistical distribution different from deep water conditions because of depth-limited breaking in shallow water. The probabilistic nature of extreme wave loads for a given sea state remains an open research question. The effects of cyclic loading from long-duration storms, multiple storms, and/or multiple tsunami waves, particularly cyclic loading from conditions less than the design conditions and its impacts on coastal infrastructure, is an important research area (NHERI Science Plan, 2020).

Related to the issue of wave loads, additional challenges include surge, wave and tsunami damage functions. Some progress has been made since the 2004 Indian Ocean tsunami and the 2011 Japan tsunami to develop empirical fragility curves for buildings and bridges. Additional work has been done to develop flood damage functions that may be suitable for coastal environments. However, the development of probabilistic approaches for community scale risk assessment remains a grand challenge. Load combinations for simultaneous flood hazards such as the static buoyancy due to flooding, the hydrodynamic drag due to currents, and the impulsive forces due to waves remains a research question. Performance-based design for coastal structures also remains a research question. Building performance over the lifecycle of the building/infrastructure accounting for conditions specific to the coastal environment like corrosion and their impact on design performance are important research questions (NHERI Science Plan, 2020).

**Coastal Erosion and Scour:** The US and many countries rely on coastal beaches and dunes to mitigate the effects of extreme storm surges. A grand challenge is to account for coastal erosion during extreme events to quantify overtopping of dunes, revetments, seawalls and other protective measures to mitigate storm surge. Moreover, coastal infrastructure including pile foundations, on-grade construction, seawalls, surface transportation, and buried pipelines depend on an understanding of the local scour to design resilient and adaptive infrastructure (NHERI Science Plan, 2020).

**Natural and Nature-Based Features for Coastal Hazard Mitigation:** Similar to our reliance on beach nourishment and dune construction, coastal communities in the world rely on natural and nature-based features (NNBF, also termed "Engineering with Nature") including coastal reefs, wetland features, and coastal forests including mangroves for coastal hazard mitigation. NNBF provides a wide range of benefits including economic and ecological functions and maybe suitable for adaptation to climate change. Although the ecological goods and services are reasonably well known, the capacity of such systems to provide adequate protection is still an open research question. These engineered systems are also expected to change over seasonal and decadal time scales, further complicating our understanding of the performance of these systems and use in engineering design. The integration of such systems into multiple lines of defense also remains on open research question (NHERI Science Plan, 2020).

**Numerical Model Development and Benchmarking:** Significant progress has been made on numerical modeling of hydraulic flows at a range of scales. Direct Numerical Simulation (DNS) is only feasible at scales much smaller than what is necessary for coastal engineering, therefore suitable methods for turbulence closure remain a challenge. Additional challenges include multi-phase flow, such as air-water-sediment. For example, accounting for air entrainment is necessary to capture impulsive breaking waves and the uplift for complex shapes which frequently trap air. The coupling of fluid structure models is also a research question. Local wave impact and structural component elasticity occur at a significantly smaller time scale (micro- to milli-seconds) than the surge, wave and tsunami load durations (seconds to kilo-seconds), necessitating multi-physics models and multi-time scale computation. Enforcing interface compatibility and matching time step are paramount for accurate long-term response prediction. Additional topics for numerical modeling and benchmarking include wave and tsunami runup, wave breaking and bottom boundary layer turbulence, sediment suspension and transport, and multi-phase (air-water-sediment) dynamics (NHERI Science Plan, 2020).

## FACILITY OVERVIEW

The HWRL EF is located in the O.H. Hinsdale Wave Research Laboratory (HWRL) on the Oregon State University main campus in Corvallis, Oregon (**Figure 1**) and is part of the School of Civil and Construction Engineering (CCE) in the College of Engineering. The HWRL is comprised of two clear-span buildings comprising a total of 5,480 $m^2$ (59,000 $ft^2$) of laboratory space. Within these buildings, there is approximately 464 $m^2$ (5,000 $ft^2$) of office space, including a large conference room, office space for visitors, a large work area for students, office space for staff, control room, an instrumentation room, a model shop area with tools, materials and supplies, and an area for health and safety equipment.


**FIGURE 1 |** Aerial view of O.H. Hinsdale Wave Research Laboratory. Image: Google Maps.

The HWRL has two major pieces of experimental equipment: the Large Wave Flume (LWF) and the Directional Wave Basin (DWB), described in detail in the following paragraphs.

It is worth mentioning that the LWF is the largest wave flume in the United States. The size of the flume enables scaling effects to be minimized in several research projects relevant to the NHERI research. The DWB has the largest wave generator of its kind in the US, allowing it to generate long waves (i.e., tsunami-like waves and other transient waves) unlike any other facility in the US. There is no other coastal facility in the US that can be used for wave-structure interaction of building systems at this scale. The LWF and DWB were specifically designed for coastal engineering research. Finally, the LWF and DWB are hosted by an academic institution and allow access by users at other universities.

### Large Wave Flume

The Large Wave Flume (**Figure 2**) is the largest of its kind in the US. Because of its size and ability to operate in high Reynolds regimes, the flume is ideally suited for a wide range of testing, including but not limited to cross-shore sediment suspension and transport; wave forces on offshore and coastal structures; nearshore hydrodynamics; wave breaking, swash dynamics, and undertow; tsunami inundation and overland flow; tsunami structure impact, debris and scour; pollutant mixing and transport; scour, pipeline stability and outfalls; liquefaction, cohesive sediments; wave runup, reflection, and overtopping; ocean wave energy systems; as well as natural and nature-based coastal engineering. The LWF specifications are 104 m (342 ft) in length, 3.7 m (12 ft) in width, and 4.6 m (15 ft) in height. The maximum water depth is 2 m (6.56 ft) for tsunami, and 2.74 m (9 ft) for windstorm waves. The wavemaker is a dry-back piston-type with hydraulic actuator assembly with active wave absorption and is capable of generating regular, irregular, solitary or tsunami-like waves (**Figure 3**, **left**). The wavemaker can generate user-defined waves in a period range from 0.8 to 12 + seconds. The maximum wave is 1.7 m (5.6 ft) at 5 s in a maximum of 2.74 m water depth. The maximum tsunami-like wave is 1.4 m (3.9 ft) in a maximum water depth of 2.0 m. The maximum stroke is 4 m (13.1 ft) at 4 m/s (13.1 ft/s). The LWF is equipped with a piecewise-continuous, movable, impermeable slope and can be adjusted to 1:12, 1:24, 1:36 and flat. The LWF is equipped with an instrumentation carriage with full cross-shore traverse and carriage-mounted vertical instrument deployment frame. The LWF also has a lightweight carriage for video and lighting applications.

### Directional Wave Basin

The Directional Wave Basin (**Figure 4**) was designed to understand the fundamental nature of tsunami inundation, tsunami-structure impact, harbor resonance and 3D wave propagation. The DWB is particularly suited for the general testing of coastal infrastructures, nearshore processes research, wave hydrodynamics, near-coast structures such as buildings, floating structures, renewable energy devices, and numerical model validation.

The DWB specifications are 48.8 m (160 ft) in length, 26.5 m (87 ft) in width, and 2.1 m (7 ft) in height. The maximum water depth is 1.5 m (4.46 ft). The wavemaker is a unique snake-type system made of 29 boards and 30 actuators with up to 2.1 m long stroke. It has been designed to generate short- and long-period multidirectional high-quality waves. The drive system is a wet-back piston-type, electric motor. The wavemaker is capable of delivering regular, irregular, tsunami, multidirectional, and user defined waves (**Figure 3**, **right**). The period range is 0.5–10 + seconds. The maximum regular wave is 0.85 m (2.5 ft) in 1.37 m (4.5 ft) water. The maximum solitary (tsunami-like) wave is 0.7 m in 1.0 m water depth. The maximum stroke of the wavemaker is 2.1 m (6.9 ft), and the maximum velocity is 2.0 m/s (6.6 ft/s). The DWB is equipped with a 1:10 removable steel beach. The DWB is equipped with the following supporting infrastructure: a 7.5 ton capacity bridge crane spanning the 2,137 $m^2$ (23,000 $ft^2$) space, and instrumentation carriage spanning the 26.5 m width of the basin, Unistrut© installed in floor and sides to secure models, and two access ramps, 2.74 m (9 ft) and 4.2 m (14 ft) wide. Steady flow currents can be installed on a project-by-project basis.

## Instrumentation and Equipment

The HWRL has a large inventory of state-of-the art and conventional instrumentation to measure hydrodynamics (free surface, velocity, wave pressure), sediment response (turbidity, sediment suspension, scour, pore-pressure), and structural response (force, pressure, stress, displacement, acceleration). The free surface can be measured with surface-piercing resistance-type paired-wire wave gages using seven 8 channel signal conditioners (ImTech), 6 self-calibrating wave gage mounts for the LWF, 7 self-calibrating wave gage mounts for the DWB, 13 fixed wave gage mounts for the LWF, 19 fixed wave gage mounts for the DWB, 18 cantilever gage mounts, and 26 runup gage mounts. The HWRL also has 8 acoustic wave gages.

**FIGURE 2 |** Large Wave Flume overview **(left)** and use of LWF for dune erosion study **(right)**.

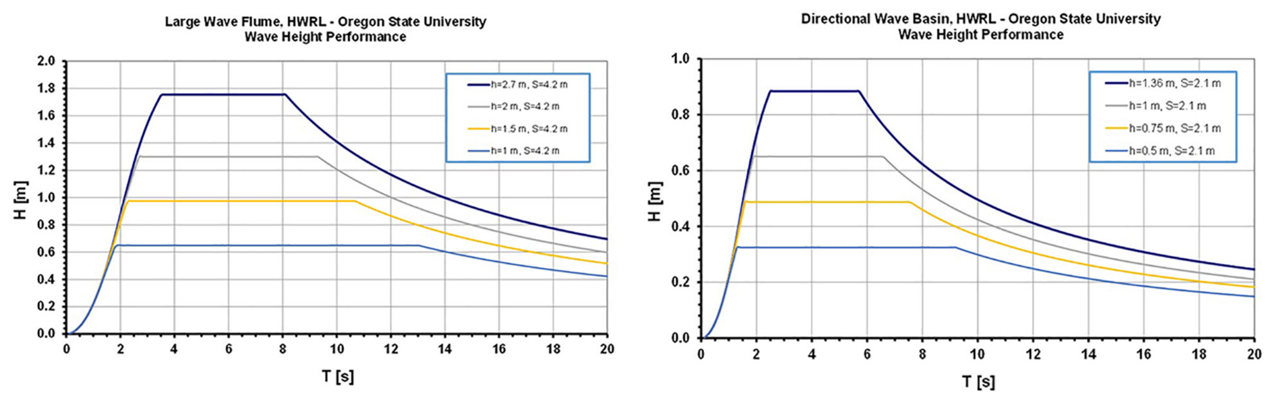


**FIGURE 3 |** Wavemaker performance for LWF **(left)** and DWB **(right)**.

The velocity can be measured with 16 3-D acoustic-Doppler velocimeter (Nortek Vectrino) and 4 2-D acoustic-Doppler velocimeter probe heads. Fluid pressure can be measured with 5 pore pressure transducers (Druck PDCR81), 24 pressure transducers (12 Druck PDCR830 and 12 PDCR1830). Four 10ch and one 4ch signal conditioners (Vishay 2100), four 222 kN (50Kip) and four 89 kN (20Kip) pancake load cells (DeltaMetrics), two 44.5 kN (10Kip), six 9 kN (2Kip) rod end load cells (DeltaMetrics), and one 18 kN/2kNm submersible multi-axial load cell. Turbidity can be measured with 16 optical backscatter sensors (D&A Instr., OBS-3). The bathymetry can be measured with two 32-component ultrasonic ranging system (SeaTek), four laser range finder 0.2–200 m (Dimetix DLS-A30), and a Leica BLK 360 Laser Scanner. Displacement can be measured with PhaseSpace Motion Capture system (8 cameras), 6 string potentiometers, LDVT and encoders. Video recording is possible with 6 PTZ HD 1080p cameras, 2 submersible HD 720p underwater cameras and lights, 6 PIX SSD-based HD video recording systems, and waterproof (GoPro) and handheld (Sony) HD cameras.

The data acquisition system (DAQ) consists of 3 modular PXI architecture DAQ systems from National Instruments, each with built-in signal conditioning and anti-aliasing, 64 channel, 16-bit analog acquisition, digital pulse generation, external device synchronization and up to16 channel RS-232 for serial communication. The DAQs can be synched to provide 192 analog channels and 48 digital channels with two additional modular PXI architecture DAQ systems. The HWRL is equipped with six PTZ web cameras (Axis) to view experiments remotely.

Wireless and wired networking and switches at the HWRL EF are supported by the College of Engineering IT group and by OSU Network Services. The fiber to the building was upgraded to a total of 10 Gbps with switches providing 1 Gbps links to every host system on the public network. Systems on the private firewalled DAQ network share a single 1 Gbps link to the outside and have 100 Mbps connectivity per DAQ host system. The wireless system at the HWRL EF is currently running dual-band 802.11n and hosts both open (public) access for visitors or guests and secure (WPA2) access for OSU only.

The HWRL EF has a full site safety plan and set of protocols that are available online for review by all potential visitors and users. The plan and protocols include mandatory documented training for any user prior to starting work at the EF. It also includes protocols for regular inspections and weekly safety meetings and reviews. The HWRL EF provides all staff and visitors personal protective equipment (PPE) including eye protection, ear protection, protective gloves, hard hats, dust masks and other PPE.

The HWRL EF can be accessed by roll up doors for entry by trucks and other equipment to offload specimens. Each door is 4.3 m (14 ft) wide by approximately 4.9 m (16 ft) tall. The HWRL EF has four pieces of heavy machinery operated by HWRL EF staff to support specimen handling, transport, and staging. These include two forklifts (5,000 and 10,000 lb), a bucket loader, and a large shooting-boom forklift (10,000 lb). Additional equipment for specimen staging or demolition is contracted out on a per-project basis. The HWRL EF is served by of a 7.5-ton bridge crane over the DWB and a 6-ton gantry crane over the LWF.

Upon request, the HWRL EF can work with users to procure other services and tools necessary for experimentation which are not listed here. Examples include local subcontractors for specimen construction, installation or removal; the addition of pumps for steady currents; or rental of industrial equipment not available on-site.

## EXAMPLE RESEARCH PROJECTS FOR NHERI 2016–2019

This section highlights the accomplishments of 10 projects conducted under the current NHERI HWRL EF award. **Table 1**

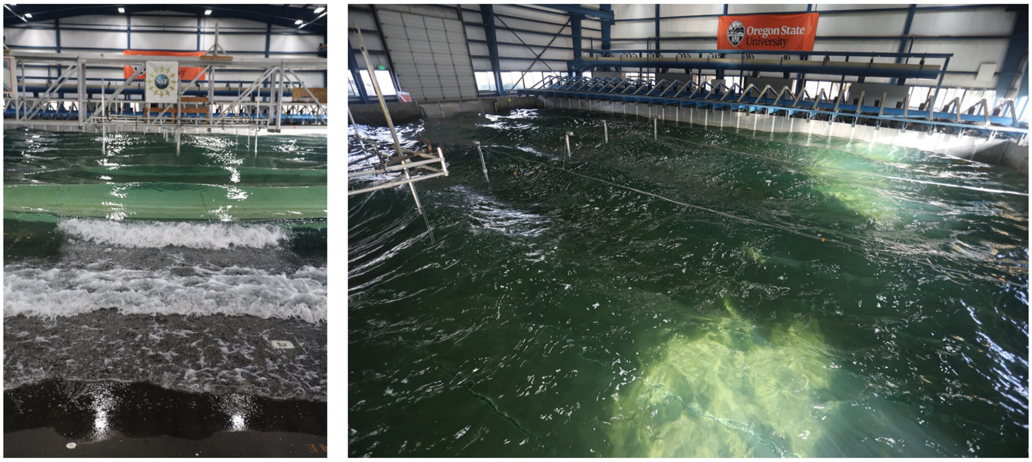


**FIGURE 4 |** Overview of Directional Wave Basin **(left)** and wavemaker detail **(right)**.

**TABLE 1 |** Projects conducted in the NHERI HWRL EF.

| NSF ID | PI | Institution | Title | Facility | Usage |
|---|---|---|---|---|---|
| 1266101 | van de | Colorado State | Collaborative Research: Fundamental Mechanics | LWF | $N_{da}$ = 66 |
| 1301016 | Lindt | | and Conditional Probabilities for Prediction of Hurricane | 2016 | $N_{tr}$ = 450 |
| | Cox | Oregon State | Surge and Wave Loads on Elevated Coastal Structures | | |
| 1538190 | Kaihatu | Texas A&M | Collaborative Research: Non-linear Long Wave | DWB | $N_{da}$ = 115 |
| 1538624 | Synolakis | U Southern | Amplification in the Shadow Zone of Offshore Islands | 2016 | $N_{tr}$ = 785 |
| | Lynett | California | | 2017 | |
| 1536198 | Motley Eberhard Arduino | U Washington | Probabilistic Assessment of Tsunami Forces on Coastal Structures | LWF 2017 | $N_{da}$ = 80 $N_{tr}$ = 723 |
| 1635115 | Dawson | U Texas | Collaborative Research: Numerical and Probabilistic | DWB | $N_{da}$ = 18 |
| 1635784 | Padgett | Rice U | Modeling of Aboveground Storage Tanks Subjected | 2017 | $N_{tr}$ = 139 |
| | | | to Multi-Hazard Storm Events | | |
| 1621727 | Cueto | Smart Walls Construction, LLC | SBIR Phase I: Telescopic Structural Flood Walls | LWF, DWB 2017 | $N_{da}$ = 15 $N_{tr}$ = 22 |
| 1552559 | Myers | Northeastern U | CAREER: Advancing multi-hazard assessment and risk-based design to promote offshore wind energy technology | LWF 2017/18 | $N_{da}$ = 85 $N_{tr}$ = 506 |
| 1735460 | Kumar Moulton | U Washington | Transient Rip Current Dynamics: Laboratory Measurements and Modeling of Surfzone Vorticity | DWB 2018 | $N_{da}$ = 30 $N_{tr}$ = 132 |
| 1459049 | Ozkan-Haller | Oregon State | Runups of Unusual Size: Predicting Unexpectedly Large Swash Events | LWF 2018 | $N_{da}$ = 43 $N_{tr}$ = 35 |
| 1563217 | Fritz | Ga. Tech | Physical modeling of submarine volcanic eruption generated tsunamis | DWB 2018 | $N_{da}$ = 50 $N_{tr}$ = 667 |
| 1661015 | Kennedy | Notre Dame | Collaborative Research: Wave, Surge, and Tsunami | DWB | $N_{da}$ = 117 |
| 1661052 | Lynett | USC | Overland Hazard, Loading and Structural Response | 2018/19 | $N_{tr}$ = 574 |
| 1661315 | Cox | Oregon State | for Developed Shorelines | | |
| 1825080 | Johnson | USNA | Experimental Investigation of Wave, Surge, and Tsunami Transformation over Natural Shorelines | DWB 2019 | $N_{da}$ = 5 $N_{tr}$ = 40 |
| 1756449 | Wengrove | Oregon State | Collaborative Research: Physics of Dune Erosion | LWF | $N_{da}$ = 95 |
| 1756477 | Feagin | Texas A&M | during Extreme Wave and Storm-Surge Events | 2019 | $N_{tr}$ = 256 |
| 1756714 | Puleo | U Delaware | | | |
| 1933355 | Evans | Oregon State | Collaborative Research: Implementation Strategies | LWF | $N_{da}$ = 20 |
| 1933350 | Montoya | N. Carolina St. | and Performance of Unsaturated Bio-Cemented Dune Sand | 2019 | $N_{tr}$ = 30 |
| 1726326 | Lehman Arduino Motley Roeder | U Washington | Vertical Evacuation Structures Subjected to Sequential Earthquake and Tsunami Loadings | LWF 2019–2020 | $N_{da}\sim$ 50 $N_{tr}\sim$ 150 |

*NSF ID is the National Science Foundation project identification, $N_{da}$ is the number of days of testing, and $N_{tr}$ is the number of trials.*

lists the projects tested at the HWRL EF under the NHERI program, including the project identification (ID), the Principal Investigators (PIs), institution(s), project title, facility used (LWF, DWB), year, number of days of testing (Nda), and the number of trials (Ntr). There were 14 projects to use the facility, of which 6 were Collaborative Proposals. Of the 25 researchers listed in the table, an overwhelming majority ($n$ = 21, 84%) were from outside the host institution and a majority ($n$ = 15, 60%) were new users. A majority of the institutions ($n$ = 8, 57%) were new to the facility. In summary, this table indicates that the HWRL EF was highly effective as a shared-use facility. Highlights include summaries of the research awards posted on NSF Fastlane and edited for brevity and relevance to NHERI EF. Publications from each project is provided in the references section.

## Collaborative Research: Fundamental Mechanics and Conditional Probabilities for Prediction of Hurricane Surge and Wave Loads on Elevated Coastal Structures

Damage to coastal structures as a result of combined surge and wave loading has been significant in recent events such as Hurricane Ivan (2004), Katrina (2005), Ike (2008) and Sandy (2012), and most recently Matthew (2016), Harvey, Irma, Maria (2017), Florence, Michael (2018), and Humberto (2019). This project focused on the impact of hurricane surge and wave loads on elevated coastal structures to understand and quantify surge and wave loads on buildings and structures that can be used to mitigate damage to the coastal structures. This collaborative project between research teams at Oregon State University and Colorado State University have combined expertise in coastal engineering and structural engineering to develop a fundamental understanding and modeling of hurricane surge and wave loads on elevated structures. The goal is to mitigate damages to shoreline infrastructures from extreme coastal storms. The analytical formulation was built on Goda's method for calculating surge forces on elevated coastal structures and have been extended to incorporate wave forces. A probabilistic approach was taken to combine surge and wave loads. Hydrodynamic hurricane wave and structure interaction were used to formulate loading on these types of structures. The formulations were validated with experiments using the LWF.

The NHERI HWRL EF developed an innovative test apparatus for independent measurements of horizontal and vertical forces of waves and tsunamis impacting an elevated coastal structure while still allowing for the entire assembly to be raised and lowered to study the role of freeboard (airgap) on the overall forces experienced by the structure (**Figure 5**). The researchers found that the maximum uplift pressures were observed when the mean water level was at the lowest horizontal member (Park et al., 2017, 2019). The data collected for this project has been used to develop new design equations proposed for the next cycle of the ASCE 7 standard in 2022 (Tomiczek et al., 2018, 2019a,b). The detailed observations of impact pressure under breaking, broken, and near breaking waves were compared with two high-resolution numerical models, OpenFOAM and Fluent, quantify uncertainties with respect to model schemes and grid resolution (Park et al., 2018a,b). This project contributed to the career development of 1 postdoctoral scholar, 2 Ph.D. students, 2 MSc students from the US Navy, and 2 Research Experience for Undergraduate (REU) students from the University of Puerto Rico in Mayaguez (UPR–Mayaguez).

## Collaborative Research: Non-linear Long Wave Amplification in the Shadow Zone of Offshore Islands

Field survey reports from recent tsunamis suggest that local residents in mainland areas shadowed by nearby islands may be under the impression that these islands protect them from tsunamis. Recent numerical results have generated substantial attention because they suggest that, in most cases, islands amplify tsunamis in the shadow zones behind them. In this application, the active learning methodology requires about 100,000 times fewer computations than conventional mathematical approaches, and it is unclear if the amplification effect is real. Through comprehensive laboratory experiments, the physical manifestation of this effect was studied. If indeed the physical experiments confirm the numerical idealizations, this research will help save lives by better targeting educational campaigns to at risk populations. For example, it will be determined if coastlines shadowed by offshore islands along the Pacific Coast of the US are more vulnerable than earlier believed. The early numerical results from active learning are only applicable for non-breaking waves. Through the laboratory experiments, it was determined if this vexing phenomenon persists when waves break. The results will help validate active learning as a mathematical procedure for uncertainty reduction which greatly reduces computational costs. Laboratory data helped to benchmark numerical computations.

This project provided one of the first laboratory measurements of hydrodynamic conditions of the near-field and far-field effects of offshore islands on tsunami run-up. The HWRL EF assisted researchers from the University of Southern California and Texas A&M University with the construction of 4 large-scale, geometrically accurate conical islands available for this project and further testing to the scientific community (**Figure 6**). The HWRL EF assisted with LiDAR (Laser Scanner) to provide highly resolved bathymetric conditions for interpretation of hydrodynamic conditions and for numerical modeling. Researchers used optical measurement techniques (i.e., Particle Tracking and Particle Image Velocimetry—PTV and PIV) to capture the flow around the two islands (Lynett et al., 2019), and used novel techniques to measure the run-up around the island (Kaihatu et al., 2018; Han et al., 2020). These experiments generated a detailed data set for the calibration of an open source code based on the extended Boussinesq equations for interactive and real-time wave simulation (Lynett, 2016). This project identified an increased risk of run-up on the leeside of the

**FIGURE 5 |** Lee-side of the specimen **(left)** and wave impacting elevated structure **(right)**.

islands under certain conditions (Keen and Lynett, 2019). Two comprehensive test campaigns were conducted with single and multi-island layout. Three Ph.D. students and 4 REU students were involved. The project included informal collaborations with researchers from Chile.

## Probabilistic Assessment of Tsunami Forces on Coastal Structures

Interest in tsunami load predictions for structural design has grown, but it is difficult to develop models that accurately predict the tsunami load response of an individual structure, much less the tsunami risk for multiple structures within a specific region. This project was designed to improve the safety and sustainability of coastal structures and, consequently, improve tsunami hazard assessments, post-event response, and recovery efforts. The primary goals of this research project were to establish an open-source modeling framework where 3D computational fluid dynamics solvers can be used efficiently to inform the development of load-prediction capabilities for existing, widely used inundation models and to develop a probabilistic framework for predicting the fluid loading and structural response of coastal structures at a community level. The research team have validated this framework against existing experimental data, assessed the effects of bathymetry and community layout on flow, refined the models to include force predictions, and extended probabilistic tsunami hazard assessment methods to include fluid loading criteria.

The HWRL EF assisted the researchers at the University of Washington (UW) to modify an existing apparatus and model specimen for use in their project, substantially reducing costs. The modifications allowed the researchers to study the structural properties of the building and the effects of macro-roughness (shielding of other buildings), and waterborne debris (**Figure 7**). The experiments incorporated the simulation of breaking and non-breaking waves on a fully instrumented elevated coastal structure. One postdoctoral scholar, 4 Ph.D. students, and 2 MSc students were involved in the testing phase of the project. Subsequent to the testing phase, the HWRL EF leadership organized a series of monthly teleconferences with the UW team to assist with the subsequent data analysis and publication phase. To date, the project has led to the publication of 3 peer-reviewed journal papers (all co-authored with UW and OSU teams) and 1 conference proceedings (Lomonaco et al., 2018; Alam et al., 2020; Shekhar et al., 2020; Winter et al., 2020). Significantly, the project led to the successful submission of the project, NSF-1933184 “Understanding and Quantifying Structural Loading from Tsunami-Induced Debris Fields” funded to the UW team. UW will use the HWRL EF for this project in 2020–2021.

**FIGURE 6 |** Installation of artificial islands **(left)** and tsunami tests in DWB **(right)**.

**FIGURE 7 |** Wave impacting the elevated structure **(left)** and shielding test **(right)**.

## Collaborative Research: Numerical and Probabilistic Modeling of Aboveground Storage Tanks Subjected to Multi-Hazard Storm Events

Aboveground storage tanks (ASTs) used to store hazardous materials, such as crude oil, can suffer major damage in severe storms resulting in spills with catastrophic social, environmental, and economic consequences. This research has provided numerical models capable of capturing the complex fluid-structure interaction (FSI) and non-linear system behavior exhibited by ASTs under multi-hazard loads. Furthermore, probabilistic models of tank performance in severe storms are being developed, filling a major gap in risk assessment of this critical industrial and energy infrastructure. The advanced computational resources and collaboration and analysis tools of the National Science Foundation-supported Natural Hazards Engineering Research Infrastructure (NHERI) cyberinfrastructure, DesignSafe-CI.org, will be utilized and enhance in this effort. This project harnessed the synergies of a multi-disciplinary team spanning computational sciences and structural engineering to provide robust numerical models of AST response under multi-flow conditions and to subsequently derive the first models of AST fragility under multiple storm-induced hazards.

The HWRL EF assisted the researchers at Rice University (Rice U) with developing an experimental research plan that would provide benchmark data for their numerical modeling work on ASTs. The HWRL EF utilized existing specimens at the facility from an earlier project and co-developed a research plan with Rice U to represent the hurricane surge and wave conditions representative of their project area in the Gulf of Mexico/Galveston Bay. The measurements included hydrodynamic conditions and pressures surrounding cylindrical ASTs under the action of regular, irregular (long-crested and short-crested) and tsunami-like waves. The test program included two tanks to provide a benchmark case for shielding by neighboring storage tanks (**Figure 8**). Observations showed the large-diameter tanks to introduce significant diffraction effects. One Ph.D. student was trained on this project. This successful project led to the publication of 4 peer-reviewed journal papers (Bernier and Padgett, 2019a,b; Dominguez et al., 2019; Bernier et al., 2020), 3 conference papers (Bernier and Padgett, 2018a,b, 2019c), 1 Ph.D. dissertation (Bernier, 2019), and was one of the first data sets to receive a DOI at DesignSafe.org (Bernier et al., 2017).

## SBIR Phase I: Telescopic Structural Flood Walls

This Small Business Innovation Research (SBIR) Phase I project aimed to develop, test and validate a retractable telescopic structural wall for applications in flood protection. This technology will enable more resilient infrastructure in flood-prone areas. The proposed concept, when validated, will provide a paradigm shift for the prefabricated concrete industry. It will also develop and validate new methods for telescopic interconnection of structural elements. The intellectual merit of this project lies in a unique concept where structural boxes, made out of fiber reinforced concrete, can be deployed telescopically to withstand forces imposed from external sources, and then return to a retracted position. Results have been validated via laboratory tests where lateral and vertical loads, as well as impact loads, were applied. The technical result of Phase I was a working prototype of the telescopic structural flood wall with extension and retraction features, and with the structural capability to withstand the forces from flood events with minimal to no damage.

The HWRL EF Leadership team worked with the researchers to develop a research testing plan for the hydraulic performance of telescopic structural walls for flood (storm surge) and wave action protection. This is one of the first NHERI projects to use both the DWB and the LWF. The hydrostatic support and sealing mechanism were evaluated in the DWB (**Figure 9**, **left**), and the stability performance under large-scale breaking waves was evaluated in the LWF (**Figure 9**, **right**). This was also the first SBIR proposal tested at this NHERI EF. The data and experience gained from these experiments supported the submission of a Phase II SBIR proposal awarded in 2018, NSF-1758544 "SBIR Phase II: Telescopic Structural Flood Walls" and a presentation in an International Conference (Cueto, 2019).

## CAREER: Advancing Multi-Hazard Assessment and Risk-Based Design to Promote Offshore Wind Energy Technology

Offshore wind energy is a resource of renewable energy that is conveniently accessible to many major population centers but harvesting offshore wind energy currently costs more than traditional sources. The research goal of this Faculty Early Career Development (CAREER) Program grant is to advance knowledge that can lead to reduction in the cost of offshore wind energy through (1) a much sharper understanding and modeling of the spatio-temporal interaction of multiple offshore hazards that impact the system-level performance of offshore wind energy farms to reduce insurance and financing costs, (2) the calculation of novel system-level performance metrics, and (3) the advancement of shallow water wave modeling to mitigate the current reliance on overly conservative design methods. This project has achieved the research goal through fundamental advancements to metamodels (surrogate models) to overcome restrictions that have previously limited the impact of such models in the context of multi-hazard assessment of spatially distributed infrastructure. The research has also explored innovative models that overcome important deficiencies in the modeling of non-linear, highly skewed shallow water waves and their associated hydrodynamic loads, including breaking waves. The research has synthesized these advances and generated system-level performance metrics that will provide a fundamentally different paradigm for designing offshore wind farms.

The HWRL EF Leadership worked with the researcher at Northeastern University to co-develop a testing program

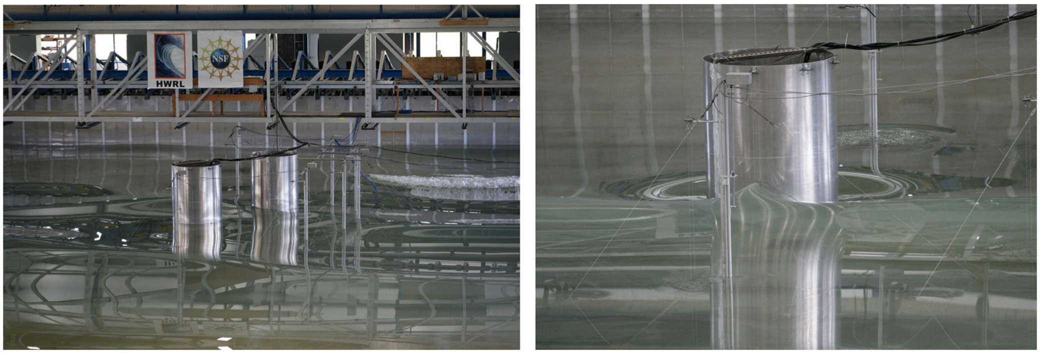


**FIGURE 8 |** AST shielding tests DWB **(left)** and detail of a solitary wave impacting an AST **(right)**.

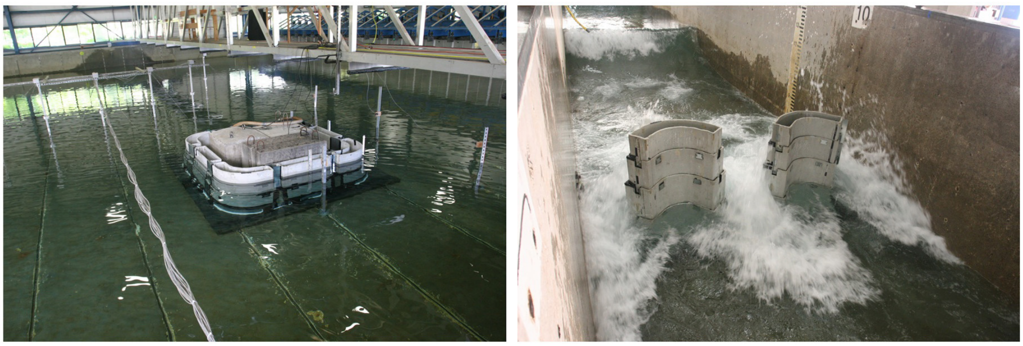

**FIGURE 9 |** Hydrostatic tests in DWB **(left)** and breaking wave tests in LWF **(right)**.

for the measurement of hydrodynamic conditions (surface elevation, velocities), and structural response (pressures, multidirectional forces, vibrations, deformations) of a vertical cylinder representing the foundation and support of offshore wind turbines, subject to breaking, broken, and non-breaking tsunami-like waves and storm waves (**Figure 10**). The testing protocol utilized a unique 6 DOF load cell to capture the structural responses of the specimen under severe wave impact loading. High-speed video and underwater cameras were used to capture details on wave run-up around the cylinder. The adaptable steel model and testing rig for FSI experimentation, is available to the scientific community for future research. This project included the participation of 2 Ph.D. students and a collaboration with University of Massachusetts – Amherst, and the publication of 3 peer-reviewed papers in International Conferences (Johlas et al., 2018; Hallowell et al., 2019; Lomonaco et al., 2019).

## Transient Rip Current Dynamics: Laboratory Measurements and Modeling of Surfzone Vorticity

The nearshore region is often compromised by pathogens and excess nutrient supply from terrestrial runoff. Understanding the transport of materials throughout the nearshore region can have important implications for ecosystem and human health. Previous studies analyzing cross-shelf exchange suggest that transient rip currents are the dominant mechanism driving exchange between the surf zone and the inner shelf. Evidence also suggests that transient rip currents are generated from the coalescence of surf zone eddies, with short-crested waves serving as the source of rotation. This project has utilized laboratory and numerical modeling to study the generation and evolution of surf zone eddies to form transient rip currents. The knowledge of mixing and exchange in the nearshore region will be significantly advanced through this study, which will have important implications for the transport of nutrients, larvae, and pollutants. In collaboration with National Oceanic and Atmospheric Administration scientists, simple predictors of transient rip currents will be developed to improve hazard forecasts for a broad range of environments. This is essential information for human safety as rip currents are the leading cause of fatalities and rescues on beaches. A graduate student has gained valuable training and education through involvement in this project. Outreach activities highlighting rip currents were developed as a part of the O.H. Hinsdale Wave Research Laboratory Outreach Program seeking to broaden participation in Science, Technology, Engineering and Mathematics (STEM).

This project highlights how the NHERI HWRL EF can be used for successfully NSF-funded research beyond the Engineering Directorate. Previous to this funding, the EF worked with the researchers at UW to investigate the suitability of the HWRL

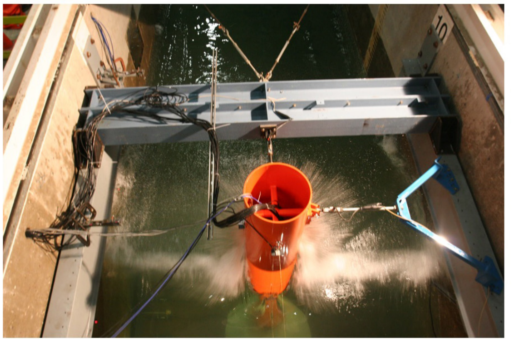

**FIGURE 10 |** Setup of specimen in LWF **(left)** and impulsive breaking wave tests **(right)**.

EF for their proposal. For the funded project, rip-currents were generated at the surf-zone with multidirectional irregular waves using a unique modular offshore bar (**Figure 11**). The HWRL EF worked with the researchers at UW to design a cost-effective solution to create these nearshore coastal conditions using the existing 1:10 slope with a modular, fixed outer bar. The components of the offshore bar can be re-used for future research. The investigation allowed for the development of optical techniques to reconstruct the surface elevation and current field using additives (surfactant, floating tracers, dyes), stereographic imagery, infrared cameras, and LiDAR. These experiments were conducted in collaboration with the US Army Corps. of Engineers and the US Navy. One Ph.D. student was supported on this project and one paper has been presented in an international conference (Baker et al., 2020).

## Physical Modeling of Submarine Volcanic Eruption Generated Tsunamis

Tsunamis are normally associated with submarine earthquakes along subduction zones, such as the 2011 Japan tsunami. However, there are significant tsunami sources related to submarine volcanic eruptions. Volcanic tsunamis, like tectonic tsunamis, typically occur with little warning and can devastate populated coastal areas at considerable distances from the volcano. There have been more than 90 volcanic tsunamis accounting for about 25% of all fatalities directly attributable to volcanic eruptions during the last 250 years. The two deadliest non-tectonic tsunamis in the past 300 years are due to the 1883 Krakatoa eruption in Indonesia with associated pyroclastic flows and Japan's Mount Unzen lava dome collapse in 1792. At the source, volcanic tsunamis can exceed tectonic tsunamis in wave height, but these volcanic tsunamis are subject to significant wave attenuation and dispersion with propagation distance. Most volcanic tsunami waves have been produced by extremely energetic explosive volcanic eruptions in submarine or near water surface settings, or by flow of voluminous pyroclastic flows or debris avalanches into the sea. The recent "orange" alert in July 2015 at the Kick 'em Jenny submarine volcano off Grenada in the Caribbean Sea highlighted the challenges in characterizing the tsunami waves for a potential submarine volcanic eruption. The ultimate long-term goal of this research is to transform assessment and mitigation of the submarine volcanic tsunami hazard through hybrid modeling of submarine volcanic eruption, tsunami generation and propagation along with the potential engulfment and caldera formation.

This experiment involved the design, construction, and implementation of a unique machine to simulate the submarine volcanic eruption for experimental validation of existing mathematical models. A large cylinder with compressed air

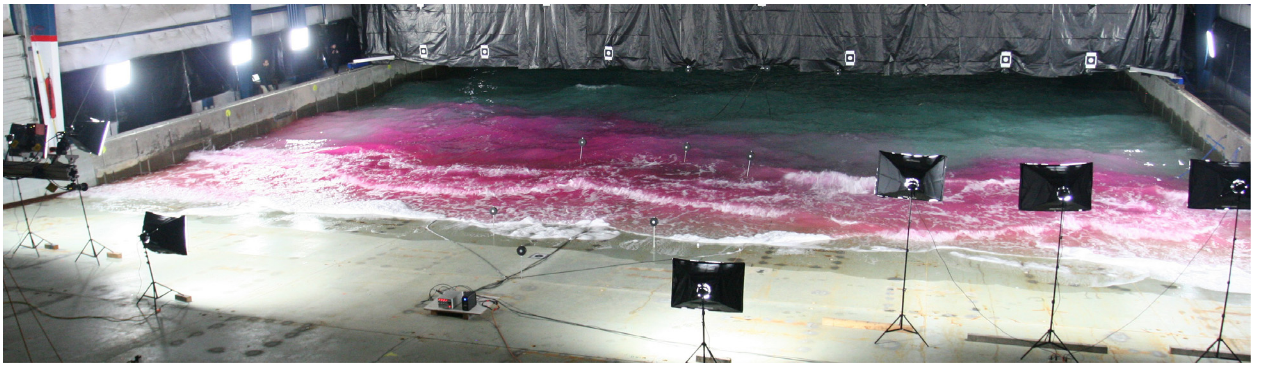

**FIGURE 11 |** Surf zone rip currents in DWB using dye tracers and optical tracking.

actuators (**Figure 12**, **left**) and a system to control stroke and velocity allowed for the generation of tsunamis to simulate different types of erupting volcanoes (**Figure 12**, **right**). Researchers from Georgia Tech included measurement of 3D velocities and surface elevation around the volcano, as well as run-up on the shoreline, submarine and overhead digital video for PIV and free surface reproduction. Two Ph.D. students and 2 undergraduate research students were involved in the study. On December 22, 2018, 3 months after the end of the experimental campaign, an underwater eruption and cone collapse of the Anak Krakatoa volcano caused a tsunami with waves up to five meters in height, affecting more than 300 km (186 mi) of coastline in Sumatra and Java, with 420 casualties, 14,000 people injured and 40,000 displaced. This event demonstrated the value of the research on underwater eruptions and the knowledge gap in the understanding of the generation and propagation of volcanic tsunamis.

## Collaborative Research: Wave, Surge, and Tsunami Overland Hazard, Loading and Structural Response for Developed Shorelines, and Experimental Investigation of Wave, Surge, and Tsunami Transformation Over Natural Shorelines

Inundation from storms like Hurricanes Katrina, Sandy, Matthew or Harvey, and the 2011 East Japan tsunami, has caused catastrophic damage to coastal communities. With increasing coastal population, and trillions of dollars of infrastructure at risk, storms and tsunamis will continue to be threats to coastal communities (Kennedy et al., 2018). Improving community resilience to these Inundation Events (IEs) requires an understanding of how they damage buildings. Prediction of structural damage in IEs can be quite difficult along developed shorelines, where some structures may partially shield buildings behind them, reducing damage in ways that are not easily predictable using the existing state-of-the-art (Kennedy and Westerink, 2019). This project will create new tools to predict structural damage from IEs along developed shorelines. The team from the University of Notre Dame, Oregon State University, and the University of Southern California are developing computer-based predictive methods for detailed building damage using laboratory tests and field data to guide development and validate accuracy. This collaborative project has examined probabilistic structural vulnerability to storm waves and tsunamis in developed regions, where structures are most concentrated but existing models perform poorly due to complex flow transformation around these structures. The laboratory and computational methodologies developed here employed deterministic and stochastic models with scales able to resolve local transformation, and that directly represent relevant processes.

The HWRL EF worked with the research teams to recreate a section of shoreline to allow for the overland flow, including overland surge. This was established by the installation of two large pumps and the construction of return sections to moderate the surge storm. This system allowed for the addition of waves superposed on the currents. On land, the HWRL EF worked with the research teams to create instrumented specimens to measure shielding effects of building and other structures such as seawalls and breakwaters (**Figure 13**, **left**). When the project was initially awarded, the HWRL EF worked with the research team to allow a payload project, aimed to study the effect of parcel-size mangrove forests on the attenuation of the incident wave energy (Tomiczek et al., 2020) (**Figure 13**, **right**). This ambitious project included experiments of dye dispersion, waterborne debris, macro-roughness sheltering, construction of a coastal community with 100 buildings, effect of a low-crested seawall, a submerged breakwater, and the sheltering of a non-overtopped seawall. The study considered the effect of regular, irregular and tsunami-like waves, with and without a steady current simulating the overland flow. The collaborative effort supported 2 Ph.D. students, 3 MSc students, 2 undergraduate research students and included the participation of 5 universities, including researchers from Japan and Korea.

## Collaborative Research: Physics of Dune Erosion During Extreme Wave and Storm-Surge Events, and Collaborative Research: Implementation Strategies and Performance of Unsaturated Bio-Cemented Dune Sand

Sand dunes are often the primary and sometimes only “line of defense” for coastal infrastructure and are increasingly constructed and actively managed to protect against extreme events. However, because extreme physical forces only interact with the dune for a relatively short, yet critical time when the water level rises, there is limited understanding on how dune sediments and vegetation can modify hydrodynamic forces and alter beach-dune profile evolution. This research focuses on dune response to a range of water level and forcing conditions that mimic the passage of an extreme storm event. A near prototype-scale laboratory experiment was conducted over a mobile bed in the LWF (**Figure 14**, **left**). Physical model studies occurred over a dune with live vegetation (**Figure 14**, **center**), and for comparison purposes over a bare dune. Data related to processes ranging from short-term (turbulence) to longer time scales (individual events) were collected and analyzed to develop a fundamental understanding of the fluid-sediment-vegetation dynamics affecting dune stability, as well as damage mitigation strategies for extreme events (**Figure 14**, **right**). The collected data will be used to validate the numerical model sedwaveFoam (created in the open-source OpenFOAM framework), capable of simulating the full profiles of sediment transport under realistic waves, and will be extended for dune erosion with or without vegetation.

This was one of the largest sediment transport experiments conducted in a large-scale laboratory, involving the contributions of a large research team of 37 people across several institutions, including 15 graduate students, 5 undergraduate and REU students, and 1 High School student and 1 teacher. Although the research dissemination phase is still underway, there was 1 presentation in the Young Coastal Scientists and Engineers Conference—YCSEC 2019 (Moragues and Lomonaco, 2019) and 5 presentations at the recent Ocean Science conference in 2020 (Bond et al., 2020; Converse et al., 2020; Holzenthal et al., 2020; Pontiki et al., 2020; Smith et al., 2020), highlighting the volume of research output. In addition to the planned experiment, two more researchers were able to leverage the installation of the mobile sediment bed to explore a novel approach for dune protection using bio-cementation to stabilize and enhance natural protective structures (**Figure 14**, **right**). The research team explored multiple treatment implementation techniques and assess their performance under extreme conditions. The resulting outcome of this work (e.g., Montoya et al., 2020) will provide guidance for enhancing coastal dunes with bio-cementation to prevent damage to infrastructure during extreme events.

**FIGURE 12 |** Setup of apparatus in DWB **(left)** filling of the DWB in preparation for testing with the submarine volcano **(right)**.

**FIGURE 13 |** Setup of overland flow in DWB **(left)** and detail of wave impact on coastal structures **(right)**.

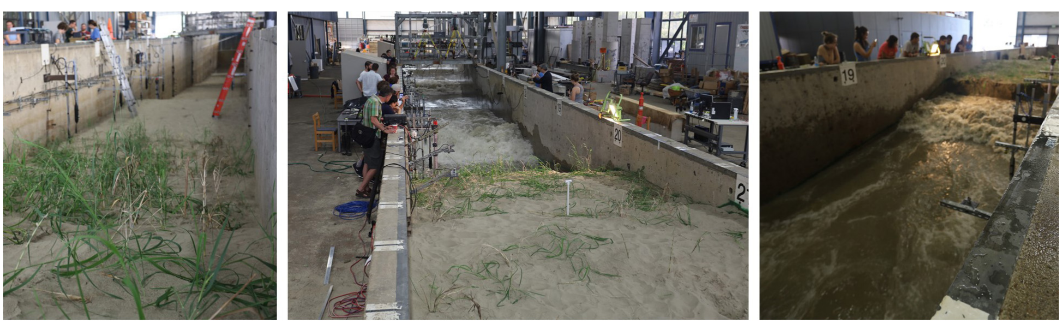

**FIGURE 14 |** Detail of vegetated duneand instrumentation **(left)**, overview of the LWF during testing **(center)**, and wave impact on dune **(right)**.

## SUMMARY AND CONCLUSION

The infrastructure and capabilities of the Natural Hazards Engineering Research Infrastructure Experimental Facility at Oregon State University were presented. The facility is an open-access infrastructure that enables researchers to conduct state-of-art engineering research, education and outreach on natural hazard mitigation for civil infrastructure systems, specifically on tsunamis caused by earthquakes and coastal wave and surge caused by windstorms with two specialized large-scale resources for physical model testing of coastal systems. The facility has the unique ability to conduct physical model testing of the natural and build environment subject to the action of storm waves, surge, tsunamis, and other hazards.

Several selected example research projects recently performed at the HWRL EF to illustrate the facility's capabilities were introduced. These projects included: (1) the assessment of wave impact forces on elevated coastal structures, (2) the effect of offshore islands on the run-up of tsunami events at the coast, (3) sheltering and debris tsunami forces on elevated coastal structures, (4) hydrodynamic forces of storm waves and tsunamis on ASTs, (5) hydrostatic and breaking wave tests of telescopic structural flood walls, (6) impact forces on fixed foundations of offshore wind turbines, (7) modeling of nearshore rip-currents with multi-directional waves, (8) formation and propagation of tsunamis generated by submarine volcanic eruptions, (9) hydrodynamics and wave impact forces on a multi-structure coastal community, and (10) erosion of a vegetated sand dune under the effect of storm waves. The examples present the broad range of experiments performed at the HWRL EF enabling the understanding of the response of the natural and built environment to different sources of coastal hazards.

All tests results and research data are shared through the NHERI DesignSafe[1].

## ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

[1] https://www.designsafe-ci.org/data/browser/public/

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# NHERI@UTexas Experimental Facility With Large-Scale Mobile Shakers for Field Studies

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The Natural Hazards Engineering Research Infrastructure (NHERI) experimental facility at the University of Texas (NHERI@UTexas) is funded by the National Science Foundation (NSF). NHERI@UTexas contributes unique, large-scale, hydraulically controllable mobile shakers and associated instrumentation to study and develop novel, *in-situ* testing methods that can be used to evaluate the needs of existing infrastructure as well as optimize the design of future infrastructure. The ability to test existing infrastructure under actual field conditions bridges the gap in the transformative tools needed for the next frontier of resilient and sustainable natural-hazards research. Further, these unique facilities are available to any NSF-funded research. The field shakers and support equipment are described. Examples of on-going and future projects in three key areas of investigation that NHERI@UTexas is targeting are presented. These examples includes: (1) performing more accurate 2D/3D subsurface geotechnical imaging up larger depths, (2) characterizing liquefaction resistance and non-linear dynamic behavior *in situ* soils, and (3) developing *in-situ* methods non-destructive soil-foundation-structure interaction (SFSI) studies.

**Keywords: NHERI@UTexas, mobile shakers, *in situ* testing, subsurface imaging, liquefaction testing, soil-structure interaction**



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## INTRODUCTION

The Natural Hazards Engineering Research Infrastructure (NHERI) Program is the United States National Science Foundation (NSF) program for the continued development and operation of a network of large-scale facilities used to support natural hazards engineering research. Originally established by NSF under the Network for Earthquake Engineering Simulation (NEES) in 2000, the large-scale facility at the University of Texas at Austin (UT), then named NEES@UTexas, was renamed NHERI@UTexas on January 1, 2016 under the NHERI program. A key feature of the NEES program, and now the NHERI program, is the nationally distributed shared use facilities to support natural hazards engineering research. Experimental and computational resources provided by these shared use, NSF-supported facilities, as well as data collected from associated research projects, are made available to the broader research community. From 2000 to 2014, NEES@UTexas supported 30 shared-use projects and more than 25 non-shared-used projects. NHERI@UTexas has continued this shared-use practice since 2016. Between 2016 and 2020, NHERI@UTexas supported 12 shared-use projects and more than 12 non-shared-used projects. Shared-use projects are research projects funded by the NSF. Any NSF support research projects can request to use NHERI@UTexas facility. Shared-use projects are typically led by researchers from other universities, sometimes in cooperation with researchers from UT. These research projects often involve developing new testing techniques for specific goals. From designing the field studies, developing and constructing sensors, conducting the field tests, to uploading and analyzing data, each project lasts about 1 to 3 years. Non-shared-use projects have not been supported by NSF and have typically been conducted by researchers at UT. These type of projects are often service oriented and often last about 6 months. In this article, the equipment capabilities at NHERI@UTexas are discussed, and key areas of investigation and example shared-use projects are presented. These examples showcase how NHERI@UTexas equipment contribute to advancements in various areas of research. More information about NHERI@UTexas and the NSF-supported NHERI program can be found at https://utexas.designsafe-ci.org/.

## OVERVIEW OF NHERI@UTexas

Natural Hazards Engineering Research Infrastructure experimental facility at the University of Texas provides unique large, mobile dynamic shakers and associated instrumentation for *in-situ* testing of civil infrastructure. These innovative field testing methods can be used to evaluate behavior of existing infrastructure and to enhance the design of future infrastructure, which will contribute to the development of more resilient communities. While laboratory shake table at both small and large scales provide valuable insights into dynamic infrastructure behavior, focusing on these methodologies exclusively, without the ability to test real structural and geotechnical systems under actual field conditions, would leave a significant gap in the transformative tools needed for the next frontier of natural hazards research.

The equipment available at the NHERI@UTexas experimental facility includes: (1) five large, hydraulically controlled shakers mounted on mobile platforms (i.e., trucks) that can provide wide-band dynamic excitation sources for geotechnical and structural systems, (2) a tractor-trailer necessary to transport the four largest shakers, (3) a field supply truck with resources for mobile shaker maintenance and refueling in the field, (4) an instrumentation van that houses data acquisition systems and power generators, (5) an air-conditioned instrumentation trailer that serves as a work space in the field, and (6) collection wide array of field instrumentation, data acquisition systems, and various sensors for measuring vibrational motions and pore water pressures (Stokoe et al., 2017).

The five mobile shakers, shown in **Figure 1** and summarized in **Table 1**, are named (1) T-Rex, (2) Liquidator, (3) Raptor, (4) Rattler, and (5) Thumper, The force and frequency generation capabilities of these shakers are shown in **Figure 2**. The two heaviest shakers are T-Rex (29,000 kg) and Liquidator (32,800 kg). T-Rex (**Figure 1a**) can generate large dynamic forces in any of three directions (vertical, horizontal in-line, and horizontal cross-line), where the shaking direction can be changed with a simple push of a button by the operator. The shaking system, mounted on an off-road, all-wheel-drive vehicle, can produce a maximum force output of around 267 kN in the vertical direction, and around 134 kN in each horizontal direction, as shown in **Figures 2A,B**, respectively. In addition to T-Rex's shaking capabilities, it can also: (1) push cone penetrometers and other custom-made vibration and/or pressure-sensing instrumentation into the ground using a hydraulic ram located on the rear bumper of the vehicle (shown in **Figure 3d**), and (2) perform pull-over tests of large-scale structural models in the field using a hydraulically operated winch on the front bumper of the vehicle. In total, T-Rex's capabilities make it unique in the world. Liquidator (**Figure 1b**) is a unique, custom-built shaker designed specifically for low-frequency, large-motion operation. To change the shaking direction from the vertical mode to the cross-line horizontal (shear) mode requires approximately two working days at the manufacturer's facilities in Tulsa, OK. The shaker can generate a maximum force output of approximately 89 kN in either mode down to a frequency of 1.3 Hz, as shown in **Figure 2**. However, a modified configuration where the entire off-road mobile platform is lifted off the ground and oscillates in the vertical mode allows Liquidator to generate maximum forces of 89 kN down to a frequency of 0.7 Hz. Below 0.7 Hz, the force level decreases but is still substantial to about 0.3 Hz. This modification provides unique capabilities that can facilitate deeper (1 km or more) active-source subsurface imaging (Stokoe et al., 2019). Like T-Rex, the Liquidator shaking system is also housed on an off-road vehicle with hydraulic penetrometer/instrumentation pushing capabilities mounted on the rear steel bumper of the vehicle and a wench with pull-over capabilities mounted on the front steel bumper. Use of these pull-over capacities are illustrated in field studies with 1/4-scale bridge bents by Stokoe et al. (2017).

Raptor and Rattler provide intermediate-level force generation. Raptor (**Figure 1c**) is called a compression-wave (P-wave) shaker in the geophysical exploration community. The maximum vertical force output is about 120 kN, as shown in **Figure 2A**. Raptor is ideal for situations where Thumper's force output (discussed below) is not sufficient for the desired testing application and T-Rex's triaxial shaking capability and/or higher force output is not required. Rattler (**Figure 1d**) is a horizontal (shear-wave) vibrator mounted on an off-road vehicle. Rattler has a frequency-force response which similar to T-Rex in the shear mode, as shown in **Figure 2B**. By having two shear-wave vibrators (T-Rex and Rattler), they can be used simultaneously with synchronized force outputs to generate a larger surface area of high shear strains. Thus, for *in-situ* liquefaction and non-linear soil testing, soil beneath the two shakers, where the instrumentation is placed, can be excited in a nearly plane-strain condition. T-Rex and Raptor can also be used in tandem to create similar conditions in the vertical direction. Since T-Rex, Liquidator, and Rattler are not street-legal, the 26-wheel, tractor-trailer rig, called the Big Rig and shown in **Figure 1f**, can be used to transport them to the test site.

Thumper (shown in **Figure 1f**) is the smallest shaker and is mounted on a street-legal truck and has a moderate force


**FIGURE 1 |** Photographs of the five mobile shakers and tractor-trailer rig available at NHERI@UTexas: **(a)** High-force, three-axis shaker called T-Rex, **(b)** Low-frequency, two-axis shaker called Liquidator, **(c)** Single-axis, vertical shaker called Raptor, **(d)** Single-axis, horizontal shaker called Rattler, **(e)** Urban, three-axis shaker called Thumper, and **(f)** Tractor-trailer rig, called the Big Rig, with T-Rex (after Stokoe et al., 2017).

**TABLE 1 |** Key features of these five shakers available at NHERI@UTexas.

| Shaker | Vehicle type | Shaking direction: main (transformable) | Max. output: main (transformable) |
|---|---|---|---|
| T-Rex | Off-road vehicle | Vertical (Horizontal in-line and cross-line) | 267 kN (134 kN) |
| Liquidator | Off-road vehicle | Vertical (Horizontal cross-line) | 89 kN (89 kN) |
| Raptor | Highway legal | Vertical | 120 kN |
| Rattler | Off-road vehicle | Horizontal cross-line | 134 kN |
| Thumper | Highway legal | Vertical (Horizontal in-line and cross-line) | 26.7 kN (26.7 kN) |

output, making it ideal for testing in urban areas. The maximum force output of Thumper in the vertical or horizontal directions is about 27 kN, as shown in **Figure 2**. With around 2 h of work in the field, Thumper's shaking direction of shaking can be changed at the test site. Hydraulic take-off connections are provided on T-Rex, Liquidator, and Thumper, which can be used to power other hydraulic equipment. For example, they could be used to run linear hydraulic actuators for *in-situ*, pushover or pullout testing of superstructure and substructure subassemblages in the field (Stokoe et al., 2017). The hydraulic shakers on the T-Rex, Liquidator, and Thumper vehicles can also be removed and mounted on a structure, while the hydraulics and electronics on the associated truck can be used to run the shaker.

Some of the NHERI@UTexas instrumentation and field support vehicles are shown in **Figure 3**. The supply truck, shown in **Figure 3a**, carries fuel and spare parts for the shaker trucks. Additionally, there is a customized Ford cargo van (not shown in **Figure 3**) and a 2.4 m by 4.8 m instrumentation trailer (shown in **Figures 3a,b**) that both provide an air-conditioned workspace, data acquisition systems, and electrical power.

The NHERI@UTexas facility also has a significant amount of field instrumentation, including: (1) two primary data acquisition systems (discussed below), (2) 85 1-Hz vertical geophones (**Figure 3c**), (3) 24 1-Hz horizontal geophones, (4) 6 high-capacity dynamic load cells, (5) 18 triaxial MEMS accelerometers, (6) cone penetrometer test (CPT) equipment and seismic CPT equipment (**Figure 3d**), and (7) 12 120-s Trillium Compact broadband seismometers (**Figure 3f**).

The two main data acquisition systems are a 64-channel Data Physics spectrum analyzer system and 10 three-channel Nanometrics Taurus digitizers (with 30 channels in total). The Data Physics system uses the SignalCalc 730 software to generate input signals (sinusoidal, stepped-sine, white noise, frequency sweeps, etc.) that drive the mobile shakers and to record output signals from various sensors. The Data Physics system (shown in **Figure 3e**) consists of three dynamic signal analyzers, which have a total of 64 channels. The Data Physics analyzers can be set up

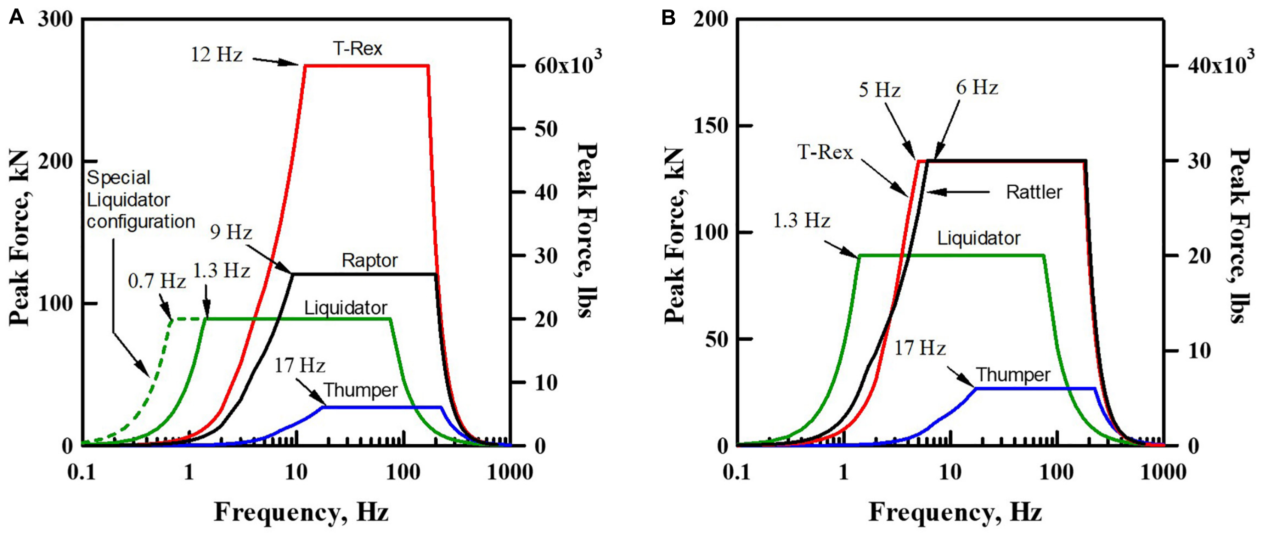


**FIGURE 2 |** Theoretical force outputs of the five mobile shakers at NHERI@UTexas in the: **(A)** vertical mode and **(B)** horizontal mode (Stokoe et al., 2017).


**FIGURE 3 |** Photographs of the field supply truck, mobile instrumentation trailer and some associated instrumentation available at NHERI@UTexas: **(a)** Field supply truck and instrumentation trailer, **(b)** Air-conditioned work space in instrumentation trailer, **(c)** 1-Hz vertical geophones and cables, **(d)** Cone penetrometer test equipment, **(e)** Data Physics analyzers, and **(f)** Trillium Compact Seismometers and Taurus Digitizers (after Stokoe et al., 2017).

as three separate units with different sampling rates, or they can be linked together as a single system. The Data Physics spectrum analyzers have the capacity to record data for hours of time at a high sampling rates up to 200,000 Hz. The Data Physics control software can also be used to perform real-time frequency domain calculations and display auto-power spectra, transfer functions, coherency, and phase plots to facilitate reviewing and analyzing data in the field.

If a distributed sensor array is required for a field study, e.g., with sensors hundreds of meters to a km apart, such as for passive surface wave testing and topographic amplification studies, the Nanometrics Taurus digitizers and Trillium seismometers can be used, as shown in **Figure 3f**. The 10 Taurus digitizers are solar powered, self-sustaining recording stations for three-dimensional (3D) motions. While designed for long-term deployments such as aftershock monitoring, but can also be used for any type of data acquisition where distributed, GPS-synchronized digitizers are required. Other types of sensors can also be connected to the Nanometrics Taurus digitizers, for example, to monitor strain or displacements of buildings and bridges.

## TEST SITE NEAR AUSTIN, TX FOR DEVELOPMENTAL, PROTOTYPE AND SHORT-TERM, FULL-SCALE PROJECTS

Many of the field experimental studies that use the large-scale mobile shakers and associated field equipment at NHERI@UTexas are located outside of the state of Texas, and even some studies have been located outside of the mainland of the United States. The reasons for these remote locations relative to Austin, TX are that the specific ground conditions in particular areas and/or the permanent structures at given locations are the focus of the investigation. **Figure 4** shows the previous test locations of NHERI@UTexas mobile shakers since 2004. To lower costs associated with traveling to remote sites, trial studies are often conducted at a local test location called the Hornsby Bend (HB) site. The HB site is located southeast of Austin, about 3.5 km north of the Austin-Bergstrom International Airport. The site, shown in **Figure 5a**, bordered by the Colorado River. Some open areas on the HB site (highlighted in **Figure 5a**) are permitted to be used by NHERI@UTexas to conduct research studies related to civil infrastructure projects.

In the past 12 years, NHERI@UTexas has conducted field studies at three locations at the HB site. These three sites are marked as Test Location 1 (TL1), Test Location 2 (TL2), and Test Location 3 (TL3) in **Figure 5b**. TL1 is on a large open field. This site is an ideal location for short-term (1 to 3 weeks long) seismic studies that require a large open field. TL2 is located on the north end of the site. Multiple studies have constructed specimens and conducted long-term tests (3 months or longer) at TL2. TL3 is located at the edge of the test field near TL1. Long-term studies are also possible in this area. A photograph taken during installation of a periodic barrier at TL2 is shown in **Figure 5b**. CPT, Spectral-Analyses-of-Surface-Waves (SASW), and crosshole seismic tests were conducted at multiple locations in the HB site, and all results are available to researchers.

## KEY AREAS OF INVESTIGATION

The science plan of NHERI@UTexas is focused on three main challenges. These three main challenges are: "(1) performing deeper, more accurate, higher resolution, 2D/3D subsurface geotechnical imaging, (2) characterizing the non-linear dynamic

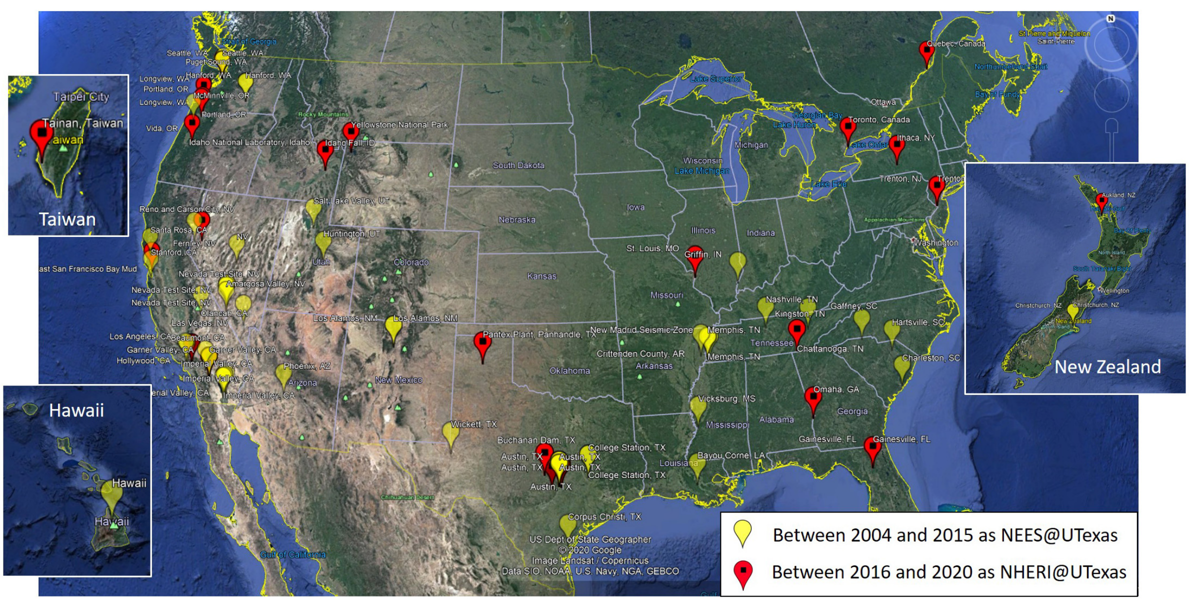


**FIGURE 4 |** Previous test locations of NHERI@UTexas mobile shakers since 2004 (from Google Earth).

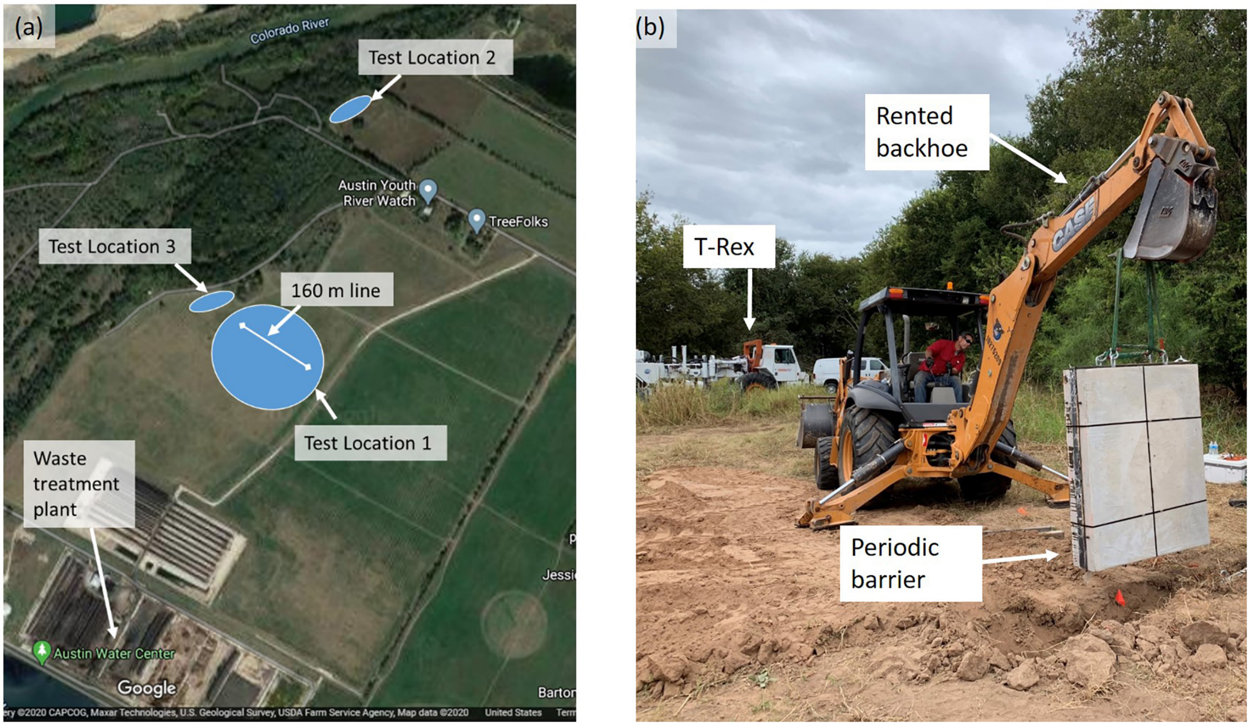


**FIGURE 5 |** A photograph and a satellite image of the Hornsby Bend (HB) site: **(a)** Satellite image of the HB site (located about 3.5 km from the Austin-Bergstrom International Airport) and **(b)** A photograph taken during installation of a periodic barrier at TL2 (from Google Maps).

response and liquefaction resistance of complex geomaterials *in situ*, and (3) developing rapid, *in-situ* methods for non-destructive structural evaluation and soil-foundation-structure interaction (SFSI) studies" (Stokoe et al., 2017). We know these challenges are significant, yet we know that the unique equipment resources of NHERI@UTexas can be used to help address them. Below, we describe progress that has been made in each of these areas over the past 4 years using NHERI@UTexas equipment is described, and some of the goals for the future are discussed.

## Performing Deeper, More Accurate, Higher Resolution, 2D/3D Subsurface Geotechnical Imaging

Imagine the limitations of current medical practice without accurate and rapid methods to look inside the body non-intrusively, such as X-ray/CAT Scan, Ultrasound and MRI technologies. Now consider that ultrasound imaging was not widely used in the United States until the 1970s, yet today parents can go to a shopping mall to obtain a color, 3D ultrasound of their yet-to-be-born baby. Amazing! Is it possible that we could make similar strides in subsurface imaging for engineering purposes over the next few decades? Imagine how the ability to develop realistic 3D images of the subsurface, with accompanying elastic properties (shear modulus/$V_s$, constrained modulus/$V_p$, Poisson's ratio, etc.), would influence engineering for more resilient and sustainable infrastructure. The equipment required to make significant progress toward this goal exists within the NHERI@UTexas facility.

While many examples could be given, we will focus on two main areas where advanced subsurface imaging capabilities would help "transform how future civil infrastructure will be designed and how existing civil infrastructure might be rehabilitated": (1) improved site-specific subsurface models for earthquake ground motion prediction, and (2) continuous 2D/3D *in-situ* profiling for anomaly detection.

### Improved Site-Specific Subsurface Models for Ground Motion Prediction

Many recent studies have used multi-depth earthquake ground motion recordings from vertical borehole array sites to investigate our ability to accurately replicate small-strain, linear-viscoelastic site response (i.e., the simplest case, which does not require modeling of soil non-linearity). While these studies have found that 1D ground response analyses (GRA's) can replicate recorded site response at a few borehole array sites, they have also shown that engineers are generally unable to accurately replicate recorded ground motions at most borehole array sites using available subsurface geotechnical information and 1D GRA's (e.g., Thompson et al., 2009, 2012; Kaklamanos et al., 2013, 2015; Afshari and Stewart, 2015, 2017; Kaklamanos and Bradley, 2018; Teague et al., 2018). When 1D GRA's fail to yield accurate predictions of recorded site response, the site is often assumed to be too complex to be accurately modeled as 1D. While 3D numerical GRA's are possible, there is rarely a true 3D subsurface model that can be used in these analyses. Indeed, even at our most valued borehole array sites in the United States and Japan, we are limited to 1D representations of $V_s$. This short coming has to change in order for progress to be made in predicting earthquake ground motions.

A recently funded NSF project titled "Collaborative Research: 3D Ambient Noise Tomography (3D ANT) for Natural Hazards Engineering" (Award Number 1930697, PI: K. Tran) is a good example of how advances in 3D subsurface imaging are being investigated using NHERI@UTexas equipment. While the project is still in its early stages, some progress has been made toward the goal of developing a deeper and more spatially extensive 3D $V_s$ model of the Garner Valley Downhole Array (GVDA) site. In October 2019, NHERI@UTexas personnel used Thumper as a high-fidelity controlled seismic source for a full waveform inversion (FWI) study at GVDA. In this study, 196 3-component land seismic sensors were deployed in a 65 m × 65 m array with a uniform 5 m receiver spacing (**Figure 6a**). The NHERI@UTexas Thumper shaker truck was used to generate broadband frequency sweeps at 84 locations inside and outside of the array. The ultimate goal of this research is to combine the active-source data from Thumper with passive-wavefield ambient noise to generate a 3D $V_s$ model of the site with meter-scale resolution over the top 50- to 100-m of the subsurface. This 3D model has not yet been completed, but the spatial variability of the fundamental site frequency ($f_0$) at GVDA is shown in **Figure 6b**. From the variability in $f_0$, it is clear that the GVDA site is not 1D. As such, a true 3D $V_s$ model is needed to support 3D GRA's at this important borehole array site. The call for deeper and more accurate subsurface models for use in seismic ground motion studies continues to grow louder. These types of 3D models, or refinements to pseudo-3D models, are needed beneath many United States cities in high seismicity areas that are underlain by sedimentary basins, such as Los Angeles, Seattle, and Salt Lake City.

## Continuous 2D/3D *in-situ* Profiling for Anomaly Detection

The ability to rapidly and non-intrusively image the subsurface in 2D/3D for the purpose of site characterization and anomaly detection would be a major scientific and engineering breakthrough. Unknown subsurface anomalies (e.g., cavities/voids, soft/weak zones, dipping layers, buried objects) cause significant problems during and after construction of many types of civil infrastructure [e.g., roads, bridges, buildings, levees, and tunnels; Sirles (2006)]. Consider for example our nation's levee systems, comprising roughly 100,000 miles of earth embankments designed to protect communities from flooding. This aging levee system is susceptible to damage from natural hazards such as flooding, hurricane inundation, and earthquakes, and the cost to repair or rehabilitate these levees is estimated to be over US$100 billion (ASCE, 2013). The ability to rapidly and reliably evaluate our nation's levee systems to find anomalies and weak zones would greatly increase the resilience of our civil infrastructure in a cost-effective way. The NHERI@UTexas equipment help address this 2D/3D imaging problem.

Full waveform inversion methods are the most promising way to obtain true 2D/3D subsurface seismic images for engineering purposes. The primary goal of FWI is to reconstruct the near-surface material profile of arbitrarily heterogeneous formations, in terms of the formation's spatially distributed elastic properties, using stress waves as the probing agent (Kallivokas et al., 2013). FWI is a challenging data-fitting procedure based on full-wavefield modeling to extract quantitative information from all wave types in the recorded seismograms (Virieux and Operto, 2009). FWI requires both a densely spaced grid of sensors

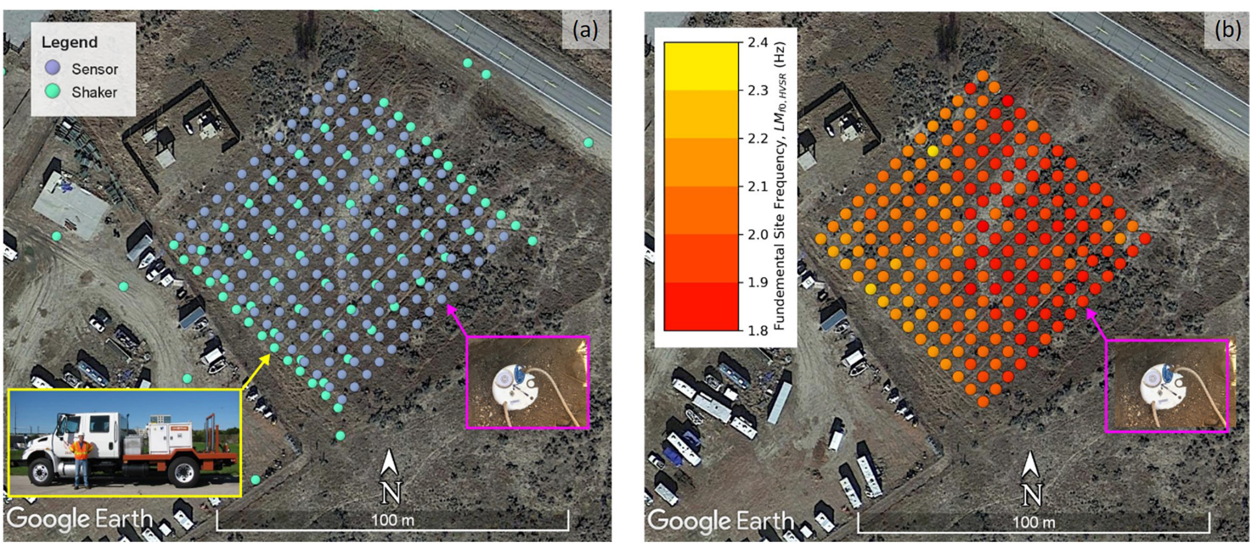


**FIGURE 6 |** Garner Valley Downhole Array (GVDA) site: **(a)** 196 3-component land seismic sensors deployed in a 65 m × 65 m array with a uniform 5-m receiver spacing and the NHERI@UTexas Thumper shaker truck that was used to generate broadband frequency sweeps at 84 locations inside and outside of the array, and **(b)** spatial variability in fundamental site frequency ($f_0$) indicating 3D site conditions.

and multiple excitation locations from a broadband seismic source, both of which are provided as part of the proposed NHERI@UTexas equipment.

As a means to illustrate progress that is being made in this area, 3D FWI imaging results that were obtained as part of an NSF project titled "Geotechnical Site Characterization with 3D Seismic Waveform Tomography" are presented (Award Number 1850696, PI: K. Tran). Also note that the imaging data for the results presented below, and published in Tran et al. (2020), were collected as part of a NHERI@UTexas user workshop that was held in Newberry, Florida. The Newberry Site consists of medium dense, fine sand and silt underlain by highly variable and karstic limestone, the top of which varies from 2- to 10-m depth across the site. Seismic surveys at the site were conducted by Prof. Tran and the NHERI@UTexas team using 48, 4.5-Hz vertical geophones located in a 4 × 12 grid at 3 m spacing on the ground surface. The seismic energy was created at 65 source locations by the NHERI@UTexas Thumper shaker truck. The final inverted 3D $V_p$ and $V_s$ models, which are 18 m deep × 36 m long × 12 m wide, are shown in **Figure 7**. The velocity models indicate soft soil layers at shallow depths, underlain by a stiffer weathered limestone layer of variable depth. Several potential voids were identified in the images. In **Figure 7**, the standard penetration test (SPT) *N*-values that were collected from a borehole drilled to verify one of the void are also shown. The *N*-values confirmed that a void does exist in the depth range from about 4 to 7 m.

Although these 3D FWI results are excellent, they are limited in terms of their depth of investigation. Future research is needed using the more powerful, low-frequency, active-source mobile shakers of NHERI@UTexas to extend the depth range of FWI for both ground motion studies and subsurface anomaly detection. Furthermore, FWI has the potential to reveal *in-situ* material damping, which has heretofore been the "holy grail" of *in-situ* site characterization. However, while significant progress has been made recently toward quantifying uncertainty from non-intrusive surface wave testing (e.g., Vantassel and Cox, 2020), research about quantifying uncertainty in FWI is virtually non-existent. This topic is another area where significant progress remains to be made. Just as in medical imaging, the potential for transformative impact on the design and rehabilitation of civil infrastructure is huge if rapid, 2D/3D *in-situ* subsurface imaging can be achieved.

## Characterizing the Non-linear Dynamic Response and Liquefaction Resistance of Complex Geomaterials *in situ*

Natural geotechnical materials, soil and rock, represent a significant fraction of all materials that impact the performance of our nation's infrastructure during earthquakes and other natural hazards, such as hurricanes and floods. For example, consider the devastating effects of soil liquefaction and site amplification in almost every significant earthquake. The role of geotechnical materials in hurricanes and floods is also important, and generally controlled by a combination of compacted soils that form levees, dams, or dikes and the underlying natural materials. Poor performance of levees during hurricanes, for instance, can adversely affect large areas due to inundation, such as the failure of levees around New Orleans, LA during Hurricane Katrina in 2005. Unfortunately, natural geotechnical materials are the least investigated, most variable, and least controlled of all materials that form part of the United States infrastructure inventory (Coduto et al., 2015). Therefore, a significant challenge to making our infrastructure resilient and sustainable is characterizing the non-linear dynamic response and liquefaction resistance of complex geomaterials *in situ*.

Non-linear dynamic soil properties are required in predicting the response of geotechnical and structural systems during earthquakes and hurricanes. The non-linear properties most often required are: (1) the variation of shear modulus (G) and material damping ratio in shear (D) with shear strain ($\gamma$), and (2) how these properties vary with soil type and number of cycles of loading. These properties are typically expressed as G-log $\gamma$ and D-log $\gamma$ relationships, since shear strains induced during natural hazards can easily range over a factor of 1000 (from below 0.001% to above 1.0%). Before the NEES/NHERI programs at NSF, these dynamic soil properties could not be measured in the field because of the inability to generate controlled, sinusoidal loading over a wide range of strains and number of cycles in the field. Therefore, the field G-log $\gamma$ and D-log $\gamma$ relationships were empirically estimated by combining large-strain non-linear measurements from small-scale dynamic laboratory testing of intact or reconstituted soil specimens with limited, low-strain, field seismic testing.

Over the past 16 years, the NEES /NHERI@UTexas mobile shakers have been used to initiate and continue development of a generalized, staged-loading approach by which G-log $\gamma$ and pore-water pressure–log $\gamma$ relationships can be measured *in situ*. This type of *in-situ* parametric testing is needed: (1) to understand the limitations of the empirical approach, and (2) because many geotechnical materials cannot be readily, or cost-effectively, tested in the laboratory. These materials include: gravelly soils, cemented alluvium, municipal solid waste, and loose gravelly, sandy, and silty soils with non-plastic or plastic fines that are prone to liquefaction. The generalized staged-testing approach involves creating an array of the appropriate sensors in the target material and shaking this material with some type of surface "loading platen."

In the past 4 years, NHERI@UTexas has been developing two new testing techniques, which focus on increasing the maximum strain level in the instrumented soil zone at depth. The first new technique utilizes two mobile shakers carefully phased together to generate vibration on top of the instrumentation array (after Zhang et al., 2019). This technique was tested in a recent field liquefaction project in the Port of Longview, WA to investigate the liquefaction susceptibility of silty soils. As shown in **Figure 8a**, T-Rex and Rattler were parked side by side on top of an instrumented array. The vibrational outputs of T-Rex and Rattler were synchronized so that shear strains generated in the instrumented array from both shakers were added on top of each other. An example of the curve of excess pore-water pressure ratio ($r_u$) versus shear strain for this site is shown in

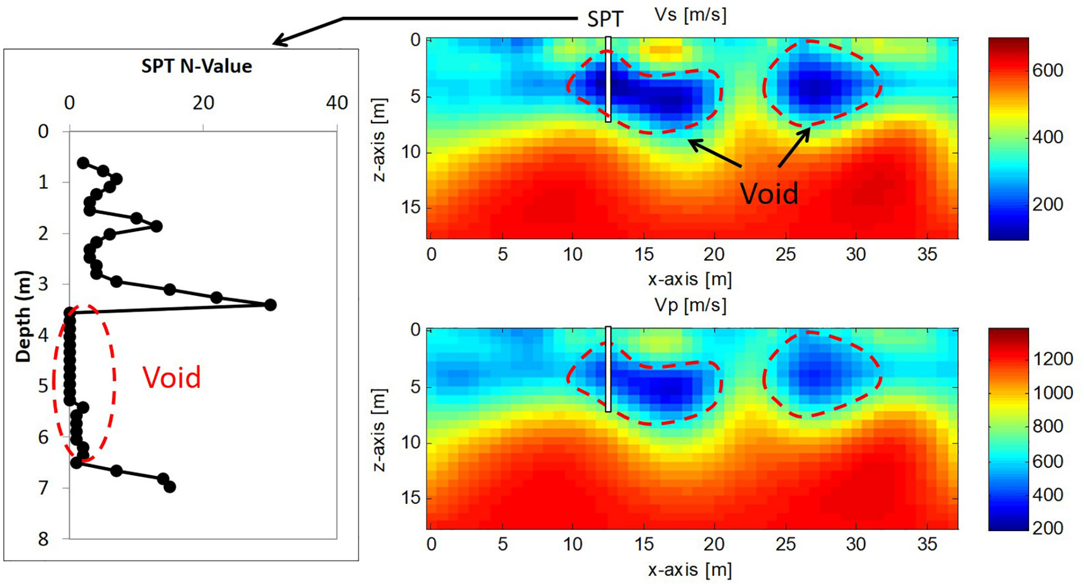


**FIGURE 7 |** Comparison of FWI seismic and invasive SPT. The inverted Vs and SPT results both show a void at about 4–7 m depth and top of bedrock at 7 m depth (after Tran et al., 2020).

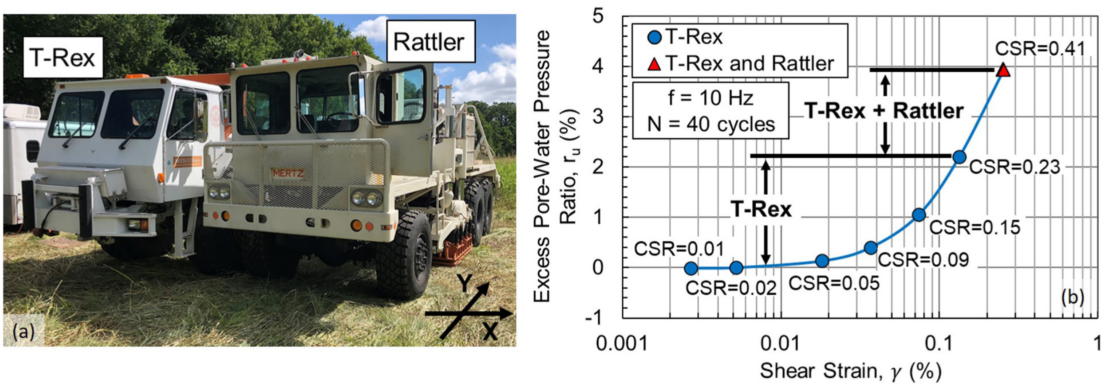


**FIGURE 8 |** Combined synchronized loading with T-Rex and Rattler in field shaking tests: **(a)** T-Rex and Rattler parked side by side and **(b)** Improved dynamic loading creates larger strains (after Zhang et al., 2019).

**Figure 8b**. Utilizing two mobile shakers approximately doubled the induced shear strain level, compared to using only one mobile shaker. The second new technique is still under development. This technique will utilize a large –diameter, 3-to-4 flight auger to transfer shear deformations to a deeper depth, as shown in **Figure 9**. In a proposed study scheduled for 2021, the large auger (about 1.5 m in diameter) will be used to transfer energy from the mobile shaker on the ground surface to the testing depth. With this setup, we expect that the maximum shear strain can reach 0.4% to a depth of 4 m or more below the ground surface.

Two recent NSF projects have focused on using NHERI@UTexas equipment to help evaluate new bio-mediated ground improvements methods to mitigate soil liquefaction. A project titled “RAPID Field Assessment of microbially induced carbonate precipitation (MICP)/microbially induced desaturation and precipitation (MIDP) Test Sections” (Award Number 1449501, PI: E. Kavazanjian) investigated soils treated using both the MICP method, and the MIDP method in Toronto, Canada. Results show a limited increase in soil stiffness from both methods. However, the MIDP method was proven effective in de-saturating both sandy and silty soils, and the desaturation was achievable in the field, as shown in **Figure 10** (Stokoe et al., 2020). The success of this study paved the way for a second study in Portland, OR on a project titled “RAPID Liquefaction Mitigation of Silts using MIDP and Field Testing with NHERI@UTexas Large Mobile Shakers” (Award Number 1935670, PI: A. Khosravifar). Continued monitoring of the desaturation level at this site by crosshole measurements

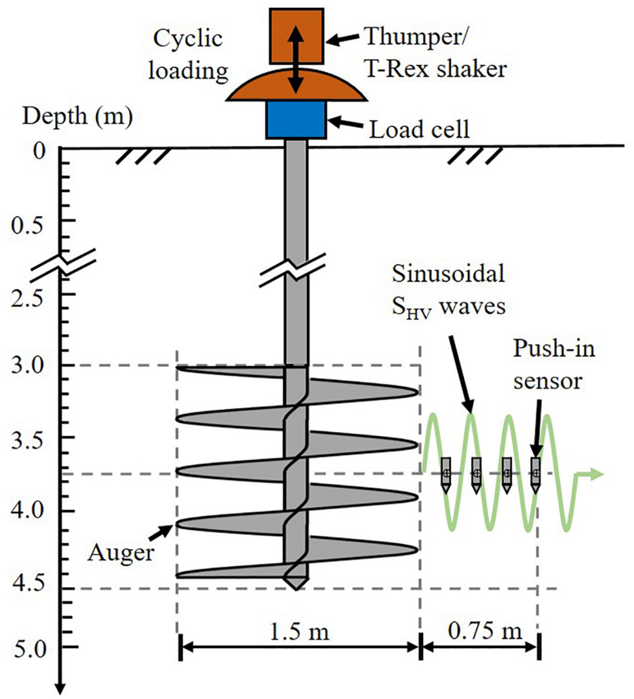


**FIGURE 9 |** Schematic of deep *in-situ* liquefaction testing using an auger.

for about 9 months after the end of treatment indicates that desaturation is persisting.

## Developing Rapid, *in-situ* Methods for Non-destructive Structural Evaluation and Soil-Foundation-Structure Interaction (SFSI) Studies

The NHERI@UTexas equipment can also be used to test structural engineering systems in the field. The vast majority of structural engineering experimental research comprises quasi-static, pseudo-dynamic, or shake table testing to characterize the performance and non-linear behavior of structural specimens with idealized boundary conditions. These types of tests, however, tend to ignore or overly idealize complex SFSI behavior that can affect performance of civil infrastructure systems. Experimental research addressing SFSI often involves small-scale structural models (with model-to-prototype scales on the order of 1:30 to 1:100) excited on a shake table or in a centrifuge in containers of perfectly uniform soil. Such small-scale specimens may not reflect realistic construction methods or structural materials and only consider a limited range of perfect soil conditions. While scaled and idealized laboratory experimental research programs are needed to better understand structural behavior, the NHERI@UTexas equipment provide capabilities to test complex, *in-situ* structure-foundation-soil systems in a range of soil conditions. The NHERI@UTexas shakers can be used to test soil-foundation-structure systems in a variety of ways, including indirect excitation of the structure, by shaking the soil; direct excitation, by driving the shaker onto the structure or by removing the shaker from the truck and attaching it directly to the structure; or by facilitating quasi-static test methods in the field. The shakers were initially designed primarily for use in testing geotechnical systems, such that the larges force outputs are in relatively high frequency ranges compared to most structural systems. Based on the maximum force vs. frequency output of each of the shakers, the shakers may not be able to provide sufficient dynamic excitation to elicit non-linear, damaging behaviors in large-scale structure, which may desirable if testing in-service infrastructure. If needed, smaller-scale structural specimens can be designed considering the shakers' force vs. frequency output capacities if non-linear behavior is of interest.

A NSF-funded project titled "EAGER: Informing Infrastructure Decisions through Large-Amplitude Forced Vibration Testing" (Award Number 1650170, PI: N. Gucunski) is an example of using the mobile shakers for direct and indirect dynamic testing of a soil-foundation-structure system in the field. The researchers in this study hypothesized that conventional approaches for structural identification using low-force or ambient vibrations do not provide sufficient excitation to investigate soil-foundation interactions or to overcome unintended composite action and stick-slip mechanisms in the structure. Thus, larger, controlled shaking levels, such as those provided by the NHERI@UTexas shakers, are needed for more robust field investigation of dynamic SFSI on large-scale structures. To this end, the T-Rex shaker was employed to dynamically test a soil-foundation-structure system, in this case an overpass bridge, located in Hamilton Township, New Jersey. T-Rex was used to input vertical, longitudinal, and transverse shaking at various locations on the bridge deck and on the ground around the bridge. 3D geophones and accelerometers were placed at various locations on the deck, bent, abutment, and ground to measure the 3D responses (**Figure 11**).

Key findings from this study (Farrag et al., 2018, 2019a,b) include evaluation of the effects of controlled, low-level shaking compared to conventional ambient vibrations, as well as evaluation of dynamic SFSI through comparison with numerical models. **Figure 12** shows an example of how forced vibrations from T-Rex are better at capturing key dynamic structural behaviors, such as transverse rocking (as indicated by the 180 degree phase angle in **Figure 12A**), compared to ambient vibrations (**Figure 12B**). Additionally, numerical models simulating dynamic SFSI behaviors via frequency-dependent translational and rotational springs at the base of the bridge piers were better able to capture the two dominant modes of lateral vibration observed during the forced-vibration tests, compared to conventional modeling approaches using fixed-base supports. While this test program was a successful demonstration of using mobile shakers to better understand SFSI effects in large-scale structures, further *in-situ* field testing of complex systems is necessary to better address research needs related to structure-foundation-soil system behavior and *in-situ* structural dynamic evaluation.

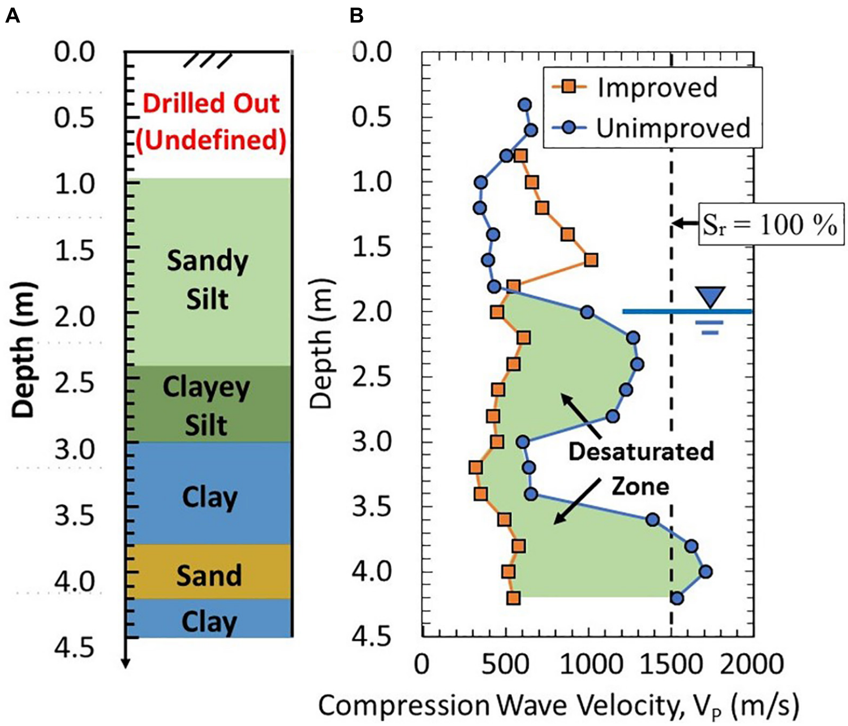


**FIGURE 10 |** Soil-type and P-wave velocity profiles showing the effectiveness of the microbially induced desaturation and precipitation (MIDP) method to desaturate natural soils: **(A)** Soil-Type Profile Based on CPT Data and **(B)** P-Wave Velocity Profiles (Stokoe et al., 2020).

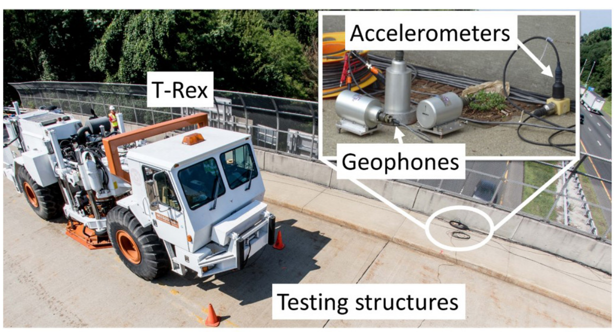


**FIGURE 11 |** T-Rex structural testing with 3D arrays of geophone and accelerometers.

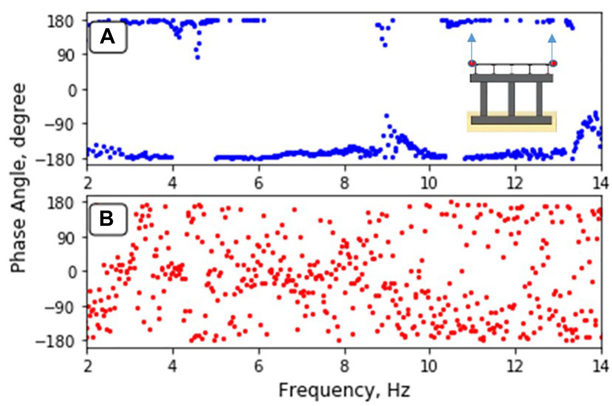


**FIGURE 12 |** Phase angles between the vertical response of the east and west sides of the bridge deck under **(A)** lateral transverse loading from T-Rex and **(B)** ambient vibrations.

## SUMMARY

Specialized, mobile field equipment that is available at the NHERI@UTexas equipment facility for dynamically and/or cyclically loading of the natural and built environments is presented in this article. Five large, hydraulically controlled shakers, a tractor-trailer to transport the largest shakers, field-support vehicles, and a large collection of field instrumentation and sensors are available to researchers around the world through the NSF NHERI shared-use policy. The science plan of NHERI@UTexas is focused on three main challenges. These three main challenges are: "(1) performing deeper, more accurate, and higher resolution 2D/3D subsurface geotechnical imaging, (2) characterizing the non-linear dynamic response and liquefaction resistance of complex geomaterials *in situ*, and (3) developing rapid, *in-situ* methods for non-destructive evaluations and SFSI studies" (Stokoe et al., 2017). Examples of the uses of this unique equipment in these three areas as well as examples of improvements to the equipment to increase the field testing capabilities are presented.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

## ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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METHODS
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# Research Needs, Challenges, and Strategic Approaches for Natural Hazards and Disaster Reconnaissance

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Natural hazards and disaster reconnaissance investigations have provided many lessons for the research and practice communities and have greatly improved our scientific understanding of extreme events. Yet, many challenges remain for these communities, including improving our ability to model hazards, make decisions in the face of uncertainty, enhance community resilience, and mitigate risk. State-of-the-art instrumentation and mobile data collection applications have significantly advanced the ability of field investigation teams to capture quickly perishable data in post-disaster settings. The NHERI RAPID Facility convened a community workshop of experts in the professional, government, and academic sectors to determine reconnaissance data needs and opportunities, and to identify the broader challenges facing the reconnaissance community that hinder data collection and use. Participants highlighted that field teams face many practical and operational challenges before and during reconnaissance investigations, including logistics concerns, safety issues, emotional trauma, and after-returning, issues with data processing and analysis. Field teams have executed many effective missions. Among the factors contributing to successful reconnaissance are having local contacts, effective teamwork, and pre-event training. Continued progress in natural hazard reconnaissance requires adaptation of new, strategic approaches that acquire and integrate data over a range of temporal, spatial, and social scales across disciplines.

**Keywords: natural hazard, disaster, reconnaissance, instrumentation, simulation, data**

## INTRODUCTION

Natural hazards and disaster reconnaissance investigations have led to important discoveries that have greatly improved our scientific understanding of hazards and their physical, social, and environmental consequences. For example, findings from one of the earliest field reconnaissance missions in the United States, the Lawson and Reid (1908) investigation of the 1906 ∼M7.9 San Francisco earthquake, led to the development of the landmark theory of elastic rebound (Reid, 1910), among other significant scientific and engineering advancements (Ellsworth, 1990). More recently, post-event reconnaissance investigations have provided new, fundamental knowledge essential for the development of computational models to simulate the physical and socioeconomic impacts of natural hazards, and for identifying ways that communities can restore their infrastructure, rebuild their built environment, and recover their socioeconomic capital (e.g., Xiao and Van Zandt, 2012; Xiao and Peacock, 2014; Cong et al., 2018; Kang et al., 2018; Nejat et al., 2019). Far from an uncaring or indifferent data-gathering exercise in the face of tragedy, reconnaissance campaigns are at their core "a humanitarian mission in the broadest sense" (Kaplan, 2010).

Natural hazards, such as wind events (i.e., tornadoes and coastal storms, including wind-generated waves and surges), earthquakes (and secondary effects such as shaking-induced damage to buildings and infrastructure, soil liquefaction and co-seismic landslides, and tsunamis), landslides, and volcanic eruptions, produce an extraordinary volume and quality of data that can inform our preparation and response to future events (Nature Geoscience, 2017). Such data are often highly ephemeral or "perishable" since they may be altered or removed during rescue and recovery activities, or by natural agents such as precipitation or wind following an event. Therefore, reconnaissance data must be collected soon after an event occurs. These data are also unique because they inherently include the real-world complexities (e.g., the interplay between natural, human, and built systems) that allow us to better understand and quantify the socio-technical dimensions related to damage, restoration, and resiliency of the built environment; such data are difficult to duplicate in a traditional laboratory setting. Reconnaissance data, once collected, processed, curated, and archived (Rathje et al., 2017), may be used and reused for a range of purposes, including (i) making discoveries and gaining fresh insights, (ii) testing and verifying models, (iii) reducing uncertainties in probabilistic models, and (iv) inspiring new simulation models, including new data-driven methods (e.g., Loggins et al., 2019).

In the past, reconnaissance investigators collected data and documented field observations using conventional recording and measurement tools, such as photography, note-taking, and surveying (Geotechnical Extreme Events Reconnaissance [GEER], 2014). Today, the availability of state-of-the-art instrumentation, mobile data collection technologies (e.g., RApp; Miles and Tanner, 2018; Berman et al., in press), training, and field support services, such as those provided by the Natural Hazards Engineering Research Infrastructure (NHERI) Natural Hazards Reconnaissance Facility (known as the RAPID) (Wartman et al., 2018; Berman et al., in press), has significantly advanced the ability of field investigation teams to capture perishable data in post-disaster settings.

This article briefly reviews the current state of natural hazards and disaster reconnaissance, including highlights from recent missions, difficulties teams face, and opportunities for progress. It then examines the grand challenges facing the natural hazards community and presents new approaches to meet these challenges through the strategic design, planning, and execution of reconnaissance campaigns. Many of the ideas presented in the article were developed with input from key stakeholders, including participants of a 2-day reconnaissance workshop, previous and current users of RAPID facility instrumentation, and other disciplinary experts in the professional, government, and academic sectors.

## NATURAL HAZARDS AND DISASTER RECONNAISSANCE

The history of natural hazard and disaster investigations spans many centuries. Interest in natural hazards, frequently by religious scholars, gathered momentum during the Renaissance and Reformation (14th to 16th centuries) when authorities began systematically cataloging earthquakes and other rare events such as plagues (Schenk, 2007; Tülüveli, 2015). Scholars often used these data in an attempt to reconcile extreme events with spiritual beliefs and religious concepts. Lawson and Reid (1908) comprehensive, two-volume report on the San Francisco, California earthquake (**Figure 1**) is one of the first rigorous scientific field studies of a major natural hazard (Ellsworth, 1990). A decade later, Prince (1920) conducted one of the first social sciences investigations of an extreme event, the Halifax, Nova Scotia, Canada explosion of a munitions ship in the city harbor. Social sciences studies of disasters became more systematic and formalized in the 1940s through the 1960s, largely due to work at the Disaster Research Center (Ohio State University), which was initially supported by the U.S. Office of Civil Defense to inform cold war civil defense efforts (e.g., Knowles, 2012). Earthquake Engineering Research Institute [EERI] (1971) conducted one of the first in-depth multidisciplinary investigations of a natural hazard event, the San Fernando, California earthquake.

The EERI was one of the first professional organizations to formalize regular reconnaissance investigations of major seismic events by establishing the Learning from Earthquakes (LFE) program in 1973. Largely multidisciplinary in its approach, the LFE program deploys teams of geoscientists, engineers, and social scientists to investigate and observe the damaging effects of significant earthquakes worldwide. Recently, the LFE program has expanded to include a virtual earthquake reconnaissance teams, or "VERT," that conduct rapid "virtual" (i.e., non-field based) assessments within 48 h of an earthquake (Fischer and Hakhamaneshi, 2019).

With the support of the U.S. National Science Foundation (NSF), the Geotechnical Extreme Events Reconnaissance (GEER) Association was formed in 1999 to conduct reconnaissance investigations of the geotechnical aspects of significant

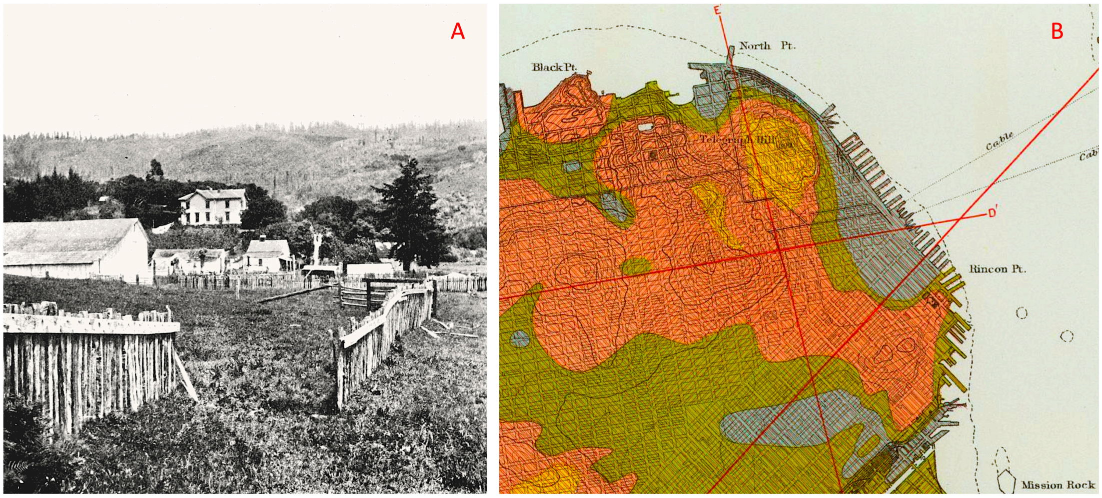


**FIGURE 1 |** The Lawson and Reid (1908) reconnaissance investigation of the 1906 San Francisco earthquake led to significant scientific and engineering advancements. **(A)** Reconnaissance photograph showing fence offset by earthquake surface fault rupture near Bolinas, Marin County, CA, United States. This observation led to the development of the theory of elastic rebound (Reid, 1910). **(B)** Excerpt of "Map of San Francisco showing apparent intensity of the earthquake shock" (Lawson and Reid, 1908) showing area of high intensity shaking revealing the modern engineering concept of non-linear site response and effects (Gray and green tones depict areas of highest local shaking intensity). Both images are reproduced from Lawson and Reid (1908).

earthquakes in the U.S. and abroad (Bray et al., 2019). In 2011, GEER's scope was expanded to include the study of the geotechnical aspects of other natural hazard events such as hurricanes, floods, and landslides (e.g., Dashti et al., 2014; Wartman et al., 2016; Hughes and Morales Vélez, 2017; Gallant et al., 2020; Montgomery et al., 2020). GEER authorizes research missions based upon (i) the opportunity to learn about new scientific hypotheses or engineering models, (ii) the availability of additional field data (e.g., ground motion recordings) to supplementary data gathered in the reconnaissance, and (iii), for international (non-U.S.) events, the potential for a similar event to occur in the future in the U.S (Geotechnical Extreme Events Reconnaissance [GEER], 2014). During the past several years, NSF began supporting other similar "extreme event reconnaissance (or research)," or EER, organizations including StEER (Structural Extreme Events Reconnaissance), OSEEER (Operations and Systems Engineering Extreme Events Research), SSEER (Social Science Extreme Events Research), ISEEER (Interdisciplinary Science and Engineering Extreme Events Research), NEER (Nearshore Extreme Events Reconnaissance), and SUstainable Material Management Extreme Events Reconnaissance (SUMMEER). These EER organizations are coordinated by CONVERGE (Peek et al., 2020), which seeks to advance ethically-grounded (Gaillard and Peek, 2019), scientifically rigorous, disciplinary, and interdisciplinary extreme events research.

There are other natural hazards reconnaissance organizations based at professional societies worldwide. The Earthquake Engineering Field Investigation Team (EEFIT), based in the United Kingdom, supports earthquake reconnaissance missions with the goals of making technical assessments, collecting geological and seismological data, assessing the effectiveness of earthquake protection systems, and investigating disaster management procedures and socioeconomic impacts (Stone et al., 2017). Italy hosts two organizations that have organized earthquake reconnaissance missions and conducted follow-on seismic policy analyses (e.g., Mazzoni et al., 2018), the Italian Network of University Laboratories for Earthquake Engineering (ReLUIS), and the European Centre for Training and Research in Earthquake Engineering (Eucentre). Elsewhere, the New Zealand Society for Earthquake Engineering (NZSEE) has supported reconnaissance investigations of earthquakes and major tsunamis worldwide for six decades (Wood P. R. et al., 2017). In Asia, the Asian Technical Committee (ATC3) "Geotechnology for Natural Hazards" has conducted reconnaissance missions following natural hazard events. Other organizations, such as the Nepalese Engineering Society, the Building Research Institute of Japan, among others, also conduct investigations in the region. Similarly, the American Society of Civil Engineers (ASCE) has supported reconnaissance missions in the U.S. and abroad through the primary society (e.g., Silva-Tulla and Nicholson, 2007) or its disciplinary institutes (e.g., Wartman et al., 2013).

In addition to these organizations, self-organized teams sometimes form in the aftermath of an event, often with a focused hypothesis-driven research question or inquiry, to collect data. **Table 1** summarizes the objectives and outcomes of recent reconnaissance investigations of several representative natural hazard events. **Figures 2** through **5** present field data collected during several of the missions highlighted in **Table 1**.

## RECONNAISSANCE INSTRUMENTATION AND NATURAL HAZARD SIMULATION

By enabling the prompt collection of high-resolution data sets, advanced reconnaissance instrumentation now plays a central

**TABLE 1 |** Examples of reconnaissance approach, objectives, and outcomes from several recent earthquake and wind hazard missions (**Figure 2**).

| Natural hazard event | Main topic of investigation | Background | Reconnaissance approach | Outcomes | Hazard and primary discipline | References |
|---|---|---|---|---|---|---|
| 2008 Hurricane Ike | Spatiotemporal variability of storm surge (**Figure 2**) | There is dramatic variability in surge-related damage along the coast, but detailed information on surge variation in space and time was not known. | Rapidly deployable onshore water level sensors are installed at moderate spatial resolution along the coast. | (1) Advanced understanding of storm surge timing and spatial distribution; and (2) Detailed data set for surge prediction validation | Wind hazard, coastal engineering | Kennedy et al., 2011 |
| 2017 Hurricane Irma | Hurricane impact on residential construction (**Figure 3**) | Majority of insured loss in < Cat 3 hurricanes is associated with roof cover and fenestration losses on residential housing. Obtain data on a large sample size critical. | UAVs used to canvas coastal neighborhoods that experienced the highest winds. Tax appraise database used to determine roof age. Ground teams document fenestration damage. FEMA wind maps accessed for hazard intensity. | Statistically significant assessments of residential performance as a function of age and wind speed | Wind hazard, structural engineering | Pinelli et al., 2018 |
| 2017 Mexico City earthquake | Public Perceptions of earthquake early warning | It was not known how Mexico City residents perceive SASMEX (earthquake early warning system), and how they responded to warnings for the earthquake relative to the system's performance. | An interdisciplinary team of geoscientists and social scientists. In-depth interviews. A convenience sample of the public, government officials, academics, business, and NGOs. | Recommendations for earthquake early warning system development in the U.S. | Earthquakes, social sciences | Allen and EERI Reconnaissance Team, 2017 |
| 2015 Nepal earthquake | Rapid assessment of post-earthquake building damage (**Figure 4**) | Techniques are needed to enable rapid assessment of building damage in the aftermath of earthquakes. Fast assessment speeds recovery and reduces the impact of earthquakes on communities. | Collect still image, SfM, and lidar data of earthquake- damaged buildings to support the development of rapid damage assessment methods. | Next-generation of damage-detection algorithms | Earthquake, structural engineering | Barbosa et al., 2017; Brando et al., 2017; Wood R. L. et al., 2017 |
| 2010–2011 Christchurch earthquake sequence | Impact of co-seismic rockfall on buildings (**Figure 5**) | Landslide risk practices require that the vulnerability of communities to landslides be known, but the information was not available to support such an assessment. | Lidar-scan ∼30 homes/sites damaged by rockfall during the Christchurch earthquake and relate impact energy to building damage indices; geotechnical-structural collaboration | A series of rigorous, data-driven fragility relationships to support risk assessment and land-use policy | Earthquakes, geotechnical engineering | Grant et al., 2018 |

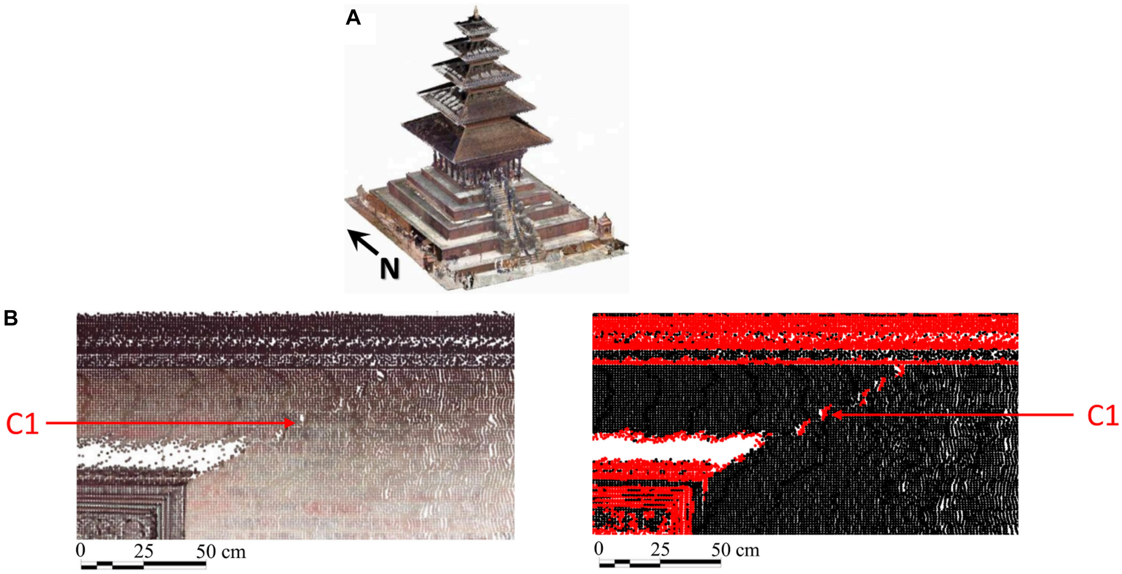


**FIGURE 2 |** Assessing the performance of buildings using lidar data collected during reconnaissance. **(A)** Lidar-derived 3D model of Nyatapola Temple following the 2015 Ghorka Nepal Earthquake **(B)** Earthquake-induced crack (designated as "C1") seen in a color point cloud (left) and detected defects shown in red (right). Reproduced from Wood P. R. et al. (2017).

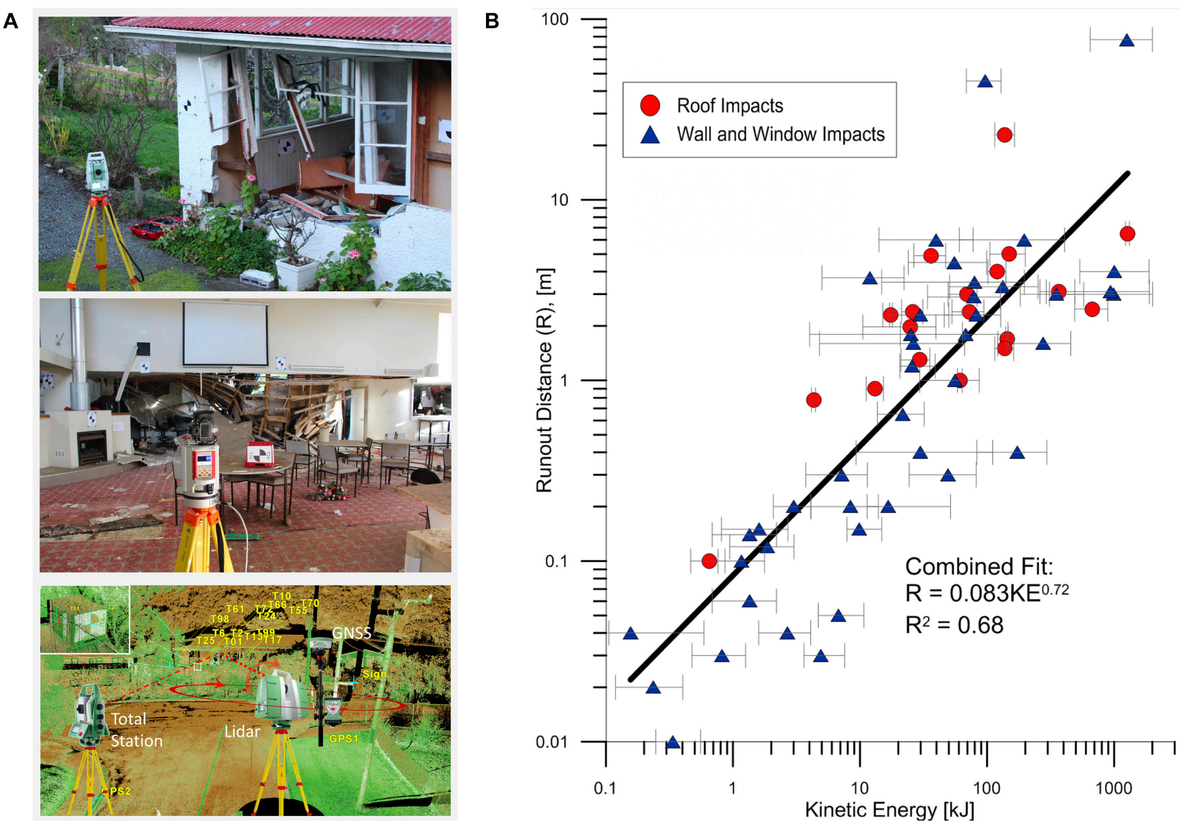


**FIGURE 3 |** Reconnaissance investigation of the impact of rockfalls on dwellings during the 2011 Christchurch, New Zealand, earthquakes. **(A)** Lidar data was collected inside and outside buildings, geo-registered, then fusing into a single 3D model. **(B)** Field data reveals a direct correlation between rockfall impact energy and rock penetration into buildings. Modified from Grant et al. (2018).

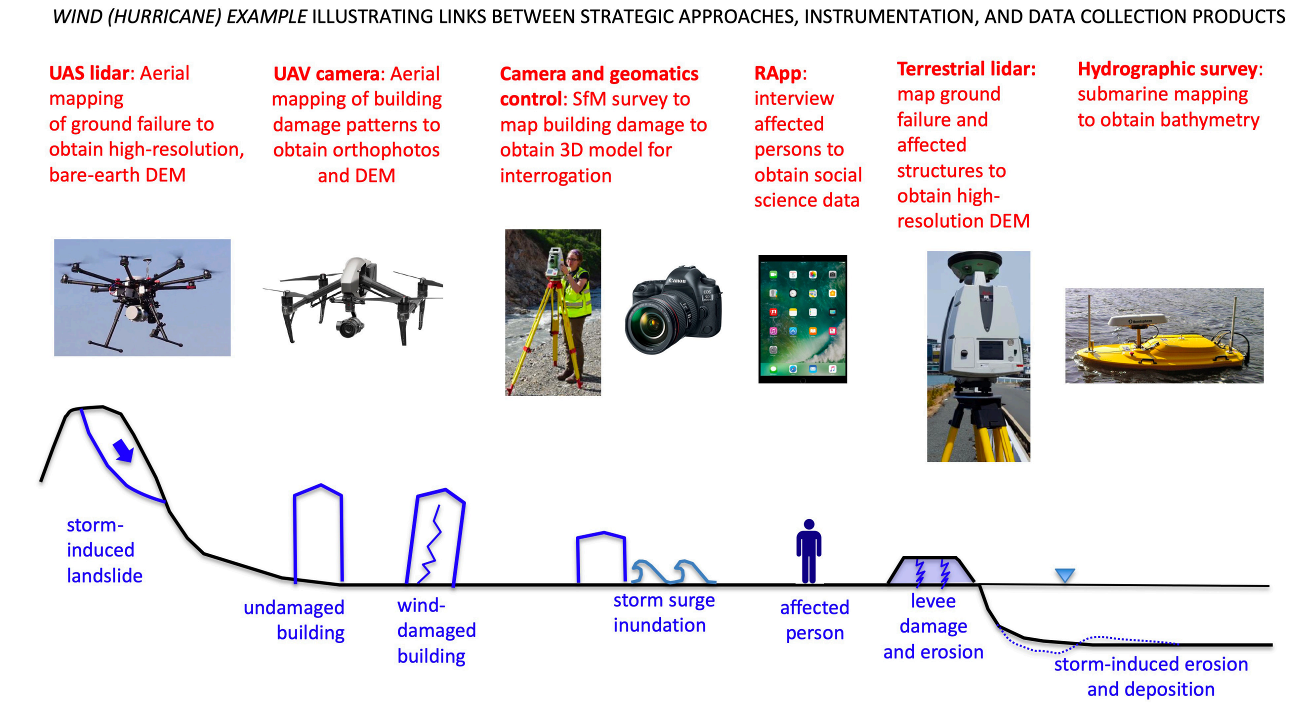


**FIGURE 4 |** Diagram depicting damage features, secondary effects, and human and societal impacts that commonly result from an extreme wind event. The diagram is similar to **Figure 7**, illustrating the commonalities between seismic and wind natural hazard events. Diagrams and inset images are as noted in **Figure 7**.

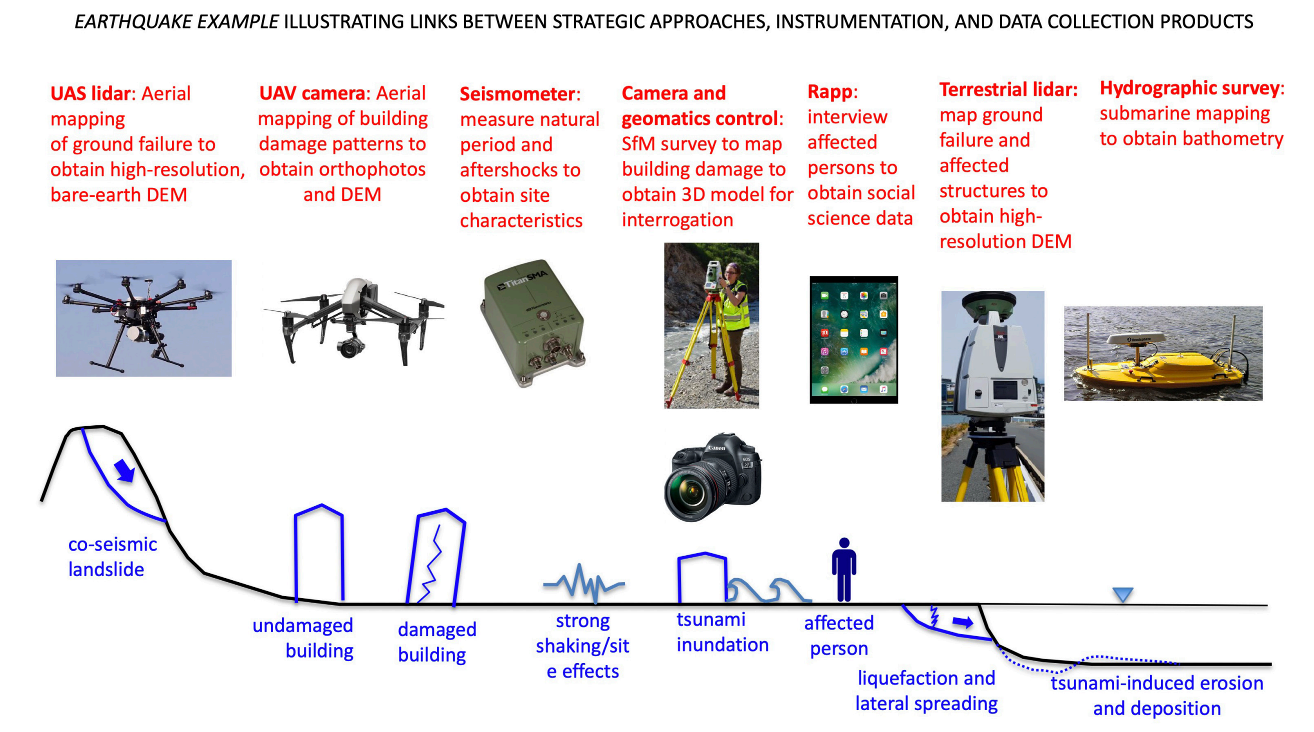


**FIGURE 5 |** Diagram illustrating damage features, secondary effects, and human and societal impacts that often result from a significant earthquake (blue illustrations and accompanying text). Superimposed above this hypothetical post-event landscape are annotations linking instrumentation (shown with inset photographs) and data collections activities and products (shown in red) to event features.

role in providing the academic, research, and professional communities with an unprecedented volume of high-quality, open-source, engineering, geophysical, social, and behavioral data. In addition, new software and cyberinfrastructure tools allow complex data sets to be archived, integrated, explored, and visualized (Rathje et al., 2017). These computational resources facilitate collaboration among experts across different fields to support advancements at the intersections of the natural hazards specialty disciplines. A unique aspect of the RAPID Facility is its portfolio of geospatial, image-centric data collection instrumentation. High-resolution georeferenced laser, image, and video data collected from full fields of view (i.e., top to bottom; inside and outside) of infrastructure within affected regions support the development of 3D post-event models (Berman et al., in press). Such models can be safely interrogated to extensive detail by geographically distributed research teams—an aspect that allows investigators the time and vision to collaboratively continue to discover new and important aspects of the impact of the surveyed event (Olsen and Kayen, 2013; Olsen et al., 2015). These types of terrestrial data sets are increasingly being fused with broader scale satellite imagery to appreciate the regional context for damage at a specific site (e.g., Yamazaki and Matsuoka, 2007; Eguchi et al., 2008; Rathje and Franke, 2016; Gallant et al., 2020).

Modeling and simulation lie at the center of the natural hazard community's broader goal to understand, simulate, and predict the performance of built, natural, and social systems during and after natural hazards events (Edge et al., 2020). Over the past decade, a portfolio of highly sophisticated natural hazards models has significantly improved our ability to simulate the effects of extreme events across a wide range of spatial and temporal scales (e.g., Roelvink et al., 2009; Dietrich et al., 2011; LeVeque et al., 2011; Pita et al., 2013; Mandli and Dawson, 2014; Yim et al., 2014; Baradaranshoraka et al., 2019). These natural hazards models have become increasingly data-driven, requiring comprehensive data sets to capture complex, system-level responses. Examples of such models include performance-based earthquake engineering (PBEE) design methods and resilience-based design methods (e.g., FEMA, 2018; McAllister et al., 2019), which require fragility data to relate structural, non-structural, and infrastructure systems performance to engineering demand parameters, and stochastic wind hazard loss models (Hamid et al., 2011; Pita et al., 2015) that require field data to better calibrate and validate the hazard, infrastructure vulnerability, costing components, and economic impacts of preparedness and mitigation policies.

The RAPID Facility's principal scientific goal is to inform natural hazards computational simulation models, infrastructure performance assessment, and economic impact analysis by supporting the collection, development, and assessment of high-quality disaster data sets (**Figure 6**). These data sets help advance our fundamental understanding of natural hazards and their impacts. Examples of reconnaissance data collection required to improve the natural hazards modeling and simulation include the following:

1. Lifelines and other elements of the built environments are ultimately socio-technical systems (Miles et al., 2014). That is, there are core social, economic, and behavioral components to the development, operation, and maintenance of all engineered systems. There is a crucial need for research to better unpack and quantify the socio-technical dimensions related to damage, restoration, and reconstruction of elements of the built environment. This research is needed to advance existing socio-technical loss (e.g., Kircher et al., 2006) and recovery models (Miles and Chang, 2011), as well as to develop new ones. Most socio-technical modeling efforts to date have focused on modeling losses.
2. Development of high-resolution, geocoded data sets, such as aerial photography, lidar, and ground-based documentation of post-event damage (e.g., Gurley and Masters, 2011; Lombardo et al., 2015), to reduce uncertainties in stochastic models characterizing the vulnerability of infrastructure to wind and earthquake damage. Modern catastrophe risk models ultimately seek to project damage, loss, and recovery time at the whole-building, infrastructure system, or regional scale; examples modeling tools include FEMA (2018) as well as the community and regional resilience modeling tools such as OpenQuake (Pagani et al., 2014) and those being developed by the Center for Risk-Based Community Resilience Planning (van de Lindt et al., 2015) and the NHERI SimCenter. These tools predict building performance through the aggregation of component failures (e.g., FEMA, 2018 for earthquake hazard and Pita et al., 2015 for wind hazard) or based on building-level models such as those incorporated in FEMA HAZUS-MH (Kircher et al., 2006). These simulation tools include numerous assumptions regarding probabilistic structural component capacities, load paths, the influence of aging, and cascading damage from neighboring structures. Thus, they benefit substantially from refinements to these assumptions informed by detailed geocoded field data stratified by building code and localized hazard intensity.

Provision of appropriate data to test, verify, and calibrate co-seismic landslide displacement models [e.g., the popular and practice-oriented Newmark et al. (1965) sliding model, as well as more advanced coupled (e.g., Rathje and Bray, 2000) or finite element formulations]. Specifically, advanced geomatics technologies such as lidar could capture intricate ground deformation patterns and landslide morphological features, eroded quickly after an event. There are relatively few high-quality case histories of co-seismic landslide displacement, which represents a pressing research need in the field of geotechnical earthquake engineering (Harp et al., 2011).

1. Provision of the appropriate data to quantify underlying physical phenomena and to develop, validate, improve, and reduce uncertainty in physics-based, computational modeling of wind, waves, storm surge, tsunami inundation, sediment transport, morphological change, and other related

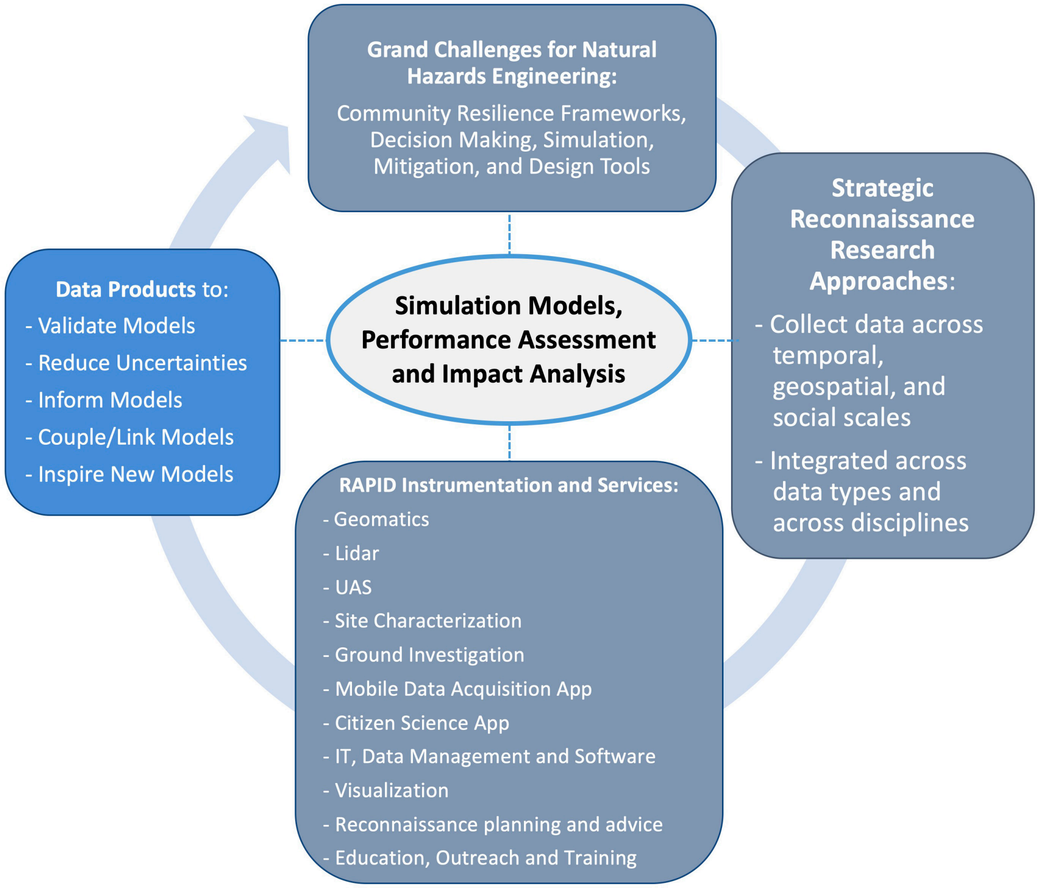


**FIGURE 6 |** Grand challenges for the natural hazards community require new strategic approaches for reconnaissance data collection utilizing RAPID instrumentation and services. This data collection will produce data products that are needed to meet grand challenges. Central to this cycle is the RAPID Facility's scientific goal of informing natural hazards computational simulation models, infrastructure performance assessment, and socioeconomic impact analysis by supporting the collection, development, and assessment of high-quality data sets [digital elevation model (DEM)].

processes representing the inter-related, destructive forcing mechanisms of natural hazards (Kennedy et al., 2020b and references therein). Specifically, modern reconnaissance instrumentation can capture rare, but critical, perishable data during and following natural hazards, including the quantification of inundation extent, flow speeds, flow depth, wave conditions, wind speeds, soil properties, erosion and accretion, and inundation-related damage to civil infrastructure and the natural environment (Kennedy et al., 2020a). These data help improve understanding of, for example, (a) the interplay between the natural landscape (land cover, topographic features), the built environment (critical infrastructure, homes), and hydrodynamics and (b) how and when concurrent multi-hazard components (e.g., wind vs. surge) lead to the functional failure of critical infrastructure—ultimately leading to more resilient communities (e.g., Baradaranshoraka et al., 2017).

2. Simulation of structural response to ground shaking is validated mainly through comparison with data from experiments in controlled laboratory environments and with data collected from reconnaissance following earthquakes. The structural models may be focused on component behaviors, building behaviors, or even the behavior of entire classes of buildings through the development of fragility functions. Recent examples of field data informing advances in local structural behavior models include Kanvinde et al. (2015), who investigated fracture of eccentrically braced frame links during the 2011 Christchurch earthquake and used collected field data helped to validate newly developed fracture models employed in detailed finite element analyses. At the macro-level, fragility functions derived from reconnaissance data on the performance of wood-frame buildings have resulted in large-scale loss estimations for San Francisco arising from the soft-story collapse of wood-frame structures and spurred public policy to encourage retrofit (FEMA, 2012). Such observation-based fragility data are also critical to loss estimation software such as FEMA (2018), FEMA HAZUS-MH (Kircher et al., 2006) and OpenQuake (Pagani et al., 2014), and the regional loss estimation tools being developed by the Center for Risk-Based Community Resilience Planning and the NHERI SimCenter.

## GRAND CHALLENGES FOR THE NATURAL HAZARDS AND DISASTER RESEARCH COMMUNITIES

In 2011, the National Research Council convened a community workshop to identify grand challenges for earthquake engineering. These challenges served to guide research after the conclusion of the George E. Brown, Jr. Network for Earthquake Engineering Simulation operations (National Research Council [NRC], 2011). While the title of the workshop highlighted earthquake engineering, the NRC steering committee noted that the identified grand challenges (community resilience, decision making, simulation, mitigation, design tools) were broad and also pertained to other natural and anthropogenic hazards. These grand challenges are adopted here as an overarching framework for identifying reconnaissance research opportunities for natural hazards and disaster research communities.

### Community Resilience

To better understand the direct and indirect impacts of natural hazards events, a framework is needed to measure, monitor, and evaluate community-level resilience. The lack of historical data on community impacts and recovery following past disasters presents a significant impediment to meeting this goal (National Research Council [NRC], 2011). Advanced reconnaissance instrumentation helps address this challenge by enabling the systematic collection and archiving integrated, interdisciplinary data pertinent to engineering and the natural and social sciences. This knowledge is necessary to evaluate the utility and validity of the range of community resilience frameworks—a significant gap in the state-of-the-art in disaster science and engineering (Miles, 2015).

### Hazard and Impact Simulation and Decision Making

Computational simulation and forecasting of the timing and regional distribution of the hazard itself (e.g., Frankel et al., 2018), as well as its physical and social impacts and recovery, are essential for decision making, planning, and mitigation. Such simulations—which span a range of temporal scales, including both short-term (e.g., informing electricity restoration with expected damage patterns) and long-term time frames (e.g., identifying local vulnerabilities for risk reduction policy-making)—present a challenge to the professional community (National Research Council [NRC], 2011). New, high-performance computing and software platforms such as the NHERI DesignSafe-CI and SimCenter (Blain et al., 2020) create the opportunity to make significant progress with this challenge. However, such simulations are highly complex and require extensive hypervariable data sets for model development and testing. Since many of these models are inherently data-driven, they also require high-quality data (e.g., initial and boundary conditions) to provide reliable forecasts.

### Mitigation

Renewal and retrofit strategies are essential to mitigate hazards posed to infrastructure systems and communities (e.g., water and wastewater supply and distribution systems, power and energy systems, at-risk buildings, and coastal communities) (National Research Council [NRC], 2011). The development of effective mitigation strategies requires computational models (see above), design methods, and construction standards that, when harmonized, are capable of identifying critical vulnerabilities and quantifying the impacts of risk reduction measures. In addition, post-event data are needed to evaluate loss estimation methodologies, such as HAZUS-MH, investigate the efficacy of mitigation approaches (e.g., Gurley and Masters, 2011), and provide feedback on state-mandated insurance incentives for homeowners who employ mitigation. New multiscale data collection tools provide the means to address these needs. For example, terrestrial lidar and building survey equipment could be used to collect data on the seismic performance of retrofitted buildings. Similarly, lidar or structure from motion (SfM)/multi view stereo photogrammetry (Eltner et al., 2016; Özyeşil et al., 2017) technology can be used in coastal communities after hurricanes to quantify morphological changes, civil infrastructure damage, and ecological damage in detail and on a large scale. Importantly, all of these data sources can be integrated and overlaid with imagery to develop three-dimensional models of impacted regions or damage-affected infrastructure.

### Design Tools

Improved capability to characterize uncertainty in the predictive ability of design tools is essential to exploit newer, more sustainable, and resilient building materials. Improved design tools are also needed to capitalize on innovative structural concepts (e.g., self- centering structural systems with replaceable fuses) (National Research Council [NRC], 2011). Performance-based design provides the framework for addressing this challenge, but such design relies on high-quality performance data to define model relationships (e.g., fragility functions). Advanced instrumentation offers a means to meet this challenge. For example, sensors could be installed on structures and earth systems to monitor response to aftershocks (Geli et al., 1988; Zhou et al., 2013), and aerial imagery could be used to validate the performance of wind-resistant roof covers.

In 2017, the Network Coordination Office (Johnson et al., 2020) of NHERI convened a task group to prepare a network-wide science plan to guide future research and to focus investigators on keeping the communities and the built environment safe from natural hazards. The NCO's NHERI network science plan was first published in July 2017 (Smith et al., 2017) and reflected many of the principals of the National Research Council Grand Challenges report (National Research Council [NRC], 2011). The NHERI network science plan highlights the need to (1) identify and quantify the characteristics of natural hazards that are damaging to civil infrastructure and disruptive to communities, (2) evaluate the physical vulnerability of civil infrastructure and the social vulnerability of populations in communities exposed to natural hazards, and (3) create the technologies and engineering tools to design, construct, retrofit, and operate multi-hazard resilient and sustainable infrastructure. The network issued a revised science plan in January 2020 (Edge et al., 2020) that reflects the potential role of several new, rapidly advancing technologies (e.g., advanced computational methods, information science, bio-inspired design, convergence science) in improving community resilience to natural hazards. The revised science plan identifies three grand challenges for the community. These include (1) identifying and quantifying the characteristics of earthquake, windstorm, and associated hazards that are damaging to civil infrastructure and disruptive to communities, (2) assessing the physical vulnerability of civil infrastructure and the social vulnerability of populations in communities, and (3) creating the technologies and engineering tools to design, construct, retrofit, and operate a multi-hazard resilient and sustainable infrastructure. In addition to the NRC workshop report and the NHERI network science plans, other reports suggest specific research activities and tasks to help meet challenges in the fields of earthquake hazard reduction (National Earthquake Hazards Reduction Program, 2008), resilience (National Research Council [NRC], 2011), windstorm and coastal inundation impact reduction (Coulbourne et al., 2014), and disaster risk reduction (Aitsi-Selmi et al., 2015).

# RESEARCH NEEDS, CHALLENGES, AND OPPORTUNITIES FOR NATURAL HAZARDS RECONNAISSANCE

## Methodology

In January 2017, the RAPID Facility convened a 2-day workshop to determine natural hazards and disaster reconnaissance data needs and opportunities and identify the broader challenges facing the reconnaissance community that encumber data collection and use. The workshop attendees—individuals having expertise across a range of natural hazards (e.g., wind events, earthquakes, and their secondary effects) and disciplines (engineering, and the natural and social sciences)—participated in three types of activities (also see **Supplementary Material**).

(1) Informational presentations to provide background material to help stimulate later discussion in activity groups
(2) Guided "brainstorming-type" small group activities
(3) Responding to open-ended questions posed on poster boards placed in the break area during the first day of the workshop

During the brainstorming activities, participants were asked to first reflect on questions individually and later to share, discuss, and synthesize their ideas in small, pre-assigned groups. For some disciplinary-focused activities, groups were organized by specialty, while in other activities, groups were intentionally interdisciplinary to allow cross-fertilization of ideas between sciences and engineering domains. The ideas developed during the individual sessions and group discussions were attached to poster boards using sticky notes. Each group reported the general themes to all of the workshop participants. Over 1,600 ideas, comments, and replies recorded on sticky notes during the workshop. After the workshop, each of these notes was assigned a unique identifier code, cataloged, and then read and transcribed to a comprehensive database, which is included as **Supplementary Material** to this article. The workshop organizers then synthesized and analyzed the database of workshop comments and transcriptions to identify significant themes on needs, challenges, and opportunities for natural hazards and disaster reconnaissance.

## Findings

Many of the workshop participants were seasoned reconnaissance investigators with the collective experience of dozens of reconnaissance missions following natural hazard events and other disasters—both natural and anthropogenic in origin. The participants responded to questions about the practical and operational challenges they have faced before, during, and after reconnaissance investigations. They also provided feedback about what went well (i.e., their "successes") during reconnaissance missions. As noted in **Table 2**, major challenges before deploying for reconnaissance mainly involve logistics in the compressed time frames intrinsic to extreme event investigations. During field missions, many of the challenges relate to the on-the-ground realities of working in a disaster zone, including safety concerns and emotional trauma. The difficulties after reconnaissance missions primarily pertain to data processing, analysis, and archiving. The participants reported a range of common themes about pre- and during deployment successes (**Table 3**), including having previously established local contacts in the affected region, teamwork and camaraderie, and prior training on instrumentation reconnaissance methods, and safety. Successes after reconnaissance missions mainly pertain to the production of unique data products, improved fundamental knowledge, and positive impacts on policy and practice.

The workshop participants were also asked to identify reconnaissance data needed to support the four National Research Council [NRC] (2011) grand challenges (i.e., community resilience framework, hazard and impact simulation and decision making, mitigation, and design tools). As indicated in **Table 3**, the responses, which form the basis of our recommended strategic approaches for natural hazards and disaster reconnaissance, are broadly themed on concepts of cross-scale, multidisciplinary data collection.

# STRATEGIC APPROACHES FOR NATURAL HAZARDS AND DISASTER RECONNAISSANCE

Post-disaster reconnaissance investigations have historically often involved the collection and development of data sets by disciplinary teams following natural hazard events. These data sets have usually been collected over limited geospatial scales (e.g., at the site or neighborhood scales)

**TABLE 2 |** Synthesis of key themes in workshop participant responses to questions about challenges and successes before, during, and after reconnaissance missions (see **Supplementary Material** for complete list).

| Reconnaissance experience | Before mission (pre-deployment) | During mission (field deployment) | After mission (post-deployment) |
|---|---|---|---|
| Challenges | • Prompt funding<br>• Travel planning<br>• Overall planning<br>• Team building<br>• Contacts and authorization<br>• Locating sites for data collection<br>• Coordination<br>• Data for planning | • Not enough time<br>• Data needs<br>• Appropriate and working tools<br>• Difficult site access<br>• Safety<br>• Dealing with traumatized people<br>• Collaboration<br>• Research in the field<br>• Limited budget | • Funding for post-reconnaissance data analysis<br>• Data formatting after reconnaissance<br>• Data processing after reconnaissance<br>• Data analysis<br>• Communication<br>• Information sharing Report writing |
| Successes | • Local contacts, relationships, and assistance<br>• Team knowledge and composition<br>• Data for pre-reconnaissance planning<br>• Equipment access, availability, and reliability<br>• Safety training | • Communication<br>• Safety<br>• Local connections<br>• Working and appropriate equipment<br>• Good teamwork<br>• Successful data collection | • Positive impact on practice, policy, and community<br>• New data available and accessible<br>• Scholarly publications and new research funding<br>• Improved understanding<br>• New professional connections and collaborators |

**TABLE 3 |** Synthesis of High Priority Reconnaissance Data Needs to address Grand Challenges for the natural hazards and disaster research communities (see **Supplementary Material** for complete list).

| Grand challenge | Reconnaissance data needs |
|---|---|
| Design tools | • Measurements of dynamic demand (i.e., "forcings")<br>• Design performance goals for structure, infrastructure, and critical systems<br>• Performance of systems with protective technologies |
| Community resilience framework | • Temporal recovery; how long does it take?<br>• Data collection that addresses equity<br>• Baseline pre-event data: social, infrastructure, topography<br>• Large-scale data at the community or regional scale that shows intersections between built, natural, social, political, cultural environments (i.e., connectivity) |
| Mitigation | • Evaluation of pre-existing hazard maps for "all hazard": for example, shaking, flooding, faults<br>• Damage with respect to hazard forcing and structural characteristics; what worked? What didn't work?<br>• Document both unsuccessful and successful performance.<br>• Lifeline performance vulnerability curve design vs. performance<br>• Multi-(geospatial) scale analyses; coarse information across large areas; detailed and specific sites |
| Hazard and impact simulation and decision making | • Population distributions at the time of the event (how does this influence death, damage, and loss?)<br>• Spatial distribution of all hazards<br>• Multidisciplinary timing and time histories of event: soil characteristics, wind speed and direction, ground motion, human behavior, structural behavior |

with little supporting metadata. As a result, such data sets can be challenging, if not impossible, to integrate. Meeting community challenges and accomplishing the scientific goal of improving simulation models requires new strategic approaches for reconnaissance investigations that acquire and integrate data over a range of temporal, spatial, and social scales across disciplines. **Figures 7**, **8** illustrate links between the strategic approaches for natural hazard reconnaissance data collection, instrumentation, and resulting data products, for a hypothetical earthquake and wind event, respectively.

## Temporal Scales

Resilience is the central, unifying goal of the natural hazards and disaster research communities (e.g., National Research Council [NRC], 2011; National Research Council, 2012). The term refers to an impacted community's ability to resist, absorb, accommodate, adapt to, transform and ultimately recover and move on from the effects of a hazard in a timely and efficient manner (United Nations, 2017). A path toward better upstanding, assessing, and improving resilience involves collecting and analyzing data over time frames representing conditions and states before, during, and after significant natural hazard events. Data on pre-event or "before" conditions are essential for understanding the pre-existing factors that influence, shape, and define a community's response to a natural hazard event. With its emphasis on post-event response, the collection of pre-event data is largely outside the scope of the traditional reconnaissance community; however, much of this data currently exists or is being collected by governmental agencies and authorities, non- governmental organizations, and the private sector.

Moreover, there exists an opportunity for the natural hazards and disaster communities to lead organized efforts to catalog, organize, and synthesize such data, making it possible to link them with reconnaissance data. Data on the direct impacts of an event ("during event data") are the traditional focus of reconnaissance investigations. These data provide critical information on the character of the loadings and the consequent physical response of the built environment, the immediate social, economic and public health impacts on communities, and interactions between these. These data also represent the starting point for recovery from natural hazard events. After an event, data collected are critical for understanding the response, recovery, and evolution of communities following events. Collecting data representing during and after events conditions requires both traditional rapid response reconnaissance investigations and follow-up data-gathering efforts. These longer-term data gathering investigations may span periods of weeks, months, or years, depending on the nature of the event and the characteristics of the affected communities.

**FIGURE 7 |** UAVs with high-resolution cameras are well-suited capture perishable data (e.g., roof cover damage, debris field), and provide complementary datasets for ground-based damage surveys. The areal perspective of UAVs reveals structural damage that is hidden from the view of ground-based damage surveyors. Photograph by Kwasi Oerry was acquired under sponsorship from the Florida Building Commission.

## Geospatial Scales

Natural hazard events often impact areas spanning 100s-to-1000s of square kilometers. Their widespread geographic distribution makes them, by definition, regional-scale events. The resulting damage and impact patterns reflect the fundamental nature of the hazard and the characteristics of the communities and built systems within affected regions. Over the past several decades, the ability to analyze the effects of natural hazards at the site- and building-scales has significantly improved, leading to better modeling tools, new building technologies, and robust building codes. In recent years the natural hazards and disaster communities have shown a growing interest in regional-scale impact modeling. A key advantage of regional-scale models is their ability to forecast the distribution of hazard impacts and thus capture system-level performance and propagation of risk across a region. Such models are particularly important when considering the impact of hazards on geographically distributed critical infrastructure systems.

Improving our understanding of hazard impacts and advancing regional scale modeling requires collection and synthesis of data over spatial scales spanning multiple orders of magnitude (i.e., from the site-specific to the regional scales; $\sim m^2$ to $\sim km^2$). This necessitates a portfolio of instrumentation that can facilitate the acquisition of fine-grained, high-resolution "site-specific" data and also support the collection in a practical manner of data from a much broader area. This also requires reconnaissance investigations to be conducted at both local and regional scales. Acquiring multiscale data enables the local impacts of a hazard to be understood in the broader context of regional-scale loading patterns and community characteristics. Equally important, this data can support the information necessary to bridge site-specific and regional scale models, which improves the ability to simulate the consequences of an extreme event across a vast region.

## Social Scales

Natural hazard events can have immensely varying impacts and consequences at all social scales, from individuals and households to neighborhoods and communities; organizations, businesses, and governments; and up to and including countries, cultures, and global consequences (e.g., Oliver-Smith, 1996; Paton and Johnston, 2001; Quarantelli, 2003; Boon et al., 2012). As the Covid-19 pandemic wreaks havoc on individual lives, senior centers, vulnerable communities, nations, and the global economy, inequities and the heterogeneity of hazard effects at different social scales have commanded renewed attention (e.g., Adams-Prassl et al., 2020). Differences in natural and built environments contribute to potentially predictable variation in hazard impacts on society and individuals and can interact with societal responses (Paton and Johnston, 2001). Infrastructure damages can hinder immediate and longer-term responses, including emergency responses, evacuation, and sheltering, but also communications and governance. Direct hazard effects on the physical environment, such as flooding, landslides, and fire, are not only potentially deadly to individuals but can also cause longer-term mental harm and disrupt social and economic activities at multiple scales. However, the lack of population-representative fine-scaled data on damages and human exposures for natural hazards and disasters continues to be called out (e.g., Bakkensen and Mendelsohn, 2016).

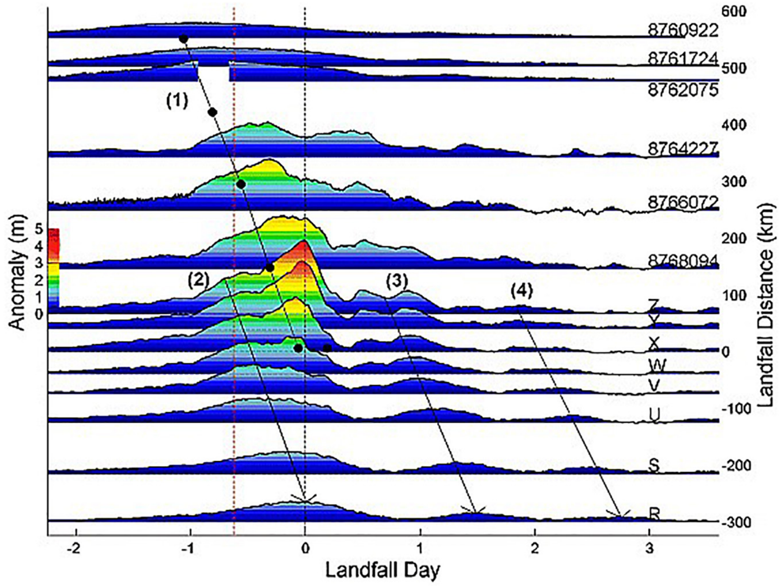


**FIGURE 8 |** Observed time series of water level anomaly during Hurricane Ike (2008) along the open coasts of Louisiana and Texas (top-to-bottom show easternmost locations to westernmost locations). Data shown include rapidly installed pressure sensors (R-Z) by A. Kennedy (University of Notre Dame) and NOAA stations (8760922, 8761724, 8762075, 8764227, 8766072, 8768094). Line 1 shows the location of Hurricane Ike, while Line 2 shows the propagation of the forerunner wave. Reproduced from Kennedy et al. (2011) with permission of the publisher.

Assessing hazard exposures and consequences across these domains and social scales requires instrumentation and data collection sensitive to and associated with social, built, and natural environmental conditions, as well as temporal and spatial scales. Data collection processes that are multi-scalar and consider the social processes that can make people hard to reach will have a better chance of representing minority populations most likely to be among the most vulnerable to the majority of hazard events (Shaghaghi et al., 2011). Data can be contextualized with the appropriate metadata, but also improved by designing direct data collections—such as observations, interviews, and surveys—to address these contextual factors and link geophysical, engineering, and social data. Social scientists have long acknowledged interactions across social scales (e.g., Bronfenbrenner and Morris, 2006). New technologies, analytical approaches, and data sources—such as biophysical and EEG (electroencephalogram) measurement tools (e.g., Bailey et al., 2017), crowdsourcing (e.g., Cobb et al., 2014), social media (e.g., Chae et al., 2014; Spence et al., 2016; Wang and Taylor, 2018), and satellite observations of night lights and other forms of evidence of human activities and interventions at larger scales (e.g., Ehrlich et al., 2009; Ceola et al., 2014)—can enable researchers to examine these interactions in new ways. They can also support insights into and simulations of how individual responses and behaviors contribute to or are shaped by responses and events at larger social scales.

## Multidisciplinary Data Sets

A disaster is a severe disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability, and capacity leading to human, material, economic and environmental losses and/or impacts (United Nations, 2020). A better understanding of the complicated relationship between hazards, the built environment, and communities requires that the physical and socioeconomic factors leading to disasters be untangled. Accomplishing this requires the reconnaissance community to collect and synthesize multidisciplinary data sets. In addition to improving our fundamental understanding of disasters, these data can play a critical role in establishing relationships between hazards and their broad consequences, ultimately leading to an improved ability to model, manage, and mitigate risk to communities.

# CONCLUSION

Natural hazard events provide extraordinary opportunities to improve our fundamental understanding of disasters and their consequences. This understanding is critical for reducing the growing human and capital losses arising from extreme events (e.g., Coronese et al., 2019). To minimize losses, the natural hazard and disaster research and practice communities must meet several key challenges related to improving modeling and design making, community resilience, and hazard mitigation (e.g., National Research Council [NRC], 2011). Reconnaissance data, which captures real-world complexities of events (e.g., the interplay between natural, human, and built systems), plays an increasingly important role in meeting these challenges. The recent availability of state-of-the-art instrumentation and mobile data collection applications has dramatically improved the quality and increased the quantity of disaster data, paving the way toward a new era of natural hazards reconnaissance. However, to fully realize the potential of these advancements, we must employ new strategic approaches for natural hazards reconnaissance that acquire and integrate data over a range of temporal, spatial, and social scales across disciplines. Specifically, this involves the following.

(1) Data collection over time frames representing conditions and states before, during, and after significant natural hazard events.
(2) The collection and synthesis of data over spatial scales spanning multiple orders of magnitude (i.e., from the site-specific to the regional scales; $\sim m^2$ to $\sim km^2$).
(3) Data collection is sensitive to and associated with social, built, and natural environmental conditions, and considers the social processes that can make populations hard to reach.
(4) The collection and synthesis of multidisciplinary data sets to establish relationships between hazard events, their antecedents, and their broad consequences, ultimately leading to an improved ability to model, manage, and mitigate disaster risk to communities.

## DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

## AUTHOR CONTRIBUTIONS

JW, JB, AB, SM, MO, KG, JI, LL, TT, and JD developed the RAPID Facility science plan reported in this article. SM and AB designed the community workshop and later worked in close collaboration with JW and JB to interpret the result and develop findings. MG, AL, and JP work with members of the reconnaissance community users to implement the science plan into field missions. All authors contributed to manuscript drafting and revision, and read and approved the submitted version.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2020.573068/full#supplementary-material

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# Natural Hazards Reconnaissance With the NHERI RAPID Facility

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In 2016, the National Science Foundation (NSF) funded a multi-institution interdisciplinary team to develop and operate the Natural Hazards Reconnaissance Facility (known as the "*RAPID*") as part of the Natural Hazards Engineering Research Infrastructure (NHERI) program. During the following 2 years, the RAPID facility developed its instrumentation portfolio and operational plan with input from the natural hazards community, the facility's leadership team, and an external steering committee. In September 2018, the RAPID began field operations, which continue today and include instrumentation, software, training, and support services to conduct reconnaissance research before, during, and after natural hazard and disaster events. Over the past 2 years, the RAPID has supported the data collection efforts for over 60 projects worldwide. Projects have spanned a wide range of disciplines and hazards and have also included data collection at large-scale experimental facilities in the United States and abroad. These projects have produced an unprecedented amount of high-quality field data archived on the DesignSafe cyberinfrastructure platform. This paper describes the RAPID facility's development, instrumentation portfolio (including the mobile application RApp), services and capabilities, and training activities. Additionally, overviews of three recent RAPID-supported projects are presented, including descriptions of field data collection workflows, details of the resulting data sets, and the impact of these project deployments on the natural hazard fields.

**Keywords: natural hazards, reconnaissance, field data collection, research instrumentation, lidar**

## INTRODUCTION

The Natural Hazards Reconnaissance Facility, known as the *RAPID*, is part of the Natural Hazards Engineering Research Infrastructure (NHERI) network supported by the National Science Foundation (NSF). Based at the University of Washington (UW), the RAPID is a collaboration between UW, Oregon State University, Virginia Tech, and the University of Florida. The facility enables the natural hazards and disaster research communities to conduct next-generation rapid response investigations to characterize civil infrastructure performance and community response to natural hazards, evaluate design methodologies' effectiveness, calibrate simulation models, and develop solutions for resilient communities. The RAPID's primary mission serves the interdisciplinary natural hazards and disaster research communities, but its resources and services are also available to other government agencies and industry. Researchers and practitioners have used the RAPID's resources effectively across various engineering, geosciences, and social science disciplines. Consistent with NSF's focus, the RAPID primarily serves reconnaissance needs for earthquake, windstorm, landslide, and tsunami hazards. However, its equipment and services are available for a broad range of applications.

The RAPID facility provides investigators with the hardware, software, and support services needed to collect, process, and assess perishable interdisciplinary data following natural hazards and disaster events. Support for the natural hazards and disaster research community is provided through training and educational activities, field deployment services, and promoting public engagement with science and engineering. Specifically, the RAPID facility engages in the following strategic activities: (1) acquisition, maintenance, and operation of state-of-the-art data collection equipment; (2) development and support of mobile applications to enable interdisciplinary field reconnaissance; (3) providing advisory services and basic logistics support for research missions; (4) facilitation of the systematic archiving, processing, and visualization of acquired data in DesignSafe (Rathje et al., 2017); (5) training a broad user base through workshops and other activities; and (6) public engagement, community outreach, and education.

The facility emphasizes three-dimensional, image-based, advanced survey data [for example, lidar and high-resolution photos from unmanned aerial systems (UASs)] to serve a range of disciplines. In addition, it has equipment for more discipline-specific data collection, including, for example, seismometers, accelerometers, ground investigation equipment, a hydrographic survey vessel, water level gauges, and flow velocity meters, among many other instruments. The RAPID has also developed, and continues to advance, a reconnaissance mobile software application called RApp (the "RAPID application"). The software RApp integrates the collection of field data such as questionnaires, photos, video, and audio, and metadata associated with RAPID instrumentation data collection, while also serving as an in-field resource for team organization and RAPID equipment user manuals (Miles and Tanner, 2018). Integration through common metadata enables linked analyses to support interdisciplinary investigations and simulations. Data collected with RApp are automatically archived on the NHERI cyberinfrastructure, DesignSafe (Rathje et al., 2017).

RAPID began supporting field deployments in September 2018 and, since then, has deployed equipment and/or staff on more than 60 missions worldwide in support of facility users. An unprecedented amount of high-resolution and high-accuracy data has been collected on the impacts of Hurricanes Florence and Michael in 2018, the 2018 Palu-Donggala earthquake and tsunami in Indonesia, the 2018 Hokkaido Eastern Iburi earthquake in Japan, the 2018 Anchorage earthquake, the 2019 Ridgecrest earthquake, and the 2019 Hurricane Dorian, among other recent natural hazards events. Data collected by the RAPID Facility are archived on DesignSafe. This paper describes the RAPID, its development, its capabilities, and its user support services. Additionally, overviews of example data collection deployments are provided along with brief examples of the collected data and an initial look at the impact of these data on addressing grand challenges in natural hazards resilience. The examples include investigation of the performance of large-volume low-rise buildings during Hurricane Michael, investigation of a large flow-slide that occurred the 2018 Palu-Donggala Earthquake in Indonesia, and monitoring of a large, slow-moving landslide in coastal Oregon.

## DEVELOPMENT OF THE RAPID

The RAPID was developed over a 2-year period and is currently supported through September 2021, with a possible 5-year renewal through 2026. The process began by engaging the natural hazards and disaster reconnaissance research communities, in order to understand their data gathering needs to advance reconnaissance research aimed at grand challenges, such as community natural hazard resilience. From that engagement, the leadership developed a plan for the facility, including its equipment and operations, in collaboration with an External Steering Committee (serving in an advisory rather than a true "steering" capacity) and NSF. The RAPID then began to acquire and commission equipment, host workshops to train potential users in field data acquisition with the equipment, produce training guides and materials, develop workflows for data acquisition and data management, and develop the software RApp.

Input from the natural hazards and disaster reconnaissance community was critical in developing the RAPID and its capabilities. To gather feedback from the community, the RAPID leadership team organized an interdisciplinary workshop in January 2017 in Seattle, Washington (Wartman et al., 2020). The workshop's purpose was to identify the grand challenges in natural hazard resilience that require perishable data from reconnaissance, the key needs and opportunities for collecting that data, and the requirements for the RAPID to help meet those needs and leverage those opportunities. User-centered design principles and processes guided the workshop's structure, which engaged more than 80 researchers, representatives from stakeholder government agencies (such as the United States Geological Survey), and practitioners. Participants included those with expertise in geotechnical engineering, structural engineering, coastal sciences and engineering, geomatics, various social sciences, and instrumentation and technologies for reconnaissance. The participants also had diverse interests in terms of natural hazards, with hurricane, tornado, earthquake, and tsunami expertise and experience well represented.

The RAPID leadership team used the workshop results to frame RAPID's mission, science plan, strategic activities, equipment portfolio, software development plan, and data management plan. The workshop also revealed the need for a new reconnaissance research landscape to help address grand challenges. This outcome helped kindle the eventual formation of CONVERGE, a NHERI node at the University of Colorado Boulder[1], which helps coordinate reconnaissance efforts across disciplines. It also provided an impetus for the expansion of the NSF-supported extreme event reconnaissance organizations (EERs) beyond geotechnical impacts (GEER)[2], to those focused on structural engineering (StEER)[3], nearshore impacts (NEER)[4], social sciences (SSEER), operations (OSEER), and sustainable materials management (SUMMEER).

During the development phase of the RAPID, an interdisciplinary and multi-hazard External Steering Committee (ESC) was engaged and regularly provided feedback. In particular, the ESC reviewed the RAPID's science plan, mission and strategic activities, and the proposed equipment portfolio. The ESC members are experts with deep experience in natural hazard and disaster reconnaissance and covered the range of disciplines and hazards the RAPID has been developed to serve.

RAPID development has continued through its period of operations. Feedback is collected routinely from users and improves the facility's operations and inform additional equipment priorities. Collaboration with CONVERGE and the other EERs through a leadership council has also helped to strengthen the RAPID's ability to serve its users and has helped to set priorities for the facility mobile software, RApp.

The RAPID science plan was developed in response to the 2017 community workshop findings and with feedback from the RAPID's ESC and other subject matter experts. As described in Wartman et al. (2020), the RAPID seeks to help address grand challenges in natural hazards resilience by enabling the collection of data products to advance our understanding of how integrated natural, engineered, and social systems respond to natural hazards. The resulting data products are designed to advance simulation capabilities for natural hazard performance and impact assessment by providing critical benchmark data for validation. To do this, RAPID maintains instrumentation and services that enable strategic and innovative approaches to integrated data collection in the field. Wartman et al. (2020) also present new field methodologies for field data collection with RAPID instrumentation.

## RAPID INSTRUMENTATION

The equipment available at the RAPID, selected with research community input, as described above, has enabled a transformation in reconnaissance approaches across multiple disciplines. As described below, RAPID maintains equipment, such as terrestrial lidar and UASs, that have applications across multiple disciplines, hazards, geospatial scales, and temporal scales as well as equipment with primary applications within specific disciplines at specific locations. Such instruments have been widely cited as critical to advancing reconnaissance data collection (e.g., Bray et al., 2019; Greenwood et al., 2019). A sampling of the available equipment, as of late 2020, is described below within several broad categories. A complete list of the RAPID equipment, including manufacturers, specifications, and use cases may be found on the facility's website[5].

### Lidar

RAPID has a collection of lidar resources that enable applications across many disciplines where 3D point capture of a scene is essential. RAPID's portfolio includes tripod-mounted terrestrial lidar systems capable of scanning ranges up to 2.4 km for landscape-scale mapping as well as smaller and extremely portable systems with a 130 m range that can complete full 360° scans for mapping at a local site scale in as little as 2 min at a rate of nearly 2 million points per second. Single point accuracy for the terrestrial lidar scanners varies from 1.2 to 10+ mm ($1 - \sigma$) depending on the selected scanner and scanning geometry such as distance to a target. The RAPID has developed simple, efficient workflows for lidar acquisition and provides facility users with guidance on the optimal lidar scanner to suit their data collection needs. Below, Case Study 1 provides an example reconnaissance effort that featured heavy use of lidar to document and assess in detail the damage to a specific building typology observed after Hurricane Michael.

RAPID also has a UAS mounted lidar system, the miniRanger, developed on a turnkey basis by Phoenix Lidar Systems. This system is customized to meet the needs of the RAPID and the natural hazards reconnaissance community. Additionally, the lidar system on the miniRanger can be removed from the UAS and attached to other vehicles for use as a mobile lidar platform. An example deployment of the miniRanger system to document and measure a landslide affecting United States Highway 101 on the Oregon coast is presented later. The miniRanger was selected for the RAPID portfolio to provide an aerial lidar platform for smaller sites where airborne lidar would be cost-prohibitive and lack sufficient resolution. The MiniRanger is ideal for sites that are less than a few square kilometers in size.

### Unmanned Aerial Systems

RAPID maintains a fleet of UASs to support natural hazards reconnaissance across several disciplines. The fleet includes small scout UASs with camera and video capabilities; mid-range UASs with excellent cameras and flight time; larger industrial systems that can fly in significant winds and light rain and have flexibility in camera and sensor mounting; UASs with Real-Time Kinematic (RTK) GNSS to simplify the ground control necessary for improving survey accuracy; and fixed-wing systems with exceptionally long flight time and the ability to cover extensive areas. Several RAPID staff members have Remote Pilot Certificates issued by the United States Federal Aviation Agency should users need certified pilots to help with their data collection.

Significantly, RAPID has developed strategies and workflows for deploying UASs in combination with ground control

[1] https://converge.colorado.edu/

[2] http://www.geerassociation.org/

[3] https://www.steer.network/

[4] https://neerassociation.org/

[5] https://rapid.designsafe-ci.org/

to ensure that the acquired imagery is best suited for its intended research purpose. This includes the generation of photogrammetric products such as centimeter-level resolution orthophotos or structure from motion/multi-view stereo (SfM/MVS) point clouds. An example UAS deployment is presented later where the data collected were used to understand the cause of a massive flowslide that occurred during the Palu, Indonesia earthquake.

## Imaging Equipment

High-resolution imaging is critical in any post-event data-gathering effort to assess the performance of the built, natural, and even social systems. As a result, the RAPID provides a variety of image collection equipment to support such data gathering. The equipment includes two StreetView camera systems with car and backpack mounts. These camera systems can collect 360° images that can be quickly processed into a Streetview environment. The Streetview systems can cover hundreds of kilometers per day as they can be used at vehicle speeds up to 95 km/h. RAPID also has a system for collecting gigapixel panoramic images along with high-resolution digital cameras set up for regular image capture as well as optimized capture of images for use in Structure-from-Motion modeling. Additionally, smaller camera and video equipment are available that can be used for rapid image collection, including specialized 360-cameras that can operate with a smartphone and a gimbal-stabilized handheld camera system that can be used for high-quality videos and images. **Figure 1** shows an example screenshot from a StreetView environment showing data from Mexico Beach, FL, obtained during a StEER mission following Hurricane Michael.

## Surveying Equipment

While lidar and UAS technology provide highly detailed point cloud and imagery products, surveying is necessary to provide accurate control for reliable measurements using these products. Additionally, these high accuracy survey instruments and positioning systems (i.e., GNSS) can be used by themselves to make precise measurements of natural hazard impact. For example, a GNSS rover can be used to "tag" water level height observations following a storm surge. RAPID provides these capabilities by maintaining a robotic total station, a suite of GNSS receivers, and a digital level.

## Geotechnical and Seismological Equipment

Characterization of the ground conditions at a site can be critical to understanding liquefaction, infrastructure damage, and ground movements. The RAPID provides an array of equipment for site characterization and ground investigation, including a lightweight dynamic cone penetration system, a larger smart dynamic cone penetration system, and a wireless multi-channel analysis of surface wave (MASW) system with 24 acquisition units. Additionally, for both recording ground motions and site characterization, RAPID has an array of six broadband seismometers.

## Structural Equipment

To support the investigation of the dynamic response of structures to hurricanes or earthquake aftershocks, the RAPID maintains a portfolio of high-quality accelerometers. The instrumentation includes three "structure sets" of instruments, each consisting of three tri-axis accelerometers, a GPS unit for synchronizing the recordings, cabling, and the necessary battery supplies to acquire data for weeks. The accelerometers are exceptional in terms of accuracy and measurement flexibility and have a wide operation frequency range (DC to 430 Hz) and a full-scale range of $\pm$ 0.25 to $\pm$ 4 g. They are hardened and can be deployed in challenging environments. The accelerometers are maintained in a "ready-to-go" state and can be rapidly deployed ahead of hurricanes or just after earthquake mainshocks.

## Coastal Equipment

Characterization of the bathymetry of affected coastal areas as well as storm surge and inundation measurements are critical data in understanding the coastal impacts of natural hazards. The RAPID maintains equipment for gathering these data, including a remotely operated hydrographic survey boat with a single beam sonar, a velocity flow profiler, water level gauges, an underwater grab sampler, underwater beacons, and a pinger-receiver system. **Figure 2** shows the hydrographic survey boat in use during a RAPID user training workshop at UW and during a combined user training and research deployment at the During Nearshore Event Experiment (DUNEX) in Duck, NC[6].

## Software for Reconnaissance Support Across Disciplines

The RAPID has developed the mobile software platform RApp to serve multiple functions in natural hazards and disaster reconnaissance. The software runs within iOS on Apple iPads. The facility has numerous iPads to support field teams when needed as well as during training. RApp serves as a platform to collect data such as questionnaires, photos, or videos. RApp also provides simple tools for capturing metadata associated with data collected using other RAPID equipment. RApp integrates with the RAPID built web-based platform for pre-deployment configuration and post-deployment review of collected data and metadata called Mission Control. RApp will also automatically upload data directly to a user's project on DesignSafe, the NHERI Cyberinfrastructure, when a Wi-Fi or cellular connection is available. **Figure 3A** shows the primary purposes of DesignSafe, Mission Control, and RApp, while **Figure 3B** shows the reconnaissance workflow utilizing them.

**Figure 4** shows the main screen of RApp, which consists of customizable tiles so that users may quickly access the RApp tools they need most frequently. All data gathered using RApp is geolocated using the iPad's integrated GPS, to facilitate investigation of regional distribution of damage and impact. Current functionality allows users to import.kml files to support pre-reconnaissance planning; develop customized questionnaires; record locations and metadata for lidar scans;

[6]https://uscoastalresearch.org/dunex

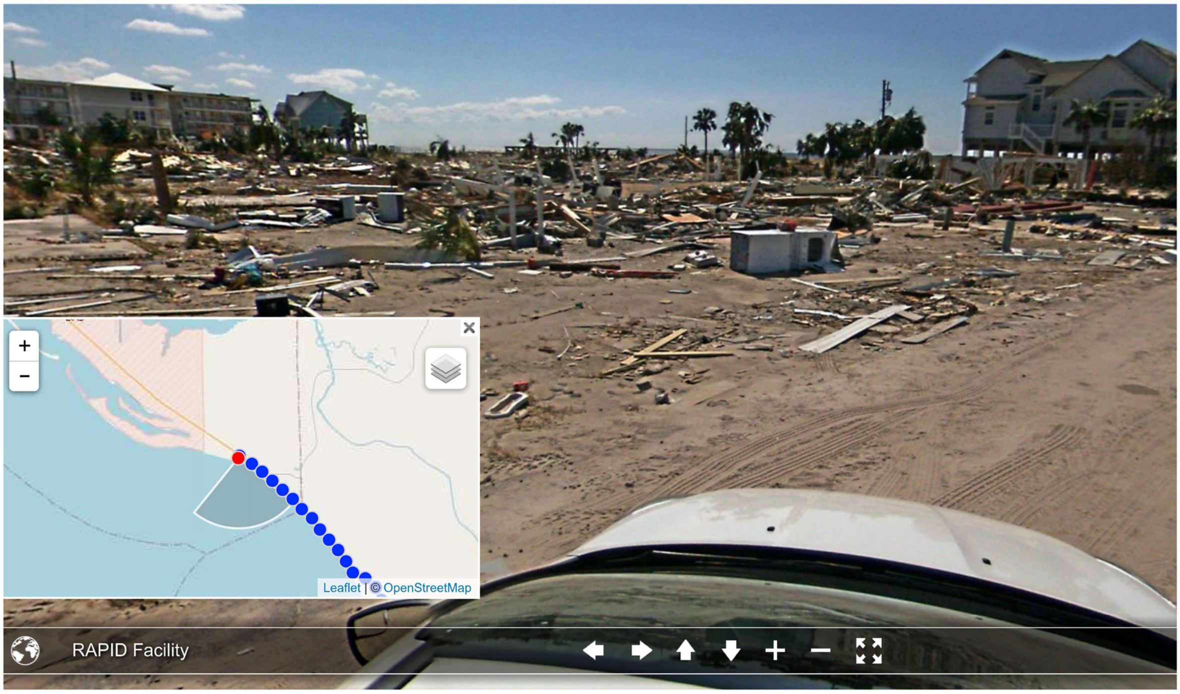


**FIGURE 1 |** StreetView images acquired with RAPID equipment during a STEER reconnaissance mission in Mexico Beach, FL, following Hurricane Michael (Roueche et al., 2020).

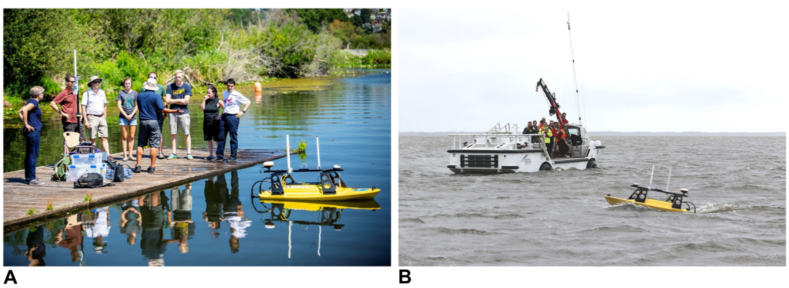

**FIGURE 2 |** Hydrographic survey boat in use: **(A)** during user training, and **(B)** at the DUNEX site.

record with audio, video, and images; and preload manuals for RAPID equipment, among other capabilities. A simplified version of RApp will be available in 2021 for use on iPhones. More information on RApp and user training are available on the RAPID website and recorded webinars hosted on the Converge website[7].

## Equipment and Software for Social Science Reconnaissance Applications

The RAPID has developed RApp as its primary tool to support Social Science reconnaissance applications, as well as interdisciplinary research that requires linking social and behavioral data with other data, in time and space. Beginning in late 2020, RApp is supporting complex questionnaires ("surveys") that have logic-based structures (i.e., conditional branching, wherein the answer to one question determines which question follows) and will include a library of pre-constructed questionnaires (a.k.a. survey instruments) that have been used in social science reconnaissance. The library of questionnaires is being developed in collaboration with CONVERGE (Peek et al., 2020). RApp also supports collection of audio and video.

The RAPID's other equipment, in particular its imaging equipment, is also of value to the social sciences. For example, RAPID equipment such as the street view systems and UAV systems can be used to capture image data that can be processed or distilled to understand communities' responses to natural hazards, long-term community recovery, and demographic changes. Additionally, image data gathered in communities

[7]https://converge.colorado.edu/communications/webinar-series/rapp-introduction-to-the-rapid-facility-field-data-collection-app


**FIGURE 3 |** DesignSafe, Mission Control, and RApp: **(A)** general purposes of each and **(B)** the field reconnaissance workflow.

before any natural hazard events can be used to help planners and policymakers consider and envision mitigation measures.

## Data Processing Equipment

Processing of data collected with some of the RAPID equipment requires substantial graphics processing power and specialized software. Necessary processing includes integration of multiple lidar scans of a single scene (referred to as registration), the development of SfM/MVS models from images, and the development of StreetView scenes from the images collected from one of RAPID's StreetView cameras. RAPID maintains a number of processing workstations and laptops with high-powered graphic processing units (GPUs) to provide facility users with access to computational resources and software necessary to do this processing. The data processing workstations and laptops are also available for use in data interrogation, i.e., exploring 3D point clouds to make detailed measurements. As described below, some processing is carried out by RAPID staff, while other data processing is the facility users' responsibility. RAPID headquarters also houses a mini-computer automatic virtual environment (mini-CAVE) system, which helps users interrogate point clouds in a 3D immersive environment. This system can help identify the key characteristics of the damage data set, which are not as apparent in 3D visualization software in a 2D workstation environment.

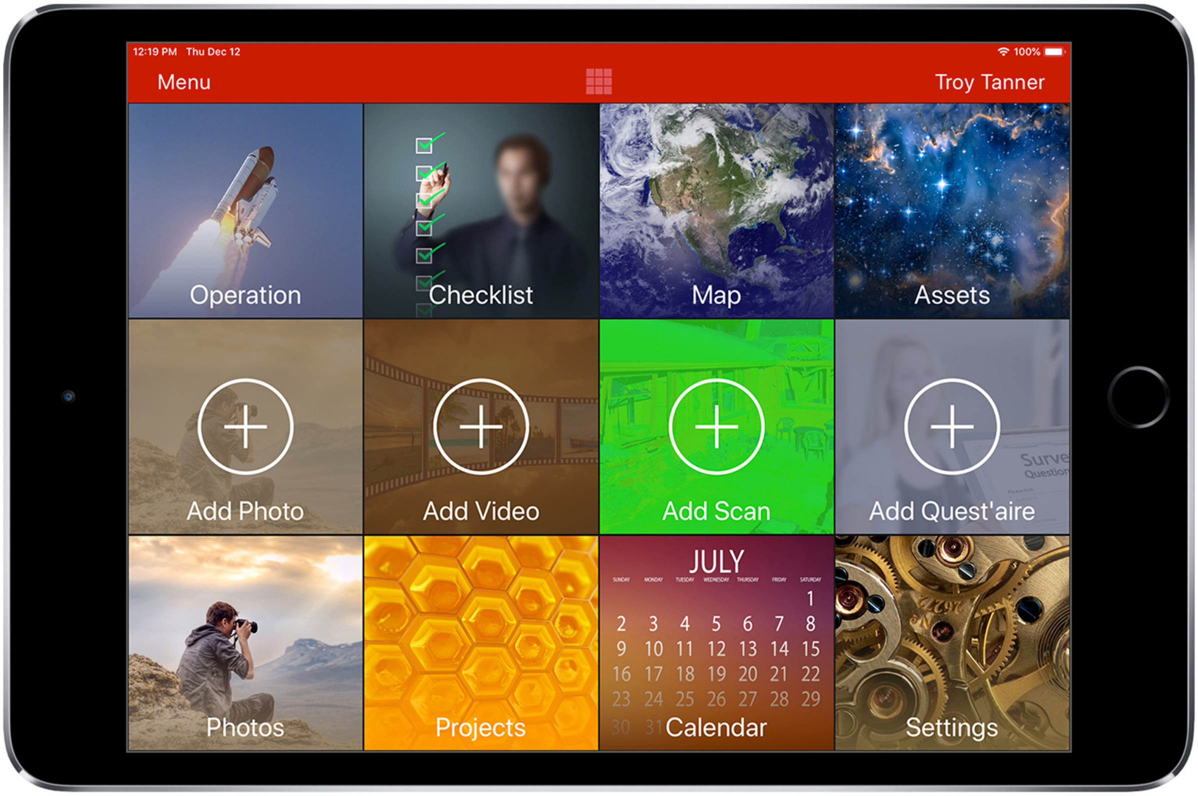


**FIGURE 4 |** RApp main screen with customizable tiles.

## RAPID SERVICES

### Field Support

RAPID staff have training and expertise in all of the facility's equipment. If desired, RAPID staff will accompany researchers into the field to collect perishable data. However, the RAPID also operates with the objective of expanding expertise in the use of the facility tools and technologies and encourages users to train on and operate the equipment themselves. Only two pieces of the RAPID's equipment require RAPID staff to operate: the hydrographic survey boat (**Figure 3**) and the UAS lidar system. Other equipment may be operated by users, except that Remote Pilot Certification from the United States Federal Aviation Administration (FAA) is required to operate RAPID's UASs.

The RAPID also offers remote field support when needed. RAPID staff can walk users through problems with the equipment and guide field operation in difficult or unforeseen conditions. All equipment is shipped with simplified user manuals that RAPID has developed to quickly assist users in the field.

### Data Processing Support and Data Archiving

The RAPID provides data processing support to maximize the advances enabled by the collected data, to ensure systematic data collection by the natural hazards reconnaissance community, and to provide confidence in data for reuse. This support includes baseline data processing for certain data types, including GNSS and total station data, the processing of StreetView data, and other basic data processing. To provide user support and software licenses for processing complex data sets such as lidar and SfM/MVS point cloud models, RAPID provides in-person data processing workshops at the RAPID headquarters, remote assistance via web conferencing, and shippable high-powered GPU laptops.

All data collected for NSF-supported natural hazards reconnaissance missions must be archived and made publicly available. The DesignSafe cyberinfrastructure is where data collected via RAPID equipment are archived. DesignSafe and RAPID have collaborated to create a data model for field data, ensuring that the necessary metadata are archived along with the data, maximizing its use in the future. RAPID staff ensure that all raw data collected with RAPID equipment are archived to the NHERI cyberinfrastructure DesignSafe and made publicly available by the users in a typical time frame of 3–9 months.

### User Training

User training is critical to the mission and operation of the RAPID. To achieve the objectives identified in the facility's science plan, data must be collected by the entire natural hazards and disaster research community as they participate in reconnaissance efforts, not just by the limited facility staff.

Therefore, training users in systematic data collection methods, basic data processing, and archiving and publishing of the data on DesignSafe is a core service provided by RAPID. Each summer, the RAPID holds an intensive weeklong workshop that provides attendees with the hands-on experience necessary to deploy RAPID equipment themselves. Attendees of this workshop, listed on the RAPID website, are considered advanced users. In the 30 months that RAPID has been operating, many workshop attendees have been deployed with RAPID equipment on reconnaissance missions. In addition to the RAPID's summer workshop, user training is also provided on a one-on-one basis as needed, including refreshers on particular instruments in the days immediately preceding fieldwork.

### Logistics Support

RAPID provides facility users with logistical support related to equipment use. For example, multiple options are available for users to receive the facility's equipment. During the first 18 months of operations, RAPID provided facility users equipment by having it (i) shipped to their home or work prior to departure, (ii) sent to a shipping facility (e.g., FedEx office) for pickup, (iii) handed off by other field teams who were using it in the same locations, (iv) accompany RAPID staff during travel to support the field researchers, and (v) picked up directly at RAPID headquarters by users traveling through Seattle on their way to the field (typically for deployments to Asia). RAPID also provides support on procedures for traveling or shipping equipment internationally, including advice on appropriate customs protocols.

## EXAMPLE DEPLOYMENTS OF RAPID RESOURCES

RAPID resources have been deployed by more than 50 researchers to gather perishable data following natural hazards and disasters and have also been used in creative ways to support other research since the facility began operations in September 2018. RAPID has supported reconnaissance following significant hurricanes in the United States and the Caribbean (e.g., Hurricanes Florence, Michael, and Dorian), earthquakes in the United States (e.g., Ridgecrest, California, and Anchorage, Alaska) and abroad (e.g., Hokkaido, Japan; Palu, Indonesia; and Puerto Rico), as well as numerous smaller events such as landslides in Oregon and Alaska. The facility also deployed lidar and imaging equipment to document the damage following the Camp Wildfires in Paradise, CA, and to support data collection for major shake table experiments at the E-Defense research facility in Japan. Thus far, the facility has served more than 40 deployments of equipment and/or staff, supporting researchers from academia, government, state agencies, and the private sector. The sections below highlight three representative deployments that illustrate the RAPID equipment's capabilities and demonstrate the scientific and engineering advances enabled by the collection of high-resolution, interdisciplinary data. More information on past RAPID deployments and links to collected, publicly available data sets are available on the RAPID's website[8].

### Case Study 1: Damaged Building Reconnaissance in Hurricane Michael

Hurricane Michael struck the Florida coast's panhandle region on 10 October 2018 as a Category 4 hurricane and caused widespread devastation. The event's impact was substantial, causing near-total destruction of the city of Mexico Beach, with maximum sustained winds exceeding 250 km/h (155 mph) and a storm surge exceeding 4 m. Panama City, FL, approximately 38 km from Mexico Beach, was also struck with winds exceeding 225 km/h (140 mph) and a storm surge of nearly 2 m.

Reconnaissance performed by StEER within a few days of the hurricane's landfall found widespread damage to buildings and infrastructure throughout the region (Alipour et al., 2018). StEER recommended detailed follow-up investigations based on their initial findings. Of those, several related to the observed high rate of failure of low-rise large-volume steel-framed buildings (LRLVBs). This prompted a second data-gathering effort, supported by a collaborative NSF RAPID grant, to collect detailed perishable data on the performance of LRLVBs and to search for potentially systematic modes of failure that might point to necessary changes in building design.

LRLVBs are an important and common structure type, as their uses include storage, shipping hubs, manufacturing, grocery and retail, and even schools (i.e., gymnasiums). They often house many jobs, especially when aggregated over a region, and severe damage to these structures can negatively affect recovery. Panama City is an industrial hub in Florida's affected region, with over 1.5 million people in its metropolitan region and many LRLVBs that suffered damage during Hurricane Michael. This area was the focus of the follow-up reconnaissance effort.

The reconnaissance team, led by Profs. David Roueche and Justin Marshall from Auburn University and Prof. Jeffrey Berman from UW, deployed RAPID staff and equipment to collect perishable data characterizing full and partially collapsed LRLVBs. The equipment utilized included long- and short-range terrestrial lidar scanners, UASs, surveying equipment (total station and GNSS), and various camera systems. The fieldwork lasted 5 days and resulted in the detailed documentation of 12 buildings for which the collected data sets are available on DesignSafe (Berman et al., 2020). The initial StEER reconnaissance efforts identified several of the buildings, and others were added by the research team while in the field.

**Figure 5** shows a photo of a damaged LRLVB, a marine storage structure constructed using a proprietary steel-framed building system and a light-gauge steel cladding. While the building system was proprietary, it was composed mainly of I-shaped beams and columns with conventional bolted connections. As shown, the building suffered a partial collapse as one of the short walls, facing the northwest, collapsed into the structure's interior.

The field team spent 1 day at this marina storage building. UAV flights were conducted to document roof and exterior damage and more than 30 lidar scans were taken of the building's

[8] https://rapid.designsafe-ci.org/

**FIGURE 5 |** Partially collapsed marine storage building in Panama City, FL.

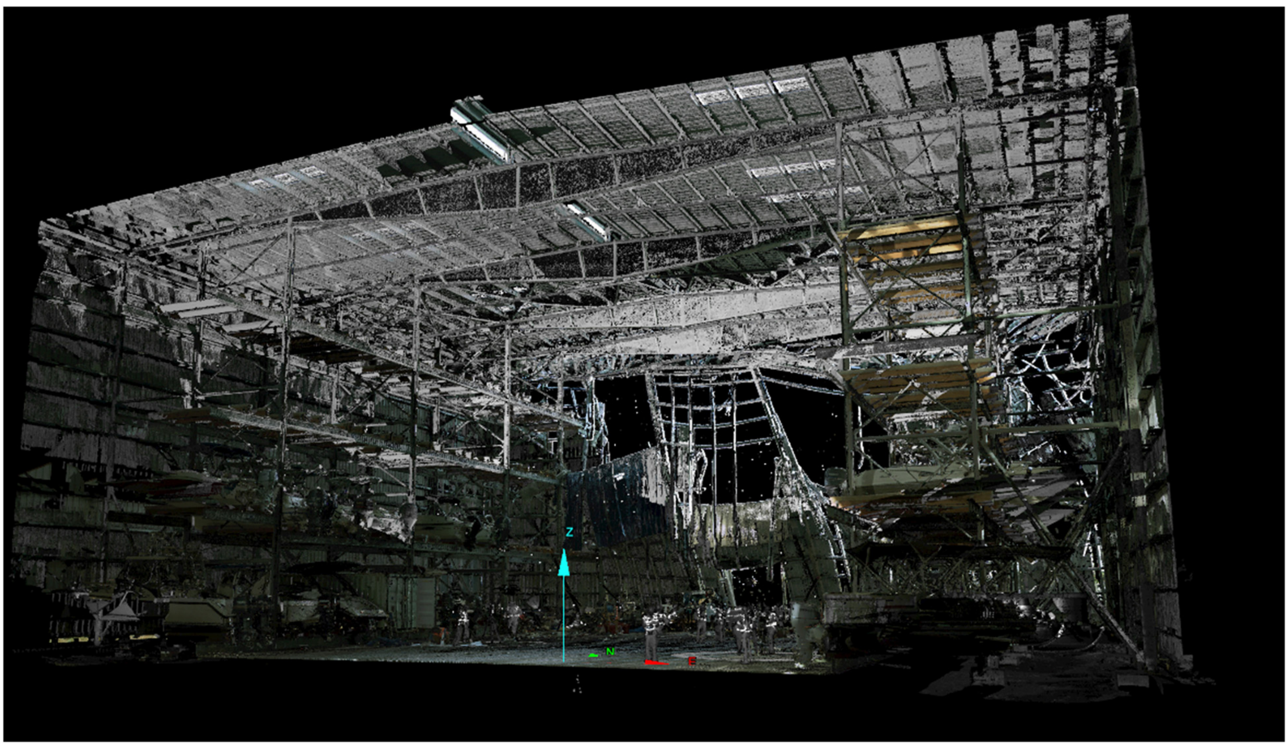

**FIGURE 6 |** 3D point cloud from lidar scans of the interior of the damaged marine storage building before cleaning (removal of debris to expose the structural system).

interior and exterior. GNSS was used to establish exterior control points for the UAV and the total station was used to survey targets captured in the lidar scans to improve registration accuracy.

The 3D point cloud of the interior of the building from the registered lidar scans is shown in **Figure 6**. As shown, the structure is difficult to observe, as the building was full of debris and of boats still in their storage racks. One advantage of lidar in reconnaissance applications is the ability to "clean" the point clouds to expose the important information and strip away extraneous objects. **Figure 7** shows a point cloud model of the building's interior following cleaning to the remove debris, storage racks, boats, and other objects. As shown, the structural system is now completely visible, enabling the measurement of spans, heights, section characteristics, connections, etc.

While the research team continues to analyze the failure modes of the LRLVBs during Hurricane Michael, trends have

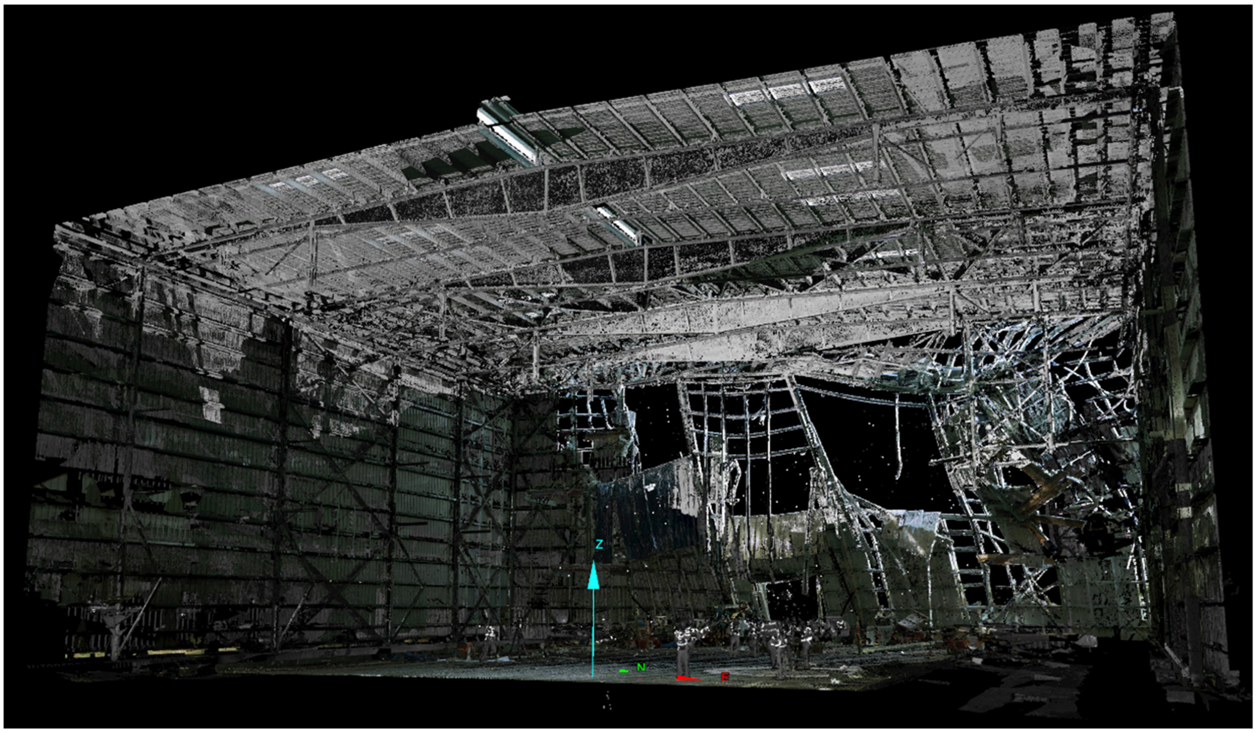


**FIGURE 7 |** 3D point cloud from lidar scans of the interior of the damaged marine storage building after cleaning (removal of debris to expose the structural system).

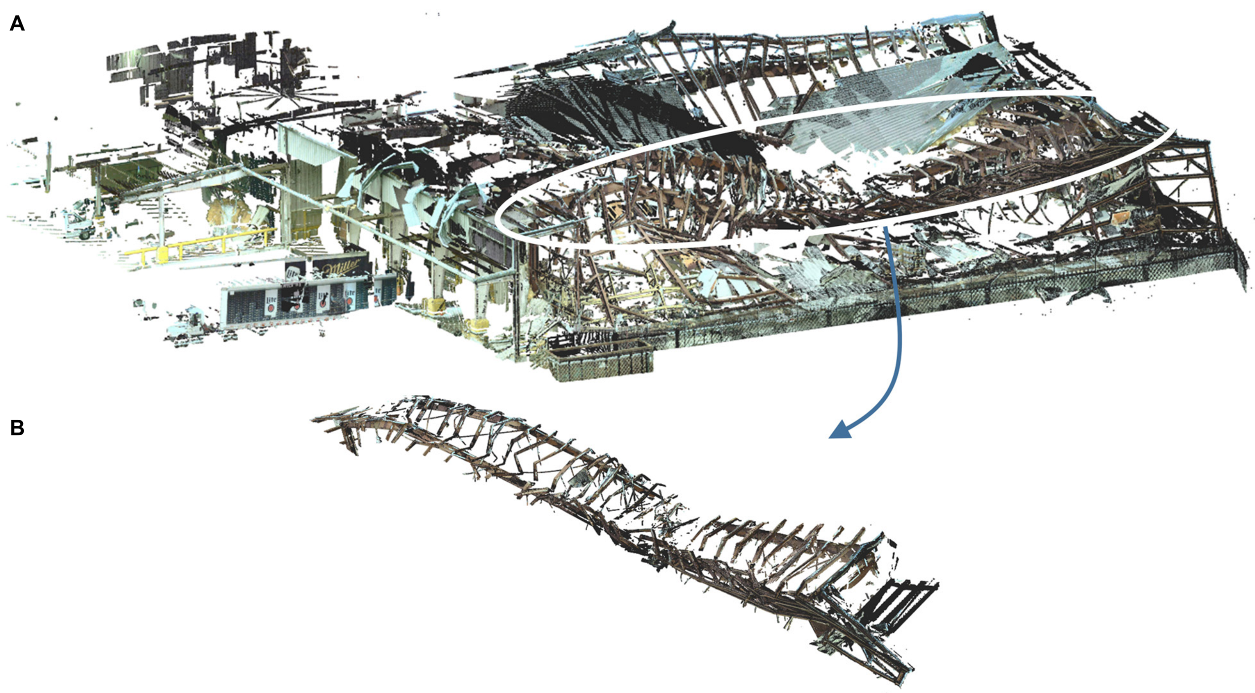


**FIGURE 8 | (A)** 3D point cloud from lidar scans of the exterior of a beverage distribution building. Scans were only obtained from one side of the building, showing the shorter face of the building and the collapsed roof framing members. **(B)** Two lines of main girders [circled in **(A)**] and their connected roof purlins extracted from the full point cloud.


**FIGURE 9 | (A)** Example of a portion of a high-resolution (~2 cm pixel) orthomosaic of a flowslide. **(B)** Shown for comparison is a post-earthquake satellite image of the same scene provided by Google Earth crisis response program. Note the dramatic difference in resolution between the images.

emerged in the collected data. In all cases, the collapse or partial collapse was initiated in a shorter wall that collapsed into the building, similar to that shown above for the Marine Storage Building, and also similar to that shown in **Figure 8**, which shows registered lidar scans of the exterior of a beverage distribution building. In these buildings, moment frame action is used to resist the wind loads applied on the longer sides of the buildings. However, wind loads on the short walls are transferred through the roof to lateral bracing along the long walls. Although work continues to identify the exact failure modes, it is believed that failure of roof purlins or trusses that are under compression to transfer those exterior wind loads from the short walls to the lateral bracing likely initiated the collapse. Those roof members would also be under negative bending moment due to suction on the roof and were likely insufficient to resist the combined compression and bending demands. **Figure 8B** shows a point cloud of the roof purlins attached to the main exterior and first interior girders extracted from the building in **Figure 8A**. Such detailed models allow for investigation of the failure mode.

**FIGURE 10 |** True-color digital surface model (shown as a "point cloud") of a flowslide.

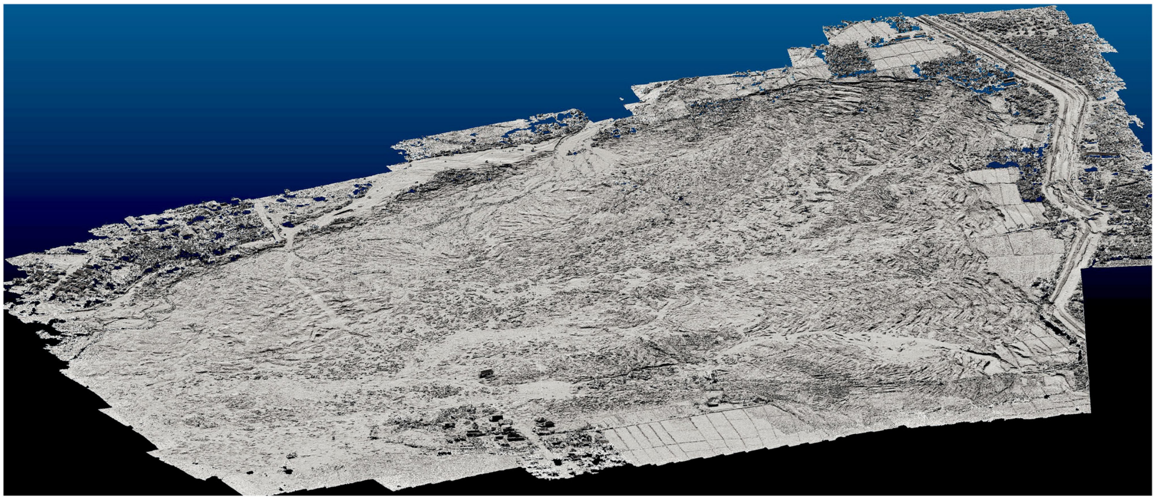

**FIGURE 11 |** Shaded relief digital surface model of a flowslide. North is toward the top. Simulated sunlight shines southward at 45° to the horizon.

The collected lidar and image data from the 12 buildings surveyed are being used to enable the development of structural models and to formulate hypotheses for the collapse mechanisms. Findings from these collected data and subsequent data will likely inform future building code and construction changes to ensure more robust LRLVB design in the future. Such advances will ultimately improve community resilience in hurricane-prone regions where such buildings provide critical economic and social functions.

## Case Study 2: Flowslide Mapping following the 2018 Palu-Donggala Earthquake

The $M_w$7.5 Palu-Donggala earthquake occurred on 28 September 2018 in Sulawesi, Indonesia. The earthquake triggered a series of massive landslides (classified as "flowslides"), collapsed both unreinforced and reinforced structures, and generated tsunami waves that impacted coastal areas surrounding Palu Bay. Government officials estimate that the earthquake and its secondary effects killed over 4,000 people and resulted in capital losses of approximately USD$900M. The significant loss of life makes the Palu-Donggala earthquake the deadliest natural disaster worldwide in 2018 and the deadliest earthquake to affect Indonesia since the 2006 Yogyakarta earthquake. A substantial majority of the fatalities were directly related to the flowslides, making this one of the most significant landslide disasters of the past several decades.

In November 2018, the Geotechnical Extreme Events Reconnaissance (GEER) association mobilized a team that arrived in the affected region and conducted 6 days of extensive fieldwork (Mason et al., 2019; Gallant et al., 2020).

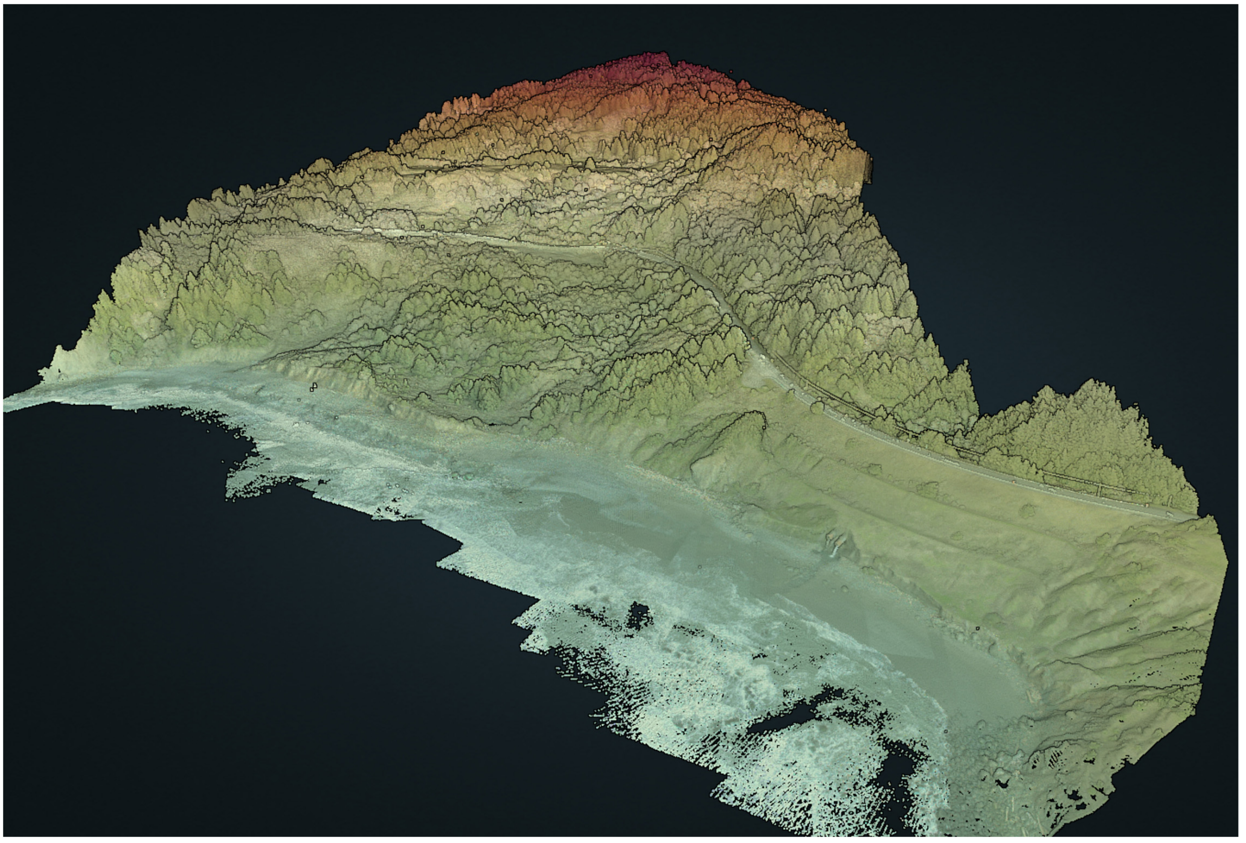

**FIGURE 12 |** UAS lidar point cloud of the Hooskanaden landslide showing overview with colors blended from elevation and RGB.

The GEER team included 5 U.S.-based and 15 Indonesian-based investigators. The team assessed local geology, collected perishable field data, and obtained eyewitness accounts to understand the mechanisms responsible for the initiation and progression of the large significant flowslides in the region.

The RAPID supported the GEER reconnaissance mission by providing in-field staffing (including a drone pilot) and instrumentation including UAVs, high-resolution GPS, and the mobile software RApp. The field team mapped the flowslides at high resolution using a DJI Inspire 2 UAV mated with a Zenmuse X4S camera (1-in. sensor, with 20 MP resolution). RTK GPS measurements were used to determine the coordinates of a network of ground control points to increase survey accuracy. The UAV flights were typically flown at an elevation of 65 m (with the nadir images having 75% overlap), providing a ground sampling distance pixel resolution of $\sim$2 cm. The GPS control allowed the post-processed digital ground surface model to achieve a 95% confidence interval geolocation accuracy of $\sim$10 cm across study areas spanning up to several square kilometers.

The UAV photographs were post-processed using the Pix4D software "Mapper" to develop high-resolution orthomosaic images and digital surface models. **Figure 9** compares an approximately 15,000 m$^2$ portion of a larger ($>$1 km$^2$) geo-referenced, true-color orthomosaic image with a post-event crisis response satellite imagery of the same area provided by Google Earth. The orthomosaic pixel size is $\sim$2 cm, providing a superb resolution that allows small features such as building components and ground cracks to be located, mapped, and measured. The full-size orthomosaic image includes information on buildings' post-earthquake conditions and critical infrastructure such as roads, canals, and levees.

**Figures 10**, **11** are true-color and shaded relief digital surface models, respectively, of the upper part of a flowslide in Palu City. The shaded relief image is a digitally derived model depicting shadows from simulated sunlight. In this case, the sunlight is generated from the right side of the model allowing the features of the terrain in the slide area to be identified via the shadows. This helps to accentuate subtle morphological features on the ground surface. Taken together, **Figures 10**, **11** reveal distinct zones with different modes of ground deformation, post-earthquake geomorphologic expression, and erosive or depositional features. Specifically, the upper part of the flowslide (to the right) is characterized by large tension cracks and graben-like down-dropped and back-rotated blocks of ground, resulting in differential settlement and lateral spreading. In the lower portion of the flowslide, the ground blocks generally disintegrate and decrease in size. Evidence of erosion is visible in some localized areas. The vegetation across the flowslide region was low lying (generally less than 50 cm tall), and therefore, the

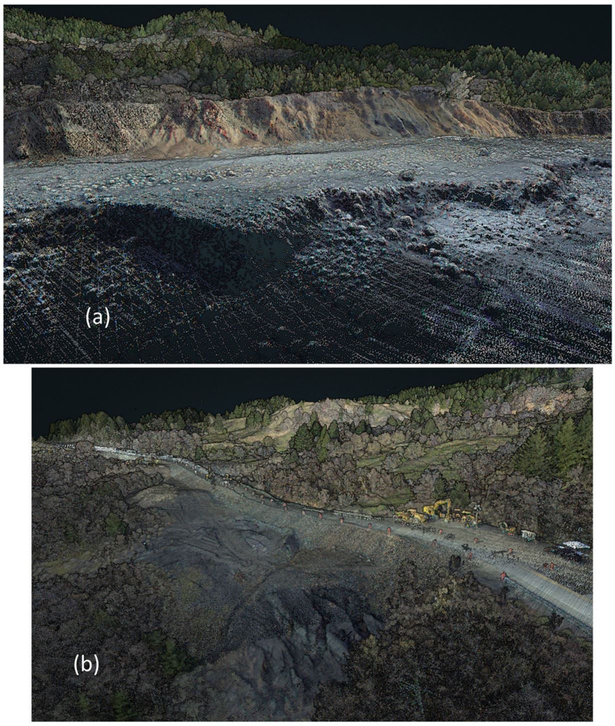


**FIGURE 13** | UAS lidar point cloud of the Hooskanaden landslide showing **(a)** uplift at the toe on the cobble beach (RGB) and **(b)** reconstruction of the highway in progress at the time of survey.

digital surface model, which includes ground cover, closely approximates a digital elevation model of the ground surface. It is also worth noting that the ground deformation entirely occurs downslope of an agricultural canal.

Based on the high-resolution UAV surveys and other reconnaissance observations, including eyewitness interviews, Mason et al. (2020) reached several key conclusions:

1. Earthquake-induced soil liquefaction triggered the flowslide movement.
2. Anthropogenic modification of the landscape played a critical role in the initiation of the flowslides. Specifically, the construction and operation of an unlined agricultural canal artificially recharged groundwater in the flowslide area.
3. The flowslides were not coseismic but instead occurred a short time after the earthquake shaking ended, which may be attributed to the phenomenon of void distribution in the liquefied soils (Mason et al., 2020).

## Case Study 3: Characterization of Damage to United States Highway 101 From the Hooskanaden Landslide

On 24 February 2019, after intense rainfall, a large surge event occurred at the Hooskanaden landslide, significantly damaging approximately 1 km of United States Highway 101 in Southwest Oregon, near the California border (**Figure 12**). The highway was closed for nearly 2 weeks while emergency operations were underway. The event resulted in 45 m of horizontal movement and 12 m of downward vertical movement of Highway 101 (Alberti et al., 2020) with horizontal velocities of up to 60 cm/h. Six meters of uplift (**Figure 13**) was observed at the toe of the slide, which daylighted on the cobble/gravel beach adjacent to the Pacific Ocean. The slide rises from 0 to 160 m in elevation with an approximate slope of 15°. Geologically, the site is predominately melange material with pockets of hard and soft material within a moderately weak soil matrix. This location is tectonically active and part of the Cascadia Subduction Zone. This seismicity, combined with high rainfall and frequent storm activity, has resulted in rugged terrain across the slide.

Over the last several decades, the Hooskanaden landslide has continually resulted in costly maintenance and repairs for Highway 101 by Oregon DOT. As a result, it was selected as one of the key sites for a long-term coastal landslide monitoring study by an Oregon State University research team consisting of Ben Leshchinsky, Michael Bunn, Matt O'Banion, Andrew Senogles, Stefano Alberti, and Joann Herrmann, and Oregon DOT collaborators Curran Mohney, Jill Dekoekkoek, Geoff Crook, and Kira Glover-Cutter. The research team had collected over 3 years of terrestrial lidar surveys at the site, established reference points for total station surveys, as well as a MEMs sensor array to track movements with high temporal frequency. Unfortunately, monitoring pins for the total station were repeatedly lost due to excessive movement of the slide and maintenance operations. The MEMs sensor sheared after approximately 1 month of operation. Given the immense size of the slide (nearly 0.5 $km^2$) and rugged terrain, it is not feasible to capture Terrestrial lidar data on the entire slide. As a result, the terrestrial lidar efforts were focused on key vantage points, including detailed scans of the sea cliff.

Two sets of UAS lidar were acquired at the site by the RAPID: March 2019 and June 2019, each requiring 3 days of field acquisition. A total of 24 and 17 flights were completed for the first and second surveys, respectively. Terrain following was implemented on the UAS, given the steep terrain changes present at the site. Not only were these data useful for the research team to aid in the interpretation of the slide, but the data were also utilized by Oregon DOT to support the emergency repairs as well as the design and reconstruction of the highway (**Figure 13**). These measurements of movement were computed by comparing UAS lidar measurements with terrestrial lidar scans acquired in Fall 2018. In addition to the measurements, the data were used by the research team and ODOT to map tension cracks and other features in the slide that could clearly be distinguished from the high-resolution DEM. Key advantages of the UAS lidar include the ability to capture the entire slide area in high detail as well as the ability to obtain an improved ground model over the terrestrial lidar given the improved vantage point above the ground.

The UAS lidar data were georeferenced by the RAPID facility using inertial explorer and Phoenix Lidar Systems' software using the GNSS receiver measurements, Inertial Navigation System (INS), and laser scanner to produce the point cloud. Following the direct georeferencing using the sensor components, a vertical

**TABLE 1** | Flight elevation (*Z*) adjustment statistics following the direct georeferencing solution for the March and June 2019 survey.

| | *Z* Adjustment (m) | |
|---|---|---|
| | **3/2019** | **6/2019** |
| Average | 0.0004 | 0.0006 |
| Std. Dev. | 0.0059 | 0.0078 |
| RMS | 0.0058 | 0.0075 |
| Min | −0.0115 | −0.0240 |
| Max | 0.0105 | 0.0118 |

($Z$) only adjustment was completed to minimize errors between the individual flights by comparing vertical offsets between overlapping flights. **Table 1** provides summary statistics of the overall adjustment. Overall, minimal adjustment was required given the relatively high agreement between flights. Nevertheless, biases of 7–10 cm were observed when comparing against terrestrial lidar scans acquired at the same time. Further, scatter of the UAS lidar data of $\pm$ 5 cm within a flight were commonly observed on hard surfaces such as the cobble/gravel beach and the road surface. The resolution was also considerably lower than the terrestrial lidar data but was relatively uniform across the site such that a 0.2 m DEM was produced for the entire slide. Herein, a simple accuracy assessment is provided. A rigorous accuracy assessment of the RAPID's UAS lidar can be found in Babbel et al. (2019), which shows similar accuracy results to those presented in this case study.

Ultimately, the ability to efficiently obtain data across the entire landslide, minimal time of mobilization, and overall quality of data made the UAS lidar the optimal choice for obtaining the post-event DEMs over alternatives such as terrestrial and airborne lidar and SfM/MVS photogrammetric methods.

## SUMMARY AND CONCLUSION

After 2 years of development and close to 2 years of field operations, the NHERI RAPID Facility is providing the natural hazards and disaster research communities with the equipment and support services to transform reconnaissance and data collection following extreme events. The RAPID hosts equipment and has developed software with applications that cross disciplines from engineering to the natural and social sciences. These developments have resulted in the collection of high-quality, high-resolution data sets that are enabling new science and engineering findings, ultimately leading to improved community resilience to natural hazards. To date, RAPID has deployed equipment and/or staff to more than 60 missions worldwide. Data have been collected following hurricanes, earthquakes, tsunamis, tornadoes, and landslides, and in other applications, such as supplementing laboratory instrumentation in large-scale structural engineering experiments.

As the example projects highlighted above demonstrate, the RAPID's equipment and workflows enable field teams to collect perishable data at multiple scales and with the resolution and accuracy necessary to make critical measurements and observations. RAPID's user training provides facility users with the expertise required to collect data themselves while RAPID's staff has expertise in all of the facility's equipment and can accompany teams when requested. RApp, the RAPID's mobile software platform, supports direct data collection such as images, audio, and custom-designed questionnaires, with an eye toward applications in the social sciences, as well as collecting metadata from the RAPID's other equipment and helping to coordinate teams in the field. Data and metadata collected with RApp are geolocated to facilitate collection and data linkage and are automatically uploaded to DesignSafe, enabling data collection over large areas and data reuse for advancing our understanding of natural hazard impacts.

With contributions and input from many in the natural hazards and disaster engineering, sciences, and social sciences communities, the newly operational NHERI RAPID Facility is transforming reconnaissance methods following natural disasters. The impact of the unprecedented volume of quality of data being collected from the real-world laboratory will not be known for some time. However, it is clear as researchers begin to use the collected data to help understand the impacts of natural hazards, inform simulation models, and link new models that cross disciplines. Such data are crucial in making discoveries that will improve community resilience. Further, the facility has raised questions and sparked recent discussions (and collaboration with CONVERGE) about integrating data across disciplines, including data formats, ethics, and questions about appropriate standardization of disaster reconnaissance data.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: Berman et al. (2020).

## ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## AUTHOR CONTRIBUTIONS

JB, JW, MO, JI, SM, KG, LL, AB, and TT collaboratively developed the RAPID Facility, its science plan, and strategic objectives, which were conveyed to NSF through internal reporting and have informed the text here. MG, AL, JP, JB, JW, JD, and MO carried out the day-to-day operations of the facility and designed the RAPID's operations. All authors contributed to manuscript revision, read, and approved the submitted version.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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METHODS
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# A Cloud-Enabled Application Framework for Simulating Regional-Scale Impacts of Natural Hazards on the Built Environment

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With the goal to facilitate evaluation and mitigation of the risks from natural hazards, the Natural Hazards Engineering Research Infrastructure's Computational Modeling, and Simulation Center (NHERI SimCenter) is developing computational workflows for regional hazard simulations. These simulations enable research to combine detailed assessments of individual facilities with comprehensive regional-scale simulations of natural hazard effects. By integration of multi-fidelity and multi-resolution models to assess natural hazard impacts on buildings, infrastructure systems and other constructed facilities, the approach enables the engineering analysis of public policies and socio-economic impacts. Effective development of platforms for high-resolution regional simulations requires modular workflows that can integrate state-of-the-art models with information technologies and high-performance computing resources. In this paper, the modular architecture of the computational workflow models is described and illustrated through testbed applications to evaluate regional building damage under an earthquake and a hurricane scenario. Developed and disseminated as open-source software on the NHERI DesignSafe Cyberinfrastructure, the computational models and workflows are enabling multi-disciplinary collaboration on research to mitigate the effects of natural hazard disasters.

**Keywords: natural hazard, earthquake, hurricane, workflow, disaster, loss assessment, simulation, cloud-based**

## INTRODUCTION

Much of the world's population lives in regions susceptible to earthquakes, tropical cyclones (hurricanes) or other natural hazards, where the risks are exacerbated by buildings and aging civil infrastructure that often are not designed to resist the hazards. These conditions, combined with the lack of information and technologies to characterize the performance of buildings and infrastructure, present enormous challenges for planning, design and management of communities that are resilient to natural hazards. Important decisions are often made in the absence of quantitative analyses about how communities will be impacted by natural hazards and how best to mitigate their devastating effects. While knowledge and data gained through field observations and experiments are fundamental to addressing these challenges, computational simulations are an essential component of the science and engineering needed to evaluate and mitigate the potential devastating effects of natural hazards.

Over the past decade, many reports have been developed that outline research needs and challenges to address the risks posed to society from natural hazards (e.g., DHS, 2010; Fenves et al., 2011; NIST, 2014, 2017). The recently published National Hazards Engineering Research Infrastructure Science Plan (NHERI, 2020) outlines three grand challenges and five research questions, all of which depend on integration of data and models through computational simulations. Specifically, simulations are critical to (1) characterize natural hazard phenomena, (2) evaluate their damaging effects on buildings, civil infrastructure and other physical assets, (3) quantify the socio-economic consequences of this damage, and (4) evaluate the effectiveness of alternative strategies to mitigate and recover from the damage. Each of these components entail simulations at varying scales, from detailed analyses of localized response of individual buildings or infrastructure components to multi-scale analyses of regionally distributed communities and infrastructure systems. The challenges are multi-disciplinary and require development and management of large datasets to translate data and analysis results between the modules.

The NHERI SimCenter was established by the National Science Foundation (NSF) to develop computational software tools that support research and education in natural hazards engineering. This paper describes the background and details of the SimCenter's ongoing development of computational workflows to integrate software applications for simulating earthquake and hurricane effects on communities. The computational workflows are illustrated in two testbed applications to quantify the effects of an earthquake and a hurricane over urban regions.

## PERFORMANCE-BASED ENGINEERING FRAMEWORK

The SimCenter's computational framework for natural hazards engineering leverages foundational advancements in performance-based engineering to integrate models and data from the physical sciences, engineering, and social sciences to evaluate and design strategies to create resilient communities. The performance-based approach aims to take full advantage of advances in computational modeling of earthquakes and storms and their damaging effects on buildings, transportation and utility infrastructure, and other constructed facilities.

Modern approaches to performance-based engineering for natural hazards trace back about 25 years to work in earthquake engineering risk assessment and rehabilitation. Two significant early milestones were the publication of the FEMA 273 NHERP Guidelines for the Seismic Rehabilitation of Buildings (FEMA, 1997) and the first release of the HAZUS software for regional earthquake risk assessment in 1997 (Kircher et al., 2006; Schneider and Schauer, 2006). Subsequently, FEMA 273 has evolved into the ASCE 41 standard for seismic evaluation and retrofit of buildings (ASCE, 2017), and HAZUS has been expanded to assess regional risks from floods, hurricanes and other hazards (Vickery et al., 2006; FEMA, 2018a). The FEMA P-58 Seismic Performance Assessment of Buildings guidelines (FEMA, 2018b), which leverages research by the Pacific Earthquake Engineering Research (PEER) center and other groups, established a comprehensive methodology with explicit damage and consequence models that rigorously incorporate uncertainties in earthquake hazards and their damaging effects (Moehle and Deierlein, 2004; Krawinkler and Miranda, 2004). Continuing efforts are underway to improve and extend comprehensive performance-based methods for the design and assessment of facilities to hurricanes, tsunamis and other hazards (e.g., Barbato et al., 2013; Lange et al., 2014; Bernardini et al., 2015; Attary et al., 2017; Ouyang and Spence, 2020).

The basic framework of performance-based engineering for natural hazards is illustrated in **Figure 1**. This figure was originally developed for earthquake engineering design, but the concept is generally applicable to other natural hazards. Moving from left to right, the process begins with the definition of a constructed facility, based on its design features and location. The next steps are to perform (1) a hazard analysis to characterize the hazard effects (e.g., earthquake ground shaking) that the facility is subjected to, (2) structural analyses to assess the response of the facility to the hazard, (3) damage analyses to quantify damage to facility components associated with the imposed deformations and forces, and (4) consequence analyses to evaluate the resulting risks to life safety, economic losses, and downtime. Input and output variables from each stage of the assessment are clearly defined as part of an underlying probabilistic formulation to propagate statistical data through the analyses. The resulting performance data inform decisions about the design and/or risk management of the facility.

Historically, methods for regional risk assessment (e.g., HAZUS) and performance-based design (e.g., FEMA P-58) were developed independently, where the former relied on simplified damage and loss models to assess large inventories of facilities, and the latter focused on detailed analyses of individual facilities. This evolution reflected both the primary goals of the methods and the capabilities of computational modeling technologies to perform the analyses. With modern high-performance computing systems, information technologies, and high-fidelity models, the assessment methods are converging to permit high-resolution simulations of regional models. In the SimCenter's framework, high-resolution multi-fidelity regional analyses are facilitated by cloud-enabled high-performance computing and informational technologies to create computational workflows.

## COMPUTATIONAL MODELING AND INFORMATION TECHNOLOGIES

Theory and experimentation have long been regarded as the two fundamental pillars of science and engineering. With the advent of high-performance computing and information

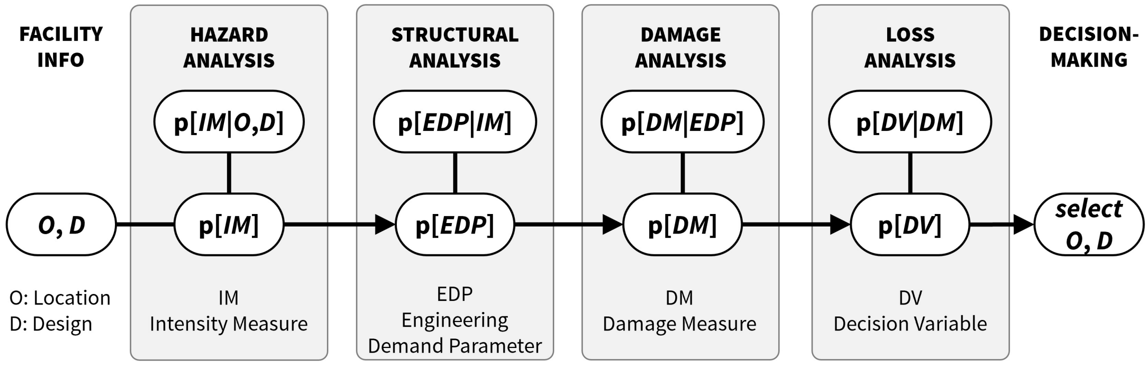


**FIGURE 1 |** Framework for performance-based engineering (after Porter, 2003).

technologies, computational and data-enabled science has become a third pillar. Numerical simulations are now used to both validate theory and inform experimentation. Validated numerical applications are routinely used to simulate the behavior of configurations that cannot be physically tested, e.g., extending data from laboratory experiments of structural components to enable simulation of buildings or simulating the response of communities experiencing regionally distributed natural hazard effects.

High-resolution simulations are now enabled by parallel computers and cloud computing resources. Parallel computing allows simulations to run faster as they utilize many processing cores of one or multiple CPUs on dedicated high performance parallel computers such as those available through NSFs Extreme Science and Engineering Discovery Environment (XSEDE), e.g., the TACC Frontera system (TACC, 2020). The research capabilities of advanced computing resources is further enabled by cloud-based information systems, which provide links to data from experiments, observation, and sensors. Such data is available through the DesignSafe Data Depot and other sources accessible through the World Wide Web.

For natural hazards engineering research, the data is diverse, dynamic, distributed and extensive. While manual gathering and processing of small data sets is possible, the overwhelming proliferation of data can inhibit its use. To help address this, the SimCenter provides a series of applications (SimCenter, 2020) that enable researchers to integrate online data and cloud computing resources. These applications perform their simulations using scientific workflows, which link together software applications, databases, and software libraries (Deelman et al., 2015). The basic concept is illustrated in **Figure 2**, where each puzzle piece represents a component of the hazard simulation that is encapsulated using pre- and post-processors to facilitate data transfer between modules. An example of such a workflow is an application (Zsarnóczay et al., 2019) that automates a FEMA P-58 type performance assessment of a building model by (1) querying the PEER NGA database server for a selection of ground motion records, (2) simulating the non-linear dynamic response of the building to the selected records using a high performance computer, (3) performing a FEMA P-58 damage and loss evaluation, incorporating the latest FEMA P-58 fragilities obtained from the web (ATC, 2020b), and (4) displaying the results to the user in graphical or tabular form. This workflow for a single building can be integrated into a workflow for detailed regional simulation of communities with large inventories of buildings. Examples of two regional simulations are presented later in the paper for an earthquake and a hurricane scenario.

The SimCenter's strategy for studying the effects of natural hazard from individual facilities to regional simulation is through the creation of an application framework for scientific workflow systems. Scientific workflow systems are applications that enable users to build, launch, and monitor scientific workflows. Referring to the jigsaw representation of a workflow shown in **Figure 2**, the framework allows users to (1) select from different applications for each jigsaw piece, (2) build their workflow, and (3) then launch and monitor the running workflow. When running the workflow, the system will launch the individual applications and pass the needed input and output data between the applications. The application framework is designed to be modular and extensible, such that researchers can introduce their preferred application for any step in the process. This functionality is achieved by standardizing the flow of information through the definition of standard interfaces. To facilitate the introduction of user-supplied workflow components, we have developed templates for pre- and post-processing links into the workflow. Included are links to databases that support the workflow, along with modules that provide routines for uncertainty quantification. Thus, new software components can be conveniently added or reconfigured by creating new pre- and post-processing links. The overall aim is to leverage existing and newly developed user-specified software by providing the ability to reconfigure and tailor the workflow tools to address specific disaster research inquiries.

In contrast to general purpose scientific workflow systems, e.g., Taverna (Oinn et al., 2003), Galaxy (Goecks et al., 2010), and Pegasus (Deelman et al., 2015), the SimCenter workflows are constrained and optimized for a limited number of applications that are systematically assembled for natural hazards engineering. The workflow architecture is aimed at facilitating use and reuse

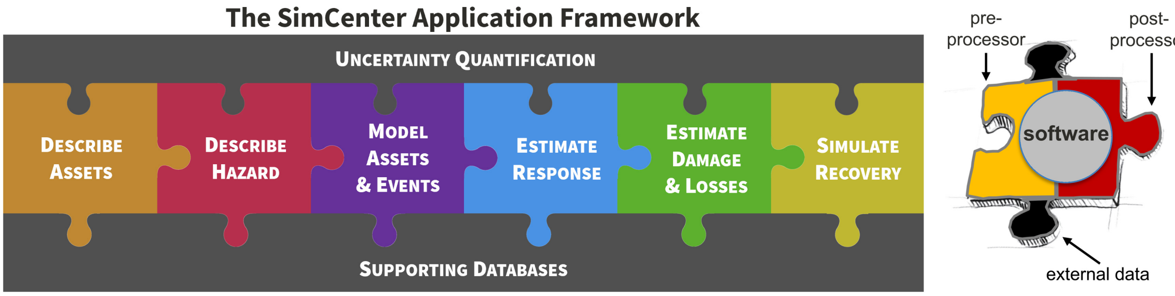


**FIGURE 2 |** Modules of the software application framework developed by the SimCenter.

of workflows by a broad range of natural hazards engineering researchers with varying levels of software skills. Some of the SimCenter applications employ simpler workflows that address only specific portions of the natural hazards application framework, whereas others encompass comprehensive regional simulation systems, include asset inventories, advanced loading options for earthquake and hurricane scenarios, fragility curves from HAZUS and FEMA P-58, supporting databases, and tools for uncertainty quantification. To facilitate use, reuse, and further development by researchers in natural hazards engineering, the software systems and workflows are designed following a best practice guide for workflows (Hettne et al., 2012), including: (1) modularity with clear interfaces to facilitate adaptation and extension, (2) well defined and visualizable outputs, (3) thorough testing and verification, (4) documentation with examples of data input and output, and (5) utilization of stable service providers (PEER and DesignSafe-CI) that allow the workflows to be readily executed from outside the local computing environment.

## COMPONENTS OF REGIONAL SIMULATIONS

The four main components (tasks) of regional natural hazard analyses consist of (1) developing an inventory of the physical assets, such as buildings, transportation systems and components, and utility systems and components, (2) quantifying the characteristics of the natural hazard event (e.g., earthquake ground shaking, hurricane wind flows and storm surge) that can impact the physical assets and the community, (3) assessing the damaging effects of the natural hazard on the physical assets, and (4) evaluating the life-safety risks and other socio-economic consequences of the damage on the affected communities. This last step provides key information to assess disruptions to communities and helps inform planning for recovery, which is key to community resilience. Further details of these four components are outlined below with specific emphasis on earthquakes and hurricanes, which are the current focus of SimCenter developments.

### Asset Inventory Development

Within the context of natural hazard risk assessment, the asset inventory encompasses information describing the locations and characteristics of buildings, transportation and infrastructure system components, industrial and port facilities, and other physical assets that are at risk of damage from the natural hazard. Ideally, the asset inventory should include all characteristics of the components necessary to evaluate the impact of the natural hazard effects (e.g., ground shaking, strong wind, storm surge) through response, damage and loss analyses. For example, for buildings subjected to earthquake ground shaking, the inventory should include information on the building height and floor area, building structural system and materials, foundation, façade, interior partitions, mechanical and electrical systems, architectural finishes. Where this information is not explicitly known for every facility in the study region, it can be inferred, using rule-based models and machine learning methods, from the building age, function, and other available characteristics.

Looking beyond the direct damage and losses, the inventory should include information that can facilitate assessment of the asset damage to the community functions and recovery. For buildings this may include information on building occupancy and use, e.g., whether it is a medical facility that is part of a regional hospital network. For network components, this includes information on the component functionality within the overall system, e.g., for water distribution systems this may include data on pipe pressure, pumps, storage, flow capacity, connectivity, etc.

For many assets, the required inventories are not readily available and must be assembled from various data sources. For building inventories, conventional data sources include tax assessor and other publically available property databases created by local and state governments, real estate databases, building permit records, and some specialty databases (e.g., CoreLogic, 2020; Emporis, 2020). For transportation and infrastructure systems, inventory databases are typically maintained by government agencies or private organizations. In some cases, the databases are proprietary, which can limit how the data is accessed, used, and shared.

Automated collection and interpretation of images is another rapidly growing resource for inventory development. This may include images collected by satellites, drones, or crowd sourcing, which may be available through publicly accessible open source or proprietary databases. Emerging machine learning algorithms, coupled with high-performance cloud-based computing, offer unprecedented capabilities for automated image interpretation.

Advanced statistical and artificial intelligence methods can further enhance the capabilities to combine information from multiple data streams.

## Regional Hazard Characterization and Modeling

For regional assessments, characterization of the natural hazard typically involves calculating the hazard and its damaging effects for one or more scenario events. While the general concept of the analysis is common to all hazards, the specific details can vary considerably. The following discussion focuses on the effects of earthquakes and hurricanes to illustrate the key concepts and outline implementation details for these hazards.

### Earthquake Hazard

Earthquakes are typically characterized by the size of rupture on an earthquake fault, e.g., using moment magnitude, Mw, which is a measure of energy release that depends on the fault mechanism, the rupture area and slip amount, rock strength, and other parameters. The resulting ground shaking in the affected region can be determined through various means. The most conventional approach for this uses ground motion prediction equations (GMPEs) to calculate intensity measures of ground shaking as a function of the earthquake Mw, distance to the fault rupture, site conditions, and other parameters. Typical ground motion intensity measures include peak ground acceleration, velocity, or displacement, spectral (period dependent) acceleration, velocity, or displacement, ground duration, and other measures. Where seismogram time series of ground motions are required for subsequent response and damage analyses, the ground motion time series can be obtained by generating samples from a numerical stochastic model or selecting and scaling historical ground motion recordings that are selected and scaled to match the site intensity measures. For example, one can calculate a target response spectrum using GMPEs and then select and scale recorded ground motions whose response spectra matches the target. The GMPEs used in this approach are the same (or similar) to ones used to create probabilistic seismic hazard maps. However, whereas seismic hazard maps represent a statistical combination of ground motion intensities from multiple earthquake events with various return periods that are independently evaluated for each site, the ground motion realizations used for regional hazard analyses are from one or more distinct earthquake events, where the models preserve the spatial correlation in the variability of earthquake shaking across a region.

An alternative approach to the conventional method using GMPEs is to directly simulate earthquake fault ruptures and the resulting ground motions using mechanistic (physics-based) models, stochastic (statistical) models, or hybrid models that combine mechanistic and stochastic models. Similar to the GMPE approach, the direct simulations begin with a definition of an earthquake fault rupture, which provides input to wave propagation models that directly generate ground motion seismograms. Examples of this direct simulation approach include the Southern California Earthquake Center's (SCEC) Broadband Platform and Cybershake project (Graves et al., 2011), the Lawrence Livermore National Laboratory's SW4 simulation platform Petersson and Sjogreen (2017), and the USGS M9 simulations (Frankel et al., 2018). These all employ physics-based methods to simulate the ground motions via the equations of motion for solid materials, including accounting for the local geologic and fault conditions. The main challenges associated with these methods are (1) collecting the data required to characterize the local fault and geologic characteristics (e.g., earthquake basins), and (2) the large computational demands – especially for full 3D models.

The SimCenter applications and workflows support both the traditional GMPE-based approach and the direct simulation approach, where either can provide ground motion seismograms for one or multiple realizations of earthquake events (Mw on a selected fault) for regionally distributed sites. Applications and workflows for the traditional approach employ earthquake hazard information available from USGS data, along with the PEER NGA ground motion database. Applications and workflows for simulated ground motions utilize tools to generate stochastic ground motions, or alternatively, tools to access and select seismograms from databases of pre-simulated earthquake events. The selected seismograms can either be used directly as input for non-linear dynamic analyses of structures (including models of the underlying soils) or to characterize intensity measures (e.g., spectral accelerations) of ground motions as input for analyses or damage models for structures.

### Hurricane Wind Hazard

Hurricanes (tropical cyclones) are commonly classified by the Saffir-Simpson scale (category) in terms of 1 min maximum sustained wind speeds. For SimCenter applications, hurricane models have been developed to generate either wind speeds or their time histories, whereby the wind loading effects on buildings and other facilities can be estimated by detailed computational fluid dynamics (CFD) analyses or other simplified methods. Further, Monte Carlo simulations of hurricanes can be carried out using hurricane wind field models, beginning with characterization of the hurricane track parameters that are translated into wind speeds.

#### *Hurricane track parameters*

Along the track of a hurricane, the characteristic indicators of the hurricane include the radius of maximum winds (RMW), intensity measures (maximum wind speeds or central pressure difference), shape parameter (Holland-B), sea surface temperature (SST) and track information (initial location, translation speed, and heading). The statistical approaches for characterizing hurricanes include sampling of parameters from probabilistic models that are estimated using an observation database from the National Oceanic and Atmospheric Administration (NOAA). In the NOAA database, the statistical best fit of the empirical track for past hurricanes has been synthesized by data fitting over heterogeneous sources. For example, by utilizing the full track model, the genesis location can be randomly selected from the historical record or generated based on its distribution function (Vickery et al., 2009). Starting from the genesis location, the track is generated by

Markov-type models, represented by auto-regressive functions in terms of hurricane parameters (latitude translation speed, sea surface temperature, etc.) as well as a random error term (Vickery et al., 2000b). The track-information then engenders other parameters by the statistical relationship models which are usually represented as expressions involving uncertainties as well.

***Hurricane wind speeds***

The mean wind speed at the local site is predicted using the output of the preceding step. This requires solving the three-dimensional non-linear, hydrodynamic, primitive equation system describing dry air motion in the hurricane boundary layer. To simplify the problem, a two-dimensional slab (height-averaged) model may be utilized (Vickery et al., 2000a). Alternatively, there are efforts to supplement these formulations with semi-empirical analyses informed by the three-dimensional equations of motion (e.g., Kepert, 2011; Snaiki and Wu, 2018). The wind speeds are solved at the gradient height, which are then converted to near-ground heights by the boundary layer wind speed profile given by statistical models in the form of equations or specific values (Vickery et al., 2009). The local terrain in this model scale is accounted for by the surface drag coefficients. Solving these equations is time-consuming, and surrogate models have been developed as an alternative to speed-up the computations (Vickery et al., 2000a,b).

By carrying out the above simulation for multiple realizations, the statistical characteristics of local hurricane winds may be determined (for example, the cumulative probability distribution of wind speeds), which together with the turbulence characteristics of hurricane winds can be used as the input for the ensuing analysis. Examples of software platforms that apply these methods include Weather Research and Forecasting (WRF) (Davis et al., 2008), HAZUS (Vickery et al., 2006), and the Florida Public Hurricane Loss Model (Hamid et al., 2010).

In the current SimCenter application tools, there are several possible approaches for characterizing the wind hazard. One approach provides access to the simplified (and quick to determine) wind speeds from the ASCE 7-16 (ASCE, 2016) maps with different mean recurrence times that is available through an API to the Applied Technology Council hazards website (ATC, 2020a). For more detailed site-specific studies, the SimCenter supports tools for implementing the Monte Carlo based scheme, described previously, to simulate the reference level winds for different recurrence intervals. The use of surrogate models based on established storm parameters can expedite the estimation of these wind speeds. These wind speeds can be used with simplified models to determine wind pressures or as direct input to damage and loss functions. Alternatively, the wind speed histories, along with the terrain consistent features of atmospheric flow prescribed in standards or derived from data-driven models of specific storms, can be used to characterize inflows for CFD analyses. To characterize the in-flow conditions for CFD computations, the SimCenter has developed an application, called TinF (Turbulance Inflow, Mackenzie-Helnwein et al., 2019), to simulate wind velocity fluctuations that are consistent with the statistical and spectral features of wind fields simulated in wind tunnels using scaled roughness blocks and barriers in advance of the location of the target structure under study.

For more advanced studies, a nested multi-scale simulation involving the three-dimensional equations of motion for the atmosphere would better represent a hurricane wind field at multiple scales, i.e., from large scales down to building scales by wrapping WRF type models around Large Eddy Simulations (LES) for assessing loads on buildings and their response to tropical storm winds. This level of advanced workflow and their software implementation is not directly part of the SimCenter workflow applications. However, similar to physics-based earthquake simulations, the SimCenter workflows can be adapted to ingest simulated wind histories, which are developed by advanced three-dimensional simulations that are run outside of the SimCenter applications.

## Hurricane Surge Hazard

The computational simulations of storm surge hazards require: (1) the hurricane wind field to drive the model; (2) the topography and bathymetry along the coastline; and (3) the land use/land cover data for the simulation of wave run up on shore. The coupling of a storm surge, nearshore wave, and wave run-up will yield geospatially-distributed time-dependent responses, which typically describe the mean water elevation, max water elevation, max water depth, and significant wave height (or limit of moderate wave action). Such responses can be generated either by a high-fidelity model or a surrogate model tuned to a database of results from these models.

***Storm surge heights and inundation***

Numerical models for storm-surge simulations are typically based on single-layer-depth averaged differential equations describing fluid motion driven by storm winds. The available numerical models differ in their computational solution strategies, which have implications on the spatial and temporal resolution of the simulations, the required computational resources and runtimes, and the required input data and model parameters. Generally, these models capture the amplitude of long-period, gravity waves, but they do not simulate short-period wave effects. Typical models include, for example, Sea, Lake and Overland Surge from Hurricanes (SLOSH), which solves equations using local grids; ADvanced CIRCulation (ADCIRC), which is commonly regarded as the state-of-the-art in coastal storm-surge simulation and capable of providing significantly more accurate simulations than methods based on SLOSH (Resio and Westerink, 2008); and GEOCLAW, which lies between SLOSH and ADCIRC in terms of modeling resolution and computational cost (Mandli et al., 2016).

***Nearshore wave models***

To simulate local wave effects, in addition to the long-wave surge heights, ADCIRC simulations have been coupled with different nearshore wave models, such as Simulating Waves Nearshore (SWAN), which computes random short-crested wind-generated waves in coastal regions and inland waters (Kennedy et al., 2012); or Steady-State Spectral Wave model (STWAVE, Smith et al., 2001), which is a steady-state finite difference spectral model for nearshore wind-wave growth and propagation based on the wave action balance equation.

***Wave run up overland***

Supplementary wave run-up simulations are required to capture the interaction of waves with the shoreline and any coastal protective features along coastal transects. To this end, inputs from the nearshore wave models can be fed into a one-dimensional Boussinesq model, executed at the pre-selected transects to estimate the wave run-up overland (Demirbilek et al., 2009). Wave run-up calculations are executed at transect locations generally selected by segmenting the defined coastline in the areas of interest and selecting the transect density proportional to computational demand.

***Surrogate modeling***

In lieu of repeated high-fidelity simulations (e.g., ADCIRC plus STWAVE/SWAN analyses), surrogate models can provide a simplified description of a storm scenario based on a small number of model parameters corresponding to its characteristics at landfall (i.e., those parameters depicted in the hurricane wind field model). The scenarios in the database of high-fidelity simulation results are then parameterized according to the surrogate model parameter vector to create an input-output training dataset. The surrogate model is then built to approximate this input-output relationship using a Kriging metamodel coupled with Principal Component Analysis (Jia and Taflanidis, 2013). Subsequently, surrogate models can be used to efficiently generate storms and their attendant features for risk and impact assessments of coastal regions.

## Response, Damage, and Consequence Modeling

Performance assessment of inventory assets (i.e., buildings, bridges, utility infrastructures, etc.) can follow one of several approaches, depending on the desired resolution and available information and tools for the assessment. Shown in **Figure 3** is an illustration of three alternative modeling approaches for evaluating asset performance. Path I in the figure represents cases where a single vulnerability function is used to determine one or more decision variables for an asset type directly from the hazard intensity measure. This path is employed in HAZUS and other similar tools for wind events, where, for example, building loss ratios are directly related to hurricane wind speeds. The Path I vulnerability curves typically distinguish between asset types based on general characteristics, age, and condition (e.g., single-family 1–2 story wood frame house, construction date, good condition). Path II uses two layers of functions, where the first (fragility) function relates hazard intensity to asset damage, and the second (consequence) function relates the damage state to the decision variable. This approach is also available in HAZUS to assess damage and loss for seismic events. Path III, the most refined approach, is employed in the FEMA P-58 method for seismic performance assessment of buildings. In FEMA P-58, a non-linear structural analysis (or an alternate empirical function) is used to calculate so-called engineering demand parameters, such as lateral drifts, accelerations, or internal forces, that are induced by earthquake ground motions. Component fragility functions are then used to relate the engineering demands to damage, which define the input to consequence functions to evaluate the associated replacement or repair measures for each component. The component level consequences are then aggregated to determine the decision variable(s) for the complete facility.

In concept, any of the three paths outlined in **Figure 3** can be adapted to evaluate the performance of practically any type of asset (i.e., buildings, transportation or lifeline components) to any natural hazard, although the details of the models and calculations can vary significantly. Moreover, since each asset is evaluated independently, alternative paths can be used for the various assets in the inventory. For example, detailed (Path III) analyses could be used for unique assets whose performance is vital to the community (e.g., tall buildings, hospitals, major bridges, power plants) while the less detailed Path I analyses could be used for assets for which simpler damage-prediction models are adequate (e.g., single-family homes, roads and highway overpasses, utility substations).

Where individual assets are part of a larger network, another layer of analysis and assessment is required to evaluate the performance of the network. For example, within a potable water network, the functionality of the network to deliver water will depend on the damage and repair times for individual pipe segments, storage tanks, pump stations, etc. Similarly, the performance of a transportation network will depend on the damage and repair of individual bridges, roadway segments, and interchanges between systems. In many cases, the network system analyses can be carried out using the same software that is used to simulate standard service functionality of the system, provided that the reduced functional state of the components and the boundary conditions (e.g., post-event transportation demands) are adjusted to reflect the natural hazard effects.

## Recovery Modeling

To assess and promote resilience to natural hazards, a final stage in the assessment is to understand and quantify the recovery from natural hazard disasters. This is important to more fully appreciate how disasters can affect communities and to develop strategies to promote recovery and, thereby, minimize the long-term effects of natural disasters. While the asset damage and estimated repair/replacement costs and time are important input data, recovery modeling goes beyond this to evaluate availability and management of resources and many other socio-economic factors that can impede or otherwise influence the recovery process. For recovery of individual buildings and infrastructure systems, some guidelines have been proposed to characterize and estimate impeding factors and offer suggested steps to facilitate recovery (e.g., REDI, 2013; Davis and Shamma, 2019). Frameworks for community resilience and recovery have been proposed (e.g., Bruneau et al., 2003; NIST, 2016a,b,c; Johnson, 2019), and work is underway by the NIST Center for Risk-Based Community Resilience Planning (Nist-COE, 2020) to develop computational models to support disaster resilience planning and

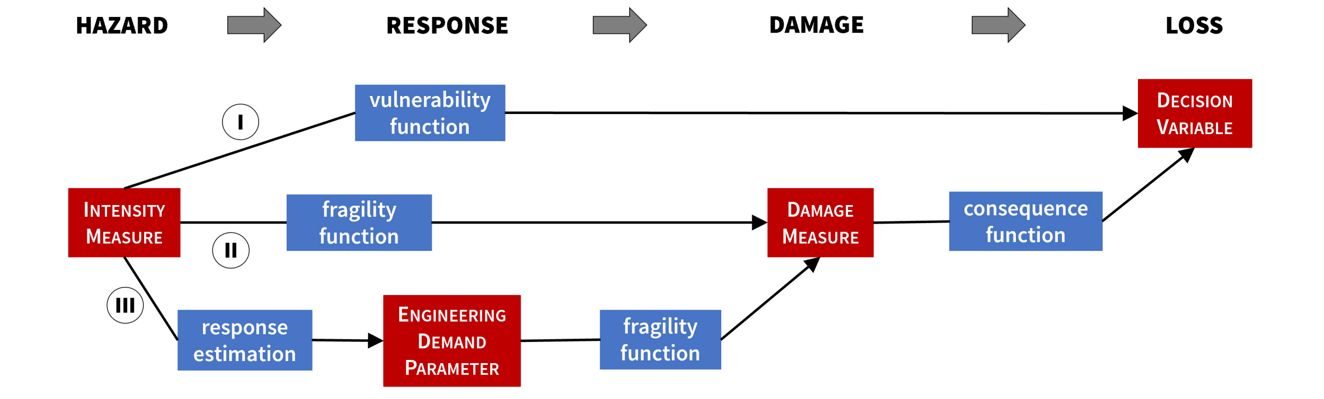


**FIGURE 3 |** Schematic workflows for asset performance assessment.

post-disaster recovery. Development of models to quantitatively simulate regional recovery, such as with agent-based models, is a continuing research need that the SimCenter tools can be extended to support.

## SIMCENTER FRAMEWORK COMPONENTS AND APPLICATIONS

As mentioned previously, the SimCenter's strategy to study effects of natural hazards from the individual building level to the regional simulation level is through the creation of an application framework for scientific workflow systems. Shown in **Figure 4** is a more detailed abstraction of the framework, where the items listed across the bottom of the figure represent key components and the applications shown higher in the figure are workflow applications that the SimCenter has developed (McKenna, 2020). **Figure 5** shows how the workflow components and applications are organized around cloud computing with supporting tools (e.g., Wilson et al., 2017; Dooley et al., 2018) to manage data transfer and interface with remote service providers, particularly those of the Texas Advanced Computing Center (TACC, 2020).

### SimCenter Framework Components

The SimCenter framework components include the following:

*BE—Built Environment Inventory*: The *BE* consists of meta-data and data files that define the inventory of physical assets for a regional simulation, including buildings, transportation components and systems, utility infrastructure components and systems, etc. By providing a framework to organize and store databases on DesignSafe, the SimCenter aims to promote best practices for collection and sharing inventory data. To help facilitate development of inventories, the SimCenter has developed artificial intelligence (AI) tools for building inventory data collection (BRAILS—Building Recognition using AI at Large Scale; Wang et al., 2019) and for data enhancement (SURF—Spatial Uncertainty Research Framework; Wang, 2019), along with web data query/collection techniques.

*EVENT—Hazard Event:* The *EVENT* consists of meta-data and data files that define the hazard data (e.g., earthquake ground motions, wind fields, storm surge inundation, tsunami inundation). For earthquake hazard studies, the SimCenter workflow tools include software applications for (i) generating earthquake target spectra from the USGS OpenSHA web service, (ii) selecting and scaling recorded ground motions from the PEER NGA database, (iii) generating simulated stochastic ground motions, and (iv) ingesting simulated ground motions from databases of simulated and recorded ground motions. For wind and storm surge studies, the workflow can support (i) generating wind field time histories stochastically or using OpenFOAM (2020), (ii) incorporating experimental wind tunnel datasets utilizing online resources such as Vortex Winds (Kareem and Kwon, 2017) and the TPU Aerodynamic Database (TPU, 2020), or a user's own local dataset, and (iii) interfaces for querying and ingesting wind speeds and storm surge inundation heights from external applications.

*SAM—Structural Analysis Model:* The *SAM* is the workflow component that includes rule-based, AI and other types of applications to translate descriptive information from the built environment inventory into information to create finite element or other types of models to simulate the structural response to the hazard effects.

*FEM—Finite Element Modeling*: The *FEM* module consists primarily of wrappers for input/output to existing finite element software to simulate the response of structures and geotechnical materials to earthquake ground shaking, wind, storm surge wave loading, and tsunami wave loading. Such analyses could also encompass CFD and structure-fluid interaction. OpenSees (2020) and OpenFOAM (2020) are the main open source applications that are called by the current *FEM* wrappers.

*EDP—Engineering Demand Parameters*: The *EDP* represents the workflow component that defines and manages the output of hazard-induced deformation or other demands from a finite element or other type of analysis model for input into the damage and loss assessment.

*DL—Damage and Losses: DL* is the workflow component where damage and losses are calculated for the assets in the built environment inventory. Since these calculations are essential to all performance assessments and not readily available in existing

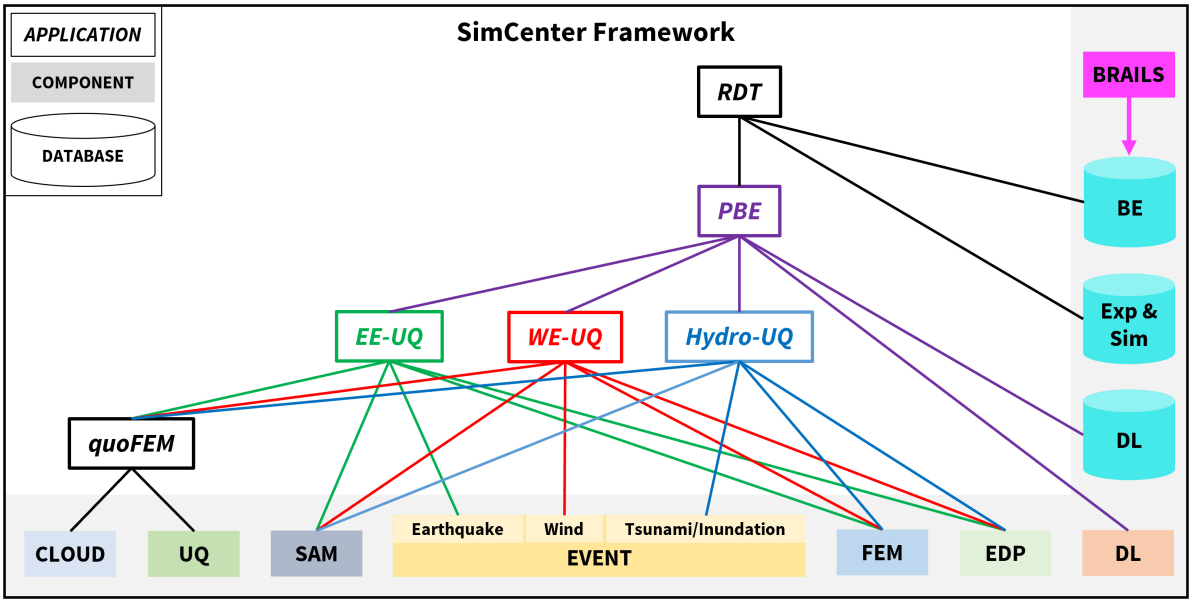


FIGURE 4 | SimCenter framework components and applications.

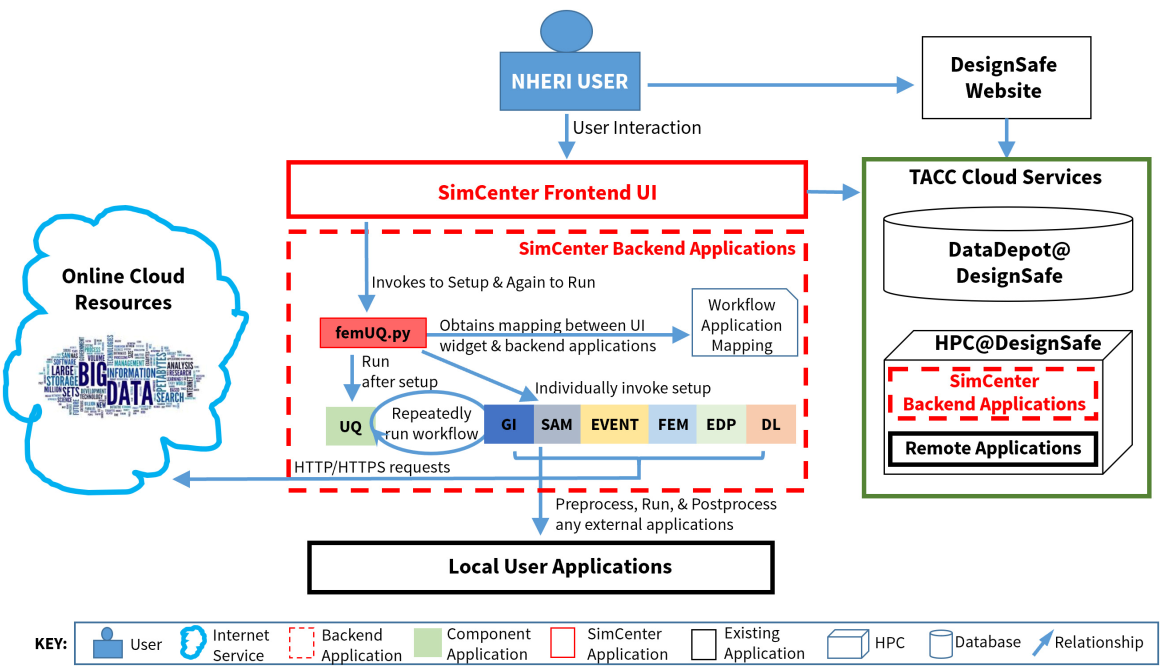


FIGURE 5 | Integration of the SimCenter framework into the NHERI computational environment.

software, the SimCenter developed an application framework called PELICUN, Probabilistic Estimation of Losses, Injuries, and Community Resilience Under Natural Disasters (Zsarnóczay, 2019; Zsarnóczay and Deierlein, 2020), to generalize the FEMA P-58 methodology to evaluate damage and losses in buildings and other facilities under earthquakes, hurricanes and other hazards. Referring back to **Figure 3**, PELICUN supports multiple paths for calculating DVs, from simplified (path I) approaches using vulnerability functions to the most detailed approach (path III). The PELICUN framework is customizable to permit a wide range of methods to address multiple facility types, multiple hazards, and multiple levels of refinement.

*UQ—Uncertainty Quantification*: The *UQ* component provides an interface to software and routines for methods of uncertainty quantification, which can be interfaced with other components. One of the registered applications supported by *UQ* is DAKOTA (Adams et al., 2019), which offers a range of methods for uncertainty quantification.

*Cloud:* Workflow component that manages communication with remote computing and data service providers and sending/receiving data over the web.

*DL Data:* Databases of fragility curves for damage and loss calculations for various types of facilities (buildings, bridges, infrastructure) subjected to demands from various hazards (earthquake, wind, surge).

*Exp/Sim Data:* Databases of experimental and/or computational research data that is utilized for machine learning *SAM* applications and code validation.

## Scientific Workflow Systems

While researchers can develop specialized workflows that include their own applications, along with applications and libraries of the SimCenter framework (**Figure 4**), the required computer programming skills and familiarity with the application framework may inhibit widespread utilization of the computational tools. To facilitate broad use of the framework components for standard research studies, several desktop applications have been developed. The desktop applications are scientific workflow systems with graphical user interfaces that create workflows to (1) run the associated computations either on the user's local computer or seamlessly with cloud computing resources, and (2) view the results of the workflows. These desktop applications have initially been implemented to run SimCenter framework components, and they can be modified to include user-supplied components. These desktop applications include:

*quoFEM:* The Quantified Uncertainty with Optimization for the Finite Element Method application facilitates the routine uncertainty quantification calculations by combining software systems for uncertainty quantification and optimization with finite element analysis to run locally or on high performance computing cloud resources. As shown in **Figure 4**, *quoFEM* is built with the *UQ* and cloud computing resources of the framework.

*EE-UQ:* This is an earthquake engineering application to determine the response, including *UQ*, of a structure to an earthquake excitation. The tool focuses on the structural model and will evolve to include soil-structure interaction models imposing boundary conditions necessary to impart the earthquake motion. The application builds upon *quoFEM*, adding the *SAM*, earthquake *EVENT* and *FEM* components of the framework.

*WE-UQ*: This is a wind engineering application to assess the response of buildings to wind loading, taking into account that the properties of the building and the wind loads are not known exactly, and given that the simulation software and the user make simplifying assumptions in the numerical modeling of the structure. It is similar in composition to *EE-UQ*, but with a wind *EVENT* component.

*Hydro-UQ*: This is a planned (future) application to assess the response of structures to water flows from storm surge or tsunamis. This tool will be similar to *EE-UQ* and *WE-UQ*, but with tsunami and coastal inundation *EVENT* components.

*PBE*: The performance-based engineering application is an extensible workflow application to evaluate the performance of buildings or other assets to natural hazards. The current release provides researchers a tool to assess the performance of a buildings to earthquake ground shaking, building off the *EE-UQ* application. As shown in **Figure 4**, future releases are anticipated to extend the features to assess building performance to wind (building off the *WE-UQ* application) and water flows (building off the planned *Hydro-UQ* application) by adding the *DL* component.

*RDT*: The Regional Decision Tool is under development to facilitate regional hazard scenario studies of the sort described in the next section of this paper.

# ILLUSTRATIVE TESTBED APPLICATIONS OF REGIONAL SIMULATIONS

To demonstrate the features and capabilities of the cloud-based regional simulations, computational workflows are described for two testbed studies that utilize components of the SimCenter framework. One is an earthquake scenario for the San Francisco Bay area, and the second is a hurricane scenario for the Atlantic City region of the New Jersey coast. Additional testbeds, including one looking at earthquake risk to a water distribution system in Memphis, are also under development.

## San Francisco Bay Area Earthquake Scenario

The San Francisco Bay Area encompasses three large cities, San Francisco, Oakland and San Jose, which together with the surrounding communities have a population of about 7.7 million people. The seismic hazard in the San Francisco Bay Area is dominated by the San Andreas and Hayward faults that straddle the region. The San Andreas Fault is located just to the west of San Francisco and is capable of a magnitude Mw 8 earthquake, such as the Mw $\sim$7.8 event that occurred in 1906. The Hayward Fault, which runs up the eastern edge of the Bay Area, is capable of a magnitude Mw 7 earthquake, such as the Mw $\sim$6.7 event that occurred in 1868. Recently, the USGS completed an earthquake scenario study for a Mw 7 event on the Hayward fault, which provided an opportunity to contrast existing regional assessment methods with the SimCenter's computational workflow.

The SimCenter workflow tools were applied to assess the performance of 1.84 M buildings in the San Francisco Bay Area due to a Mw 7.0 earthquake rupture on the Hayward fault. Probabilistic assessment of earthquake consequences with building (parcel) level resolution at this scale is only feasible using high performance computing resources, which is facilitated by SimCenter's regional Workflow for Hazard and Loss Estimation (rWHALE, Elhaddad et al., 2019). The testbed focuses on assessment of response, damage, repair costs, and repair times for all 1.84 M buildings in the simulation.

### Building Inventory

This study used a parcel-level inventory of buildings in the Bay Area that was developed by UrbanSim (Waddell, 2002) using public resources such as the City and County of San Francisco's data portal (DataSF, 2020) and tax assessor databases. The database includes locations (latitude, longitude), total floor areas, number of stories, year of construction, and the occupancy type for each building. The available information about location and building geometry were refined by merging the UrbanSim database with the publicly available Microsoft Building Footprint data (Microsoft, 2020) for the testbed area. These data were used to populate two additional attributes, replacement cost and structure type, based on a ruleset that considers local design practice and real estate pricing. For further details about the database and ruleset see Elhaddad et al. (2019).

### Earthquake Event

The ground motions for the Mw 7.0 Hayward earthquake were simulated by Rodgers et al. (2019) at the Lawrence Livermore National Lab (LLNL) using the SW4 finite difference code (Petersson and Sjogreen, 2017). SW4 solves the elasto dynamic equations of motion in the time domain for a 3D solid. A 77 × 13 km rupture surface was projected onto the fault geometry in the 3D geologic and seismic model for the Bay Area (USGS, 2018) with a hypocenter near the San Leandro salient. Waveforms were sampled in three dimensions on a 2 km grid over the 120 × 80 km surface of a 35 km deep solid body. The resulting waveforms capture ground shaking reliably over the 0–5 Hz frequency domain for sites with a characteristic shear wave velocity above 500 m/s. The computations were run using more than 8,000 nodes (∼500,000 processors) on the Cori Phase-II cluster (NERSC, 2020).

The raw results at 2301 grid points were processed by the SimCenter and converted to the JSON file format used by our workflow applications. These data provide sets of three-component seismograms for grid points spaced every 2 km throughout the study region. The ground motions are assigned to buildings using a nearest-neighbor search algorithm, where the four nearest grid points are identified for each building and a set of 25 seismograms are assigned by weighted random sampling of the set of time histories from the nearest grid points. The weight of each grid point is inversely proportional to its squared distance from the building.

### Response Simulation

The non-linear response of buildings to ground shaking is simulated using OpenSees (OpenSees 2020) and an application, MDOF-LU, that generates an idealized structural analysis model based on structure type, height, plan area, year of construction and the type of occupancy. The MDOF-LU application is based on a method developed by Lu et al. (2014) that uses the building configurations in the HAZUS earthquake technical manual and corresponding capacity curve descriptions to define a multi-story non-linear shear-column finite element model with lumped masses.

Each of the 1.84 M building models is analyzed for 25 pairs of 2D ground motions, where the peak story drift ratios and peak floor accelerations are recorded for subsequent damage and loss analyses. The approximations and uncertainties in the structural model and behavior are considered by treating the initial stiffness and the damping ratio as random variables with a 0.1 coefficient of variation. These uncertainties are propagated through the analysis using different realizations of the stiffness and damping parameters for each of the 25 non-linear dynamic analyses for each building.

### Performance Assessment

The building performance assessment was performed on a story-level basis using PELICUN (Zsarnóczay and Deierlein, 2020), where damage and losses are calculated with story-level fragility functions based on the peak story drift and floor acceleration demands. The story-based damage and loss fragility functions are derived from corresponding building-level damage and loss functions from the HAZUS earthquake model (FEMA, 2018a) based on the characteristic data for each building (e.g., year of construction, structure type, occupancy type). Collapse safety limit states are evaluated directly from the story drift demands, where a collapse of one or more stories is considered as partial collapse of the entire building. The story drift and floor accelerations from 25 non-linear analyses of each building are used to define multivariate lognormal distributions of peak drifts and accelerations for each story of the building, and the dispersion in the drift and acceleration demands is inflated by 0.22 to account for additional modeling uncertainties not considered in the non-linear dynamic analyses. Using the distributions of earthquake demands, and damage and loss functions, PELICUN generates 20,000 realizations of damage and losses for each building, and stores statistics of the resulting performance data that are relevant for regional-scale evaluation. The results are output as HDF5 (Hierarchical Data Format) files that can be processed and visualized through MatLab, Python, Jupyter notebooks, or converted to CSV format.

### Computational Challenges

Although the applications used in this testbed and rWHALE are available on multiple platforms, analyses on desktop computers are typically limited to small test runs before starting the full set of computations on a high-performance cluster computer. For perspective, the analyses for this study of 1.84 M buildings (each represented by a simplified non-linear MDOF model analyzed for 25 ground motions with OpenSees, and subsequently 20,000 damage/loss realizations with PELICUN) required about 16 h of computing time on 12,800 Intel Knights Landing cores on Stampede2 (TACC, 2020), made available by DesignSafe. Staff at the SimCenter and DesignSafe collaborated to develop and fine-tune the details of rWHALE to maximize performance. In particular, (1) the size and number of files, file operations, and memory use need to be kept under control, and (2) versions and special characteristics of the hardware, external tools, compilers, and dependencies need to be considered in allocating resources and other decisions in processing the analyses.

The SimCenter testbed workflow provides an opportunity to test and improve rWHALE with the ultimate goal of allowing researchers to run such simulations without having

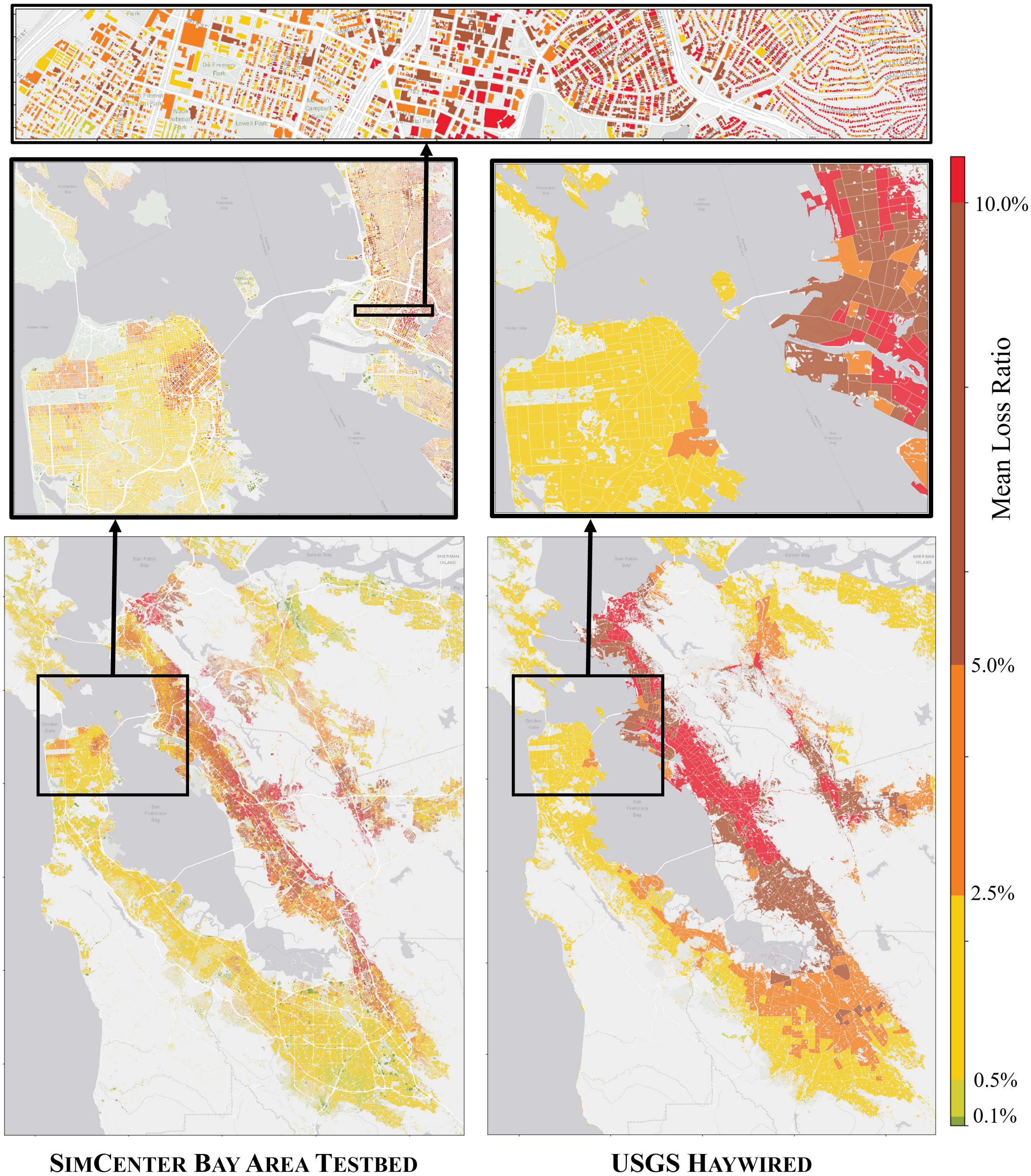


**FIGURE 6 |** Comparison of building loss ratios from San Francisco testbed—SimCenter **(left)**, USGS-Haywired **(right)**.

to concern themselves with details of the high-performance computing environment. The simulation is controlled by data and configuration text files, prepared in the JSON file format. The default data file includes the building information and ground motion data. The configuration file assigns workflow applications to the various tasks in the workflow and sets a small number of parameters (such as the number of samples generated) to configure the workflow applications. Researchers can customize their simulations by downloading and modifying these files. Currently, rWHALE is controlled either through the web interface of DesignSafe or through a terminal after logging in to Stampede2 (TACC, 2020).

### Illustrative Results

An example of the resulting losses calculated for the Mw 7.0 Hayward scenario are shown in **Figure 6**. The color shading represents the loss ratios for each building, calculated as the mean repair costs normalized by the building replacement value. Also shown in the figure is a comparison to the loss ratios reported in the USGS Mw 7.0 Haywired Earthquake

Scenario (Hudnut et al., 2018). Exposure and losses in the Haywired scenario were calculated using the HAZUS software. While it is instructive to compare results between the two studies, there are differences in the input data, scope and goals of the studies which are important to keep in mind. As the main purpose of the SimCenter testbed was to assemble and exercise the computational workflow, the models and results in the SimCenter study are preliminary, based on readily available information and implemented by a small team over a couple months. This contrasts with the multi-year multi-investigator Haywired study, whose goal is to inform earthquake planning and preparedness for the San Francisco Bay Area.

Both studies were based on Mw 7.0 Hayward fault ruptures simulated using the SW4 software by the LLNL research group, however, the ground motion time histories are different for the two studies. Epicenters for the two earthquake scenarios are close (East Oakland and San Leandro for Haywired and SimCenter, respectively), but other rupture characteristics are different and the SimCenter ground motions were simulated with more recent versions of the SW4 engine and the USGS geophysical model of the Bay Area. In general, the ground motions used in the SimCenter study are less severe than those used in the earlier Haywired study, and they are in better agreement with expectations based on past earthquake data.

The Haywired study extends over an area including the counties of Monterey, Sacramento, and Sonoma, whereas the SimCenter testbed is limited to the central six counties from Santa Clara to Marin. Due to the larger coverage, the Haywired study had a larger total building population (3.04 M), but the number of buildings in the six central counties in the Haywired study (1.71 M) is comparable to the number in the SimCenter database (1.84M). There are, however, large differences in the total square footage (in the central six counties) and inventory value (replacement values) between the building exposure databases, which make comparisons of total losses between the two studies questionable.

To reduce the influence of the differences in the building exposure values in the two studies, the comparison is limited to damage and loss ratios in the six central counties. The average loss ratio over the entire building population is less in the SimCenter testbed (∼3% of replacement value) as compared to the Haywired study (∼5% of replacement value). Nevertheless, as shown in **Figure 6**, the geographical distribution of losses shows good agreement between the two. The SimCenter study predicts a larger ratio of non-structural to structural damage (7.5:1 vs. 4.5:1 in the Haywired study) and considerably smaller fractions of the building stock being collapsed (less than 0.01 vs. 0.8%) and red-tagged (0.1 vs. 10%). Accordingly, the proportion of buildings that sustain minor or no damage is higher in the SimCenter study compared to Haywired (58 vs. 49%). These results are consistent with the less intense ground motions in the SimCenter scenario, and they highlight the sensitivity of results of such complex studies to inventory data, models for response, damage, and losses, and the input ground motions.

An important distinction between the HAZUS-based Haywired study and the SimCenter workflow simulation is the level of resolution in the assessment and the propagation of various sources of uncertainty throughout the simulation. Whereas the HAZUS-based study aggregates building damage and losses based on census track (zip code) data, the SimCenter workflow has resolution down to the building parcel level, and it can disaggregate losses within a building down to individual components on each floor. This feature, coupled with a detailed description of the probability distributions of damage and losses for each building, can allow urban planners and policy makers to query various possible outcomes–including the rare, but catastrophic ones–of the earthquake scenario. High-resolution results (see upper panels in **Figure 6**) provide valuable data for exercises in emergency response, and simulations of post-disaster recovery. In addition, the SimCenter workflow and underlying tools facilitate the combination of models with varying levels of fidelity, where for example, performance for some buildings can be determined using simplified HAZUS type loss functions, while performance for other buildings can be determined using the detailed non-linear structural analysis models and FEMA P-58 component-based damage and loss functions. As such, the high-resolution and multi-fidelity workflow simulations offer increased opportunities to explore questions related to land use planning and zoning, seismic design and retrofit requirements, public policy and administrative initiatives, and other actions to enhance community resilience.

## Atlantic City Hurricane Scenario

Wind and coastal hazards affect a wide spectrum of the built environment, from low-rise wood-frame residential construction through to tall, flexible buildings susceptible to dynamic wind effects. The selection of Atlantic City for the hurricane testbed prioritized a locale where (1) both of these extremes of building type were present within a compact footprint, (2) open-data was sufficient to describe the building inventory, and (3) high-fidelity characterizations of wind, storm surge and wave action were readily available to exercise computational workflows for damage assessment. The open data inventory and development of a Storm Hazard Projection (SHP) tool in the NJ Coast project (Kijewski-Correa et al., 2019; NJ Coast, 2020) makes New Jersey, and specifically Atlantic City, well suited for the hurricane hazard testbed, offering a well-defined metro area with a blend of low-rise commercial (1–3 stories), industrial, high-rise hotels/casinos (over 20 stories), and single/multi-family residential construction. The testbed domain, shown in **Figure 7**, includes 20,654 parcels with diverse building typologies (wood-frame, masonry, steel/RC frames, metal building systems) spread across five municipalities.

The following sections describe the initial approach to each module of the workflow, which prioritized wind effects on wood-frame residential construction, as well as module capabilities to be added in future releases of the testbed. The workflow was initially demonstrated for a hazard scenario estimated using the NJcoast SHP Tool and a Maximum of Maximums approach across 25 hurricane tracks with Category 5 intensity (central pressure differential of 75–100 mbar, RMW of 15.4–98 mi) making landfall near the Atlantic City Beach Patrol Station (39.348308, −74.452544) under average tides. This scenario is sufficient to

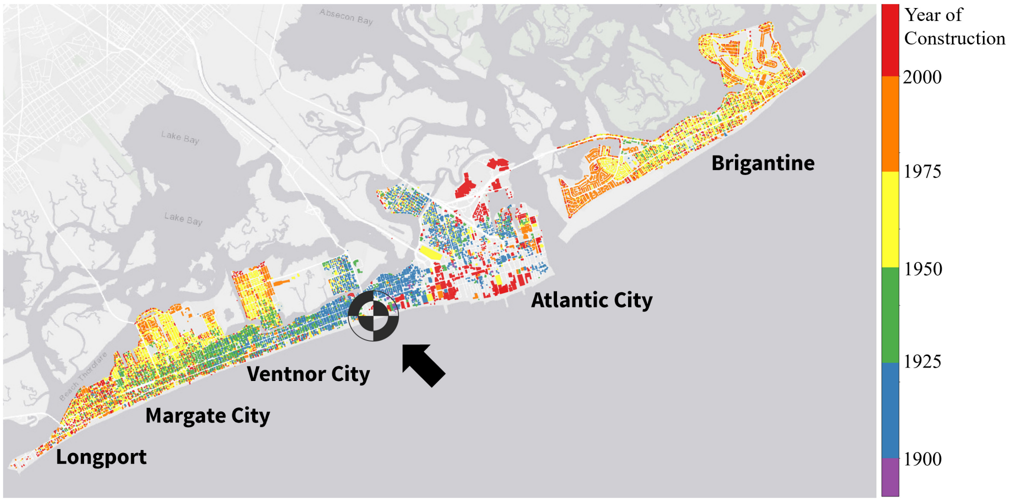


**FIGURE 7 |** Atlantic City testbed inventory (across five municipalities) by year of construction with landfall location marked by target icon.

inundate the entire inventory and generate significant wave run-up in some locales.

## Building Inventory

The description of assets in the inventory adopts an augmented parcel approach that initiates with the assignment of HAZUS-consistent building classifications through a series of rulesets using fields common in tax assessor data, called MOD IV in the New Jersey database (NJGIN, 2020). To overcome inevitable gaps and errors in these large state-wide datasets, a SimCenter developed AI-powered Spatial Uncertainty Research Framework package, SURF (Wang, 2019), is employed to discover patterns in the dataset and to enhance it. SURF employs a neural network, which is trained on the raw dataset to learn the patterns of building attributes; it is then used to predict values for parcels that have empty data fields. As roof geometry is not a standard field in MOD IV data, satellite imagery is processed to further augment the basic parcel data. The SimCenter developed application Building Recognition using Artificial Intelligence at Large Scales, BRAILS (Wang et al., 2019), is used to interpret satellite images of building roofs, which are collected from Google Maps. The satellite images are labeled with shape types to form a dataset, upon which a Convolutional Neural Network is trained so that it can give rapid predictions of roof types when given new images of roofs. Microsoft Building Footprint data is used as the location index when downloading images automatically from Google Maps. While more complex roof shapes could, in theory, be classified, the current use of HAZUS damage and loss functions required the use of similitude measures to define each roof as an "effective" gable, hip or flat geometry. Using BRAILS, this classification was achieved with approximately 85% accuracy based on validation studies. BRAILS is under active development and in the next iteration of the testbed it is expected to be able to extract fully three-dimensional building geometries using satellite plus StreetView imagery, enabling fluid pressures to be calculated over building surfaces. Automated image processing of this type can also mine detailed dimensional and geometric data (e.g., roof pitch, eave length, elevations of lowest horizontal structural member, etc.), as well as classify building components (e.g., envelope cover, foundation systems, breakaway walls, and more).

## Wind Model

The initial implementation of the testbed directly integrates the highly efficient, linear analytical model for the boundary layer winds of a moving hurricane developed by Snaiki and Wu (2017a,b) as implemented in the NJcoast SHP Tool. To account for the exposure in each New Jersey county, an effective roughness length (weighted average) of the upwind terrain is used based on the Land Use/Land Cover data reported by the state's Bureau of GIS. While the model is fully height-resolving and time-evolving, for a given five parameter hurricane scenario, the wind hazard is characterized by the maximum 10 min mean wind speed observed during the entire hurricane track. This is reported at the reference height of 10 m over a uniform grid (0.85-mile spacing, 1.37 km), which is then accordingly adjusted for compatibility with the averaging interval assumed by the HAZUS Hurricane Damage and Loss Model. Alternatively, the basic wind speeds defined in ASCE 7–16 are also available as inputs to the simulation by taking advantage of the Applied Technology Council (ATC) Hazards by Location API (ATC 2020a). Wind fields described by either approach are then locally interpolated to the site of each parcel in the inventory.

## Storm Surge Model

Coastal hazard descriptions use the outputs of the aforementioned SHP Tool, which estimates storm surge and total run up due to the breaking of near-shore waves for an arbitrary hurricane scenario using surrogate modeling techniques (Jia and Taflanidis, 2013; Jia et al., 2015). The SHP Tool leverages the US Army Corps of Engineers (USACE) NACCS: North Atlantic Coastal Comprehensive Study (Nadal-Caraballo et al., 2015), which contains over 1,000 high-fidelity numerical simulations of hurricanes using the ADCIRC (Luettich et al., 1992) storm surge model, coupled with STWAVE (Smith et al., 2001) to capture the additional effects of waves offshore. The NACCS database was further enhanced with wave run-up simulations that capture the interaction of the waves with site-specific bathymetry/topography (2015 USGS CoNED Topobathy DEM: New Jersey and Delaware (1888–2014) dataset) to project the total run up inland, along transects spaced 0.5 km apart along the New Jersey coast. This results in a prediction of storm surge height at the USACE-defined save points along the New Jersey coast that are, on average, 200 m apart, with finer resolution in areas with complex topographies. The SHP Tool was executed for the testbed scenario to estimate the depth of storm surge above ground, geospatially interpolated to 110,000 nearshore locations at approximately 120 m spacing, accompanied by the Limit of Moderate Wave Action (LiMWA) and wet-dry boundary, respectively, defining the extent of damaging waves and inundation over land at each of the transect points. These are then interpolated to the location of the coastal parcels to express the property exposure to storm surge and possibly damaging wave action.

## Building Damage and Loss Modeling

The initial implementation of the hurricane testbed, which is described here, is limited to consideration of wind damage and losses. Further, the calculation of wind effects does not require structural analysis to estimate EDPs, but rather adopts an approach (Path II in **Figure 3**) where damage and losses are calculated directly from the wind speed. Damage and loss functions from the HAZUS Hurricane Damage and Loss Model (FEMA, 2018a) were implemented in PELICUN to support HAZUS's 3520 different wooden building configurations available for hurricane loss modeling. The HAZUS functions consist of tabular data to describe the fragility or expected losses as a function of wind speed. These data were used to calibrate coupled damage and loss models to estimate the damage state and the corresponding expected loss ratio for each building configuration in PELICUN. Continuous functions (Normal or Lognormal cumulative distribution functions) were fit to the synthetic data by maximizing the likelihood of the observations assuming a Binomial distribution of outcomes at each discrete wind speed in the HAZUS database. Only data up to 200 mph wind speeds were used because the substantial reduction in the number of observations introduces significant measurement error above that level. Coupling the damage and loss models in this way ensures more realistic outcomes (e.g., a building with no damage cannot have total loss when the two models are coupled), and the parameterized models allow for more efficient storage and computations within the workflow.

The HAZUS damage and loss functions are grouped into five main classes by building material, with additional subclasses by building type. For each building class, e.g., wood single-family homes 1–2 + stories, a collection of attributes are used to define key features of the load path and components (e.g., roof shape, secondary water resistance, roof deck attachment, roof-wall connection, shutters, garage) as well as the exposure (terrain roughness previously estimated in the Wind Hazard Model) to assign the corresponding fragility. A rules engine was developed using a combination of historical New Jersey model building codes, surveys capturing owner-driven mitigation actions (e.g., Javeline and Kijewski-Correa, 2019), and market data to assign these attributes to each parcel based on age and other available building information (e.g., MOD IV data). Libraries of damage and loss functions associated with storm surge from the USACE and other recent studies in the literature are planned for future releases of PELICUN. Eventually, these damage and loss descriptions will be supplemented with more advanced models as the testbed is progressively refined to include component-based fragilities and fault-trees that capture cascading damage sequences resulting from breaches of the building envelope.

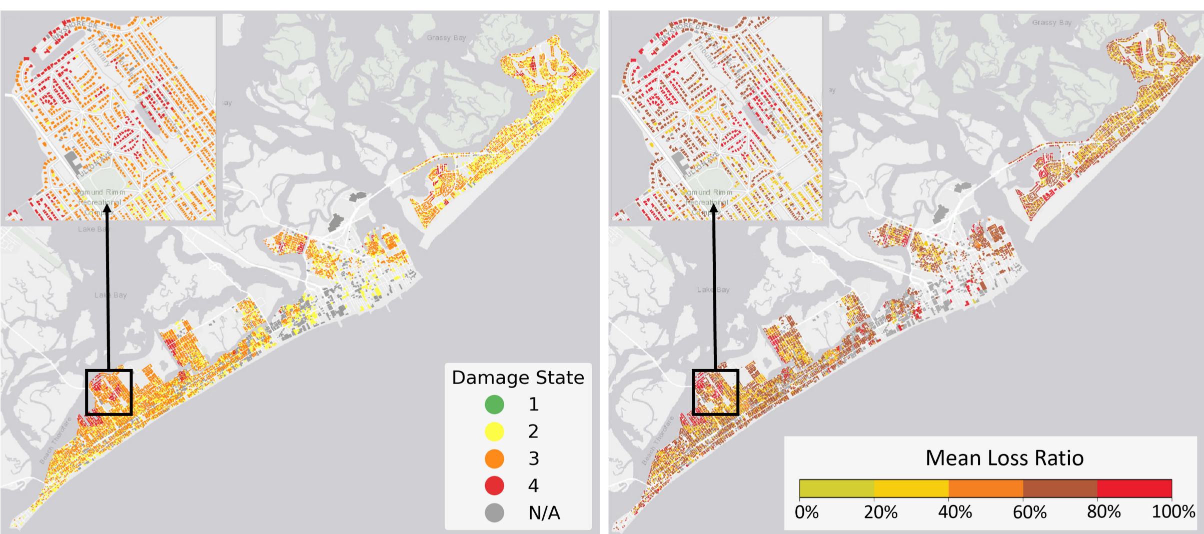


**FIGURE 8 |** Atlantic City testbed for category 5 hurricane wind scenario: damage states **(left)** and mean loss ratio **(right)**.

### Illustrative Results

The first implementation of the hurricane testbed adopted the augmented parcels approach to assemble required building information and the analytical hurricane wind field described previously. Shown in **Figure 8** are the results of the initial analyses of wind damage to wood-frame residential houses, determined based on the assumptions and techniques described above. The categories of damage states and loss ratios, shown in **Figure 8**, follow from the HAZUS fragility functions and the rule-based engine developed to associate the appropriate function with each building. The ability to resolve damage and losses to specific properties provides a level of granularity that is not currently available to planning authorities. These capabilities to execute high-resolution damage scenarios are valuable to guide hurricane mitigation investments in Atlantic City, which is undergoing redevelopment in the aftermath of Hurricane Sandy to make the city more resilient to future storms and hurricanes.

## CONCLUDING REMARKS

As described in this paper, the computational open source workflow tools and applications that have been released and continue to be developed by the SimCenter are organized around a framework to facilitate the integration and sharing of models and data for comprehensive analyses of natural hazards and their effects on the built environment. The development and testbed applications of these workflows have identified how open data and high-fidelity simulation capabilities can shift the paradigm from empirical fragilities projecting losses over census blocks to direct simulation of site-specific building performance for natural hazard scenarios. These applications have also identified gaps and limitations of available data and models and how the contributions of the research community can be leveraged to advance regional simulation of damage, consequences, and recovery of buildings and lifeline systems. The SimCenter looks forward to continued collaboration with the NHERI research community to develop and expand computational workflows for integrating data and simulation models across the multidisciplinary fields of natural hazards engineering.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://simcenter.designsafe-ci.org.

## AUTHOR CONTRIBUTIONS

Specific contributions beyond general planning, review and editing include: GD: outline, drafted main body, earthquake modeling, overall detailed editing. FM and WE: cloud computing framework. AZ and WE: earthquake testbed. TK-C: hurricane testbed. AK: hurricane modeling. All authors contributed to preparation of the manuscript.

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# Enhancing Research in Natural Hazards Engineering Through the DesignSafe Cyberinfrastructure

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The DesignSafe cyberinfrastructure (www.designsafe-ci.org) is part of the NSF-funded Natural Hazard Engineering Research Infrastructure (NHERI) and provides cloud-based tools to manage, analyze, understand, and publish critical data for research to understand the impacts of natural hazards. The DesignSafe Data Depot provides private and public disk space to support research collaboration and data publishing through a web interface. The DesignSafe Reconnaissance Portal uses a map interface to provide easy access to data collected to investigate the effects of natural hazards, and the DesignSafe Workspace provides cloud-based tools for simulation, data analytics, and visualization; as well as access to high performance computing (HPC). This paper provides an overview of the DesignSafe cyberinfrastructure and describes specific examples of the use of DesignSafe in research for natural hazards. These examples include electronic data reports that use Jupyter notebooks to allow researchers to interrogate data interactively within the web portal, computational workflows that integrate ensembles of HPC-based simulations and surrogate modeling, and the publication of field research data after natural hazard events that utilize a variety of DesignSafe tools. The paper also provides an overall assessment of current DesignSafe impact and usage, demonstrating how DesignSafe is enhancing research in natural hazards.

**Keywords: cyberinfrastructure, cloud-based tools, data analytics, data repository, natural hazards**

## INTRODUCTION

The DesignSafe cyberinfrastructure (www.designsafe-ci.org, Rathje et al., 2017) has been developed as part of the Natural Hazards Engineering Research Infrastructure (NHERI) to enable and facilitate transformative research to understand the impacts of natural hazards, which necessarily spans across multiple disciplines (e.g., engineering, earth science, and social science) and can take advantage of advancements in computation, experimentation, and data analysis.

DesignSafe allows researchers to more effectively share, find, analyze, and publish data; perform numerical simulations and utilize high performance computing (HPC); and integrate diverse datasets. DesignSafe has been developed as a flexible, extensible, community-driven cyberinfrastructure and it embraces a cloud strategy for the big data generated to study the impacts of natural hazards. It provides a comprehensive cyberinfrastructure (CI) that supports the full research lifecycle, from planning to execution to analysis to publication and curation. DesignSafe represents the next-generation cyberinfrastructure that evolved after NEEShub (Hacker et al., 2013), the cyberinfrastructure that supported research in earthquake engineering from 2009 to 2015. NEEShub played an important role in promoting data publishing within the earthquake engineering community, and DesignSafe is building on that effort to foster a cultural shift toward the pervasive use of cyberinfrastructure and the ubiquitous publishing/reuse of data in natural hazards research.

This paper summarizes the DesignSafe components available to facilitate research and describes examples of how DesignSafe is being used by the community. These examples are derived from current work being enabled by DesignSafe, and include (1) a Jupyter notebook that allows researchers to interrogate experimental data interactively within the DesignSafe web portal (Arduino et al., 2018), (2) a computational workflow that integrates ensembles of HPC-based storm surge simulations and uncertainty quantification to estimate wind drag coefficients, (3) a computational workflow that optimizes building shape for wind effects using HPC-based computational fluid dynamics simulations and surrogate modeling (Ding et al., 2019), and (4) published field reconnaissance datasets from recent natural hazards (e.g., Kijewski-Correa et al., 2018; Brandenberg et al., 2020). We conclude with an overall assessment of current DesignSafe impact and usage.

## DESIGNSAFE COMPONENTS

The DesignSafe vision is to deliver a (CI) that is an integral part of research discovery and enables breakthroughs that could not be made otherwise. The three main DesignSafe components that are at the core of realizing this vision are: the Data Depot data repository, the Workspace with its cloud-based tools and access to HPC, and the Reconnaissance Portal to interface with field research data collected after natural hazard events (**Figure 1**). These components have been designed to quickly share, publish, and find data, to easily perform cloud-based analytics, and to lower the bar toward using high performance computing. The use of these tools is facilitated by the tutorials provided in the Learning Center (**Figure 1**).

The Data Depot is the central shared data repository that supports the full research lifecycle, from data creation to analysis to curation and publication. Researchers have access to a private "My Data" space, a semi-private and collaborative "My Projects" space, and a "Published" space for curated and publicly available data. Upload/download of data is streamlined through a range of interactive and automated options for both single file and bulk transfer, including drag and drop file upload, federation with existing cloud data services (e.g., Box, Dropbox, Google Drive, Globus), and command line interfaces that can be automated by power users. There are no limitations regarding data format, such that users are free to use the format that best supports their research, and large data volumes can also be accommodated.

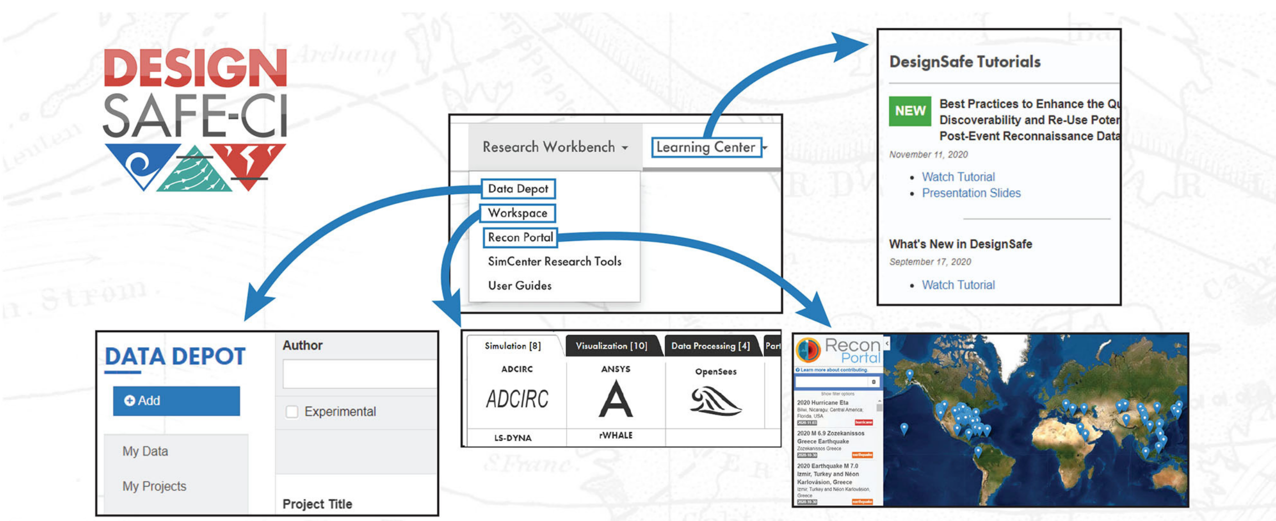


**FIGURE 1 |** Main components of the DesignSafe cyberinfrastructure.

Data curation services are provided to all users in DesignSafe. Curation involves organizing data and gathering the documentation that is needed for its use now and in the future. DesignSafe provides the tools and resources required to fully curate complex datasets that are ultimately published within the Data Depot. These tools have been developed to handle the unique characteristics of different types of datasets, specifically Experimental data, Simulation data, Hybrid Simulation data, Field Research data, as well as Other data. DesignSafe has adopted a progressive approach to data curation, in which the research team can provide the curation information during the course of the research, and thus shares responsibility for the curation process. When initially uploaded, data may have limited or even no user-supplied metadata. As data progresses toward publication, the requirements for metadata increase and at publication the user may edit the metadata and complete the process of assigning Digital Object Identifiers (DOIs) and applying the appropriate license. On demand assistance from a curator is available to provide training and to guide users through their data curation and publication needs. Published datasets are available within the "Published" area of the Data Depot, which is fully indexed and searchable.

The Workspace provides tools for researchers to analyze, visualize, and transform their data in the cloud, and to perform simulations using the most sophisticated computational tools available. Within the web portal, the Workspace provides a wide variety of Apps that can access the files in the Data Depot, and user-defined Apps can be installed with assistance from DesignSafe staff. The Apps available within the Workspace are continuously evolving, but the current deployment of tools includes computational simulation tools (e.g., OpenSees, ADCIRC, OpenFOAM, LS-Dyna), as well as tools for both data analytics and visualization (e.g., MATLAB; Jupyter; HazMapper, QGIS). Open source codes are preferred but commercial codes also are available, with the commercial codes requiring an active license for the user to access them. Jupyter is a particularly noteworthy component of DesignSafe. A Jupyter notebook is an electronic notebook that allows users to embed rich text elements, as well as computer code, graphs, and visualizations, within a single notebook that can be shared through the web. The JupyterHub deployed as part of DesignSafe supports notebooks written in the common coding languages of Python and R, making it a versatile tool that can enable research workflows as well as data processing and analysis.

Many of the tools within the Workspace have access to HPC resources, making it easy for researchers to employ these resources in their work. These HPC-enabled tools in the Workspace can be used without request of a specific DesignSafe HPC allocation. We can also provide command line access to HPC resources for more advanced researchers. Details regarding the DesignSafe HPC allocation policy can be found at https://www.designsafe-ci.org/rw/user-guides/allocations-policy/.

The Reconnaissance Portal is the main access point for data collected during the reconnaissance after windstorm and earthquake events. Reconnaissance activities produce diverse data, including infrastructure performance data (e.g., damage estimates, ground movements, coastal erosion, wind field estimates), remotely sensed data (e.g., photos, video, LIDAR point clouds, satellite imagery data), or human experiential data (e.g., social media data, societal impact data, survey or interview data). These diverse data types have different metadata requirements, but their use hinges on information regarding the location from which the data were collected. Therefore, the Reconnaissance Portal utilizes a mapping framework to display the natural hazard events for which reconnaissance data are available. The reconnaissance data is physically located in the Data Depot and accessible by analytics and visualization tools in the Workspace (e.g., HazMapper, QGIS), but the Reconnaissance Portal provide improved discoverability of the data.

Another feature that can be used by all DesignSafe users is the DesignSafe Slack team, which can be accessed through a web host (https://designsafe-ci.slack.com) or the Slack App. Slack is an online collaborative communication tool that represents a modern, highly capable and integrative user forum. Communication can take place publicly via organized, topical channels (e.g., Jupyter, OpenSees, or a specific natural hazard event), or privately through direct messages between individuals or small groups. Files can be shared easily through drag and drop, and all content is indexed for easy search.

## THE USE OF DESIGNSAFE IN NATURAL HAZARDS ENGINEERING RESEARCH

The NHERI Science Plan (Edge et al., 2020) includes three Grand Challenges with five Key Research Questions to guide NHERI research to deliver technical breakthroughs to improve the resilience and sustainability of the built environment. Two of the Key Research Questions relate directly to DesignSafe functionalities that enable simulation and data sharing, but at some level all of the research questions require access to the big data, cloud-based tools, and HPC resources provided by DesignSafe. And thus, DesignSafe plays an important role toward enabling the vision of the NHERI Science Plan.

The key to transforming research in natural hazards engineering is transforming research workflows by providing access to the data and tools required to innovate. Approximately 4 years after initial deployment, it is clear that DesignSafe is influencing the research being performed in natural hazards engineering and the approaches being employed. Jupyter notebooks are being used to interact with data, and they are also being used as workflow engines that integrate large-scale simulations and data analytics. The Reconnaissance Portal, along with other reconnaissance tools, are actively being used by the field research community and the CONVERGE extreme events research networks (https://converge.colorado.edu/research-networks). Below are specific examples of how DesignSafe is being used by the research community.

### Interactive Jupyter Notebook Interfaces With Datasets

Damage to coastal communities caused by tsunamis is often the result of the water inundation and transported debris. Although efforts to characterize forces from single debris impacts exist, a more general scenario of multiple debris impacts is necessary. To address this need, experimental studies were conducted at the O.H. Hinsdale Wave Research Laboratory's Large Wave Flume (LWF) at Oregon State University to study the impact of debris carried by waves.

Impact and damming forces on a calibrated instrumentation box were evaluated both qualitatively and quantitatively to provide insight into the nature of these forces. While the dimensions of individual pieces of debris were the same, the number of debris pieces, the orientation of debris pieces, and the relative layout of multiple debris pieces were changed. The main parameter of interest was the force recorded through nine load cells strategically located on the instrumentation box to record forces in different directions. The collected data were curated and are available in the DesignSafe project PRJ-1709—NHERI Debris Impact Experiments (Arduino et al., 2018).

A Jupyter notebook was published with the dataset to provide a clear description of the experimental work, allow navigation and visualization of the recorded data within the cloud, and facilitate basic analysis of the recorded data. For this purpose, the notebook is split into six sections each of which employs widgets to display information relevant to the viewer. This includes:

- *Project Description*, providing an overview of the experiments.
- *Large Wave Flume*, describing the experimental facility, with multiple tabs displaying specific flume information.
- *Sensor Arrangement and Positioning*, describing the location and arrangement of the load cells used in the experiment.
- *Debris Layouts and Orientation*, describing the physical properties of the debris blocks and layouts considered, with multiple tabs displaying debris dimensions, experimental layouts, test photos and videos.
- *Data Viewer*, allowing the user to select any particular case/layout and sensor and view the time-history of the forces.
- *Frequency Analysis*, allowing the user to apply a low pass frequency filter to the force time histories recorded by any sensor in any layout combination and a view its effect on frequency content and time history plots.

**Figure 2** displays extracts of the Jupyter notebook corresponding to the *Data Viewer* and *Frequency Analysis* windows. The layout and load cell boxes in both windows allow for the selection of the specific case to visualize. The sliders in the data viewer window allow expansion of the X axis. The Window Width [Hz] and Center [Hz] boxes in the Frequency Analysis window allows selection of the frequency range to consider in the low pass frequency filtering. The plots show the unfiltered and filtered signals in the time and frequency domains and selected frequency range. Together, the NEHRI Debris experiments dataset and notebook provide useful information that can be used to guide further experimental and numerical studies on debris-laden tsunami flows.

## Jupyter Workflow for Storm Surge Modeling

Storm surge is often the leading cause of life and property loss during hurricanes and extratropical cyclones. Accurate storm surge forecasting relies both on accurately forecasted winds and accurately modeled air–sea drag, which parameterizes the transfer of momentum from air to the water column. In operational models, typically the wind drag is parameterized in terms of the wind speed at 10-m height, however, this remains an active field of research, see Bryant and Akbar (2016) for a review. The large number of recent hurricanes for which there are large quantities of measured data (e.g., hurricane track, wind speeds, wave heights, storm surge, etc.) provide an opportunity to quantify the uncertainty in a given choice of wind drag parameterization. Uncertainty quantification algorithms combined with forward models for predicting storm surge given wind data, provide a framework for estimating wind drag given measured storm surge data (i.e., water elevations at gage locations).

The Python package LUQ (forthcoming at https://github.com/CU-Denver-UQ/LUQ/), developed by S. M. Mattis (CSU post-doctoral scholar) and T. Butler (CU Denver professor) as part of Mattis et al. (2020), encodes a framework for Learning Uncertain Quantities from the output of dynamical systems (i.e., from time series data) for the data-consistent solutions of stochastic inverse problems (SIP). This provides a conceptual and computational framework for uncertainty quantification of dynamical systems, namely, for propagating uncertainties in model outputs to uncertainties in model inputs that are otherwise not directly observable. Practically, this framework requires running an ensemble of hundreds to thousands of forward simulations to accurately solve a given SIP.

In research led by C. N. Dawson and K. R. Steffen at the University of Texas at Austin, this framework is being used in uncertainty quantification of wind drag parameters for storm surge modeling due to extratropical cyclones using the Advanced Circulation (ADCIRC) framework. Ensembles of ADCIRC simulations are generated using pylauncher (https://github.com/TACC/pylauncher, developed by V. Eijkhout), generating hundreds to thousands of time series (e.g., water surface elevations at a specific location). Jupyter notebooks developed by Butler, Mattis, and Steffen as part of Mattis et al. (2020) provide an interactive environment for experimental analysis of the time series data and solution of the stochastic inverse problem for the model inputs. Useful features of the Jupyter Notebook environment include: the wide selection of Python packages available through pip or conda that can be integrated into a Jupyter notebook through a few clicks and one or two lines of code; interactive plots of raw data, processed data, and results; and the capability to experiment with hyperparameters, such as the effect of additive noise, desired accuracy, etc.

Preliminary work used a test problem on a small ADCIRC domain spanning ∼100 km by 100 km, discretized with ∼5,000 triangular elements. A wind drag parameterization $C_d = \min[10^{-3} \cdot (0.75 + \lambda_1 u_{10}), \lambda_2]$ is proposed as a generalization of the commonly used parameterizations: $C_d$ increases linearly with $u_{10}$ (wind speed at 10-m) for small wind speeds, up to some cut-off (saturation) given by $\lambda_2$. Then, the following SIP is solved: given a set of 100 (synthetic) observations (i.e., time series of water surface elevation measured at a specific location) and initial probability distributions on the parameters $\lambda_1$ and $\lambda_2$, compute

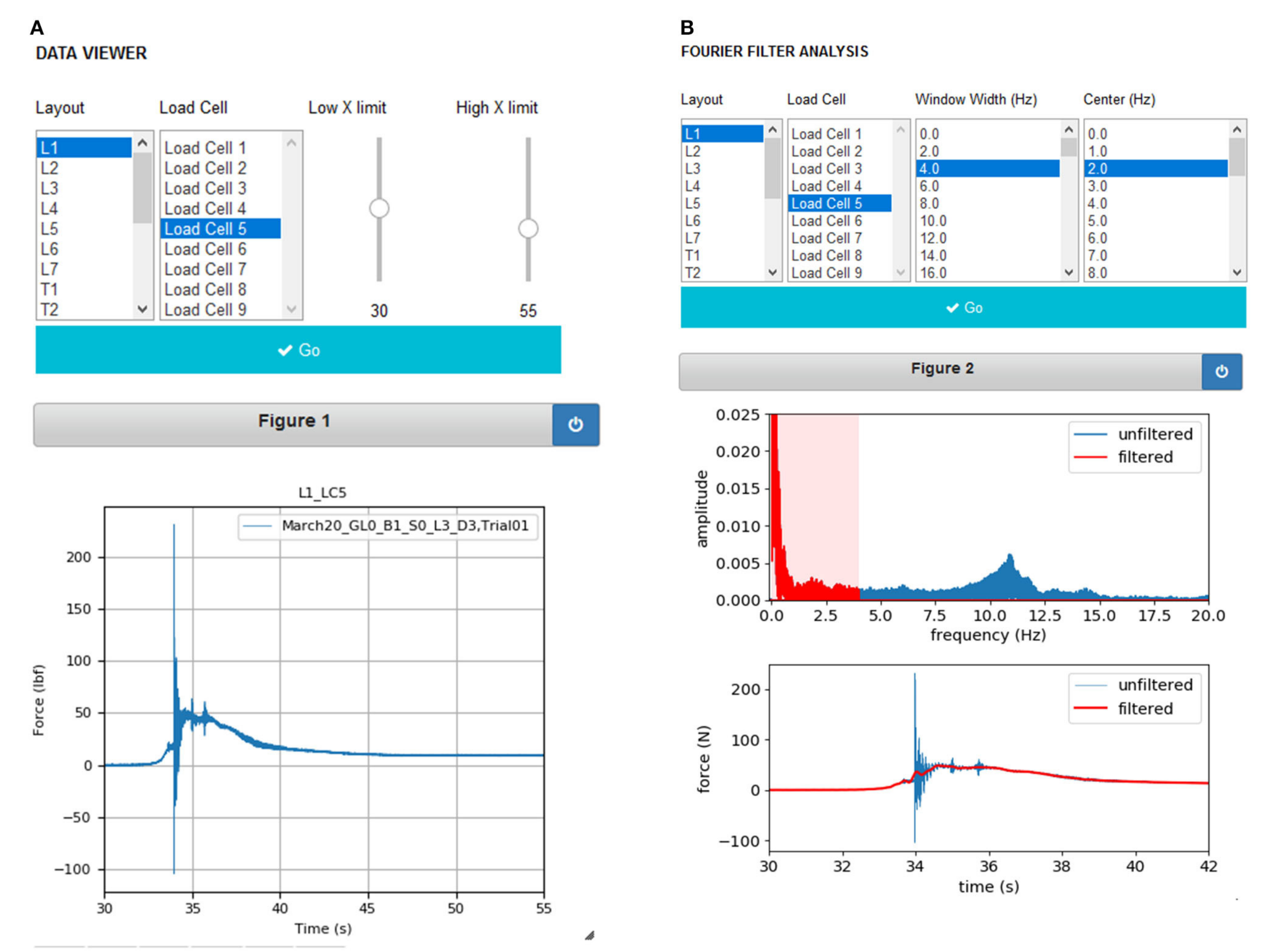


FIGURE 2 | Debris Impact Jupyter Notebook: **(A)** Data Viewer window showing a recorded load-time history, **(B)** Frequency Analysis window showing the application of a low pass filter.

updated probability distributions that are data-consistent in the sense that they are calibrated to the probabilistic information available in the observed data.

Results from a Jupyter notebook implementation of the approach, are presented in **Figure 3**. The probability distributions for $\lambda_1$ and $\lambda_2$ used to create the set of 100 synthetic ADCIRC observed time series are two Beta distributions, as shown in green in **Figure 3**. The initial (prior) probability distributions are uniform distributions and are shown in blue. The prior probability distributions are used to generate 1,000 predicted ADCIRC time series, which are used within the LUQ framework to solve the SIP. The updated distributions resulting from the SIP are shown in orange, and do not require a forward ADCIRC simulation. Given the excellent match between the solution (in orange) and the synthetic distribution (in green), the experiment demonstrates that the uncertainty in the model inputs $\lambda_1$ and $\lambda_2$ has been accurately calibrated to the probabilistic information in the synthetic data set analyzed within the LUQ framework.

DesignSafe enables this research through the Workspace, where both Jupyter and ADCIRC are installed as applications, and where python-based packages such as LUQ can be utilized. Current research is focused on developing a complete workflow within a single Jupyter notebook. The workflow will generate multiple ADCIRC ensembles and submit jobs within the Jupyter notebook using pylauncher, then use the LUQ package to estimate the distribution of wind drag given the measured data and ensemble predictions. This algorithm will be used to estimate wind drag for storms in Western Alaska, where potential ice cover leads to an additional source of uncertainty for wind drag formulations. The model input, ensemble output, and overall results of the research will be archived and published through the DesignSafe Data Depot.

```python
# Plot predicted marginal densities for parameters

fig, axs = plt.subplots(1, 2, figsize=(20,10))

for i in range(params.shape[1]):
    x_min = min(min(params[:, i]), min(params_obs[:, i]))
    x_max = max(max(params[:, i]), max(params_obs[:, i]))
    delt = 0.25*(x_max - x_min)
    x = np.linspace(x_min-delt, x_max+delt, 100)
    axs[i].plot(x, unif_dist(x, param_range[i, :]),
         label = 'Initial', linewidth=4)
    mar = np.zeros(x.shape)
    for j in range(learn.num_clusters):
        mar += param_marginals[i][j](x) * cluster_weights[j]
    axs[i].plot(x, mar, label = 'Updated', linewidth=4, linestyle='dashed')
    axs[i].plot(x, true_param_marginals[i](x), label = 'Data-generating',
            linewidth=4, linestyle='dotted')
    axs[i].set_title('Densities for parameter ' + param_labels[i])
    axs[i].legend()
```

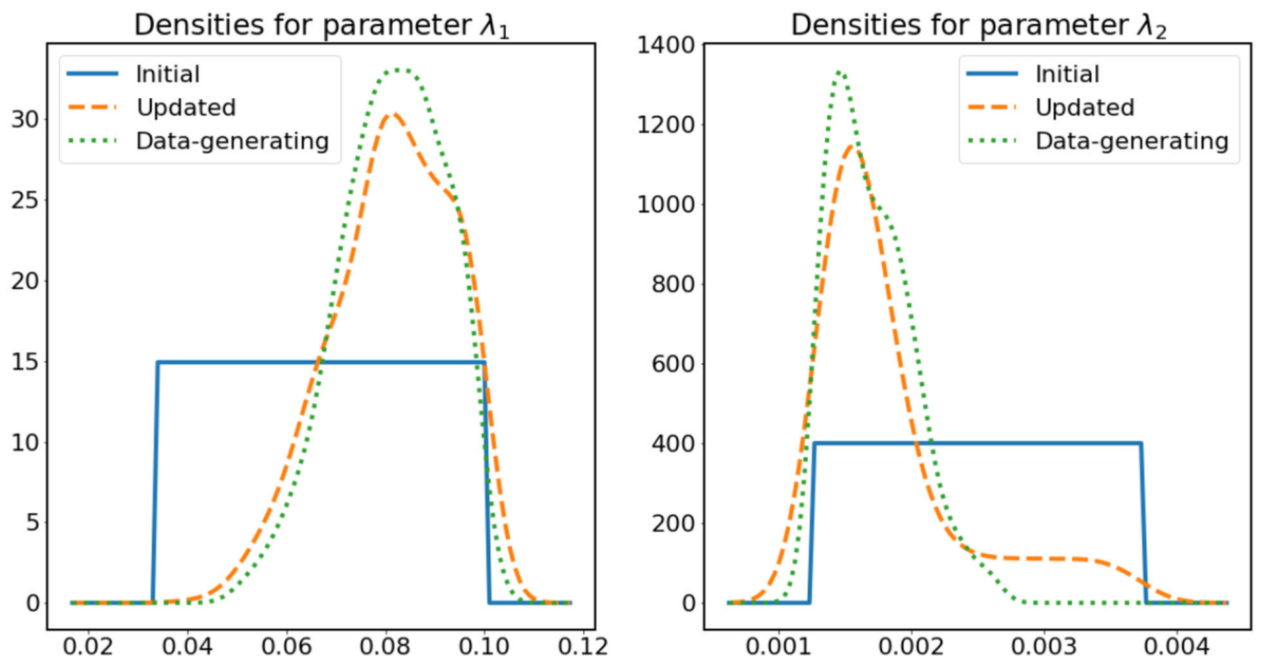


**FIGURE 3 |** Jupyter notebook that utilizes the LUQ framework to solve for the probability distribution of the ADCIRC wind drag coefficient parameters based on observed storm surge water surface elevations.

## Integration of HPC Simulations and Surrogate Modeling for Wind Design of Buildings

Tall buildings exposed to wind undergo complex interactions, which precludes a functional relationship between wind and its load effects. In the digital age with burgeoning growth in computational resources and parallel advances in computational fluid dynamics (CFD), computational simulations are evolving with a promise of becoming versatile, convenient, and reliable means of assessing wind load effects. DesignSafe offers an effective cloud-based platform to promote the use of computational technologies to address these challenges. Herein an illustrative example is presented, in which aerodynamic shape sculpting of tall buildings was carried using the open-source OpenFOAM CFD software available on the HPC resources provided by DesignSafe. While such an assessment is currently performed via wind tunnels with a very limited set of configurations, computational platforms based on CFD promise to explore the optimal configuration in a large search design space (Ding et al., 2019).

In this study, the relationship between the shape variation of the cross-section of the building and its aerodynamic characteristics is systematically investigated through this digital design platform. The scheme is schematically outlined in **Figure 4**. The aerodynamic characteristics are defined as the mean drag coefficient ($\mu_{Cd}$) and the standard deviation of the lift perpendicular to the wind (i.e., lift force coefficient, $\sigma_{Cl}$). The goal is to minimize these two competing aerodynamic objectives by modifying the cross-section shape in terms of ($\Delta y_1^*, \Delta y_2^*$), which yield the Pareto optimal solutions. The biggest concern that exists in aerodynamic shape optimization is the significant computational challenge posed by the multiple CFD

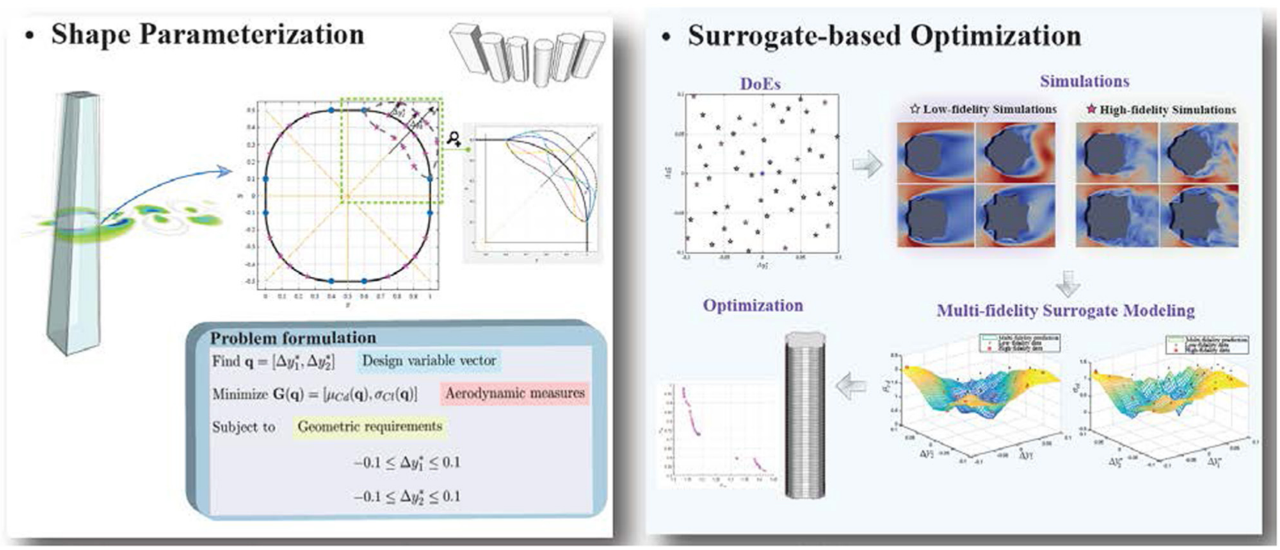


**FIGURE 4 |** Schematic of aerodynamic shape optimization on a computational platform (Ding and Kareem, 2020).

simulations involved in the shape optimization process. One remedy involves the use of surrogate models that can replace computationally prohibitive simulations with computationally tractable approximate models.

A surrogate model is built based on regression against the limited set of observations from computational simulations. It starts with the design of experiments (DoEs, Forrester et al., 2008) that generate samples of $(\Delta y_1^*, \Delta y_2^*)$ for the calibration of the surrogate model as shown in **Figure 4**. CFD is employed to evaluate the aerodynamic objective functions [i.e., $\mu_{Cd} = f\left(\Delta y_1^*, \Delta y_2^*\right), \sigma_{Cl} = f\left(\Delta y_1^*, \Delta y_2^*\right)$] on buildings with the sampled geometric profiles. The response surfaces of the surrogate models are used to emulate the original CFD simulations of the two aerodynamic quantities. Optimization algorithms guide the search of the optimal geometric configurations with the best aerodynamic performance to inform the building design.

The success of using the surrogate model largely depends upon the accuracy of the simulation data that are used for model calibration. In the context of CFD simulations for the separated wind flow around bluff bodies, two fundamental approaches are primarily used to numerically capture the massively separated wind flows around buildings (Ferziger et al., 2002), Reynolds-averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES). Currently, RANS is the workhorse of CFD but its model accuracy is compromised. LES enhances the accuracy of the low-fidelity RANS models, but at a major additional computational effort. Therefore, a multi-fidelity surrogate modeling approach is introduced in the aerodynamic shape optimization, which utilizes hierarchical surrogate models relating low-fidelity (i.e., RANS) to high-fidelity (i.e., LES) models (Ding and Kareem, 2018). It has been shown to provide high-quality predictions without significantly increasing the computational effort.

This example demonstrates that the HPC-enabled codes available on the cloud platform offered by DesignSafe is facilitating such advances that are helping to promote and take advantage of CFD to address real world problems.

## Use of DesignSafe in Reconnaissance Efforts

The last few years have been an active time for natural hazards, with many damaging hurricanes (e.g., Harvey, Maria, Dorian) and earthquakes (e.g., Ridgecrest, CA, Palu Indonesia, Anchorage AK) happening around the world. These events provide an opportunity for the natural hazards reconnaissance community to make use of various DesignSafe functionalities that facilitate activities during field deployments and data integration/publishing after field deployments. Datasets associated with each of the natural hazard events are available via the Reconnaissance Portal (https://www.designsafe-ci.org/recon-portal/, **Figure 5**). Selection of a natural hazard event, either from the list on the left or the map on the right, takes the user to an event page that provides details of the event and links to available datasets.

The Geotechnical Extreme Events Reconnaissance (GEER, www.geerassociation.org) Association, part of the CONVERGE network, deployed a team to Ridgecrest, CA following the Ridgecrest earthquake sequence on July 4 and 5, 2019, and made significant use of DesignSafe resources to coordinate their field efforts, curate and publish their data, and visualize their data products (Brandenberg et al., 2019, 2020; Stewart et al., 2019). The data were published in the Data Depot using the "Field Research Project" data model, and are organized into collections representing different types of data.

Researchers utilized the DesignSafe HazMapper tool to organize their GPS track logs and geotagged photos, and GeoJSON files saved from the HazMapper tool are published

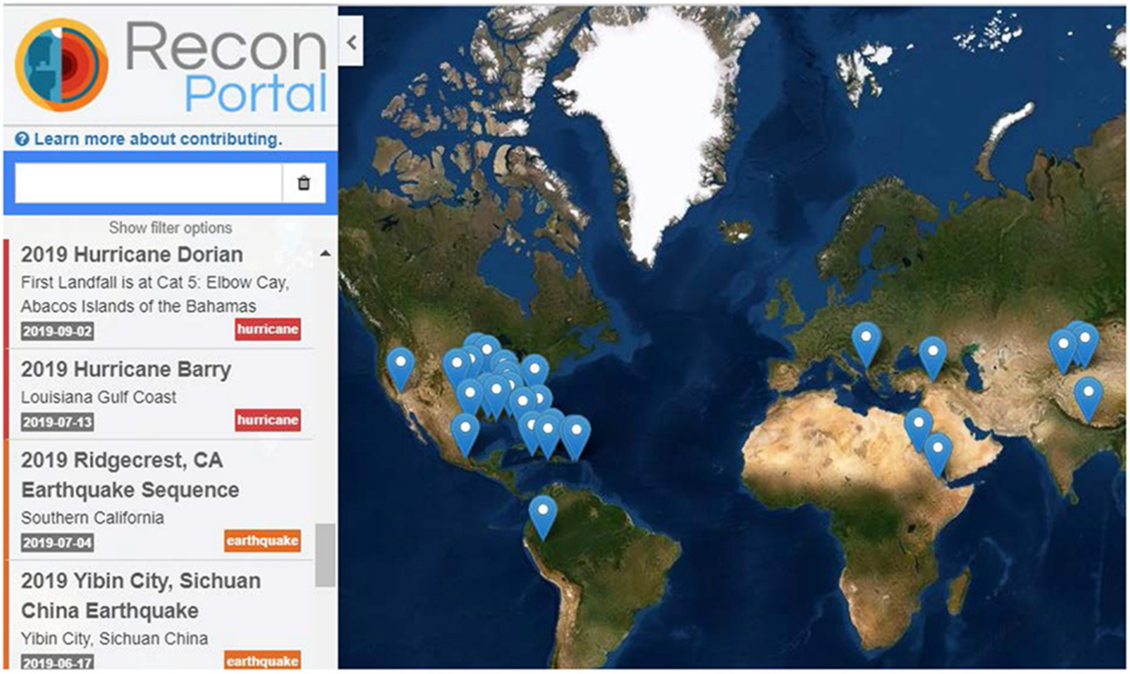


**FIGURE 5 |** DesignSafe Reconnaissance Portal and natural hazard events for which data are available.

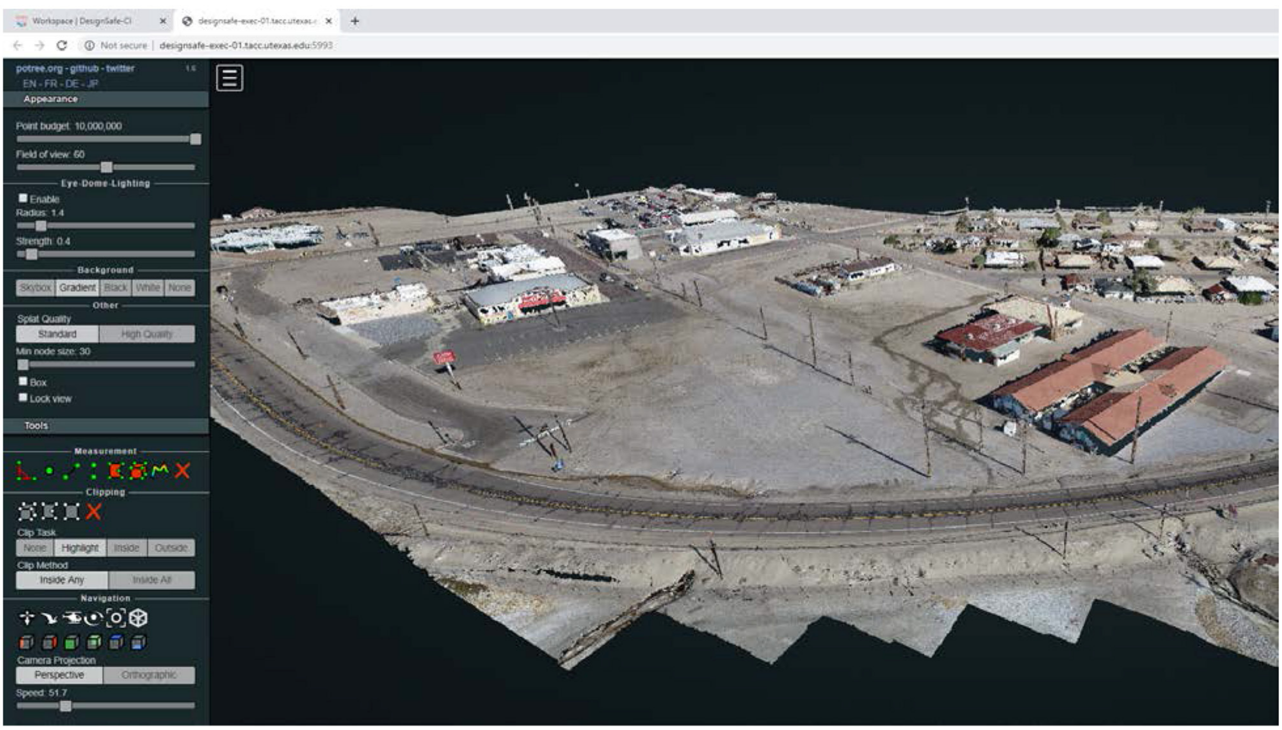


**FIGURE 6 |** Potree viewer screen shot of point cloud generated from UAV data collected over Trona, CA following the Ridgecrest earthquake sequence.

and can be viewed directly in DesignSafe. A reduced resolution version of each image is stored in the GeoJSON files, and full resolution images are also published with the data. Hand measurements made in the field, including ground crack observations, were synthesized into tables and published with the project data. UAV's equipped with cameras were flown over several key sites of interest to gather digital images and produce orthomosaics and point clouds using structure from motion techniques. **Figure 6** shows a screenshot of a point cloud in Trona, CA, where liquefaction and lateral spreading features were observed. These data were processed and visualized using the Potree converter and viewer available through the DesignSafe Workspace. Dense aerial LiDAR data gathered over the surface rupture features for the M6.4 and M7.1 events are currently being processed in Potree, and will be compared with hand measurements of the fault crack features.

The free open source geographic information system, QGIS, is also available in the DesignSafe Workspace and was utilized to integrate field observations with other geospatial data, such as surface geology maps and orthomosaic images. Figures published in the GEER report and subsequent papers were generated in DesignSafe using QGIS and the Potree viewer. DesignSafe therefore provided an important resource to the GEER team for coordinating their efforts and learning from the data they collected as part of their reconnaissance efforts. This also marked the first time, to our knowledge, that a GEER reconnaissance team published and assigned a DOI to their data products; typically GEER reports are published, but the data are not.

The Structural Extreme Event Reconnaissance network (StEER, https://www.steer.network/) intends to deepen the structural natural hazards engineering community's capacity for reliable post-event reconnaissance. DesignSafe makes possible an integrated disaster assessment workflow through various stages of deployment, which enhances the ability of StEER to collect higher-quality perishable data and more rapidly process, curate, and publish reconnaissance data. This workflow was first tested during the 2017 hurricane season with hurricane deployments for Harvey, Irma, and Maria (Kijewski-Correa et al., 2018). During the 2018 hurricane season, the workflow was enhanced when DesignSafe facilitated the action of StEER during reconnaissance efforts after Hurricane Michael hit Florida. It was again fully implemented when Hurricane Dorian hit the Bahamas in 2019 (Marshall et al., 2019). This collaborative effort provides a template for deployments in other parts of the world (Robertson et al., 2019), and it is being replicated for other hazards as well (Mosalam et al., 2019).

During the pre-deployment stage, the StEER team assembles data on the event from public sources and issues a Preliminary Virtual Reconnaissance Report (PVRR) (e.g., Kijewski-Correa et al., 2019). These reports, which are published in the DesignSafe Data Depot and are posted in the DesignSafe Reconnaissance Portal, inform the action of the field assessment teams. In addition, teams and interested stakeholders can use Slack as a central communication hub to discuss early observations and deployment strategies.

During deployment, DesignSafe Slack facilitates communication between Field Assessment Structural Teams (FAST) and central coordination and management teams. DesignSafe also supports the direct synchronization of data and metadata from certain data collection platforms, including the RAPID mobile application, and the Fulcrum mobile smartphone application (Spatial Networks Inc., 2017; Pinelli et al., 2018). Using this workflow, data and metadata can be synced to a specified DesignSafe project in real-time or at regular intervals (e.g., daily) as connectivity permits.

Following the completion of field deployments, the FAST publishes an overview of the damage and their preliminary findings in an Early Access Reconnaissance Report (EARR) on DesignSafe (e.g., Marshall et al., 2019 for Hurricane Dorian). It is worth noting that that this workflow is flexible enough so that in extraordinary circumstances where field deployment is not possible (e.g., during coronavirus pandemic), DesignSafe can still provide valuable data. In Spring 2020, StEER decided that events that would traditionally warrant an EARR will still be documented solely through a Preliminary Virtual Reconnaissance Report (PVRR). Events that would traditionally warrant a PVRR will be documented by an Event Briefing. Aerial and satellite data will still be made available through DesignSafe.

StEER also takes advantage of the other DesignSafe cloud-based tools to enhance the post-processing, aggregation, curation, and publication of the reconnaissance datasets with appropriate metadata. Tools such as Hazmapper and QGIS allow for rapid visualization and analysis of spatial data. Jupyter notebooks can be used to join damage assessment data with external data sources such as county parcel attributes. The DesignSafe Slack facilitates the communication between data librarians to ensure the proper standardization, aggregation and quality control of the damage assessment datasets. During this process, DesignSafe provides tools for synthesizing the variety of processed damage assessment data types (e.g., point clouds, orthomosaics) to support the curation process. For example, data librarians can supplement ground-based, door-to-door observations of building damage with three-dimensional views of the building using the Potree viewer tool to ensure all damage is accurately identified and quantified.

## ASSESSMENT OF IMPACT AND USAGE

As of September 30, 2020, the DesignSafe cyberinfrastructure has over 5,000 registered users. More than 2,200 of these users have accessed DesignSafe over the last year, averaging more than 7 logins per user. We can also infer significant usage by unregistered visitors, based on the more than 50,000 Google analytics web hits of our training and documentation, as well as the number of file downloads detailed below. DesignSafe registered users span a range of technical disciplines (e.g., structural engineering, geotechnical engineering, coastal engineering, and social science) and they investigate a diverse set of natural hazards (e.g., wind storms, tsunami, storm surge, and earthquake). Users are predominantly located in the United States, but ∼35% are from other countries.

As stated earlier, our vision for DesignSafe is that it serves users throughout the research lifecycle, from data creation to

**TABLE 1** | Scholarly Citations of DesignSafe.

| Year | DesignSafe citation | Primary data use | Subsequent data reuse | Totals |
|---|---|---|---|---|
| 2020 | 42 | 64 | 49 | 155 |
| 2019 | 20 | 29 | 26 | 75 |
| 2018 | 26 | 31 | 13 | 70 |

analysis to curation and publication. As a result, DesignSafe becomes more than simply a data publisher, but becomes a comprehensive research environment that is an integral part of research and discovery. The Workspace and Data Depot are critical parts of enabling this vision, and various metrics indicate significant activity by our users. In the Workspace, we see that almost 450 unique users have run a job through a Workspace App during the last year. Separately, we see an explosion of the use of Jupyter for data analysis, computation, and visualization, with over 1,300 unique users accessing our JupyterHub and over 35,000 Jupyter notebooks created. Within the Data Depot, over 1,100 projects have been created in which researchers are sharing, organizing, and curating data from across the coastal, earthquake, wind, and social science domains. Over 316 TB of data are currently stored within these projects and within the private "My Data" space, demonstrating that researchers are using the Data Depot as part of their day-to-day research.

Of course, the Data Depot also represents a traditional data repository, in which data are formally published and made publicly available. More than 34 TB of publicly accessible data is currently available within the 293 projects published in the Data Depot and these projects are authored by 411 unique researchers. From these projects, we see more than 40,000 downloads over the last year. Also available in the Data Depot are the 265 projects with 28 TB of associated data that were previously published during the 10-year NEES program. The large volume of data published in the Data Depot over a relatively short time period of 4 years is a testament to our strategy of facilitating and simplifying the data curation and publication process.

Finally, the impact of DesignSafe can be evaluated by identifying research papers that cite the use of DesignSafe or the data available at DesignSafe. **Table 1** lists identified citations during 2018, 2019, and through October 2020 as determined from papers identified via Google Alerts. The first column represents papers that make any reference to DesignSafe through citation of the DesignSafe marker paper (Rathje et al., 2017) or through the acknowledgments. The next column represents papers in which a researcher cites their own data in DesignSafe as a part of the original research project, and the third column represents papers that re-use data available in DesignSafe after the original project is over. Note that a paper may contribute to multiple columns in **Table 1**. For instance, a data re-use paper may also reference the marker paper, or a paper may cite more than one dataset. There is a meaningful number of total citations that reference the use of DesignSafe and the data published in DesignSafe, and the rate of citations has increased noticeably in 2020. While Google Alerts may not capture all of the citations and mentions of DesignSafe datasets that are available in the literature, the positive trend highlights the value of publishing data, the importance of citing data in the references using DOIs, and the types of research being conducted using data published in DesignSafe.

## CONCLUSIONS

The future of natural hazards research requires integration of diverse data sets from a variety of sources, including experiments, computational simulation, and field research. The DesignSafe cyberinfrastructure provides the functionalities that will enable transformative research in natural hazards through the availability of datasets, computational resources, and cloud-based tools that allow for a fundamental change in the way that research is performed. In particular, we are now at the precipice of a new paradigm where the natural hazards community can embrace the publishing of datasets, scripts, and workflows, the use of high-performance computing, and the potential of artificial intelligence and machine learning techniques. In particular, Jupyter notebooks are being used within DesignSafe to provide improved access and integration of experimental and simulation data, the Reconnaissance Portal and HazMapper App are being used to improve field research activities and data sharing, and the use of the DesignSafe Slack team is facilitating a virtual community of researchers who can easily interface to improve their research. The DesignSafe cyberinfrastructure is available to the global natural hazard research community and account registration is free. We encourage researchers to join and explore the ways in which DesignSafe can be used in their research.

## DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. These data can be found in the Data Depot data repository of the DesignSafe cyberinfrastructure (www.designsafe-ci.org), and are cited in the references section along with their DOIs.

## AUTHOR CONTRIBUTIONS

The authors have all been involved in the design, development, and testing of the DesignSafe Cyberinfrastructure.

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# NHERI@UC San Diego 6-DOF Large High-Performance Outdoor Shake Table Facility

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Since its commissioning in 2004, the UC San Diego Large High-Performance Outdoor Shake Table (LHPOST) has enabled the seismic testing of large structural, geostructural and soil-foundation-structural systems, with its ability to accurately reproduce far- and near-field ground motions. Thirty-four (34) landmark projects were conducted on the LHPOST as a national shared-use equipment facility part of the National Science Foundation (NSF) Network for Earthquake Engineering Simulation (NEES) and currently Natural Hazards Engineering Research Infrastructure (NHERI) programs, and an ISO/IEC Standard 17025:2005 accredited facility. The tallest structures ever tested on a shake table were conducted on the LHPOST, free from height restrictions. Experiments using the LHPOST generate essential knowledge that has greatly advanced seismic design practice and response predictive capabilities for structural, geostructural, and non-structural systems, leading to improved earthquake safety in the community overall. Indeed, the ability to test full-size structures has made it possible to physically validate the seismic performance of various systems that previously could only be studied at reduced scale or with computer models. However, the LHPOST's limitation of 1-DOF (uni-directional) input motion prevented the investigation of important aspects of the seismic response of 3-D structural systems. The LHPOST was originally conceived as a six degrees-of-freedom (6-DOF) shake table but built as a single degree-of-freedom (1-DOF) system due to budget limitations. The LHPOST is currently being upgraded to 6-DOF capabilities. The 6-DOF upgraded LHPOST (LHPOST6) will create a unique, large-scale, high-performance, experimental research facility that will enable research for the advancement of the science, technology, and practice in earthquake engineering. Testing of infrastructure at large scale under realistic multi-DOF seismic excitation is essential to fully understand the seismic response behavior of civil infrastructure systems. The upgraded 6-DOF capabilities will enable the development, calibration, and validation of predictive high-fidelity mathematical/computational models, and verifying effective methods for earthquake disaster mitigation and prevention. Research conducted using the LHPOST6 will improve design codes and construction standards and develop accurate decision-making tools necessary to build and maintain sustainable and disaster-resilient communities. Moreover, it will support the advancement of new and innovative materials, manufacturing methods, detailing, earthquake protective systems, seismic retrofit methods, and construction methods. This paper will provide a brief overview of the 1-DOF LHPOST and the impact of some past landmark projects. It will also describe the upgrade to 6-DOF and the new seismic research and testing that the LHPOST6 facility will enable.

**Keywords: six-degree-of-freedom shake table, large/full-scale experiments, multi-directional earthquake excitation, rotational ground motions, structural/geo-structural/soil-foundation-structural specimens**

## INTRODUCTION

The upgrade of the University of California at San Diego Large High Performance Outdoor Shake Table (LHPOST) funded by the National Science Foundation (NSF) Natural Hazard Engineering Research Infrastructure (NHERI) network from one to six degrees of freedom (6-DOF) is critical for the economical design, construction, and implementation of improved seismic mitigation strategies. Since its commissioning in 2004, the LHPOST has enabled the seismic testing of large structural, geostructural and soil-foundation-structural systems, with its ability to accurately reproduce far- and near-field ground motions. Thirty-four (34) landmark projects were conducted on the LHPOST as an NSF-sponsored national shared-use Network for Earthquake Engineering Simulation (NEES) and currently NHERI equipment facility. The LHPOST has the largest payload capacity in the world and ranks second in size after Japan's E-Defense shake table. The tallest structures ever tested on a shake table have used the LHPOST, which has no roof overhead, and is therefore free from height or crane capacity restrictions. Tall cranes and heavy lifting equipment can easily be used to construct full-scale buildings and other structures. The ability to test full-size structures has made it possible to physically validate the seismic performance of various systems that previously could only be studied at reduced scale or with computer models. However, the LHPOST's limitation of 1-DOF (uni-directional) input motion has prevented the investigation of many important aspects of the seismic response performance of 3-D structural systems. Currently, E-Defense has the only large-capacity 6-DOF shake table in the world. The LHPOST was designed initially as a 6-DOF shake table but built as a 1-DOF system due to budget limitations. The current upgrade of the LHPOST to 6-DOFs, termed LHPOST6 thereafter, is funded by a grant from the NSF and additional resources from UC San Diego. The LHPOST6 will be the largest shake table facility in the U.S. and the second largest in the world that will address research needs pertinent to design and construction practices in the U.S. and worldwide.

The LHPOST6 will provide a unique, large-scale, high-performance, experimental research facility that will enable research for the advancement of the science, technology, and engineering practice in earthquake disaster mitigation and prevention. Testing of infrastructure at large scale under realistic multi-DOF seismic excitation is essential to fully understand the seismic response behavior of civil infrastructure systems, calibrate, validate, and improve mathematical models, and develop and verify effective methods for earthquake disaster mitigation. Research conducted using the LHPOST6 will improve design codes and construction standards, validate high-fidelity computational models, and develop accurate decision-making tools necessary to build and maintain sustainable and disaster-resilient communities. Moreover, it will support the advancement of new and innovative materials, detailing, and construction methods.

Research activities using the LHPOST6 will broadly impact science, engineering, and education. Next-generation researchers, educators, and practitioners will be trained and will achieve a fundamental and holistic understanding of the system-level behavior of structures. They will be the contributors and future leaders in world-wide natural disaster-prevention efforts. NHERI@UC San Diego annual training workshops will inform potential users of the upgraded shake table's capabilities and new opportunities for experimental research in earthquake engineering. Large-scale experiments conducted on the LHPOST6 will be persuasive life-size demonstrations that will raise natural disaster awareness and public support for efforts to develop effective technologies and adequate policies to prevent societal disasters caused by natural hazards. Finally, the upgrade project itself will provide valuable technical information for future shake table design, construction and operation since, when completed, the LHPOST will be the highest capacity 6-DOF shake table in the world, providing researchers in the U.S. and worldwide a unique facility to advance earthquake design and construction practice.

Section Description of the 1-DOF LHPOST Facility and Its Capabilities provides an overview of the 1-DOF LHPOST. Section Description of LHPOST Upgrade to 6-DOF Capability describes the technical upgrade to six degrees-of-freedom. Section Past Experiments Conducted on the LHPOST and their Impact highlights some past landmark projects and their impacts. Finally, new seismic research and testing opportunities offered by the LHPOST6 will be discussed in Section Future Research Enabled by the LHPOST6.

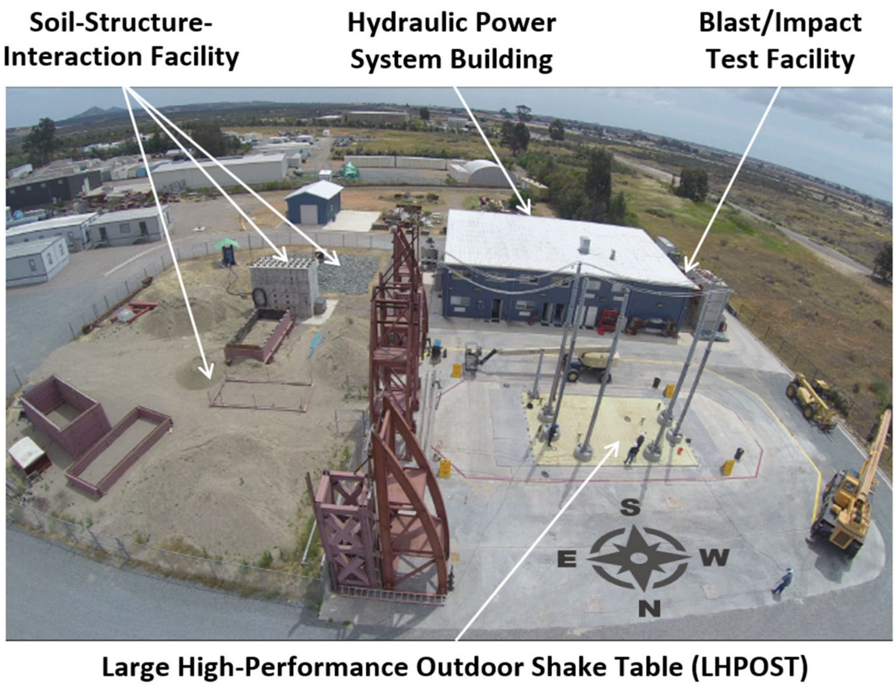


**FIGURE 1 |** Englekirk Structural Engineering Center at UC San Diego.

## DESCRIPTION OF THE 1-DOF LHPOST FACILITY AND ITS CAPABILITIES

The NHERI@UC San Diego LHPOST is located within the Englekirk Structural Engineering Center (ESEC), 16 km east of the UC San Diego main campus in La Jolla, California (see **Figure 1**). ESEC is an outdoor large-scale structural laboratory complex that, since 2009, has met the requirements of the International Accreditation Service for Testing Laboratories. It is the first known large-scale structural testing laboratory in the U.S. to demonstrate compliance with International Standards Organization ISO/IEC 17025 (International Organization for Standardization ISO, 2018).

The LHPOST is a unique outdoor shake table facility designed in 2001–2002 through a joint effort between UC San Diego and MTS Systems Corporation for the seismic testing of large systems, up to a weight of 20 MN, with a capability to accurately reproduce far- and near-field ground motions. The NSF NEES (2004–2014) and NSF NHERI (2016–present) programs have funded operations to allow the LHPOST to serve as a national shared-use research facility, enabling a wide range of landmark experiments on very large- or full-scale systems. The main research objectives of these one-of-a-kind large-scale, system level experiments have been (1) calibration, validation and improvement of analytical simulation tools to predict the seismic response of these systems, and (2) validation of the seismic performance of systems and components.

**Figure 2** shows a schematic of the LHPOST mechanical and servo-hydraulic components in its 1-DOF configuration. Component 1 is the 12.2 m long by 7.6 m wide by 2.2 m deep honeycomb steel platen with a grid of multi-purpose, high-capacity, tie-down points spaced at 610 mm on center. The platen has an effective weight of 1.45 MN. Component 2 is the reinforced concrete reaction mass and the service tunnel that connects to the Hydraulic Power System Building. The reaction mass is 33.12 m long, 19.61 m wide, and extends to a depth of 5.79 m. A smaller central area of the foundation housing the hold-down struts extends to a depth of 7.92 m. The reaction mass has a weight of 43.8 MN. The unconventional (low–weight) design of the NHERI@UC San Diego reaction mass took advantage of the natural conditions at the site in terms of high soil stiffness to build a lighter and considerably less costly foundation, which resulted in a high characteristic frequency (between 11.2 and 12.5 Hz) and a large effective (radiation) damping ratio (between 32 and 42%) (Luco et al., 2011) as opposed to conventional design that relies on the use of a massive foundation to achieve a low characteristic frequency (e.g., Ogawa et al., 2001). The reaction mass also has a grid of multi-purpose, high-capacity vertical tie-downs for the deployment of safety towers, measurement frames, or reaction frames as needed for hybrid testing. Component 3 consists of the set of two ±750 mm stroke servo-controlled dynamic horizontal (longitudinal) single-ended actuators (with one actuator at each end) having a combined maximum force of 6.80 MN (1,530 kips). Each actuator is equipped with two high-flow four-stage servovalves (each rated for a flow of 10,000 liter/min (2,500 gpm) @ 7 MPa (1,000 psi) pressure drop). Thus, the two actuators together can accommodate a peak flow of 38 $m^3$/min (10,000 gpm) which is needed to produce a platen velocity of 1.8 m/s (5.9 ft/s). Component 4 in **Figure 2** consists of six vertical pressure balanced bearings (providing a hydrostatic

A

B

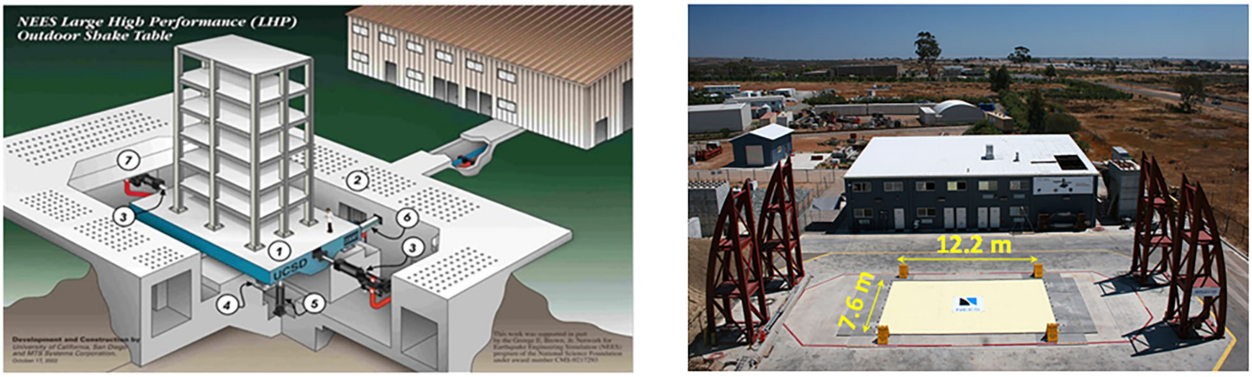


**FIGURE 2 |** LHPOST in its 1-DOF configuration: **(A)** Schematic of mechanical and servo-hydraulic components, and **(B)** picture under bare table condition.

A

B

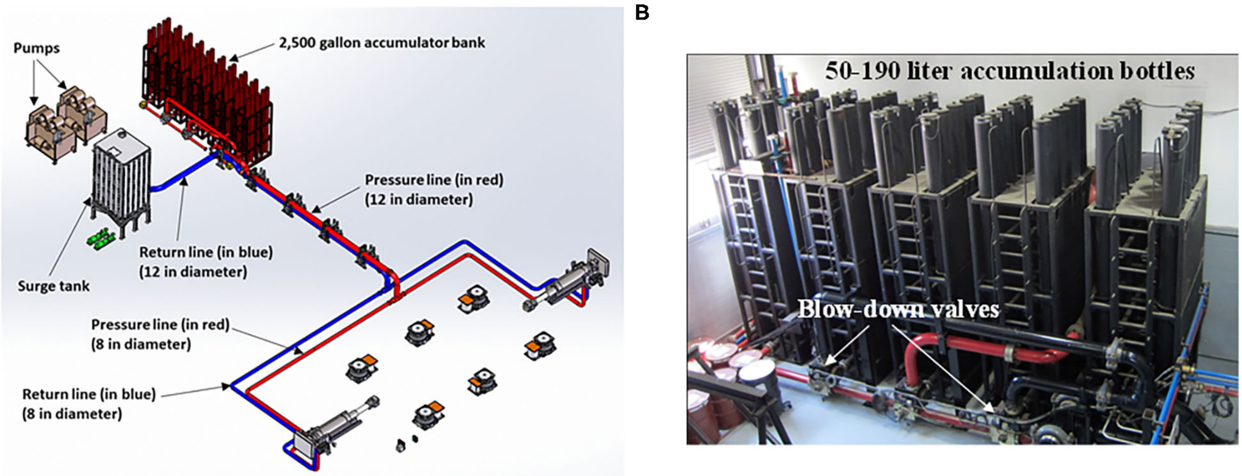


**FIGURE 3 | (A)** Hydraulic power system for the 1-DOF LHPOST, and **(B)** accumulator bank.

bearing film) to support the shake table platen. In 2009, these pressure balanced bearings were upgraded with vertical actuators (equipped with pressure balanced bearings) having a stroke of ±0.127 m (±5 in). They were mounted with very small-flow 57 liter/min (15 gpm) servovalves which were controlled to balance the vertical actuator forces but did not have dynamic motion capabilities. The overturning moment resistance of the LHPOST is provided by a combination of gravity loading (test specimen plus platen) and a pair of low-stiffness vertical nitrogen gas-filled cylinders or hold-down struts (Component 5). These cylinders passively pre-compress the platen against the vertical pressure balanced bearings, work with a nitrogen pressure of 13.8 MPa (2,000 psi) corresponding to a hold-down force of 2.1 MN (470 kips) each, and have a uniaxial stroke of 2 m (79 in). Component 6 is the lateral (or yaw) restraint system (consisting of two pairs of transversal actuators, one at each longitudinal end of the platen, with each pair comprising two coupled actuators with pressure balanced bearings, one on each longitudinal side of the platen) to prevent the platen from undesirable yaw (i.e., to position the table centered) in the single axis configuration of the table. Finally, Component 7 is a weatherproofing system consisting of removable concrete covers.

The Hydraulic Power System (see **Figure 3A**) consists of two pumps with a flow capacity of 720 liter/min at 21 MPa (190 gpm at 3,000 psi) and 430 liter/min at 35 MPa (114 gpm at 5,000 psi), respectively, an accumulator bank composed of 50 bottles of 190 liter each for a total accumulator volume of 9,500 liter (9.5 $m^3$) and a maximum pressure of 35 MPa (5,000 psi), a blow-down system (with peak flow capacity of 38,000 liter/min), a 20 $m^3$ capacity surge tank, a cooling tower and a 1.5 MW electrical power substation with a 2,500 amp transformer. During a shake table test, the hydraulic power is supplied to the actuators by the accumulator bank (charged up at 35 MPa before the test) through two blow-down valves (see **Figure 3B**), which convert the high-pressure oil from the accumulators (between 21 and 35 MPa) to a system pressure output of 21 MPa (3,000 psi) for controlling

**TABLE 1 |** Performance characteristics of LHPOST in its 1-DOF configuration for sinusoidal motions.

| | |
|---|---|
| Platen size | 12.2 m × 7.6 m (40 ft × 25 ft) |
| Max. Translational Displacement | ±0.75 m (30 in) |
| Max. Translational Velocity | ±1.8 m/s (6 ft/s) |
| Max. Translational Acceleration | ±4.2 g (bare table condition); ±1.28 g with 4 MN (900 kip) rigid payload |
| Frequency Bandwidth | 0–33 Hz |
| Horizontal Actuators Force Capacity | 6.80 MN (1,530 kip) |
| Vertical Payload Capacity | 20 MN (4,400 kip) |
| Overturning Moment Capacity under bare table condition | 35 MN-m (26,000 kip-ft) |
| Overturning Moment Capacity with 5 MN (1,100 kip) rigid payload | 50 MN-m (37,000 kip-ft) |

the actuators (through their servovalves), and through direct pumping with the 430 liter/min at 35 MPa (114 gpm at 5,000 psi) pump, which also charges the accumulator bank (before and during the test).

The accumulator bank is composed of 50 bottles of 190 liters (50 gallons) each for a total accumulator volume of 9,500 liters (9.5 $m^3$ or 2,500 gallons). When the hydraulic power system is turned off, each of the accumulation bottles is completely filled with nitrogen gas at 21 MPa (3,000 psi). When the accumulator bank is charged with nitrogen at 35 MPa (5,000 psi), the pressurized oil occupies approximately the bottom 20 percent of the total volume of the bottles. During a shake table test, the other pump (720 liter/min at 21 MPa) provides flow for the servovalve spools, the lateral (yaw) restraint system, and the vertical actuators. The hydraulic oil at 21 MPa (3,000 psi) is transported from the accumulator bank to the longitudinal actuators first through a 0.3 m (12 in) diameter schedule 160 steel piping (pressure line) from the accumulator bank through the service tunnel connecting the hydraulic power building to the reaction mass and then into the reaction mass through two 0.2 m (8 in) diameter steel pipes (one for each longitudinal actuator), see **Figure 3A**. The return flow from the actuators is directed to a 20 $m^3$ capacity surge tank through 0.2 m (8 in) diameter steel piping (one from each longitudinal actuator) in the reaction mass and then through a single 0.3 m (12 in) diameter steel pipe from the reaction mass to the surge tank located in the hydraulic power system building. The pilot flow pressure and return lines consist of 0.05 m (2 in) diameter steel pipes.

The performance characteristics of the LHPOST in its uniaxial configuration are reported in **Table 1**. The overturning moment capacity of 50 MN-m can resist an effective specimen mass of 200 tons at an effective height of 10 m with an acceleration of 2.5 g. Distinguishing performance characteristics of the 1-DOF LHPOST are its peak velocity of 1.8 m/s which allows the reproduction of near-field ground motions and its maximum payload capacity of 20 MN.

The LHPOST is controlled via an MTS 469D controller located on the first floor of the Hydraulic Power System building. An Operator Control Room resides on the second floor of the same building and houses a PC workstation directly connected to the 469D that functions as the main user interface for operations and control of the LHPOST. A second workstation serves as the Data Acquisition Central Communication Computer to interface with the National Instruments DAQ nodes used to sample the sensors deployed on the specimen tested on the shake table.

The LHPOST includes a hardware and software platform for real-time hybrid shake-table (RTHST) testing. These capabilities were verified in commissioning tests in 2017 (Vega et al., 2020). The RTHST hardware and control equipment available consist of a 500 kN, ±203 mm dynamic actuator, a four-channel MTS FlexTest controller, and a SCRAMNet ring for real-time communication and synchronization of data flow between the shake-table controller, the FlexTest controller, and Simulink Real-time Target PC. Numerical substructures can be programmed in Simulink for hard real-time implementation or in OpenSees (McKenna et al., 2020) using high performance computers capable of extending application to complex structural models. The OpenSees/OpenFresco (Schellenberg et al., 2008) open source software framework for hybrid simulation implemented in LHPOST is readily extendable to 6-DOF shake table substructure testing (Schellenberg et al., 2014).

## DESCRIPTION OF LHPOST UPGRADE TO 6-DOF CAPABILITY

As mentioned earlier, the LHPOST pictured in **Figure 1** was conceptually designed as a 6-DOF shake table. However, it was constructed as a 1-DOF (uniaxial) system in 2002–2004 to accommodate funding available at the time. With a grant from the National Science Foundation and additional financial resources from UC San Diego, the LHPOST is being upgraded so that it can operate along all six degrees of freedom, namely the longitudinal (E-W direction or X), transverse (N-S direction or Y), and vertical (Z) translational, and roll (about the X-axis or $R_X$), pitch (about the Y-axis or $R_Y$), and yaw (about the Z-axis or $R_Z$) rotational motions. This is achieved by doubling the number of existing horizontal actuators and arranging them in V-shape configuration, adding a hold-down strut at the center of the table, and equipping each of the existing vertical actuators with a high-flow and high-speed servovalve. The upgrade also requires a major increase in the hydraulic power system capacity: number of pumps, accumulator bank capacity, and piping layout.

Similar to the original design of the LHPOST, the preliminary design of the LHPOST6 was developed in a collaborative effort between UC San Diego and MTS Systems Corporation. The target performance of the LHPOST6 was defined through its ability to reproduce the six tri-axial strong ground motions defined in **Table 2**. These ground motions are from the 1978 Tabas (Iran), 1994 Northridge (California), 1995 Kobe (Japan), 1999 Chi-Chi (Taiwan), and 2015 Nepal earthquakes, and an AC-156 compatible artificial earthquake record developed for seismic qualification testing (ICC Evaluation Services Inc., 2007).

The above design criterion requires a significant expansion of the 1-DOF LHPOST hydraulic power system. The original 9.5 $m^3$ of accumulator banks will be upgraded to a new 36.9

**TABLE 2 |** Tri-axial strong ground motion records considered for the preliminary design of the LHPOST6.

| Event name | Station name | M | PGA (g) | | | PGV (m/s) | | | PGD (m) | | | High pass freq. (Hz) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | EW | NS | UP | EW | NS | UP | EW | NS | UP | |
| Tabas, 1978 | Tabas, Iran | 7.4 | 0.97 | 0.88 | 0.72 | 1.0 | 0.87 | 0.33 | 0.62 | 0.33 | 0.11 | 0.16 |
| Chi-Chi, Taiwan, 1999 | TCU065 | 7.6 | 0.72 | 0.49 | 0.23 | 0.82 | 0.73 | 0.38 | 0.36 | 0.24 | 0.10 | 0.25 |
| Kobe, 1995 | Takatori, Japan | 6.9 | 0.62 | 0.67 | 0.28 | 1.21 | 1.23 | 0.16 | 0.40 | 0.30 | 0.04 | 0.125 |
| Northridge, 1994 | Rinaldi Receiving Station | 6.7 | 0.87 | 0.47 | 0.96 | 1.48 | 0.75 | 0.42 | 0.42 | 0.23 | 0.04 | 0.10 |
| Nepal, 2015 | Kathmandu, Nepal | 7.8 | 0.16 | 0.17 | 0.15 | 0.43 | 0.40 | 0.26 | 0.30 | 0.20 | 0.10 | 0.25 |
| AC-156 compatible earthquake | | – | 1.01 | 0.96 | 0.71 | 1.04 | 1.13 | 0.77 | 0.22 | 0.21 | 0.12 | 0.70 |

**TABLE 3 |** Peak demand flow rate and total demand flow required to reproduce the tri-axial strong ground motion records defined in **Table 2**; bare table condition.

| Earthquake record | Peak flow rate [$m^3$/min] ([gpm]) | Total flow [$m^3$] ([gallons]) |
|---|---|---|
| Tabas, 1978 | 79.0 (20,859) | 7.1 (1,872) |
| Chi-Chi, Taiwan, 1999 | 82.6 (21,815) | 8.0 (2,125) |
| Kobe, 1995 | 52.5 (13,858) | 5.1 (1,349) |
| Northridge, 1994 | 89.7 (23,687) | 2.6 (687) |
| Nepal, 2015 | 33.8 (8,938) | 8.3 (2,188) |
| AC-156 compatible | 106.6 (28,158) | 4.3 (1,130) |

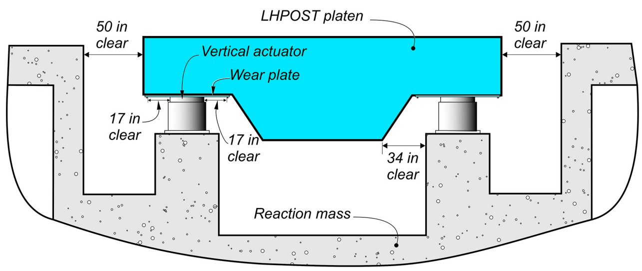


**FIGURE 4 |** Displacement limit in the transverse (N-S) direction.

$m^3$ system of accumulator banks consisting of 75 bottles of 0.38 $m^3$ (130 gallon) each. The expanded hydraulic power system was designed using inverse simulation. Inverse simulation uses a target tri-axial ground motion record as input and computes the system demands in terms of displacement, velocity, acceleration, force, servovalve opening, oil flow and pressure, assuming that the shake table controller can perfectly track the signal and accounting for the actual hydraulic power (accumulator banks and pumps). The inverse model takes into consideration many parameters including the equation of motion of the platen in six DOFs, the non-linear flow equations in the servovalves, as well as the dissipative forces between the platen and the vertical actuators. Inverse simulation is useful for determining (a) the physical demands for producing a desired table motion, and (b) whether a test will exceed any of the physical capacities of the system. The physical capacities of the system include actuator stroke (i.e., displacement limit), flow limits which induce velocity limits, and actuator force limits. **Table 3** reports the peak demand flow rate and total demand flow required to reproduce the six considered tri-axial earthquake records in **Table 2**. It is observed that the Chi-Chi and Nepal earthquake records require a total flow demand exceeding 8.0 $m^3$ (2,100 gallons), dictating the need for a new 36.9 $m^3$ (9,750 gallon) accumulator bank, which can provide approximately 9.0 $m^3$ (2,300 gallons) of oil at 20.7 MPa (3,000 psi).

The ability of the LHPOST6 to reproduce tri-axial strong ground motions such as those considered in the design requires a very high flow, particularly through the large-diameter vertical actuators. As a result, each of the six existing vertical actuators will be ported with a 19 $m^3$/min (5,000 gpm) high-flow 3-way servovalve.

The V-shaped horizontal actuator configuration is kinematically capable of producing a transverse displacement of the platen (in the N-S direction) of ± 0.94 m (±37 in) dynamically and ± 1.16 m (±45.7 in) statically (in the cushions). However, due to the geometry of the transverse cross-section consisting of the platen, reaction mass, and vertical actuators, the platen is constrained to move transversally in the range ± 0.43 m (± 17 in) as shown in **Figure 4**. With this new horizontal actuator configuration, it will be possible for the actuators to drive the table into an interference condition (impact between shake table platen and reaction mass or vertical actuators) in an out of control situation (e.g., loss of power) or operator programming error. There will be three lines of defense against such potential interference. The first line of defense will consist of a software limit detector (i.e., if a programmed limit is exceeded, the hydraulic system automatically shuts down). The second line of defense will consist of physical limit switches connected to a Programmable Logic Controller, which is connected to the shake table controller. A crash protection system defined later will provide the third line of defense in case of an interference. The bumpers of the crash protection system consume 0.05 m (2 in) of the available travel range in the N-S direction to dissipate the required energy in an impact condition, thus limiting the shake table travel range in the N-S direction to ± 0.38 m (±15 in).

The uniaxial sinusoidal performance characteristics of the LHPOST6 for sinusoidal motions are shown in **Table 4** for bare table condition and for the table loaded with a rigid payload of 4.9 MN (500 metric tons), respectively. The performance

**TABLE 4 |** Uniaxial performance characteristics of the LHPOST6 Sinusoidal motions—Bare table condition—Centered rigid payload of 4.9 MN (1,100 kips).

| | | | | | | |
|---|---|---|---|---|---|---|
| Platen size | 12.2 m × 7.6 m (40 ft × 25 ft) | | | | | |
| Frequency Bandwidth | 0–33 Hz | | | | | |
| Vertical Payload Capacity | 20 MN (4,500 kip) | | | | | |
| | Sinusoidal motions—Bare table condition | | | Sinusoidal motions—Centered rigid payload of 4.9 MN (1,100 kips) | | |
| | Horizontal X (E-W) | Horizontal Y (N-S) | Vertical Z (–) | Horizontal X (E-W) | Horizontal Y (N-S) | Vertical Z (–) |
| Peak Translational Displacement | ±0.89 m (±35 in) | ±0.38 m (±15 in) | ±0.127 m (±5 in) | ±0.89 m (±35 in) | ±0.38 m (±15 in) | ±0.127 m (±5 in) |
| Peak Translational Velocity | 2.5 m/s (100 in/s) | 2.0 m/s (80 in/s) | 0.6 m/s (25 in/s) | 2.5 m/s (100 in/s) | 2.0 m/s (80 in/s) | 0.6 m/s (25 in/s) |
| Peak Translational Acceleration | 5.9 g | 4.6 g | 4.7 g (1) | 1.6 g | 1.2 g | 2.0 g (1) |
| Peak Translational Force | 10.6 MN (2,380 kip) | 8.38 MN (1,890 kip) | 54.8 MN (2) (12,300 kip) | 10.6 MN (2,380 kip) | 8.38 MN (1,890 kip) | 54.8 MN (2) (12,300 kip) |
| Peak Rotation | 2.22 deg (3) | 1.45 deg (3) | 4.0 deg | 2.22 deg (3) | 1.45 deg (3) | 4.0 deg |
| Peak Rotational Velocity | 21.0 deg/s | 12.4 deg/s | 40.5 deg/s | 21.0 deg/s | 12.4 deg/s | 40.5 deg/s |
| Peak Moment | 23.1 MN-m (17,000 kip-ft) | 31.4 MN-m (23,200 kip-ft) | 47.0 MN-m (34,600 kip-ft) | 37.2 MN-m (27,400 kip-ft) | 49.0 MN-m (36,200 kip-ft) | 47.0 MN-m (34,600 kip-ft) |
| Overturning Moment Capacity | 32.0 MN-m (23,600 kip-ft) | 35.0 MN-m (25,800 kip-ft) | | 45.1 MN-m (33,200 kip-ft) | 50.0 MN-m (36,900 kip-ft) | |

(1) *Peak vertical downward acceleration.*
(2) *Peak compressive force in the compression-only vertical actuators.*
(3) *Due to kinematics of the piston seals of the vertical actuators.*

characteristics were determined using inverse modeling of the upgraded table system configuration.

**Figure 5** provides a rendering of the hydraulic power system (HPS) for the LHPOST6 design. The accumulator bank is equipped with six blow-down valves (manifolds) which convert the high-pressure oil from the accumulators (between 21 and 35 MPa) to a system pressure output of 21 MPa (3,000 psi) for supplying the system actuators. This pressure may be allowed to drop below 21 MPa near the end of a shake table test.

For the LHPOST6, two 0.3 m (12 in) diameter pressure lines transport the high-pressure oil from the existing building to the entrance in the reaction mass, instead of one pressure line for the 1-DOF LHPOST, see **Figures 3A**, **5**. In the reaction mass, these two pressure lines feed a "pressure" ring main (0.3 m diameter single steel pipe) that goes around the inside of the reaction mass passing through and feeding the servovalves of all the horizontal and vertical actuators as shown in **Figures 5A,C** (red colored piping in the figure images). The return flow from all the horizontal and vertical actuators is directed to the surge tank through a "return" ring main that goes around the inside of the reaction mass and then through two 0.3 m (12 in) diameter steel tubes that cross the tunnel between the reaction mass and the hydraulic power system building as shown in **Figure 5** (blue colored piping in the figure images). The 0.05 m (2 in) diameter pilot flow pressure and return lines for the 1-DOF LHPOST will be extended accordingly and replaced with 0.075 m (3 in) diameter steel piping. The existing surge tank capacity (20 $m^3$ or 5,280 gallon) is sufficient for the 6-DOF upgrade. As mentioned previously, the upgrade also requires the doubling of the pumps, i.e., one 720 liter/min at 21 MPa (190 gpm at 3,000 psi) pump to provide pilot flow to the servovalves of all actuators for servo-control, and three 430 liter/min at 35 MPa (114 gpm at 5,000 psi) pumps to pressurize (charge) the accumulator banks (see **Figure 5**) before and during a shake table test, as well as a new transfer pump for each of the two new pumps. The electrical power substation must be upgraded to 2.5 MW with a 3,000 amp transformer to support the power requirement of the LHPOST6. **Figure 6** shows the 19 $m^3$/min (5,000 gpm) high-flow 3-way servovalve, which will be added to each of the six vertical actuators in order to provide the very high flow required to reproduce tri-axial strong ground motions such as those considered in the upgrade design (see **Table 2**). The additional hold-down strut at the center of the platen required by the upgrade can be seen in **Figure 6C**. It is identical to the other two hold-down struts used for the LHPOST.

The LHPOST6 required a redesign of the cover plate system comprising of twenty steel plates (19 mm thick) supported on high-speed castor wheels and hinges, corner tubes, and concrete planks. The cover plate system provides physical protection to the servo-hydraulic system in the reaction mass from falling debris and objects. The cover plate system also offers a degree of protection against the elements and prevent wild animals from falling into the reaction mass pit. The cover plate system must satisfy many physical constraints while accommodating multi-DOF movements of the platen. **Figure 7A** depicts the cover plates with the platen at the rest position. At the corners, the plates are connected via a series of telescopic tubes, see **Figure 7B**. Several removable rubber membranes in the form of fish scales will be

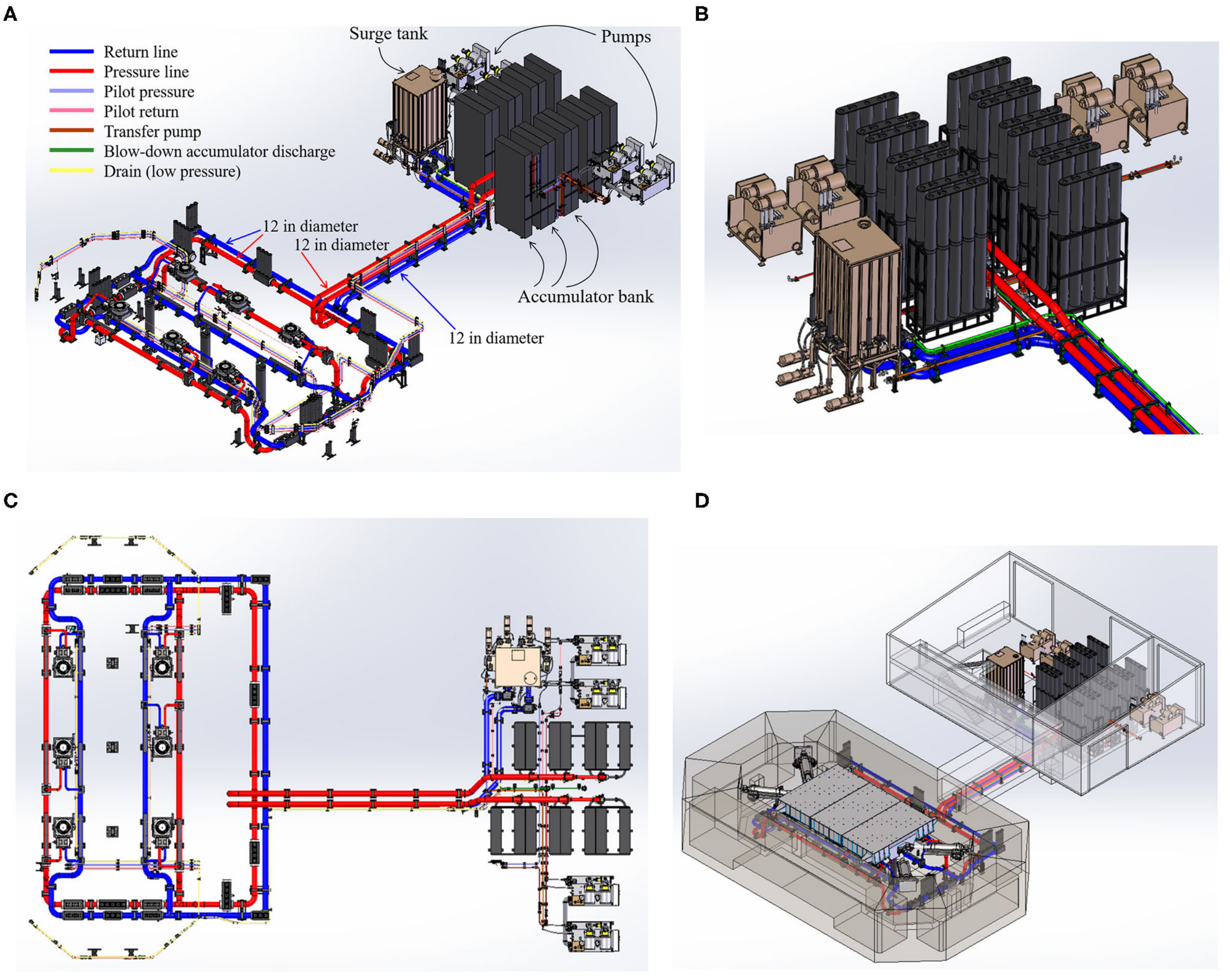


**FIGURE 5 |** Hydraulic power system (HPS) the LHPOST6. **(A)** Isometric of HPS, **(B)** Primary HPS components, **(C)** Plan view of HPS and Piping Layout, and **(D)** HPS in Pump House and Reaction Mass.

placed on top of the tubes and the edges of the steel plates. These membranes will be removed during shake table testing to provide adequate ventilation to the reaction mass pit.

## Crash Protection System

The objective of the crash protection system is to prevent or minimize damage to the shake table system or reaction mass from an uncontrolled motion condition (impact hazard) due to a loss of power or operator programming error which are not caught properly by the first two lines of defense (software limit detector and physical limit switches). The crash protection system consists of four energy dissipation devices (bumpers) mounted near the four corners of the platen through heavy steel plates bolted to the top and bottom plates of the platen as shown in **Figure 8**. The main design criterion for the crash protection system is to absorb the kinetic energy of a specimen mass of 10 MN (1,000 ton), in addition to the platen mass of 1.75 MN (178 ton), moving at 1 m/s into the bumpers (including the actuator driving force) and dissipate this energy over a bumper travel of 0.05 m (2 in). For two bumpers (per side of the platen), this results in a force of 10 MN per bumper. In each bumper, the compressive impact force is transferred into 42 tensile rods of highly ductile stainless steel (see **Figures 8A,B**) engaging into a plastic tensile yielding behavior at near-constant force. After an impact, the yielded tensile members would be replaced. A detailed non-linear finite element analysis of the reinforced concrete reaction mass was performed and showed that an impact force of 10 MN will be resisted with very small displacements and deformations (fractions of a mm) of the reaction mass.

## Horizontal Actuators

The two new horizontal actuators will have the same functionality and performance capabilities as the two horizontal actuators for the 1-DOF LHPOST. The new actuators will have different manifold configurations to support the operation of the system in the 6-DOF mode. The existing two horizontal actuators will also be equipped with the new manifold configurations. **Figure 9**

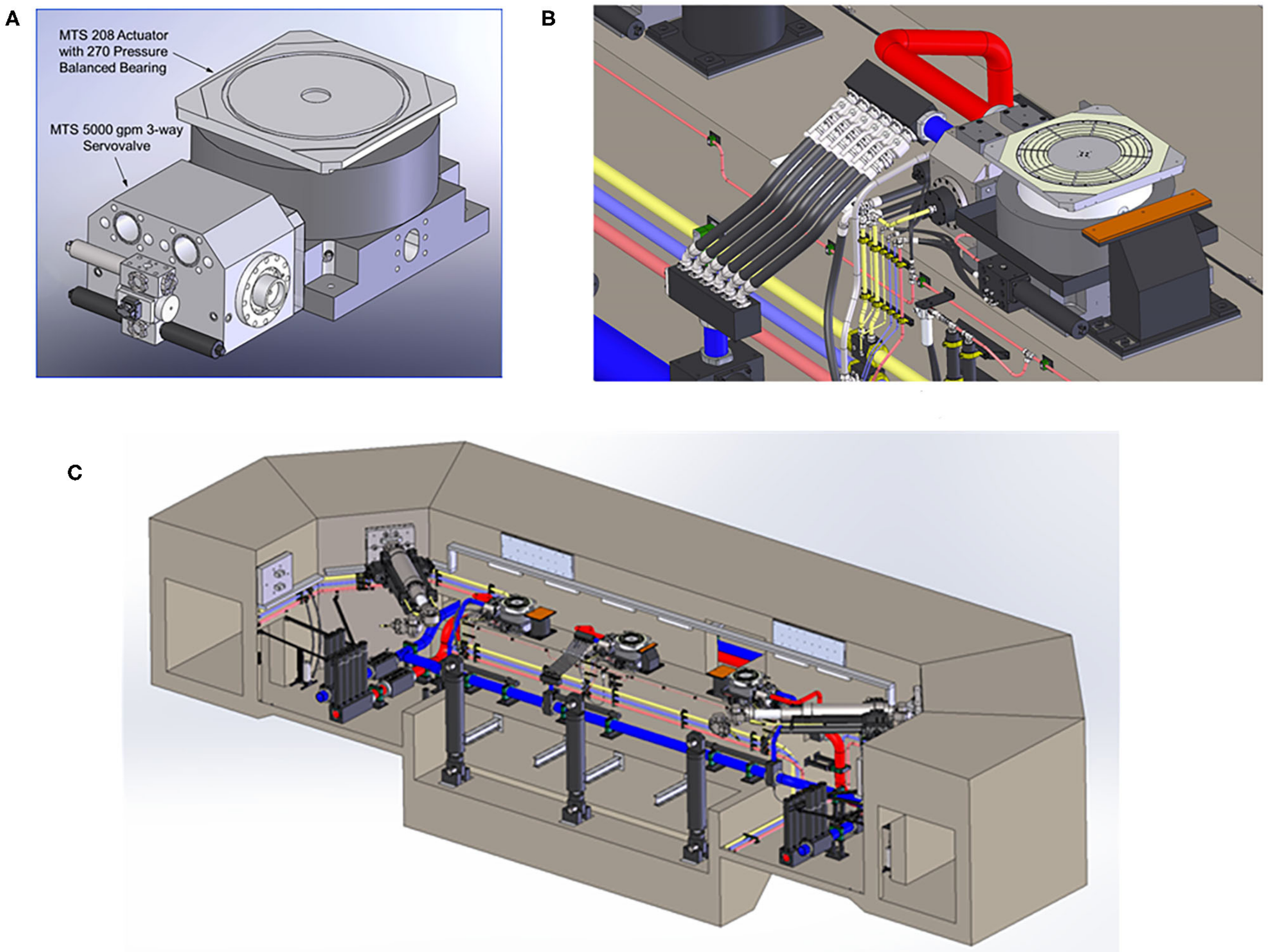


**FIGURE 6 |** High-flow servovalves for vertical actuators: **(A)** servovalve-actuator pair, **(B)** connection of servovalve to pressure (red) and return (blue) pipes, and **(C)** longitudinal cut through the reaction mass longitudinal axis.

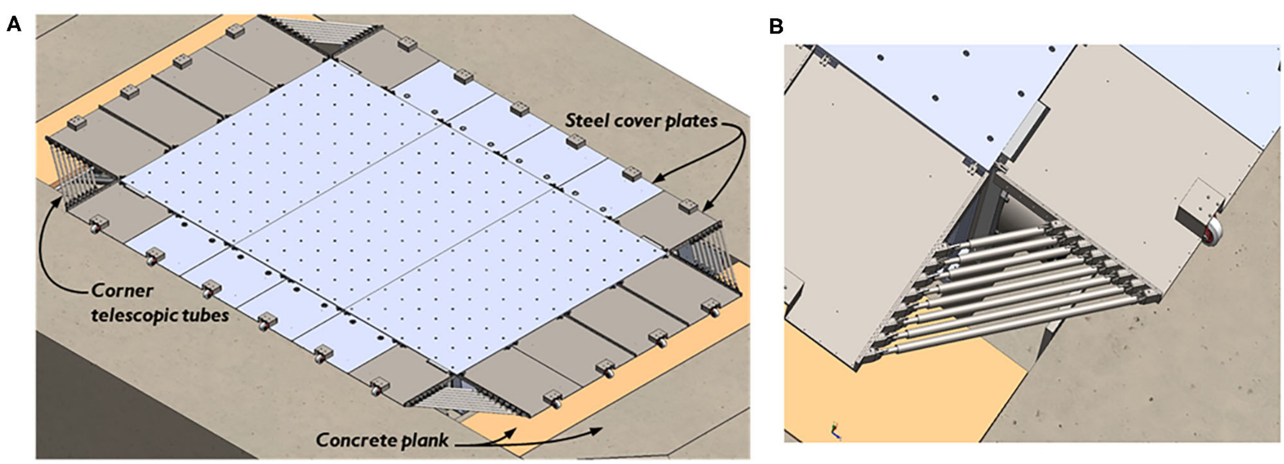


**FIGURE 7 |** View and rendering of the cover plate system: **(A)** steel plates locations in the at rest position, and **(B)** steel plates and telescopic tubes at the corners.

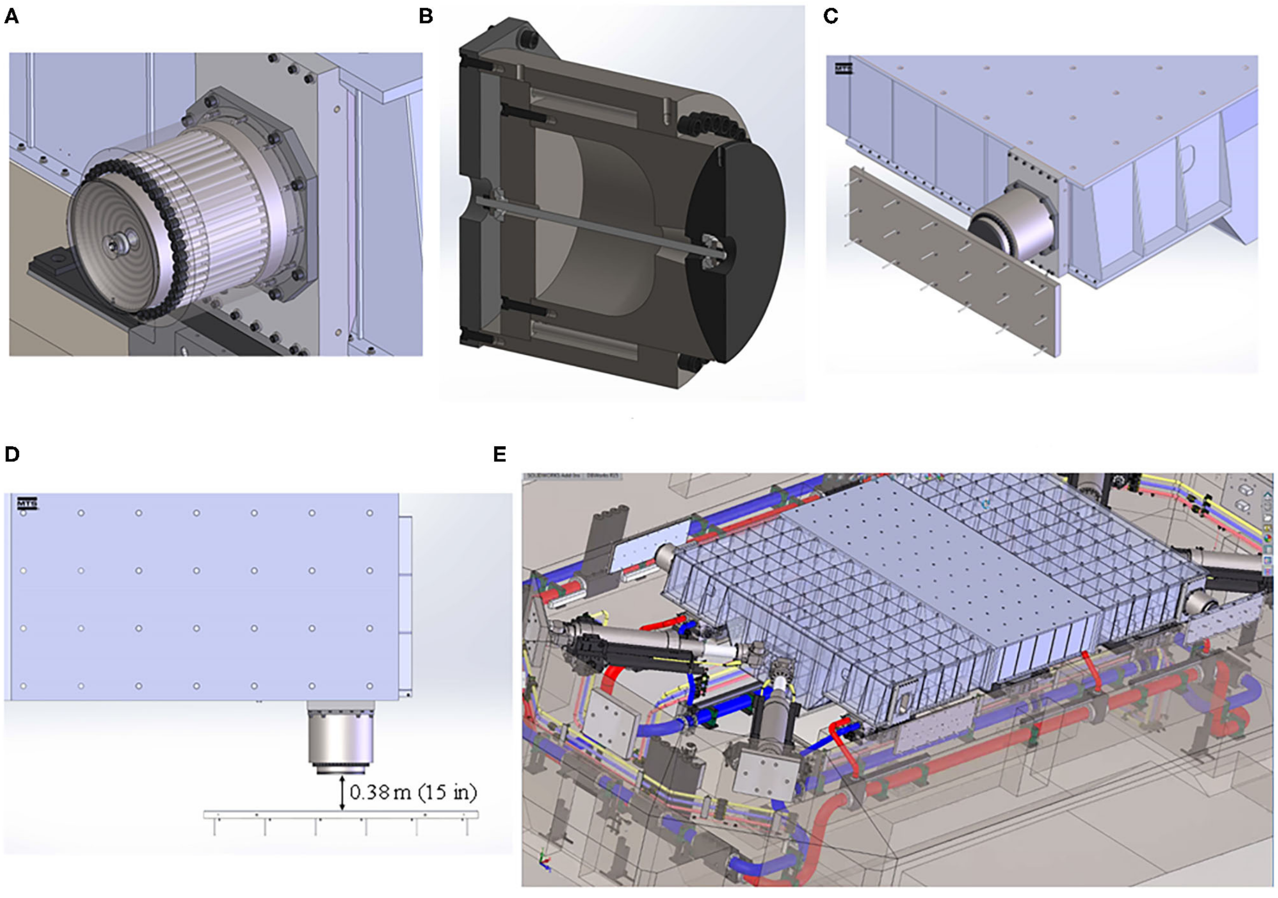


**FIGURE 8 |** Crash protection system: **(A)** view of 42 tensile rods, **(B)** internals of crash protection device, **(C)** crash protection device and impact plate, **(D)** distance between crash protection devices and impact plates, and **(E)** overall view of shake table platen and two of the crash protection devices.

shows several views of the LHPOST6 with its horizontal actuators in V-shape configuration within the reaction mass.

## LHPOST6 Controller

The existing MTS 469D Seismic System Controller used on the 1-DOF LHPOST will be completely replaced with MTS' latest electronics and control software. The new MTS 469D controller will provide for simpler shake table tuning, system operation, and test execution. It will permit faster set up and more "tools" to handle difficult (e.g., non-linear degrading) specimens. The control software provides an advanced graphical user interface (GUI) with full functionality provided for system tuning, test set up and operation, table data acquisition, and advanced high-level adaptive control for high fidelity earthquake waveform reproduction. It also includes a set of high level fixed control techniques such as: (i) Degree of Freedom Control (DOF), (ii) Three Variable Control (TVC), (iii) Delta Pressure Stabilization (DPS), (iv) Adaptive Control Techniques (e.g., Adaptive Inverse Control—AIC), (v) EZ Tune (automatic tuning wizard for AIC), and (vi) Safe Abort, as well as tools for Off-Line Iterative (OLI) Compensation. The Safe Abort option allows a test to be interrupted with a very quick smoothly damped trajectory to a safe position without causing abrupt system motion which can damage the specimen. This Safe Abort, like all MTS safety limits, can be triggered by system limit detectors, or operator intervention. The new MTS 469D controller will be customized for the characteristics of the LHPOST6. The two existing table feedback uniaxial accelerometers will be replaced with a set of eleven uniaxial feedback accelerometers (3 E-W, 3 N-S, and 5 vertical) to control all six degrees of freedom of the LHPOST6.

The TVC portion of the 6-DOF 469D controller is exactly the same for each of the six DOFs and the same as for the 1-DOF LHPOST. There are six control channels, one for each DOF, and the controller for each DOF takes only feedback associated with that DOF (i.e., the TVC does not mix DOF feedbacks between the SDOF controllers). The controller uses back-and-forth transformations from Cartesian DOFs to actuator DOFs (from Cartesian space to actuator space). The dynamic cross-coupling between DOFs is mitigated by Adaptive Inverse Control (AIC) and Off-Line Iterative (OLI) Compensation, which take care of the diagonal and off-diagonal terms of the 6×6 total shake table transfer function matrix. The load balancing control algorithm for the LHPOST6 remains the same as for the 1-DOF LHPOST. The only difference is that the vertical actuators have dynamic capabilities (i.e., are capable of more velocity) in the LHPOST6.

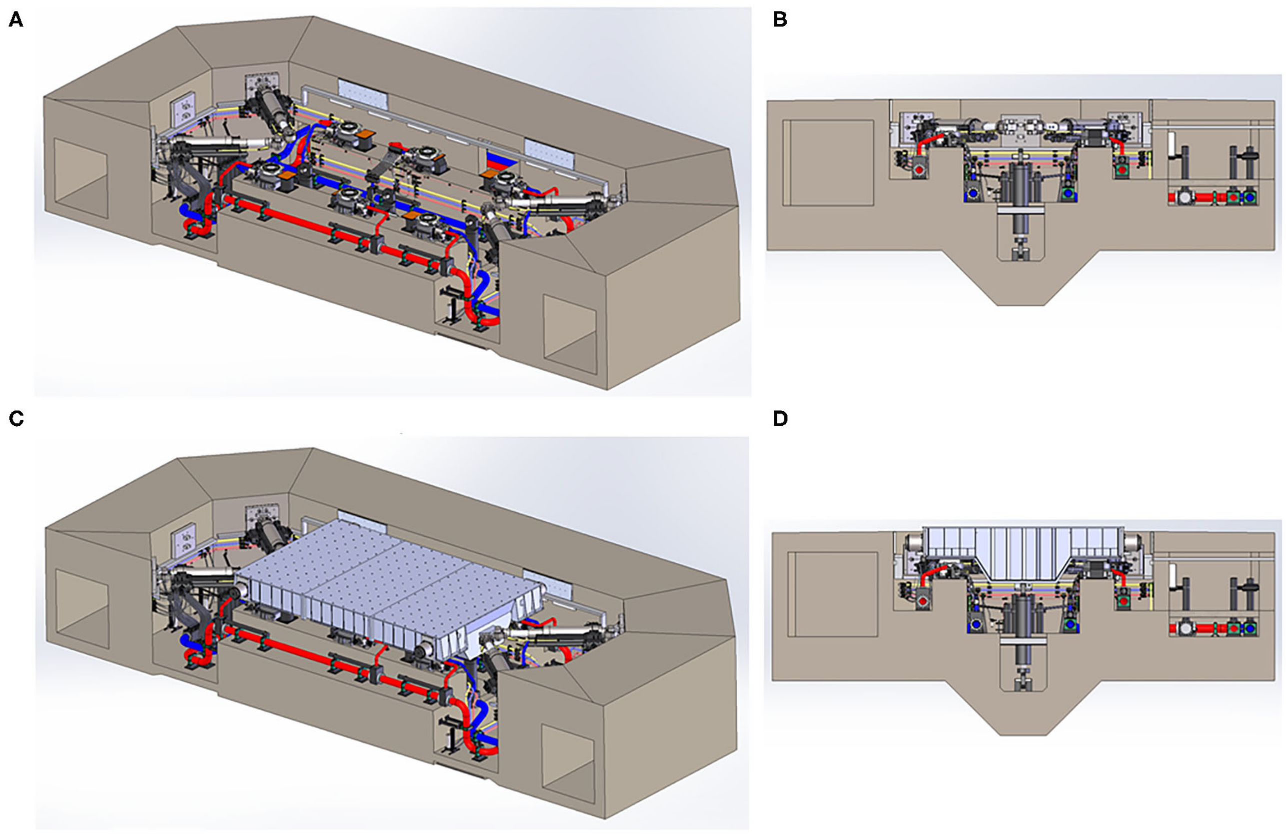


**FIGURE 9 |** Overall design configuration of the LHPOST6: **(A)** horizontal actuators in V-shape configuration, vertical actuators and pedestals to park the platen, **(B)** transverse view with horizontal actuators and hold-down struts, **(C)** horizontal actuators connected to shake table platen equipped with crash protection devices, and **(D)** transverse view with shake table platen equipped with crash protection devices.

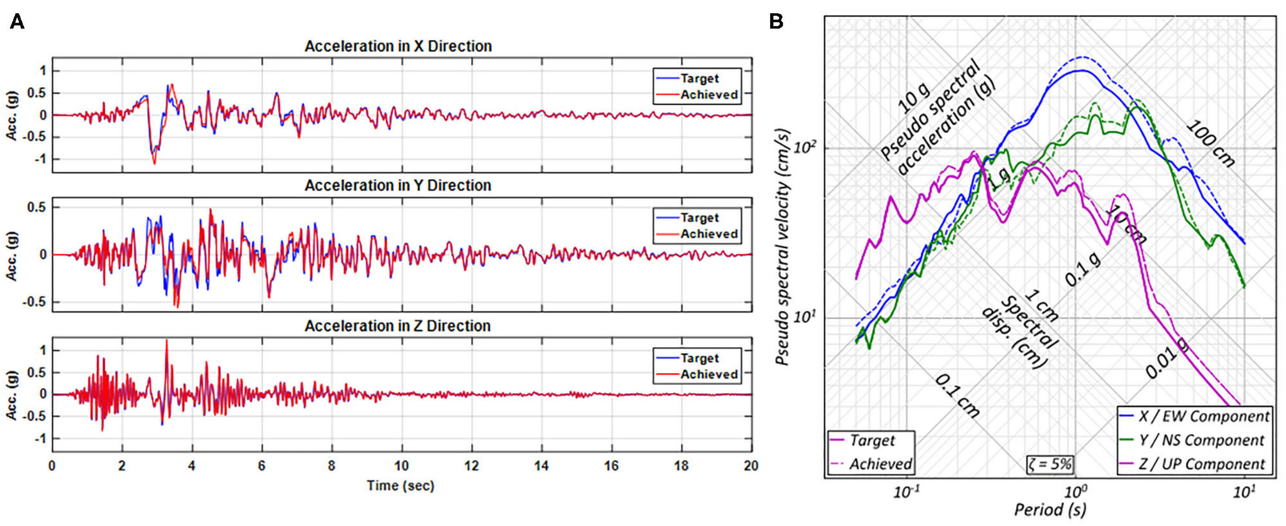


**FIGURE 10 |** Comparison of target and (simulated) achieved tri-axial 1994 Northridge earthquake record (see **Table 2**): **(A)** acceleration time histories, and **(B)** 5% damped tri-partite linear elastic response spectra.

**TABLE 5** | Prediction of oil column frequencies and modes for the LHPOST6 (bare table).

| Oil column frequency | Oil column mode |
|---|---|
| $f_1 = 7.40$ Hz | Y/N-S/Transverse Direction |
| $f_2 = 8.87$ Hz | Yaw |
| $f_3 = 9.33$ Hz | X/E-W/Longitudinal Direction |
| $f_4 = 40.66$ Hz | Coupled Longitudinal (X)—Pitch ($R_Y$) |
| $f_5 = 44.07$ Hz | Z/Vertical Direction |
| $f_6 = 53.03$ Hz | Coupled Transverse (Y)—Roll ($R_X$) |

## Performance Simulation of LHPOST6

The design of the LHPOST6 was modeled using inverse simulation and was then validated using forward simulation. The forward model of the LHPOST6 includes the rigid body dynamics in 6-DOFs of both the platen and a rigid specimen, servovalve and actuator dynamics (with non-linear flow equations), accumulator banks and line accumulators, and a virtual replica of the MTS 469D controller that will be installed on the LHPOST6 (Thoen, 2019). In the forward model, the controller was tuned for the characteristics of the LHPOST6 design using the new 469D Auto-Tuner capability. The tuned closed-loop forward model provides the ability to perform "dry runs" of the LHPOST6 system and thus evaluate, pre-construction, its signal tracking performance capability. After completion of the LHPOST upgrade, the forward model will also allow for offline tuning based on the test specimen characteristics and will be very useful for safe offline operator training (i.e., shake table simulator). **Figure 10A** compares the target (or desired) and simulated achieved translational acceleration time histories of the shake table, and **Figure 10B** compares the target and achieved five-percent damped tri-partite (displacement/pseudo-velocity/pseudo-acceleration) linear elastic response spectra for the three components of the 1994 Northridge earthquake record (refer to **Table 2**). Similar levels of signal tracking fidelity were observed for the other strong tri-axial earthquake records considered for the upgrade design. These comparisons show a good signal tracking capability of the LHPOST6 design. This is especially true for the vertical ground motion components, given the fact that the vertical actuators of the LHPOST are single-acting, i.e., they can only push (upwards) and cannot pull (downwards) the platen since they have zero retraction force. The nitrogen-filled hold-down struts pull the platen down but without closed-loop dynamic capabilities. The level of fidelity in signal reproduction for the vertical component and other motion components can also be further improved through the advanced control capabilities built in the MTS 469D controller such as Adaptive Inverse Control (AIC), On-Line Iteration (OLI) and Specimen Dynamics Compensation (SDC) (Thoen et al., 2012).

A simple mechanical model of the rigid platen supported by the oil column springs of the 4 horizontal and 6 vertical actuators results in the oil column frequencies and modes reported in **Table 5**. The frequency of the oil column mode in the longitudinal (E-W) direction of the 1-DOF configuration of the LHPOST is approximately 10.6 Hz. The three lowest oil column frequencies of the LHPOST6 are 7.4, 8.9, and 9.3 Hz in the transverse, yaw, and longitudinal directions, respectively. As for the 1-DOF LHPOST, the resonant peaks of the oil column modes will be damped out numerically by the shake table controller using the delta-pressure feedback gains and adjusting the notch filters' parameters.

## Instrumentation of Test Specimens and Data Acquisition System

Experiments conducted on the LHPOST typically require fifty to six-hundred sensor measurement channels. The NHERI LHPOST facility has a large inventory of sensors available to instrument test specimens. These sensors and their quantities include: (i) MEMS-based accelerometers (205), (ii) Linear displacement transducers (142), (iii) String potentiometer displacement transducers (119), (iv) Load jacks (4), (v) Load cells (31), (vi) Soil pressure transducers (32), and (vii) GPS System with RTD_NET Software by Geodetics with 3 receivers operating at 50 Hz to measure translational motions in 3D with a precision of 1.5 mm. Strain gauges are used extensively but are considered disposable instrumentation. The site also has an array of 1080 and 4K high definition (HD) video cameras running at 30 frames per second (fps) that are fully synchronized with the sensors: GoPros 4K (15), Axis 240Q/241Q video servers streaming (4), IQeye streaming/time-lapse video (3).

The LHPOST6 facility will be equipped with a new data acquisition (DAQ) system consisting of 12 nodes with 64 channels each (for a total of 768 measurement channels) at 24-bit Analog-to-Digital resolution, simultaneous sampling, and a sampling rate up to 25.6 kS/s per channel. This DAQ will provide superior aliasing rejection with user-configurable digital anti-aliasing filters, and zero skew time between different channels due to simultaneous sampling, thus enabling accurate recordings from very small (ambient vibrations) to very large (seismic testing) motions.

The site is open to explore the use of new measurement/sensor technologies such as Digital Image Correlation techniques to measure the motion and deformation of test specimens. However, the site's top priority is to provide highly reliable measurements and high-quality data to the researchers and/or commercial clients. Research teams using the site are also encouraged to deploy payload projects exploring innovative sensing technologies (e.g., low-power wireless sensors).

The site also has calibration equipment for sensors and data acquisition systems, as required for its ISO/IEC Standard 17025:2005 accreditation. The NHERI@UC San Diego Experimental Facility also has a fully configured, end-to-end, live video streaming production system with high resolution and low latency. NHERI@UC San Diego is on social media (youtube, facebook, twitter).

## PAST EXPERIMENTS CONDUCTED ON THE LHPOST AND IMPACTS

Since the LHPOST commissioning on October 1, 2004, and until its closure on October 1, 2019 for the 6-DOF upgrade, 34 major research and commercial projects were conducted on the LHPOST during its life as a national shared-use NSF-NEES and NHERI equipment facility. The following is the list of specimens tested, in chronological order, on the LHPOST from 2004 to 2019, with the scale of the specimen and a picture of each of them provided in **Figure 11**: (1) seven story structural wall building slice (full-scale) (Panagiotou et al., 2011); (2) seismic base isolator (miniature scale); (3) bridge abutment and soil embankment inside large laminar soil box (scale: distorted); (4) new type masonry building structure and masonry veneer—Phase 1 (full-scale); (5) precast concrete building with deformable diaphragms and re-centering post-tensioned RC walls (scale: 0.40) (Belleri et al., 2014); (6) non-ductile RC frames with infill walls—Phase 1 (full-scale) (Billington et al., 2009); (7) new type masonry structure and masonry veneer—Phase 2 (full-scale); (8) non-ductile RC frames with infill walls—Phase 2 (full-scale); (9) retaining wall with and without sound wall inside large laminar soil box (scale: distorted) (Mock and Cheng, 2015); (10) 65-kW steel wind turbine (full-scale) (Prowell et al., 2011); (11) industrial-type metal building (full-scale) (Uang et al., 2011); (12) RC bridge pier (full-scale) (Schoettler et al., 2009); (13) reinforced masonry wall building (full-scale) (Stavridis et al., 2016); (14) five story dual wall-frame RC building with non-structural components and systems (full-scale) or BNCS project (Chen et al., 2016; Pantoli et al., 2016a); (15) reinforced masonry wall building (full-scale); (16) geogrid reinforced soil retaining wall inside large stiff soil confinement box (full-scale); (17) RC bridge columns supported on rocking shallow foundations (scale: 0.333) (Antonellis et al., 2015); (18) four story woodframe building with soft bottom story (full-scale) (Bahmani et al., 2017); (19) four story RC building with inertial force-limiting floor anchorage system (scale: 0.4) (Zhang et al., 2018); (20) partially grouted reinforced masonry building (full-scale); (21) seismically isolated unibody residential building (full-scale); (22) 500kV bus support structure with retrofit added to the base of the pylons (full-scale); (23) cut-and-cover shallow tunnel embedded in soil inside large laminar soil box (scale: 0.111) (Kim and Elgamal, 2017a); (24) helical piles embedded in soil inside large laminar soil box (full-scale) (ElSawy et al., 2018); (25) spillway retaining wall embedded in soil inside large laminar soil box (distorted scale) (Kim and Elgamal, 2017b); (26) six story light-gauge cold-formed steel framed building subjected to seismic and fire tests (full-scale) (Wang et al., 2015b); (27) electrical relay racks (full-scale); (28) seismic isolated RC slabs for hybrid shake table commissioning tests (scale: 0.25) (Vega et al., 2020); (29) two-story cross-laminated (heavy) timber building with re-centering (rocking) post-tensioned walls (full-scale) (Pei et al., 2019); (30) pile foundation in multi-layer saturated soil strata inside the large laminar soil box (distorted scale); (31) shear-dominated reinforced masonry wall system—Phase 1 (full-scale); (32) repetitively framed mid-rise cold-formed steel building (full-scale); (33) shear-dominated reinforced masonry wall system—Phase 2 (full-scale); (34) steel building with seismic collectors (scale: 0.5). The geo-structures require the shake table to be used in combination with one of the two large soil boxes available at ESEC: (1) a steel laminar soil shear box of dimensions 6.7 m (L) × 3.0 m (W) × 4.7 m (H), and (2) a composite steel-concrete stiff soil confinement box of dimensions 10.0 m (L) × 4.6 m or 5.8 m (W) × 7.6 m (H) (Fox et al., 2015).

Most tests performed on the LHPOST are landmark tests. The seven-story structural wall building slice (see insert 1 in **Figure 11**) and reinforced concrete bridge pier (see insert 12 in **Figure 11**), which were densely instrumented and tested to the brink of collapse, provided the community with a unique dataset. Blind predictions were organized for these two tests, and the predictions provided a unique opportunity to look into model uncertainty and human error (Restrepo, 2007; Terzic et al., 2015).

The three-story precast concrete building (see insert 5 in **Figure 11**) was a capstone of the multi-university (University of Arizona, Lehigh University, and UC San Diego) Diaphragm Seismic Design Methodology (DSDM) research project jointly funded by the Precast/Prestressed Concrete Institute (PCI) and NSF with outstanding industry support and input. Three different types of precast concrete diaphragms were incorporated into this building. Because the test program included many (sixteen) design earthquake tests, a pair low-damage re-centering precast post-tensioned concrete walls were used to provide lateral load resistance to the building. The DSDM project was extremely successful and culminated with the inclusion of floor acceleration provisions for precast building diaphragms and other systems in the ASCE 7–16 standard.

The large-scale tests conducted on masonry structures with the LHPOST facility represent major masonry research efforts in the US to advance the seismic performance assessment and design of existing as well as new masonry construction. In particular, data from the masonry-infilled non-ductile reinforced concrete frame study (see inserts 6 and 8 in **Figure 11**) led to improved performance assessment methods that have been adopted into ASCE 41–17. Data from the studies of reinforced masonry (see inserts 13, 15, and 20 in **Figure 11**) contributed to the development of new shear-friction design provisions in TMS 402–16, and led to the development of improve load-displacement backbone curves for masonry walls, which are being implemented in ASCE 41. Data from the building system tests (see inserts 15, 31, and 33 in **Figure 11**) provided new insight into the displacement capacity of masonry buildings and has been used to validate detailed as well as simplified numerical models that were used to solve the short-period building performance paradox in the ATC 116 project.

The BNCS project (see insert 14 in **Figure 11**) enabled, for the first time, the full-scale experimental investigation of a wide range of functioning non-structural components when installed in a system setting. Subjected to service, design and maximum credible earthquake scenarios, the various NCSs in this total building specimen were allowed to interact with the structural system as well as with other NCSs. Vertical and horizontal spanning NCSs were installed within the test building, using seismic and non-seismic


**FIGURE 11 |** Specimens tested on the LHPOST in the period 2004–2019.

compliant detailing. Findings from these tests demonstrate the efficacy of building base isolation, as the building and its NCSs were undamaged and the system suffered no loss of functionality. Under fixed base condition, the BNCS building earthquake test results also facilitated advancements to design and practice provisions within ASCE 7 (ASCE/SEI, 2016), including provisions for ductile corner connections for precast concrete facades (Pantoli et al., 2016b), higher importance factors for stairs (Wang et al., 2015a), and improved boundary condition detailing for elevators (Wang et al., 2016), to name a few important impacts.

The data, information and knowledge gained from the experiments conducted on the LHPOST have greatly advanced analysis and design tools, design guidelines and codes, design practice, and seismic response predictive capabilities for buildings (old and new), bridges, critical facilities, non-structural components and systems, wind turbines, geo-structures and foundation systems, leading to improved earthquake safety in the community overall. Moreover, the full-scale dynamic testing capability provided by the LHPOST has enabled new and innovative low-damage earthquake protective systems to be tested and incorporated into practice. Indeed, the ability to test full size structures has made it possible to physically validate the seismic performance of many systems that previously could only be assessed with computer models or using small-scale physical models. However, with the limitation of the LHPOST in its 1-DOF configuration, important aspects of seismic response for many problems in earthquake engineering and application scenarios could not be investigated. Currently, the only large-capacity 6-DOF shake table capable of performing such tests is the E-Defense facility in Japan (Nakashima et al., 2018). The only shake table in the world that has a larger payload capacity than the E-Defense table is the LHPOST. Existing moderate to large scale 6-DOF shake tables in the U.S. at the University of California at Berkeley (0.70 MN payload), University at Buffalo (2 × 0.45 MN payload), and University of Nevada Reno (0.45 MN payload) have contributed toward understanding the multi-component seismic response of equipment, building and bridges, albeit at reduced scale for large structural systems. The multiple tables at Buffalo and Reno (when paired with three additional bi-directional tables) have supported landmark testing of long-span bridge structures.

## FUTURE RESEARCH ENABLED BY THE LHPOST6

The LHPOST6 will enable ground-breaking experimental research in earthquake engineering related to structural, geo-structural, soil-foundation-structural, and non-structural components and systems, including how these systems behave during realistic multi-component earthquake excitations, and how they should be conceived and designed to resist such excitations best. A select set of important research areas and studies that will be made possible by the LHPOST6 are described in the following sections.

### Building Structures

One of the largest and diverse areas of research is in low-rise, mid-rise, or high-rise buildings made out of a variety of materials such as structural steel, cold-formed steel, reinforced/prestressed/precast concrete, high-performance concrete, wood-frame, cross-laminated (heavy) timber, unreinforced and reinforced masonry, and advanced materials. Topics also include the seismic performance of total building systems, those designed with super columns or outriggers, and special issues such as floor vibration isolation.

#### Masonry Components and Systems

Unreinforced Masonry (URM) buildings have suffered severe damage or collapse in past earthquakes. The failure of an URM building in a seismic event has often been characterized by the out-of-plane collapse of the walls (Felice and Giannini, 2001). The resistance of an URM wall to out-of-plane forces relies on arching action, which could be weakened by damage caused by in-plane forces. As a result, bi-axial horizontal ground motions are particularly damaging to an URM building, and URM walls subjected to uniaxial in-plane forces have been reported to exhibit significantly better performance compared with bi-axial loading conditions. Furthermore, the vertical ground acceleration could change the axial load on a wall and thus its in-plane and out-of-plane shear resistance, while also affecting the arching mechanism and stability of the wall. The LHPOST6 will enable the robust assessment of the seismic safety of URM buildings and the development of effective retrofit and strengthening methods.

#### Steel Systems

There has been extensive research on the seismic performance of hot-rolled structural steel and cold-formed steel systems in the areas of structural stability and progressive collapse mitigation, connection behavior, and seismic risk and life-cycle cost quantification (Stojadinović et al., 2000; Khandelwal et al., 2008). However, additional research is needed to assess interactions in building systems undergoing earthquakes, e.g., competing inelasticity in vertical and horizontal lateral-force resisting systems, overstrength and system effects derived from the participation of gravity and non-structural framing in lateral response (e.g., Imanpour et al., 2016; Peterman et al., 2016; Cravero et al., 2020).

#### Structural Concrete Systems

Structural concrete has been a prevailing construction material for low, high-rise, and super-tall buildings. However, most research supporting seismic design with structural concrete has been limited to components (e.g., Kurama et al., 1999; Lehman et al., 2004; Naish et al., 2013; Tazarv and Saiid Saiidi, 2016) or reduced-scale models of building systems (e.g., Rodriguez et al., 1995). In the US, only three landmark building tests were performed at large- or full-scale on a shaking table (Schoettler et al., 2009; Chen et al., 2016; Zhang et al., 2018) but under single-axis excitation. Therefore, research is needed on innovative, resilient, seismic-resistant concrete systems under multi-axial excitation, specifically to improve modeling and analysis capabilities for component and system behavior. Of particular interest are the use of high strength materials (reinforcing bars and concrete) and advanced materials for seismic civil applications, special concrete moment frames, and structural walls including the combination of dual systems, precast concrete frame, and wall structures, and sustainable reinforced concrete structures utilizing recycled materials. Of great interest, and somewhat neglected in research, is the evaluation of the seismic performance of commercial tilt-up buildings. Many such buildings behaved poorly during the 1994 Northridge earthquake (Mitchell et al., 1995), which prompted the need to revisit various diaphragm-to-wall connection methods. Recent research indicates that some of these structures may still be quite earthquake vulnerable (Koliou et al., 2016). The LHPOST6 will benefit the above research areas by providing the opportunity to conduct large-scale multi-axial shake table tests of complete buildings and structures of complex geometries.

Current seismic design standards, such as (ACI, 2014; AISC, 2016; ASCE/SEI, 2016, 2017; TMS, 2016) are largely based on data obtained from quasi-static testing of structural components, most of which were conducted with in-plane horizontal loading. While such data are crucial for the development of design and detailing requirements to ensure the ductile behavior of structural members, how a building will perform in an earthquake is also highly dependent on how these components are proportioned, connected, and interact with each other as a system. Without due consideration of the system's behavior in design, the actual seismic response and load-resisting mechanism of a building could differ significantly from what is anticipated by current design standards. Current design standards also rely on 3D computational models of structures to extrapolate results of uniaxial shake table tests to project structural performance under multi-axial loading conditions. The lack of pertinent data to validate the accuracy of computational models for these predictive analyses is an important issue. Multi-axis shaking-table tests are needed to study more realistically the behavior of civil structures and to improve current seismic design methods and standards.

### Non-structural Components and Systems (NCSs)

NCSs, generally categorized as architectural, mechanical, electrical, and plumbing, or building contents, are elements that facilitate operation of a building. Importantly, they typically comprise 75–85% of the construction cost of commercial buildings (Miranda and Taghavi, 2003). NCSs have suffered significant damage, led to appreciable losses, and endangered occupants during past earthquakes (Federal Emergency Management Agency FEMA E-74, 2012). Significant efforts have been undertaken to develop simplified design procedures to account for the range of practical NCSs configurations, and the limitations are well-known (Filiatrault and Sullivan, 2014). The scarceness of full-scale building shake table tests that incorporate NCSs limits our understanding of the seismic response of these non-structural components. For example, the landmark NSF-funded Building Non-structural Components and Systems (BNCS) test program (refer to #14 in **Figure 10**, Pantoli et al., 2016a) incorporated a complete suite of NCSs, including operable egress (stairs and elevators), facades (precast concrete and light-weight cold-formed steel), and interior equipment and architectural support contents (ceilings, HVAC, piping, etc.). This project focused on the "total building" and, in particular, the interactions between components (non-structural-to-non-structural and structural-to-non-structural) and offered new insight into understanding the seismic response of a wide range of NCSs, but the tests were carried out under single-axis ground motions. This test program would have immensely benefited from the upcoming capability of the LHPOST6. NCSs are by their nature secondary systems; their response depends upon the response of the supporting primary system, in most cases a building. The varying vibratory response of a building under multi-directional input motion will then naturally affect the input motion to the NCSs. Important to enveloping a building, the wide range of architectural facades have a high degree of variability in their connectivity to the supporting structure, and thus their response to multi-axis input requires understanding (Pantoli et al., 2016b). Limited recent tests, supported by field observations, demonstrate the importance of advancing our understanding and predictive capabilities under multi-directional loading of NCSs in building systems. Full-scale multi-axial shake table tests are needed to advance the development of a reliable, unified design strategy for NCSs accounting for multi-directional earthquake excitation.

## Advanced/Innovative Earthquake Protective Systems

Extensive damage in conventional buildings have caused a push in earthquake affected communities in the past two decades to use low-damage structural earthquake protective systems. Such systems can sustain significant non-linear response, large lateral displacements, and damping with practically no damage and maintained operability after strong earthquake ground motions. This is currently a very active research area that includes base isolation, rocking foundations and systems, self-centering systems, inertial force-limiting floor anchorage systems, dampers, buckling-restrained braces, and new materials (Ozbulut et al., 2011; Belleri et al., 2014; Bahmani et al., 2017; Pei et al., 2019).

Many structures have survived strong earthquakes unscathed, courtesy of rocking of the foundation (Housner, 1963). In competent soils not susceptible to liquefaction, rocking can be used as a mechanism that concentrates the non-linear response and provides energy dissipation in some structures. This aspect has been widely demonstrated in centrifuge, field, and 1-g shake table testing (e.g., Deng and Kutter, 2012; Gelagoti et al., 2012; Pecker et al., 2014). At the LHPOST facility, Antonellis et al. (2015) carried out shake-table testing of two 1:3 scale bridge piers with shallow foundations designed to rock (refer to #17 in **Figure 10**). The test specimens were placed inside the large stiff soil confinement box described in Fox et al. (2015), which was partially filled with poorly graded medium sand and water. Because of the uni-directional limitation of the LHPOST, one of the test units was aligned with the direction of the excitation, whereas the other was rotated 30 degrees. While this promoted multi-directional input to the specimen, the two horizontal translational input motions were fully correlated. The LHPOST6 used in combination with a large soil box will enable more realistic investigation of earthquake protective systems of all types at large or full-scale, including passive, semi-active, and active seismic response modification devices such as dampers, low-cost unbonded fiber-reinforced elastomeric bearings, and buckling-restrained braces, as well as new electroactive and electromagnetic materials and shape memory alloys (Ozbulut et al., 2011).

## Dynamic Soil-Structure Interaction (SSI)

The LHPOST6 is ideally suited for experimental investigations of dynamic SSI. The kinematic interaction of the foundation with the soil (in the absence of the superstructure) under internal seismic wave excitation leads to translational and rotational components of foundation input motion. This occurs for embedded foundations for all types of elastic wave excitation and for surface foundation subjected to non-vertically incident waves and to spatially random ground motions. When a superstructure is present, the inertial interaction results in additional rocking components of motion of the foundation and additional torsional components, particularly, when the structure is not symmetrical. Thus, even when it can be assumed that the foundation is sufficiently rigid, the motion of the foundation will have at least 6-DOFs, including translational and rotational components of motion (e.g., Luco, 1980; Roesset, 1980). The following three general types of experimental SSI studies can be envisioned with the LHPOST6:

### Verification Studies Under Tri-axial Excitation

Computer models of the complete soil, foundation, structure system can be used to obtain the total translational and rotational motion of the foundation, which can then be applied at the base of the structure placed on the LHPOST6. The resulting experimental motion of the structure can be compared with the numerical simulation to validate both the theoretical model and computational method. Independent of the validation justification, the response of structures to simultaneous translational and rotational motions is of interest for research aimed at representing the free-field ground motion as consisting of both translational and rotational components, extending the current practice of including only translational components (in the absence of SSI) (Lee and Trifunac, 1985, 1987).

### Hybrid Tests

In these ambitious tests, the soil will be modeled in the computer, and the foundation input motion (i.e., the response of the foundation to seismic waves) computed numerically; the compliance matrix (i.e., used to compute the response of the "foundation and soil" to external forces from the superstructure) will be computed numerically as well. In the test, the total foundation motion will be applied (through the shake table platen) at the base of the structure placed on the shake table and the force that the structure exerts on the platen will be obtained from the motion of the structure thus closing the loop. These tests could be used to study the non-linear seismic response of structures in the presence of soil-structure interaction, as well as studies of the torsional response of structures.

### Large Soil Box Tests Under Tri-axial Excitation

In these tests, scaled models of structures will be supported on soils placed in one of the large soil boxes available. The soil box will be subjected to tri-axial base motions to better simulate the seismic excitation. These tests could be used to study the non-linear response of soils, the response of partially saturated soils, and the non-linear interaction of foundations, structures, and the soil. The contribution of radiation damping into the soil to the apparent damping in the structure could also be studied in this fashion. The effects of the coupling through the soil on the seismic response of adjacent structures, a topic of importance in the urban environment and in farms of storage tanks and wind turbines, could also be investigated through this approach.

## Geostructures

Soil Foundation Structure Interaction (SFSI) can be beneficial or detrimental to the performance of structures during earthquakes. Design guidelines considering these effects are mostly based on analytical models, computational simulations, small-scale shake-table experiments in centrifuges, large-scale field testing of pile and slab foundations, and field observations from past earthquake events. Large-scale field testing provides pertinent data to calibrate soil properties in analytical and computational models; however, it cannot conclusively validate how SFSI affects structural response during an earthquake because these tests neglect the dynamics of soil response and the inertial interaction with the superstructure. Moreover, they are generally at amplitudes lower than design target earthquake demands. The scale of SFS specimens in centrifuge tests must be necessarily very small. This means that detailing of superstructure elements and materials for these tests necessitates simplicity due to the small scale. Therefore, the results of such tests will have limited accuracy regarding the behavior of the actual structure or foundation. Shake-table tests used in combination with large soil boxes with reasonable size foundation and structural models are needed to complement centrifuge tests to validate corresponding computational models. These types of tests can also be used to study the performance of underground structures (such as energy vaults, pipelines, and deep and shallow tunnels), bridge abutments, earth retaining walls, levees, embankments, large cut and fills, and slope stability in hillside construction. The LHPOST6 can support the testing of underground pipelines subject to liquefaction loads or fault crossing demands by taking advantage of the large displacement capacity of the LHPOST6, enabling researchers to conduct large-scale dynamic testing of underground facilities and pipelines and techniques for evaluating ground movement patterns and stability for a variety of excavation, tunneling, micro-tunneling, and mining conditions (O'Rourke et al., 2008).

## SUMMARY AND CONCLUSIONS

The Natural Hazards Engineering Research Infrastructure (NHERI) UC San Diego Large High-Performance Outdoor Shake

Table (LHPOST) Experimental Facility and its capabilities under its past 1-DOF configuration (LHPOST) and future 6-DOF configuration (LHPOST6) were described. The LHPOST is a national shared-use facility supported by the National Science Foundation and available to researchers to conduct research in earthquake engineering and seismic hazard mitigation. The LHPOST is the largest facility of its kind in the US for conducting earthquake engineering research. It has the largest payload capacity in the world (20MN) and ranks second in size after Japan's E-Defense shake table. The tallest structures ever tested on a shake table have used the LHPOST, which is free from height restrictions.

The vision for the NHERI@UC San Diego Shake Table Experimental Facility is rooted on three critical needs for advancing the science, technology, and practice in earthquake disaster mitigation and prevention: (1) fundamental knowledge for understanding the system-level behavior of buildings (including non-structural components and systems), critical facilities (e.g., energy structures), bridges, and geo-structures during earthquakes, from the initiation of damage to the onset of collapse; (2) Experimental data to support the development, calibration and validation of high-fidelity physics-based computational models of structural/geotechnical/soil-foundation-structural systems that will progressively shift the current reliance on physical testing to model-based simulation for the seismic design and performance assessment of civil infrastructure systems; and (3) Proof of concept, benchmark and validation/verification tests for seismic retrofit methods, protective systems, and the use of new materials, manufacturing methods, components, systems, and construction methods that can protect civil infrastructure systems against earthquakes.

The LHPOST was conceptually designed as a 6-DOF shake table. However, it was constructed as a 1-DOF system in the period 2002–2004 to accommodate funding available at the time. Since its commissioning on October 1, 2004, 34 landmark research and commercial projects have been conducted on the LHPOST, contributing to advancing our understanding of the seismic response behavior of civil infrastructure systems, improving design codes and standards, validating high-fidelity 3D computational models, and developing accurate decision-making tools necessary to build and maintain sustainable and disaster-resilient communities. Some of these research projects were briefly described in this paper. All test results and research data are shared through the NHERI Data Depot repository at NHERI DesignSafe (https://www.designsafe-ci.org/data/browser/public/).

The LHPOST6 is currently being built and is scheduled to reopen for operations in fall 2021. Once upgraded, the LHPOST will be able to reproduce all six components of ground motion experienced during earthquakes, which will enable the investigation of many important aspects of the seismic response of structural, geostructural and soil-foundation-structural systems that could not be researched experimentally with the past limitation of the LHPOST to uni-directional input motion. The LHPOST6 will allow researchers to investigate the combined effect of realistic near-field translational and rotational earthquake ground motions applied as dynamic excitation to full 3D and at large- or full-scale structural, geotechnical, or soil-foundation-structural systems, including the effects of SSI (both kinematic and inertial), non-linear soil and structural responses, and soil liquefaction. A select set of important research areas that will be made possible by the LHPOST6 were discussed in this paper.

More information about the NHERI@UC San Diego Experimental Facility can be found at the facility's website at https://ucsd.designsafe-ci.org/. This information includes the facility overview, equipment portfolio, experimental protocol, payload projects, workshops, resources, and contact information.

## DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://www.designsafe-ci.org/data/browser/public/.

## AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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frontiers in Built Environment

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# StEER: A Community-Centered Approach to Assessing the Performance of the Built Environment after Natural Hazard Events

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Since its founding in 2018, the Structural Extreme Events Reconnaissance (StEER) Network has worked to deepen the capacity of the Natural Hazards Engineering (NHE) community for coordinated and standardized assessments of the performance of the built environment following natural hazard events. This paper positions StEER within the field of engineering reconnaissance and the Natural Hazards Engineering Research Infrastructure (NHERI), outlining its organizational model for coordinated community-led responses to wind, seismic, and coastal hazard events. The paper's examination of StEER's event response workflow, engaging a range of hardware and delivering a suite of products, demonstrates StEER's contributions in the areas of: workflow and data standardization, data reliability to enable field-observation-driven research & development, efficiency in data collection and dissemination to speed knowledge sharing, near-real- time open data access for enhanced coordination and transparency, and flexibility in collaboration modes to reduce the "overhead" associated with reconnaissance and foster broad NHE community engagement in event responses as part of field and virtual assessment structural teams (FAST/VAST). StEER's creation of efficient systems to deliver well-documented, reliable data suitable for diverse re-uses as well as rapidly disseminated synopses of the impact of natural hazard events on the built environment provide a distinctive complement to existing post-event reconnaissance initiatives. The implementation of these policies, protocols and workflows is then demonstrated with case studies from five events illustrating StEER's different field response strategies: the Nashville, Tennessee Tornadoes (2020) – a Hazard Gradient Survey; the Palu Earthquake and Tsunami in Indonesia (2018) – a Representative Performance Study; the Puerto Rico Earthquakes (2019/2020) – using Targeted Case Studies; Hurricane Laura (2020) – leveraging Rapid Surveys to enable virtual assessments; and Hurricane Dorian (2019) in the Bahamas – a Phased Multi-Hazard Investigation. The use of these strategies has enabled StEER to respond to 36 natural hazard events, involving over 150 different individuals to produce 45 published reports/briefings, over 5000 publicly available app-based structural assessments, and over 1600 km (1000 mi) of street-level panoramic imagery in its first 2years of operation.

**Keywords: StEER, reconnaissance, damage assessment, structures, hurricanes, earthquakes, tornadoes, tsunamis**

## INTRODUCTION

As the most faithful living laboratory for the study of the built environment's performance, field observations play a critical role in fueling what the authors define as the Data to Knowledge (D2K) Life Cycle following natural hazard events. Depicted in **Figure 1A**, this feedback loop has historically responded to a hazard-affected community by (1) gathering field observations that (2) inform hypothesis-driven research, (3) operationalized through various regulatory mechanisms to generate top-down mitigation measures taking the form of policies, codes and standards to increase the requirements or restrictions on construction in response to identified vulnerabilities. Existing knowledge transfer pipelines then (4) propagate this new construction guidance back to affected communities. Thus, as the initiator of the this D2K feedback loop, field observations remain one of the most valuable means to understand the connection between geospatial hazard data, site-specific load effects and ensuing response of structures, as well as the more complex questions of how this performance in turn affects households and communities (Edge et al., 2020).

However, this D2K Life Cycle in **Figure 1A** can take years to drive change in affected communities, opening opportunities to create new pathways that accelerate the translation of knowledge generated through field observations to various stakeholders in the D2K Life Cycle, particularly affected communities (**Figure 1B**). While different constituencies that respond following natural hazard events are themselves exploring ways to generate these new pathways, the authors posit that the Natural Hazards Engineering (NHE) community has a particularly unique opportunity, and arguably responsibility, given it occupies critical roles at multiple points in this cycle. In addition to collecting field observations (**Figure 1**, step 2), the NHE community has made considerable advances in experimental, computational and hybrid simulations informed by these field observations (**Figure 1**, step 3), as well as providing expert testimony to policy decisions and driving the consensus processes that revise codes and standards (**Figure 1**, step 4). Moreover, the NHE community is seeking to dramatically transform its capacities for these varied roles through more granular risk assessment, performance-based design and holistic evaluations of community resilience, all of which depend upon or at minimum are best informed by reliable and timely collection of field observations.

In response to these needs and desiring a more coordinated response to hazard events by the NHE community, the US National Science Foundation (NSF) issued EAGER funding for the formation of the Structural Extreme Events Reconnaissance (StEER) Network in 2018. NSF's impetus for the creation of StEER centered on better coordinating and standardizing post-event reconnaissance of the built environment, noting that responding teams had historically worked independently with little coordination, collecting data that was often not shared with the NHE community in any reusable way. In response, StEER offered a venue where members of the NHE community could dynamically form teams in response to a natural hazard event and collectively execute standard data collection protocols to generate high-quality communal data shared openly to inform diverse lines of continued research. StEER also established new pathways to more rapidly synthesize and disseminate collective knowledge from these efforts through short-form briefings and long-form reports shared with diverse audiences. More importantly, as a hazard-agnostic organization, StEER was uniquely positioned to cross-cut and unify the hazard communities under this shared vision.

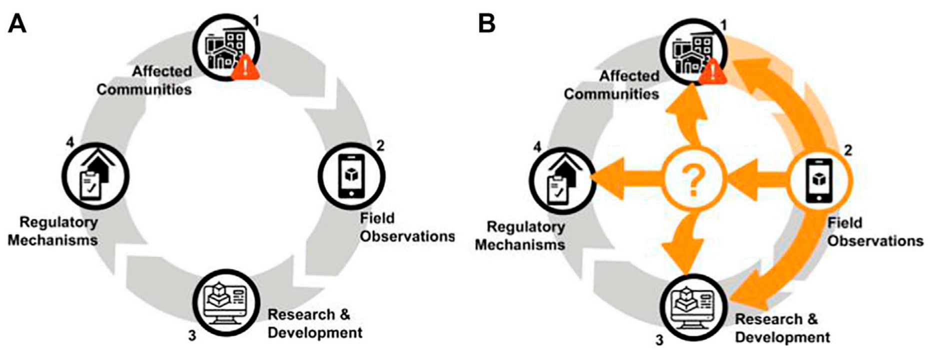


**FIGURE 1 |** Data to Knowledge Life Cycle: **(A)** traditional 4-step cycle in grey and **(B)** opportunities for Field Observation organizations working in first quarter of the life cycle to accelerate feedback process through new conduits in orange.

Over the past 2 years, the authors, as StEER's initial Leadership Team, have worked to usher in this paradigm shift through an emphasis on (i) capacity building - promoting data standards, best practices, and training for field reconnaissance, (ii) coordination – facilitating early, efficient and impactful event responses, and (iii) collaboration - broadly engaging communities of research, practice and policy to accelerate learning from natural hazard events. This was made possible by building upon the long history of post-event reconnaissance by past and contemporary organizations, while capitalizing on new technologies and advances in collaborative research infrastructure. This has in turn enabled StEER to make a number of contributions in the areas of: workflow and data standardization, data reliability to enable field-observation-driven research & development, efficiency in data collection and dissemination to speed knowledge sharing, near-real-time open data access for enhanced coordination and transparency, and flexibility in collaboration modes to reduce the "overhead" associated with reconnaissance and foster broad NHE community engagement in event responses.

These contributions are demonstrated in this paper, which first positions StEER and its organizational model within the wider landscape of forensic engineering and post-event reconnaissance. The paper then steps through StEER's event response workflow, including engaged hardware platforms, field response strategies, data enrichment and quality control processes, and resulting products: detailed reports and well-documented data suitable for diverse re-uses. The paper closes with illustrative examples of five different field response strategies, highlighting some of the notable observations and lessons learned in piloting this new initiative over the past 2 years. Before doing so, it is important to note that StEER is in its infancy. The confines of a manuscript are insufficient to capture all the details of these dynamic (and continuously evolving) organization and its decision processes, policies, protocols and workflows. Thus, throughout the discussions that follow, the authors will refer interested readers to various handbooks, guidelines and other resources whose latest versions are housed on the StEER website[1].

## ORIGINS AND OPPORTUNITIES

The understanding of failures is central to advancing the state-of-the-art in NHE, as evidenced from the impact of Forensic Engineering to promote learning from the rare cases of building collapse and progressive collapse under service conditions (Delatte, 2008). In natural hazard events, the challenge then lies in scaling up the essential principles of Forensic Engineering to widely canvass the failure of hundreds or thousands of structures and then effectively parsing and sharing that valuable information (NRC, 2007). Building on the long-standing tradition of learning from disasters (Wartman et al., 2020), the NHE community has worked for more than half a century to achieve the effective scale up of these principles. The 1971 San Fernando earthquake is the first documented post-earthquake reconnaissance mission in the archives of the Earthquake Engineering Research Institute (EERI) Learning From Earthquakes (LFE) program (EERI, 1971), subsequently followed by a number of other notable US events (EERI, 1989; Hall et al., 1994). In that same period, the US Army Corps of Engineers (USACE), National Institute of Standards and Technology (NIST) and the Federal Emergency Management Agency (FEMA) spearheaded investigations of major hurricanes and later tornadoes (USACE, 1965; Sparks, 1990; FEMA, 1992; FEMA, 1993; FEMA, 1999; FEMA, 2005a,b; FEMA, 2006; FEMA, 2012). Internationally, major tsunamis were similarly documented by teams during this same timeframe (Shimamoto et al., 1995; CAEE, 2005). Building on these early efforts, the number of post-disaster investigations, particularly led by academics, has steadily risen (Butcher et al., 1988; O'Rourke et al., 1990; Dickenson and Werner, 1996; Miller, 1998; Sezen et al., 2000; Prevatt et al., 2011; Chen et al., 2016; Gurley and Masters 2011; Kuligowski et al., 2014; Kijewski-Correa et al., 2018; Synolakis and Kong, 2006; Kennedy et al., 2011; Yeh et al., 2013; Tomiczek, et al., 2014; Tomiczek, et al., 2017), due to both growth in the field of disaster science/engineering and the increasing frequency of damaging events. Unfortunately, while some clearinghouses and event-specific databases were established during this time, coordination and practices around data sharing were inconsistent, with many valuable datasets maintained as proprietary, for a variety of reasons, or shared selectively with colleagues and collaborators.

The Geotechnical Extreme Events Reconnaissance (GEER) Association shifted this paradigm toward community-wide coordinated reconnaissance with a governance model that placed shared data and knowledge ahead of individual research gains (GEER, 2014). While GEER set the standard for such collaboratives within the NHE community, much has changed since GEER's founding. Emerging technologies for rapid assessment of damage, mobile platforms for collecting and sharing data, and increasingly agile modes of virtual collaboration and data fusion have dramatically transformed the NHE community's potential modes of fieldwork. Advances in ubiquitous technologies such as mobile devices with high-resolution cameras and web-based platforms that enable the open exchange of content generated by diverse actors have radically transformed the modalities for post-event data gathering, processing and dissemination. With the global population's increased access to smartphones and social media, the barriers to generating and sharing web content have dissolved, effectively "instrumenting" the entire planet. The seamlessness, expansiveness and efficiency of these information flows have created the potential to broaden the community that reconnaissance engages and serves. In an attempt to mainstream these new digital workflows and flexible online collaboration models, the authors' piloted a NHE community response to the 2017 hurricane season, which initiated with a GEER-sponsored response to Hurricane Harvey (Kijewski-Correa et al., 2018; Pinelli et al., 2018; Prevatt et al., 2018; Cox et al., 2019). This helped to

[1]https://www.steer.network/resources

inform their subsequent launch of the StEER network in 2018, which formalized these digital modalities of perishable data collection and knowledge generation within the NHE community, including the potential for strategic sampling to swiftly generate large volumes of geotagged damage assessments for statistical analysis of underlying damage patterns (Roueche et al., 2018). More importantly, the arrival of the Natural Hazards Engineering Research Infrastructure (NHERI) signaled a departure from the historical silos separating hazards and disciplines by offering communal research infrastructure. Event responses could now be backed by investments in shared hardware for field data collection (Berman et al., 2020), cyberinfrastructure for streamlined data curation (Rathje et al., 2017; Pinelli et al., 2020), and opportunities for data re-use to inform backend computational simulations (Deierlein et al., 2020). With the arrival of NHERI Converge and its network of extreme events reconnaissance and research (EER) organizations (Peek et al., 2020), StEER and GEER both have new potentials for interdisciplinary investigations and longitudinal studies. Today, technology and shared infrastructure have closed the gap between citizens tweeting self-documented damage in their community, the StEER members conducting follow-up forensic assessments with their personal smartphones with RAPID EF drones overhead, and the mission agencies reviewing those assessments on NHERI DesignSafe real-time communication platforms (i.e., Slack). These experiences have affirmed that a broad community, well beyond academics, has the potential to contribute to and benefit from the information generated by Converge's EERs.

Unfortunately, those benefits have not always reached affected communities (Kendra and Gregory, 2019), requiring an intentional effort to more efficiently channel the NHE community's expert assessments and learnings back to affected communities and the diverse stakeholders supporting their recovery. Federally-mandated responses such as the FEMA Mitigation Assessment Teams (MATs) and NIST Disasters and Failure Studies efforts excel at conducting expert assessments that capture lessons learned from a disaster that are then shared with affected communities, policy makers, and other stakeholders to improve regulatory systems (USGS, 2000; Milano, 2015). However, the data collected in these efforts is typically not widely available to the NHE community in any standardized way, details of the data sampling methods are typically lacking, and the reports culminating from these efforts typically take months or even years to produce, although this limitation is sometimes offset with publication of intermediate advisories (e.g., FEMA, 2005c). Thus, there is an opportunity within the NHE community to more swiftly respond to events in a way that balances both the need to return practical knowledge to the affected communities and the need to generate high quality data suitable for academic research. The remainder of this paper will focus on the policies, protocols and workflows that have enabled StEER to distinctively address this two-pronged need and in a manner that is complementary to existing post-disaster reconnaissance efforts.

## ORGANIZATIONAL MODEL

Funded under an NSF EAGER Award, StEER has operated to date under the leadership of the authors. The first author serves as the Director overseeing StEER's core operations and governance, liaising with other NSF-funded EERs in event responses under the NHERI Converge Leadership Corps as well as other partnering professional societies, agencies, firms and technical organizations. The last three authors serve as the respective Associate Directors for Seismic, Wind and Coastal Hazards, liaising with individuals and organizations affiliated with those hazard communities in support of event responses and guiding the technical requirements of assessment workflows tailored for these hazards. As the Associate Director for Data Standards, the second author works across these hazard communities as the architect of StEER's data workflows and its Data Enrichment and Quality Control (DEQC) process discussed in *Data Enrichment and Quality Control*. While StEER's governance is presently expanding through a formal StEERing Committee, Working Groups and other advisory bodies, these directors currently make the decisions to activate the network in response to an event.

StEER membership is open to those in the natural hazard engineering and allied fields, with enrollment simply requiring submission of an application available through the StEER website[2] and acceptance of the terms of participation in StEER's Member Guidelines (Kijewski-Correa et al., 2019a). The leadership team coordinates and supports the efforts of hundreds of StEER members worldwide, largely natural hazard engineers from academia, the private sector and government agencies, in response to a hazard event of interest. The ability to draw upon these members to swiftly form teams in response to an event, noting that these individuals may have no prior experience working together, relies in part on the robust NHERI research infrastructure that has been put in place (for example, providing access to a common Slack workspace for rapid coordination and dissemination by diverse teams centered around a common event of interest), but also in the rational way StEER evaluates members' prior experience, assigns members to levels (described below), and builds their capacity to elevate to higher membership levels through resources managed in a Shared Google Drive accessible to all members.

Building on concepts piloted in the earthquake and post-windstorm reconnaissance communities (Womble et al., 2008; Barrington et al., 2012), StEER sought to broaden participation of its members by valuing virtual reconnaissance equal to the traditional forms of field-based reconnaissance. This included recognizing the role of virtual reconnaissance as an important education and communications tool for civil engineering students, as first demonstrated through the Wind Hazard Damage Assessment Group[3] established by the fourth author in 2012. This established a model for online self-publication of forensic reports within days of wind hazard events by students

[2]https://www.steer.network/membership
[3]http://windhazard.davidoprevatt.com/

**TABLE 1 |** Membership levels and corresponding participation levels.

| | VAST | FAST |
|---|---|---|
| Level 1: No prior field reconnaissance experience nor substantive experience in virtual reconnaissance | Member | N/A |
| Level 2: No prior field reconnaissance experience but substantive experience in virtual reconnaissance | Lead | Trainee |
| Level 3: Some experience in field reconnaissance | Lead | Member |
| Level 4: Substantive experience in field reconnaissance | Lead | Lead |

using available online information sources. In 2015, Virtual Earthquake Reconnaissance Teams (VERTs)[4] were formed for seismic hazards (Fischer and Hakhamaneshi, 2019), adopting a similar model serving younger EERI members preparing a slide deck briefing for the LFE Executive Committee.

Seeking to formalize this further, StEER defined two modalities for member participation: Virtual Assessment Structural Teams (VASTs) who work remotely to compile relevant data and analyze observations from the field and Field Assessment Structural Teams (FASTs) who collect data under the traditional conception of field reconnaissance. Member eligibility to participate within these VASTs and FASTs is a function of their past experience and levels of training in post-event reconnaissance, with each member assigned to one of four levels, as outlined in **Table 1**. Those new to the field of post-event reconnaissance enter StEER as Level 1 members, working on VASTs to build up experience necessary to advance to StEER Level 2 where they can serve as FAST trainees, mentoring under more experienced Level 3 or 4 members in the field, with the latter being seasoned reconnaissance experts capable of leading FASTs on StEER field responses. Less experienced members such as undergraduate and graduate students can accelerate their progression through the StEER qualification tiers by serving as Data Librarians, charged with executing StEER's rigorous DEQC process, and in doing so, gain valuable experience in the principles of Forensic Engineering and StEER's data standards. The roles of StEER's leadership and the engagement of its VASTs, FASTs and Data Librarians in StEER's event response workflows is discussed in the following section.

## EVENT RESPONSE

The StEER Leadership monitors for natural hazard events that would warrant a formal response, also responding to requests for activation of the network directed by its members, partners or other EERs via Converge. Given finite resources, StEER must make judicious decisions regarding when to activate the network and the associated level of response. Admittedly, this can be highly speculative and must consider StEER's focus on evaluating the effectiveness of design practices and mitigation measures focused on the structural load path, which emphasizes hazards inducing dynamic load effects at the expense of other hazards like inland flooding or wildfires. It is thus important to position StEER's investigations within the wider landscape of organizations responding to natural hazard events with complementary intentions to document other hazards and contributors to community resilience such as losses associated with non-structural damage, service disruption, and other human, environmental and societal impacts. While each organization has a specific mandate, these collective inquiries are now capable of creating a more complete picture of the impact of natural hazard events on our communities (Peek et al., 2020).

Given StEER's desire to deploy quickly to capture perishable data before it is greatly disturbed by recovery activities, event response decisions must be made based on the information available immediately after the event. It is then expected that the research community can use this early-access data to inform subsequent field investigations with specific hypotheses and more focused data collection, leveraging the NSF RAPID funding mechanism or other sources. The evaluation of this evolving information considers both the intensity of the hazard, as well as the potential the event offers to generate new knowledge on the performance of the built environment. While high-intensity events such as major hurricanes (Category 3 or higher) consistently warrant consideration, even moderate-intensity events have warranted responses, particularly if they offer the ability to evaluate recent changes in construction practices, to document performance of typologies that are comparatively under-investigated, or resulted in unique compound or cumulative hazard exposure. International events, which have considerable logistical challenges and expense, also deserve careful consideration when the hazard characteristics or built environment vulnerabilities have important corollaries to US hazard exposure or construction practices. Given that StEER is still building out its organization, it has thus prioritized domestic responses to deepen its capacity and test its protocols. While engaging in only a select number of international responses to date, StEER anticipates building greater international partnerships to do so more effectively in the future. The complete catalog of StEER Event Responses is available online[5].

With this context in mind, StEER has adopted a three-tier response activation protocol:

- **Tier 1:** hazard events that have little potential to generate new knowledge on the performance of the structural load path, yet still warrant commentary from StEER to emphasize key takeaways for policy and practice. These takeaways are communicated through an Event Briefing

[4]http://www.learningfromearthquakes.org/activities/vert

[5]https://www.steer.network/responses

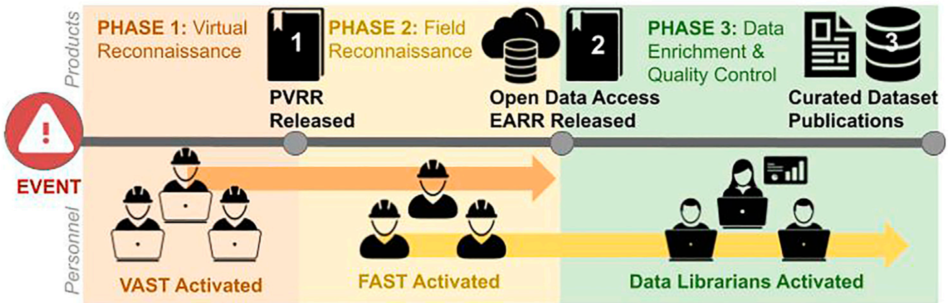


**FIGURE 2 |** Evolution of products and personnel across the three phases of a typical StEER field response.

authored by StEER Leadership with the possible participation of a small pool of interested StEER members.

- **Tier 2:** hazard events with the potential to generate new knowledge on the performance of the structural load path. In such cases StEER will activate its VAST to begin assembling publicly available information, compiled in a detailed Preliminary Virtual Reconnaissance Report (PVRR) that will inform whether to further escalate the response to Tier 3.
- **Tier 3:** hazard events with confirmed potential to generate new knowledge on the performance of the structural load path. In such cases StEER will activate its FAST to collect field observations, culminating in an Early Access Reconnaissance Report (EARR) followed by a curated dataset.

It is important to emphasize that this tiered-response model relies heavily upon virtual reconnaissance, reiterating the VAST's value to knowledge generation and the potential for broad NHE community engagement through this more flexible mode of participation.

The following sections offer further details on elements supporting this tiered-response model. With particular emphasis on Tier 3, *Field Response Workflow* explains the process of initiating a field response, with *Hardware Platforms* introducing the equipment that may be engaged in the different *Field Response Strategies*. *Data Enrichment and Quality Control* then describes the process applied to data collected in the field, with *Event Response Products* introducing the outputs of this tiered-response model.

## Field Response Workflow

**Figure 2** provides a visual representation of the personnel activated and participating at each phase of a Tier 3 response, as well as the products generated in each phase. Tier 3 responses still initiate with a phase of Virtual Reconnaissance, with a geographically distributed VAST working to compile information from social media, news outlets, local authorities and mission agencies to inform the PVRR, which (like all of StEER's narrative products) is collaboratively written in real-time using Google Documents stored on the Google Drive shared with all StEER members. Participation in this VAST (and the eventual FAST) is solicited shortly after the event through a mass email to StEER members and announcements posted on multiple NHERI DesignSafe Slack channels and StEER's website. StEER does not limit the size of the VAST, and participants customarily devote several distributed hours to the effort, as their time allows. **Table 2** summarizes the roles of the StEER leadership in this first phase of the workflow, which includes the engagement of NHERI Converge to begin coordinating across other EERs also responding to the event.

As the first product of the workflow in **Figure 2**, the PVRR informs the design of the next phase of Field Reconnaissance. The field response may deploy multiple parallel or sequential FASTs, based on levels of access and the adopted field response strategy. The size of the FASTs is capped given the resource constraints on available rental cars/hotel rooms in the impacted area and available budget. As the number of interested StEER members often exceeds available slots, those not selected for the FAST often continue to participate on the VAST. Though rare, if there is not sufficient FAST interest, StEER will demote the response back down to Tier 2.

FAST members commit to deploy for a few days to a week (depending on the scope of the response and travel time), in addition to time spent before and after the deployment in preparations and data curation tasks. While VAST effort is not financially compensated, FASTs have all travel and equipment rental expenses reimbursed by NSF funds, receiving a per diem to offset the costs of participation for each day in the field. Drawing from the individuals responding to the aforementioned call for participation, the FAST's composition is dictated by the required hazard/typology/methodological expertise, member availability, and balance of experience to include at least one Level 2 trainee and a Level 4 FAST lead. In many cases, the proximity of members to the affected area heavily influences team composition, as it can speed the collection of valuable forensic evidence before cleanup, debris removal, repairs or roof tarping initiates. Leveraging this proximity, StEER has been able to begin collecting data as early as hours after an event.

As outlined in **Table 2**, StEER leadership takes a particularly active role in designing the field response, adopting one of StEER's five field response strategies, discussed later in *Field Response Strategies*. The selected strategy depends on a variety of factors related to the hazard characteristics, the built environment characteristics, FAST expertise, available

**TABLE 2 |** Organizational structure and roles in event response phases.

| Supporting Parties | PHASE 1: Virtual | PHASE 2: Field | PHASE 3: DEQC |
|---|---|---|---|
| Director | Team formation, collaboration tools | Team formation, coordination | Data Curation workflow |
| Assoc. Director for Data Standards | Exchange data sources | Target selection, Field response strategy | Leads DEQC Process |
| Assoc. Directors for Seismic, Wind, Coastal Hazards | Engage community, information sharing | Engage community, monitor response | Engage community, interpret data |
| StEER Member Participation | Virtual Assessment Structural Team | Field Assessment Structural Team | Data Librarians |
| Supporting NHERI Element | Converge | RAPID Facility | DesignSafe-CI |

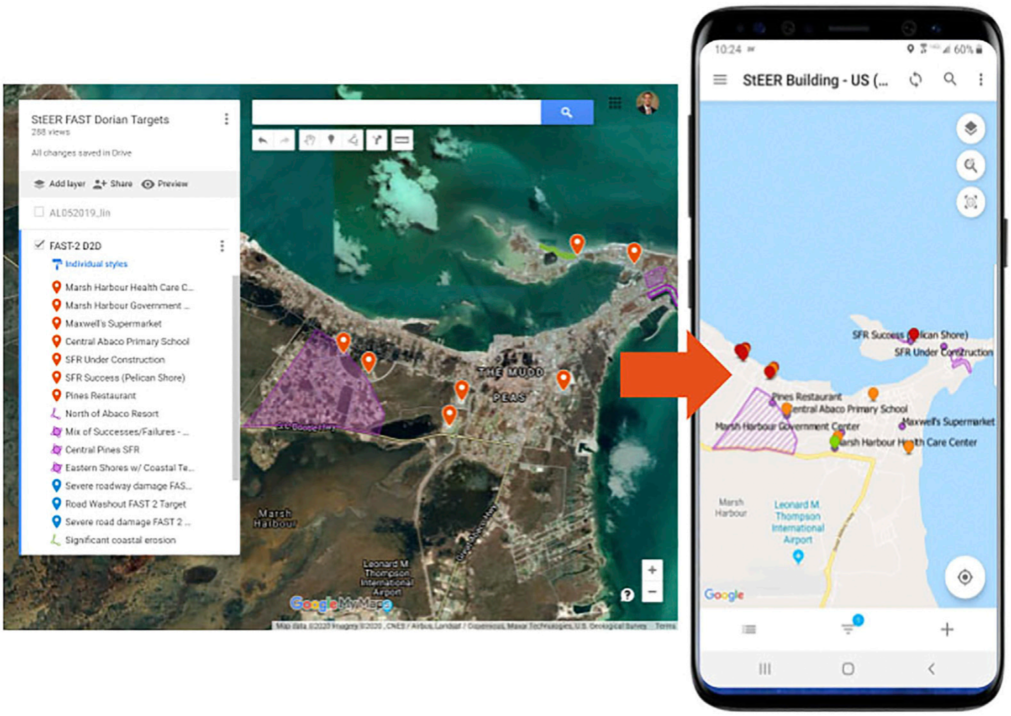


**FIGURE 3 |** Example of Google Map with target selection for FASTs responding to Hurricane Dorian in the Bahamas, imported as a cached layer into the Fulcrum mobile app, which also visualizes via the color-coded pins the location and global damage rating of assessments conducted by the FAST.

equipment and site conditions. The StEER leadership will then work with the FAST to define broad objectives for the field response, generally not focusing on a specific class of construction like traditional hypothesis-driven research that may, for example, study solely unreinforced masonry buildings or metal building systems. Instead, StEER's objectives center on canvassing performance more broadly to generate data that can be valuable to a wide range of the NHE community. The adopted strategy and its objectives are captured in a Pre-Deployment Briefing. This internal document guiding the FAST includes: team structure, objectives, itinerary (coverage, dates), equipment, logistics, maps, access/conditions, preparation instructions, standard StEER resources, third party resources, and local points of contact. As discussed later in *Event Response Products*, these Pre-Deployment Briefings are curated with each StEER dataset (see Roueche et al. (2020a)) Directory D0 for an example).

A key element of the Pre-Deployment Briefing is the identified targets for the FAST. Target selection initiates by cataloging any field observations of the hazards in a Google Map (see example from Hurricane Laura in **Supplementary Figure S1**), as well as reviewing simulations of the spatial distribution of hazard intensity, post-event satellite imagery, inventory data and notable structures/regions identified in the PVRR. While the need to mobilize quickly before forensic evidence is significantly disturbed does not permit a robust solicitation of community input as part of target selection and mission design, notable case study structures or geographic areas of interest are exchanged by the research community and practitioners on the DesignSafe Slack channels. All these sources of information are used to define FAST targets that operate within the adopted field response strategy, responsive to community-sourced targets of opportunity, and canvas the various building and infrastructure classes of interest. Targets can take the following forms: driving routes (e.g., roads that move across the hazard gradient), clusters of buildings (e.g., a specific subdivision with desired characteristics such as age or style of construction), or specific structures (e.g., a notable collapse documented in PVRR). These targets are also compiled in a Google Map as demonstrated by the case of Hurricane Dorian in **Figure 3** (see additional example from Hurricane Laura in **Supplementary Figure S2**). This phase also works closely with the NHERI RAPID Facility (Berman et al., 2020) to obtain necessary hardware (discussed in *Hardware Platforms*), depending on the adopted field response strategy (discussed in *Field Response Strategies*).

Using the best practices in StEER's FAST Handbook (Kijewski-Correa et al., 2019b), data collection over days or weeks is supported by regular communications with the Field Response Coordinator (typically the first author) and the Associate Director for Data Standards (the second author) to troubleshoot, resolve issues, secure site access, and share new intel. These two individuals communicate the FAST's findings with the wider community and VAST members working on related reports using DesignSafe Slack channels. FASTs aid in these communications by sharing Daily Summaries that culminate in the second product of the workflow: the EARR. These Daily Summaries are curated with each StEER dataset (see Roueche et al. (2020a) Directory D8 for an example). It is important to note that even while the FAST is collecting data in the field, the VAST continues to work remotely to share information from other efforts on DesignSafe Slack to aid in the interpretation of the FAST's field observations. More importantly, the VAST is able to access the FAST's app-based structural assessments in near-real time (connectivity permitting) to support the analysis and synthesis of field observations for the EARR. These open data platforms are also available to the wider NHE community and public-at-large, as discussed further in *Dissemination Pathways*, reiterating the importance of creating flexible modalities for the wider community to access the data throughout the workflow.

This third and final phase in **Figure 2** is focused on Data Enrichment and Quality Control. The scope of the DEQC process depends on the type of data collection methodology (hardware platform) adopted and field response strategy. The DEQC process is intended to ensure the curated dataset is complete and standardized so it can be re-used by others. This DEQC process is discussed in *Data Enrichment and Quality Control*. As noted in **Table 2**, the StEER Leadership continues to support this phase, supervising the DEQC process and leading the wider data curation workflow that organizes and documents the collected data through a comprehensive Data Report. While DesignSafe supports all phases of StEER event responses, it is particularly critical in this third phase, as its Field Research Data model ensures StEER's curated data is discoverable (specifics of the dataset organization and the accompanying Data Report are discussed in *Event Response Products*). In parallel, the FAST often continues to engage in the interpretation of the field observations in the preparation of publications and presentations to communities of research, policy and practice, as well as in soliciting funding for ongoing research on observed vulnerabilities.

## Hardware Platforms

The field response design includes the selection of an appropriate suite of hardware platforms, weighing the field response strategy and objectives, availability of equipment, time available for field assessment, FAST capacity and expertise, levels of access and site conditions. The standard hardware platforms used by StEER for structural performance assessment are now introduced. Note that StEER may also couple these with other discipline-specific methodologies such as hazard intensity mapping, e.g., coastal surveys and tree fall mapping, or non-destructive evaluation and material testing, as demonstrated later in *Illustrative Field Responses*.

### Panoramic Imaging

Small teams of 1-2 persons utilizing street-level panoramic cameras can rapidly capture near continuous surface imagery of building exteriors and other aspects of the built environment. These imaging platforms have also been deployed in handheld (360-camera), drone-based, backpack-mounted and even boat-mounted implementations to generate panoramas in vehicle-inaccessible areas. StEER commonly uses a vehicle-mounted NCTech Pulsar system (available through the NHERI RAPID facility), which consists of four cameras canvassing a 360 × 145-degree field of view. Each camera has a resolution of 12.3 MP, sensor size of 3042 × 4062, and fisheye lenses with fixed focus and aperture size of f/2.6. The system includes GNSS-tracking via a U-BLOX Neo M8N receiver to geotag each image location with approximately 2.5 m accuracy. StEER typically captures frames every 4 m along the routes driven, enabling near-continuous coverage of the built environment along the route. Images collected from the multiple cameras of these systems are post-processed to create seamless 360-degree panoramas that can be uploaded into the Google Street View platform or Mapillary, as discussed in *Dissemination Pathways*. As the subsequent Hurricane Laura case study demonstrates (see *Rapid Surveys*), this efficient data capture method can reduce the size of the FAST by enabling a larger VAST to remotely view the panoramas to assess performance, although details of the structural load path and finer damage details are not likely to be discernible from this imagery. Other potential re-uses of StEER's panoramic imaging data include automated image processing to extract damage features, documenting the performance of distributed power systems (e.g., counting the number of leaning or broken poles), or estimating the volume and distribution of curbside debris indicative of interior damage.

### Unmanned Aerial Systems

Unmanned Aerial Systems (UAS) offer a complementary large-scale data collection platform that has been used in a range of implementations in StEER field responses. While LiDAR and multispectral units are available, StEER currently focuses on the acquisition of high resolution imagery in one of two use cases: (1)

the capture of high-resolution nadir or oblique (off-nadir) photographs in a predefined grid, with front and side overlap, from which orthomosaics, digital surface models (DSMs), and densified point clouds are generated using Structure-from-motion (SfM) photogrammetry methods (Westoby et al., 2012; Zhou et al., 2016); (2) the acquisition of high resolution, free-flight photographs from various perspectives and elevations to provide a bird's-eye view of the structure or site in plan. StEER uses a range of UAS hardware supplied by its members or the RAPID Facility, though the DJI Mavic 2 (20.0 MP RGB camera with 1" CMOS sensor, f/2.8-f/11 aperture size) and DJI Inspire with ZenMuse 5 camera (16.0 MP RGB camera with 4/3" CMOS sensor, f/1.7-f/16 aperture size) have been most commonly deployed to date.

## App-Based Structural Assessments

StEER has created a suite of mobile applications, each with a standard format and embedded guidance to aid FAST members in executing comprehensive evaluations of structural performance. The standardization in a digital app creates consistency across FASTs and field responses, helps to reduce potential for data loss/user error, and enables future re-users of the data to use automated processing to discover underlying trends and patterns. The apps have four primary components for data input: (1) a series of standardized data fields, (2) photograph upload fields that prompt the field investigator to attach high-resolution photographs, (3) an audio recording field that gives the field investigator the ability to dictate observations into an audio file, and (4) freeform text fields for additional written observations. The standardized data fields record basic details of the investigation, structural attributes organized by subsystem/component, and a direct quantification of component performance, reporting the percent damage to different component classes, which can be easily related to established damage rating systems, e.g., FEMA (2003) for windstorms, Baggio et al. (2007) for earthquakes. Since the specific fields and rating systems vary by hazard, StEER currently employs multiple apps. For windstorms it has separate apps for building and non-building structures, constructed using elements from ATC-45 (ATC, 2005a,b), the U.S. Army Corps of Engineers (Woolpert, 2006), Friedland (2012), FEMA MAT standard operating procedures (FEMA, 2008), as well as the second and fourth author's own experiences conducting post-windstorm assessments. A third windstorm app is used to record evidence of hazard intensity such as treefall patterns or high water marks. For seismic events, StEER currently utilizes an Earthquake Rapid Evaluation form inspired by ATC-20 (Rojahn, 2005). While these four apps are regularly used by StEER FASTs, StEER has actually created nearly a dozen apps for different hazards, structural classes and assessment objectives (in-depth forensic vs. rapid evaluation) over the years. The Supplementary Materials (**Supplementary Table S1**) provides a list of the apps developed to date. For the four apps discussed herein, additional tables in the Supplementary Materials list the data fields (**Supplementary Material SM.2-SM.5**).

To reduce the complexity of the app for the user and reduce user error, the apps are programmed with field-dependent logic patterns to accordingly sequence follow up fields, e.g., once a user specifies a building typology, the app logic is structured to sequence only the component assessments relevant to that typology. To further reduce the burden on FASTs with limited time on the ground, the apps prioritize the fields that should be completed by trained experts leveraging on-site forensic data (e.g., details of the structural load path) vs. other information (e.g., year of construction, basic building geometry) more efficiently gathered afterward leveraging supplemental data sources and/or automated processes (these fields are denoted in **Supplementary Material SM.2-SM.5**). Utilizing this approach increases the efficiency of field data collection by allowing the FAST to focus its efforts on truly perishable data. Each app is also accompanied by a guidance document to instruct users in configuring their mobile devices, completing a field assessment, and interpreting specific fields (Roueche et al., 2019a; Roueche et al., 2020b). For example, this guidance instructs FASTs to photograph each side of a building, with additional photos capturing any important details.

All StEER apps are currently implemented in the Fulcrum data collection platform (Spatial Networks, 2018)[6], a mobile data collection service that unifies the various fields, media and metadata associated with an assessment into a single geolocated record compiled into an event-response-specific database easily exportable to common formats like CSV, ESRI Shapefile, and GeoJSON for curation in DesignSafe. StEER is specifically part of an open-data initiative called Fulcrum Community[7] that provides disaster response and recovery organizations open platform access at no-cost. Within Fulcrum, users can enhance the platform's standard geospatial visualizations by uploading custom base layers: StEER specifically uses this feature to preload high-resolution aerial imagery (from mission agencies such as NOAA for domestic events or purchased from vendors for international events) or overlays of the targets selected in the field response design (exported out of Google Maps). **Figure 3** provides a demonstration of the latter. Users can access Fulcrum's geospatial visualizations in one of two ways: directly through the mobile app (**Figure 3**) or by logging into Fulcrumapp.com and accessing the browser-based dashboard (shown later in **Figure 4B**). StEER takes advantage of Fulcrum's real time updating of damage assessments in these interfaces to coordinate the efforts of multiple FAST members working in the field simultaneously. The apps store all acquired data on the FAST member's mobile device until connectivity allows for cloud synchronization, with the Fulcrum back end infrastructure (**Figure 4B**) enabling near-real-time access to VAST members preparing the EARR, Data Librarians enacting the DEQC process, or NHE community members seeking to view the data. Moreover, anyone can freely create a user account on StEER's Fulcrum Community page to access the apps and data for use outside of StEER-sponsored events.

[6]https://www.fulcrumapp.com/

[7]https://web.fulcrumapp.com/communities/nsf-rapid

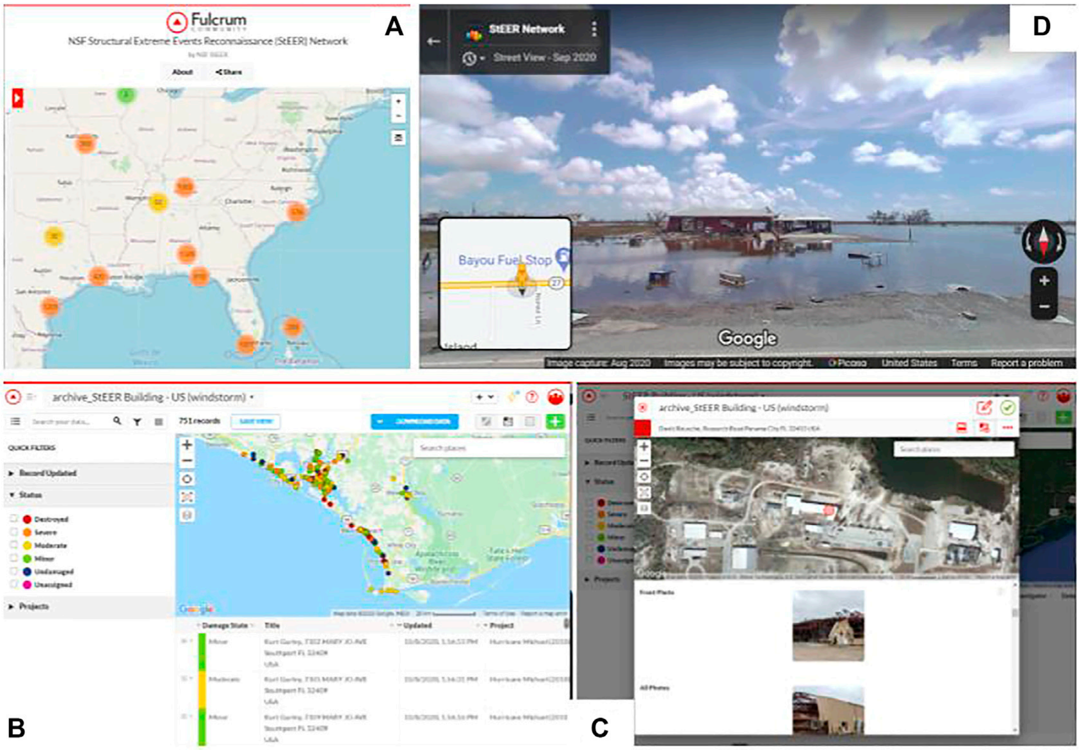


**FIGURE 4 |** Open platforms for sharing StEER field data: (**A**) Fulcrum Community public map viewer for app-based structural assessments, (**B**) backend Fulcrum dashboard for querying and filtering app-based structural assessments with ability to click any record for (**C**) pop-up with all fields, metadata and collected media (example from Hurricane Michael); (**D**) example of StEER street-level panoramas posted to Google Maps Streetview platform (example from Hurricane Laura).

Finally, the StEER mobile app suite is still being built-out to accommodate additional hazard types (e.g., tsunami) and structure classes, and further realigned to promote greater consistency between the apps used for different hazard types. While these efforts are ongoing, and the apps described above will likely undergo future revisions accordingly, the core elements of app-based structural assessment will remain the same, promoting consistency in damage assessments across hazard events and across the various FASTs conducting these assessments.

### Terrestrial Scanning

Due to its time-intensiveness and required expertise, StEER has made judicious use of terrestrial scanning technologies such as the Faro Focus LiDAR scanner, reserving it for notable case study structures. Each implementation includes careful planning to determine the optimum number of scans and their positions such that the scans can be accurately registered to maximize coverage with minimal occlusions. The selection of the scanning parameters must balance available site access (relative to both permission and safety), the structure's geometry (ensuring line-of-sight), and time constraints. Once the protocol is defined, it is executed by the terrestrial scanner, which records the 3D information of the targeted objects (point cloud) registered to the relative coordinate system of the scanner. The data is then post-processed using standard software to register, process (colorize) and export the scan to open-source formats (e.g., .las). Kijewski-Correa et al. (2018) provides an example of the configurations and applications of this type of hardware to document hurricane damage.

## Field Response Strategies

Over the first 2 years of its existence, StEER has implemented five different field response strategies: Hazard Gradient Survey, Representative Performance Study, Targeted Case Studies, Rapid Surveys, and Phased Multi-Hazard Investigations. These strategies may integrate data from multiple hardware platforms to efficiently capture and comprehensively document the structural performance and site context. These strategies are each introduced, followed by a discussion of how StEER Leadership ultimately selects the field response strategy for a given event. Note that an example of each field response strategy is introduced later in *Illustrative Field Responses*.

### Hazard Gradient Survey

Structural damage is a function of many factors, but hazard intensity is typically assumed, and has often proven to be, the most significant predictor of damage (e.g., Egnew et al., 2018). Structures assessed in a hazard gradient survey are sampled from pre-identified clusters or along transects that cut across the hazard gradient to provide an unbiased estimate of the fundamental hazard-damage relationships, suitable for the development of fragility descriptions. As such, Hazard

Gradient Surveys are one of the primary field response strategies adopted by StEER. FASTs routinely work door-to-door (D2D) on foot in a cluster of buildings or along a transect, assessing every third building to ensure a representative sample (Liang et al., 2012). This field response strategy often couples FAST members working D2D to sample buildings in a cluster for app-based structural assessments, while vehicle-mounted street-level panoramic images are collected along all streets in the cluster, and aerial imagery covering the entire cluster is captured overhead by UAS. However, this field response strategy requires a reasonable estimate of the hazard gradient as well as access to inventory data to inform target selection (transects or building clusters). To date, StEER has employed Hazard Gradient Surveys in both tornadoes and hurricanes, including sampling the performance of coastal structures across significant storm surge hazard gradients in events such as Hurricane Michael (2018) (Kennedy et al., 2020).

### Representative Performance Study

This strategy is typically adopted when the conditions/logistics limit the scope of a field response or when it is advisable to deploy a small FAST to scout an impacted area as a prelude to a more in-depth field response by StEER FASTs or other groups. Depending on the event, the engaged FAST may be interdisciplinary in order to gain a more holistic impression of the effects of the event. When using this strategy, the FAST generates overall impressions of the impacts and local conditions through field notes and photographs of selected structures and facilities.

### Targeted Case Studies

This strategy develops detailed photographic accounts of structural and nonstructural damage to structures. This type of field response strategy has particular value when specific structures can be identified (and accessed) for in-depth evaluation. Such targets include structures with high societal value, e.g., hospitals, structures where design details/drawings are known, structures employing notable retrofits or mitigation strategies, structures whose responses in the event have been recorded by embedded instrumentation, or structures in close proximity to sites recording the hazard intensity, e.g., strong motion stations. When using this strategy, the FAST acquires multiple high-resolution photographs of each structure, capturing specific load path details, annotated by field notes. When feasible, UAS and/or terrestrial scanning can be used to generate detailed 3D digital models for further off-site analysis. Physical samples may also be acquired for off-site testing to establish material properties.

### Rapid Surveys

Hurricane Laura was just one of a series of hurricanes that made landfall in the record-setting 2020 Atlantic Hurricane season, all during the COVID-19 pandemic, creating challenging dynamics for evacuation, sheltering, recovery and reconnaissance efforts (Roueche et al., 2020c). With many universities operating under travel restrictions and the pandemic-related restrictions on shelters creating greater demand for hotels to house evacuated households, StEER was challenged to conceive of new modalities to safely respond. This resulted in a new rapid survey field response strategy that solicited participation from small, self-contained regional teams, in some cases commuting daily from their homes, to collect street-level panoramic imaging that could be shared with a larger virtual team working from their homes to conduct app-based structural assessments (using the Fulcrum backend). This strategy is capable of generating hundreds of kilometers of data using a two-person team working only 2 to 3 days, minimizing the need for interactions with the affected population and a larger multi-institutional FAST, in compliance with StEER's COVID-19 protocols. These street-level panoramas are equally valuable to document societal impacts of disasters, damage to distributed infrastructure such as utility networks, and debris piles that can infer the level of interior losses due to rainwater intrusion or flooding. As such, StEER anticipates greater use of this strategy in the future to rapidly collect data that can be efficiently processed to document the impacts of the event with minimal intrusion on the affected community, while identifying targets for a follow up FAST employing a Targeted Case Study or Hazard Gradient Survey, if warranted.

### Phased Multi-Hazard Investigations

These are the most complex StEER field response strategies, using a small scout team to assess conditions on the ground and potential targets to inform a follow-up field response by larger interdisciplinary teams that will work both to document the performance of the built environment as well as characterize the hazards. Depending on the information available and the characteristics of the inventory, this performance assessment can adopt elements of the aforementioned Hazard Gradient Survey or Targeted Case Studies, engaging a range of assessment technologies depending on transport constraints. This field response strategy configuration is particularly beneficial in events with catastrophic damage, events with limited ground support or local coordination, and/or events for which limited information on the hazard characteristics is available. As a result, this strategy is often advantageous for international field responses.

The selection of any of the above field response strategies for a given event considers the data that are likely of greatest value to the NHE community, the FAST expertise and available equipment, the characteristics of the hazard and built environment, and other contextual factors. For example, if the StEER members who expressed interest in participating in a FAST have expertise in field assessing multiple building typologies, and the hazard impacted a broad variety of building types with similar intensities, then a Representative Performance Study would likely be chosen. Whereas if the members expressing interest have little experience with detailed forensic investigations, but have close regional proximity to the event and access to vehicle-mounted panoramic imaging systems, then a Rapid Survey may be the best choice for the initial FAST, while a subsequent FAST could conduct a Hazard Gradient Survey or conduct Targeted Case Studies to add depth to the initial field response.

## Data Enrichment and Quality Control

Referring back to **Figure 2**, the last phase of the field response is devoted to Data Enhancement and Quality Control (DEQC) by

StEER's Data Librarians. The different hardware platforms and field response strategies place varying demands on the DEQC process. As panoramic imaging, unmanned aerial systems and terrestrial scanning all benefit from automated file generation and post-processing by software native to these hardware environments, no additional enrichment of the data is required, and quality control focuses solely on ensuring all data are properly documented, organized into a logical directory structure by date and location, and completely transferred to the DesignSafe project that will serve as its long-term curation home. For field response strategies that acquire photos outside of StEER's standard apps, the DEQC process includes a quality control review of the photos to remove any redundant, blurry or inappropriate (e.g., bystander faces) images and enrichment of the photographic data through the compilation of a photo log listing the extracted metadata/geotags from each photo, as well as a description of the photo.

The most effort intensive aspect of the DEQC process is associated with app-based structural assessment data. StEER Data Librarians work for months after the FAST returns to enrich the assessments using supplemental data sources to populate the fields that were not completed on-site by the FAST. To do so, Data Librarians work in the web-based Fulcrum backend described in *App-Based Structural Assessments*, using its robust version control capabilities. Data Librarians review the media (photo, audio) files captured by the FAST, other third-party imagery sources (e.g., public aerial imagery from federal or state agencies, which is automatically ingested by Fulcrum and linked to each assessment), and public databases (e.g., tax assessor data or realtor websites) to gather information needed to complete the outstanding fields in each assessment and quality control the fields completed by the FAST. Custom web-crawler scripts, GIS analysis and other tools batch process the data to reduce the burden on Data Librarians, e.g., using spatial joins between assessment locations and building footprints or parcel polygons to match available attribute data from tax assessor or realtor databases.

In addition to enriching each assessment, a multi-dimensional control process is also undertaken to ensure the datasets are suitable for advanced knowledge discovery. The quality control component of the DEQC process focuses on four key data quality dimensions as defined in Fox et al. (1994), consisting of accuracy, currentness, completeness, and consistency.

- *Accuracy* relates to the agreement of the various data values contained in the assessment to the true value. The DEQC process maximizes *accuracy* by parsing data from reliable sources such as tax assessor databases, permit databases, real estate services like Zillow, Google Streetview (for comparative pre/post-event imagery), processed imagery from the FAST (e.g., 3D models generated from UAS imagery) and mission agency aerial imagery (e.g., NOAA post-hurricane imagery websites), and referring to StEER guidance to recognize and accurately define data values from imagery.
- *Currentness* recognizes that most data are a static snapshot of a dynamic process, and therefore data should reference back to the same nominal time, or have an accurate time indicator. This is important in post-event reconnaissance, when the landscape changes rapidly during response and recovery operations. This requires determining if the structure's condition at the time of FAST-assessment was significantly altered from its immediate post-event state, including disassembly, repair and/or replacement. Identification of these situations primarily relies on reviewing and comparing data from multiple timescales after the event, and using the earliest post-event data to define the damage states (e.g., structure damage visible in aerial imagery captured 24-48 h after the event takes precedence over on-site FAST data captured possibly 1-2 weeks after the event when significant differences are noted).
- *Completeness* relates to the percentage of populated fields, as well as interpretation of various null value indicators.
- *Consistency* traditionally relates to data values satisfying any known constraints. For example, if a global damage rating is defined using quantitative criteria such as component-level damage percentages, then these should be assigned consistent with the assigned global damage rating. Consistency in post-disaster assessments also relates to how various uncertainties or unique circumstances are handled. For example, StEER has protocols for how data values are to be assigned for fields that assume all sides of a structure are visible, when in reality only two sides of a structure were visible in imagery from various data sources.

This multi-dimensional quality control effort is enabled by establishing clear guidelines in the DEQC training materials, a central communication hub on DesignSafe Slack for open discussions by the Data Librarians, automated checks for missing/incompatible data values, and independent audit by at least one other Data Librarian so that all assessments involve at least two independent contributors.

The status of enrichment and quality control tasks for each assessment is tracked using codes assigned by the Data Librarians (**Table 3**), which indicate the DEQC stage that assessment has undergone to date. The Data Librarians' work is progressive, advancing the entire collection of assessments for an event to DEQC Stage 1; then working back through the entire collection of assessments to achieve DEQC Stage 2. By the conclusion of this progressive process, some assessments may achieve a higher DEQC Stage (e.g., Stage 3) than others (e.g., remain at 2) due to availability of parcel-specific data. These concepts are illustrated in more detail in Roueche et al. (2019a, 2020b). Such continuous updating of these codes is critical not only for managing the collective effort of multiple Data Librarians across universities but also for users of the data who can still access assessments in real-time via the Fulcrum Community website and thus need to know the DEQC stage achieved to date on any given assessment. This then empowers the user to decide if that assessment meets their threshold for inclusion in their analysis.

Finally, StEER continues to explore human-machine interfaces for further automation given that the current DEQC process on average requires approximately 30 minutes of human

**TABLE 3 |** Stages of DEQC Process.

| Stage | Scope |
|---|---|
| 1 | Verify record location |
| 2 | Verify or populate fields minimally required for complete record |
| 3 | Verify, update or populate fields visible from photographs and supplemental data sources, e.g., percent component damage, building attributes |
| 4 | Verify, update or populate fields not captured by FAST and not available/applicable for all buildings |
| 5 | Final QC validation, checks for blank fields, inconsistent terminology, etc. |

**TABLE 4 |** Overview of primary StEER event response products.

| Product | Purpose | Target Release | Authorship |
|---|---|---|---|
| Event Briefing | Emphasize key takeaways for policy and practice following a natural hazard event based on publicly available information | < 1 week after event | Small VAST (≤ 5 persons) |
| Preliminary Virtual Reconnaissance Report (PVRR) | Systematic investigation of structural performance following a natural hazard event based on publicly available information with recommendations for further response | < 2 weeks after event | Larger VAST (> 5 persons) |
| Early Access Reconnaissance Report (EARR) | Summary of findings and observations from Field Assessment Structural Teams with recommendations for further study by the NHE community | < 2 weeks after FAST concludes | FAST and VAST |
| Dataset | Collection of data captured by Field Assessment Structural Teams with documentation to support re-use | < 3 months after FAST concludes | Data Librarians, FAST |

effort, with each assessment progressing on average through eleven different versions before reaching its final published state. Still there is considerable value in retaining human involvement in this process, as it provides excellent opportunities for training students and prepares them for future participation in StEER field responses.

## Event Response Products

The StEER event response workflow typically produces at least one of the following products for each event: (1) Event Briefing, (2) Preliminary Virtual Reconnaissance Report (PVRR), and (3) Early Access Reconnaissance Report (EARR), subsequently accompanied by a curated dataset. As summarized in **Table 4**, each product serves a distinct purpose and accordingly differs in scope, publication time, and authorship. This section provides a brief introduction to the structure and content of each of these products, citing an illustrative example for each. Note that a full compilation of the Event Briefings, PVRRs, EARRs, and datasets published to date on DesignSafe are available on the StEER website[8]. StEER has also issued a handbook (Kijewski-Correa et al., 2020a) that explains the process supporting the production of the Event Briefing, PVRR and EARR, the standard elements of these products, and associated Google Document templates. Each of these products is now briefly introduced.

### Event Briefing

Typically issued within a week of an event, these abbreviated summaries of natural hazard events and their impacts contain standard sections: (1) introducing the event and its timeline, (2) summarizing hazard characteristics, (3) overviewing the damage to structures, (4) reporting impacts to community resilience, and (5) recommending a response strategy with topics for further investigation. These briefings are substantiated by reports shared by news and government agencies, professional societies, local collaborators and social media, using photos shared publicly by these entities. The primary contribution of the Event Briefing is the documentation of an event culminating in Key Lessons for future policy and practice based on the available observations. See Gunay et al. (2020a) for an illustrative example for the 15 December 2019 earthquake in the Philippines.

### Preliminary Virtual Reconnaissance Report

Typically released within 2 weeks of the event, these reports are issued for events with magnitude and impacts that have potential to advance learning related to structural performance. PVRRs may be followed by an Early Access Reconnaissance Report (EARR) in a Tier 3 response, or stand alone in events where deployment of FASTs is not warranted or feasible (Tier 2 response). A PVRR contains a more detailed accounting of the event and includes standard sections: (1) introducing the event's significance and impacts, (2) describing hazard characteristics, (3) defining the local codes and construction practices, (4) overviewing the damage to buildings and other infrastructure, (5) reporting geotechnical failures, (6) establishing current conditions and access, and (7) recommending a response strategy. The majority of the report focuses on structural performance, which may be organized by structure class (e.g., single-family residences, hospitals, commercial buildings), geographic region, or instigating hazard (when multi-hazard impacts are observed). As with the Event Briefing, all information is derived from public sources. The primary contribution of the PVRR is the detailed documentation of an event culminating in recommendations for possible formation of a FAST and themes

[8]https://www.steer.network/products

emerging for further investigation by StEER or other responding groups. See Gunay et al. (2020b) for an illustrative example for the 30 October 2020 earthquake and tsunami in the Aegean Sea.

### Early Access Reconnaissance Report

Typically released within 2 weeks of the conclusion of the initial FAST response, these reports are issued for events involving StEER FASTs. An EARR contains many of the same elements as a PVRR and refers to the published PVRR heavily. Thus, the EARR's standard sections are meant to document any new understanding of the event or observations of its hazards since the publication of the PVRR: (1) introducing the event with updated estimates of impacts, (2) sharing any new quantifications of the hazard intensity, (3) describing the FAST's response strategy, (4) expanding the understanding of local codes and construction practices based on experiences in the field, (5) detailing the methodologies used by the FAST, (6) overviewing the observed performance of buildings and other infrastructure, (7) documenting observed geotechnical failures, (8) summarizing observed evidence of hazard intensity, e.g., high water marks, and (8) recommending areas for further study. The syntheses of structural performance included in an EARR are drawn from direct observations by the FAST rather than public sources, again organized by structure class, geographic region, instigating hazard or failure mechanism. The primary contributions of the EARR are summaries of the FAST observations and key findings, in turn informing recommendations for further hypothesis-driven research. See Roueche et al. (2019b) for an illustrative example for the 3 March 2019 Tornadoes in the southeastern United States.

### Datasets

StEER's Product Curation Handbook (Kijewski-Correa, et al., 2020b) describes in detail how StEER structures its datasets to operate within the NHERI DesignSafe Field Data Research Model. The standard directory structure used in StEER datasets is organized around the different technologies described in *Hardware Platforms* and is defined as follows: (1) Planning Documents (including Pre-Deployment Briefing(s)), (2) Damage Assessments (e.g., app-based structural assessments), (3) Panoramic Imaging, (4) Unmanned Aerial Systems, (5) Terrestrial Scanning, (6) Other Ground-based Observations (i.e., photos acquired by FAST outside of StEER mobile apps), (7) GPS Data (routes or waypoints of data collection sites), (8) Daily Summaries (nightly briefings from FAST), and (9) Dissemination Products (presentations, publications or other derived data products). As detailed in Kijewski-Correa et al. (2020b), both raw and processed data for each of the hardware platforms used are ultimately included in the curated dataset on DesignSafe.

A Data Report is also curated with this dataset. These reports provide the necessary documentation to enable re-use of the curated data. Each Data Report has the following standard sections: (1) summary of the event and FAST configuration, (2) details of the data collection methodology (includes description of hardware), (3) chronology of field response with geographies, (4) description of post-processing for all data types, (5) dataset's directory structure (using the standard directories defined above), (6) points of contact for user queries, (7) references, and (8) appendices summarizing fields in any app-based structural assessments and/or UAS flight parameters. Note that while StEER has standardized this directory structure and associated sections of its Data Reports, not all of these are used for all field responses, since the adopted field response strategies, hardware and FAST configurations are unique to each event. The Hurricane Michael Dataset illustrates one of the more comprehensive examples (Roueche et al. 2020a), showcased in a NHERI DesignSafe webinar[9].

In total, these products have some important distinctions from the products of other efforts in the field. For example, while typically not as in-depth as some of the federally-mandated response reports (e.g., FEMA MAT, NIST Disaster and Failure Studies) or initiatives by larger professional organizations (e.g., EERI LFE), the StEER products described above complement these efforts and fill a critical need for the NHE community in that they are (1) rapid, typically being issued within days to weeks after an event, rather than months to years; (2) have authorship open to variable levels of participation from any interested members of the NHE community through the VAST/FAST; and (3) are tailored to the needs of the NHE community, signaling opportunities for ongoing analysis of the event and lines of future research. This last point is made possible through StEER's open sharing of standardized data, a contribution unique from other federally-mandated or professionally coordinated reconnaissance efforts. In addition to the inherent value to academic researchers, these products have also been consumed by mission agencies like NIST and FEMA, segments of the insurance/reinsurance industry, code officials, practicing engineers and manufacturers, each finding a unique value-added as summarized in **Table 5**.

## DISSEMINATION PATHWAYS

All the aforementioned StEER products are long-term curated in DesignSafe, with the resulting DOIs circulated through DesignSafe Slack Channels and StEER email listservs, and archived on the StEER website. However, recent event responses described in *Illustrative Field Responses* have demonstrated that this data can have immediate value to response and recovery actions (well before it completes the DEQC process and is curated in DesignSafe). StEER has balanced this potential for immediate impacts with the need to create quality-assured archival data products by making two of its data classes publicly available in near-real-time. The use of the aforementioned Fulcrum Community platform opens immediate and ongoing public access to app-based structural assessments as they synchronize in the cloud, with the QC code (**Table 3**) providing transparency as to each assessment's current stage of review. Fulcrum's public-facing map provides a high-level

[9]https://www.youtube.com/watch?v=xUyFJwZmyqM&feature=youtu.be

**TABLE 5 |** StEER products value-added for different stakeholder groups.

| Stakeholders | Value-Added |
|---|---|
| NSF and Academic Researchers | Recommendations for further study, potentially through RAPID Awards, data to support further investigation |
| Federal, State and Local Agencies | Synthesis of damage at community scale |
| Insurance Industry | Structural assessment data as a function of diverse variables |
| Building Code Officials | Performance summaries for code-compliant structures |
| Practicing Engineers | Case studies highlighting effective mitigation measures or systemic vulnerabilities in local construction practices |
| Building Materials Manufacturers | Performance of common materials/components |

**TABLE 6 |** Summary of StEER event responses (Sept. 2018-Dec.2020).

| | Total: Domestic, Intl.[a] | Tier 1 | Tier 2 | Tier 3 | Total Participants[b] |
|---|---|---|---|---|---|
| Earthquake | 16: 10, 6 | 9 | 6 | 1 | 167 |
| Derecho | 1: 1, 0 | 0 | 0 | 1 | 4 |
| Hurricane | 10: 7, 3 | 6 | 0 | 4 | 146 |
| Tornado | 6: 6, 0 | 1 | 0 | 5 | 75 |
| Tsunami[c] | 2: 0, 2 | 0 | 1 | 1 | 16 |
| Typhoon + Earthquake | 1: 0, 1 | 1 | 0 | 0 | 5 |
| **Total** | **36** | **17** | **7** | **12** | **413** |

[a]*Hurricane responses may include impacts to international and US locations along the track, but are included in the count of the primary focus of documented impacts.*
[b]*Count of total number of individuals participating in each event of this type; some individuals have participated in multiple events within hazard type or across multiple hazard types.*
[c]*Earthquakes inducing tsunamis are included in this count provided that the tsunami was the genesis of most of the observed damage. If the earthquake was the genesis of most of the observed damage, it is instead included in the earthquake count. This was the case for one event, the Aegean Sea Earthquake of 30 October 2020 for which tsunami impacts are also included in the PVRR.*

visualization of the geospatial distribution of damage assessments (**Figure 4A**), while those registering for a free Fulcrum Community account have full access to the more powerful backend dashboard to query and explore records across the StEER app suite (**Figure 4B**), clicking on any pin to see the detailed assessment record with photos (**Figure 4C**). Meanwhile, StEER street-level panoramas have been uploaded to Mapillary and Google Map's Streetview (now available as part of its time lapsed image captures), branded by StEER (**Figure 4D**), UW RAPID Facility, or SiteView 360, depending on who managed the post-processing and upload to the platform. The time lapsing feature native to Google makes this particularly useful for pre/post comparisons, though going forward, StEER will centralize its street-level panoramas at Mapillary to take advantage of more powerful capabilities to automate and discover community-contributed data. These and other public access points are detailed in the Data Availability Statement.

A number of the stakeholder groups engaging these products (**Table 5**) are themselves StEER and/or NHERI members and receive StEER's email communications and other NHERI messages announcing the release of these products. These members have been important allies in disseminating post-event products through their professional networks and organizations. However, these members are but a small sample of potential stakeholders. StEER has in parallel built contacts in affected communities during the course of field responses, including with local media, which have been leveraged to share learnings and data access points. With that being said, StEER products are currently not tailored to audiences outside of the NHE community, making the creation of new short-form and targeted communications for different non-academic audiences a key future priority, as well as mobilizing more robust dissemination channels to convey these communications to intended audiences in policy and practice.

## ILLUSTRATIVE FIELD RESPONSES

In the 2 years since its founding, StEER has led three dozen event responses with over 400 participants, with a dozen of these events culminating in a field response (see **Table 6** for breakdown by hazard and response tier). The following representative case studies provide additional details of implementations of each of StEER's field response strategies between 2018 and 2020, across different hazards and geographies. Each case study introduces the event, the implementation of a given field response strategy, as well as some of the major learnings informed by field observations. These field responses involved over 90 individuals, who could not all be included herein due to space limits, but are recognized in the Supplementary Material (**Supplementary Material SM.6**). Each case study cites the associated StEER products, including reports that provide detailed accounts of the hazards, societal impacts, built environment performance, and recommendations for further study.

### Hazard Gradient Survey

One example of a Hazard Gradient Survey was in response to the 3 March 2020 tornado outbreak, which included ten tornadoes in Tennessee (Roueche et al., 2020d). The most impactful tornadoes

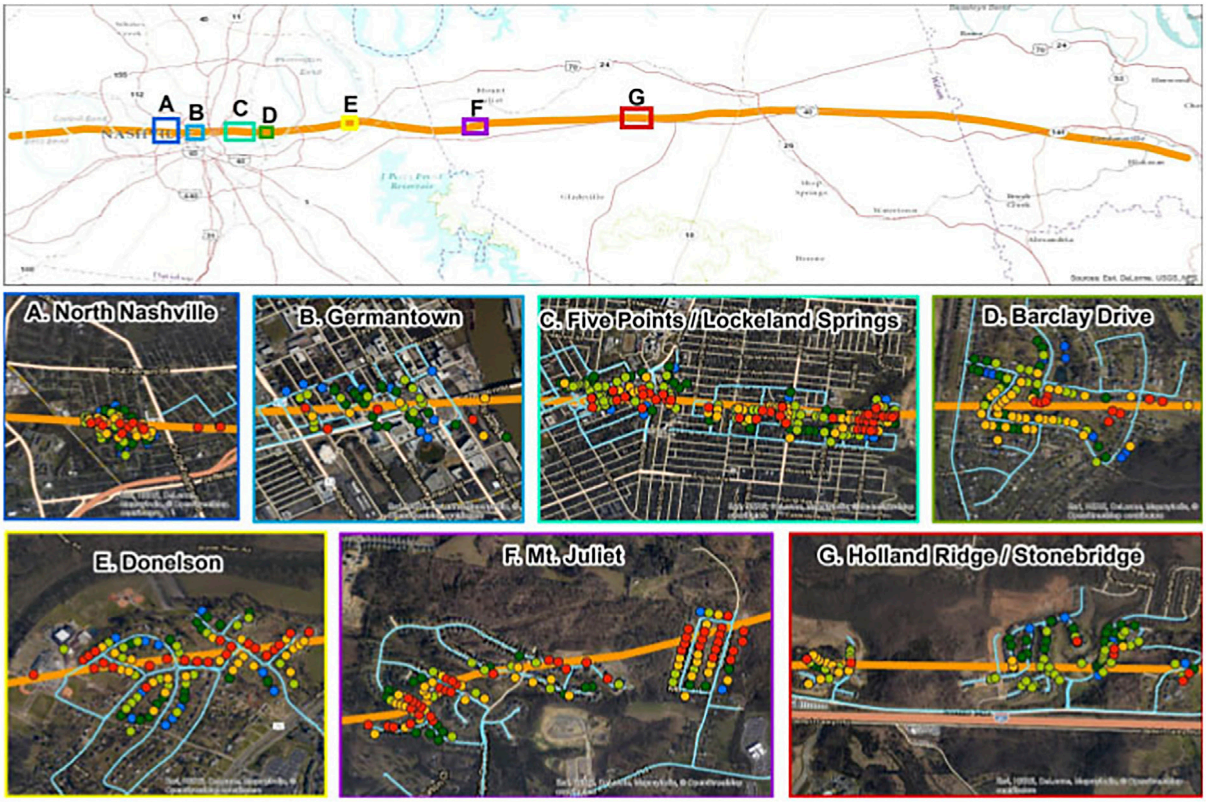


**FIGURE 5 |** StEER FAST app-based structural assessments in response to the Nashville tornadoes in key geographic regions relative to the tornado centerline. Blue lines in the detail plots indicate routes captured with street-level panoramas. Colored circles indicate locations of app-based structural assessments, where red to blue shading indicates high to low severity of damage.

had a 97 km (60 mile) track that passed through Nashville, TN and Lebanon, TN with wind speeds estimated at 74 m/s (165 mph) and a damage width of 730 m (800 yards) at its widest point; and a tornado with a 13 km (8.3 mile) track that struck Cookeville, TN with wind speeds estimated at 78 m/s (175 mph) and a damage width of 274 m (300 yards) at its widest point. The Nashville tornadoes was rated an EF-3 on the Enhanced Fujita (EF) tornado intensity scale (McDonald Mehta, 2006), while the Cookeville tornado was rated an EF-4. Full details of the hazard characteristics can be found in Wood et al. (2020). The tornadoes in combination caused 25 fatalities, at least 309 reported injuries, and approximately $1.6B in economic losses (NOAA, 2020). StEER sampled across the width of the tornadoes within preselected clusters dispersed along the length of the tornado track (**Figure 5**), in order to capture intensity variations in both the transverse (highest winds at the center of the track and decaying outwards) and longitudinal (intensity cycles of the tornado itself) directions.

## Implementation

The VAST and ensuing PVRR (Roueche et al., 2020d) summarized the impacts of the tornadoes and recommended deployment of a FAST based on several factors, including: (1) the high number of fatalities (25), with many occurring in modern residential construction, (2) the severe damage to several schools, and (3) the severe damage to many commercial buildings (as the Nashville tornado passed through downtown Nashville and two different industrial parks). Based on these recommendations, a FAST was activated as described more fully in Wood et al. (2020). The FAST consisted of engineering experts from academia and industry, led by Richard Wood from the University of Nebraska and the second author, with team members Keith Cullum, Brett Davis, Mariantonieta Gutierrez Soto, Sajad Javadinasab Hormozabad, Yijun Liao, Frank Lombardo, Mohammad Moravej, Stephanie Pilkington, and the fourth author, whose affiliations are provided in the Supplementary Materials (**Supplementary Table SM.6**). These individuals were supported by a wider VAST, also listed in the Supplementary Material (**Supplementary Material SM.6**). Team members began arriving and collecting data in the Nashville area on 8 March 2020 and continued through 12 March 2020. The FAST engaged a range of hardware platforms including app-based structural assessments, UAS, and street-level panoramic imaging. In total, the FAST conducted 1163 individual app-based structural assessments (1098 buildings, 22 non-building structures, and 43 hazard indicators), 15 UAS surveys capturing 25,100 aerial photographs and generating high-resolution orthomosaics (ground sample distance between 1.5-3 cm) covering 10.6 sq. km, and 161 km of 11-megapixel street-level panoramas, documenting nearly the entire network of roads transecting the tornado paths as part of this Hazard Gradient Survey.

### Major Learnings

The FAST repeatedly observed highly vulnerable structural details that were already identified in multiple previous post-tornado reports (Prevatt et al., 2012a; FEMA, 2012; Coulbourne et al., 2015). These included schools lacking safe sheltering options, big box buildings with little load path redundancy suffering complete collapses with high life safety risk, and anchorage failure in mobile and manufactured homes. More concerning was the FAST observation that the majority of modern, code-compliant single-family homes assessed had glaring deficiencies in the load path to the foundation. Specifically, the majority of homes rested on unreinforced, and at times even ungrouted, concrete masonry block stem walls with little to no positive resistance to wind uplift forces. This load path relies primarily upon the weight of the home to resist uplift forces and as a result, fails in a structurally brittle fashion leading to rapid and catastrophic collapses that compromise life safety.

For most of these vulnerabilities, engineered solutions exist but for many reasons have simply not yet been adopted. Indeed, the current building code requirements lack any tornado-resilient criteria that could provide some resistance against tornado loads. Research has established tornado-resilient design is economically feasible and need not exceed the criteria that are popular and widely used in Florida (Prevatt et al., 2012b; Simmons et al., 2015), yet there is only one jurisdiction (Moore, OK) out of 89,000 in the US that has actually adopted tornado-resilient building design guides. This implies society has accepted the continuation of life loss and catastrophic structural damage over a large expanse of this country, annually. Retrofitting just a few houses to achieve a continuous load path or even one or two schools to include hardened rooms or corridors for adequate refuge would be insufficient to tangibly alter the deaths, injuries and building damage repeated in these tornado events.

## Representative Performance Study

A 7.5 magnitude earthquake and subsequent tsunami hit Palu and Donggala in Central Sulawesi, Indonesia just after 6 pm local time on 28 September 2018, killing at least 2245 people. At the time of the FAST response, some 1075 people were missing and over 10,000 were injured, 4000 seriously. Nearly 75,000 were displaced in the three most affected areas: Donggala, Palu City, and Sigi. The earthquake was caused by movement on a strike-slip fault known as the Palu-Koro Fault (Robertson et al., 2019a). An earthquake of this type and magnitude is not generally anticipated to generate a damaging tsunami, hence the interest from international tsunami researchers. It is believed that the tsunami waves were generated by a combination of lateral movement of the steep bathymetry of Palu Bay and numerous submarine landslides around the bay (Aranguiz et al., 2020). Through the use of aerial imagery and field investigations, the FAST and its collaborators were able to identify thirteen distinct landslide locations along the bay shoreline, many of which are known to have triggered local tsunami waves (Robertson et al., 2019a).

### Implementation

This earthquake and tsunami event was an early example of a Representative Performance Study, initiating with a PVRR (then referred to as a P-VAT) to gather available online data to guide the subsequent FAST (Robertson et al., 2018). Because of its remote foreign location and strict governmental controls on external investigators, it made sense for StEER, which was still in its infancy, to send only one representative (the last author) to serve as a scout embedded with a larger international multi-disciplinary team organized by tsunami researchers in Japan and Indonesia. The team collected data from 27-31 October 2018 along the entire coastline of Palu Bay. The international research team (see Supplementary Materials Table **Supplementary Material SM.6** for full list of names and affiliations) was organized by Tomoya Shibayama, Miguel Esteban into four distinct survey groups:

- **Tsunami Inundation Survey:** Shibayama, Takahito Mikami and Tomoyuki Takabatake performed tsunami inundation elevation and runup surveys on all sides of Palu Bay and as far North as the earthquake epicenter (Mikami et al., 2019).
- **Bathymetric Survey:** Esteban performed sonar scans of the West and South coastal zones of Palu bay to identify potential submarine landslide evidence.
- **Aerial Survey:** Ryota Nakamura and Yuta Nishida performed numerous aerial surveys using a DJI Phantom 4 Pro+ quadcopter drone covering tsunami inundation regions and individual structures damaged by the earthquake and liquefaction-induced lateral spreading.
- **Structural Damage Survey:** The last author, Jacob Stolle and Clemens Krautwald conducted a Representative Performance Study on all sides of Palu Bay and at significant earthquake damaged buildings in Palu City.

Apart from the bathymetric survey, each group was accompanied by one of three Indonesian collaborators. While the groups performed their reconnaissance, the collaborators interviewed local residents who had witnessed the tsunami firsthand. During the 3 days they completed over 200 interviews, collecting useful data about how residents in the tsunami inundation area responded to the event.

FAST's Representative Performance Study focused on tsunami damage along the coastline of Palu Bay for 2 days, and spent 1 day focused on earthquake damage in Palu City. The sites selected for particular attention were determined prior to the trip based on the PVRR (Robertson et al., 2018) and available aerial imagery at the time. In addition to conducting a visual inspection and capturing photographic evidence of the performance of various structures, eyewitnesses were interviewed when possible to determine the sequence of damage, particularly in structures subjected to sequential earthquake and tsunami loading.

More importantly, by teaming with international researchers interested in various aspects of the tsunami generation, inundation, damage and social consequences, the last author was able to leverage data collected by others on the team,


**FIGURE 6 |** Damage induced by the Palu Earthquake and Tsunami: Roa-Roa Hotel in Palu, built in 2013, (**A**) before the earthquake and (**B**) after the earthquake, steel double arch Palu Bridge IV over the mouth of the Palu River (**C**) before the earthquake and (**D**) after the earthquake and tsunami; (**E**) collapse of gantry crane in the Port of Pantoloan due to earthquake shaking; (**F**) naval ship washed ashore at Watusampu Naval Base.

while adding consideration of both structural and geotechnical failures caused by the earthquake, to generate a comprehensive EARR (Robertson et al., 2019a). In total, the FAST documented 68 sites in this Representative Performance Survey, interpreted in light of 3 UAS surveys conducted by the Aerial Survey Team (capturing 2520 aerial photographs generating high-resolution orthomosaics covering 1.5 sq. km). All data collected by the FAST in response to this event, including eye-witness videos and geolocated photographs, are included in the published dataset in DesignSafe (Robertson et al., 2019b).

## Major Learnings

This Representative Performance Study documented significant damage to a wide cross-section of engineered and non-engineered construction as a result of the earthquake and/or tsunami. A number of multi-story reinforced concrete buildings collapsed during the earthquake, most notably the eight-story Roa-Roa Hotel which resulted in multiple deaths (**Figure 6A,B**). A reinforced concrete shopping center in Palu experienced partial collapse during the earthquake, and a number of mosques also suffered severe damage or even collapse. The iconic twin steel arch cable-suspended Palu Bridge IV over the mouth of the Palu River also collapsed during the earthquake. The bridge had a total span of 250 m and the steel box arches were 20 m tall (**Figure 6C,D**). A number of port facilities were damaged either by the earthquake or tsunami, and many ships, barges and boats were washed ashore or out to sea (**Figure 6E,F**). Damage to lifelines included extensive road damage due to surface faulting and liquefaction, cracks in the Palu airport runway, and loss of power and telecommunications. The tsunami caused considerable damage to light-framed wood structures, while some taller engineered structures survived, protecting those who vertically evacuated. At various locations, floating debris appeared to have induced at least part of the observed tsunami damage (Stolle et al., 2019); the damaging effect of scour on structural foundations was also documented (Krautwald et al., 2020). These observations have led to two modifications to the debris loading provisions in the latest edition of ASCE 7, 2022. Extensive lateral spreading due to liquefaction caused by the earthquake also resulted in extensive damage to

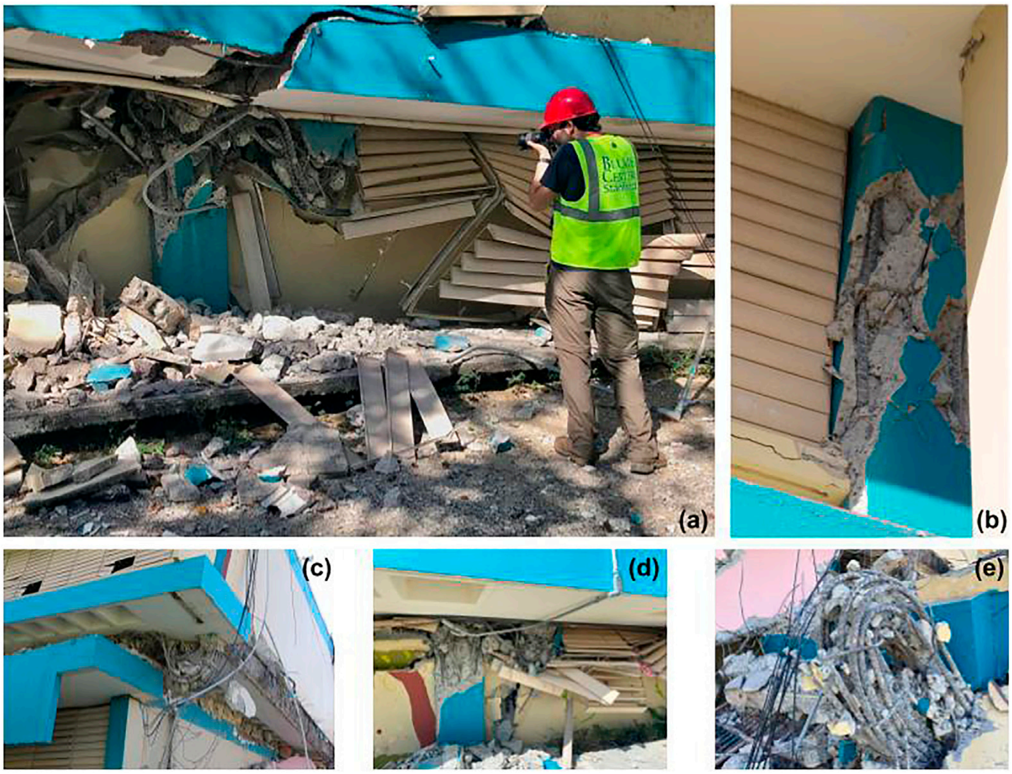


**FIGURE 7 |** Collapsed Agripina Seda School in Guánica, Puerto Rico: (**A**) in-depth photographic documentation with inset examples of load path vulnerabilities to (**B**) captive columns, (**C-D**) soft-story failure and (**E**) mangled reinforcement from crushed column.

residential and agricultural structures in a number of inland areas. Tragically, Indonesia has a long and painful history of earthquake and tsunami hazards, with yet another earthquake hitting this general area in early 2021 (Gunay et al., 2021), with this event reiterating vulnerabilities, potential mitigation measures and risk management strategies that can enhance resilience to future events.

## Targeted Case Studies

On 6 January 2020, at 6:32 am local time, a moment magnitude 5.8 earthquake occurred approximately 13 km SSE of Indios at a depth of 6.0 km and epicentral coordinates of 17.868°N 66.819°W. This earthquake was followed by a stronger earthquake with moment magnitude 6.4 on 7 January 2020, at 4:24 am local time, 8 km S of Indios at a depth of 10.0 km and epicentral coordinates of 17.916°N 66.813°W. These two earthquakes were part of an earthquake sequence in southwest Puerto Rico that initiated with a Mw 4.7 earthquake on 28 December 2019. Many hundreds of aftershocks occurred in the region, with the largest having a moment magnitude of 5.9. As detailed in the PVRR for this event (Miranda et al., 2020a), these earthquakes caused the collapse of at least 80 structures and damage to more than 10,000 residential units with significant societal impact. In addition to damage to buildings, bridges, roads, and other infrastructure, two thirds of the island lost power as a result of the Mw 6.4 earthquake on 7 January.

The Puerto Rico earthquakes were particularly well-suited to the Targeted Case Study field response strategy because of lags in assessments (tagging of damaged structures) by local officials and thus the need for detailed structure-by-structure evaluations given the concerns over reoccupying buildings during the aftershock sequence that resulted in notable collapses. According to data provided by the local government, over 8000 people had been displaced from their homes and were forced to move into shelters, and a significantly larger number were forced to sleep in tents in the streets or open spaces due to fear of their homes collapsing during an aftershock.

### Implementation

Under the joint sponsorship of the John A. Blume Earthquake Engineering Center at Stanford University, the FAST was led by Eduardo Miranda and included Pablo Heresi, Armando Messina, Isamar Rosa, and Jorge Archbold (see Supplementary Material Table **Supplementary Material SM.6** for full list of participants and affiliations). The FAST was deployed 8-12 January 2020, conducting field reconnaissance across six cities in Puerto Rico. The FAST visited instrumented buildings, bridges, and other engineered structures located near ground motion stations of the Puerto Rico Strong-Motion Program (PRSMP). The FAST also assessed structures that had been evacuated because of reported structural damage as well as a range of other typologies in the epicentral region (Guayanilla, Guánica, and Yauco). The FAST

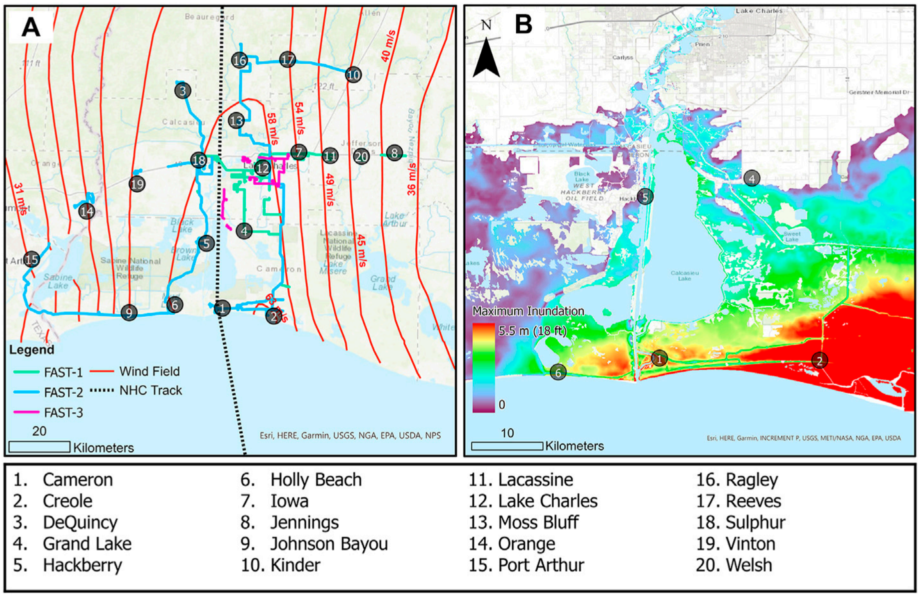


**FIGURE 8 |** Visual summary of surveyed communities relative to (**A**) preliminary Hurricane Laura track from the National Hurricane Center (NHC) and standardized gust wind speed estimates (red contours showing 3-second averaging time, 10˚m height, open exposure) from Applied Research Associates (Version 3 wind field), including FAST street-level panorama routes (colored blue, green and fuchsia lines); and (**B**) colored heatmap of maximum inundation depth above ground from ADCIRC hindcast (NHC best Track).

noted basic information about the structures as well as any signs of structural and nonstructural damage, largely from the exterior, but secured access to nine buildings for interior inspections. In total, the FAST documented 61 structures with a collection of over 7,250 high-resolution photographs, as part of this Targeted Case Study. A reduced subset of 744 photographs were subsequently ported into 61 app-based structural assessments by Data Librarians.

### Major Learnings

As outlined in the StEER EARR for this event (Miranda et al., 2020b), the largest impact of this earthquake was on residential structures. Preliminary observations indicate that the primary deficiency in many of these structures was the presence of soft-stories created by elevated single-family residential structures supported by concrete (typical) columns, locally known as "casas en zancos." This sequence of earthquakes also highlighted the challenges faced by regions subjected to multiple hazards, with frequent hurricane exposure promoting elevated first floors and heavier concrete roof slabs, which, unless adequately designed and detailed, make structures more vulnerable during seismic events (Kijewski-Correa et al., 2018). This is compounded in areas such as Haiti or Puerto Rico where large, damaging earthquakes had not occurred in many decades. Several school buildings throughout the region were damaged, including the Agripina Seda school in Guánica where three out of six buildings collapsed in the aftershock sequence (**Figure 7**). Several of the collapsed buildings in this school had captive columns whose lateral deformations were partially restrained by the presence of partial-height masonry walls in the longitudinal direction, a severe structural deficiency identified in many other school buildings in the region. At least three recently constructed reinforced concrete government buildings in the epicentral region had a floor system eccentric to the columns. In this system, bending arising in the floor system must be transferred to the columns through a combination of shear and torsion in a short beam, whose failure can lead to loss of vertical carrying capacity. This mechanism resulted in a near collapse of a government building in Guánica. A number of buildings had been retrofitted through the installation of exterior steel concentric braced frames and appeared to perform well structurally. Finally, several bridges suffered significant structural damage, possibly due to seismic joints allowing larger lateral deformations in the transverse direction, severe pounding at the abutments, large deformations at the rocker bearings, and damage to transverse shear keys.

## Rapid Surveys

As detailed in Roueche et al. (2020c), Hurricane Laura made landfall as a strong Category 4 storm near Cameron, LA in the early hours of 27 August 2020, tying the Last Island Hurricane of 1856 as the strongest land-falling hurricane in Louisiana history. Wind speeds are estimated to have reached or exceeded the design wind speeds for Risk Category II buildings and other structures, as defined in ASCE 7-16 and the 2018 International Building Code (MRI = 700 years), by as much as 8 km/h (5 mph) near Lake Charles, LA (specifically, northeastern Calcasieu Parish and the eastern half of Beauregard Parish) (NIST/ARA, 2020). Meanwhile storm surge resulted in high water marks of over 5 m (17 ft) above ground in Oak Grove, LA in Cameron Parish

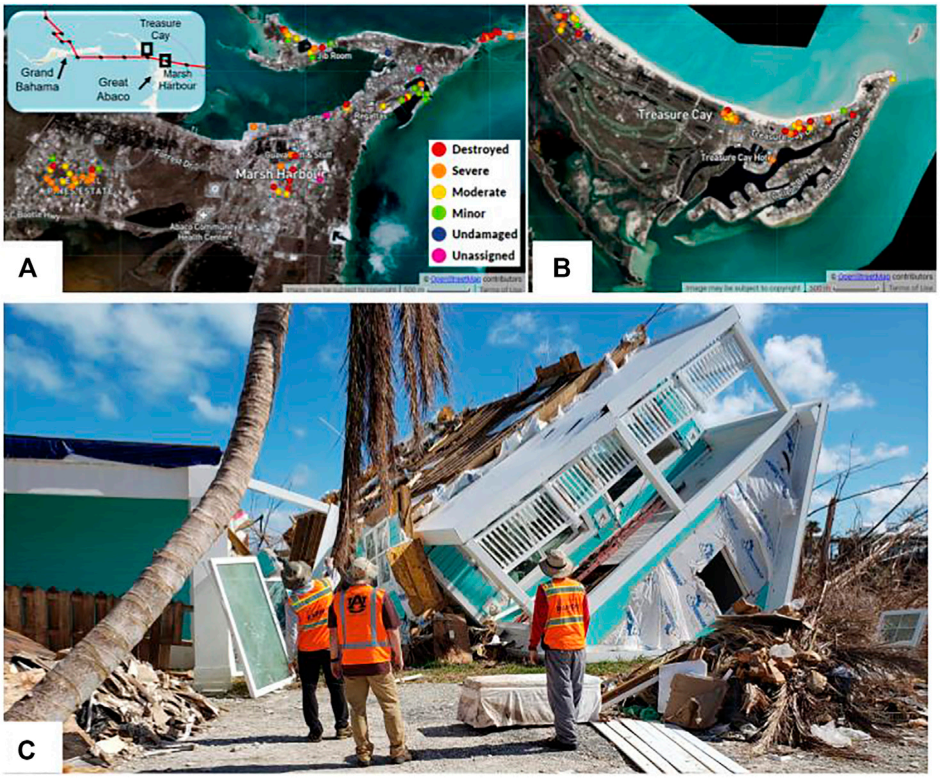


**FIGURE 9 |** Summary of app-based structural assessments (colored circles) conducted by FAST-1 after Hurricane Dorian in the Bahamas: (**A**) Marsh Harbour with inset map showing locations relative to hurricane track, (**B**) Treasure Cay, and example of recurring failure theme: (**C**) use of hurricane straps at the roof/wall connection, but poor bottom plate connections.

(USGS, 2020). These combined hazards resulted in estimated insured losses between $4B to $12B (Claims Journal, 2020), with substantial impacts to port and industrial facilities serving the oil and gas sector, widespread damages in the residential sector, and sustained outages of water and power impacting the operation of hospitals providing critical care during a pandemic. Notable damage was reported to commercial facilities, particularly to hotels, including high-rise buildings in Lake Charles associated with the casinos and resorts. As the storm's well-predicted track facilitated coordinated, multi-entity surface measurements of wind fields and storm surge, Laura is one of the best documented storm events and thus provides novel opportunities to understand the vulnerabilities underpinning losses across a diversity of building occupancies and other critical infrastructure.

## Implementation

As mentioned in *Field Response Strategies*, Hurricane Laura was the impetus to develop a new event response strategy using Rapid Surveys. This strategy was ultimately re-engaged when Hurricane Delta made landfall approximately 16 km (10 mi) east of Laura's landfall site to create a rich longitudinal dataset of the compound effects of these hurricanes (Roueche et al., 2020e). The initial implementation in the Hurricane Laura response leveraged small, self-contained, regional FASTs deploying in phases with vehicle-mounted street-level panoramic imaging platforms, with select use of UAS. FAST-1 led by the second author and Justin Marshall mobilized immediately, reaching the impacted areas at 1 pm CDT on 27 August, and collected data through 29 August in Lake Charles, LA and surrounding communities, as access allowed. They were followed on 2 September 2020 by FAST-2 led by Sabarethinam Kameshwar and Naqib Mashrur, who continued to collect street-level panoramas, accessing some of the coastal areas impassable to FAST-1. A final round of panoramic imaging and UAS data collection was completed by Michael Vorce 11-12 September (see Supplementary Material Table **Supplementary Material SM.6** for full team and affiliations). Routes selected for street-level imaging were based on inventory data and sites of post-Rita construction to ensure a range of building classes/ occupancies, typologies, and vintages were canvassed. Given the excellent coverage of wind field observations in this event, as discussed in Roueche et al. (2020c), emphasis was placed on documenting areas in close proximity to deployed wind instrumentation, as well as documenting performance along the hazard gradient to the east and west of the storm's track. The FASTs covered a wide geographical area from Port Arthur, TX to the west all the way to Jennings, LA to the east, Longville, LA to the north, and Holly Beach, LA to the south (**Figure 8**). These panoramas were uploaded to Google Maps and Mapillary, permitting rapid access to the VAST, as well as various federal mission agencies (who were not able to field deploy), remotely evaluating the storm's impacts. In select areas where street-level panoramas and UAS orthomosaic data was available, the VAST sampled every structure to remotely complete structural assessments in Fulcrum, emulating the process normally undertaken by FAST members in the field. In total, five UAS surveys capturing 1230 aerial photographs and generating high-resolution orthomosaics (ground sample distance between 1.5-3 cm) covering 0.308 sq. km and 842 km of 1160-megapixel street-level panoramas were generated by this Rapid Survey. These data enabled 402 app-based structural assessments to be completed remotely by the VAST.

### Major Learnings

The extensive and timely coverage of the StEER FASTs for this design-level wind event, with exceptional documentation of the windfield by surface observation networks and mobile radar, makes Hurricane Laura an ideal opportunity to advance knowledge and practice. Notably, the areas impacted by Laura were previously impacted by Hurricane Rita (2005), with many structures reconstructed or repaired and unfortunately again damaged. While there were notable successes, particularly in government buildings and other critical facilities, there were considerable losses in other building classes such as commercial (retail), hotels, religious institutions, and industrial facilities. Case studies such as the Capital One Tower in Lake Charles, LA remain important opportunities for detailed forensic investigation of buildings repaired/reconstructed post-Rita. Furthermore, a large swath of modern (post-IBC/IRC construction) single-family residential structures were impacted by design-level winds during Hurricane Laura, underscoring vulnerabilities to garage doors, which fortunately did not propagate to structural failures, and high rates of roof cover losses, particularly associated with hip and ridge cap shingles. The damage to the roofing systems may have resulted in substantive interior damage and losses due to water ingress that could not be documented by the approach and timing of StEER's data collection. This was compounded by the mixed performance of mobile homes, including failures of even Zone II anchorages. StEER also documented damage to large fuel storage tanks under combined wind, storm surge and wave action, underscoring their susceptibility to buoyancy, buckling, and overturning.

Moreover, as a design-level wind event over a built up urban area, Hurricane Laura also presented an opportunity to evaluate the public's perceptions around the performance of code-compliant vs. code-plus construction, akin to the post-event perception studies executed after other hazard events (Porter, 2016), as well as the decision factors driving the regrettably low rates of impact-resistant fenestration observed by the FASTs across the region. These issues in preparation for this hurricane were only compounded by the challenges of the COVID-19 pandemic, which impacted evacuation and sheltering options, spurred more sheltering-in-place over fears of infection, reduced the response capacity of charitable organizations and agencies, and increased both the economic losses and health impacts.

## Phased Multi-Hazard Investigation

As detailed further in Kijewski-Correa et al. (2019c), with its three landfalls from 1–3 September 2019, Hurricane Dorian broke many records, including the highest estimated gust wind speed at 362 km/hr (225 mph) and the longest duration for a Category 5 hurricane over land, with storm surge in excess of 6 m (20 ft). The overall cost of this destruction was estimated at $7 Billion (at least), or nearly 60% of the 2017 annual GDP for this tiny nation of 386,000 people. Dorian destroyed 13,000 houses or 45% of the housing inventory on Abaco and Grand Bahama Islands in the northwest sector of the Bahamian archipelago, causing a humanitarian crisis for most of the 60,000 people living there, with 60 confirmed deaths and hundreds of others still missing at the time StEER field deployed. Most houses in informal settlements like the Mudd and Pigeon Peas were completely destroyed by storm surge. The dire post-landfall conditions only compounded the logistical challenges of traveling across a chain of islands whose port and airport infrastructure had been significantly damaged. While the losses were staggering, a number of "bright spots" presented opportunities to document successful mitigation strategies in one of the strongest Category 5 hurricanes on record. Given the parallels between construction practices in Florida, this event further offered an important validation of principles used in US hurricane zones.

### Implementation

Hurricane Dorian presents a perfect example of a Phased Multi-Hazard Investigation intended to document both structural performance and characterize the multiple hazards in an international event with challenging field logistics and limited direct observations of the hazards during landfall. StEER was initially contacted by a Floridian with a vacation home on Great Abaco Island, Steve Pece, who offered to transport (by personal private plane), arrange logistics, and personally guide a StEER team across the island given the dire need for engineering assessments. FAST-1 included a small veteran team of structural engineers led by Justin Marshall with Daniel Smith and included imaging support from the RAPID EF's Andrew Lyda. Guided by Pece, FAST-1 scouted the conditions by collecting street-level panoramas from 24-26 September 2019 across Marsh Harbour and Treasure Cay on Great Abaco Island. As time permitted, the FAST recorded app-based structural assessments on select targets in these locales (**Figure 9A,B**). The experiences of FAST-1, as documented in the subsequent EARR (Marshall et al., 2019), then enabled FAST-2's more ambitious, multi-island deployment. FAST-2 was sub-organized into a Coastal Survey Team led by Andrew Kennedy with James Kaihatu, a Structural Assessment Team led by Doug Allen who liaised locally with Bahamian structural engineers Davon Edgecombe, Terran Brice and Kevin Brown to contextualize observations within Bahamian regulatory practices, and a Rapid Imaging Team led by Richard Wood with Henry Lester and Mike Vorce (see Supplementary Materials Table **Supplementary Material SM.6** for supporting team and affiliations). The Coastal Survey Team and Structural Assessment Team initially returned to Great

Abaco Island 5-7 October 2019 to expand upon the work of FAST-1, employing app-based structural assessments and documenting high water marks and the extent of inundation, while accessing new areas such as Man-o-War Cay. They then joined the Rapid Imaging Team on Grand Bahama Island late 7 October, which had been working since 5 October to document damage along the hazard gradients on Grand Bahama Island using street-level panoramic imaging, terrestrial scanning, and app-based structural assessments. The combined teams then conducted joint assessments of storm-surge induced damage on 8 October. In total, these FASTs were able to assess a representative sampling of engineered construction such as hospitals, government buildings, airport and port facilities, commercial buildings and hotels. Their efforts resulted in 369 individual app-based structural assessments, approximately 475 km of panoramic imaging at 5 m or less spacing, and 45 coastal surveys for this Phased Multi-Hazard Investigation. Logistically this was the most complex field response that StEER has undertaken to date, involving international travel by chartered private planes and boats to move across islands with limited access to fresh water, food and electricity.

### Major Learnings

While there was significant emphasis placed upon the catastrophic losses in Hurricane Dorian, a cross-section of residential, institutional, and commercial buildings performed quite well structurally, providing critical learning opportunities for enhancing hurricane resilience. Unfortunately, buildings that survived structurally were often subjected to storm surge and rainwater ingress that destroyed interior contents. Many coastal structures were completely washed away. FAST-1 and FAST-2 observed that failures were often driven by the limited capacity of the attachment of the superstructure to the foundation (**Figure 9C**). FAST-2 further noted that structural roof damage in wood-framed construction were consistently accompanied by envelope failures. While FAST-2 observed the use of a number of recognized mitigation measures, such as hurricane clips or breakaway walls in elevated structures, the implementation did not result in the intended benefit due to improper installation or failure to properly execute critical details. Beyond these structural considerations, Dorian highlighted the need for disaster risk reduction interventions in informal settlements, which are a historical legacy of colonization in Latin America and the Caribbean. Moreover, this event reiterated the need to reframe disaster risk for small island nations. As was the case with Hurricanes Irma and Maria's impacts on the US Virgin Islands and Puerto Rico (Prevatt et al., 2018), the projected losses in Hurricane Dorian were a sizeable percentage of the annual GDP of the Bahamas and thus posits if a more risk-averse approach to design is warranted in such settings. But perhaps the most critical lesson in Hurricane Dorian was the realization that early-arriving NHE reconnaissance teams can provide immediate value to the affected communities and those supporting their recovery. A number of humanitarian organizations and government officials requested access to StEER's data, particularly the street-level panoramas for the purposes of assessing damage and coordinating recovery efforts, which the RAPID EF supported on their local servers and eventually on Google Maps Streetview platform. StEER then shared these access points, as well as the Fulcrum Community webpage and its published reports, with any interested party the FASTs engaged (see Data Availability Statement for these access points).

## CONCLUDING REMARKS

Field observations play a critical role in fueling the Data to Knowledge (D2K) Life Cycle after natural hazard events, though previous limitations in technologies for capturing and broadly disseminating this data constrained the speed and reach of efforts to share these valuable observations. However, when effectively operationalized, field observations can drive fundamental research and technology transfer that ultimately results in the diffusion of mitigation measures back to affected communities. By embracing a number of recent technological advances, the Structural Extreme Events Reconnaissance (StEER) Network has been able to help streamline this life cycle further, introducing new modalities for the Natural Hazards Engineering (NHE) Community to capture, analyze and communicate our evolving understanding of natural hazard impacts on the built environment. This paper overviewed StEER's initial suite of policies, protocols and workflows, which have enabled contributions in the areas of: workflow and data standardization, data reliability to enable field-observation-driven research & development, efficiency in data collection and dissemination to speed knowledge sharing, near-real time open data access for enhanced coordination and transparency, and flexibility in collaboration modes to reduce the "overhead" associated with reconnaissance and foster broad engagement in event responses. StEER's creation of efficient systems to deliver well-documented, reliable data suitable for diverse re-uses as well as rapidly disseminated synopses of the impact of natural hazard events on the built environment provides a distinctive complement to existing post-event reconnaissance initiatives.

The introduction of this new model for community-led reconnaissance has underscored a number of important considerations. First, such community-facing initiatives require a commitment to transparency with clear external communications on event responses and real-time open access to collected data, in this case relying on platforms like Fulcrum Community, Mapillary and Google Maps Streetview. This real-time access is made possible by the use of completely digital workflows, which streamline data collection, reporting and curation to minimize human effort. Moreover, these rapidly-formed, geospatially distributed teams require more than just logistical support; their efficiency is reliant upon centralized knowledge management and real-time collaboration on web-based platforms like Google Drive and Slack, standardized operating procedures, and thoughtful design of event responses. This last point is achieved using five different event response strategies described in this paper, with pre-defined targets to maximize precious time in the field. StEER has also invested considerably in developing data standards, guidance documents, templates and training resources to build the capacity of its diverse member base. The consistency and reliability of structural assessments collected by dozens of different investigators is further assured through the use of mobile apps that create a consistent template focused on quantifying component-level damage, coupled with a rigorous Data Enrichment and Quality Control (DEQC) process. Finally, the valuation of virtual reconnaissance in these event responses cannot be underestimated, both for member capacity building and as a means to broaden participation across a larger portion of the NHE community.

The five case studies included in this paper: the Nashville Tornadoes (2020), the Palu Earthquake and Tsunami in Indonesia (2018), the Puerto Rico Earthquakes (2019/2020), Hurricane Laura (2020) and Hurricane Dorian in the Bahamas (2019) serve as illustrative examples of the different event response strategies StEER has employed since 2018 for 36 different hazard events, producing 28 reports and 17 briefings, and involving over 150 different individuals - approximately 50% of the over 300 individuals approved as StEER members. This success is a direct result of reducing the overhead associated with reconnaissance by offering well-structured and flexible modes of participation. StEER's mobile data collection platform (Fulcrum) has over 5000 publicly available structural assessments and nearly 400 enrolled users, demonstrating uptake beyond StEER's formal members to include stakeholders in the public and private sector. Furthermore, by making its mobile apps, templates and guidance documents publicly available at www.steer.network, StEER promotes best practices and data standards regardless of whether those investigations are formally affiliated with StEER. The authors look forward to a future where this impact is only deepened through the automation of its assessment processes and a more expansive engagement of communities of research, policy and practice to further accelerate the D2K life cycle.

## DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: All StEER products, resources and policies are available at www.steer.network; App-based structural assessments are available on the StEER Fulcrum Community page: https://web.fulcrumapp.com/communities/nsf-rapid; Panoramic images hosted on Mapillary (for Hurricane Laura): https://www.mapillary.com and Google Maps: https://www.google.com/maps/ (StreetView Platform); Hurricane Dorian (street-level panoramas by vehicle) are hosted at Mapillary: https://www.mapillary.com and also hosted by the RAPID Facility on a public server: Abaco: http://streetview.rapidfacility.org/Projects/AbacoBahamas/player/; Grand Bahama: http://streetview.rapidfacility.org/Projects/Bahamas-Fast-2/player/; Curated datasets and published reports are available at DesignSafe: https://www.designsafe-ci.org/data/browser/public/ (search keyword StEER).

## AUTHOR CONTRIBUTIONS

All the authors have contributed to the content for this paper through their participation in the design, implementation and operation of StEER over the past 2 years, including varying degrees of involvement in each of the case studies in this paper (see Supplementary Material). TKC led the overall writing and revision process; all authors contributed sections to this effort through at least one case study (TKC: Hurricane Laura, DBR: Nashville Tornadoes, IR: Palu Earthquake and Tsunami, DOP: Hurricane Dorian, KM: Puerto Rico Earthquakes), as well as content for the other sections; DBR contributed major elements of *Event Response*; all authors contributed to the review and editing of the paper; TKC and DBR designed the images for the paper; TKC serves as corresponding author.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fbuil.2021.636197/full#supplementary-material

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