THE POWER OF CITIZEN SEISMOLOGY: SCIENCE AND SOCIAL IMPACTS

EDITED BY: Remy Bossu, Kate Huihsuan Chen and Wen-Tzong Liang
PUBLISHED IN: Frontiers in Earth Science and Frontiers in Communication

frontiers Research Topics

Frontiers eBook Copyright Statement

The copyright in the text of individual articles in this eBook is the property of their respective authors or their respective institutions or funders. The copyright in graphics and images within each article may be subject to copyright of other parties. In both cases this is subject to a license granted to Frontiers.

The compilation of articles constituting this eBook is the property of Frontiers.

Each article within this eBook, and the eBook itself, are published under the most recent version of the Creative Commons CC-BY licence. The version current at the date of publication of this eBook is CC-BY 4.0. If the CC-BY licence is updated, the licence granted by Frontiers is automatically updated to the new version.

When exercising any right under the CC-BY licence, Frontiers must be attributed as the original publisher of the article or eBook, as applicable.

Authors have the responsibility of ensuring that any graphics or other materials which are the property of others may be included in the CC-BY licence, but this should be checked before relying on the CC-BY licence to reproduce those materials. Any copyright notices relating to those materials must be complied with.

Copyright and source acknowledgement notices may not be removed and must be displayed in any copy, derivative work or partial copy which includes the elements in question.

All copyright, and all rights therein, are protected by national and international copyright laws. The above represents a summary only. For further information please read Frontiers' Conditions for Website Use and Copyright Statement, and the applicable CC-BY licence.

ISSN 1664-8714
ISBN 978-2-88966-330-9
DOI 10.3389/978-2-88966-330-9

About Frontiers

Frontiers is more than just an open-access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers Journal Series

The Frontiers Journal Series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the Frontiers Journal Series operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to Quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews.
Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the Frontiers Journals Series: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area! Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers Editorial Office: researchtopics@frontiersin.org

THE POWER OF CITIZEN SEISMOLOGY: SCIENCE AND SOCIAL IMPACTS

Topic Editors:
Remy Bossu, European-Mediterranean Seismological Centre, France
Kate Huihsuan Chen, National Taiwan Normal University, Taiwan
Wen-Tzong Liang, Institute of Earth Sciences, Taiwan

Citation: Bossu, R., Chen, K. H., Liang, W.-T., eds. (2021). The Power of Citizen Seismology: Science and Social Impacts. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-88966-330-9

Table of Contents

frontiers in Earth Science

EDITORIAL
published: 12 November 2020
doi: 10.3389/feart.2020.610813

Editorial: The Power of Citizen Seismology: Science and Social Impacts

Kate Huihsuan Chen[1], Remy Bossu[2] and Wen-Tzong Liang[3]*

[1]Department of Earth Sciences, National Taiwan Normal University, Taipei, Taiwan, [2]European-Mediterranean Seismological Centre, Paris, France, [3]Institute of Earth Sciences, Academia Sinica, Nankang, Taiwan

Keywords: citizen seismology, social media, smart phone, earthquake monitoring, crowdsourced, education

Editorial on the Research Topic

The Power of Citizen Seismology: Science and Social Impacts

Citizen seismology that refers to research collaborations between seismologists and non-scientists volunteers is a growing field. In a place with poor coverage of seismic network, such collaborations provide an increasingly integrated data collections that make a real-time monitoring of earthquake possible. In an area with dense enough seismic network, it allows more public involvement that helps on the awareness and preparation toward seismic impact. The recently published special issue of "The power of citizen seismology: Science and social impacts" brings together experiences from different countries with different aspects. Below is a brief overview for their successes, challenges, and prospects.

The significant information of earthquakes can be gained through social media and smartphone. USGS "Did you feel it?" is one of the well-developed systems that collects shaking and damage reports from internet users shortly after the felt events in California, since 1999. In this special issue, Quitoriano and Wald demonstrate how eyewitnesses' observations guide the media and the public toward a more suitable way to describe the variations of earthquake shaking. In conjunction with "Did you feel it," the US based smartphone app "MyShake" delivers information for early warning purpose in California since 2019; In the article by Strauss et al., the context, programmatic elements, and challenges at the intersection of science, public communication, and technology is outlined. "Earthquake Network" app also collected information from smartphones globally for early warning purpose, which the history, main features, and problems are fully addressed in the article by Finazzi. Another powerful, EU based crowdsourced tool in EMSC website and LastQuake app are documented by Bondar et al., where they addressed the performance of EMSC-based CsLoc services on locating earthquake precisely and the development directions. Fallou et al. introduced how the users' experience helped on scientific discoveries through LastQuake, during a surprisingly large number of earthquake swarm in Mayotte in 2018. While Fallou et al. highlighted the importance of public communication during the earthquake, Bossu et al. and Yen et al. focused on augmenting data collection and rapid situation awareness for the destructive earthquake and tsunami.

Meanwhile, the availability of cheap sensors (Raspberry Shake or Quake Catcher Network) opened the way not only to provide advanced scientific exploration but also to structure communities of amateurs seismologists. The good examples include the increase in earthquake detectability down to magnitude 1.5–2.0 for the earthquakes in Haiti (by Calais et al.) and a new magnitude equation using the data collected during the 2014 M7.8 Gorkha earthquake in Nepal (by Subedi et al.). Jeddi et al. on the other hand, demonstrates the monitoring of earthquake, cryoseisms, and landslides in Arctic. In Taiwan, a near-real time earthquake competition game was

OPEN ACCESS

Edited and reviewed by:
Christine Thomas, University of Münster, Germany

****Correspondence:***
Kate Huishuan Chen
katepili@gmail.com

Specialty section:
This article was submitted to Solid Earth Geophysics, a section of the journal Frontiers in Earth Science

Received: *27 September 2020*
Accepted: *23 October 2020*
Published: *12 November 2020*

Citation:
Chen KH, Bossu R and Liang W-T (2020) Editorial: The Power of Citizen Seismology: Science and Social Impacts. Front. Earth Sci. 8:610813. doi: 10.3389/feart.2020.610813

developed for the citizen to process the location, magnitude, seismic intensity, and focal mechanisms for each inland M > 4 earthquakes, as introduced by Chen et al. With a lot more data collected from witnesses and volunteers, how the citizen gains a better understanding of seismology? In this special issue, there are also several articles focusing on the educational purpose including Bravo et al., Tang et al., and Chen et al. They address different classroom activities or online platform that may help the learning of real seismic data and scientific findings from the citizen contribution.

In summary, the innovative technologies have made the data exchange between citizens and the seismological community possible. With the growing volume of data, crowdsourced detections improve early warning of earthquake, rapid information education, and public awareness. For promoting citizen seismology in the future, a better link with urban seismology (as addressed in Diaz et al.) and improvement on the relationship between scientific facts, media reporting, and public communication (as addressed by Camilleri et al.) should be all considered. With the integrated efforts, an improved dialogue between science and society as well as the societal value of seismology can be expected.

AUTHOR CONTRIBUTIONS

KC wrote this article, while RB and W-TL provided comments for improvement on this brief overview.

Conflict of Interest: The 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.

Copyright © 2020 Chen, Bossu and Liang. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

PERSPECTIVE
published: 05 February 2020
doi: 10.3389/feart.2020.00009

Seismometers Within Cities: A Tool to Connect Earth Sciences and Society

Jordi Diaz, Martin Schimmel, Mario Ruiz and Ramon Carbonell*

Institute of Earth Sciences Jaume Almera, ICTJA-CSIC, Barcelona, Spain

The high degree of human activities in urban environments produces large background vibrations that makes it difficult to use data acquired in these areas for classical seismology. Seismometers installed within cities have been typically been used for the study of seismic hazard or for monitoring civil engineering problems. However, with the development of monitoring techniques based on the interpretation of the so-called seismic ambient noise, these data have gained scientific interest. Our objective is to discuss an additional utility of seismometers deployed within a city; its use as a tool to connect society with Earth sciences. Many citizen activities, from traffic to music concerts, produce vibrations that can be recorded seismically, and our experience shows that these records attract the attention of the media and social networks. With the emergence of low-cost and easy-to-use instruments in recent years, more citizens can now record ground motion and become interested in the interpretation of the recorded seismograms. The installation of permanent seismic networks in educational centers has proven to be a good approach to introduce students to Earth sciences at the national level and can also be developed at the urban scale using this new instrumentation. In this contribution we will first review the previous results related to the identification of the sources of vibration in urban areas and then present a new ongoing project based on the deployment of a seismic network in educational centers located in the city of Barcelona.

Keywords: urban seismology, seismic ambient noise, secondary schools, sources of ground vibrations, subsoil imaging

OPEN ACCESS

Edited by:
Remy Bossu,
European-Mediterranean Seismological Centre, France

Reviewed by:
Aurelien Dupont,
Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA), France
Xiaofeng Liang,
Institute of Geology and Geophysics (CAS), China

****Correspondence:***
Jordi Diaz
jdiaz@ictja.csic.es

Specialty section:
This article was submitted to Solid Earth Geophysics, a section of the journal Frontiers in Earth Science

Received: *19 November 2019*
Accepted: *17 January 2020*
Published: *05 February 2020*

Citation:
Diaz J, Schimmel M, Ruiz M and Carbonell R (2020) Seismometers Within Cities: A Tool to Connect Earth Sciences and Society. Front. Earth Sci. 8:9. doi: 10.3389/feart.2020.00009

INTRODUCTION

The high degree of human activities in urban environments results in a large level of background vibrations that often mask the arrival of seismic waves originated by earthquakes. Therefore, classical seismology, based on the identification of such waves, is difficult to achieve in urban environments. Most of the seismic recordings within cities are focused on refining the hazard maps used for risk assessment, typically using techniques as the microtremor horizontal to vertical spectral ratio to obtain the characteristic frequency of each site and hence characterize the subsoil. With the emergence of monitoring techniques based on the interpretation of the vibrations recorded in absence of earthquakes (Campillo and Paul, 2003), often referred as ambient noise, seismic records in noisy environments as cities have gained scientific interest, although the applicability of these methods in urban areas remains an open question.

In this contribution we will focus on a complementary use of seismic deployments in urban environments, directly related to the concept of "citizen science." The idea is to involve the secondary school community in the recording and interpretation of seismic data acquired within cities. Previous results have shown that many citizen activities produce vibrations that can be recorded seismically, including traffic (Riahi and Gerstoft, 2015), subway systems (Sheen et al., 2009), music concerts (Green and Bowers, 2008) or football games (Díaz et al., 2017). The identification of the vibrations generated by this kind of sources is useful to correctly interpret ambient noise data, but also to attract the attention of mass media (journals, radio, TV) and social networks and be used as a valuable tool for spreading news related to seismology and, in general, Earth sciences to the main public. The emergence of low cost seismic instruments connected to the global network has resulted in a densification of instruments installed in or near urban areas and the involvement of a significant number of amateur seismologists. This new community is an opportunity to create citizen seismological networks whose results could be used for scientific purposes, besides of attracting the interest of the youngest generation toward seismological research. We will first review the sources of ground vibration in urban areas and then present a new ongoing project based on the deployment of a seismic network in educational centers located in the city of Barcelona, that is expected to provide more information on the identification of such kind of sources.

CHARACTERIZATION OF THE SOURCES OF BACKGROUND VIBRATIONS IN URBAN ENVIRONMENTS

Since the early 2000s, several seismic networks have been deployed with the aim of investigating the uppermost crust using ambient seismic noise. Methods based on spatial autocorrelation of seismic data (SPAC, e.g., Okada, 2006) or on the analysis of the microtremor horizontal to vertical spectral ratio (MHVSR. e.g., Molnar et al., 2018) are widely used for site characterization. MHVSR is based on short-term recordings at multiple sites and usually does not take into consideration the origin of the recorded vibrations. In the last decades, seismic arrays acquiring data for periods of several weeks to months have been deployed in different cities. We can highlight the pioneering work carried out in Bucharest, where around 30 stations were deployed in the early 2000s to map the dominant sources of noise (Groos and Ritter, 2009) and investigate the uppermost shear wave velocity structure (Manea et al., 2016). A particular case is the deployment of 5200 sensors spaced 100 m away in the city of Long Beach (California, United States). The acquired data have proven that high resolution shear velocity structure can be recovered using ambient noise tomography in areas with high human activity (Lin et al., 2013). With regard to noise sources, road traffic and train transportation systems are the main contributors, although other moving sources, as aircraft departing and landing have also been identified (Riahi and Gerstoft, 2015). A recent work in the Benevento city (S. Italy) using accelerometers, short period and broad band stations has shown that the analysis of seismic noise using a small aperture array is a valid tool for subsurface characterization in urban areas even if using only a limited number of stations (Vassallo et al., 2019).

The biggest source of vibrations in urban areas are the road traffic and the train and subway transport systems. However, several other sources, both from natural and anthropogenic origin, are recorded regularly and their identification is often possible based on the spectral properties of the signals. **Figure 1** illustrates some examples of seismic signals recorded at different stations located within the city of Barcelona. **Figure 1A** shows the envelope of the vertical component of the seismic signal recorded at a station installed in the Monestir of Pedralbes, a monastery still in operation located at only 50 m of a subterranean section of the Barcelona ring road. This site was operated during one month to monitor the activity of this road as part of a documentary for a television network. The figure shows the vertical component of the seismic data, filtered between 8 and 12 Hz, during a period of 16 days (18th February–6th March 2017). Seismic energy at frequencies around 10 Hz is clearly related to the road traffic activity, as shown by its temporal changes in amplitude. Day/night and working day/week-end variations are easily identified in the data. Rush hours during business days appear in the morning and in the afternoon, but also around noon, as a large number of schools are located near this area and some of the students come back at home during lunch time. **Figure 2B** shows an example of the second major source of vibrations typically recorded within large cities, those induced by subway transport systems. The image reproduces the vertical component of the seismic record and the corresponding spectrogram for the BAIN accelerometric station, part of the ICGC network and installed in the center of Barcelona. The time variations in amplitude follow narrowly the operating times of the subway system, that runs between 5 am and 12 pm on business days, between 5 am and 2 am on Fridays and the 24 h between Saturdays and Sundays. The subway signal can be observed between 2 and 100 Hz, with highest amplitude in the 20–50 Hz band. **Figure 1C** shows an example of vibrations of natural origin recorded within the city. The seismic data in the 4–9 Hz band clearly shows the record of a short but heavy rainfall event the 15th November 2018. Returning to vibrations of man-made origin, **Figure 1D** presents the seismic signal recorded during the passage of the Barcelona marathon runners near the ICJA seismic station. The energy is concentrated in a narrow frequency band around 2.8 Hz, equivalent to 170 steps per minute, a typical pace for marathon runners. A careful inspection of the data shows that the first runners follow a higher pace than the rest of participants, as expected for sport events mixing professional and popular runners. Finally, **Figure 1E** shows a particular type of vibration recorded at the ICJA station, located at about 500 m of the FC Barcelona football stadium. The celebration of Barça fans after Messi's goals during a Champions League match between FC Barcelona and Liverpool FC are clearly recorded on the seismometer, spanning the seismic spectra between 2 and 7 Hz.

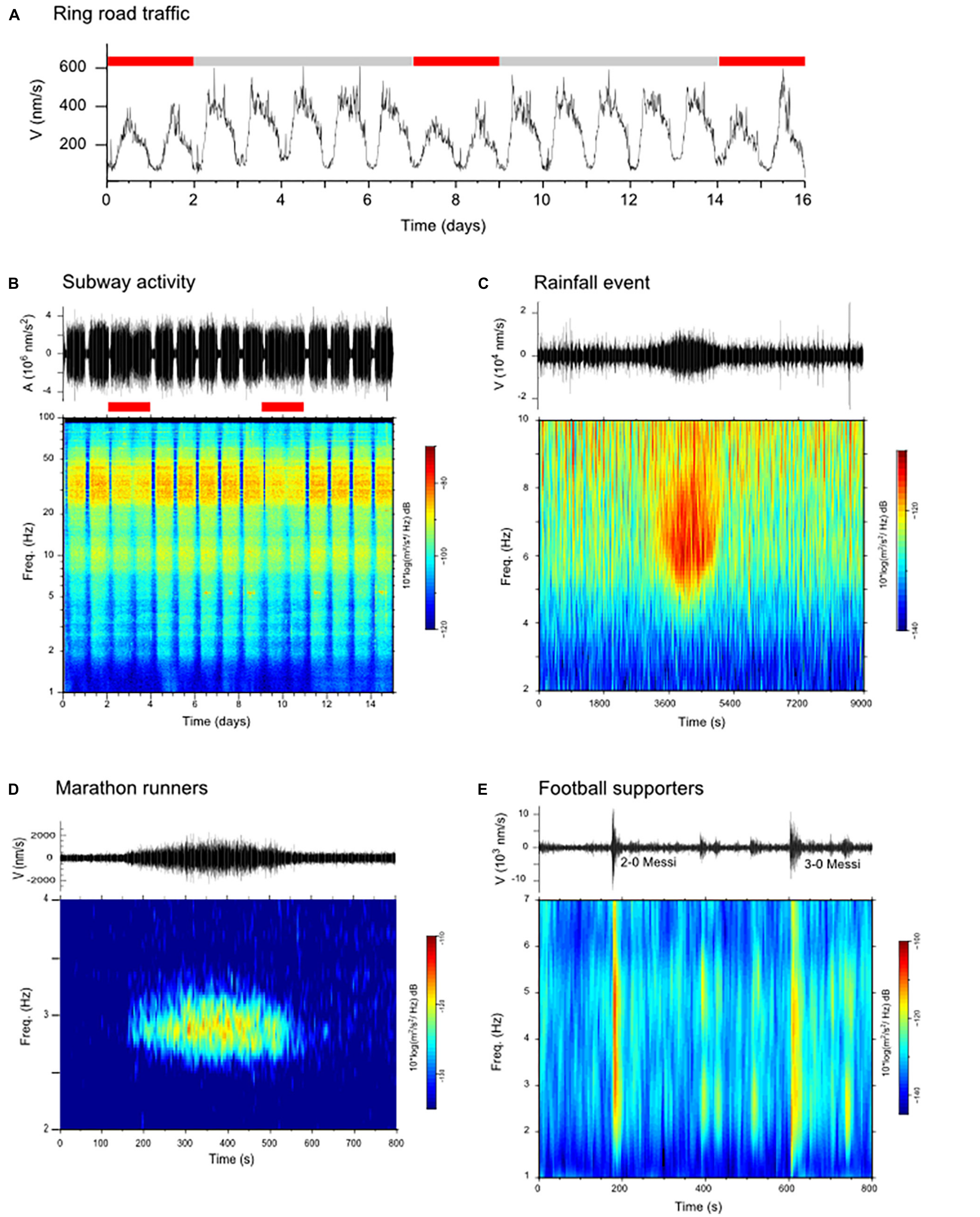


FIGURE 1 | Examples of non-tectonic seismic signals recorded in urban environments. **(A)** Envelope of the vertical seismic component at a site close to the Barcelona ring road, filtered between 4 and 12 Hz and decimated to six samples per hour. Red and gray bars show week-end and business days (18/2/2017–6/3/2017). **(B)** Vertical component and spectrogram for the CA.BAIN accelerometric station, installed in central Barcelona, showing the activity of the subway system. Week-end days are marked by red bars (1/11/2018–16/11/2018). **(C)** Seismic data (filtered between 4 and 8 Hz) and spectrogram recorded at CA.ICJA during a heavy rainfall event the 15/11/2018. **(D)** Seismic record (filtered between 2.4 and 3.4 Hz) and spectrogram of the passage of the Barcelona Marathon runners near the CA.ICJA seismic station (11/3/2018). **(E)** Seismic record at the CA.ICJA station during the FCB-Liverpool Champions League match (1/5/2019), showing the shaking generated by the supporters celebration of Messi's goals.

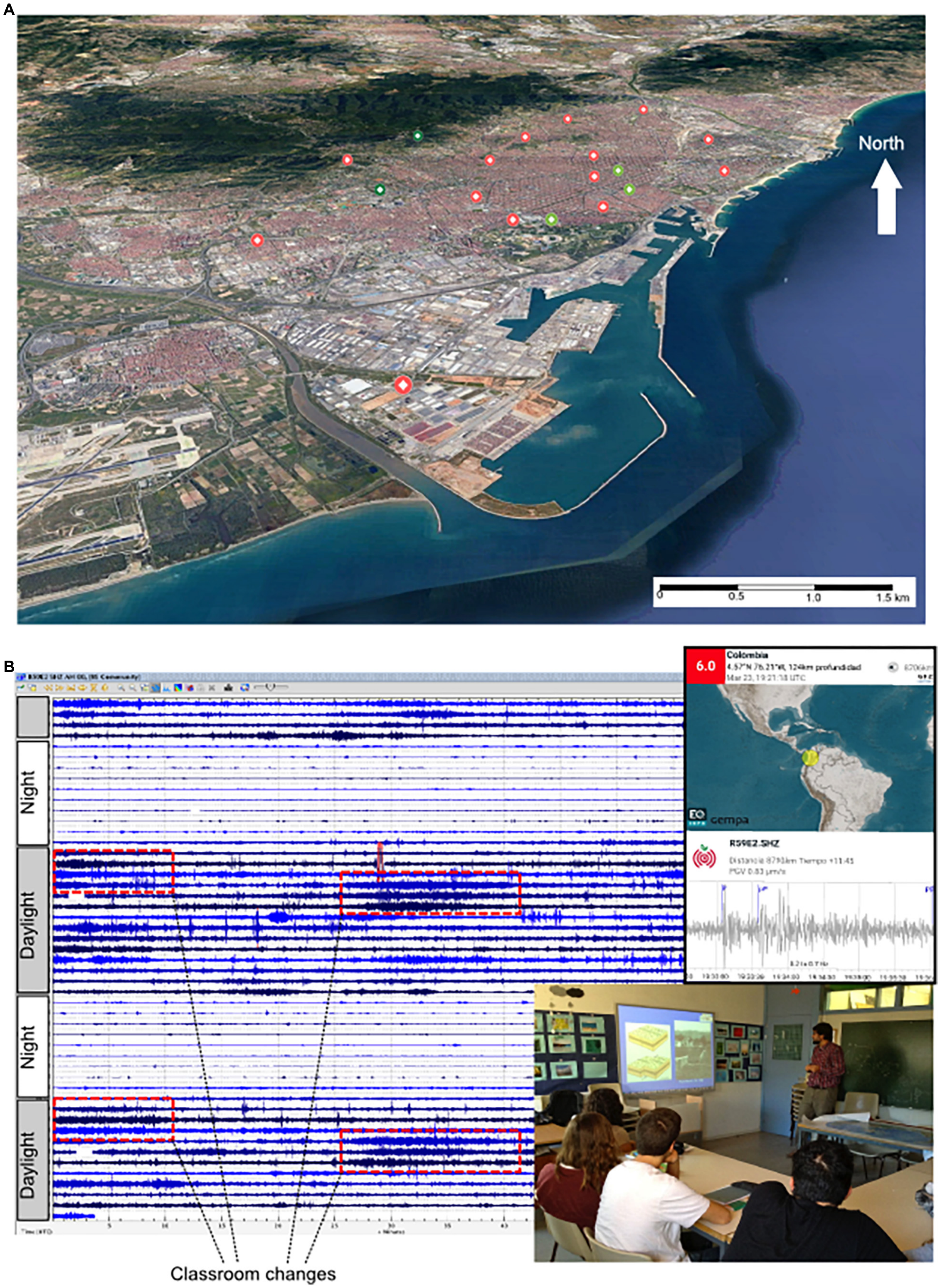


FIGURE 2 | Deployment of seismic stations in secondary schools. **(A)** Map view of the seismic stations deployed in secondary schools within the Barcelona area. Red dots show the newly deployed stations, while light and dark green dots show the available broad-band and accelerometric stations. **(B)** Example of seismic records in a secondary school in Barcelona (1 h per line) clearly showing the day/night variations and the scholar activity pattern; red dashed boxes show the 5 min-long periods of larger noise observed every hour during classroom changes. The upper side panel shows an example of the seismic alerts that can be received by the students using mobile phone apps, while the lower side panel illustrates the dissemination talks given in schools.

The identification of the noise sources and their spatial distribution is of great interest to correctly process and interpret the ambient noise data. The seismic waves generated by these sources travel through the shallow subsoil and, depending on their characteristics, can be used with different analysis techniques to study the seismic structure beneath pavements and buildings.

THE ROLE OF CITY EDUCATIONAL SEISMIC NETWORKS

Seismic networks installed in educational centers have been developed throughout the world during the last decades. Some of the most successful examples are the different educational networks integrated in the project "Seismographs in school," promoted by the Incorporated Research Institutions for Seismology (IRIS) in the United States[1], the United Kingdom "Schools Seismology Network" administered by the British Geological Survey[2], the Australian AuSIS network[3], the french "Sismo à l'école" projects[4] or the "Seismology in Schools" project managed by the Dublin Institute for Advanced Studies (DIAS) in Ireland[5]. These initatives have proven to be useful for connecting the students to Earth sciences, in particular in regions with moderate levels of seismic activity (e.g., Courboulex et al., 2012; Balfour et al., 2014). Data from some of these networks are nowadays distributed through the FDSNW service following the same protocol than for scientific networks.

In this contribution we want to present a new initiative carried out in Spain as part of a research project founded by the Spanish Ministry of Science, Research and Innovation. This network, installed during November 2019, has the particularity of having a high resolution scale, since it covers an area of approximately 10 km^2 within the city of Barcelona with 14 temporary stations and integrating the five permanent sites already on duty. Twelve of the temporary sites have been installed in the premises of secondary schools, seeking to involve educational centers in the city to participate in the project. In return, students in those centers will be trained in the use of seismic instruments and the first analysis of the data. The objective is to close the gap between educational and research objectives, as the project aims to promote the knowledge on seismology and Earth Science among secondary school students, but also acquire data of scientific interest to investigate the feasibility of ambient noise studies in urban environments. The same project includes also the deployment of broad-band stations and high-resolution nodes in the eastern Pyrenees, to analyze the subsoil with similar methods but in a calmer environment.

Figure 2A shows a map view of the seismic stations that have been deployed in Barcelona. Red dots mark the new stations, while light and dark green dots show the available broad-band and accelerometric stations. The geometry of the network has been chosen to sample the main geological units of the Barcelona area. The network, expected to remain operative until the summer 2020, benefits from both professional three component short period instruments and one-component RaspberryShake (RS) seismometers equipped with 4.5 Hz[6]. It is planned that both kind of instruments will cover each site in different time periods to benefit from their respective advantages. Professional seismometers provide high quality data, but are difficult to be accessed in real time due to limitations in internet connectivity implemented in most educational centers for security reasons. The RS instruments have been designed to avoid these problems by transmitting the recorded data to an external data management center, an approach that makes easier the data collection for scientific objectives. However, as the data are sent through the network, they are more likely to contain gaps that can make it difficult to apply seismic methods based on the analysis of ambient seismic noise. It can be noted that RS instruments have been compared with geophones in field experiments with good results (Anthony et al., 2018).

With respect to the educational objectives of the project, the underlying idea is to use of the fascination power of earthquakes to introduce students in Earth Sciences and stimulate their motivation to continue learning using the multiple tools available online. Our experience shows that students are attracted to directly see how the waves from distant earthquakes shake the school building in a detectable way, a fact that seems obvious to Earth scientists, but that is surprising to people without training in this field. More generally, students will be introduced to the development of a research project, from its initial planning to the final presentation of the obtained results.

During the deployment of the seismometer in the secondary schools, an introductory talk is given to the students (**Figure 2B**), with the main objective of increasing their curiosity about issues related to seismology and, in particular, how seismic waves are recorded and what information can be retrieved from their study. The research team has a long tradition in dissemination projects, because since 2009 it has been regularly offering a workshop named "Looking for Earthquakes" to secondary schools in and around Barcelona. This introductory talk is complemented in this case by a hands-on session in which the data acquired in each school are inspected. Students first notice the day/night and business day/weekend variations of the background noise, as well as the noise variations directly related to the scholar activity; e.g., the intervals of about 5 min of higher amplitude correspond to the classroom changes that students usually make every hour (**Figure 2B**). These observations can be used to develop students' abilities to read and interpret graphs, propose hypotheses to explain the data and seek additional information to validate or not the hypothesis. Students can also investigate aspects directly related to Earth sciences, as the distribution and rate of occurrence of earthquakes, their relationship with plate tectonics, the concepts of intensity and magnitude and the aspects related to seismic hazards, all of them elements included

[1] https://www.iris.edu/hq/sis
[2] http://www.bgs.ac.uk/schoolSeismology/
[3] https://auspass.edu.au/networks/ausis.html
[4] http://edumed.unice.fr
[5] https://www.dias.ie/sis/
[6] https://raspberryshake.org/products/raspberry-shake-1d/

in the official curricula. The students are invited to use phone apps as EqInfo[7], which allow them to track in real time seismic detections in the network stations (**Figure 2B**). The research team will support the centers most committed to the project with guidance and appropriate software tools so that students can locate earthquakes and study the propagation of seismic waves.

The degree of involvement of each school will vary depending on their respective pedagogical plans. For example, the installation of the seismic network can be used to implement transversal educational projects that involve not only the natural sciences, but also physics, technology, and even social sciences. Seismometers can be used to study the pendulum laws, electromagnetic induction, elastic wave propagation or frequency analyses. The network can also be a motivation to develop technological projects with the objective of designing in-house seismometers based in existent and affordable elements and to develop programing exercises for processing the recorded data. Finally, aspects related to social sciences, including the economic aspects of seismic risk or the historical interest of the most reputed philosophers in the origin of earthquakes and the Earth internal structure can also be addressed. The scientific team will provide support to the centers that decide to carry out this type of initiatives.

With respect to the scientific objective of the Barcelona scholar seismic network, the acquired data will be first used to map in detail the sources of vibrations around the city, an information that is relevant to check its applicability for tomographic investigations (e.g., Yang and Ritzwoller, 2008). The data will be used to verify and expand the MHVSR studies already available in the Barcelona zone (Cadet et al., 2011 and references therein). Having continuous records for several months will make it possible to verify whether temporal variations in background noise can affect the MHVSR measurements. Salinas et al. (2014) have already pointed that f_0 resonance peaks retrieved from MHVSR studies can vary strongly between very close sites and Macau et al. (2015) have also observed that some locations in the Barcelona conurbation present two HVSR peaks, which makes it difficult to determine what the representative value for engineering studies is.

Finally, we plan to use also the data to test the applicability of the methods based on Rayleigh wave ellipticity inversion (e.g., Berbellini et al., 2019) and ambient noise tomography (e.g., Nuñez et al., 2019) in an urban environment. Since the noise tomography approach relies on a diffusive noise wave field, that is, without directivity, it is not clear whether or how well it can be used in an active environment such as Barcelona. However, the characterization of the sources discussed previously may help to select appropriate time windows and hence allow to extract inter-station surface wave Green's functions as required for the tomographic images of the shallow structure beneath Barcelona. Although the viability of such approaches is medium/low, if the data allows to obtain tomographic images on the subsurface levels below a city, this will have a high impact in hazard and risk assessment. Therefore, this task can be considered as a high risk/high impact study.

[7] https://www.gempa.de/news/?t=EQInfo

CONCLUDING REMARKS

Although the most obvious way to involve citizen to Earth sciences is to share information about the local effects of natural seismicity, other forms of involvement can be explored. We propose here to focus the attention on secondary schools students by installing seismometers in their centers and involve the students in their management, with the ultimate goal of developing their curiosity about the sources of the recorded vibrations and, in general, providing hypotheses to explain data.

We are convinced that this can be a positive approach to increase the interest of society toward Earth sciences, in particular in countries not often affected by large earthquakes. The presence of Earth sciences in the curricula of secondary education has been decreasing in recent years in Spain and we believe it is urgent to promote actions to attract students' attention to this field.

Our experience has shown that we can have a relatively high impact on social networks (Twitter, Facebook, Instagram) and mass media by unraveling and making the public aware that seismic sensors can detect activities such as traffic, subway trains or citizen activities as football games, music concerts or fireworks. We believe that attracting the attention of the public is of maximum interest for the future of our research field.

In addition to these aspects related to dissemination, we expect that data obtained by citizen networks installed in educational centers within the city of Barcelona can be useful from a scientific point of view, as the characterization of the sources of background vibrations in urban environments is of great interest to study the seismic structure beneath pavements and buildings using ambient noise data and hence make possible a better imaging of the geology beneath the city and an improving of the available seismic hazard maps.

DATA AVAILABILITY STATEMENT

The datasets analyzed for this study can be found in the ORFEUS Data Center (http://www.orfeus-eu.org/fdsnws/dataselect/1/) and in the Institut Cartográfic i Geológic de Catalunya repository (http://ws.icgc.cat/fdsnws/dataselect/1/).

AUTHOR CONTRIBUTIONS

JD, MS, MR, and RC contributed to the conception and design of the project. MR organized the database of the seismic data. JD wrote the first draft of the manuscript and figures. All authors contributed to manuscript revision, read and approved the submitted version.

FUNDING

This is a contribution of the SANIMS project (RTI2018-095594-B-I00), funded by the Spanish Ministry of Science, Innovation and Universities, with additional support from the Generalitat de Catalunya grant 2017SGR1022.

REFERENCES

Anthony, R. E., Ringler, A. T., Wilson, D. C., and Wolin, E. (2018). Do low-cost seismographs perform well enough for your network? An overview of laboratory tests and field observations of the OSOP raspberry shake 4D. *Seis. Res. Lett.* 90, 219–228. doi: 10.1785/0220180251

Balfour, N. J., Salmon, M., and Sambridge, M. (2014). The Australian seismometers in schools network: education, outreach research, and monitoring. *Seismol. Res. Lett.* 85, 1063–1068. doi: 10.1785/0220140025

Berbellini, A., Schimmel, M., Ferreira, A. M. G., and Morelli, A. (2019). Constraining S -wave velocity using Rayleigh wave ellipticity from polarization analysis of seismic noise. *Geophys. J. Int.* 216, 1817–1830. doi: 10.1093/gji/ggy512

Cadet, H., Macau, A., Benjumea, B., Bellmunt, F., and Figueras, S. (2011). From ambient noise recordings to site effect assessment: the case study of Barcelona microzonation. *Soil Dyn. Earthq. Eng.* 31, 271–281. doi: 10.1016/j.soildyn.2010.07.005

Campillo, M., and Paul, A. (2003). Long range correlations in the diffuse seismic coda. *Science* 299, 547–549. doi: 10.1126/science.1078551

Courboulex, F., Berenguer, J. L., Tocheport, A., Bouin, M. P., Calais, E., Esnault, Y., et al. (2012). Sismos à l'Ecole: a worldwide network of real-time seismometers in schools. *Seismol. Res. Lett.* 83, 870–873. doi: 10.1785/0220110139

Díaz, J., Ruiz, M., Sánchez-Pastor, P. S., and Romero, P. (2017). Urban seismology: on the origin of earth vibrations within a city. *Sci. Rep.* 7:15296. doi: 10.1038/s41598-017-15499-y

Green, D. N., and Bowers, D. (2008). Seismic raves: tremor observations from an electronic dance music festival. *Seismol. Res. Lett.* 79, 546–553. doi: 10.1785/gssrl.79.4.546

Groos, J. C., and Ritter, J. R. R. (2009). Time domain classification and quantification of seismic noise in an urban environment. *Geophys. J. Int.* 179, 1213–1231. doi: 10.1111/j.1365-246x.2009.04343.x

Lin, F., Li, D., Clayton, R. W., and Hollis, D. (2013). High-resolution 3D shallow crustal structure in Long Beach, California: application of ambient noise tomography on a dense seismic array. *Geophysics* 78, Q45–Q56. doi: 10.1190/geo2012-0453.1

Macau, A., Benjumea, B., Gabàs, A., Figueras, S., and Vilà, M. (2015). The effect of shallow quaternary deposits on the shape of the H/V spectral ratio. *Surv. Geophys.* 36, 185–208. doi: 10.1007/s10712-014-9305-z

Manea, E. F., Michel, C., Poggi, V., and Donat, F. (2016). Improving the shear wave velocity structure beneath Bucharest (Romania) using ambient vibrations. *Geophys. J. Int.* 207, 848–861. doi: 10.1093/gji/ggw306

Molnar, S., Cassidy, J. F., Castellaro, S., Cornou, C., Crow, H., Hunter, J. A., et al. (2018). Application of Microtremor Horizontal-to-Vertical Spectral Ratio (MHVSR) analysis for site characterization: state of the art. *Surv. Geophys.* 39, 613–631. doi: 10.1007/s10712-018-9464-4

Nuñez, E., Schimmel, M., Stich, D., and Iglesias, A. (2019). Crustal velocity anomalies in costa rica from ambient noise tomography. *Pure Appl. Geophys.* 1–20. doi: 10.1007/s00024-019-02315-z

Okada, H. (2006). Theory of efficient array observations of microtremors with special reference to the SPAC method. *Explor. Geophys.* 37, 73–85. doi: 10.1071/eg06073

Riahi, N., and Gerstoft, P. (2015). The seismic traffic footprint: tracking trains, aircraft, and cars seismically. *Geophys. Res. Lett.* 42, 2674–2681. doi: 10.1002/2015gl063558

Salinas, V., Caselles, J. O., Pérez-Gracia, V., Santos-Assunçao, S., Clapes, J., Pujades, L. G., et al. (2014). Nanozonation in dense cities: testing a combined methodology in Barcelona City (Spain). *J. Earthq. Eng.* 18, 90–112. doi: 10.1080/13632469.2013.841601

Sheen, D. H., Shin, J. S., Kang, T. S., and Baag, C. E. (2009). Low frequency cultural noise. *Geophys. Res. Lett.* 36, 1–5. doi: 10.1029/2009GL039625

Vassallo, M., De Matteis, R., Bobbio, A., Di Giulio, G., Adinolfi, G. M., Cantore, L., et al. (2019). Seismic noise cross-correlation in the urban area of Benevento city (Southern Italy). *Geophys. J. Int.* 217, 1524–1542. doi: 10.1093/gji/ggz101

Yang, Y., and Ritzwoller, M. H. (2008). Characteristics of ambient seismic noise as a source for surface wave tomography. *Geochem. Geophys. Geosyst.* 9:Q02008. doi: 10.1029/2007GC001814

Conflict of Interest: The 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.

Copyright © 2020 Diaz, Schimmel, Ruiz and Carbonell. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

ORIGINAL RESEARCH
published: 09 April 2020
doi: 10.3389/feart.2020.00073

Check for updates

Seismology at School in Nepal: A Program for Educational and Citizen Seismology Through a Low-Cost Seismic Network

Shiba Subedi[1]*, György Hetényi[1], Paul Denton[2†] and Anne Sauron[3]

[1] Institute of Earth Sciences, Faculty of Geosciences and Environment, University of Lausanne, Lausanne, Switzerland, [2] British Geological Survey, Nottingham, United Kingdom, [3] HES-SO Valais-Wallis, Sion, Switzerland

OPEN ACCESS

Edited by:
Remy Bossu,
European-Mediterranean Seismological Centre, France

Reviewed by:
Gerasimos Chouliaras,
National Observatory of Athens, Greece
Emily Wolin,
USGS Albuquerque Seismological Laboratory (ASL), United States

***Correspondence:**
Shiba Subedi
shiba.subedi@unil.ch

†Present address:
Paul Denton,
Denton Seismo Ltd., Oakham, United Kingdom

Specialty section:
This article was submitted to Solid Earth Geophysics, a section of the journal Frontiers in Earth Science

Received: 09 December 2019
Accepted: 28 February 2020
Published: 09 April 2020

Citation:
Subedi S, Hetényi G, Denton P and Sauron A (2020) Seismology at School in Nepal: A Program for Educational and Citizen Seismology Through a Low-Cost Seismic Network. Front. Earth Sci. 8:73. doi: 10.3389/feart.2020.00073

Nepal, located above the convergent India-Eurasia plate boundary, has repeatedly experienced devastating earthquakes. During the 2015 magnitude 7.8 Gorkha earthquake, an often-reported experience was that people were not aware of the threatening seismic hazard and had an insufficient level of preparedness. An important source of the problem is that earthquake-related topics are not part of the school curriculum. Earthquake education reaching a broad group of the population early in their lives is therefore strongly needed. We established an initiative in Nepal to introduce seismology in schools, with a focus on education and citizen seismology. We have prepared educational materials adapted to the Nepali school system, which we distributed and also share on our program's website: http://seismoschoolnp.org. In selected schools, we also installed a low-cost seismometer to record seismicity and to allow learning-by-doing classroom activities. Our approach was very well received and we hope it will help make earthquake-safe communities across Nepal. The seismic sensor which we installed in schools is a Raspberry Shake 1D (RS1D), this was selected based on its performance in laboratory tests and suitability for the field conditions. At a test site in Switzerland we were able to record magnitude 1.0 events up to 50 km distance with a RS1D. In Nepal, 22 such seismometers installed in schools create the Nepal School Seismology Network providing online data openly. The seismometer in each school allows students to be informed of earthquakes, visualize the respective waveforms, and estimate the distance and magnitude of the event. For significant local and regional events, we provide record sections and network instrumental intensity maps on our program's website. In 6 months of network operation, more than 194 local and teleseismic earthquakes of $M \geq 4$ have been recorded. From a local and a global catalog, complemented with our own visual identifications, we have provided an earthquake wave detectability graph in distance and magnitude domain. Based on our observations, we have calibrated a new magnitude equation for Nepal, related to the epicentral distance *D [km]* and to the observed peak vertical ground velocity PGV_V *[μm/s]*. The calibration is done to best fit local catalog magnitudes, and yields the following equation: $M = 1.05 \times \log_{10}(PGV_V) + 1.08 \times \log_{10}(D) + 0.75$.

Keywords: educational seismology, citizen science, seismic hazard, earthquake magnitude, Nepal

INTRODUCTION AND BACKGROUND

Nepal is located above the Himalayan convergent plate boundary between the Indian and Eurasian plates (Aitchison et al., 2007), and consequently in the heart of the most active continental seismic hazard zone. The recent geological and geodetic shortening accommodated across the Himalayas is about 2 cm/yr (Bilham et al., 1997; Lavé and Avouac, 2001; Jouanne et al., 2004; Zheng et al., 2017). The surface expression of this shortening is the Main Frontal Thrust, which continues at depth, to about 15 km below the surface, for more than 100 km toward the North, forming the Main Himalayan Thrust (Cattin and Avouac, 2000; Duputel et al., 2016; Elliott et al., 2016). This is the megathrust interface which hosts major earthquakes all along the 2’500 km long Himalayan range. The mountain belt has experienced devastating earthquakes throughout the geological, historical and recent past, claiming lives and causing significant damage. Nepal, in the central part of the Himalaya, occupies nearly one third of the mountain belt, and is the home of ca. 30 million people who live in a very high seismic hazard zone.

The largest instrumentally recorded earthquake in Nepal, the 1934 Mw8.2 event has been followed by the Mw7.8 Gorkha earthquake and a second, Mw7.3 event in 2015 in Central Nepal (**Figure 1**). Paleoseismic investigations along strike of the active frontal thrust reveal further large historical earthquakes (e.g., Bollinger et al., 2016), the oldest known earthquake described in a primary source having occurred in 1223 (Bollinger et al., 2016), but its description remains unreadable due to defaced letters and words. The greatest event in Nepal, which is also the most recent great earthquake in Western Nepal, occurred in 1505, as reported in historical chronicles (Ambraseys and Jackson, 2003; Ghazoui et al., 2019). The elapsed time since then leads to the existence of a well-identified seismic gap in which another large earthquake is due (Bollinger et al., 2016). This fits the overall view of the seismic cycle in the Himalayas, which has recorded a major earthquake all along the mountain belt in the past 500 years (Hetényi et al., 2016). Earthquakes are the most common and most deadly natural disaster in Nepal, claiming more than 19 thousand lives since 1934, which is more than 80% of the total casualties from natural disasters (Ministry of Home Affairs [Moha], 2015).

Despite the clearly high seismic hazard, permanent seismological observatories with open data are rare in the region (**Figure 1**). The only government facility in Nepal is the National Seismological Center (NSC), which has been operating a permanent seismic network for decades within the framework of international collaboration, and is currently operating 21 short-period and broadband stations in the country. The NSC publishes earthquake information to the population for earthquakes inside Nepal when the local magnitude M_L equals or exceeds 4. Other seismic networks in the area are typically temporary research networks, they are installed for a few years, but their data is only openly accessible after a few years of delay and in a format far less comprehensible to the general public.

Scientific results based on these seismological data are abundant and should be acknowledged for pushing the limits of knowledge in an area where fieldwork conditions are not straightforward. Geophysically imaging the structure of the orogen at depth (e.g., Schulte-Pelkum et al., 2005; Nábělek et al., 2009; Singer et al., 2017; Subedi et al., 2018) is very important to establish quantitative models of seismic hazard. Locating the seismicity both during the inter- and the post-seismic periods (e.g., Bollinger et al., 2007; Adhikari et al., 2015; Diehl et al., 2017; Hoste-Colomer et al., 2018) are equally important to understand the mechanical behavior and dynamics of the orogenic wedge. Nevertheless, state-of-the-art geoscience knowledge reaches only a very small fraction of the population. For example, recent publications report that there is an increased risk of a future major ($M > 8$) earthquake in the area between west of Nepal and India (Galetzka et al., 2015; Avouac et al., 2015), and recent estimates of average return period for great earthquakes ranges from 300 to 870 years plus uncertainties (Avouac et al., 2001; Bollinger et al., 2014). However, the local population has almost no information about these recent findings.

What the local population is aware of are their own felt-earthquake experiences, the fresh memory of the 2015 Gorkha earthquakes, and the announcements of the NSC ($M_L \geq 4$ events in Nepal). The latter information is spread through the NSC webpage[1], through social media, and – with some time lag – through newspapers and online articles. Still, the general level of information about what a person should do in case of a seismic event is surprisingly low. Citizen’s awareness is a key element for seismic risk mitigation, which is clearly missing in the field. Some efforts by various organizations after the 2015 Gorkha earthquake around the capital city Kathmandu were initiated, but these have not reached people in the countryside. The majority of Nepal’s population has either a mythological perception or no clear idea about what causes earthquakes and what is the best behavior and practice to protect themselves. In addition, ways to communicate about earthquakes and related topics are not well established in the community.

Our initiative aims to tackle two challenges with a combined approach, for which we start our program in an area of high seismic hazard but relatively limited (although not the lowest) level of information in the country. First, it is crucial to increase the awareness of the local population about the fact that they live in a region where the accumulated energy is sufficient to produce a large earthquake. Second, we need to teach and train citizens in the community for better preparedness and what actions they can undertake to lower their chances of being hurt. In the countryside, no other source of information like television and newspapers are easily accessible, and also in cities it is difficult to gather knowledge from these kinds of sources. Hence, we found that the best way to engage people in learning about earthquakes is through the educational system, as what information students receive at school can be transmitted to their families and communities most efficiently.

In order to undertake this approach, it is necessary to connect communities to citizen science in Nepal. That is why we installed the first 22 low-cost seismic stations in local schools as a part of the Nepal School Seismological Network (**Figure 1**). This network is already used both for teaching and for sharing locally

[1] www.seismonepal.gov.np

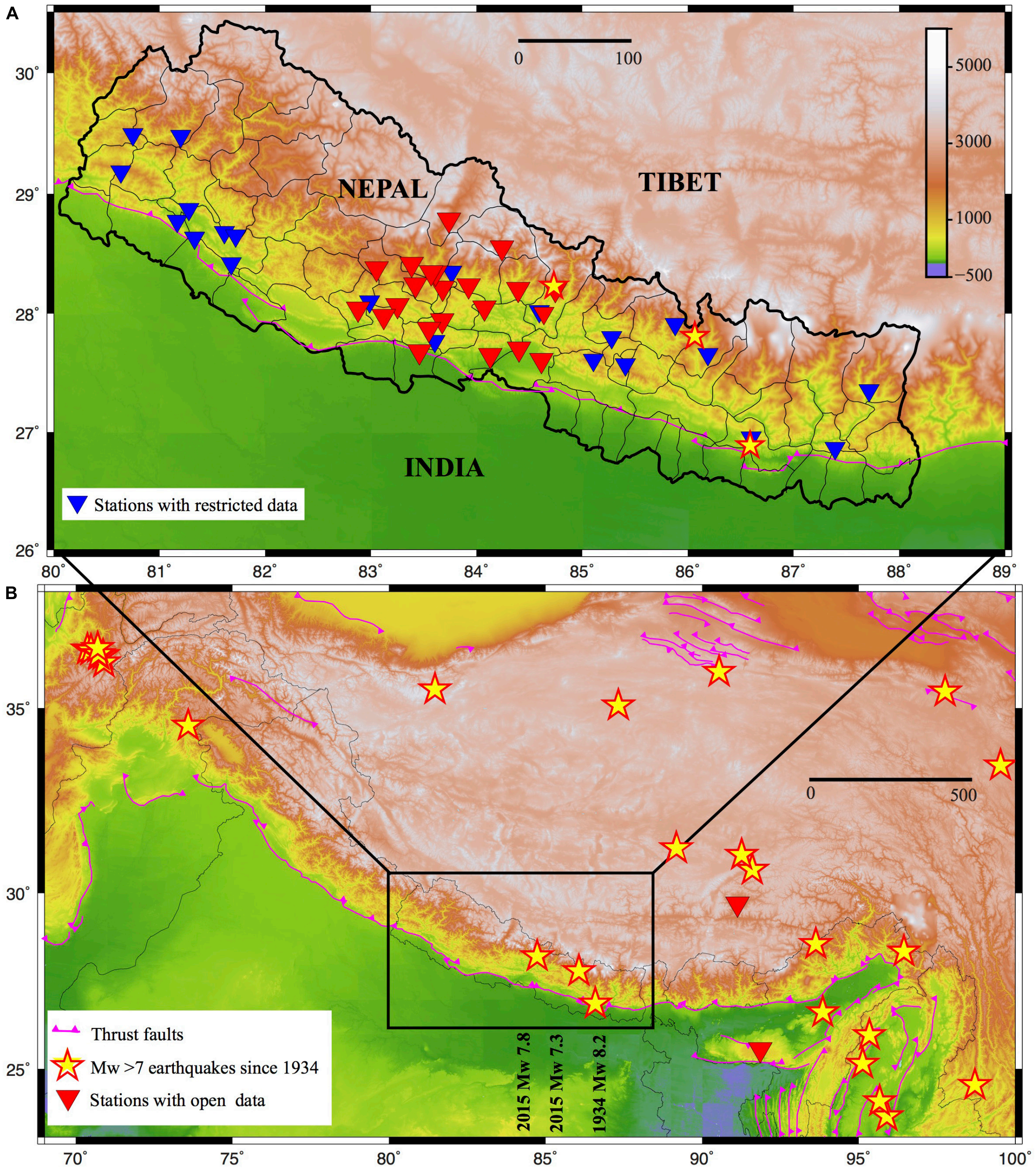


FIGURE 1 | Studied area maps. **(B)** The Himalaya-Tibet region, with large and great earthquakes ($M \geq 7$) since 1934 from the USGS catalog (https://earthquake.usgs.gov/earthquakes/search/). Permanent seismic stations with open data are shown in red. **(A)** Focus on Nepal, showing 21 permanent seismic stations of the National Seismological Center with restricted data in blue, and 22 Nepal School Seismology Network (this project) stations in Western Nepal with open data in red. Pink lines are thrust faults in the area (Styron et al., 2010). Distance scales are in kilometers.

recorded data openly. We hope that the example set in Western Nepal will spread across the entire country, and that our program helps to make earthquake-safer communities.

PREPARATORY PHASE

The project's preparatory phase included planning, laboratory, logistic and field work, which we carried out as mostly parallel tasks as follows: (1) definition of the study area and site planning, (2) preparation of educational material, (3) seismic sensor survey, testing and selection. This section describes our approach in detail, and the next section focuses on the implementation in Nepal.

Site Selection

Within the broader frame of educational activities, we planned to build the Nepal School Seismic Network (NSSN) in western Nepal (83–85°E) over an area of ca. 200 km east-west extent, including the epicenter village of the 2015 Gorkha earthquake and westwards from there. The area is relatively densely populated, but is too far from the capital Kathmandu to be included in initiatives aiming to implement earthquake education. There were some case studies for earthquake risk management and risk mitigation in the Kathmandu valley (Asian Disaster Preparedness Center [ADPC], 2000; Moha/Hmgn-Jica, 2002). However, even after the 2015 Gorkha earthquake, when national and international non-governmental organizations had tried to initiate earthquake preparedness projects around Kathmandu for local people, the efforts remained geographically limited (see e.g., the following reports and websites on disaster management and safer constructions: https://www.usaid.gov/sites/default/files/documents/1861/Pages%202-3.pdf, http://www.safernepal.net, https://www.rosie-may.com/2017/07/28/rebuild-nepal/; other projects are on the way]. Our approach, located away from the capital, is different, and complementary in scope.

To the best of our knowledge, no efforts have been reported outside the Kathmandu valley for educational and citizen seismology. We have selected Western Nepal to start our program because (i) people have very limited to no opportunity to learn about earthquakes, (ii) there was no major earthquake in the last 500 years and therefore the probability of such an event is high, and (iii) travel time between the different sites is within reasonable bounds. The main goal in setting up the NSSN was therefore to establish a broadly and possibly homogeneously distributed network across the region, to initiate earthquake education in schools and also to build a seismic network able to provide useful data for both education and basic research. To establish a broad base for site selection, we used social media (*facebook* and *twitter*, both popular in Nepal) to spread information about our program, and also asked interested schools to fill out a request form. An excellent knowledge of the region's geography and social relations, as well as communications skills were required for this step. The non-Nepali co-authors of this work believe that foreigners alone would have had no chance to start and implement this project due to a lack of sufficient local contacts and knowledge of Nepali society.

More than 100 schools submitted a request form from the defined study area. Out of these, we selected 22 along the criteria for good sites as follows:

- the school hosts a large number of students from the area,
- high motivation of the school administrative board,
- feasibility to install the seismometer on the ground floor,
- school located relatively far from a major road, village, or city, to avoid cultural noise (minimum distance from a road or highway must be 200 m),
- the school having its own internet connection and alternate power supply (technical priority criteria),
- the school is reachable by vehicle or short walk.

Each submitted form was evaluated individually to see which site met as many criteria as possible. In many cases, compromises were necessary. We also aimed to have an overall geographical distribution of schools that covers the study area evenly. With the final selection of sites, we covered the administrative regions of Province 5 and Gandaki Province in western Nepal. Finally, to prepare the field implementation phase, we have validated our remote site choices by visiting all schools in person during a reconnaissance trip in April-May 2018. The selected school's name is listed in **Supplementary Table 1**, the map of the NSSN is shown in **Figure 1**, and photos of two typical school buildings are shown in **Figure 2**.

Educational Materials

School education in Nepal occurs at basic and secondary level (**Table 1**). Schooling begins with basic level and the school starting age for children is 5 years old; however, attendance is not compulsory. As of the 2017 Department of Education survey, a total of 35′222 operational schools (from grade 1) received a total of 7′752′601 pupils (Department of Education [DOE], 2017), which is more than 25% of Nepal's population. We therefore believe that the schools are the best platforms to share the required knowledge with the community, as relevant education not only teaches the children, but, through their families also reaches further into society. Seismology is not part of the curriculum in schools, a problem we aim to tackle in our program toward better preparedness.

In the context of Earth science education in Nepal, we could find only very limited information about earthquakes in textbooks. We therefore based our approach on existing educational seismology projects around the world. There are a number of similar initiatives running currently (or until recently), mostly in developed countries, such as the United Kingdom school seismology project, the Swiss Seismo@school project, the Irish Seismology in Schools project, the Texas Educational Seismic Project (United States), and the Australian Seismometers in Schools project. We have held discussions with specialists from different countries to gain knowledge from their experiences and to build up ideas for the educational material development for Nepal. We also looked for existing materials which might be suitable for our purpose and context. Numerous suggestions and experiences shared by experts were taken into account in the preparation of several educational materials adapted to the Nepali school system and language.

One of the most important educational material is a flyer, as partially shown in **Figure 3A**. This leaflet was designed by the Earthquake Education Center in Sion, Switzerland and translated into Nepalese for our schools. This leaflet delivers detailed information on how to prepare before an earthquake, how to save one's life during an earthquake, and what to do after an earthquake, well-illustrated with drawings and sketches. Information about the contact person and/or office in case of an earthquake, and games related to earthquakes for kids are also included in the flyer. Further educational tools were prepared in advance of our field visit, which we describe in detail under the implementation phase of the project in section "Educational Implementation."

FIGURE 2 | School buildings participating in our program. **(A)** *Shree Himalaya Secondary School* in Barpak, *Gorkha* district. A reinforced cement concrete (RCC) building was newly constructed after the 2015 Gorkha earthquake. A total of 672 students study in the school. **(B)** *Shree Bhanubhakta Acharya Secondary School* in Galyang, *Syangja* district. RCC building, but the third story is not cemented: it is brick, with tin roof on top. A total of 925 students study in this school.

TABLE 1 | Education system in Nepal and key numbers, according to Department of Education [DOE] (2017).

Education level	Grade	Student age (year)	Number of schools	Number of students
Early childhood	–	<5	36'568	958'127
Basic	1–5	5–9	35'211	3'970'016
	6–8	10–12	15'632	1'866'716
Secondary	9–10	13–14	9'447	970'720
	11–12	15–16	3'781	584'072
University (campuses)	Bachelor and above	>16	15 (1'407)	361'077
Total				8'710'728

Instrument Selection

The seismic sensor should achieve two different goals of the program, namely to be able to detect relatively low magnitude earthquakes, and to be able to be used as a teaching instrument to share knowledge with students in an efficient way in the classroom. Therefore, we needed to find a compromise between a simple pendulum which is a common instrument in Nepali schools to teach physics, and research quality modern broadband sensors that are very expensive. Following literature review and based on personal communications with several experts in the field, we found many low-cost seismological instruments which seems to satisfy both our target criteria. We carried out a market survey on low-cost sensors available around the world by defining criteria as follows:

- total cost including the delivery charge is cheap, below 500 USD,
- easily applicable for educational purposes,
- reasonably high sensitivity to detect local earthquakes,
- easy to handle,
- possibility to record data without an additional computer.

Our initial list included a total of 16 types of seismometers, some of these were already adopted in programs with similar purposes to ours (e.g., in the United Kingdom, at IRIS). From this list and using the criteria above, we have selected four types of sensors: the Quake Catcher Network (QCN), the Lego, the Slinky, and the Raspberry Shake 1D (**Figure 4**). We purchased a sample instrument of each, and carried out various tests in laboratory conditions to assess their respective sensitivity, detection threshold, noise level, frequency band, ease of use, adequacy to field conditions, etc. Our findings are synthesized in

FIGURE 3 | (A) An important teaching material: a flyer prepared in Nepali language on what to do before, during and after an earthquake, illustrated in detail with pictures. The flyer is adopted from the English version which was initially prepared by and for the Earthquake Education Center, Switzerland (http://www.cpps-vs.ch). The full flyer is freely available from our website directly at: http://seismoschoolnp.org/wp-content/uploads/2019/11/Be-Prepared-Nepali.pdf. **(B)** Earthquake awareness sticker aimed as a reminder, in English and Nepalese language.

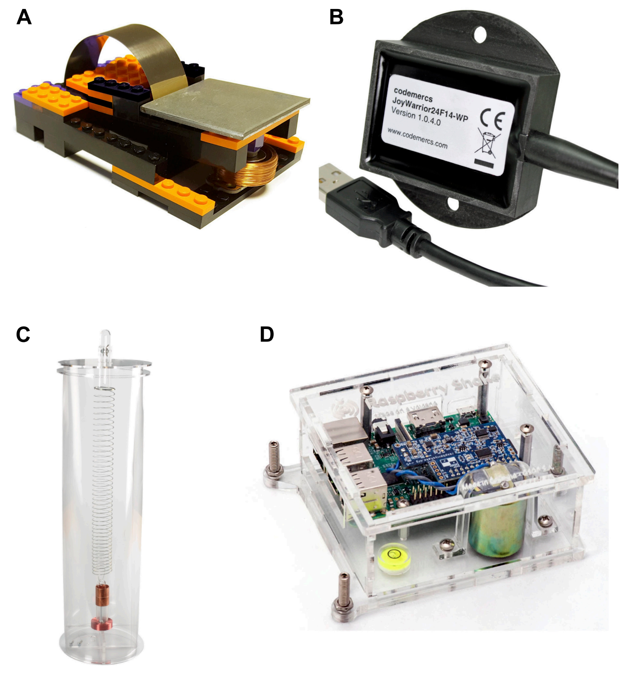


FIGURE 4 | Low-cost sensors purchased and tested before selecting one for our program: **(A)** Lego, **(B)** Quake Catcher, **(C)** Slinky, **(D)** Raspberry Shake 1D. See **Table 2** for the characteristics of each sensor and our evaluation.

Table 2, in which two other sensors are also included from Zollo et al. (2014). After this comparison of performance, the RS1D instrument was found best for our purposes and selected for our project. Subsequently, we found that Anthony et al. (2019) judged the RS1D suitable for studying local and regional earthquakes.

To complement our laboratory tests, we also installed an RS1D sensor at a field test site at a low-noise location in Grimisuat, in Valais canton, Switzerland. This region is known to be that with the highest seismic activity in Switzerland, with recurrent damaging events. The latest major event occurred in 1946 in Sierre, and had a magnitude of 5.8 with strong aftershocks (Fäh et al., 2011). We installed a sensor in March 2019, and shortly after we were able to detect an earthquake of M_L1.0 at 36 km distance, located by the Swiss Seismological Service (SED). This was a surprise to us, and the good performance of the sensor was confirmed by the recording of a "footquake" at less than 3 km distance following the hitherto earliest goal (10 s after kick-off) scored in the Swiss top league which was celebrated by ca. 7′000. At our test site, during 6 months of operation, more than 210 events ($0.4 \leq M_L \leq 4.2$) have been recorded. These events are extracted from the SED web catalog[2,3]. The observed peak ground velocity values are discussed below. The data recorded at this station is available as sensor ID R291C of the AM (RaspberryShake) network, and real-time data can be viewed directly at https://raspberryshake.net/stationview/#?net=AM&sta=R291C.

[2]http://www.seismo.ethz.ch/en/earthquakes/switzerland/all-earthquakes/
[3]http://arclink.ethz.ch/fdsnws/event/1/

IMPLEMENTATION IN NEPAL

After several preparatory discussions, we decided to apply a people-centered approach in our project, where students and local people have the opportunity to directly interact with scientists; this is considered to be more effective than a top–down approach (Scolobig et al., 2015). The preparatory phase of fieldwork consisted of a ca. 1-month reconnaissance trip in Nepal during which all selected schools were visited and cooperation agreements signed, as well as the first earthquake-focused classes were taught in Spring, 2018. The implementation phase started with a 2-day educational workshop for school teachers in Pokhara, followed by visits to every school where the low-cost seismometers were installed and full educational activities started in Spring, 2019. The implementation phase lasted 34 working days including all travel to Nepal and ca. 3’700 km travel on roads in Nepal in ca. 480 h. About 6 months later, all sites were visited again for station maintenance (where needed) and updates on the educational side. Up to now, a total of ca. 77 extended working days (ca. 980 h) and ca. 9’200 km distance traveled were spent in the field.

Educational Implementation

During our early visits, we could ascertain that schools play a vital role in teaching the essential elements of common values and culture. The teachers were well respected, the students still wore uniforms (sometimes classical, sometimes modern), and in most cases a class or group of students were waiting for our visit. Therefore, teaching earthquake related themes to students in schools still seemed a good idea after the field visit. A critical element was to do most of the work in the Nepali language: while most teachers we met spoke English and most students understood English, it was easier for them to talk in Nepali and ask practical questions, or simply to overcome a normal level of shyness.

During the reconnaissance trip, we talked to the school principals and management committees about our program and its benefit to the community. The level of interest was very high and they were excited to see the appearance of someone for earthquake education in the school for the first time ever. We have given a few lectures and taught students key information about earthquakes in every school. In our experience, students are highly interested to learn about earthquake science, but they lack relatively basic knowledge to start with. We have focused on delivering some of this knowledge in an easy and simple way. For example, regarding the Himalayas, we talked about the height of Mount Everest, which was known to every student, but also the age of the Himalayas, to which nobody knew the answer (despite some geological evidence sold in the area as tourist souvenirs). Giving the age ourselves, we could then continue onto the formation of the Himalayas as a consequence of subduction of the Indian plate beneath Tibet and the collision history. This then led onto moving plates, which are the source of energy stored beneath the surface, episodically released to create earthquakes. We also demonstrated what can be done in case an earthquake hits the school or their homes, and performed earthquake drill

TABLE 2 | List of seismological instruments tested for the educational purposes and comparison of their characteristics.

	QCN	LEGO	Slinky	AS-1	SEP	RS1D
Sensor	Digital accelerometer	Analog	Analog	Analog	Analog	Digital geophone
Components	3 (X-Y-Z)	1 vertical	1 vertical	1 horizontal	1 horizontal	1 vertical
Sensitivity	Low	High	High	Low	High	Very high
Bandwidth	10 s – 20 Hz	2 – 20 Hz	1 – 20 Hz	2 s – 3 Hz	20 s – 10 Hz	1.25 s – 29 Hz
Digitizer	16 bit	16 bit	16 bit	12 bit	16 bit	24 bit
Timing	PC clock	PC clock	PC clock	PC clock	PC clock	Network Timing Protocol
Continuous data available	No	Yes	Yes	Yes	Yes	Yes
PC needed	Yes	Yes	Yes	Yes	Yes	No
Real-time data	Yes	Yes	Yes	Yes	Yes	Yes
Additional software needed	Yes	Yes	Yes	Yes	Yes	No
Installation procedure	Simple	Difficult	Difficult	Difficult	Difficult	Simple
Overall user experience	Complex	Simple	Simple	Simple	Simple	Plug-and-play
Educational appeal	Poor	Good	Good	Good	Good	Medium
Manufacturer	Stanford University, United States *	Mindsets, United Kingdom	Mindsets, United Kingdom	United States seismology community	United Kingdom seismology community *	OSOP, Panama
Approximate cost (USD)	77	210	137	500	700	375

*A smaller part of the information (on AS-1 and SEP) is from Zollo et al. (2014). *: sensor no longer manufactured.*

exercises to shelter beneath tables, doorframes, or to evacuate to a safe place.

A delicate point of the communication was not to cause confrontation between science and people's religious or mythological views. We prepared this partly with the help of a Hinduism specialist. The strategy for teaching and discussions relied on two main points. First, to express that we have come to explain our views, and not to argue with their devout opinion or judge in any way. Second, we presented them a picture of the Earth, showing symbols of twelve major religions that exist, and then added symbols representing research and science, which is another view on how the Earth functions, the one which we came to present them. This strategy has worked well so far.

During the reconnaissance trip, we had already distributed the Nepali earthquake preparedness flyers (**Figure 3A**). We added further elements to this in our main fieldwork in 2019. We designed a 9-by-5 cm sticker (**Figure 3B**) to remind people about earthquake hazard, which we distributed to students and teachers (3'000 copies, >100 for each school so far), which should increase people's level of awareness. We also prepared an "Emergency Meeting Point" sign in Nepali, of which we distributed plasticized copies to each school. All these materials are freely available for download from our program's website Download page. Moreover, we have offered a slinky to each school: a colorful plastic spring with the help of which teachers can demonstrate P and S wave propagation in the classroom (**Figure 5**).

Workshop

Even though our occasional visits to the schools with lectures, training and discussion are a special opportunity for both students and teachers, this effort alone would not be sufficient to reach our goals, either in terms of education of the topic, or to reach further into their communities. To increase the frequency and efficiency of learning, we therefore organized a workshop primarily for school teachers at the beginning of the implementation phase, and in the center of the study area, Pokhara. This event was very important both for knowledge transfer and for crossing the language boundaries: international experts presented their knowledge in English to 96 local participants, who then are able to disseminate this in the Nepali language to their respective audiences. The 2 days of workshop allowed plenty of time for discussions, translations, and also for sharing educational experiences between Nepali and foreign school teachers. Out of 96 participants, over 70 were teachers from the 22 selected schools and further 10 from other, interested schools (mainly science, computer science, social subject teachers, as well as school principals), and there was a representative presence of the Province, of the Nepal Army, Nepal Police and Nepal Armed Police Forces, of the National Seismological Center, a few university and college students, as well as several journalists. The teaching by the international experts covered a broad spectrum of topics, from wave physics to Himalayan geology, earthquakes to plate tectonics, teaching methods to practical advices regarding earthquake preparedness, and several demonstrations with and without seismometer involving highly motivated volunteers from the audience (**Figure 5**). A local earthquake occurring during a workshop session provided a very good demonstration and analysis topic. All the workshop material, including videos, is freely available from our program's website. Furthermore, a number of relevant and presented Earth Learning Ideas[4] are also directly linked.

One of the most interesting sessions of the workshop was the very wide *ask-me-anything* session. The presenting experts received a plethora of questions from the audience; some to clarify terms and concepts, and some really unexpected ones

[4]www.earthlearningidea.com

FIGURE 5 | Educational demonstration examples. **(A)** Nature of the S-wave propagation using a slinky, explained by *Dr. Paul Denton* (with microphone) and performed by a voluntary participant during the *First International Workshop on Education Seismology* in April 2019 in Pokhara, Nepal. More than 80 school teachers participated in the workshop. (Photo Credit: Peter Loader). **(B)** *Shiba Subedi* (in T-shirt) demonstrates a P-wave using a slinky and discusses its nature with students in *Balmandir Secondary School, Gorkha* district. (Photo Credit: School). All people or their legal representatives on the photos have agreed to be taken on picture and to be presented in frame of this research project.

which lead to very interesting discussions. Here we list a few examples:

- Do tectonic plates always move in the same direction?
- Do you necessarily make earthquakes on faults?
- Why do mythological explanations of earthquakes often involve animals?
- Which discipline studies the relationship between Hinduism and earthquakes?
- If the Earth is an ellipsoid, with the poles being closer to the center of Earth than the equator, is the heat flow higher at the poles?

The full board of experts answered all questions based on their scientific, technical and personal knowledge, sometimes helped by Nepali translations.

The event was a big success according to both the participants and speakers, and the teachers seemed to leave happy and with a high level of satisfaction. The school teachers reported that the workshop greatly helped them to make their first steps of teaching earthquake related topics in the classroom, and that the workshop format was helpful for an easier transfer of new knowledge. They were grateful for the memorable event, and that the organizers cared more about their earthquake safety than they themselves did. The presence of many journalists from different media had a high impact regarding earthquake awareness, as the workshop and the program featured in 23 articles in national and regional newspapers, and in an extended live interview on the most widely watched Nepali television station. This ultimately increases the attention of people toward earthquakes and education of related themes. Based on the overall experience, we believe that this workshop made a long-term impact and contributed to earthquake-safer communities in Nepal.

Seismological Implementation

The visit of the schools started immediately after the workshop, and by early May 2019 we had successfully installed the Nepal School Seismology Network (**Figure 1**). The preparation for the full network installation in the field was based on the useful experience and lessons learned from the pilot station. By the end of the field work, all 22 RS1D seismometers had been installed on the ground floor, in most cases in the computer lab, the principal's room, or the science lab. We fixed the sensors on a small wooden platform cemented to the ground to avoid minor flooding. In the future, we plan to replace the wooden platform by paving stone or small cement platform. We also added either a simple (wooden box) or thermal (survival sheet covered polystyrene box) shielding around the sensor. Each station is also equipped with an uninterruptable power supply, and wired internet connection directly from a router. The NSSN can be cited through this article as well as under the digital object identifier doi: 10.5281/zenodo.3406345. Raw seismological data from the NSSN is available through RaspberryShake, currently archived for 2 years, and NSSN stations are also regrouped under the virtual network _NSSN[5]. The data recorded by the NSSN can be downloaded freely via the following fdsnws server and command line, adapted by replacing the italic text by the wanted values: https://fdsnws.raspberryshakedata.com/fdsnws/dataselect/1/query?net=AM&sta=*stationID*&loc=00&cha=*HZ&start=*starttime*&end=*endtime*. To download data from a particular station of NSSN, for example, R732B and for the two hours' time period on 2020 March 25 starting at 01:00:00 UTC, following command is applicable to download the desired data directly "https://fdsnws.raspberryshakedata.com/fdsnws/dataselect/1/query?net=AM&sta=R732B&loc=00&cha=EHZ&start=2020-03-25T01:00:00&end=2020-03-25T03:00:00".

To facilitate educational activities and also troubleshooting simple problems, we prepared detailed guidelines on how to visualize waveforms recorded by the seismometer on a computer, how to use the *EQInfo* smartphone application (Weber and Herrnkind, 2014), and how to estimate magnitude and distance of local earthquakes from their own school's waveform recording. This document was distributed in every school and is also

[5]http://ds.iris.edu/mda/_NSSN

published at our website. We encouraged teachers to spread the information to citizens from the community, so that they can also share the experience without being at the school. Teachers report they use the *EQInfo* application for classroom activities.

A few participating schools have had the opportunity to receive additional funding from the local government to facilitate the logistics necessary to host an NSSN station. For example, Prabha Secondary School, Pyuthan has been selected by the Information and Communication Technology program and awarded ca. 5'000 USD from the Nepal government to equip a full computer room, purchase an alternate power supply, and to establish the internet connection for the school. Janak Secondary School, Gaindakot has received ca. 1'200 USD for creating a new, wired internet connection and power backup installation from the nearby Gaindakot Municipality, Nawalpur district. In the majority of schools, the seismometer is installed in a room corner separated by a thin wooden or aluminum wall, which improves signal-to-noise ratio, visibility and security (**Figure 6**). We are proud to report that we also reached the epicenter village of the 2015 Gorkha earthquake, Barpak, a remote place where 72 people died from the most recent major earthquake. At the moment of our first field visit, people were back to daily business after the devastating earthquake, but schools were in temporary shelters. By the time of the installation, the school managed to receive support from the government-owned telecommunication service provider, Nepal Telecom[6], to install the first wired internet connection in Barpak, which made the installation of the seismometer possible.

During the sensor installation, schools have invited high level authorities from the district (e.g., Mayor of the municipality, Chief District Officer, etc.) to show how the sensor records earthquakes, and to demonstrate that the school participates in the earthquake education program. The local news coverage about seismometer installation typically followed within hours or one day[7]. Since the entire network has been installed, we are communicating with schools using social media (*twitter*, *facebook*) to keep the teachers' attention on the project. On our program website, we are posting figures of recorded waveforms from local, NSC-reported earthquakes. Our approach has been very well received by schools and also appreciated by the local governments. We hope that the ideas will spread to other regions of the country as well, and we will seek opportunities in this direction.

FIGURE 6 | Example of the setting of an installed seismometer, in *Shree Siddha Baba Secondary School, Gulmi* district. The sensor is installed on the ground floor by making a partition in the Accounting Room; it is fixed to a wooden block which is itself fixed into a ca. 2 cm thick cemented base on the ground (inset). The station is connected to a desktop computer for real-time data visualization via the jAmaSeis (Drago et al., 2009) software. Detailed information on how to visualize waveforms on a smartphone using the *EQInfo* app is printed on the wall (A4 paper). The word "Seismometer" is written in on the wall in Nepali (and English) language.

RESULTS AND DISCUSSION

Education

Teachers are at the first line of communication with the students. With high motivation, they are doing regular exercises with their students by showing waveforms recorded by the seismometer at the school (mostly for $M_L \geq 4$ local earthquakes). In each school, we encouraged teachers to practice evacuation exercises. The lessons learned from these drills helps the school community to respond more efficiently in case of a large earthquake, which increases the school's resilience.

Teachers gave very good feedback on the main workshop and took it as a great opportunity to learn about earthquakes at their level. "*I am more interested in Earth sciences after this workshop*" said one teacher after the conference; a school principal expressed his gratitude because we were more worried about their earthquake safety than they were.

To evaluate the efficiency of our program and to assess the level of knowledge before its start and after 1 year of operation, we conducted a survey during the reconnaissance trip. A representative group of students from the selected schools, teachers and local people completed the survey with ca. 30 questions, and ca. 350 full sets of answers were collected. We plan to carry out the second survey in 2020 and compare it to the first one's results to analyze the changes our program may have promoted.

With our program, school teachers estimate to have reached a broad audience in the studied area: directly more than 18'000 students benefited from the program, and indirectly ca. 150'000 people in the region could have been reached (**Supplementary Table 1**). While evaluating the indirect effect, an average family size in the community and the sociological situation were also taken into account. To share our activities and knowledge continuously with an even broader community in Nepal, we have developed the program's own webpage[8]. All materials for the education,

[6]https://www.ntc.net.np/

[7]http://seismoschoolnp.org/?page_id=746

[8]www.seismoschoolnp.org

information of recorded earthquakes, guidelines for exercises, important questions and answers are available on the webpage. This page had 9'880 visitors in 12 months (last access on February 11th, 2020).

Seismology: Waveforms and Instrumental Intensity Map

The NSSN was successfully installed by May 2019 and operates well since then. While 18 stations have been recording data continuously, four others encountered problems due to the unstable internet connection and/or power supply, therefore a small amount of data is missing from those sites. In the monsoon season, (only) one of the sensors broke, which we could then replace. The site selection criteria, as described earlier, made us make compromises between education and seismological purposes. For example, a station in a populated area will reach more people through education, but the site will have a higher noise level. Using the data from June to December 2019, hourly power spectral density probability density functions (PSD PDFs) have been computed, with 50% overlap. Looking at the median values of these by station (**Figure 7**), most of sites are below the high-noise model (Peterson, 1993), whereas three sites CHITN (R8C46), GAIDA (R6EC4) and NAWAL(R51F6) are badly affected by daytime noise (road traffic, urban environment) but are still able to provide useful data at night. Nevertheless, most stations seem to represent a reasonable compromise between education and observation, and some have even very good signal-to-noise ratios.

We have observed that the low-cost seismometers record earthquakes not only from local sources inside the network, but also across Nepal and from regional and teleseismic distances. For earthquakes in Nepal, our reference information comes from the earthquake catalog published by the NSC[9], while for more distant events we rely on global catalogs such as the one from the European-Mediterranean Seismological Center (EMSC) and the United States Geological Survey (USGS). **Figure 8** shows three examples of recorded waveforms, for a local, a regional and a teleseismic earthquake. The arrival of P and S phases is clearly visible, although somewhat different from simplistic theoretical arrival times. For local events, we detect all earthquakes that the NSC publish: these are detected by an STA/LTA-trigger at the NSC network, but only $M_L \geq 4$ events in Nepal are published on their website. The NSSN recorded some regional events in the Hindu Kush region, in

[9]http://seismonepal.gov.np/earthquakes

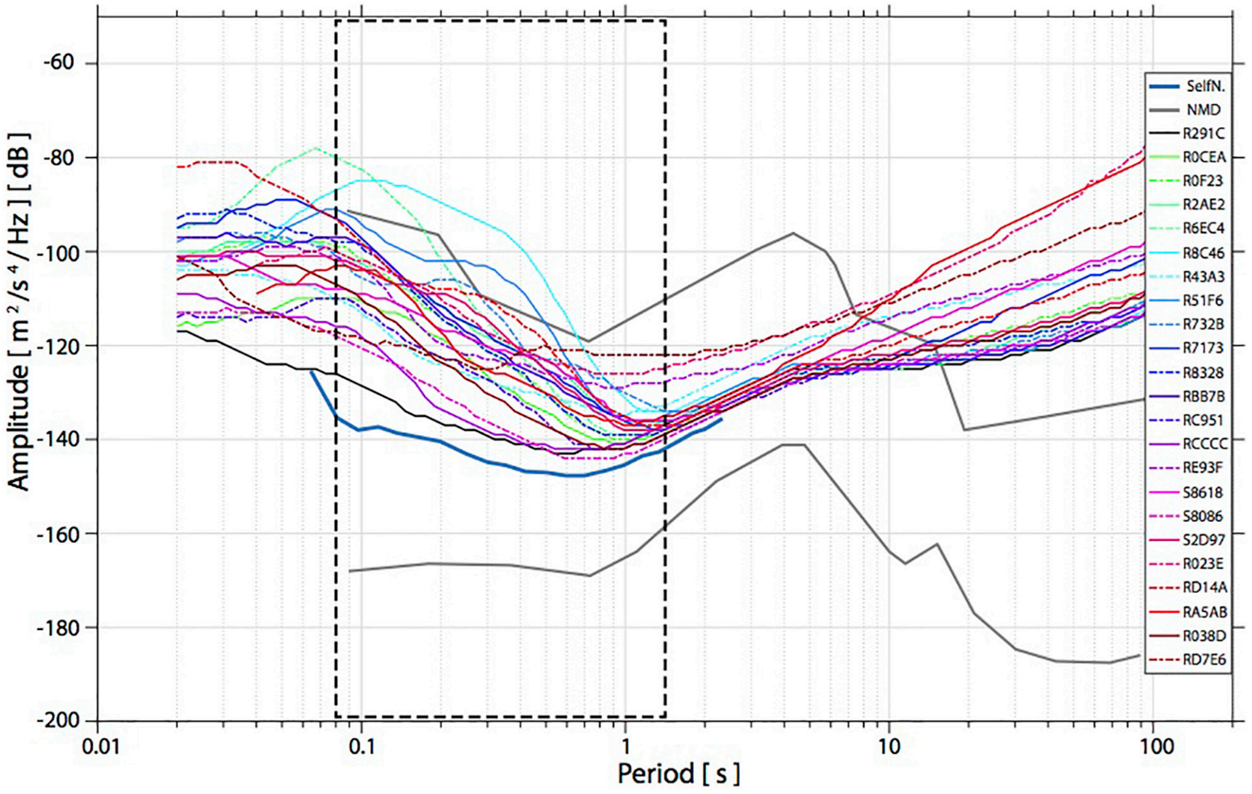


FIGURE 7 | Power spectral density probability density function's median value for each NSSN station as a function of period. Thick gray lines are the high and low noise models (according to Peterson, 1993; McNamara and Buland, 2004). For comparison, we also plot the same curve from the test site in Switzerland (R291C), and the instrument self-noise as provided by the manufacturer. The dashed black line highlights the bandwidth of flat instrument response. The curves are constructed using hourly PSDs with 50% overlap during the period from June to December 2019.

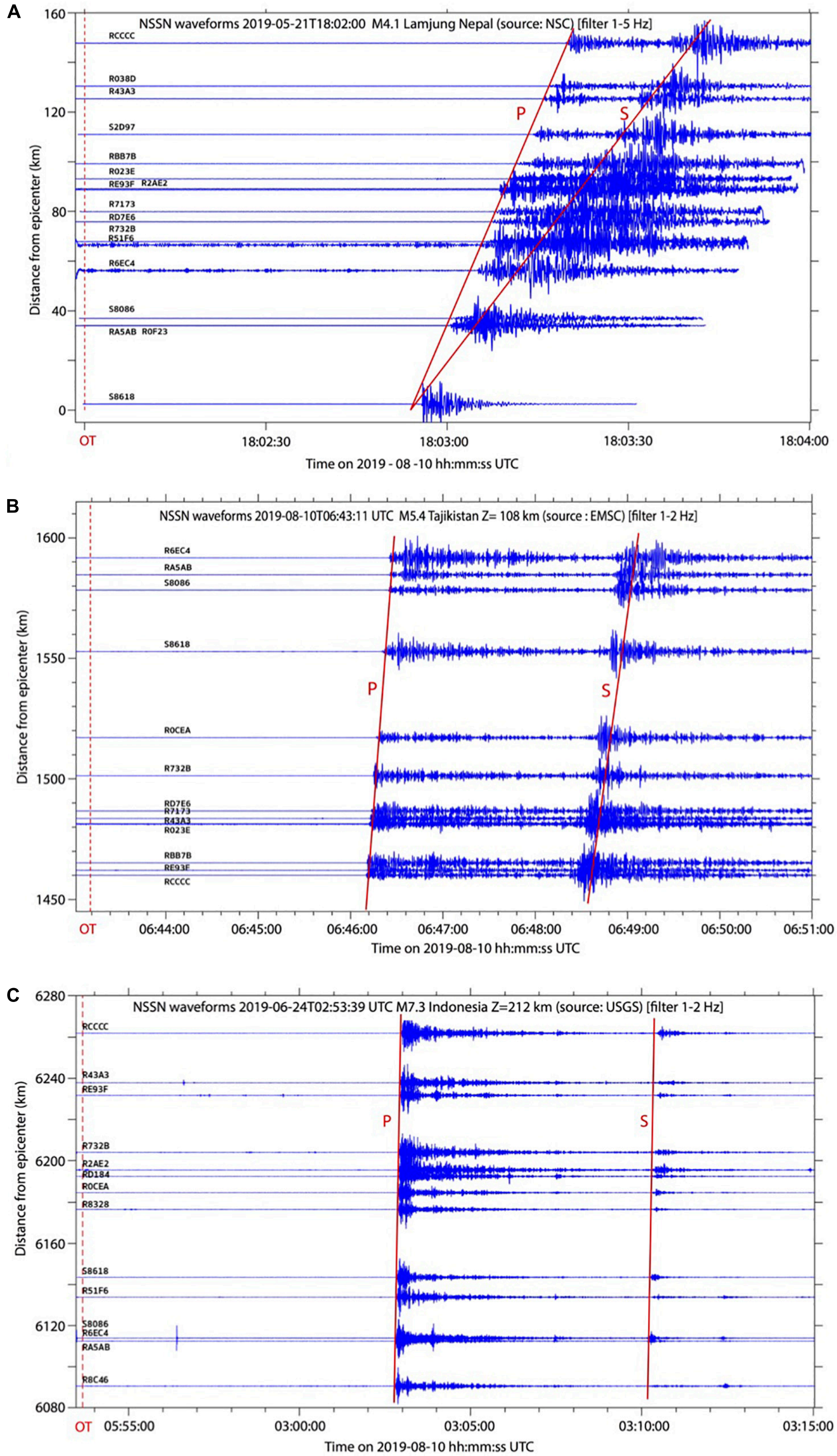


FIGURE 8 | Examples of earthquakes' waveforms recorded by the NSSN. The dashed red line in each figure denotes the origin time of the earthquake in the available catalog. **(A)** Filtered waveforms in the 1–5 Hz frequency band of a local event, with solid red lines plotted for the theoretical P and S wave arrival times using local velocity model in Nepal (Pandey et al., 1995). **(B,C)** Waveforms of a regional event in Tajikistan and of a teleseismic event in Indonesia, filtered between 1–2 Hz. Solid red lines are plotted for the theoretical P and S wave arrival time using global *iasp91* velocity model (Kennett and Engdahl, 1991). First order information of each event is written on top of each figure, including the source of the information. NSC, National Seismological Centre, Kathmandu; EMSC, European-Mediterranean Seismological Centre; USGS, United States Geological Survey. All waveforms are normalized to the same maximum amplitude.

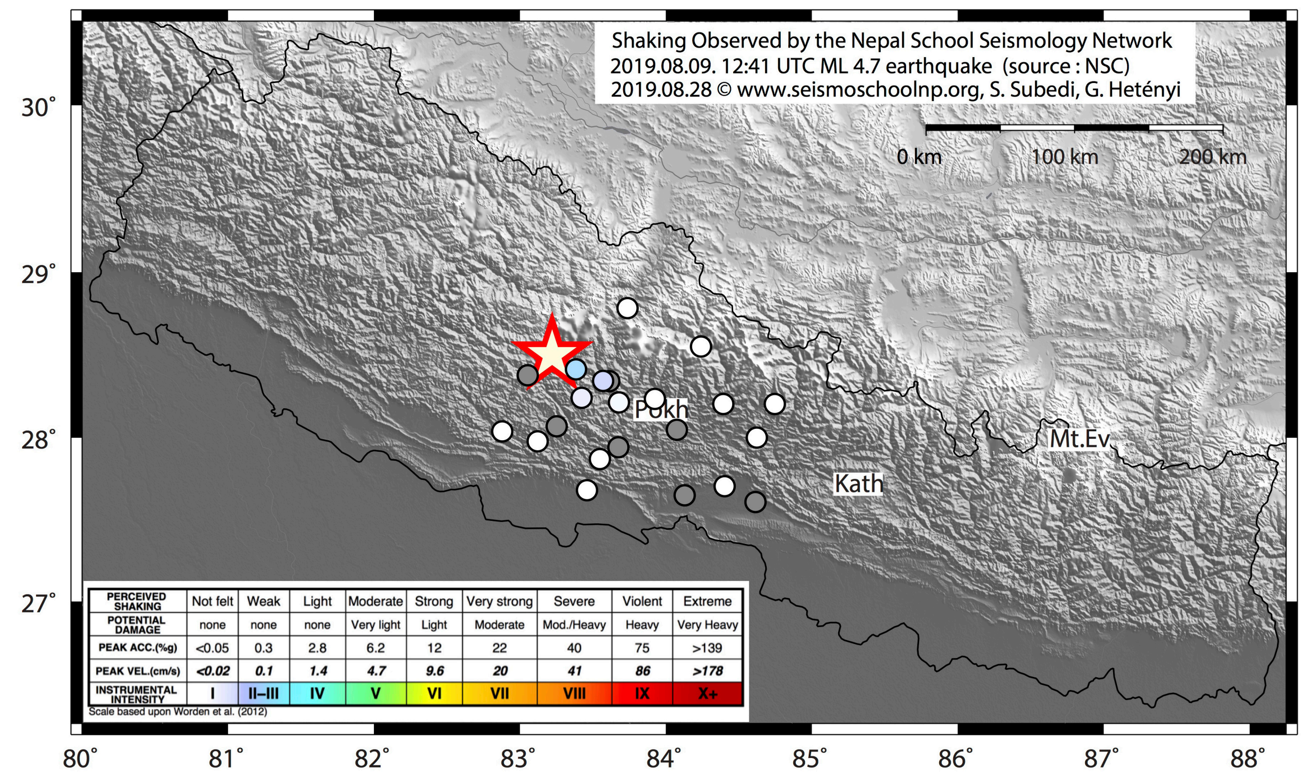


FIGURE 9 | Observed instrumental intensity map from the 2019 August 9 M_L4.7 Myagdi earthquake. The observed intensity data at NSSN stations are plotted in circles and are color-coded according to their value based on Worden et al. (2012) as shown in the legend. Gray color means no data for the event from that station (either no internet or no power supply). The capital city of Nepal, Kathmandu is denoted by *Kath*, the highest point of the Earth, Mount Everest is denoted by *Mt.Ev*, and the capital city Pokhara of the Gandaki province is denoted by *Pokh*.

China and in Myanmar. Likewise, we have recorded almost all $M > 7$ events around the globe, mostly at thousands of kilometers distance, including in Japan and in Indonesia region. We also clearly identified the Mw8.0 earthquake on 26 May 2019 in Peru at ca. 16'000 km distance. For large events, we clearly observe the more slowly propagating surface waves arriving after the body (P and S) waves. In 6 months of operational time, a total of 194 reported earthquakes have been identified in our records.

In **Figure 8**, the theoretical P and S wave arrival times are plotted on top of the recorded waveforms using different velocity models. We have used local velocity model in Nepal (Pandey et al., 1995) for local earthquakes, *iasp91* (Kennett and Engdahl, 1991) for regional and global events. The slope of the theoretical P and S wave arrivals do not exactly fit that of the observed waveforms for the local earthquake, which is probably related to the variation of the local crustal structure with respect to the 1D model. We estimate the origin time of the local event at 18:02:54 UTC, however 18:02 UTC is reported in the published catalog, the information about the seconds is truncated (**Figure 8A**). Similarly, P but especially S phases show different arrivals times from the theoretical ones for the regional earthquake in Afghanistan, which again points to more complex velocity model of the orogenic region along the raypath than the 1D model used. For the teleseismic event, the P and S wave arrivals match relatively well the theoretical arrival times.

Some of the events we recorded are felt by the people involved in our school seismology program, who were naturally interested to learn more. For that purpose, it is very instructive to produce instrumental intensity maps that shows measured intensity values at stations across the NSSN. We produce such maps routinely for felt events in the study area, and represent shaking as instrumental intensity converted from peak ground velocity (which in our sensors is recorded on the vertical component, hence we note it PGV_V), following the scale of Worden et al. (2012). The instrumental intensity map for the event causing one of the largest intensities so far, an M_L4.7 earthquake inside the network is presented in **Figure 9**. The station closest to the epicenter, *Janapriya Secondary School, Darwang, Myagdi* district, clearly felt the shaking with an intensity of II-III, while stations further from the epicenter have not recorded felt-shaking (intensity I). The largest PGV_V measured so far was recorded very close to a M_L4.5 event, at a value of 1.22 mm/s. The instrumental intensity map will not be delivered for large events as the sensors will reach their limits of recording (clip) (Anthony et al., 2019) at 22 mm/s (peak-to-peak) according to the manufacturer. Nevertheless, the

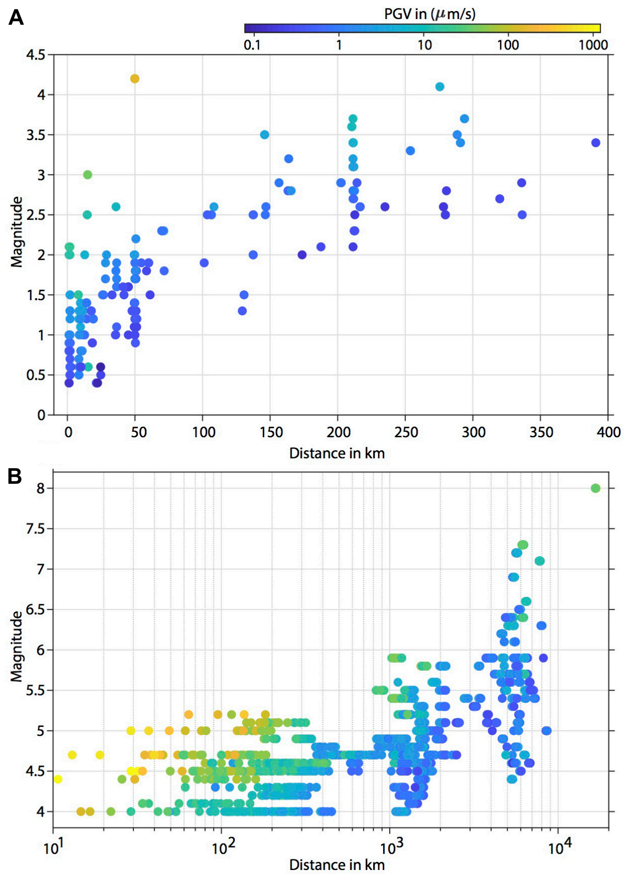


FIGURE 10 | Observed vertical peak ground velocity (PGV_V) as a function of magnitude and distance at **(A)** our test site in Grimisuat, Switzerland, and **(B)** across the NSSN. Each circle in the plot represents the observed maximum amplitude motion at a station following a single earthquake. In total 210 events for the station in Switzerland and 194 events for NSSN are plotted using the 6-month data from the catalogs. Sources of earthquake catalogs: SED in Switzerland **(A)**, NSC and USGS for stations in Nepal **(B)**.

micro- to moderate size seismicity can be very well monitored. In general, the instrumental intensity map representing measured shaking is critical to estimate the damage after an earthquake and to prepare an emergency response and rescue; in the frame of our educational seismology project, it shows all schools together and demonstrates the connection within the community of schools.

Seismology: Detection Threshold

By collecting detected phase arrivals from a representative number of earthquakes, the detection threshold of the RS1D in real field conditions can be mapped. This strongly depends on the selected sites, and here we present our findings (**Figure 10**).

At the test site in Switzerland, which is relatively quiet, we are able to record relatively small earthquakes ($M_L \leq 1.0$) earthquakes at surprisingly large (50 km) distances. This was possible as the background noise level of this site is low, typically around 0.2 μm/s or less. The observed peak ground velocity (PGV_V) for all events recorded at this site is plotted as a function of epicentral distance and magnitude in **Figure 10A**. Observed ground velocity increases with magnitude and decreases with distance, as expected. Still, typical felt (M_L~2.5) events are detected up to ca. 300 km distance.

In Nepal, information on micro earthquakes ($M_L < 4$) is not publicly accessible. Nevertheless, all reported local earthquakes of this size and larger are clearly recorded, and also some regional events of M_L 4 beyond 1'000 km distance have been detected (**Figure 10B**). The magnitude and distance dependence of PGV_V show the same pattern as for the test site: increasing with the magnitude, decreasing with the distance when other parameters are kept constant. The list of earthquakes used in this study is provided in the **Supplementary Table 2**. The location of micro earthquakes inside the NSSN is currently being investigated, and is beyond the scope of this article.

Seismology: Magnitude Calibration for Earthquake Monitoring

An important parameter in seismology is the magnitude of an earthquake. Due to various definitions of magnitude, it is not always straightforward to compare one event measured on one scale with another event measures on another scale. Typically, local magnitudes M_L for a given region are converted to moment magnitude Mw for an energy based comparison. In Nepal, M_L is provided by the NSC, and for coherency with the nationally used scale, we here quantitatively calibrate our own seismic observations to fit that scale.

Our approach is based on the presented by Allen et al. (2012) who fit a general equation on intensity and how it attenuates with epicentral distance and earthquake magnitude. Our mathematical approach is the same, but instead of intensity values, we work with vertical-component peak ground velocity PGV_V, in μm/s. Following Allen et al. (2012), we assume the following formula:

$$\log_{10}(PGV_V) = a + b \times M_{NSSN} + c \times \log_{10}(D) + S, \quad (1)$$

where M_{NSSN} is the local magnitude determined by the NSSN, D is epicentral distance in kilometers, and S is a site effect term which we first consider to be 0. The value of PGV_V at each station is determined as the maximum amplitude recorded by a vertical-component low-cost seismometer, typically of the Sg or Sn seismic phase, after second-order Butterworth band-pass filtering between 0.7 and 7 Hz. The three constants *a*, *b*, and *c* are the parameters we have to determine by regression. Once the values are known, we can rearrange the equation to compute M_{NSSN} as a function of observed PGV_V and D:

$$M_{NSSN} = (1/b) \times \log_{10}(PGV_V) - (c/b) \times \log_{10}(D) - (a/b) \quad (2)$$

The full observed dataset is presented in **Figure 11**. For the regression, we considered events located by the NSC

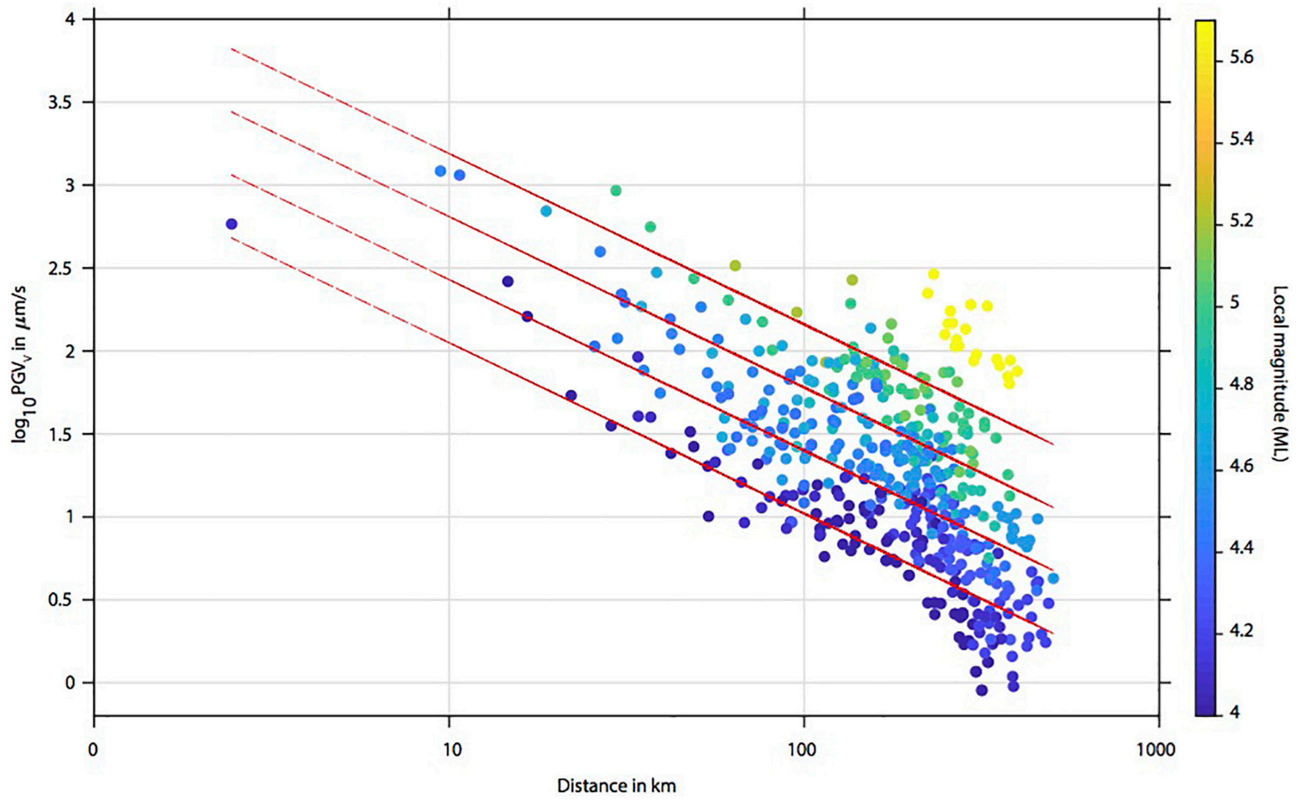


FIGURE 11 | Observed peak ground velocity (PGV_V) across the NSSN as a function of earthquake magnitude and epicentral distance. Each circle in the plot represents a single earthquake detection at a station, colored by magnitude. Six months data are considered from April 2019. Source of earthquake data is the National Seismological Center's published catalog. Red lines represent the fitted *PGV_V-distance* lines for M4.0, M4.4, M4.8, and M5.2 earthquakes after the regression (see text for details).

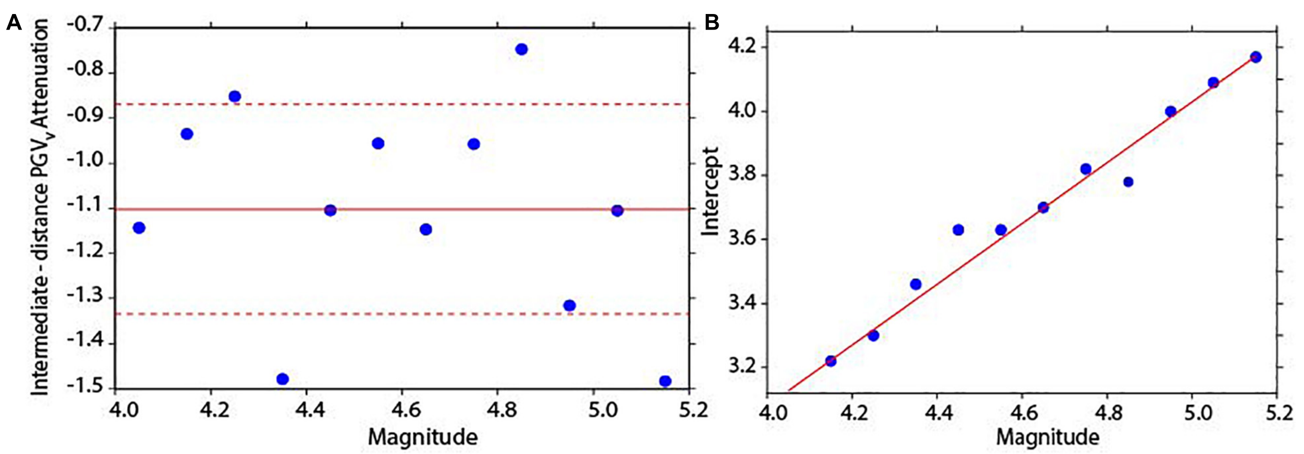


FIGURE 12 | (A) Intermediate-distance PGV_V attenuation *c* plotted for magnitude bins. Data points beyond the 1σ variability (0.30, red dashed lines) of the raw mean (–1.39, solid red line) are trimmed and the median of the remaining *PGV_V* attenuation provided parameter *c* in Eq. 1, which is found to be –1.03 across the dataset. **(B)** Fitting the distance and *PGV_V* data for each magnitude window using the constant slope value *c* to find the slope and intercept of the magnitude dependence (respectively *b* and *a* in Eq. 1), regressed using the linear least squares.

in the distance range 31–450 km (within Nepal), and we omit the single M_L5.7 event as it is 0.5 magnitude units away from the rest of the dataset. Events having epicentral distances smaller than 31 km [i.e., $\log_{10}(D) < 1.5$] have not been considered to avoid near-source effects and because of uncertain focal depth determinations. Then, for each 0.1-wide

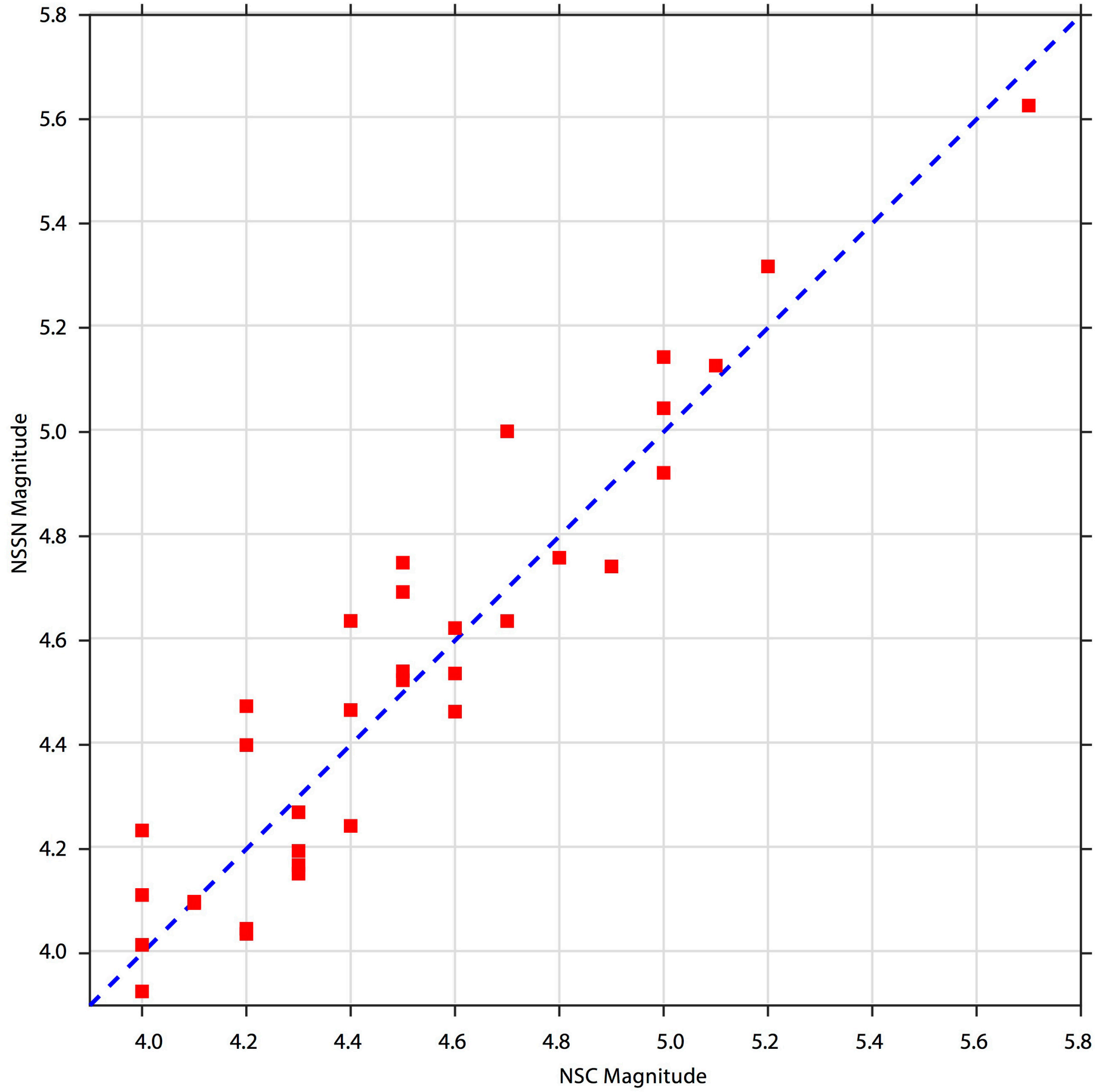


FIGURE 13 | Magnitude comparison plot. The NSC-reported magnitude is plotted against the NSSN magnitude using the newly calibrated magnitude equation (Eq. 3). Note that the site effect at each NSSN station is considered as described in the text. The maximum difference between the two magnitude scales for any given event is <0.3 unit of M_L.

bin of earthquake magnitude (including overlap as catalog magnitudes are rounded to the nearest 0.1 unit), we regress for the intermediate distance intensity attenuation value, *c*, and obtain the results shown in **Figure 12A**. The median value of this dataset, trimmed by 1σ around the raw mean value, is taken as the most fitting attenuation value *c*. The value turns out to be –1.03, and since no clear trend of variability is observed with magnitude, it is used as a constant for further regression analysis.

In a second step, in order to find the values of the slope *b* and intercept value *a* of the magnitude dependence in Equation 1, we have fitted the *PGV–distance* data for each magnitude window using the constant slope value *c* and regressed using the linear least squares (**Figures 11**, **12B**). The values we find are $a = -0.72$ and $b = 0.95$. (The same calibration including the M_L5.7 event gives slightly different values for *a*, *b*, and *c*: as −0.53, 0.94 and –1.10, respectively, but the change in M_{NSSN} is negligible, <0.1).

Hence, replacing these into Equation 2, we obtain the calibrated magnitude equation for the NSSN:

$$M_{NSSN} = 1.05 \times \log_{10}(PGV_V) + 1.08 \times \log_{10}(D) + 0.75 \quad (3)$$

Finally, using the determined value of *a*, *b,* and *c* and Equation 1, we have estimated theoretical values of PGV_V for each event and each station. By subtracting this from the observed PGV_V

values for all events, the average residual of PGV_V is calculated for each station, which is effectively gives the site effect term *S*. As the nominal sensitivity of the RS1D sensors is provided with a 10% uncertainty, we have considered the value of *S* in Equation 1 for a station only when its value exceeded 0.1 (10 sites, largest value 0.29). With this value, we can correct the observed value of PGV_V when computing M_{NSSN} in the future.

To assess and to appreciate the magnitude calibration equation, we plot the NSSN-observed magnitude value against the local M_L as provided by the NSC in **Figure 13**. The largest difference is below 0.3 units, which is a very reasonable value considering that the value of *b* (magnitude-dependence of PGV_V) is on the order of 1, and that network-wide determined magnitude values are averaged from individual station magnitudes with a standard deviation that can exceed this difference. Although the magnitude equation was calibrated using data from M_L4.0–5.2 earthquakes, the fit to the so far single M_L5.7 event is very good.

Although the seismometers in the NSSN are relatively inexpensive, this program for schools allowed us to build a network with real observatory capabilities for seismic monitoring. This somewhat unexpected point further highlights the very important role that schools and their environment can play in monitoring, understanding and preparing for earthquakes.

CONCLUSION

In less than 2 years of work, we have established the framework of the *Seismology at School in Nepal* program, and successfully implemented it in the field. The program carries both educational and seismological aspects, results of which can be summarized as the following:

- The program jointly established an educational network with the close involvement of 22 schools, each hosting a low-cost seismometer which spans the Nepal School Seismology Network in the region where a great earthquake is due.
- Various educational activities were performed, involving schools, students, teachers and communities in earthquake education; teachers were trained primarily during a 2-day dedicated workshop.
- With only 6 months of data, useful seismological results could be produced for both education (record sections, shake-maps) and research (event detectability).
- A new local magnitude equation for Nepal is calibrated based on the data observed by the NSSN, which is applicable to consistently compute the magnitude of forthcoming local events.
- Openly available data and educational resources through our program's website contribute to the broadest possible outreach.

On the basis of our bottom-up approach, earthquake preparedness and earthquake awareness have increased in the local communities. In this sense, the project has started to help this region of Nepal to prepare for future earthquakes, and we hope that the initiative is spread to other regions of Nepal.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are freely available and can be downloaded from the fdsn server for network code AM, https://www.fdsn.org/networks/detail/AM/.

AUTHOR CONTRIBUTIONS

SS and GH developed the project concept and implementation details with input from AS on the educational and by PD on the instrumentation aspects. SS carried out most of the fieldwork with some help by the other co-authors. SS did the manuscript preparation, figures, tables, and the calculations, guided and verified by GH. All authors discussed the results, and contributed to the final manuscript.

FUNDING

Funding for SS's Ph.D. was provided by the Swiss Confederation through a Swiss Government Excellence Scholarship. Instrumentation was financed by the Royal Astronomical Society (RAS), United Kingdom and Faculty of Geoscience and Environment, University of Lausanne. The cost for teachers to attend and participate in the Pokhara workshop was funded by the American Geophysical Union 100 years celebration major grant. Part of the field expenses were covered by the Institute of Earth Sciences, University of Lausanne.

ACKNOWLEDGMENTS

The Ph.D. thesis of SS is funded by the Federal Commission for Scholarships for Foreign Students (FCS), Switzerland. We greatly acknowledge the Institute of Earth Sciences and the Faculty of Geosciences and Environment at the University of Lausanne for hosting SS as a Ph.D. student and for their support toward the instrumentation of the project, for which we also express our gratitude to the, Royal Astronomical Society. We are indebted to the American Geophysical Union for their AGU100 support which allowed all Nepali participants to attend the teacher's training workshop in Pokhara. We are very thankful to Pete Loader for his enthusiasm and participation at the Pokhara workshop and all the advices. We are thankful to Mathias Dessimoz (http://mo-ma.ch/) for his great design of the earthquake awareness sticker. We warmly thank Laurent Bollinger, Jérôme Vergne, Lok Bijaya Adhikari, and John Clinton for useful discussion and valuable suggestions. Numerous other colleagues and experts of seismology, education, Nepal, and a combination of these provided us valuable ideas – we are thankful to them even if the list is too long to fit here. The kind support of the Robyr family for the installation and operation of our test site in Switzerland is much appreciated. We are grateful to Branden Christensen and entire OSOP team for their technical supports and suggestions. We are particularly thankful to all teachers and students from the Nepali schools for their enthusiastic participation in the program.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.00073/full#supplementary-material

REFERENCES

Asian Disaster Preparedness Center [ADPC] (2000). *Project Completion Report of the Kathmandu Valley Earthquake Risk Management Project* Available online at: https://www.adpc.net/Igo/contents/Publications/publications-Details.asp?pid=187&t=Naga%20City%20Disaster%20Mitigation%20Plan(accesed Nov 18, 2019).

Adhikari, L. B., Gautam, U. P., Koirala, B. P., Bhattarai, M., Kandel, T., Gupta, R. M., et al. (2015). The aftershock sequence of the 2015 April 25 Gorkha-Nepal earthquake. *Geophys. Suppl. Monthly Notices R. Astronom. Soc.* 203, 2119–2124. doi: 10.1093/gji/ggv412

Aitchison, J. C., Ali, J. R., and Davis, A. M. (2007). When and where did India and Asia collide? *J. Geophys. Res.* 112:B05423. doi: 10.1029/2006JB004706

Allen, T. I., Wald, D. J., and Worden, C. B. (2012). Intensity attenuation for active crustal regions. *J. Seismol.* 16, 409–433. doi: 10.1007/s10950-012-9278-7

Ambraseys, N., and Jackson, D. (2003). A note on early earthquakes in northern India and southern Tibet. *Curr. Sci.* 84, 570–582.

Anthony, R. E., Ringler, A. T., Wilson, D. C., and Wolin, E. (2019). Do low-cost seismographs perform well enough for your network? An overview of laboratory tests and field observations of the OSOP Raspberry Shake 4D. *Seismol. Res. Lett.* 90, 219–228. doi: 10.1785/0220180251

Avouac, J. P., Bollinger, L., Lavé, J., Cattin, R., and Flouzat, M. (2001). Le cycle sismique en Himalaya. *Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary Science* 333, 513–529. doi: 10.1016/s1251-8050(01)01573-7

Avouac, J. P., Meng, L., Wei, S., Wang, T., and Ampuero, J. P. (2015). Lower edge of locked main himalayan thrust unzipped by the 2015 Gorkha earthquake. *Nat. Geosci.* 8:708. doi: 10.1038/ngeo2518

Bilham, R., Larson, K., and Freymueller, J. (1997). GPS measurements of present-day convergence across the Nepal Himalaya. *Nature* 386:61. doi: 10.1038/386061a0

Bollinger, L., Perrier, F., Avouac, J. P., Sapkota, S., Gautam, U. T. D. R., and Tiwari, D. R. (2007). Seasonal modulation of seismicity in the Himalaya of Nepal. *Geophys. Res. Lett.* 34:L08304. doi: 10.1029/2006gl029192

Bollinger, L., Sapkota, S. N., Tapponnier, P., Klinger, Y., Rizza, M., Van Der Woerd, J., et al. (2014). Estimating the return times of great Himalayan earthquakes in eastern Nepal: evidence from the Patu and Bardibas strands of the Main Frontal Thrust. *J. Geophys. Res.Solid Earth* 119, 7123–7163. doi: 10.1002/2014jb010970

Bollinger, L., Tapponnier, P., Sapkota, S. N., and Klinger, Y. (2016). Slip deficit in central Nepal: omen for a repeat of the 1344 AD earthquake? *Earth Planets Space* 68:12. doi: 10.1186/s40623-016-0389-1

Cattin, R., and Avouac, J. P. (2000). Modeling mountain building and the seismic cycle in the Himalaya of Nepal. *J. Geophys. Res. Solid Earth* 105, 13389–13407. doi: 10.1029/2000jb900032

Department of Education [DOE] (2017). *Education in Figures 2017 (At A Glance)*. Available online at: https://moe.gov.np/assets/uploads/files/Education_in_Figures_2017.pdf, last accessed on Nov.15, 2019).

Diehl, T., Singer, J., Hetényi, G., Grujic, D., Clinton, J., Giardini, D., et al. (2017). Seismotectonics of Bhutan: evidence for segmentation of the Eastern Himalayas and link to foreland deformation. *Earth Planet. Sci. Lett.* 471, 54–64. doi: 10.1016/j.epsl.2017.04.038

Drago, J., Ginther, J., Viglione, P., Wicklund, E., and Coleman, B. (2009). "jAmaseis: seismology software meeting the needs of educators," in *Midstates Conference for Undergraduate Research in Computer Science and Mathematics*, (Milwaukee, WI: Marquette University), 27.

Duputel, Z., Vergne, J., Rivera, L., Wittlinger, G., Farra, V., and Hetényi, G. (2016). The 2015 Gorkha earthquake: a large event illuminating the Main Himalayan Thrust fault. *Geophys. Res. Lett.* 43, 2517–2525. doi: 10.1002/2016GL068083

Elliott, J. R., Jolivet, R., González, P. J., Avouac, J. P., Hollingsworth, J., Searle, M. P., et al. (2016). Himalayan megathrust geometry and relation to topography revealed by the Gorkha earthquake. *Nat. Geosci.* 9, 174–180. doi: 10.1038/ngeo2623

Fäh, D., Giardini, D., Kästli, P., Deichmann, N., Gisler, M., Schwarz-Zanetti, G., et al. (2011). *ECOS-09 earthquake catalogue of Switzerland release 2011 report and database. Public catalogue, 17.4.2011. Report SED/RISK/R/001/20110417*. Zurich: Swiss Seismological Service ETH Zurich.

Galetzka, J., Melgar, D., Genrich, J. F., Geng, J., Owen, S., Lindsey, E. O., et al. (2015). Slip pulse and resonance of the Kathmandu basin during the 2015 Gorkha earthquake. *Nepal. Sci.* 349, 1091–1095. doi: 10.1126/science.aac6383

Ghazoui, Z., Bertrand, S., Vanneste, K., Yokoyama, Y., Nomade, J., Gajurel, A. P., et al. (2019). Potentially large post-1505 AD earthquakes in western Nepal revealed by a lake sediment record. *Nat. Commun.* 10:2258. doi: 10.1038/s41467-019-10093-4

Hetényi, G., Le Roux-Mallouf, R., Berthet, T., Cattin, R., Cauzzi, C., Phuntsho, K., et al. (2016). Joint approach combining damage and paleoseismology observations constrains the 1714 AD Bhutan earthquake at magnitude 8±0.5. *Geophys. Res. Lett.* 43, 10–695. doi: 10.1002/2016gl071033

Hoste-Colomer, R., Bollinger, L., Lyon-Caen, H., Adhikari, L. B., Baillard, C., Benoit, A., et al. (2018). Lateral variations of the midcrustal seismicity in western Nepal: Seismotectonic implications. *Earth Planet. Sci. Lett.* 504, 115–125. doi: 10.1016/j.epsl.2018.09.041

Jouanne, F., Mugnier, J. L., Gamond, J. F., Le Fort, P., Pandey, M. R., Bollinger, L., et al. (2004). Current shortening across the Himalayas of Nepal. *Geophys. J. Int.* 157, 1–14. doi: 10.1111/j.1365-246x.2004.02180.x

Kennett, B. L. N., and Engdahl, E. R. (1991). Travel times for global earthquake location and phase identification. *Geophys. J. Int.* 105, 429–465. doi: 10.1111/j.1365-246x.1991.tb06724.x

Lavé, J., and Avouac, J. P. (2001). Fluvial incision and tectonic uplift across the Himalayas of central Nepal. *J. Geophys. Res. Solid Earth* 106, 26561–26591. doi: 10.1029/2001JB000359

McNamara, D. E., and Buland, R. P. (2004). Ambient noise levels in the continental United States. *Bull. Seismol. Soc. Am.* 94, 1517–1527. doi: 10.1785/012003001

Ministry of Home Affairs [Moha] (2015). *Nepal Disaster Report 2015. ISBN 978-9937-0-0324-7*. Available at http://www.drrportal.gov.np/uploads/document/329.pdf, (accessed Nov 15, 2019).

Moha/Hmgn-Jica (2002). *The Study on Earthquake disaster Mitigation of Kathmandu Valley, Kingdom of Nepal, Project Report*. Kathmandu: Ministry of Home Affairs, HMG/N.

Nábělek, J., Hetényi, G., Vergne, J., Sapkota, S., Kafle, B., Jiang, M., et al. (2009). Underplating in the Himalaya-Tibet collision zone revealed by the Hi-CLIMB experiment. *Science* 325, 1371–1374. doi: 10.1126/science.1167719

Pandey, M. R., Tandukar, R. P., Avouac, J. P., Lave, J., and Massot, J. P. (1995). Interseismic strain accumulation on the Himalayan crustal ramp (Nepal). *Geophys. Res. Lett.* 22, 751–754. doi: 10.1029/94GL0297

Peterson, J. R. (1993). *Observations and Modeling of Seismic Background noise (No. 93-322)*. Reston, VA: US Geological Survey.

Schulte-Pelkum, V., Monsalve, G., Sheehan, A., Pandey, M. R., Sapkota, S., Bilham, R., et al. (2005). Imaging the Indian subcontinent beneath the Himalaya. *Nature* 435, 1222–1225. doi: 10.1038/nature03678

Scolobig, A., Prior, T., Schröter, D., Jörin, J., and Patt, A. (2015). Towards people-centred approaches for effective disaster risk management: balancing rhetoric with reality. *Int. J. Disaster Risk Reduct.* 12, 202–212. doi: 10.1016/j.ijdrr.2015.01.006

Singer, J., Kissling, E., Diehl, T., and Hetényi, G. (2017). The underthrusting Indian crust and its role in collision dynamics of the eastern himalaya in bhutan: insights from receiver function imaging. *Jo. Geophys. Res.Solid Earth* 122, 1152–1178. doi: 10.1002/2016JB013337

Styron, R., Taylor, M., and Okoronkwo, K. (2010). Database of active structures from the Indo-Asian collision. *Eos Trans. AGU* 91, 181–182. doi: 10.1029/2010EO200001

Subedi, S., Hetényi, G., Vergne, J., Bollinger, L., Lyon-Caen, H., Farra, V., et al. (2018). Imaging the moho and the main himalayan thrust in western nepal with receiver functions. *Geophys. Res. Lett.* 45, 13–222. doi: 10.1029/2018gl080911

Weber, B., and Herrnkind, S. (2014). "EQInfo-earthquakes world-wide," in *EGU General Assembly Conference Abstracts*, Vol. 16, Munich.

Worden, C. B., Gerstenberger, M. C., Rhoades, D. A., and Wald, D. J. (2012). Probabilistic relationships between ground-motion parameters and modified Mercalli intensity in California. *Bull. Seismol. Soc. Am.* 102, 204–221. doi: 10.1785/0120110156

Zheng, G., Wang, H., Wright, T. J., Lou, Y., Zhang, R., Zhang, W., et al. (2017). Crustal deformation in the India-Eurasia collision zone from 25years of GPS measurements. *J. Geophys. Res.Solid Earth* 122, 9290–9312. doi: 10.1002/2017jb014465

Zollo, A., Bobbio, A., Berenguer, J. L., Courboulex, F., Denton, P., Festa, G., et al. (2014). "). The European experience of educational seismology," in *Geoscience Research and Outreach*, Dordrecht: Springer, 145–170. doi: 10.1007/978-94-007-6943-4_10

Conflict of Interest: The 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.

Copyright © 2020 Subedi, Hetényi, Denton and Sauron. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

BRIEF RESEARCH REPORT
published: 13 May 2020
doi: 10.3389/feart.2020.00139

Check for updates

Citizen Seismology in the Arctic

Zeinab Jeddi[1]*, Peter H. Voss[2], Mathilde B. Sørensen[1], Finn Danielsen[3], Trine Dahl-Jensen[2], Tine B. Larsen[2], Gerth Nielsen[4], Adam Hansen[5], Pâviârak Jakobsen[6] and Per Ole Frederiksen[7]

[1] Department of Earth Science, University of Bergen, Bergen, Norway, [2] Geological Survey of Denmark and Greenland, Copenhagen, Denmark, [3] Nordic Foundation for Development and Ecology, Copenhagen, Denmark, [4] Independent Researcher, Akunnaaq, Greenland, [5] Independent Researcher, Aasiaat, Greenland, [6] Qeqertalik Municipality, Aasiaat, Greenland, [7] Independent Researcher, Attu, Greenland

Landslides, earthquakes and other natural disasters are expected to increase in the Arctic, yet our ability to make informed decisions about safety is tightly limited by lack of data. As part of the Integrated Arctic Observation System (INTAROS) project, geophones were installed by residents in Greenland and by University of Bergen in Svalbard in 2018. The purpose of the installations was to explore challenges and benefits of community-based data collection for seismological monitoring in the Arctic region. Raspberry Shake units with one/three-component velocity sensors were selected for the deployment, due to their user-friendly configuration, easy installation, and well established digital platform and web services. The purpose of engaging community members in the use of geophone sensors was to monitor earthquakes, cryoseisms (events generated by ice mass), and landslides. We report our findings with respect to challenges regarding the installation and operation of the Raspberry Shake sensors at both locations. Connecting community-based recordings with permanent seismological networks improved both the detection capability and the data support for understanding seismic events in Greenland. In contrast, finding suitable locations for deployments in Longyearbyen turned out to be challenging, because most buildings are constructed on poles due to the permafrost and indoor space is expensive. Promoting citizen seismology in the Arctic could improve monitoring of seismic events in the Arctic while simultaneously raising community awareness of natural hazards.

Keywords: citizen seismology, Raspberry Shake, Arctic, seismology, citizen science, Greenland, Longyearbyen, Svalbard

OPEN ACCESS

Edited by:
Kate Huihsuan Chen, National Taiwan Normal University, Taiwan

Reviewed by:
Robert E. Anthony, United States Geological Survey (USGS), United States
Masaki Kanao, National Institute of Polar Research, Japan

***Correspondence:**
Zeinab Jeddi
zeinab.jeddi@uib.no; zeinab.jeddi@gmail.com

Specialty section:
This article was submitted to Solid Earth Geophysics, a section of the journal Frontiers in Earth Science

Received: *31 January 2020*
Accepted: *15 April 2020*
Published: *13 May 2020*

Citation:
Jeddi Z, Voss PH, Sørensen MB, Danielsen F, Dahl-Jensen T, Larsen TB, Nielsen G, Hansen A, Jakobsen P and Frederiksen PO (2020) Citizen Seismology in the Arctic. Front. Earth Sci. 8:139. doi: 10.3389/feart.2020.00139

NOMENCLATURE

CS: citizen seismology
INTAROS: Integrated Arctic Observation System
UNIS: University Center in Svalbard.

INTRODUCTION

Natural disasters, e.g., landslides or earthquakes among others, are likely to increase with the changes in the climatic conditions in the Arctic (e.g., Dahl-Jensen et al., 2004; Hestnes et al., 2016; Clinton et al., 2017). The European Union funded project, Integrated Arctic Observation System (INTAROS)[1], aims to contribute to innovative solutions to fill some of the critical gaps

[1] see http://intaros.eu/

in the *in situ* observation networks in the Arctic. Most efforts to monitor natural phenomena in the Arctic have been conducted by scientists and are usually "externally driven" approaches in which experts from outside the study area organize the experiment and process the data (Danielsen et al., 2009, 2020). Involvement of community members in one or more steps of the monitoring process is a complementary way to improve the knowledge of the natural phenomena and is included as one of the main components of the INTAROS[2]. Some scientists question the quality of data due to the limited facilities and methods that can be used by non-experts while installing instruments and collecting data (Root and Alpert, 1994; Penrose and Call, 1995). However, community-based approaches are rapidly increasing among different scientific branches and expected to result in dynamic interaction between locals, authorities and scientists (Johnson et al., 2015; Hecker et al., 2018; Cuyler et al., 2020; Eicken et al., under review). The "MyShake" and "QuakeCatcher" platforms are examples of citizen science approaches in seismology. "MyShake" connects users from all over the world to form a global mobile-phone-based earthquake early warning network (Allen et al., 2020). "QuakeCatcher" is a research project aiming to provide critical earthquake information using computer-based accelerometers (Cochran et al., 2009).

Here, we will focus on seismological data collection in two villages in western Greenland (**Figures 1A,B**) and in Longyearbyen, Svalbard (**Figures 1A,C**). The permanent seismological network is not dense in the Arctic due to (1) difficult access to the area and (2) the earthquakes impose less risk to the region compared to other regions due to sparse human populations. In addition to the recent technologies, which have improved the access to the region, continued climatic changes may provide easier access to the Arctic in the future. However, limited infrastructure (e.g., power and communication systems) and strict environmental regulations continue to keep the *in situ* research efforts expensive and logistically challenging in the Arctic. The Geological Survey of Denmark and Greenland and University of Bergen have worked with local citizens in monitoring the seismic activity in Greenland and Svalbard to address the challenges and benefits of citizen seismology (CS) data. By engaging locals in this pilot study, we would like to point to advantages and challenges in the interaction between society and scientists in different social environments (Greenland and Svalbard in this case). We also show the achieved monitoring improvements by using denser seismic networks.

THE GEOPHONE SYSTEM: RASPBERRY SHAKE

We chose the Raspberry Shake[3] instrument for citizen seismological monitoring in this study (Raspberry Shake, 2016). The Raspberry Shake seismograph is an all-in-one, Internet-Of-Things (IoT) plug-and-go solution for seismological applications, which can detect and record high-frequency (0.5–15 Hz) energy from earthquakes. It was developed by OSOP (Observatorio Sismológico del Occidente de Panamá), S.A., a geophysical instrument company headquartered in Panamá, and integrates geophone sensors, digitizers, period-extension circuits and a computer into a single enclosure. The units used in Greenland are both equipped with vertical geophones, in Longyearbyen one uses a vertical geophone and one with three orthogonal geophones. All units use the Network Timing Protocol (NTP) for timing as opposed to the satellite-derived timing commonly used for most seismic stations. Performance of Raspberry Shakes has been evaluated in several studies with the conclusion that they are suitable to complement existing networks for studying local and regional earthquakes (e.g., Anthony et al., 2018; Manconi et al., 2018; Hicks et al., 2019). The instruments are also becoming increasingly popular as an educational tool for teaching and public science exhibitions (e.g., BLOSSM, Bridging Local Outreach & Seismic Signal Monitoring, project in Oklahoma[4]). The Raspberry Shake is low cost, easy to install/maintain, and has near real-time data transmission. Power and an internet connection are the only technical requirements which make the Raspberry Shake suitable for engaging community members. Note that even if there is no internet, the instrument has internal data storage. An additional requirement is to install the instrument at a quiet location with little man-made and natural noise. The installation needs to have good coupling to the ground, preferably to bedrock. Information on online Raspberry Shake sensors is accessible for display through a website[5] where data can also be displayed.

GREENLAND CASE

In Greenland, close collaboration exist between fishermen, hunters, and the authorities (Piniakkanik Sumiiffinni Nalunaarsuineq, PISUNA[6]), where community members (e.g., an experienced fisherman) keep track of changes in the status of living resources, discuss and interpret their observations, and propose management interventions to the authorities (Danielsen et al., 2014). The Greenlandic Ministry of Fisheries, Hunting, and Agriculture in collaboration with Qeqertalik and Avannaata municipalities has developed this monitoring and management system specifically to enable fishermen and hunters to document trends in living resources, to propose management decisions themselves and to take an active role in stewardship of the resources. In April 2018, two families living in the villages Akunnaaq (**Figures 1D,E**) and Aasiaat in Disko Bay area ("DB" in **Figure 1B**) in western Greenland, and already engaged in PISUNA, installed Raspberry Shakes in their basements. These CS monitoring stations have been named AKUG and ASIG, respectively (**Figure 1B**). The installation instruction was simply to place the instrument on bedrock, connect the instrument to their Internet router via the LAN cable and power up the unit.

[2] see https://mkp28.wixsite.com/CBM-best-practice

[3] see https://raspberryshake.org/

[4] see http://www.ou.edu/ogs/education/Educopps

[5] see https://raspberryshake.net/stationview/

[6] see http://www.pisuna.org/ and https://eloka-arctic.org/pisuna-net/en/

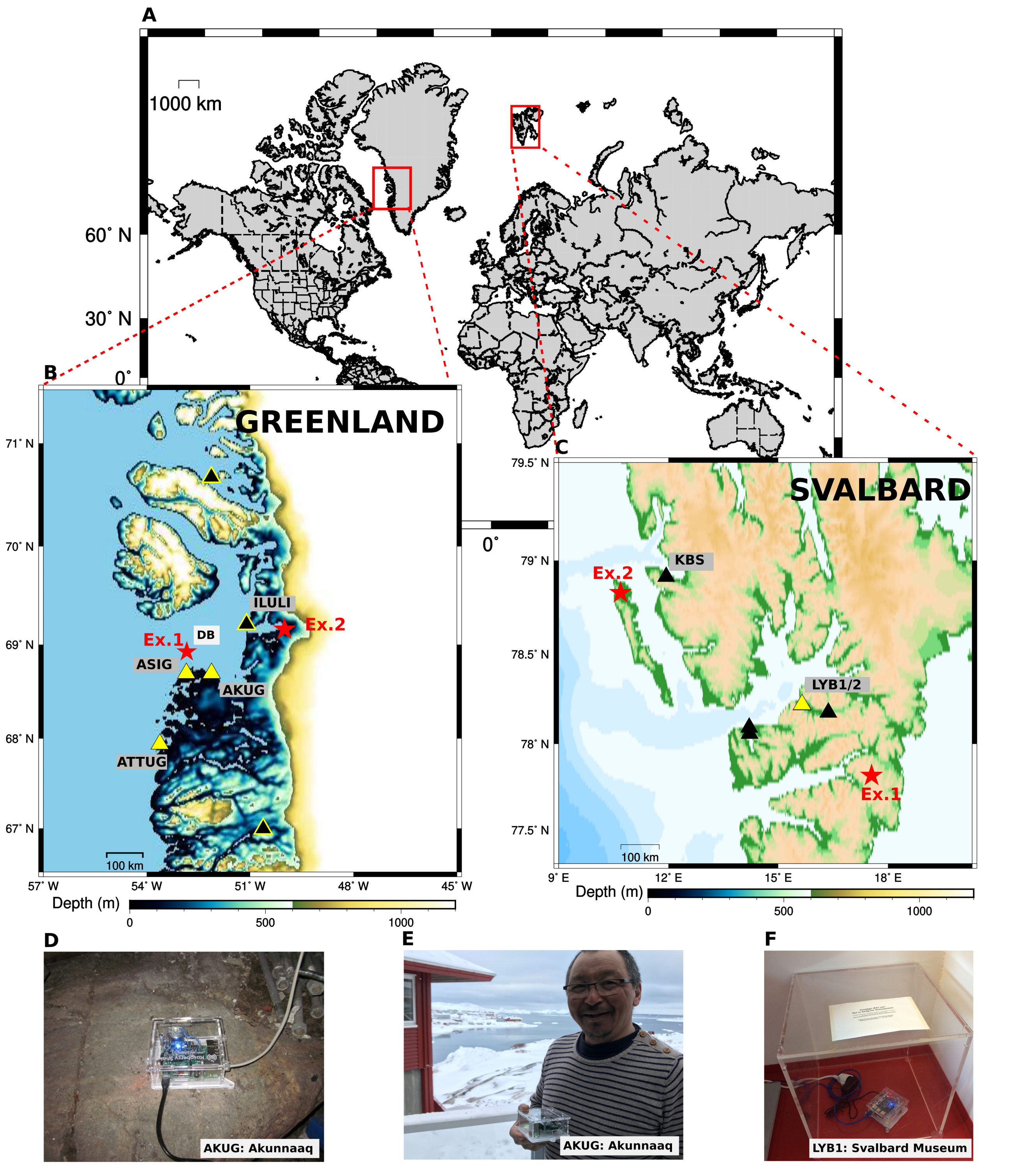


FIGURE 1 | (A) World map. The two study areas are shown with red boxes. **(B)** Map of west Greenland. Citizen seismology (CS) sensors and permanent stations are shown with yellow and black triangles, respectively. "DB" refers to "Disko Bay." "Ex.1" and "Ex.2" are the location of two events in **Figures 3B,C**. **(C)** Map of Svalbard. CS sensors and permanent stations are shown with yellow and black triangles, respectively. "Ex.1" and "Ex.2" are the location of two events in **Figures 4D–I**. **(D)** Sensor installed in Akunnaaq, Greenland (Photo: G. Nielsen). **(E)** Gerth Nielsen*, Akunnaaq, before installing CS sensor on the rock below his house (Photo: F. Danielsen). **(F)** Sensor installed in Longyearbyen, Svalbard museum. The Raspberry Shake is covered with a glass lid. Bathymetry in panels **(B)** and **(C)**: ETOPO1 taken from National Oceanic and Atmospheric Administration (NOAA; Amante and Eakins, 2009). *(*Written informed consent was obtained from the individual in* **Figure 1E** *for the publication in this article).*

The units automatically connected to the Raspberry Shake server and started uploading data. The ASIG sensor moved to a new location in Attu in 2019 due to the landowner not being able to host the instrument any longer. The new site is named ATTUG. Therefore, AKUG was recording between April 2018 and July 2019, ASIG recorded data between April 2018 and December 2018 and then ATTUG was monitoring between June 2019 and December 2019.

Since the first data became available on the Raspberry Shake server, the data has been analyzed together with data from the permanent seismological stations in Greenland. The performance of the deployments was first assessed by computing daily power spectral densities for the entire deployment period. The power spectral density of seismic recording is defined as the power of the signal distributed over a range of frequencies and it is the primary method by which all seismometers are evaluated in terms of noise. We calculated the power spectral densities over hourly segments with 50% overlap and then stacked them to daily spectrograms. The processing is done using methodology of McNamara and Buland (2004) implemented in the open-source software Seisan (Havskov et al., 2020). The data were plotted as probability density functions for the vertical component of the deployments in Greenland (**Figures 2A–C**). The poor performance of the Raspberry Shake at long periods (>10 s) is expected due to high levels of instrument self-noise (Anthony et al., 2018). Thus, these stations are not observing ambient ground motion at longer periods and only one of the microseismic peaks, the secondary microseismic peak, is visible. The noise levels at higher frequencies are lower than the New High Noise Model of Peterson (1993); however, they are partly limited by the instruments' self-noise. At stations AKUG and ASIG, the spectrograms are able to monitor actual ground motion between 0.5 and 5 s. In comparison to the other two stations, the spectrograms at ATUUG have higher ambient noise level at wider range between 0.1 and 5 s. A narrow band around 10 Hz with slightly higher noise level in ATUUG may be due to the day time activities near the sensor. A similar quality assessment is performed for one of the nearby permanent broadband stations (ILULI) for comparison (**Figure 2D**).

The two CS sensors provided very useful data and their signal to noise ratio for many events was comparable to permanents stations at frequencies above 4.5 Hz (**Figures 3B,C**). To detect new events, the daily screening for seismic events in Greenland is done manually on selected stations. Data from observed events are thereafter extracted in 10 min segments from all stations including the CS sensors and analyzed. For some events the CS sensors were closer to the epicenter than any of the permanent stations (**Figure 3B**) and for some events a location of the event would not have been possible without the CS sensors. During the time period between April 20, 2018 and September 23, 2019, 280 events have been recorded by the CS sensors (**Figure 3A**). Thirteen of those events were observed on only one or two seismic sensors and 48 events were observed on less than four seismic sensors. The CS sensors thereby contributed to an acceptable location of 232 events. By relocating the 280 events without the observations from the CS sensor we find that 71 events are observed by less than four seismic stations. The CS sensors have enabled the location, by four or more stations, of 23 events and have improved the location of 209 events. The continuous screening, phase readings and location processes are done in Seisan software (Havskov et al., 2020).

The Disko Bay ("DB" in **Figure 1B**) area is subject to high glacial activity from the nearby outlet glaciers. During calving (breaking of ice from the glacier edge) or other movement of the cryosphere, seismic signals detectable at long distances may be generated (Podolskiy and Walter, 2016). Of the 280 events observed on the CS sensors, 53 have been classified as of cryospheric origin (blue stars in **Figure 3A**), mainly from glacial activity during calving or from other displacements of glaciers or icequakes. The classification is done manually during analyses based on frequency content of seismic events, epicenter location and analyst experience. The cryo-generated seismic signals have different signatures. Some are several minutes in duration without clear P-phases and with multiple S-phases and peak amplitudes between 5 and 10 Hz, larger events often generate low frequency signals (below 0.03 Hz) with amplitudes equal to magnitude five earthquakes (Nettles and Ekström, 2010). Smaller events are similar in duration to smaller earthquakes with magnitudes of 2 or lower, but typically with lower frequencies. It is not unusual to see two or three cryoseismic events within a 15 min window. The remaining events have been presumed to be of tectonic origin (red stars in **Figure 3A**). **Figure 3** shows event locations in western Greenland which are processed using CS sensors together with one example for each event type. In the first example (**Figure 3B**), the seismic recording is classified as a tectonic event and the two CS units are nearest to the epicenter. In this case, the two Raspberry Shakes have higher signal-to-noise ratios than the permanent station for the P-wave phases and they improve the event location. **Figure 3C** is an example of a cryoseismic event that was also well recorded on the Raspberry Shakes.

LONGYEARBYEN (SVALBARD) CASE

The deployment of two CS sensors in Svalbard was carried out in July 2018. To accommodate the technical requirements for deployment (access to power and internet), as well as the citizen science perspective of the study, we wished to locate deployments within the town of Longyearbyen. To keep up the educational value of having these instruments in town, several public places were approached (e.g., the library, school, church, Svalbard museum, Radisson Blu Polar hotel, Svalbard art gallery, the Fire station, and airport). However, unexpectedly, only two places could fulfill our basic technical requirements (power and a cabled internet connection), provide appropriate locations for the sensors (on the ground floor of the building) and were willing to host the instruments: Svalbard museum and Radisson Blu Polar hotel. Most potential sites were abandoned due to lack of power and/or Internet connection at the location that could be provided by the host. Also, due to the high cost and limited availability of indoor area in Longyearbyen, our request was rejected by some hosts due to lack of space, despite the fact that these instruments do not need much space (**Figure 1F**). A major challenge turned out to be that nearly all buildings in Longyearbyen (and Svalbard) are built on poles (timber poles hammered into the permafrost

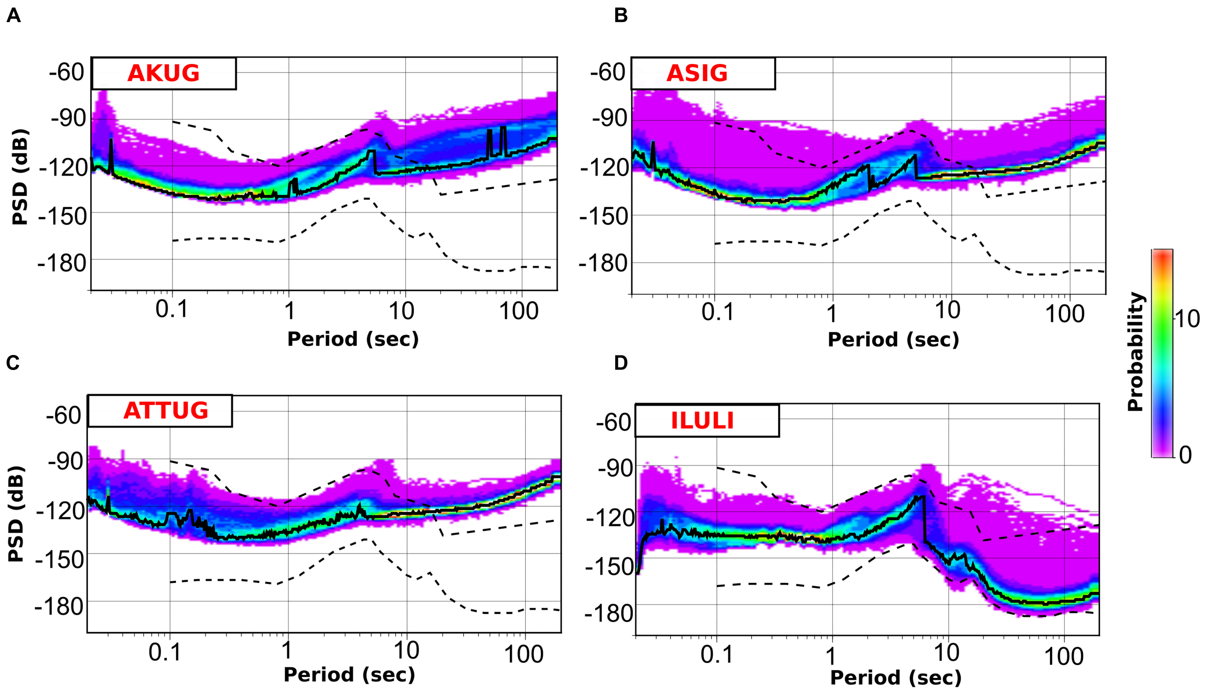


FIGURE 2 | (A–D) Hourly probability density functions of the vertical component for AKUG, ASIG, ATTUG, and ILULI installations, respectively. The dashed black lines show the global New High and Low Noise Models for seismic monitoring stations of Peterson (1993), respectively. The solid black curve is the mode value of the spectrograms. The x-axis is logarithmic.

ground), in order to provide a stable foundation for the building in the permafrost. Such locations provide a poor coupling to the ground and will thus limit the performance of the deployments[7]. Both Svalbard museum and Radisson Blu Polar hotel, which were our only options in Longyearbyen, are built on poles.

The installations (**Figure 1C**) were both made in July 2018, in close collaboration with our hosts. In Svalbard museum, a corner of an abandoned office was used to set up the instrument and launch the recording. The host also provided a lid to protect the instrument (**Figure 1F**). The other instrument was installed in a storage room in Radisson Blu Polar hotel. We had access to data in nearly real time and immediately noticed the high level of noise in both locations, as expected. However, further effort to find alternative locations were not successful. The monitoring was therefore continued at the initial locations.

The performance of the data was assessed similarly for the Longyearbyen installations (**Figures 4A,B**) by noise analyses through calculations of power spectral densities. However, in this case the high frequencies are also suffering from very high levels of noise, exceeding the New High Noise Model of Peterson (1993) in LYB2 (Radisson Blu Polar Hotel). The Svalbard museum installation (LYB1) is slightly better and this is probably because of the lid which is used to cover the instrument in addition to the building itself. The high noise levels confirm that the buildings in Longyearbyen, which are built on poles in the permafrost, are inappropriate for seismic monitoring. A similar noise analysis for one of the nearby permanent stations (KBS) is shown in **Figure 4C**. This station has drastically lower noise levels than the CS sensors.

Initially, it was planned to have a live view of the recordings in the museum and in the hotel, to share the data with the public (mainly students and tourists). However, the high noise levels meant that few events were visible in the collected data, and it was decided to abandon the idea of public displays. **Figures 4D–I** show recordings from two examples with local magnitude of 1.5 and 3.6 on the CS sensors as well as on the closest permanent station (KBS).

DISCUSSION AND LEARNED LESSONS

Monitoring of seismic activity in western Greenland has been ongoing for more than 100 years (Gregersen, 1982), not due to local earthquakes, but because of Greenland's unique location for observing earthquakes on a global scale due to low level of man-made noise. However, this is to our knowledge the first time in Greenland that geophones have been established in communities and setup by local residents. In recent years, earthquake monitoring in Greenland has shown its value both for the understanding of the geological structures (e.g., Darbyshire et al., 2017) and detection of new events such as felt earthquakes, landslides (e.g., Clinton et al., 2017) and cryoseismic phenomena (e.g., Clinton et al., 2014). The cryo-generated events (e.g., Nettles and Ekström, 2010) have raised awareness globally

[7]see https://manual.raspberryshake.org/quickstart.html#note-for-the-raspberry-shake-rs3d-and-rs4d

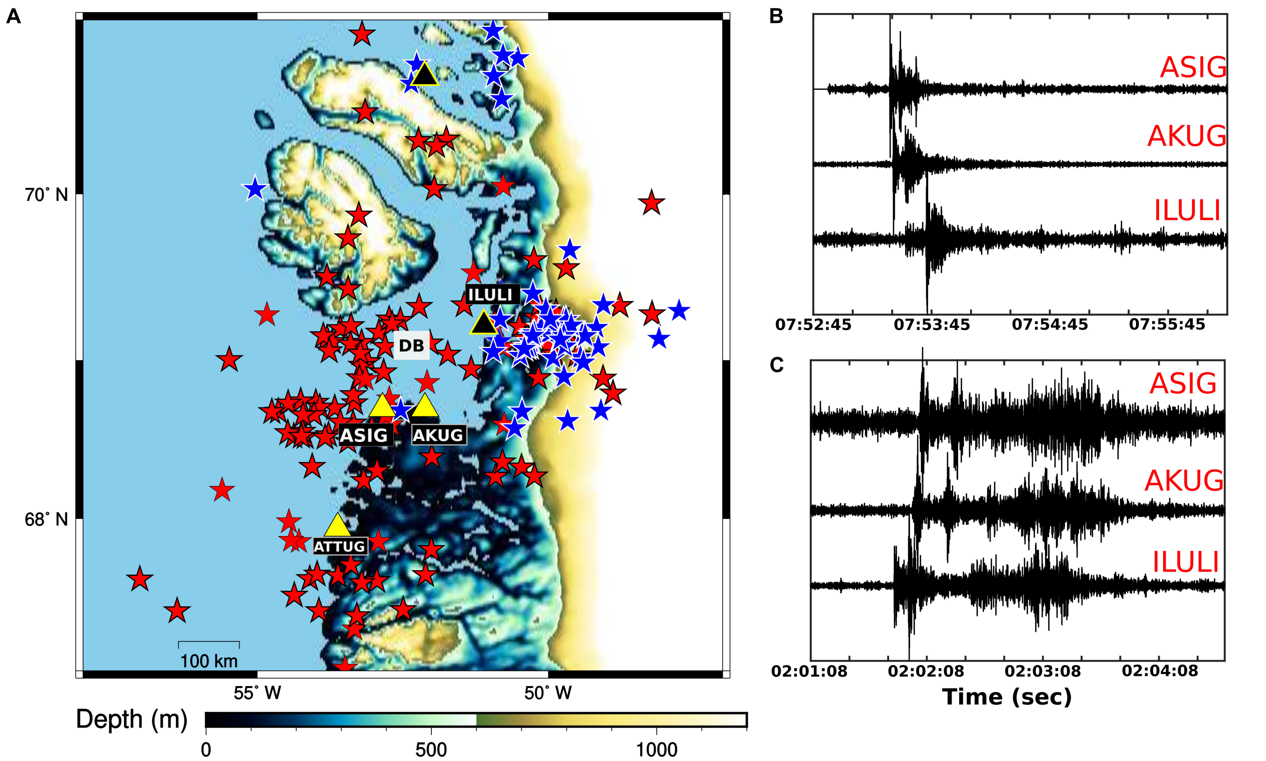


FIGURE 3 | (A) Map of west Greenland. Blue stars indicate events thought to be generated by glacial activity and red ones are classified as tectonic events. The CS sensors are the yellow triangles and permanent stations are black triangles. Three CS sensors and the closest permanent station to those deployments are marked with a label. "DB" refers to "Disko Bay." Bathymetry: ETOPO1 taken from National Oceanic and Atmospheric Administration (NOAA; Amante and Eakins, 2009). **(B)** Example of tectonic-originated seismic recording on May 4, 2018, 5–10 Hz bandpass. Location of the event is shown on **Figure 1B** as "Ex.1" (latitude: 68.93N, longitude: 52.84W). **(C)** Example of cryo-originated seismic recording on May 21, 2018, 5–10 Hz bandpass. Location of the event is shown on **Figure 1B** as "Ex. 2" (latitude: 69.15N, longitude: 50.00W).

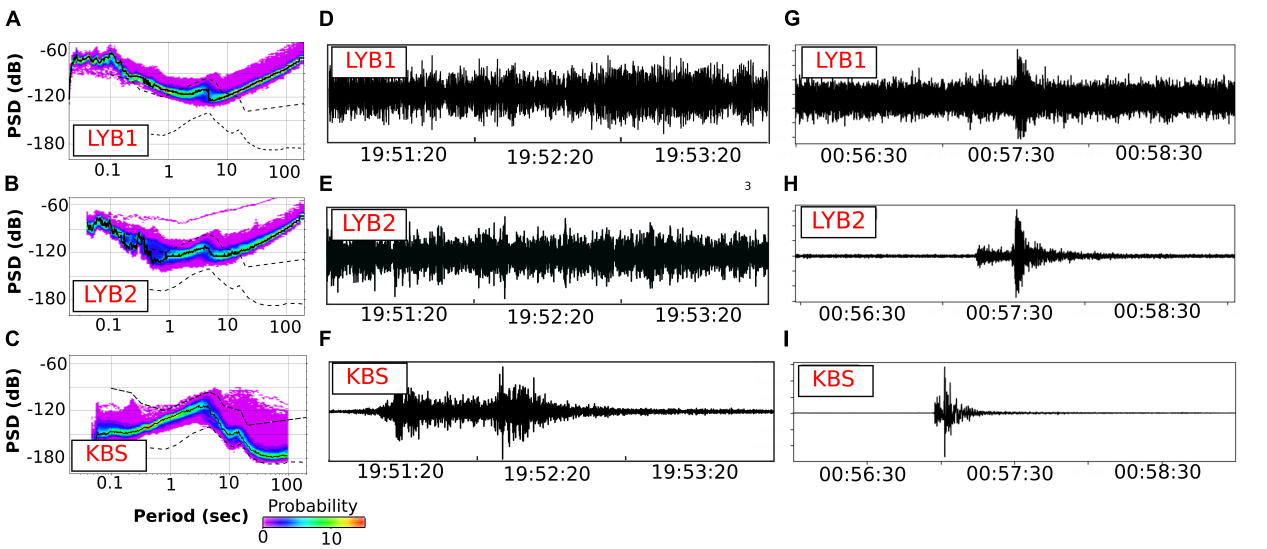


FIGURE 4 | (A–C) Hourly probability density functions of the vertical component for LYB1, LYB2 and KBS, respectively. The dashed black lines show the global New High and Low Noise Models for seismic monitoring stations of Peterson (1993). The solid black curve is the mode value of the spectrograms. The x-axis is logarithmic. **(D–F)** Example of seismic waveform on October 28, 2019, 3–15 Hz bandpass. The event is not observed on either CS sensor. Location of the event is marked as "Ex. 1" in **Figure 1C** (latitude: 77.23N, longitude: 17.96E). **(G–I)** Example of seismic waveform on October 18, 2019, 3–15 Hz bandpass. Only one of the CS sensors recorded the event clearly. Location of the event is marked as "Ex. 2" in **Figure 1C** (latitude: 78.83N, longitude: 10.69E).

due to its possible connection to climatic changes. Recent felt earthquakes and especially the 2017 landslide north of the Disko Bay (Clinton et al., 2017) have highlighted the importance of local seismic monitoring in western Greenland.

The CS sensors provided valuable improvements in the location of seismic events in western Greenland, and in some cases unique recordings of first motion polarities of seismic waves, which are critical for understanding the causal mechanisms behind events. Furthermore, the CS sensors gave us information about the seismic noise level at the three sites (**Figure 2**). The noise analyses show that the site noise is below the self-noise of the Raspberry Shake and hence, future deployment of broadband seismic sensors may be selected based on these noise analyses.

The community-based data collection in western Greenland only encounters a few challenges. One seismic sensor was moved to a new settlement, so we requested the Raspberry Shake community to change the meta data for the location of the instrument on the web site, but that was unfortunately not possible at present. The Raspberry Shake stopped transmitting data from time to time, which required manual power cycling. An estimate of Internet usage by the Raspberry Shakes was not easy to attain. In Greenland, Internet is often paid by usage, and the flat rate has just recently been introduced. The data rate is therefore important for the host of a CS system, since it will affect the cost of an Internet connection.

For the Longyearbyen deployments, we faced extraordinary challenges in finding sites capable of producing useful seismic data. Longyearbyen has developed due to the coal excavation in the surrounding mountains, and has been built by the mining industry over the past century up to 1990. The town has now evolved into a varied business community with tourism, research and education being its main industries (Misund, 2017). Due to the fragile, Arctic surroundings, strict zoning and planning regulations have been implemented in Longyearbyen, and very limited space is available for construction. Due to the permafrost, most buildings are constructed on poles and thus unsuitable sites for seismological monitoring. The University Center in Svalbard (UNIS) is one of the main institutions in Longyearbyen. A large proportion of the population is affiliated with UNIS, either as employees or students, and a wide range of Arctic research is conducted there. These points introduce Longyearbyen as a special place where many people are already engaged in research in some way, and may therefore be more reluctant to participate in citizen seismological studies. In addition, indoor space is limited and expensive, and therefore finding a quiet 0.5 m by 0.5 m corner is challenging. If one wishes to further explore the potential for community-based seismological monitoring in Svalbard, one option could be to search for potential sites outside Longyearbyen. Abandoned coal mines and settlements (such as Pyramiden) would in that case be possible locations where one may find the technical facilities needed. Since some of these locations are now popular tourist destinations, the community focus could be maintained with such locations.

Our experience with deploying four CS sensors in Longyearbyen and in western Greenland suggests that local factors drive the level of success in CS in the Arctic region. In Greenland stable locations providing high signal-to-noise ratios were obtained at each site. The families in Greenland were keen on installing the sensors at the bedrocks under their houses, probably because of the trust and respect and collaboration that already existed between the fishermen, hunters, and the authorities within the PISUNA monitoring and management system (Danielsen et al., 2017). The CS conducted in western Greenland therefore provided high quality data for the observation of seismic events in the region. In Longyearbyen, on the contrary, with the limited availability of appropriate locations (building not on poles), combined with the high cost of indoor space, finding suitable locations for the instruments turned out to be impossible. This was probably strengthened by the strong presence of research environments in Longyearbyen, making people less likely to engage themselves in "yet another research project."

Citizen seismology has high potential for raising community awareness of natural hazards. Our future efforts in Disko Bay area will therefore include meetings and workshops with the communities in Akunnaaq, Attu and Aasiaat, the municipality and central authorities. Our findings in the current study, the implications of the seismological monitoring and decision making procedures for safety in the region are going to be discussed.

DATA AVAILABILITY STATEMENT

The datasets analyzed for this study can be found in the FDSN web services (doi: 10.7914/SN/AM) with the network code "AM." "R2310," "Rf95F" are Greenland's Raspberry Shake sensor codes. "RC131" and "RD8D1" are Longyearbyen's Raspberry Shake sensor codes. The data for "KBS" station is available with the network code "1U" and location code "10" via the European Integrated Data Archive (EIDA) services (doi: 10.7914/SN/IU). The Swiss Seismological Service (SED) can be used to retrieve data for "ILULI" station under "DK" network code.

AUTHOR CONTRIBUTIONS

PV and MS were involved in planning and supervised the work. ZJ, GN, AH, PJ, PF, and FD contributed to the installation and performance of the sensors. PV, TD-J, and TL processed and interpret the Greenland data. ZJ performed the Longyearbyen data processes, noise analysis, drafted the manuscript and designed the figures. MS and ZJ discussed the Longyearbyen challenges. ZJ, PV, MS, and FD are mainly contributed to the manuscript editing.

FUNDING

This work was supported by Integrated Arctic Observation System (INTAROS) project which is funded by the European Union's Horizon 2020 Research and Innovation Program under GA No. 727890.

ACKNOWLEDGMENTS

We acknowledge the Svalbard museum (Mikael Amadeus Bjerkestrand) and Radisson Blu Polar hotel (Kristoffer Halvarp) for hosting the geophones in Longyearbyen. The Piniakkanik Sumiiffinni Nalunaarsuineq (PISUNA) programme and Qeqertalik Municipality for advice and support in Greenland. We are grateful to Lisbeth Iversen, Angel Rodriguez, Hanne Sagen, Stein Sandven and Terje Utheim for valuable support. We appreciate Nicolai Rinds for assistance in signal processing. We also thank the Arctic Ice sheet monitoring program (GLISN) and International Federation of Digital Seismograph Networks (FDSN). We appreciate the constructive comments of RA and MK. We also thank the associate editor, KC.

REFERENCES

Allen, R. M., Kong, Q., and Martin-Short, R. (2020). The myshake platform: a global vision for earthquake early warning. *Pure Appl. Geophys.* 177, 1699–1712. doi: 10.1007/s00024-019-02337-2337

Amante, C., and Eakins, B. W. (2009). *ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24*. Boulder, CO: National Geophysical Data Center, doi: 10.7289/V5C8276M

Anthony, R. E., Ringler, A. T., Wilson, D. C., and Wolin, E. (2018). Do low-cost seismographs perform well enough for your network? An overview of laboratory tests and field observations of the OSOP Raspberry Shake 4D. *Seismol. Res. Lett.* 90, 219–228. doi: 10.1785/0220180251

Clinton, J., Larsen, T., Dahl-Jensen, T., Voss, P., and Nettles, M. (2017). *Special Event: Nuugaatsiaq Greenland Landslide and Tsunami. Incorporated Research Institutions for Seismology Washington DC.* Available online at: https://ds.iris.edu/ds/nodes/dmc/specialevents/2017/06/22/nuugaatsiaq-greenland-landslide-and-tsunami/ (accessed March 20, 2020).

Clinton, J. F., Nettles, M., Walter, F., Anderson, K., Dahl-Jensen, T., Giardini, D., et al. (2014). Real-time geophysical data enhance Earth system monitoring in Greenland, Eos Trans. *AGU* 95, 13–14. doi: 10.1002/2014EO020001

Cochran, E. S., Lawrence, J. F., Christensen, C., and Jakka, R. S. (2009). The quake-catcher network: citizen science expanding seismic horizons. *Seismol. Res. Lett.* 80, 26–30. doi: 10.1785/gssrl.80.1.26

Cuyler, C., Daniel, C. J., Enghoff, M., Levermann, N., Møller-Lund, N., Hansen, P. N., et al. (2020). Using local ecological knowledge as evidence to guide management: a community led harvest calculator for muskoxen in Greenland. *Conserv. Sci. Pract.* 2:e159.

Dahl-Jensen, T., Larsen, L. M., Pedersen, S. A. S., Pedersen, J., Jespsen, H. F., Pedersen, G., et al. (2004). Landslide and Tsunami 21 November 2000 in Paatuut, West Greenland. *Nat. Hazards* 31, 277–287.

Danielsen, F., Johnson, N., Lee, O., Fidel, M., Iversen, L., Poulsen, M. K., et al. (2020). *Community-based Monitoring in the Arctic*. Fairbanks, AK: University Alaska Press.

Danielsen, F., Burgess, N. D., Balmford, A., Donald, P. F., Funder, M., Jones, J. P. G., et al. (2009). Local participation in natural resource monitoring: a characterization of approaches. *Conserv. Biol.* 23, 31–42. doi: 10.1111/j.1523-1739.2008.01063.x18798859

Danielsen, F., Enghoff, M., Magnussen, E., Mustonen, T., Degteva, A., Hansen, K. K., et al. (2017). *Citizen Science Tools for Engaging Local Stakeholders and Promoting Local and Traditional Knowledge in Landscape Stewardship. The Science and Practice of Landscape Stewardship*. Cambridge: Cambridge University Press, 80–89.

Danielsen, F., Topp-Jørgensen, E., Levermann, N., Løvstrøm, P., Schiøtz, M., Enghoff, M., et al. (2014). Counting what counts: using local knowledge to improve Arctic resource management. *Polar Geogr.* 37, 69–91. doi: 10.1080/1088937X.2014.890960

Darbyshire, F. A., Dahl-Jensen, T., Larsen, T. B., Voss, P. H., and Joyal, G. (2017). Crust and uppermost-mantle structure of Greenland and the Northwest Atlantic from Rayleigh wave group velocity tomography. *Geophys. J. Int.* 212, 1546–1569. doi: 10.1093/gji/ggx479

Gregersen, S. (1982). Earthquakes in Greenland. *Bull. Geol. Soc. Denmark* 31, 11–27. doi: 10.1007/978-94-009-2311-9_20

Havskov, J., Voss, P. H., and Ottemöller, L. (2020). Seismological observatory software: 30 Yr of SEISAN. *Seismol. Res. Lett.* doi: 10.1785/0220190313 [Epub ahead of print].

Hecker, S., Haklay, M., Bowser, A., Makuch, Z., and Vogel, J. (eds) (2018). *Citizen Science: Innovation in Open Science, Society and Policy*. London: UCL Press.

Hestnes, E., Bakkehøi, S., and Jaedike, C. (2016). "Longyearbyen, Svalbard – vulnerability and risk management of an Arctic settlement under changing climate – a challenge to authorities and experts," in *Proceedings Of the International Snow Science Workshop 2016*, Breckenridge.

Hicks, S. P., Verdon, J., Baptie, B., Luckett, R., Mildon, Z. K., and Gernon, T. (2019). A shallow earthquake swarm close to hydrocarbon activities: discriminating between natural and induced causes for the 2018–2019 Surrey, United Kingdom, Earthquake Sequence. *Seismol. Res. Lett.* 90, 2095–2110. doi: 10.1785/0220190125

Johnson, N., Alessa, L., Behe, C., Danielsen, F., Gearheard, S., Gofman-Wallingford, V., et al. (2015). The contributions of community-based monitoring and traditional knowledge to Arctic observing networks: reflections on the state of the field. *Arctic* 68(Suppl. 1), 28–40.

Manconi, A., Coviello, V., Galletti, M., and Seifert, R. (2018). Short communication: monitoring rock falls with the Raspberry Shake. *Earth Surf. Dyn.* 6, 1219–1227. doi: 10.5194/esurf-6-1219-2018

McNamara, D. E., and Buland, R. P. (2004). Ambient noise levels in the continental united states. *Bull. Seismol. Soc. Am.* 94, 1517–1527.

Misund, O. A. (2017). Academia in Svalbard: an increasingly important role for research and education as tools for Norwegian policy. *Polar Res.* 36:1308131. doi: 10.1080/17518369.2017.1308131

Nettles, M., and Ekström, G. (2010). Glacial earthquakes in Greenland and Antarctica. *Annu. Rev. Earth Planet. Sci.* 38, 467–491. doi: 10.1146/annurev-earth-040809-152414

Penrose, D., and Call, S. M. (1995). Volunteer monitoring of benthic macroinvertebrates: regulatory biologists' perspectives. *J. No. Am. Benthol. Soc.* 14, 203–209.

Peterson, J. (1993). *Observation and Modeling of Seismic Background Noise*. Albuquerque, NM: U. S. Geological Survey.

Podolskiy, E. A., and Walter, F. (2016). Cryoseismology. *Rev. Geophys.* 54, 708–758. doi: 10.1002/2016RG000526

Raspberry Shake, S. A. (2016). Raspberry Shake - OSOP. International Federation of Digital Seismograph Networks. Dataset/Seismic Network. doi: 10.7914/SN/AM

Root, T. L., and Alpert, P. (1994). Volunteers and the NBS. *Science* 263, 1205–1205.

Conflict of Interest: The 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.

Copyright © 2020 Jeddi, Voss, Sørensen, Danielsen, Dahl-Jensen, Larsen, Nielsen, Hansen, Jakobsen and Frederiksen. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

ORIGINAL RESEARCH
published: 15 May 2020
doi: 10.3389/feart.2020.00141

Analysis of Online News Coverage on Earthquakes Through Text Mining

Stephen Camilleri[1], Matthew R. Agius[2,3]* and Joel Azzopardi[1]**

[1] Dipartiment tal-Intelliġenza Artifiċjali, Fakultà tat-Teknoloġija tal-Informatika u l-Komunikazzjoni, L-Università ta' Malta, Msida, Malta, [2] Dipartiment tal-Ġeoxjenza, Fakultà tax-Xjenza, L-Università ta' Malta, Msida, Malta, [3] Dipartimento di Scienze, Università Roma Tre, Rome, Italy

News agencies work around the clock to report critical news such as earthquakes. We investigate the relationship between online news articles and seismic events that happen around the world in real time. We utilize computer text mining tools to automatically harvest, identify, cluster and extract information from earthquake-related reports, and carry out cross-validation on the mined information. Earthquake parameters retrieved from the United States Geological Survey (USGS) Application Programming Interface (API) are organized into earthquake events, with each event consisting of daily earthquake readings taking place in a particular geographical location. The results are then visualized on a user-friendly dashboard. 268,182 news reports published by 23 news agencies from different parts of the world and 14,717 earthquakes of magnitude ranging from 4 to 8.2 listed in the bulletin were processed during a 1-year study between 2018 and 2019. 1.25% of the analyzed articles had the word "quake" and 0.4% were clustered and then mapped to an earthquake event. The use of multilingual news sources from 16 countries (6 languages) gives the advantage of reducing potential news bias originating from English-written reports only. The mapping of articles with an earthquake catalog helps verify earthquake reports and determine relationships. We find that the distribution of the reported seismicity is from earthquakes that occur on or very close to land. We propose a general relationship between the number of news agencies, the earthquake magnitude and the anticipated number of published articles. News reports tend to mention higher earthquake magnitudes than those in the USGS earthquake catalog, and the reports on earthquakes can last from a few days to a couple of weeks following the earthquake.

Keywords: big data and analytics, information extraction, earthquakes, news agencies, online news analysis

OPEN ACCESS

Edited by:
Remy Bossu,
European-Mediterranean Seismological Centre, France

Reviewed by:
Mark Quigley,
The University of Melbourne, Australia
Maud H. Devès,
UMR 7154 Institut de Physique du Globe de Paris (IPGP), France

****Correspondence:***
Stephen Camilleri
stephen.camilleri.03@um.edu.mt
Matthew R. Agius
matthew.agius@um.edu.mt
Joel Azzopardi
joel.azzopardi@um.edu.mt

Specialty section:
This article was submitted to Geohazards and Georisks, a section of the journal Frontiers in Earth Science

Received: *28 December 2019*
Accepted: *16 April 2020*
Published: *15 May 2020*

Citation:
Camilleri S, Agius MR and Azzopardi J (2020) Analysis of Online News Coverage on Earthquakes Through Text Mining. Front. Earth Sci. 8:141. doi: 10.3389/feart.2020.00141

INTRODUCTION

Many researchers have tried to identify the factors that determine the level of coverage news agencies give following major earthquake events (Suzanne, 2006; Eisensee and Strömberg, 2007; Stomberg, 2012; Le Texier et al., 2016). These studies do not specify that data was automatically gathered, clustered and processed for information extraction in real time and, moreover, these studies have been limited to specific earthquakes or focused on a particular geographical region. This makes it difficult to quantify how quickly news agencies react to such earthquake events, how accurate the news agencies are when reporting such events, what earthquake features are mostly mentioned in the news as well as other parameters such as how long an earthquake event remains mentioned in the news and the extent of global coverage given to the earthquake.

Early studies investigated the correlation between earthquake events and television news coverage (Adams, 1986; Simon, 1997; Van Belle, 2000). They carried out a regression analysis to determine the most important earthquake-related features that are taken into consideration when allocating TV time slots for different seismic events. The three studies identified a correlation between TV news coverage reporting on earthquake events versus the logarithm of initial number of people estimated to be killed/affected (Adams, 1986; Simon, 1997; Van Belle, 2000) and how far the catastrophic event took place from a specific city such as New York (Adams, 1986; Simon, 1997). Interestingly, some of the identified relationships seem peculiar, such as the one between the amount of news coverage given in relation to the ties the United States has with the stricken country (Simon, 1997), or the popularity of the earthquake-hit country with American tourists (Adams, 1986; Van Belle, 2000). Similarly, Van Belle (2000) identified an increase in coverage when the impacted country had better social and cultural ties with the United States, which tend to lead to increased assistance to the earthquake-affected country following the aftermath of the earthquake (Heeger, 2007). Heeger (2007) went farther, stating that while a strong correlation was found between students who followed earthquake news on TV and the financial assistance Americans provided, the relationship between the amount of time watching the event unfold and the financial contributions given, was weak.

Other studies focused on the correlation between earthquake events and newspaper coverage. For example, Suzanne (2006) analyzed 64 daily and weekly publications in 9 countries, to determine the basis on which western media opt to cover disaster-related events, as well as the difference in coverage between Europe and the United States. Suzanne (2006) sustains that there is no relationship between the severity of the natural event taking place and the media's attention. On the other hand, Adams (1986) and Eisensee and Strömberg (2007) claimed that the amount of news coverage allocated on other local current affairs that are being reported affects the news coverage given on catastrophic events.

Others state that the reporting of earthquake news is based on the devastation left by the seismic event on the affected country. Devastation is expressed in terms of damage to the infrastructure, culture, economy, labor, and environmental consequences that follow, as well as political strength that could help minimize the impact, and social adaptedness (as analyzed by Brown (2012) and Dhakal (2018) in multiple sources). Suzanne (2006) mentions that the motivation of the news coverage in the West is politically derived, i.e., to help the victims of the disaster in return for political votes to gain favorable publicity to hold key worldwide events (e.g., the Olympics). As a result, Suzanne (2006) identified a correlation between news coverage and its effect on the Western market. Culture too is considered as being a factor for American and Japanese influence in determining whether an article is written about an earthquake event according to Stomberg (2012), who analyzed American and Japanese newspapers over a period of 36 days.

More recently, the use of "tweets" (short messages on online social media platform Twitter[1]) assisted in providing more real-time information on the geographical region of the "news" where the earthquake took place and the amount of structural damage caused (Earle et al., 2010, 2012; Sakaki et al., 2010; Liang et al., 2013; Avvenuti et al., 2015; Bossu et al., 2015; Hicks, 2019). Panagiotou et al. (2016) noticed a relationship between the time Twitter users tweeted and the time the event took place, highlighting the importance of social media users acting as news collaborators. Liang et al. (2013) analyzed how fast the news spread over a period of 90 minutes and managed to identify a correlation between retweet densities and tweeting count per user versus the distance from the earthquake's epicenter. Similarly, Avvenuti et al. (2015) studied the relationship between the earthquake's magnitude and how tweets are spread around the geographical area hit by the earthquake. They took into consideration unique Twitter users and the mean value of tweets submitted following the earthquake event. However, this highly depends on the population of the area (Earle et al., 2010). Other studies have investigated user traffic on dedicated earthquake websites to gauge the interest of the general public (Bossu et al., 2008, 2014) and also to understand how long the general public stay interested (Quigley and Forte, 2017).

Recently, Devès et al. (2019) analyzed the articles published by worldwide newspapers in 2015 in English, Spanish and French. They found that the press covered a very small number of earthquake events. Coverage was mostly dedicated to 3 major earthquakes that happened in that year (e.g., Nepal). They found that the duration of the coverage was very short, with news focus on short-term issues: the event magnitude, tsunami alerts, human losses, material damage and rescue operations. Longer-term issues linked to the recovery, restoration, reconstruction, mitigation and prevention were barely addressed.

Our study aims to automate and run in real time the entire process to investigate relationships between earthquakes and online news coverage. It also aims to decrease the potential bias from online news reports arising from a limited number of sources (typically those in the English language and associated with the western world) and from a limited focus on specific earthquake events or geographical region. This is done by (i) harvesting data from as many online news sources as possible by downloading directly from their respective websites or through Application Programming Interface (API) or Really Simple Syndication (RSS) endpoints; (ii) use text mining tools to identify, cluster and extract information from earthquake-related news; (iii) cluster daily earthquake parameters retrieved from the United States Geological Survey (USGS) international seismological bulletin API endpoint into earthquake events based on the geographical location; (iv) map the news clusters and earthquake locations in near real time, and (v) provide analysis on the results and possible relationships between news coverage and earthquake events. Novel approaches adopted here are that the software filters, clusters, and mines information from news

[1] http://www.twitter.com

sources automatically and in real time; and that the sources are from several, multilingual websites, which will help reduce potential bias originating from English written newspapers only.

DATA AND METHOD

The main objective in the algorithm is to automatically create a dataset of harvested news articles mapped to actual earthquakes that have occurred. This is done by (i) cleaning and translating news articles to English; (ii) identifying news articles referring to earthquakes; (iii) grouping news articles referring to earthquakes into clusters; (iv) extracting earthquake parameters such as the date, location, magnitude and other parameters such as number of casualties and quantifiable structural damage; and (v) cross-validating the information extracted from multiple articles across each cluster.

The prototype, named QuakeNews Analyser, was programmed to download news published on the websites of news agency and traditional newspapers through the API/RSS endpoints and from hyperlinks within the endpoints to scrape the content from news agencies websites. All the harvested news content is initially pre-processed by applying text cleaning techniques (Guy et al., 2010; Oh et al., 2010; Piskorski and Atkinson, 2011; Azzopardi and Staff, 2012; He et al., 2013; Asghar et al., 2014; Khumoyun et al., 2016). This typically entails discarding headers, footers, embedded images and JavaScript, as well as removing special characters and HTML tags. The language of the news content is also detected and translated to English if the language is otherwise. Translated news articles containing the word "quake" were then identified for clustering on the basis of a keyword-based search, while the rest of the articles were stored for statistical purposes. From manual evaluation, when alternate words such as "seismic," "shaking" etc. were used, the word "quake" or "earthquake" was also found in the text (as it commonly referred to by the general public). News articles were filtered using the bag-of-words model (frequency of the words in a news article) and words that were weighted. In this way, words which appear frequently in many articles (words such as "the," "so," and "there") were given less importance than those which were explicitly found in certain articles. Earthquake attributes from the text written in each article were then automatically extracted and articles were grouped into clusters using the Term Frequency-Inverse Document Frequency (TF-IDF) and No-*K*-Means approaches. TD-IDF is a statistical measure that evaluates how relevant a word is to a document in a collection of documents, and No-*K*-Means is used in the analysis of data mining by partitioning observations into clusters based on a similarity threshold value. These rigorous approaches were aimed to minimize the possibility that a news cluster contains articles reporting different earthquakes.

Information extraction is then carried out on each of the translated clustered articles, where six common earthquake-related features were extracted: the event magnitude, the date and geographic location of the event, the number of casualties, people injured, and structural quantifiable damage caused by the seismic event. The values of the features extracted from all the articles within each cluster were then cross validated. In order to validate the news articles, a list of earthquakes is compiled from those issued by USGS and aggregated into a list of events in such a way that an event can represent multiple earthquake readings taking place on the same day within the same country. A minimum earthquake magnitude threshold of 4 was chosen because this is the typical lower-bound magnitude of felt earthquakes (e.g., Coburn and Spence, 2002), and thus with a higher likelihood that moderately sized earthquakes were reported in newspapers. Each earthquake event from USGS is then mapped against an extracted magnitude, range of dates and list of locations retrieved from each news cluster (containing one or many news articles mentioning the same earthquake event).

There are computational challenges and limitations when exploiting the text mining tools (e.g., Radinsky et al., 2012; Asghar et al., 2014), particularly problems when extracting information from unstructured sources such as websites (Vannella et al., 2014). One challenging problem arises from the use of part of speech taggers, including incorrect tagging of words, vague classification of entities (Asghar et al., 2014; Jurafsky and Martin, 2014), language-related issues (Pinto et al., 2016), extraction of temporal expressions (Mani and Wilson, 2000; Kisilevich et al., 2010; Bögel et al., 2014; Derczynski and Gaizauskas, 2015) and geographical locations (Kisilevich et al., 2010; Piskorski and Atkinson, 2011) as discussed by Gupta (2016). Another case is with interpreting the content written by different journalists especially when using technical terms (Liu, 2010), the translation of words denoting numerical values into numbers (Miner et al., 2012), and the mapping of articles referring to earthquakes with the characteristics provided by USGS (Le Texier et al., 2016). Another limitation the current prototype has is the 5,000 character limit imposed by Google translator library (GoogleTrans) on identifying the language of the news article and translating it. Generally, the number of words for a text made up of 5,000 characters is approximately 500 to 1,000 words. Studies have shown that key facts are usually placed in the beginning of the content (e.g., Bell and Garrett, 1998; Tanev et al., 2008; Piskorski and Atkinson, 2011). It is anticipated that at least the word "quake" and other relevant information (date, location, magnitude, damage, etc.) are mentioned in the first 5,000 characters of the translated articles.

Depending on the complexity of the texts, articles may result being mapped to the wrong earthquake event. Rigorous text analysis are in place to cross validate such cases; however, this resulted in a reduced amount of mapped articles with listed events. A detailed technical description of the algorithm and tests performed on the datasets are in Camilleri et al., 2019 and Camilleri, 2019.

In summary, we extracted news reports from 23 international news agencies in 6 different languages (**Table 1**). The news sources were chosen based on whether the data could be retrieved from RSS/API for free, on the popularity of the news agency, and on which country the news agency is focused so as to widen the coverage of news articles published across six continents. We ran the prototype in real time for a period of 12 months from the 10th of January 2018 to the 10th of January 2019. A total of 14,717 earthquakes listed in the USGS bulletin with

TABLE 1 | List of news agency internet sites mined for data.

Country	Source name	Data provider	RSS/API
Argentina	La Nacion (local)	La Nacion	RSS
Argentina	La Nacion (world)	La Nacion	RSS
Australia	ABC (local)	ABC	RSS
Australia	ABC (world)	ABC	RSS
Brazil	Grupo Globo (local)	Grupo Globo	RSS
Brazil	Grupo Globo (world)	Grupo Globo	RSS
Chile	Soy Chile (local)	Soy Chile	RSS
Chile	Soy Chile (world)	Soy Chile	RSS
China	China Daily (local)	China Daily	RSS
China	China Daily (world)	China Daily	RSS
China	Shanghai Daily (local)	Shanghai Daily	RSS
China	Shanghai Daily (world)	Shanghai Daily	RSS
China	Xinhua Net	Google News	API
Germany	Die Zeit	Die Zeit	API
India	India Today (local)	India Today	RSS
India	India Today (world)	India Today	RSS
Italy	TGCOM24 (local)	TGCOM24	RSS
Italy	TGCOM24 (world)	TGCOM24	RSS
Japan	Japan Times	Japan Times	RSS
Qatar	Al Jazeera	Google News	API
Russia	TASS	TASS	RSS
South Africa	News24 (local)	News 24	RSS
South Africa	News24 (world)	News 24	RSS
Spain	El Mundo	Google News	API
Spain	El Pais (local)	El Pais	RSS
Spain	El Pais (world)	El Pais	RSS
Sudan	Sudan Tribune	Sudan Tribune	RSS
United Kingdom	BBC	Google News	API
United Kingdom	Metro End	Google News	API
United Kingdom	Reuters	Google News	API
United Kingdom	The Guardian	The Guardian	API
United States	Associated Press	Google News	API
United States	USA Today	Google News	API

a magnitude between 4 and 8.2 were retrieved and aggregated into a list of 7,359 earthquake events. Many of these earthquake events include aftershocks (or sequence of earthquakes) that happen on the same day in the same country. At the same time, a total of 268,182 articles were analyzed; 3,355 articles (1.25%) had the word "quake" of which 1,042 articles (0.4%, or 31% of 3,355) were grouped into clusters and mapped to the earthquake events. These resulted in successfully mapping 698 earthquake events with articles. Here we discuss the outcome of the results in the context of earthquakes and the relationship with the online news media.

RESULTS

This study has widened considerably the source of news coverage for investigation when compared to previous studies reaching out to news agency websites spread across 16 different countries from six continents (North America, South America, Europe, Africa, Asia, and Australia - refer to **Table 1**) and translating 6 languages to English in the process. The study produced some interesting observations that shed more light on how news agencies reacted with recent earthquakes.

We compared the amount of earthquake reporting between news agencies. Out of the 3,355 articles containing the word "quake," Japan Times, TGCOM24, ABC, and El Pais wrote the highest number of articles: 16.4, 11, 10.5, and 10.3% (**Figure 1**). The most reported earthquake-feature in the extracted news articles was the magnitude parameter (22%), followed by the number of casualties (14.9%), quantifiable structural damage caused (5.8%), and the number of injuries (5.7%).

One has to be careful not to over interpret these numbers. Some agency portals provided users with two different API/RSS endpoints – one disseminating local news and the other disseminating international news (e.g., La Nacion, ABC, and Grupo Globo), while others publish the local and international news through one API/RSS endpoint (e.g., Die Zeit, Japan Times, Al Jazeera, and The Guardian). QuakeNews Analyser is programmed to extract data from both sources when available, which may result in some agencies publishing more reports that

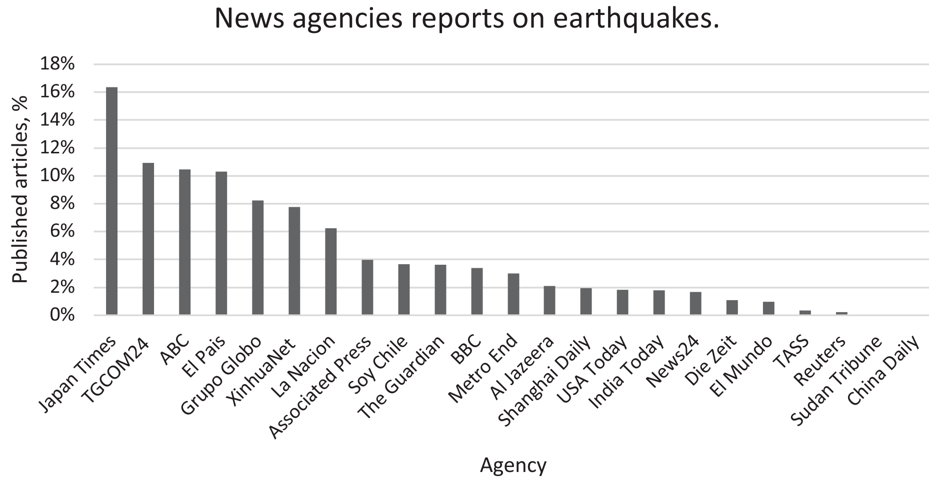


FIGURE 1 | Comparison of published earthquake-related articles per news agency.

include many local earthquakes than other agencies who report only international earthquakes.

Figure 2 shows the distribution of earthquake epicenters from the analyzed reports, and the location of the reporting online news agencies. The distribution of the reported seismicity is from earthquakes that occur on or very close to land with most of the earthquakes that happen along mid-ocean ridges not reported. This follows the trend observed in Le Texier et al. (2016).

Figure 3 shows the timeline of detected reports binned in weeks. The number of published online articles per week are on the same order of magnitude (tens to hundreds) of those reported by Devès et al. (2019) for daily media coverage (with the exception of the Nepal earthquake in reference). Spikes in the number of news articles coincide with notable earthquakes such as the week following the 7.5 magnitude earthquake on September 28, 2018 near Palu, Indonesia, which also triggered a devastating tsunami (weeks 39–41). Similarly, but for a smaller peak was the Hawaiian earthquake on May 4, 2018, with a magnitude of 6.9, which also involved a series of volcanic eruptions over a number of weeks (weeks 18–24). Another peak in the number of published articles at the end of the year is also related to a volcanic eruption, this time from Etna in Italy, following a series of earthquakes. Interestingly, the greatest earthquake for 2018 had a magnitude of 8.2 on August 19 (week 34) located beneath Fiji, however this was under reported probably because of its very deep hypocenter (>500 km) which led to a few numbers of local felt reports and minimal risk to generate a tsunami. Other deep earthquakes (>100 km depth) are mostly not reported (e.g., during the Hawaii volcanic eruption, **Figure 3**).

The discrepancy between the number of articles which had the word "quake" and the number of articles mapped to an earthquake event from USGS (**Figure 3A**) is mainly due to reports mentioning earthquakes in a vague or general context making it difficult for the article to be mapped. For example, the Hawaiian earthquake was followed by articles reporting the volcanic activity and briefly mentioning the seismic activity leaving out crucial details that enable mapping that article with an earthquake event. On the other hand, thanks to the rigorous parsing of articles that extracts key earthquake parameters (e.g., location, time, and magnitude) we focus our results on the mapped articles, making it possible to investigate relationships of published articles with magnitude.

In general, the expected trend of an increased number of published articles for the larger magnitude earthquakes holds (e.g., Le Texier et al., 2016) keeping in mind that there are far less earthquakes of higher magnitude. In **Figure 4A** we divide the number of articles with the number of global earthquakes of 2018 in the respective magnitude category, clearly showing a higher ratio of published articles for the larger magnitude earthquakes. We propose a power-law relationship between the number of news agencies (A), the earthquake magnitude (M), and the anticipated number of published articles during the 1-year study:

$$Predicted\ articles = A^{(M/M_t)}$$

where M_t is the minimum earthquake magnitude threshold reported (**Figure 4B**). Unlike Le Texier et al. (2016), who developed a model to explain the number of mentions each earthquake of magnitude greater than 5 gets by its geophysical characteristics (earthquake magnitude, depth, localization and concentration), our model takes into consideration the earthquake magnitude of any size as well as the number of news agencies available. Thus, for typical minimum reported earthquake magnitude M_t of 4 and 23 news agencies one would expect about 23 articles for earthquakes of this magnitude. Similarly, for earthquakes of magnitude 7 or more one would expect about 240 news reports annually. These accumulative reports could either be from unique news agencies or perhaps multiple reports from a fewer number of agencies. This simple, direct relationship assumes that the global distributed seismicity for the various magnitude ranges remains the same. The

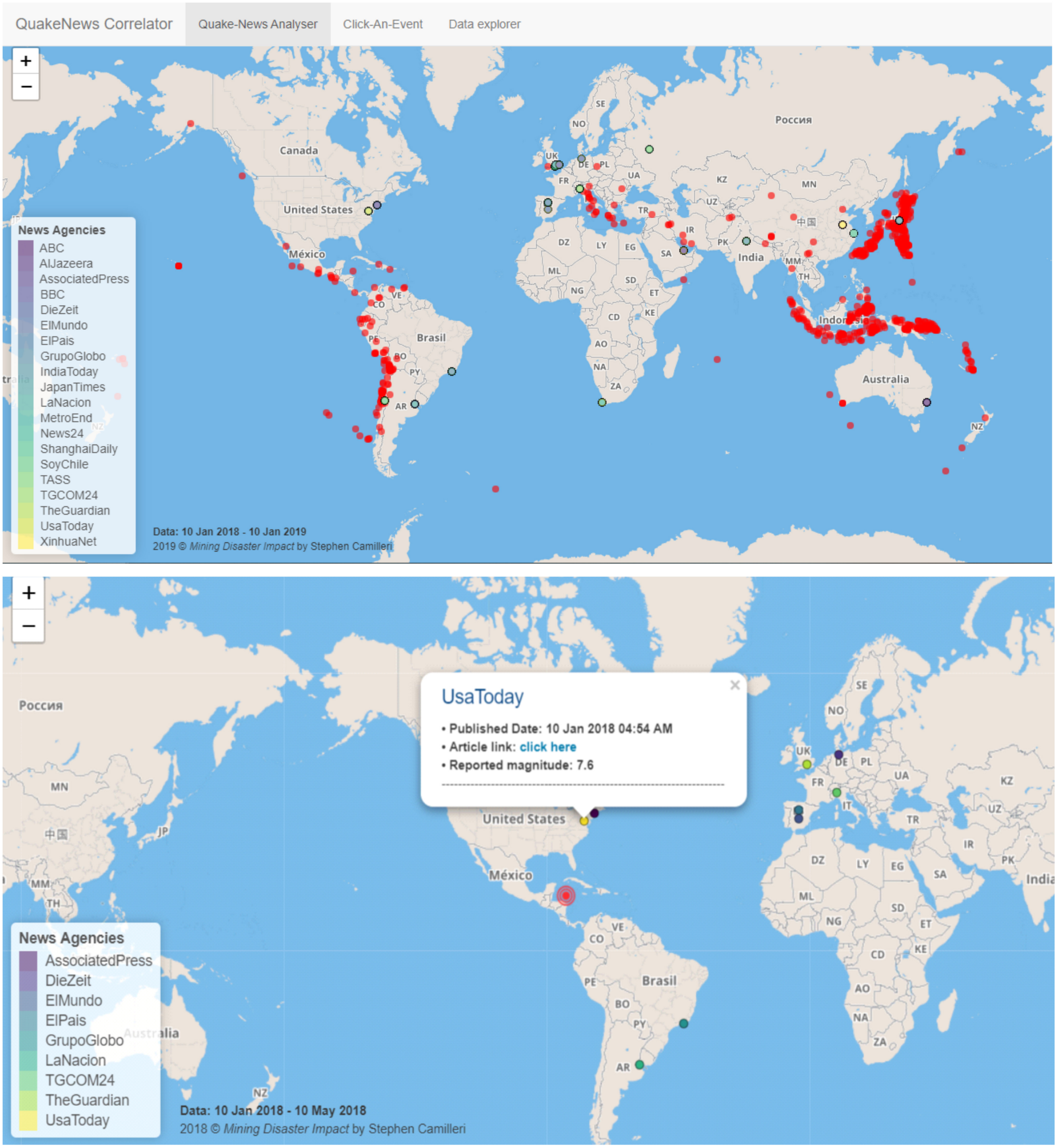


FIGURE 2 | Graphic user interface of QuakeNews Analyser. Top map shows the location of 698 earthquake epicenters (red dots), and the location of news agencies' headquarters who reported about these events (color shaded dots). Bottom map shows an example of the news coverage for a magnitude 7.6 earthquake that occurred on Great Swan Island off the coast of Honduras on the 9th of January 2018 (red marker) (see also **Figure 3**). Colored dots show the agencies which reported the event. Tab shows details of a published article by USA Today.

relationship is likely to be a lower bound because of our limited dataset, strict parsing of articles and careful mapping of articles with earthquake events. Furthermore, the application does not take into consideration the republishing of articles via the diverse media streams and use of online social media.

DISCUSSION

Earthquakes and Their Coverage

The majority of events during the study period took place along the seismically active Pacific Rim, in the regions of

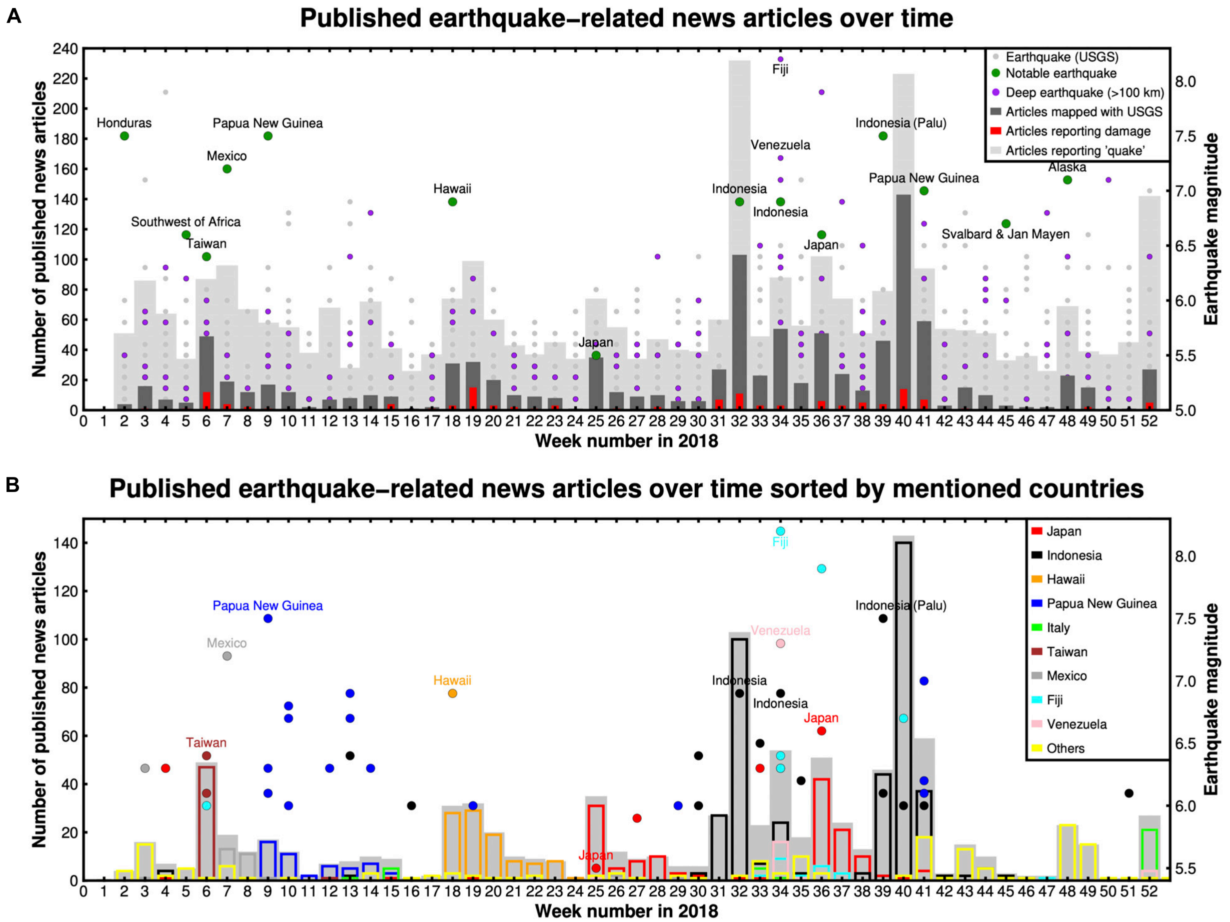


FIGURE 3 | Weekly bins of detected earthquake-related news articles during 2018. **(A)** Light gray bars represent the number of articles which had the word "quake" in the text (3,355). Dark gray bars represent the number of articles which were mapped with an earthquake event (1,042). Red bars represent the number of articles which reported earthquake damage. Green dots are notable earthquakes corresponding to peaks in the bins or discussed in the text. Purple dots are deep earthquakes (> 100 km) with strong magnitudes. Gray dots are other earthquakes listed in the USGS catalog that occurred during the year. **(B)** Same as top graph but sorted by color-coded countries referred to in the articles. Dots are earthquakes color-coded by country and have a magnitude ≥ 6 (except for Japan weeks 25–30 with lower magnitude M ≥ 5.5). Note that the *y*-axes have been expanded for better viewing, and that some events may happen at the end of a week resulting in articles flowing onto the next week bin.

Japan (282 earthquake events), Indonesia (155 seismic events), Papua New Guinea (85 earthquake events), and Chile (57 seismic events), making up 83% of the seismic events (579 out of 698 earthquake events) which were mapped to news clusters (**Figure 2**). One of the most mentioned single event was the magnitude 7.5 earthquake in Papua New Guinea that occurred on the February 25, 2018 (week 9), with 50 articles over a span of 48 days (7 weeks, **Figure 3B**). Similarly, Taiwan's magnitude 6.4 earthquake on the 6th of February 2018 was mentioned in 47 articles, however, over a span of 5 days only.

Not all major earthquakes got the same news coverage. For example, the magnitude 7.1 earthquake that took place in Anchorage, Alaska on the 30th of November 2018 (week 48, **Figure 3**), did not receive as much coverage despite the many aftershocks over the following days. In all, the event was mentioned in 15 articles, with news agencies reporting a magnitude ranging between 5.7 and 7.0. One possible reason for such lack of coverage is that Alaska is sparsely populated and that there were no casualties even though a few buildings suffered structural damage. In other cases, strong earthquakes did not get any news coverage at all. For example, the magnitude 6.6 earthquake in Southwest of Africa on the 28th of January 2018 (week 5, **Figure 3A**) and the magnitude 6.7 in Jan Mayen on 9 November 2018 (week 45) are two such cases. The most likely reason for the lack of coverage is that the events took place in uninhabited, remote areas.

While many news agencies are quick to report an earthquake and update readers with the latest news within a few hours of the earlier reports (e.g., **Figure 5**), levels of interest from news agencies on the aftermath of the earthquake varies. The trend on the duration an earthquake event is reported correlates with the damage caused rather with the magnitude of the earthquake. Very large magnitude earthquakes are at times either reported

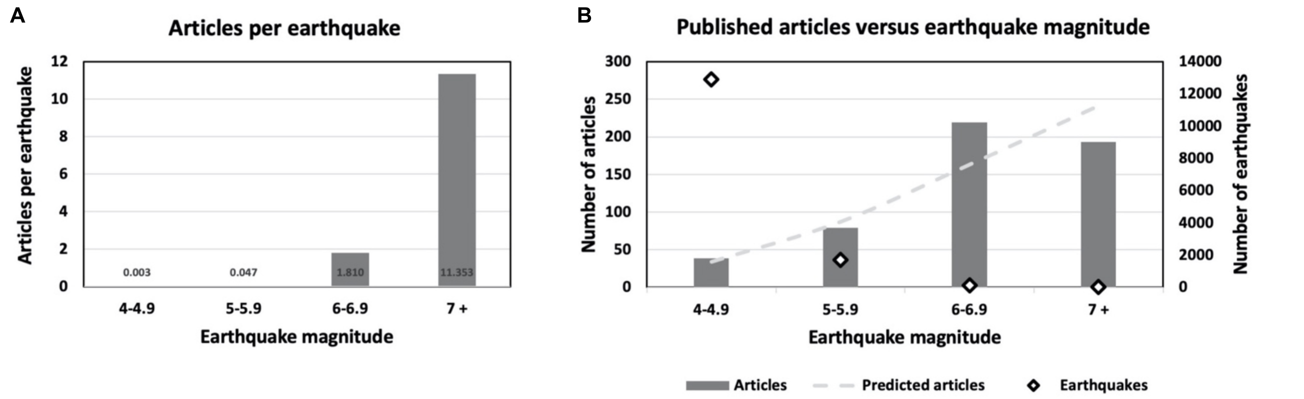


FIGURE 4 | Graphs showing the relationship of published articles with the number of global earthquakes and earthquake magnitude. **(A)** Ratio of number of articles per earthquake sorted by magnitude. **(B)** Number of articles with the corresponding magnitude ranges. Dashed line is the modeled number of articles (Correlation coefficient of 0.88, and R-squared value of 0.78). Diamond symbols show the number of earthquakes listed in the 2018 USGS catalog.

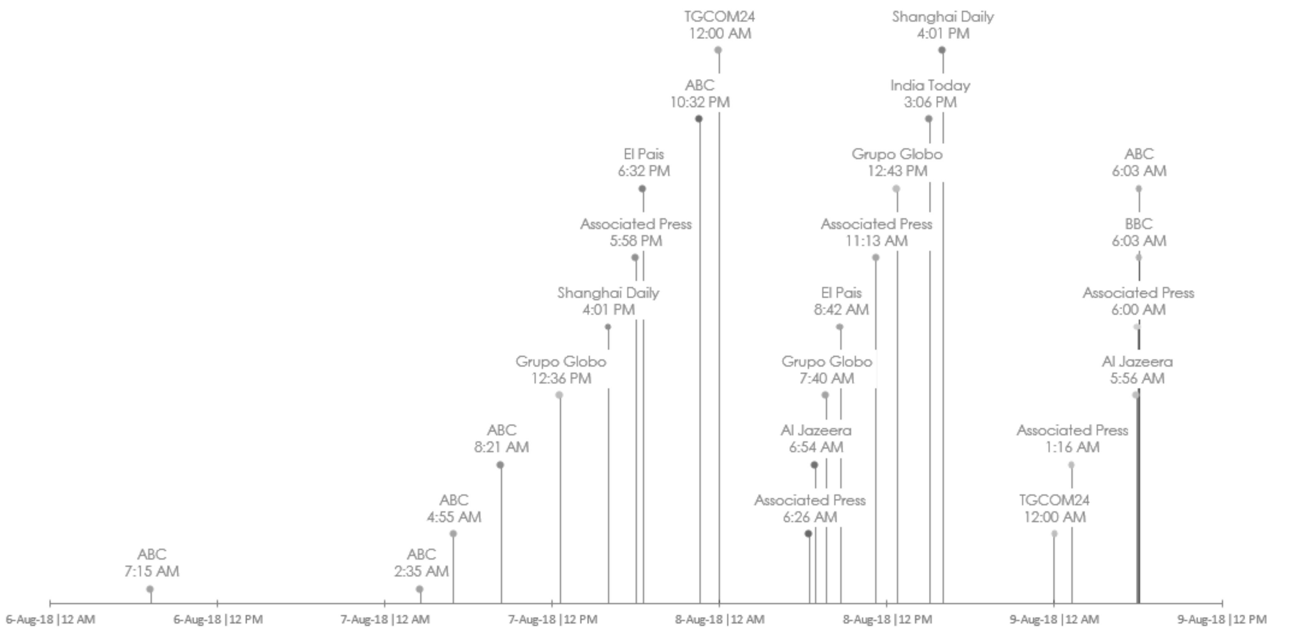


FIGURE 5 | Timeline showing the reports from different news agencies as Indonesia was experiencing earthquakes frequently. The date represents the timestamp when the article was published by the news agency.

briefly or none at all (**Figure 3**), whereas earthquakes with a lower magnitude but cause some damage tend to have a temporal decay that lasts from a few days to a few weeks, example: Taiwan 1 week, Mexico 2 weeks (7–8), Hawaii 7 weeks (18–24). During 2018 there were two cases of long-enduring earthquake sequences which kept the attention of the media, one in Papua New Guinea and one in Indonesia. In the case of the latter, the seismic activity took place between the 30th of June and the 12th of October 2018, with reports continuing over the following weeks (week numbers 26–45, **Figure 3B**). Throughout this period, 98 earthquake events out of 104 earthquakes listed by USGS were mapped against at least one news cluster, with the number of news articles published by news agencies totaling 400. During the three and a half months there was a significant earthquake recorded almost every day somewhere in the country, of which 42 earthquakes were equal or above magnitude 5, and 6 were above magnitude 6. Probably, the extensive coverage was due to the seismic activity claiming thousands of lives, injuring thousands of people and causing a large amount of structural damage (**Table 2**). **Figure 5** shows an example of a timeline of some extracted reports between the 6th to the 8th of August 2018 during the earthquake sequence.

Earthquake Magnitude

In the case of reported earthquake magnitudes, in general, they either match those listed by USGS or are higher (**Figure 6**).

TABLE 2 | Example of news reports when Indonesia was frequently experiencing earthquakes.

Source	Title	Date	Magnitude	Damage	Link[1]
ABC	"People were screaming": Witness describes chaos when quake hit Gili Islands	06-08-2018 07:15:42	6.9		http://www.abc.net.au/news/2018-08-06/witness-describes-chaos-when-earthquake-hit-the-gili-islands/10078808
ABC	How the Lombok earthquake happened	07-08-2018 04:55:39	9.1		http://www.abc.net.au/news/2018-08-07/what-creates-quake-risk-on-lombok/10082912
ABC	Survivors pulled from rubble in Indonesia's quake-hit Lombok	07-08-2018 22:32:58	7	230	http://www.abc.net.au/news/2018-08-08/rescuers-pull-people-out-alive-from-rubble-in-indonesias-lombok/10087980
TGCOM24	Terremoto in Indonesia, si aggrava il bilancio: morti salgono a 347	08-08-2018 00:00:00	6.9		http://www.tgcom24.mediaset.it/mondo/terremoto-in-indonesia-si-aggrava-il-bilancio-morti-salgono-a-347_3156866-201802a.shtml
Associated press	Food, aid reaching quake-stricken parts of Indonesian island	08-08-2018 06:26:58	7		https://apnews.com/e481d46a399c4d5b83ae96cff5df7193
Associated press	The Latest: Death toll rises to 131 in Indonesian quake	08-08-2018 11:13:30	7	156000	https://apnews.com/6abd9ea6f3f04bad8ed83590adebcc1f
Shanghai Daily	Quake leaves 156,000 homeless	08-08-2018 16:01:00	6.9	131	http://www.shanghaidaily.com/world/Quake-leaves-156000-homeless/shdaily.shtml
TGCOM24	Indonesia, nuovo forte terremoto sull'isola di Lombok: magnitudo 5.9	09-08-2018 00:00:00	5.9		http://www.tgcom24.mediaset.it/mondo/indonesia-nuovo-forte-terremoto-sull-isola-di-lombok-magnitudo-5-9_3156949-201802a.shtml
Associated press	Quake put life on hold in damaged, hungry Indonesian village	09-08-2018 01:16:06	7		https://apnews.com/924cdf5ef27a47cdbd21138d7aecddbe
ABC	Another strong quake hits Indonesia's Lombok, witnesses say buildings have collapsed	09-08-2018 06:03:35	6.2		http://www.abc.net.au/news/2018-08-09/another-strong-quake-hits-indonesia-lombok-buildings-col/10102422

[1] *Internet links last accessed on December 16, 2019. Entries correspond to the timeline in* ***Figure 5****. The date represents the timestamp when the article was published by the news agency.*

For example, the magnitude of the earthquake that struck the Great Swan Island off the coast of Honduras on the 9th of January (**Figure 2**) was reported as 7.6 by United States Today, whereas the USGS magnitude is 7.5 (**Figure 3**). There are various factors that may influence this outcome. For instance, many news agencies quote earthquake magnitudes published by USGS, while others report the earthquake magnitude from other seismic monitoring agencies. Different earthquake agencies are likely to report slightly different magnitude values either because of different type of estimate (e.g., local, body wave, surface wave, and moment magnitude) or because using different parameters such as the number of seismic stations (e.g., Chung and Bernreuter, 1981; Kanamori, 1983). In other instances, some reporters tend to give rounded "ceiling" values for the earthquake magnitude reporting a higher than the actual value. Another reason could be the news agencies tendency to exaggerate the news of small-magnitude earthquakes to attract the public's interest (e.g., Dhakal, 2018). Also, the earthquake magnitudes are sometimes revised by seismologists resulting in a different value other than what was initially reported by USGS. In the case of aftershocks, reporters sometimes remind the readers of the larger magnitude of the earthquake sequence rather than the magnitude of the recent earthquake. Additionally, QuakeNews Analyser might extract the wrong magnitude when a past event is mentioned in the article as is the case for the Lombok earthquake reported by ABC, where the software picked a magnitude of 9.1, which was referring to the 2004 Indian Ocean tsunami (**Table 2**).

It has also been noted that the magnitude is not always reported in news articles because news editors uses arbitrary words such as "strong" to describe the energy of the earthquake particularly for reporting on past events. Also, the magnitude parameter may have been missed because of the limited number of words allowed for translation by the Google API, adopted by xthis prototype.

Earthquake Damage

With regards to quantifying damage caused by an earthquake solely based on reports, it is a challenging task. One has to first define what is "damage." It can take different forms such as deaths, displaced people, collapsed buildings, etc. Thus, unlike the magnitude, which is usually described with a number gauged by a seismograph and is one of the most reported parameters to describe an earthquake, one has to look for specific words to capture the context of the report and determine the level of damage. Secondly, reports on damage may change from day to day following an earthquake as initial reports tend to report "minimal" amount of damage. Then, as the story unfolds, the damage is better assessed however

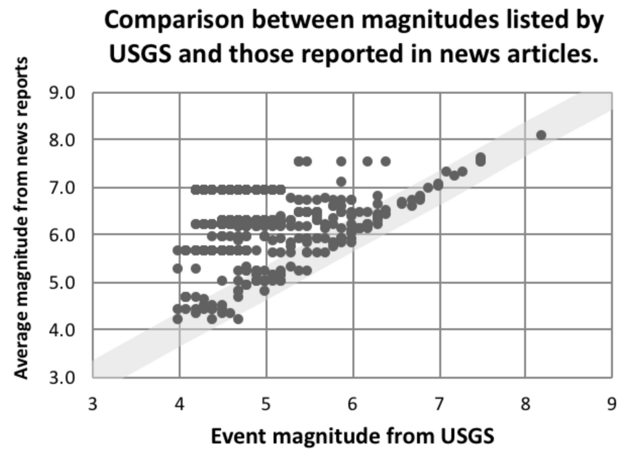


FIGURE 6 | Comparison between magnitudes published by USGS and the average of magnitudes reported by different agencies. The thick gray line represents the expected 1-to-1 relationship.

fewer agencies continue reporting details. Furthermore, these latter reports may lack earthquake details that make mapping the article to the original earthquake event difficult. A more comprehensive algorithm than that presented here, which takes into account a wider range of grammar and words related to damage, is necessary to extract complete information on damage. Nonetheless, in **Figure 3**, we show the trends of articles which report damage. The number of detected reports mentioning damage are much less than those reporting on the earthquakes however they follow similar trends in the peaks and coincide with earthquakes. The number of articles mentioning damage related to an earthquake event can last from 1 week to couple of weeks following a significant earthquake (e.g., Taiwan, Mexico, and Hawaii, **Figure 3**), and contribute to the duration on how long the event is mentioned in the press (see section "Earthquakes and Their Coverage"). **Table 3** summarizes the number of reported casualties and the number of reporting articles also sorted by magnitude. The devastating earthquakes in Indonesia during 2018 dominated the list of casualties.

Alternative Uses

Enhanced applications of tools such as this can have alternative uses of far more important implications than just statistical analysis aimed at finding which earthquake is being reported. For example, it can be used to automatically map the felt intensity of an earthquake-struck region based on the macroseismic scale, traditionally limited to people filling in local felt report forms (e.g., Wald et al., 2012; Bossu et al., 2016; Van Noten et al., 2017). Another use could be to detect mistaken news reports about wrongly reported seismic activity such as the case with Kenya's "crack" in 2018[2,3,4], whereby the reports can be validated automatically with earthquake bulletins. Such applications can also be used for other natural disasters such as tsunamis, hurricanes, forest fires, etc., simply by changing the searched keywords.

Another alternative use could be for global campaigns aimed at relief efforts as might be necessary in the case of large-scale disasters (earthquake or otherwise). The spread of news reports across the world is indicative of the attention the disaster brought on to the world. In general, the international community responds positively to calls for international aid and provide support to the affected community, however, the focus on the devastation fades out as new stories catch the media's attention (e.g., Devès et al., 2019). Thus, the gathering of information on news reporting in real time can help plan campaigns for relief efforts or fundraising particularly when the news reports are declining but the attention is still necessary. Similarly, such a tool can provide useful information to keep on-going educational campaigns for rare, large-scale disasters like tsunamis, which may need the occasional

[2]https://face2faceafrica.com/article/africa-splitting-two-tear-kenyas-rift-valley-video (last accessed March 12, 2020)

[3]https://www.theguardian.com/science/blog/2018/apr/06/africa-is-slowly-splitting-in-two-but-this-crack-in-kenya-rift-valley-has-little-to-do-with-it (last accessed March 12, 2020)

[4]https://www.forbes.com/sites/davidbressan/2018/04/05/seismologists-are-not-happy-how-media-reported-the-kenya-crack/ (last accessed March 12, 2020)

TABLE 3 | Table shows the number of casualties (when extracted) and the related number of articles published, and also sorted by reported magnitude.

Number of casualties	Number of articles, which extracted casualties value	Number of articles (magnitude not mentioned)	Number of articles (M 4–5)	Number of articles (M 5–6)	Number of articles (M 6–7)	Number of articles (M 7–8)
1	10	1	0	0	2	7
1–10	66	13	1	1	42	9
10–100	105	28	0	4	40	33
100–1000	80	31	0	4	21	24
1000–10000	49	31	0	2	2	14
10000–100000	2	1	0	0	1	0
100000+	3	0	0	0	1	2

Initial reports tend to report minimal number of damage.

article as part of maintaining a good level of preparedness within the community in general.

CONCLUSION

We investigate the relationship between earthquakes and online news portals. We use an inhouse developed software that automatically extracts earthquake reports in real time from 23 news agencies and authored in 6 different languages available at the time in order to reduce bias from reports. Out of 268,182 articles collected during a 1-year time period, 1.25% had the word "quake" and 0.4%, were mapped to the earthquake events listed in the USGS earthquake bulletin to validate its authenticity and establish relationships.

We find that the distribution of the reported seismicity is from earthquakes that occur on or very close to land with most of the earthquakes that happen along mid-ocean ridges not reported, as has been noted in previous studies. Our results also confirm that the number of published articles online about an earthquake depends on its magnitude, on the duration of the seismicity which can be linked to the same main shock and, of course, on the number of news agencies considered. Based on the news agencies and reports analyzed here, we propose a lower bound relationship between the number of news agencies, the earthquake magnitude and the anticipated number of published articles online in a year. We find that, in general, reports mention higher earthquake magnitudes than those in the USGS earthquake catalog, and the reports on earthquakes can last for a few days to a couple of weeks following the earthquake.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

SC has worked on the design of the software, acquired the data, made the analysis, worked on the interpretation of the data, and wrote the manuscript. MA has conceived the project, contributed to the analysis and interpretation of the data, and revised the manuscript. JA contributed to the design of the work, data acquisition, analysis and interpretation of the data, and revised the manuscript.

FUNDING

MA has received funding from the European Union's Horizon 2020 Research and Innovation Program under the Marie Skłodowska-Curie Grant Agreement No. 843696.

ACKNOWLEDGMENTS

The authors would like to thank two reviewers and Pauline Galea for helping improve the manuscript. Some figures were made using Generic Mapping Tools software (Wessel et al., 2013; Agius, 2018).

REFERENCES

Adams, W. C. (1986). Whose lives count? TV coverage of natural disasters. *J. Commun.* 36, 113–122.

Agius, M. R. (2018). "Getting started with GMT: an introduction for seismologists," in *Moment Tensor Solutions*, ed. S. D'Amico (Cham: Springer Natural Hazards, Springer). Available at: https://link.springer.com/chapter/10.1007/978-3-319-77359-9_31

Asghar, M. Z., Khan, A., Ahmad, S., and Kundi, F. M. (2014). A review of feature extraction in sentiment analysis. *J. Basic Appl. Sci. Res.* 4, 181–186.

Avvenuti, M., Del Vigna, F., Cresci, S., Marchetti, A., and Tesconi, M. (2015). "Pulling information from social media in the aftermath of unpredictable disasters," in *2015 2nd International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)*, Piscataway, NJ: IEEE, 258–264.

Azzopardi, J., and Staff, C. (2012). Incremental clustering of news reports. *Algorithms* 5, 364–378.

Bell, A., and Garrett, P. D. (1998). *Approaches to Media Discourse*. Hoboken, NJ: Wiley-Blackwell.

Bögel, T., Strötgen, J., and Gertz, M. (2014). Computational narratology: extracting tense clusters from narrative texts. *Proc. Ed. Lang. Resour. Eval. Conf.* 14, 950–955.

Bossu, R., Landès, M., Roussel, F., Steed, R., Mazet-Roux, G., Martin, S. S., et al. (2016). Thumbnail-based questionnaires for the rapid and efficient collection of macroseismic data from global earthquakes. *Seismol. Res. Lett.* 88, 72–81.

Bossu, R., Laurin, M., Mazet-Roux, G., Roussel, F., and Steed, R. (2015). The importance of smartphones as public earthquake-information tools and tools for the rapid engagement with eyewitnesses: a case study of the 2015 Nepal earthquake sequence. *Seismol. Res. Lett.* 86, 1587–1592.

Bossu, R., Lefebvre, S., Cansi, Y., and Mazet-Roux, G. (2014). Characterization of the 2011 Mineral, Virginia, earthquake effects and epicenter from website traffic analysis. *Seismol. Res. Lett.* 85, 91–97.

Bossu, R., Mazet-Roux, G., Douet, V., Rives, S., Marin, S., and Aupetit, M. (2008). Internet users as seismic sensors for improved earthquake response. *Trans. Am. Geophys. Union* 89, 225–226.

Brown, H. L. (2012). *Representations of Haiti in Western news media: Coverage of the January 2010 earthquake in Haiti*. PhD thesis, Georgia State University, Atlanta.

Camilleri, S. (2019). *Mining Disaster Impact*. Master's thesis, University of Malta, Malta.

Camilleri, S., Azzopardi, J., and Agius, M. R. (2019). "Investigating the relationship between earthquakes and online news," in *2019 IEEE Second International Conference on Artificial Intelligence and Knowledge Engineering (AIKE)*, Sardinia, 1–8.

Chung, D. H., and Bernreuter, D. L. (1981). Regional relationships among earthquake magnitude scales. *Rev. Geophys.* 19, 649–663.

Coburn, A., and Spence, R. (2002). *Earthquake Protection. 2nd End*. Hoboken, NJ: Wiley.

Derczynski, L., and Gaizauskas, R. (2015). "Temporal relation classification using a model of tense and aspect," in *Proceedings of Recent Advances in Natural Language Processing*, Madrid: Incoma Ltd, 118–122.

Devès, M. H., Texier, M. L., Pecout, H., and Grasland, C. (2019). Seismic risk: the biases of earthquake media coverage. *Geosci. Commun.* 2, 125–141.

Dhakal, S. P. (2018). Analysing news media coverage of the 2015 Nepal earthquake using a community capitals lens: implications for disaster resilience. *Disasters* 42, 294–313. doi: 10.1111/disa.12244

Earle, P., Guy, M., Buckmaster, R., Ostrum, C., Horvath, S., and Vaughan, A. (2010). OMG earthquake! can twitter improve earthquake response? *Seismol. Res. Lett.* 81, 246–251.

Earle, P. S., Bowden, D. C., and Guy, M. (2012). Twitter earthquake detection: earthquake monitoring in a social world. *Ann. Geophys.* 54, 708–715.

Eisensee, T., and Strömberg, D. (2007). News droughts, news floods, and US disaster relief. *Q. J. Econ.* 122, 693–728.

Gupta, D. (2016). "Event search and analytics: detecting events in semantically annotated corpora for search and analytics," in *Proceedings of the 9th ACM International Conference on Web Search and Data Mining*, New York, NY: ACM, 705–705.

Guy, M., Earle, P., Ostrum, C., Gruchalla, K., and Horvath, S. (2010). Integration and dissemination of citizen reported and seismically derived earthquake information via social network technologies. *Adv. Intell. Data Anal.* 9, 42–53.

He, W., Zha, S., and Li, L. (2013). Social media competitive analysis and text mining: a case study in the pizza industry. *Int. J. Inform. Manag.* 33, 464–472.

Heeger, B. (2007). *Natural Disasters and CNN: The Importance of TV News Coverage for Provoking Private Donations for Disaster Relief*. Rhode: Brown University, Providence.

Hicks, S. P. (2019). Geoscience analysis on Twitter. *Nat. Geosci.* 12, 585–586. doi: 10.1038/s41561-019-0425-4

Jurafsky, D., and Martin, J. H. (2014). *Speech and Language Processing*, 2nd Edn. London: Pearson.

Kanamori, H. (1983). Magnitude scale and quantification of earthquakes. *Tectonophysics* 93, 185–199.

Khumoyun, A., Cui, Y., and Lee, H. (2016). Real-time information classification in twitter using storm. *Bangk. Int. Conf.* 49, 1–4.

Kisilevich, S., Mansmann, F., and Keim, D. (2010). "P-DBSCAN: A density-based clustering algorithm for exploration and analysis of attractive areas using collections of geo-tagged photos," in *Proceedings of the 1st International Conference and Exhibition on Computing for Geospatial Research and Application* , Vol. 38, New York, NY: ACM, 1–4.

Le Texier, M., Devès, M. H., Grasland, C., and De Chabalier, J. B. (2016). Earthquakes media coverage in the digital age. *Espace Géogr.* 45, 5–24. doi: 10.3390/ijerph16183239

Liang, Y., Caverlee, J., and Mander, J. (2013). "Text vs. images: on the viability of social media to assess earthquake damage," in *Proceedings of the 22nd International Conference on World Wide Web*, New York, NY: ACM, 1003–1006.

Liu, D. (2010). *A Comparative look at the Coverage of the Sichuan Earthquake in Chinese and American Newspapers*. Ames, LA: Iowa State University. Master's thesis.

Mani, I., and Wilson, G. (2000). "Robust temporal processing of news," in *Proceedings of the 38th Annual Meeting on Association for Computational Linguistics*, Stroudsburg, PA: Association for Computational Linguistics, 69–76.

Miner, G., Elder, J., Fast, A., Hill, T., Nisbet, R., and Delen, D. (2012). *Practical Text Mining and Statistical Analysis for Non-structured Text Data Applications*. Cambridge, MA: Academic Press.

Oh, O., Kwon, K. H., and Rao, H. R. (2010). "An exploration of social media in extreme events: rumor theory and Twitter during the Haiti earthquake 2010," in *Proceedings of the International Conference on Information Systems*, Saint Louis, MO, 231.

Panagiotou, N., Katakis, I., and Gunopulos, D. (2016). "Detecting events in online social networks: definitions, trends and challenges," in *Solving Large Scale Learning Tasks. Challenges and Algorithms*, eds S. Michaelis, N. Piatkowski, and M. Stolpe (Berlin: Springer), 42–84.

Pinto, A., Oliveira, H. G., and Alves, A. O. (2016). "Comparing the performance of different NLP toolkits in formal and social media text," in *OpenAccess Series in Informatics*, Vol. 51, (Wadern: Dagstuhl Publishing), 1–16.

Piskorski, J., and Atkinson, M. (2011). "Frontex real-time news event extraction framework," in *Proceedings of the 17th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, New York, NY: ACM, 749–752.

Quigley, M. C., and Forte, A. M. (2017). Science website traffic in earthquakes. *Seismol. Res. Lett.* 88, 867–874.

Radinsky, K., Davidovich, S., and Markovitch, S. (2012). Learning to predict from textual data. *J. Artif. Intell. Res.* 45, 641–684.

Sakaki, T., Okazaki, M., and Matsuo, Y. (2010). "Earthquake shakes Twitter users: real-time event detection by social sensors," in *Proceedings of the 19th International Conference on World Wide Web*, New York, NY: ACM, 851–860.

Simon, A. F. (1997). Television news and international earthquake relief. *J. Commun.* 47, 82–93.

Stomberg, D. R. (2012). *Disasters in the Media: A Content Analysis of the March 2011 Japan Earthquake/Tsunami and Nuclear Disasters*. Fort Collins, CO: Colorado State University. PhD thesis.

Suzanne, F. (2006). The CARMA report: western media coverage of humanitarian disasters. *Polit. Q.* 77, 1–17.

Tanev, H., Piskorski, J., and Atkinson, M. (2008). "Real-time news event extraction for global crisis monitoring," in *International Conference on Application of Natural Language to Information Systems*, Berlin: Springer, 207–218.

Van Belle, D. A. (2000). New York times and network TV news coverage of foreign disasters: the significance of the insignificant variables. *Journal. Mass Commun. Q.* 77, 50–70.

Van Noten, K., Lecocq, T., Sira, C., Hinzen, K. G., and Camelbeeck, T. (2017). Path and site effects deduced from merged transfrontier internet macroseismic data of two recent M4 earthquakes in northwest Europe using a grid cell approach. *Solid Earth* 8, 453–477.

Vannella, D., Flati, T., and Navigli, R. (2014). "WoSIT: A word sense induction toolkit for search result clustering and diversification," in *Proceedings of 52nd Annual Meeting of the Association for Computational Linguistics: System Demonstrations*, Stroudsburg, PA: Association for Computational Linguistics, 67–72.

Wald, D. J., Quitoriano, V., Worden, C. B., Hopper, M., and Dewey, J. W. (2012). USGS "Did You Feel It?" internet-based macroseismic intensity maps. *Ann. Geophys.* 54, 688–707.

Wessel, P., Smith, W. H. F., Scharroo, R., Luis, J., and Wobbe, F. (2013). Generic mapping tools: improved version released. *Trans. Am. Geophys. Union* 94, 409–410. doi: 10.1002/2013EO450001

Conflict of Interest: The 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.

Copyright © 2020 Camilleri, Agius and Azzopardi. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Communication

COMMUNITY CASE STUDY
published: 19 May 2020
doi: 10.3389/fcomm.2020.00032

MyShake Citizen Seismologists Help Launch Dual-Use Seismic Network in California

Jennifer A. Strauss, Qingkai Kong, Sharon Pothan, Stephen Thompson, Ramon F. Mejia, Steven Allen, Sarina Patel and Richard M. Allen*

Berkeley Seismology Lab, University of California, Berkeley, Berkeley, CA, United States

The MyShake app began delivering earthquake early warning alerts to users in California on October 17, 2019. The app delivers alerts from ShakeAlert when the estimated magnitude is 4.5 or greater to phones in the Modified Mercalli Intensity (MMI) III or greater zone. MyShake users receive the alerts, but also serve as citizen seismologists for the system. They contribute accelerometer data allowing this dual-use network to serve as an alert delivery platform and an earthquake monitoring network. Users are also now afforded the ability to interactively share their experience in an earthquake with others on the system through the use of an experience report. The design and maintenance of this system requires the interoperability of many technical systems (servers, code, smartphones) and stakeholders (scientists, federal and state agencies, public). This imparts some constraints on our ability to address problems and implement new features, but ultimately provides a considered framework within which we can design for future use cases. We discuss new features of the app, such as the experience report, the collection of timing information to improve delivery latencies, and examples of how human centered design responds to user needs. We also look at privacy constraints and ways MyShake can continue to improve in the future.

Keywords: citizen science, seismology, smartphone, human-centered design, earthquake early warning

OPEN ACCESS

Edited by:
Kate Huihsuan Chen, National Taiwan Normal University, Taiwan

Reviewed by:
Dayi Chen, Central Weather Bureau, Taiwan
David Jay Wald, United States Geological Survey (USGS), United States

****Correspondence:***
Jennifer A. Strauss
jastrauss@berkeley.edu

Specialty section:
This article was submitted to Science and Environmental Communication, a section of the journal Frontiers in Communication

Received: *28 January 2020*
Accepted: *22 April 2020*
Published: *19 May 2020*

Citation:
Strauss JA, Kong Q, Pothan S, Thompson S, Mejia RF, Allen S, Patel S and Allen RM (2020) MyShake Citizen Seismologists Help Launch Dual-Use Seismic Network in California. Front. Commun. 5:32. doi: 10.3389/fcomm.2020.00032

INTRODUCTION

The MyShake™ Global smartphone network works at the intersection of science, community, and public safety with a goal of building an international platform that can benefit communities in earthquake prone regions (Allen et al., 2019). MyShake scientists collect both real-time earthquake triggers from the accelerometers in phones as well as the off-line waveform data recordings near active earthquakes to better understand some problems in seismology and engineering, such as earthquake early warning (Kong et al., 2016a), routine seismic network operations (Kong et al., 2016b, 2019b), array processing (Inbal et al., 2019), and structural health monitoring (Kong et al., 2018). This community not only interacts with the scientists by providing data, but can also interact with each other through the reporting features in the app to improve post-quake awareness in their neighborhood. MyShake uses the platform to provide educational safety information about what to do before, during and after a quake. Furthering this commitment to safety, MyShake is also now delivering earthquake ShakeAlerts™ (Given et al., 2018) to phones in the area of shaking in California, USA.

Many earthquake smartphone applications are available on the Google Play and Apple App stores today. Some, like the apps from American Red Cross and Earthquakes Tracker (https://www.redcross.org/get-help/how-to-prepare-for-emergencies/mobile-apps.html, https://play.google.com/store/apps/details?id=com.rsoftr.android.earthquakestracker.add), provide information on recent earthquakes. Others, like LastQuake[1] (Bossu et al., 2018) and Earthquake Network[2] (Finazzi, 2016), go a step further to collect crowdsourcing evidence reports and sensor triggers and deliver fast notifications to people in the areas affected by an earthquake shaking. MyShake is unique in this space in the way that it combines information from global earthquake catalogs, earthquake early warning (EEW) alerts from traditional seismic networks, an on-board artificial neural network (Kong et al., 2019a) to provide phone-derived alerts (in testing), as well as reports from local users on road and building conditions.

There are additional related efforts using the power of crowdsourcing to detect and evaluate earthquakes, such as the Taiwan Scientific Earthquake Reporting System, which crowdsources reports from volunteers on damage after an earthquake (Liang et al., 2019); Did You Feel It (DYFI; Wald et al., 1999), which compiles online surveys after earthquakes to evaluate the felt shaking intensity at various places; P-Alert, Community Seismic Network (CSN), QuakeCatcher network, Raspberry Shake, etc. which all use low-cost sensors to detect earthquakes (Chung et al., 2011; Clayton et al., 2015; Jan et al., 2018; Anthony et al., 2019), and finally, using Tweets as social sensors to detect the occurrences of an earthquake (Earle, 2010; Sakaki et al., 2010).

Innovations in this space will be crucial as more countries adopt the technology publicly. MyShake is working with stakeholders in the scientific, government, and local communities to determine the best most actionable ways to provide alerts to the people who need it most. We also probe what could be done in the sphere of public communication to improve earthquake knowledge and safety for the affected communities. Experience reports on the MyShake app were created using a human-centered design process to make them informative public communication tools and simple to use (Rochford et al., 2018). Rochford et al. (2018) outlined the purpose and process for the design of the reports, but as the iOS version was only available after the redesign was complete, we can here examine how the reports are being used by the community and the iOS version serves as a good control group for assessing the impact of design improvements. Timing information data was incorporated into the app and backend servers to see how quickly people are actually getting earthquake alerts. For alerts, speed of alert delivery is a critical part of the public communication and being able to measure this accurately will improve delivery speeds. The overarching goal of MyShake's design process is to avoid simply pushing information to people, but the acknowledgment that the users are citizen scientists as well and have their own experience and information to contribute. This synergy between science, community, and safety allows us to figure out what people do want in terms of information and balance that with the needs of the scientific community.

CONTEXT

The people of California, USA have been waiting on EEW to become a public reality for many years. Since 2006, a group of scientists from Universities on the West Coast and the United States Geological Survey have been developing the technology to provide earthquake early warning alerts using traditional seismic technology—much like is done in other countries like Mexico and Japan (Aranda et al., 1995; Kamigaichi, 2004; Allen and Melgar, 2019). This system, called ShakeAlert™ (Given et al., 2018), has developed over the years from a demonstration product (in 2012), to piloting automated controls (in 2016), and finally as a way to provide alerts that can be redistributed to the public (in 2019).

The Berkeley Seismology Lab took the lead in developing a proof of concept smartphone application to demonstrate the possibility of providing public alerts through this pathway. The app was called MyEEW and was tested with a small group of ShakeAlert stakeholders beginning in 2015. A short film containing a vignette of a teacher receiving the alert and taking action to protect the school kids in her care became an impactful vision of how EEW could work in real-world applications. Later, UC Berkeley merged the alerting technology of MyEEW with the citizen science initiative of their MyShake app to create a single app, which could serve both communities.

MyShake remained in testing mode with just a small number of users receiving alerts until the emergency management community and other stakeholders were comfortable with more wide-spread public alerting. The lessons learned from the North Bay California fires in 2017 and 2018, made it clear that providing information to people can be critical in a disaster so they can act accordingly. The affected community called for more information about the fires in real time; people wanted information as quickly and as accurately as they could get it. Mirroring that need from wildfire emergencies to a future need after a damaging earthquake, it became clear that the time to transition from internal testing to external prototyping had come. Berkeley Seismology Lab, in partnership with the California Office of Emergency Services and the Governor's office of California, worked with the United States Geological Survey and the rest of ShakeAlert team to make the public pilot of MyShake possible.

The MyShake app EEW capability was rolled out publicly by an announcement from Gov. Gavin Newsom on the 30th anniversary of the Loma Prieta earthquake, October 17, 2019 (**Figure 1**). Within 2 months, more than 600,000 user downloads proved the desire for EEW in California. ShakeAlert messages are sent automatically to MyShake servers, which send the information to phones running the MyShake app. For this prototype phase, alerts are sent for earthquakes estimated to be >M4.5 to phones in the MMI III or greater shaking area (light shaking). The alerts contain built-in safety and preparedness

[1] https://play.google.com/store/apps/details?id=org.emsc_csem.lastquake
[2] https://play.google.com/store/apps/details?id=com.finazzi.distquake

FIGURE 1 | On October 17, 2019, stakeholders gathered at a special event where Governor Gavin Newsom announced the launch of MyShake as the official EEW app for California. From left to right are Director Richard Allen (UC Berkeley), State Senator Jerry Hill, Director Mark Ghilarducci (CalOES), and Governor Newsom.

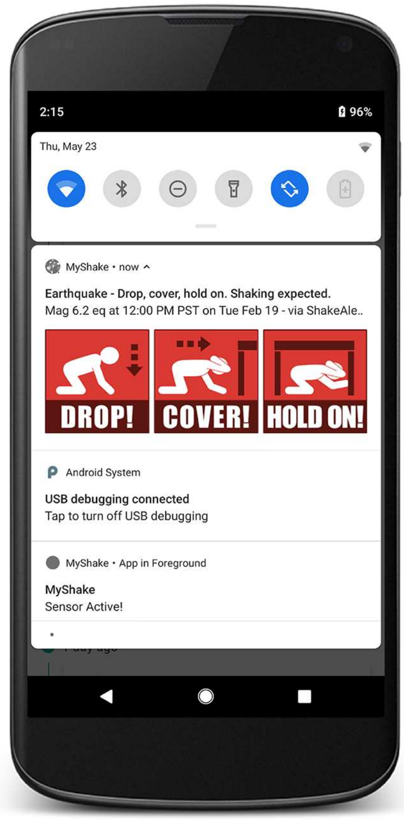


FIGURE 2 | The EEW notification appears on a phone providing information on the nearby earthquake and what the user should do.

information. The audio alert states: *Earthquake, drop, cover, hold-on shaking expected* (**Figure 2**). Text on the alert card provides the same information as the audio alert and additionally includes the estimated magnitude, time of the event, and a reminder that the alert is provided by ShakeAlert. Visually the app reminds users what to do when they receive an alert using Earthquake Country Alliance's Drop, Cover, Hold-On triptych (image Courtesy Earthquake Country Alliance[3]). Clicking on the link, takes users to the map where a bulls-eye icon displays the preliminary location for the event. As more information becomes available from the official USGS earthquake catalog, an event will appear on the map and users will be able to click to read more about the event and share their experience. In the case of a false alert, any follow-up information about the false alert provided by ShakeAlert will be forwarded to users who were initially alerted. The bulls-eye on the map will also disappear with no earthquake information appearing in its place.

In addition to sending/receiving ShakeAlert messages, MyShake phones also have the capability to detect earthquake shaking using the accelerometer in all smartphones. When stationary, phones run an on-board artificial neural network that is trained to determine if shaking is earthquake-like or not. If the determination is yes, a real-time message is sent back to the cloud server with location, time and amplitude of the shaking, where a spatial and temporal clustering algorithm will confirm the occurrence of the earthquake. Meanwhile, the phones record the accelerations in three components observed by the accelerometer sensor during the earthquake and automatically send those seismic recordings to scientists when the phones connected to power and WiFi (Kong et al., 2019a). This enables MyShake scientists to collect data from a very dense smartphone seismic network in areas where people are located. An analysis of the use of accelerometers inside the phones to characterize seismic data is beyond the scope of this paper, but has been reported in previous papers. Interested readers can read the more recent development (Kong et al., 2019a,b).

[3]https://www.earthquakecountry.org/

DETAIL TO UNDERSTAND KEY PROGRAMMATIC ELEMENTS

We are using the smartphone app to innovate on how people engage with earthquakes. Many current options for earthquake information transfer, or collection of seismic data using smartphones are in essence one-way streets. Information is pushed and data is collected. The user is rendered a passive part of the equation. One notable exception is the Did You Feel It (DYFI) survey, which "provides a two-way flow of post-earthquake information" (Wald et al., 2011). A one-way flow of information used to be true for map and driving applications, but the past decade has seen innovation in that area as well and we now get traffic conditions, can report accidents, and have a give-and take-relationship with our daily commute (waze, google maps, mapquest, apple maps). The MyShake team has a goal to improve the familiarity and awareness of our community of users through engagement with the app.

Public involvement is important to help tailor provided information to reflect what the populous seeks to learn. Feedback from users also allows the project to hone in on awareness

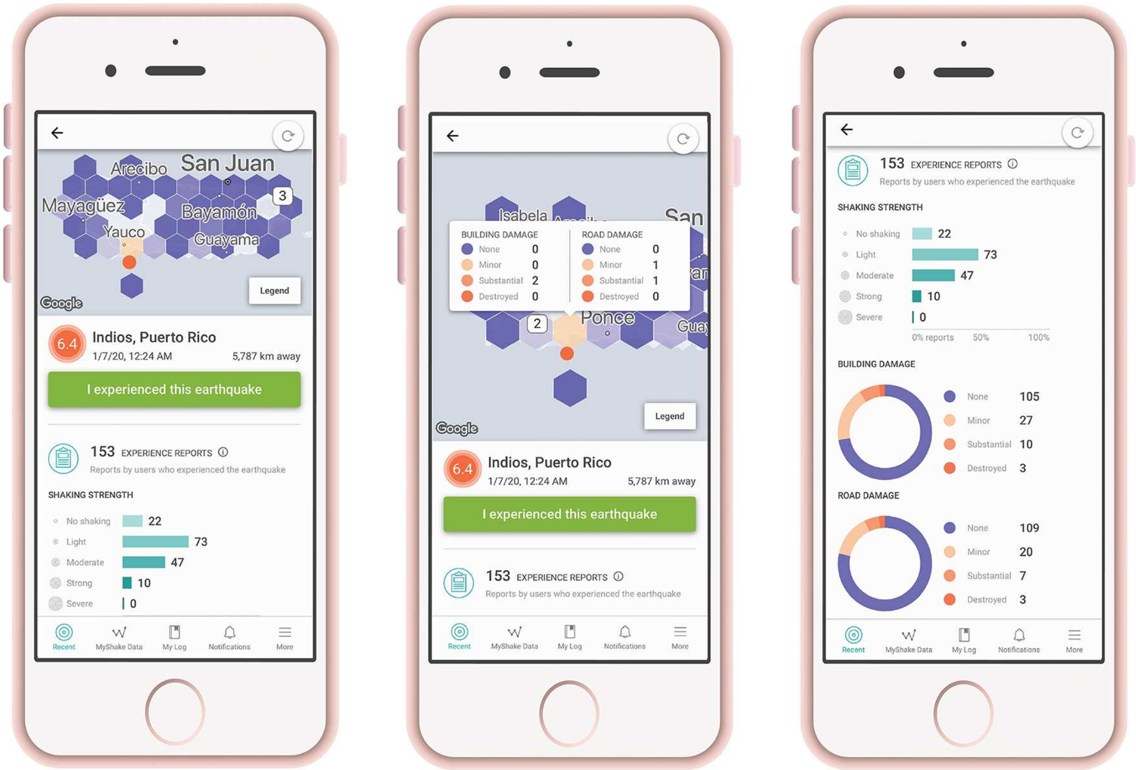


FIGURE 3 | Screenshots from the initial user reports on the earthquake page for the Indios, Puerto Rico quake. On the left, is the main page that shows the hexbins plotted on the map. In the middle screenshot, the user has clicked on one hexbin and a pop-up appears showing the building and road damage reports for that area. On the right phone, the user scrolled further down the page to display statistics on user submitted shaking and damage reports.

and misconceptions the public may have about seismic impact, seismic safety best practices, and how to better prepare before an event. We maintain a website, twitter account, and monitor email, google play store, and apple app store replies and requests to collect feedback. Through an iterative recording, coding, and evaluation process, key themes are highlighted. From there, we can improve on the app itself, or how we communicate the information in the app to align it more with expectations, needs, and correct science. One of the ways to engage the participation of users is the Experience Report.

An Experience Report is an interactive experience in the app that allows people to report on their observations after the quake through a simple to use interface. The first aspect of the report regards shaking intensity. Users are asked to report the level of shaking they experienced using a series of graded images and descriptions. This questionnaire is a simplified version of the USGS Did You Feel It (DYFI) assessment, and has a different objective. DYFI walks respondents through a very detailed questionnaire to probe as closely as possible the Modified Mercalli Intensity (MMI) value at their location. This allows DYFI, in part, to correlate DYFI responses to instrument data and fill in missing data (Worden et al., 2018). MyShake, in contrast, is focused on providing general information about nearby shaking to the users, so they can be informed about their neighborhood, and thus does not need such scientific precision. Both MyShake and DYFI have a goal of information sharing and a sense of community, but our single purpose of community allows us to simplify the process. The second aspect of the experience report is the ability to report on local building, bridge, and road damage. Directly after a quake it may not be clear which areas were hardest hit and the best ways to get around a user's area. By crowdsourcing this information and linking it with the experience of others, we aim to provide users with quick general information that they can use right in the moment.

One recent example is from the M6.4 Indios earthquake which occurred on January 7th, 2020 on the Southern Coast of Puerto Rico (USGS event id us70006vll). Users began immediately filling out their Experience Reports, suggesting that the app may be a convenient way of reporting right in the moment. **Figure 3** shows snapshots of the earthquake page for this quake. The purple and orange hexbins on the map are aggregate reports from users about damage intensity color coded by severity (with orange being higher damage). Below the map are tables and infographics that break the data down in more easily digestible chunks. One hundred fifty-three people submitted experience reports for the event throughout the island. Reported road and building damage was highest near the epicenter. Users in other areas continue to fill out Experience Reports after felt events. From this continued engagement, we can surmise that this added feature was well received by the user community.

The MyShake app contains other features and upgrades that we can now test. The earliest version of MyShake was released only on the Android platform, while the current update was released on both Android and iOS, thus providing a unique opportunity to evaluate our redesign decisions. The previous Android-only release featured a colorful map and color-coded earthquake rings indicating the intensity and recency of earthquake events. The redesign, in contrast, moved toward a more minimalistic design to simplify user tasks that would increase user awareness and activity. Analyzing feedback on the Google Play and Apple App Stores allowed us to evaluate how the design decisions, outlined in Rochford et al. (2018), impacted user satisfaction.

Most of the legacy Android users expressed their frustration over the redesign citing "*bring back the original map*," and "*I wish you would return to the red & blue used before…*" This feedback, while not inherently positive, was expected as any changes take some time getting used to. In contrast, iPhone users, who were experiencing the interface for the first time, had a positive reaction toward the user interface (UI) citing "*Amazing UI, great app*," and "*Love the map feature, and earthquake log*." We note that while most of the legacy Android users were not pleased with the new UI, they still enjoyed the features and functionality of the app. As for the iPhone users, while they enjoyed the minimalistic design, they did express frustration regarding the lack of some features that are available only on the Android version. The Android specific features include (at the time of writing): the ability to create custom notifications, and having a battery-saving-mode option.

Acting on feedback from users helps to improve the app in the same way that sharing information on performance with government stakeholders, operating system designers, and cellular carriers help improve the system and infrastructure as a whole. One of the key questions asked by stakeholders is the speed at which alerts can get to phones. Earthquakes travel very quickly, so alerts would only be useful if they are timely. This new release of the MyShake app collects data to understand and analyze alert delivery timing, or latency, which is a key driver for system improvements toward improved earthquake early warning.

MyShake is building a data collection architecture into the app and the backend servers to collect timing information to assess message delivery latencies. Such data are vital for evaluating strategies for delivering and communicating alerts: an earthquake warning system is a success only if it can send thousands, or millions, of messages to the affected users with low latencies. In order to get this key metric, the app sends silent alerts on a regular basis, which do not interrupt the user, or their use of the app, but sends valuable information back without having to wait for a real earthquake alert to occur to test delivery speeds. This is crucial because the only way to speed up alert delivery is to identify which facets of alert delivery are bottlenecks and can be improved. The clocks on the MyShake servers, the ShakeAlerts, the Google Firebase Cloud Messaging Service, and the end user's phones are not all in the same time domain, so simply collecting time stamps on each system individually is an insufficient methodology. The first phase of the timing architecture design involves requesting time receipts back to our server to record everything in the server time domain to ensure the highest accuracy possible.

TABLE 1 | Alert latency delivery data for the MyShake app.

UTC time	Location	Magnitude	# of phones alerted	Median alert latency (s)
2020-03-18 22:08:20	15 km W of Petrolia, CA	5.2	190	2.19
2020-03-22 16:27:38	47 km WNW of Petrolia, CA	4.8	3,217	4.58
2020-04-04 01:53:18	17 km ESE of Anza, CA	4.9	874	2.8

The UTC time, location, and magnitude values are courtesy of the USGS earthquake catalog. The number of phones alerted and alert latency are from MyShake data.

The silent alerts can help MyShake diagnose areas for improvement, while the real live alerts provide concrete data on alert performance. **Table 1** outlines the three largest alerts (in terms of number of users alerted) that the MyShake system distributed in 2020 (as of the time of this writing). The number of phones alerted refers to the number of active phones running MyShake at the time of the event, which were determined to be in the estimated MMI III or higher shaking level areas defined by the alert provided by ShakeAlert. MyShake determines whether a phone meets those criteria, and then sends the alert. The median alert latency is defined as the time between receipt of the ShakeAlert message at the MyShake server and the arrival of the alert at a users phone for 50% of the alerted users.

Lessons learned from this initial stage are setting the groundwork for a more detailed analysis of the communication pathway speeds. MyShake continues to work at the intersection of earth science and telecommunications to make improvements to the data collection and delivery latencies.

DISCUSSION

There are many practical implications of using public smartphones as an earthquake monitoring network, which include: the ethical considerations of privacy, expectation setting, and exogenous system changes. Some of these fall under the control of the app developers, such as ensuring user privacy, and expectation setting. Whereas, exogenous system changes to the Android or iOS framework is something the developers need to react to and plan for without being able to provide input.

The 2019 Ridgecrest earthquake sequence tested user expectation for alert delivery through the ShakeAlertLA app pilot. This provided an opportunity for MyShake to make changes to our app based on their experience, since like MyShake, ShakeAlertLA delivers ShakeAlert messages through their app to end users. The ShakeAlertLA app was available only to Angelinos at the time of the quakes and had a set threshold of MMI IV, below which no alerts would be delivered to user's phones. The largest earthquake in this sequence was the M7.1 event on July 5th, 2019. ShakeAlert underestimated the quake as a M6.3, so while the true observed shaking intensity did reach above

MMI IV in Los Angeles, the estimate was lower, at an MMI III, so no deliveries were made to phones. The ShakeAlertLA app performed just as it should have, but public expectations were not met. Subsequently, the thresholds were refined by USGS to put them more in line with the expectations of the public, and that is now reflected in both apps. A delicate balance between alerting to meet expectations of the public who experience shaking and not over-alerting those who do not needs to be struck.

Intensity estimation errors, like those seen in the Ridgecrest sequence, can arise both from magnitude/location estimation errors, but also in local site variations. The soil type, building type, and other variables at a local site can have an impact on whether a user experiences the reported average shaking intensity for their area. Therefore, threshold refinements alone are not sufficient to address this issue. Continued education for the public that the alerts are best timely estimates and not exact, combined with training on what to do when shaking occurs should help. Further social science research into best practices and user behavior is needed. Moreover, there will be things to learn and refinements to be made as more alerts go out to the public over time.

Keeping up with exogenous changes such as Android/iOS updates, policy updates from ShakeAlert, and feedback from users regarding their perception of things is the third major practical implication and is ongoing. Android and iOS respond to their own user and business feedback by deploying new features and new improvements to their systems on a regular basis. Unfortunately for app developers, some of these changes require significant updates on the backend servers and application user interface to ensure continued operation. Examples of this are new protocols for message handling, updates or transitions to new cloud messaging systems, or changes to the available information in log files produced by the operating system. Developers constantly test the app to ensure that the message delivery and earthquake monitoring continue to function with each new update.

A simpler to implement, but continually ongoing exogenous requirement is the interface with the ShakeAlert System. Novel products produced by the United States Geological Survey will change the available information with which MyShake redistributes ShakeAlert information. Currently, thresholds are set to M4.5 and MMI III for smartphone apps, but that could change in the future as social science learns more about how people best respond to EEW information. Best practices in messaging, or new tone requirements put forward by ShakeAlert could impose new features or requirements on the application.

CONSTRAINTS AND CONCLUSION

We have outlined many of the constraints and considerations that go into developing an earthquake information app that combines citizen science and public warning aspects. Timely alert delivery is required in order for people to take action and drop, cover, hold on before shaking causes damage. Improving the timing requires technical cooperation between the external partners, internal developers, cloud servers, and the user's smartphones, all of which have different operational constraints and goals and requirements of their own. Unlike traditional seismic networks that make use of dedicated equipment that can be maintained and repaired by a centralized field crew, using smartphones as the seismic sensors removes much of the control we have over the instrumentation. Our network can only be as good as the phones available in the marketplace. Phones may be several generations old, or utilize very different accelerometer sensors with variable noise levels. Some users may heavily use their phones, whereas others may forget to turn them on for days. The team of developers do not have access to all of these phone types for testing, so much of the troubleshooting must be done after deployment.

Maintaining the privacy of our users and their data is an important constraint and consideration for both the software and user interface development. Our commitment to protecting privacy through anonymizing user information renders troubleshooting issues on individual phones more difficult. It also raises questions about long-term connectivity. Earthquakes that require alert delivery do not occur in a particular region on a regular basis. A particular user may wait months or years before an earthquake alert satisfying the threshold criteria strikes their area. Longevity studies on app performance and alert delivery will need to be undertaken. It remains unclear whether the underlying operating system will silence or put to sleep an app after months of non-use.

To conclude, many people work together to build this system, but not all stakeholders agree on which possible solutions to issues or new initiatives are the best. Reaching consensus requires presentation of known data and observations, transparency about the pros/cons of each pathway, and a consideration of each stakeholder's definition of project success. The public may have a very different idea of what makes a very successful earthquake app than the state, or the software development group. Understanding each perspective, distilling down what is possible and most useful, and then making decisions is the strategy we employ to keep the app relevant and useful.

The MyShake team works at the intersection of science, public communication, and technology to create a useable product for interested users around the world. The rollout of the app in October, 2019 as the official EEW for the State of California significantly increased our capacity to communicate with the public and solicit their feedback to improve the system. Lessons learned from the rollout inform our choices not only for public communication, but on the science and technology side as well. A large project like this, with many stakeholders and exogenous demands, navigates through a field of constraints. These challenges help us build a better system for the users, push forward technology and really understand system latencies, and harness the power of citizen scientists to create the seismic data sets of the future.

AUTHOR CONTRIBUTIONS

JS, QK, and RA drafted the manuscript. RA approved the publication of the content. JS, QK, SPo, ST, RM, SA,

SPa, and RA contributed to the conception and design the MyShake rollout.

FUNDING

Funding for the MyShake app alert delivery project was provided under a standard agreement with the California Governor's Office of Emergency Services (6142-2018).

ACKNOWLEDGMENTS

MyShake team would like to thank the Governor of California's Office for Emergency Services for their support and ongoing funding of this effort. We thank Dayi Chen and David Jay Wald for their review of the manuscript. We would also like to thank the USGS ShakeAlert project as well as the Gordon and Betty Moore foundation for the initial seed funding.

REFERENCES

Allen, R. M., Kong, Q., and Martin-Short, R. (2019). The myshake platform: a global vision for earthquake early warning. *Pure Appl. Geophys*. 177, 1699–1712. doi: 10.1007/s00024-019-02337-7

Allen, R. M., and Melgar, D. (2019). Earthquake early warning: advances, scientific challenges, and societal needs. *Annu. Rev. Earth Planet. Sci*. 47, 361–388. doi: 10.1146/annurev-earth-053018-060457

Anthony, R. E., Ringler, A. T., Wilson, D. C., and Wolin, E. (2019). Do low-cost seismographs perform well enough for your network? An overview of laboratory tests and field observations of the osop raspberry shake 4D. *Seismol. Res. Lett*. 90, 219–228. doi: 10.1785/0220180251

Aranda, J. M. E., Jimenez, A., Ibarrola, G., Alcantar, F., Aguilar, A., Inostroza, M., et al. (1995). Mexico city seismic alert system. *Seismol. Res. Lett*. 66, 42–53.

Bossu, R., Roussel, F., Fallou, L., Landès, M., Steed, R., Mazet-Roux, G., et al. (2018). LastQuake: from rapid information to global seismic risk reduction. *Int. J. Dis. Risk Red*. 28, 32–42. doi: 10.1016/j.ijdrr.2018.02.024

Chung, A. I., Neighbors, C., Belmonte, A., Miller, M., Sepulveda, H. H., Christensen, C., et al. (2011). The quake-catcher network rapid aftershock mobilization program following the 2010 m 8.8 Maule, Chile earthquake. *Seismol. Res. Lett*. 82, 526–532. doi: 10.1785/gssrl.82.4.526

Clayton, R. W., Heaton, T., Kohler, M., Chandy, M., Guy, R., and Bunn, J. (2015). Community seismic network: a dense array to sense earthquake strong motion. *Seismol. Res. Lett*. 86, 1354–1363. doi: 10.1785/0220150094

Earle, P. (2010). Earthquake twitter. *Nat. Geosci*. 3, 221–222. doi: 10.1038/ngeo832

Finazzi, F. (2016). The earthquake network project: toward a crowdsourced smartphone-based earthquake early warning system. *Bull. Seismol. Soc. Am*. 106, 1088–1099. doi: 10.1785/0120150354

Given, D. D., Allen, R. M., Baltay, A. S., Bodin, P., Cochran, E. S., Creager, K., et al. (2018). *Revised Technical Implementation Plan for the ShakeAlert System—An Earthquake Early Warning System for the West Coast of the United States. US Geological Survey. Available online* at: https://pubs.er.usgs.gov/publication/ofr20181155 (accessed May, 2020).

Inbal, A., Kong, Q., Savran, W., and Allen, R. M. (2019). On the feasibility of using the dense myshake smartphone array for earthquake location. *Seismol. Res. Lett*. 90, 1209–1218. doi: 10.1785/0220180349

Jan, J. C., Huang, H. H., Wu, Y. M., and Chen, C. C. (2018). Near-real-time estimates on earthquake rupture directivity using near-field ground motion data from a dense low-cost seismic network. *Geophys. Res. Lett*. 45, 7496–7503. doi: 10.1029/2018GL078262

Kamigaichi, O. (2004). JMA earthquake early warning. *J. Jpn. Assoc. Earthquake Eng. 4,* 134–137. doi: 10.5610/jaee.4.3_134

Kong, Q., Allen, R. M., Kohler, M. D., Heaton, T. H., and Bunn, J. (2018). Structural health monitoring of buildings using smartphone sensors. *Seismol. Res. Lett*. 89, 594–602. doi: 10.1785/0220170111

Kong, Q., Allen, R. M., and Schreier, L. (2016a). MyShake: initial observations from a global smartphone seismic network. *Geophys. Res. Lett*. 43, 9588–9594. doi: 10.1002/2016GL070955

Kong, Q., Allen, R. M., Schreier, L., and Kwon, Y. W. (2016b). MyShake: a smartphone seismic network for earthquake early warning and beyond. *Sci. Adv*. 2:e1501055. doi: 10.1126/sciadv.1501055

Kong, Q., Inbal, A., Allen, R. M., Lv, Q., and Puder, A. (2019a). Machine learning aspects of the myshake global smartphone seismic network. *Seismol. Res. Lett*. 90, 546–552. doi: 10.1785/0220180309

Kong, Q., Patel, S., and Inbal, A. (2019b). Assessing the sensitivity and accuracy of the MyShake smartphone seismic network to detect and characterize earthquakes. *Seismol. Res. Lett*. 90, 1937–1949. doi: 10.1785/0220190097

Liang, W. T., Lee, J. C., and Hsiao, N. C. (2019). Crowdsourcing platform toward seismic disaster reduction: the Taiwan Scientific Earthquake Reporting (TSER) system. *Front Earth Sci. Chin*. 7:79. doi: 10.3389/feart.2019.00079

Rochford, K., Strauss, J. A., Kong, Q., and Allen, R. M. (2018). MyShake: using human-centered design methods to promote engagement in a smartphone-based global seismic network. *Front Earth Sci. Chin*. 6:237. doi: 10.3389/feart.2018.00237

Sakaki, T., Okazaki, M., and Matsuo, Y. (2010). "Earthquake shakes twitter users: real-time event detection by social sensors," in *Proceedings of the 19th International Conference on World Wide Web (ACM)* (Raleigh, NC), 851–860. doi: 10.1145/1772690.1772777

Wald, D. J., Quitoriano, V., Dengler, L. A., and Dewey, J. (1999). Utilization of the internet for rapid community intensity maps. *Seismol. Res. Lett*. 70, 680–697. doi: 10.1785/gssrl.70.6.680

Wald, D. J., Quitoriano, V., Worden, M., Hopper, C. B., and, Dewey, J. W. (2011). USGS "did you feel it?" internet based macroseismic intensity maps. *Ann. Geophys*. 39, 688–709. doi: 10.4401/ag-5354

Worden, C. B., Thompson, E. M., Baker, J. W., Bradley, B. A., Luco, N., and, Wald, D. J. (2018). *Spatial and* spectral interpolation of ground motion intensity measure observations. *Bull. Seism. Soc. Am*. 108, 866–875. doi: 10.1785/0120170201

Conflict of Interest: The 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.

Copyright © 2020 Strauss, Kong, Pothan, Thompson, Mejia, Allen, Patel and Allen. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

REVIEW
published: 20 May 2020
doi: 10.3389/feart.2020.00120

Check for updates

USGS "Did You Feel It?"—Science and Lessons From 20 Years of Citizen Science-Based Macroseismology

*Vincent Quitoriano and David J. Wald**

National Earthquake Information Center, U.S. Geological Survey, Golden, CO, United States

OPEN ACCESS

Edited by:
Kate Huihsuan Chen,
National Taiwan Normal University, Taiwan

Reviewed by:
Dayi Chen,
Central Weather Bureau, Taiwan
John Taber,
Incorporated Research Institutions for Seismology, United States

Correspondence:
David J. Wald
wald@usgs.gov

Specialty section:
This article was submitted to Solid Earth Geophysics, a section of the journal Frontiers in Earth Science

Received: *28 January 2020*
Accepted: *30 March 2020*
Published: *20 May 2020*

Citation:
Quitoriano V and Wald DJ (2020) USGS "Did You Feel It?"—Science and Lessons From 20 Years of Citizen Science-Based Macroseismology. Front. Earth Sci. 8:120. doi: 10.3389/feart.2020.00120

The U.S. Geological Survey (USGS) "Did You Feel It?" (DYFI) system is an automatic method for rapidly collecting macroseismic intensity (MI) data from internet users' shaking and damage reports and for generating intensity maps immediately following felt earthquakes. DYFI has been in operation for nearly two decades (1999–2019) in the United States, and for nearly 15 years globally. During that period, the amount of data collected is astounding: Over 5 million individual DYFI intensity reports—spanning all magnitude and distance ranges—have been amassed and archived. DYFI allows for macroseismic data collection at rates and quantities never before imagined, and thus high-quality MI maps can be made almost immediately, and with more complete coverage at higher resolution than in the past. DYFI also allows for valuable positive interactions of the citizenry with a Federal science agency. In essence, the widespread adoption of DYFI – along with ShakeMap—has facilitated the general acceptance of the very concept of shaking intensity, fundamentally improving our agency's ability to communicate both hazard and risk to the population. DYFI effectively confirms the importance of reporting and inculcating the public's understanding of intensity – in addition to magnitude – for a proper perspective of earthquake risk-related decision-making. Furthermore, the vast amount of DYFI data allows for data-rich analyses of otherwise intractable seismological, sociological, and earthquake impact studies, such as quantifying the shaking due to induced earthquakes, human response and risk perception, relating recorded shaking metrics to macroseismic effects, and the attenuation of intensity with magnitude and distance. Naturally, web-based data collection also poses challenges. After two decades of experience acquiring data with the DYFI system, we address some of these challenges by documenting refinements to our algorithmic and operational procedures that have evolved over that time. Lastly, we outline new opportune research and development directions for our DYFI approach to citizen seismology.

Keywords: citizen science, seismology, science communication, seismic hazard, open data, macroseismology, earthquake intensity, ShakeMap

INTRODUCTION

An impressive, rapid evolution has taken place in the realm of macroseismic intensity (MI) data collection and assignment since the revision of the European Macroseismic Scale of 1998 (EMS-98; Grünthal, 1998), wherein well-defined building vulnerability classes combined with damage matrices facilitated reliable MI assignments, particularly at high intensities. A more recent revolution in the field began with web-based macroseismic surveys and assignments following Dengler and Dewey (1998) and Wald et al. (1999a) followed by parallel developments in Italy by Sbarra et al. (2010). At the same time, internet-based access to reconnaissance photos and media accounts significantly improved the availability of testimonials and images (as well as their locations) of earthquake effects for analysis. The latest innovation is to reduce data collection to convenient-to-use cartoons that readily allow for a user-selected MI value among a choice of intensity levels visually depicted, as in the LastQuake mobile application by the European-Mediterranean Seismological Centre (EMSC; Bossu et al., 2017).

Over the past two decades, the U.S. Geological Survey (USGS) has relied on the "Did You Feel It?" (DYFI) portal (Wald et al., 2011) to collect shaking and damage reports from internet users immediately following felt events, effectively scaling back and deemphasizing more traditional postal questionnaires and reconnaissance surveys. The USGS has been operating DYFI since 1999 in California, since 2000 for the rest of the United States, and since 2004 globally. DYFI is essential for systematically collecting macroseismic data for all felt seismic events in the United States and has become one of the most popular interactive web sites within the United States Government.

For earthquakes outside the United States, DYFI data rapidly signal or confirm earthquake occurrence for seismic analysts and scientists at the USGS National Earthquake Information Center (NEIC), giving a quick indication of the extent and severity of shaking effects. Intensity data from DYFI are automatically used to provide valuable shaking constraints for the USGS Global ShakeMap system (Wald et al., 1999b), which in turn is the fundamental hazard input for the USGS Prompt Assessment of Global Earthquakes for Response (PAGER; Wald et al., 2008) system that allows the USGS to alert agencies and users around the world of significant earthquakes and their likely impacts.

The data collection and assignment of DYFI-based intensity depart from traditional expert-assigned intensities (e.g., Musson et al., 2010) but they are made more rapidly; provide better coverage and at higher spatial resolutions; and allow citizen input and interaction. A widely felt earthquake near a populated area can provide thousands or tens of thousands of independent observations over a wide geographic extent, far more than can be collected from traditional assessments.

This paper provides an overview of the DYFI system – after 20 years of experience – with emphasis on the citizen science-based macroseismic data that we have collected as well as the resulting research that those data have allowed or facilitated. We first provide background on the current system and processing software, which has been recently reengineered and made open source. We then focus on data collection and how quality assurance is maintained given the nature of internet-based data contributors. Next, we present examples of unique studies that employ DYFI data in both the seismological and social science realms; in particular, the general adoption of MI as a metric for communicating hazard and risk is emphasized since intensity is such a vastly more useful descriptor than earthquake magnitude alone. Lastly, we describe challenges and limitations of DYFI and suggest both potential solutions and new directions that will facilitate even more widespread adoption of DYFI as a citizen-science portal for both societal benefits and scientific advancements.

THE DYFI SYSTEM

The DYFI software package is fully open source, written in Python, and available publicly through GitHub since 2018[1]. Incoming entries from multiple web servers are processed and aggregated over postal ZIP codes (in the United States) and 1-km and 10-km aggregated boxes for every earthquake. These data are used to make interactive maps and plots (e.g., **Figures 1–5**) served via the USGS Earthquake Program web pages[2].

One of the key procedures of the DYFI process is the aggregation of responses within compact spatial areas. Aggregation allows us to combine the observations of many users and fill in the gaps in relevant intensity markers. For example, one contributor might observe objects falling off shelves (the *shelf* index) but have no pictures hanging on their wall. Another nearby might have no objects on shelves but report pictures falling off their wall (the *picture* index). The two relevant questionnaire indices are combined (not averaged) with other users in their community to produce an intensity calculation. For details, see the section below.

Quality Assurance

"Did You Feel It?" maps and products have been updated occasionally, sometimes systematically, over the last two decades of operation. DYFI maps are aggregated models of MI that change over time. Of course, users often contribute data for months or longer after an earthquake. More importantly, while the intensity calculation of Wald et al. (2011) has not changed, operational and postprocessing procedures have improved over the years. DYFI maps and products are expected to change and improve over time. Many DYFI improvements and quality control strategies have been implemented incrementally but have been refined and standardized in the new code base. We now systematically track and document all code changes on GitHub, which preserves all versions of the code and is publicly available online. Previously, changes were done on a more *ad hoc* basis, generally only to improve or fix operational issues.

"Did You Feel It?" originally defined the communities used for aggregation as ZIP codes and cities (outside the United States).

[1] https://code.usgs.gov/ghsc/esi/dyfi
[2] https://earthquake.usgs.gov

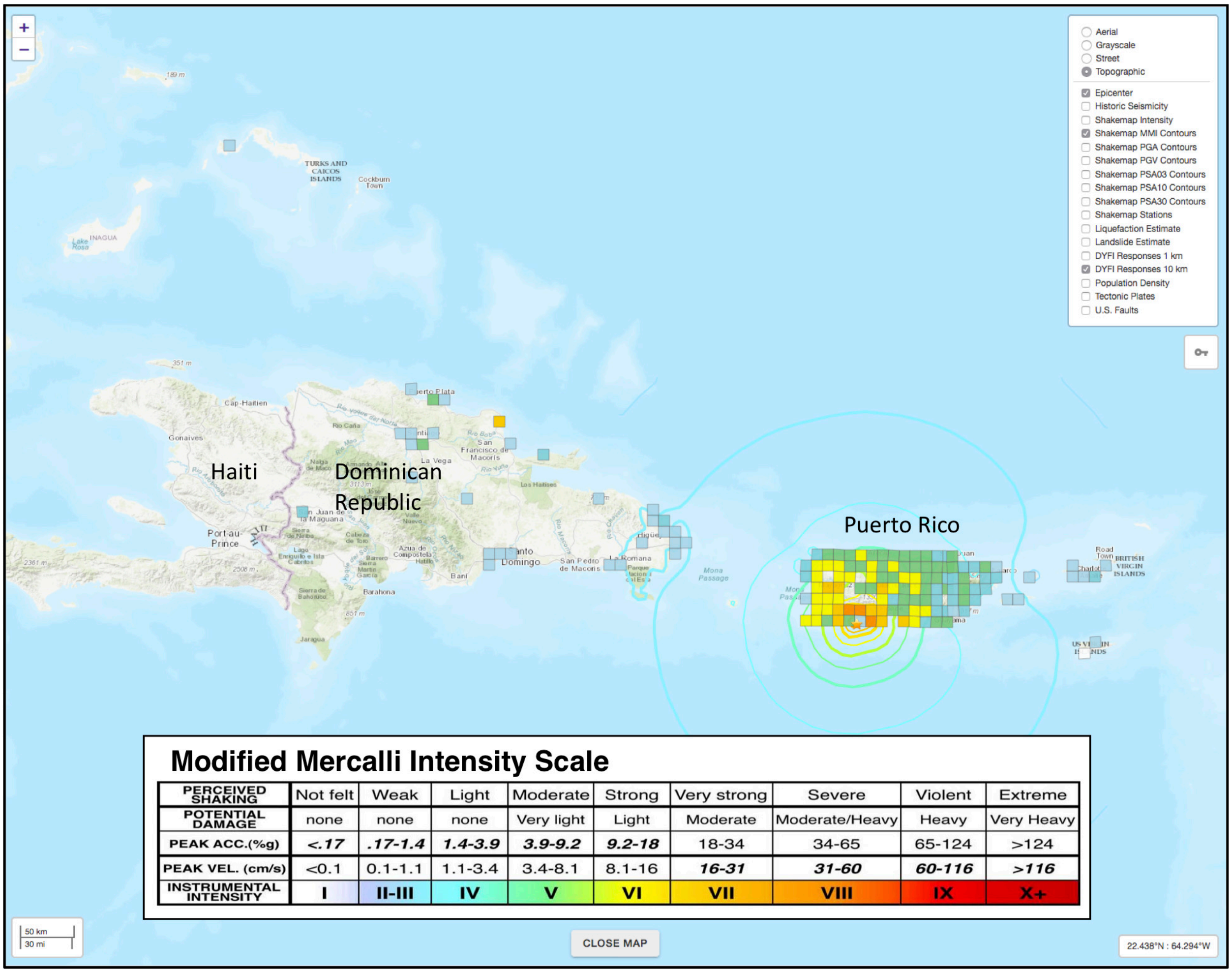


FIGURE 1 | Interactive map from the USGS event web pages for the M6.4 Indios, Puerto Rico earthquake at a regional scale displayed in 10-km square blocks color-coded to the inset legend used by DYFI and ShakeMap to show the intensity (Wald et al., 2011). ShakeMap isoseismal contours are shown using the same color scheme (Source: U.S. Geological Survey).

This was problematic as some ZIP codes are much larger in area than others, and cities are not evenly distributed; in addition, both ZIP code boundaries and city names change with time. In order to standardize aggregation sizes, we have now switched to a system based on the Universal Transverse Mercator (UTM) Geographic Grid. DYFI now automatically geolocates each user response (down to the level of street address in most cases), aggregates questionnaire responses using UTM coordinates to define 1-km and 10-km blocks, and computes intensities using the responses within each box. We find that sparsely felt events benefit from using 10-km blocks to combine more responses for each intensity calculation. Alternatively, for events near population centers, 1-km blocks allow us to show fine variations in the felt intensities. Maps and datafiles for both aggregations are produced for every DYFI event. UTM blocks do not change with time, which makes the comparison of earthquake data at different times much less complicated. We encourage researchers to use geocoded UTM- aggregated datasets instead of older ZIP code aggregated datasets because of these reasons.

A note of caution: We have redone the geocoding of all DYFI entries using modern, online geocoding services. While geocoding tends to yield consistent results, they are not perfect. Some observer entries likely have been moved, added, or removed from their original aggregations in the intervening years as online geocoding services have improved.

We have updated the automatic removal of outlier intensities from the DYFI dataset. Each event is assigned a region-dependent intensity prediction equation (IPE) that is a function of magnitude and distance from the epicenter. Each geocoded block, ZIP code, or city with a computed intensity more than a certain threshold away from the expected intensity is flagged as an outlier and not included in DYFI products. The current filtering threshold is 3 intensity units above or below the value expected from the IPE. For significant events, we sometimes manually flag entries which are obvious outliers,

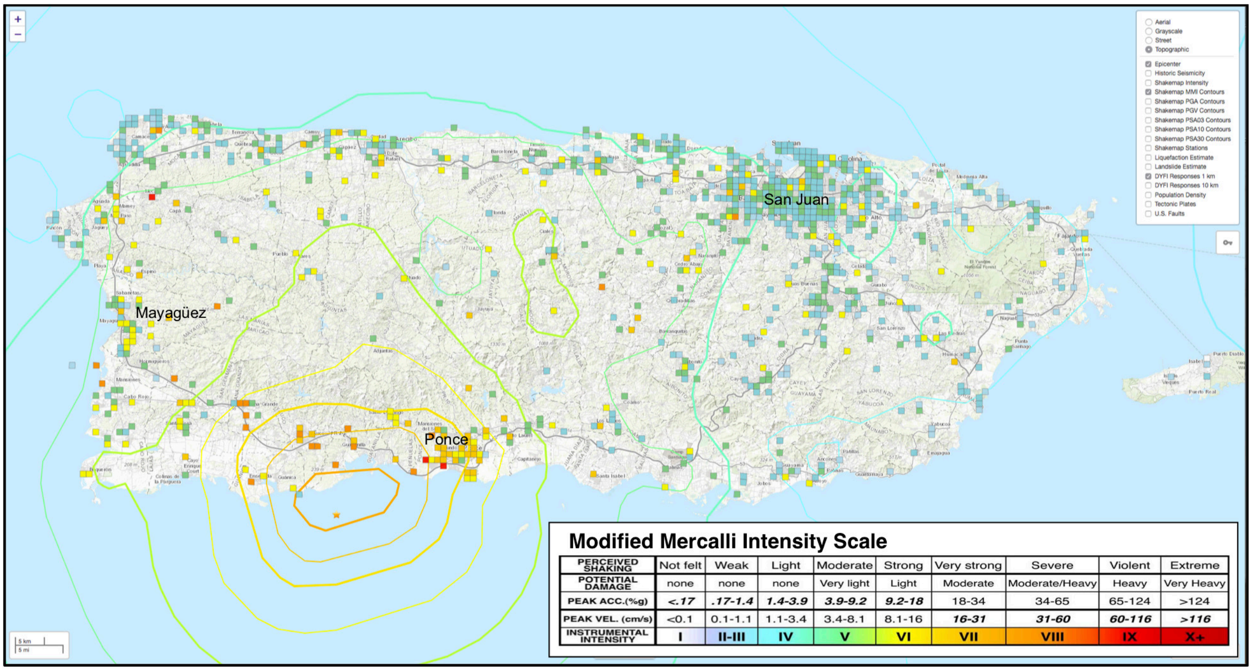


FIGURE 2 | Interactive map from the USGS event web pages for the 2019 magnitude 6.4 Indios, Puerto Rico earthquake at a regional scale. Over 2,500 DYFI data in the region are displayed in 1-km square blocks color-coded to the inset legend used by DYFI and ShakeMap to show the intensity (Wald et al., 2011). ShakeMap isoseismal contours are shown using the same color scheme (Source: U.S. Geological Survey).

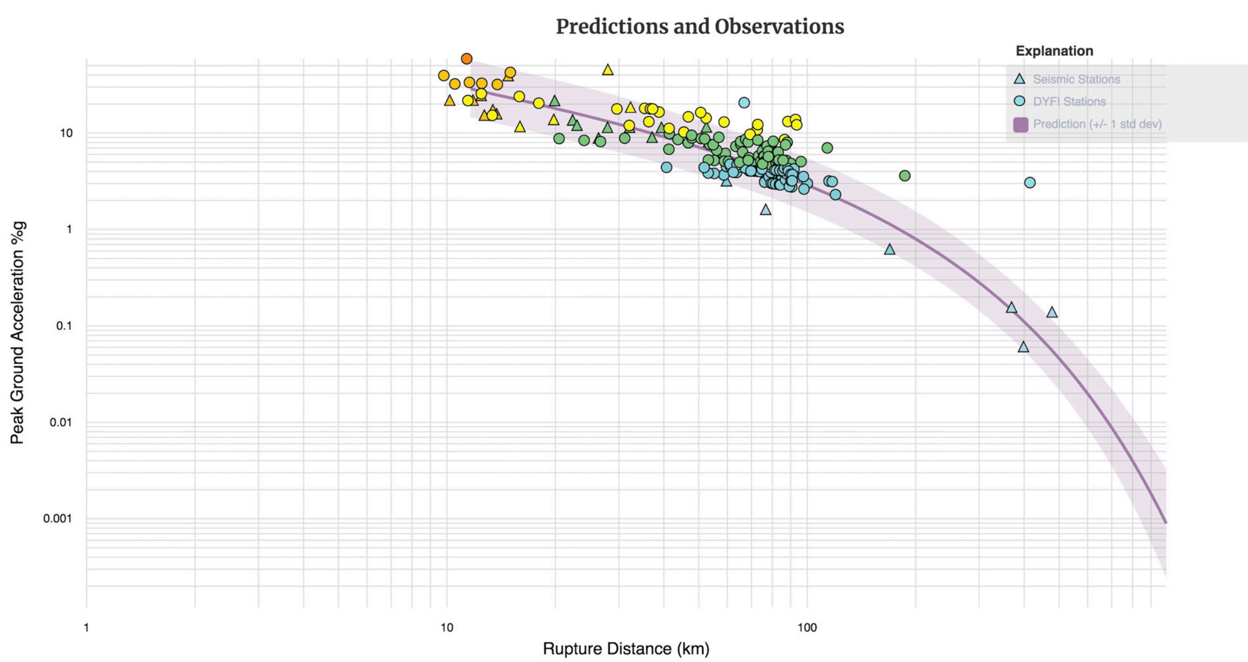


FIGURE 3 | Interactive plot of intensity versus distance from the epicenter for the M6.4 Indios, Puerto Rico earthquake. Scrolling over individual circles would show the data for individual geocoded blocks. The colored trend line is the predicted acceleration based on the ground motion prediction equations used in ShakeMap. The shaded area is one standard deviation above and below the predicted accelerations. Circles correspond to DYFI 1-km geocoded block intensities converted to peak ground acceleration (PGA; Worden et al., 2012). Triangles are seismic stations reporting to ShakeMap. Circles and triangles are color-coded to the intensity scale shown in **Figure 1**; for ShakeMap stations, intensities are converted from ground motion values using Worden et al. (2012) (Source: U.S. Geological Survey).

FIGURE 4 | Response rate of DYFI report entries for the M6.4 Indios, Puerto Rico earthquake. For example, scrolling over the curve would show the number of responses at different times. Shown here is the number of responses submitted up to 1 h after the origin time, when nearly 1,200 of 2,200 responses were received (Source: U.S. Geological Survey).

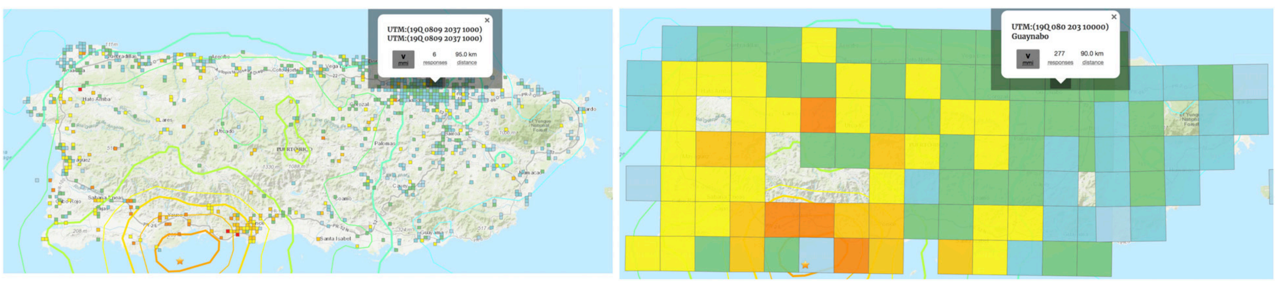


FIGURE 5 | Comparison of 1-km (left) and 10-km (right) UTM blocks for the M6.4 Indios, Puerto Rico earthquake. Both maps are the same scale. Intensity, number of responses, and distance from the UTM area centroid to the epicenter are shown for representative areas in each map. Blocks are color-coded to the intensity scale shown in **Figure 1** (Source: U.S. Geological Survey).

duplicates, or spurious responses. This usually happens in the days after an event, but occasionally we receive requests to manually check data at a much later date by detail-oriented users.

The problem of associating user responses to the correct event can be complicated during an earthquake sequence with multiple foreshocks and/or aftershocks. DYFI contributors tend to select the most recent earthquake displayed on the USGS website, which might not be the event that corresponds to their observations; or to the "Unknown Event Form," which has no associated event. Whenever DYFI processes an event, it checks for unassociated entries and for other entries that are likely to be associated to that event. We are still examining various ways of improving this process and sometimes resort to manually disentangling entries if possible; but often, little distinguishes between mainshock and aftershock reports for lower intensity observations.

Viewing DYFI products from a particular moment in time is sometimes useful, for example, at a certain period after an earthquake, to compare different versions, or to see the evolution of the DYFI map days after a significant event. In the past, we replicated these "snapshots" by rerunning the DYFI process on subsets of DYFI entries within the desired timeframe. Recently, the development of the Advanced National Seismic System's Comprehensive Earthquake Catalog (ComCat) has enabled the storage and retrieval of USGS real-time products (Guy et al., 2015). ComCat archives all versions of the products that were sent and displayed online, so previous versions of DYFI products in ComCat can now be accessed easily for comparison.

An additional point about the DYFI intensity algorithm is warranted: Intensity is computed for a consensus (or numerical average) separately for each question in the questionnaire; each question can be answered by more or fewer observers. The consensus values are then weighted and summed to compute the intensity (see Wald et al., 2011, for details). Entries that do not answer a particular question (as opposed to answering "None") do not count for the corresponding index in the computation. For example, let us take a hypothetical community of several observers who did not answer the *picture* index ("Did pictures on walls move or get knocked askew?"), perhaps because they were in rooms with no pictures. In this case, the addition of one observer who does answer positively will represent an N of 1 for the *picture* index, and the answer for the whole community for that index switches from 0 to 1. Thus, a single added or corrected entry could change the intensity much more substantially than would be expected from simply averaging intensity scores.

Data Sampling Bias

Unlike traditional postal MI questionnaires, DYFI and other internet collection systems are self-selecting. First, coverage is dependent on population and internet access, so areas with dense populations and adequate internet access are overrepresented compared to sparsely populated regions or populations that lack internet access (see, for example, Montalvo-Arrieta et al., 2019). Second, responses are overwhelmingly from users who felt an event. Less than 3% of DYFI responses are from contributors who respond with "not felt." These biases may be mitigated by a statistical approach. Mak and Schorlemmer (2016) model the reliability of DYFI data based on population density and socioeconomic parameters. Tosi et al. (2015) and Boatwright and Phillips (2017) propose methods of combining reporting and non-reporting communities to improve intensity estimates at the lower intensity range.

Another method of reducing non-reporting bias is to reach out to potential contributors. The Istituto Nazionale di Geofisica e Vulcanologia (INGV, Italy) invites users to pre-register on their website then notifies them of earthquakes in their area (Tosi et al., 2015). EMSC benefits from similar notifications using their mobile app. Linking DYFI to third party applications such as the MyShake Early Warning Platform (Allen et al., 2020) would allow us to solicit contributions from registered users near an identified or suspected event.

Effect of Observer Conditions

Observer location, building type, and situation all affect intensity reporting (e.g., Sbarra et al., 2014). Though Sbarra et al. (2014) report a variance of about 0.6 intensity units from such effects, the DYFI questionnaire requests those data but does not use them to systematically correct intensity assignments. Rather, we assume that, with sufficient numbers of observers, such details are averaged out. The tradeoff considered is between (potentially) more precise measurements and additional required questions for each user.

Network Performance

In the minutes after a widely felt earthquake near a populated region, the biggest challenge for DYFI is to accommodate the immediate deluge of web traffic and input data. The sheer number of responses after a significantly felt earthquake puts unprecedented stress on the performance of the USGS internet download and web capacity. As DYFI has grown in popularity, the USGS has radically improved capacity via both hardware and software improvements in order to handle the spike in internet traffic following such events, such as running multiple servers and containerized processing. For the largest events, even these efforts may be insufficient. The collection and storage of incoming user responses are done separately from the backend processes of aggregating data, computing intensities, and creating DYFI products. Thus, raw data are collected and stored safely even during extreme processing loads. While new responses come in continuously, the backend processes only refresh the online maps every 5 min to avoid processing and network overload.

DYFI DATA

A recent example of the nature of DYFI data can be visualized for the 2019 magnitude 6.4 Indios, Puerto Rico earthquake. **Figure 1** shows over 2,500 DYFI responses in the region aggregated in 10-km square blocks. **Figure 2** is zoomed into the area of the island of Puerto Rico, and switches to geocoded data aggregated into 1-km blocks. Also shown are ShakeMap intensity contours for comparison. In fact, it can be seen that the DYFI data, which are much more numerous than the seismic stations used in ShakeMap (see **Figure 3**), play an important role in constraining the ShakeMap intensity contour pattern in **Figures 1**, **2** (see section "Integration into ShakeMap," below). **Figure 3** also provides an indication of the variability of the DYFI data (circles) and their distribution with distance from the epicenter at a regional scale in comparison to the recorded accelerations (triangles). In general, the intensity data fit estimates of ground acceleration quite well, despite being converted from intensity to acceleration (Worden et al., 2012).

Figure 4 provides the rate of DYFI report entries for the Indios, Puerto Rico earthquake: Nearly 1,200 of the total 2,200 responses were submitted in the first hour after the origin time. **Figure 5** provides a comparison of the 1-km and 10-km aggregated DYFI data. As with the other interactive maps, the intensity value, number of responses, and the geocoded box location are easily accessible via mouseover.

More general statistics further attest to the growth of internet-based macroseismic data collection. When it first went online in 2003, DYFI received about 110,000 responses, primarily from California earthquakes. Since then, over five million entries have been amassed over two decades. Currently, 64 events have more than 10,000 responses, and 550 events have over 1,000 responses. In 2018 (which we consider a typical year), more than 300,000 entries were received for 4,500 earthquakes (**Figure 6**). The year with the highest absolute number of responses was 2010, with nearly 600,000; for this time period, the largest impact event was the April 4, 2010, M7.2 Baja California earthquake, with nearly 80,000 responses.

The highest number of responses for a single earthquake is more than 146,000, for the 2011 M5.8 Mineral, Virginia event, which was felt by more Americans than any other in history. Response rates reached 62,000 submissions per hour (more than 1,000 per minute). For the 2014 M6.0 South Napa, California earthquake, 26,000 were received within the first hour and a total of 44,000 were ultimately received. Typically, about 60–90 percent of the entries are received within the first hour of an earthquake. For the largest earthquakes, response times peak at more than 30 responses per second.

The growth of DYFI contributions is accompanied by an evolution of MI reporting through the years. In 2003, 42%

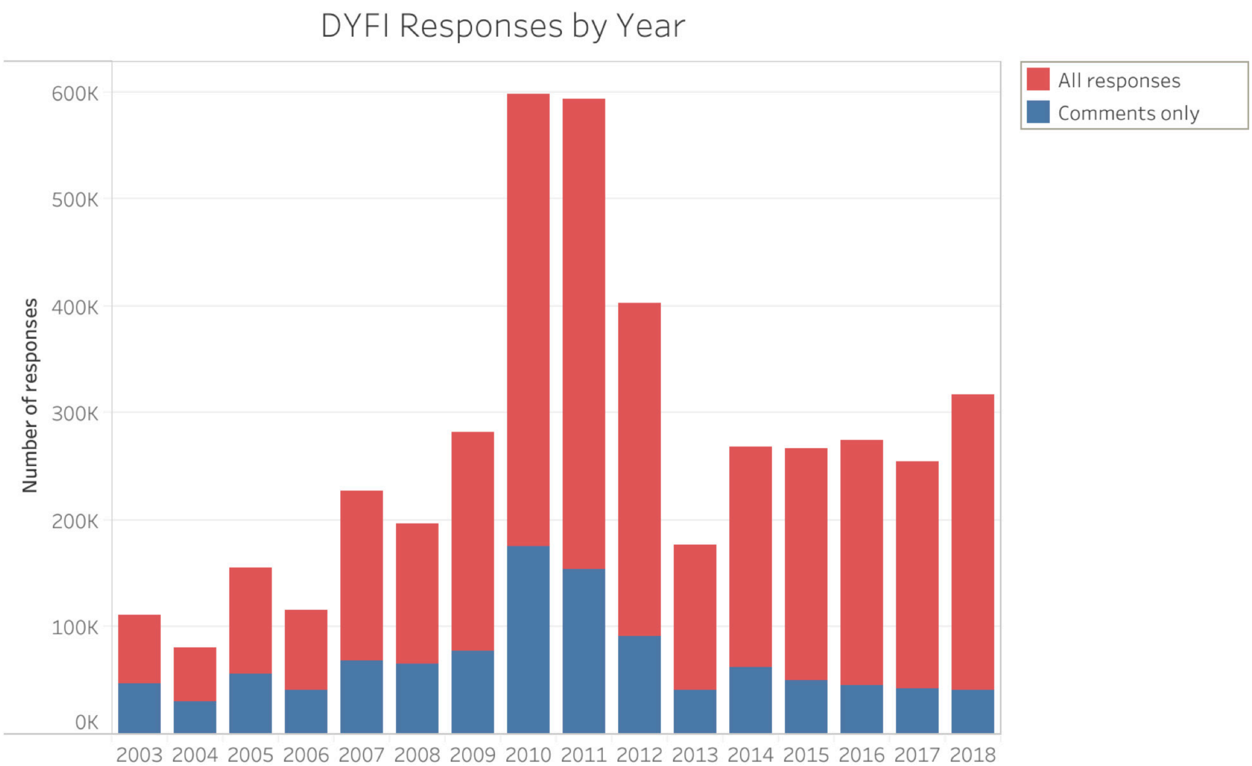


FIGURE 6 | Number of DYFI responses received from all countries each year. Red bars count all responses. Blue portions count only responses which also include comments.

of contributors left a comment in addition to filling out the checkbox portion of the questionnaire. These comments have proven useful to social scientists exploring people's responses to earthquakes (see below). Since then, the number of responses that include comments has fallen to 13% of all responses, even as the absolute number of responses with comments has been relatively steady at roughly 50,000 per year. We attribute this phenomenon to the transformation of internet access from desktop computers toward mobile phones, tablets, and other portable devices and the ubiquity of social media outlets for reporting human experiences.

With two decades of DYFI reports, we can now map out the maximum MI of shaking reported over the entire United States during that time period (**Figure 7**), and nearly every felt earthquake in the United States is or can now be reported. Thus, this map represents the actual distribution of reported shaking intensity over the entire nation for nearly two decades, up through 2018. **Figure 7** depicts several easily recognizable seismological observables: First, most states experience some shaking over this time scale. Second, the pattern of shaking reflects many of the general trends of the USGS Probabilistic Seismic Hazard Assessment maps (PSHA, e.g., Petersen et al., 2020), but many of the intensity reports mapped in the Central United States are dominated by induced earthquakes, which were not explicitly considered in the 2014 or 2018 PSHA assessment. Lastly, felt areas are significantly larger for Central and Eastern events than those in the West, a well-documented difference in crustal attenuation (e.g., Atkinson and Wald, 2007).

EARTHQUAKE RESPONSE AND SCIENCE USING DYFI DATA

Many of the earlier studies using DYI data were summarized by Wald et al. (2011). Here, we provide a partial summary of subsequent analyses.

Integration Into ShakeMap

Since its inception, ShakeMap has used DYFI intensity observations as proxies for ground motion data in areas with sparse instrumental coverage. The newest version of ShakeMap takes into account the uncertainties of its various inputs using a conditional multivariate normal (MVN) distribution (Worden et al., 2018) in order to combine data from different sources. Macroseismic intensities derived from DYFI observations have an intrinsic variability as a function of the number of responses (Worden et al., 2012). DYFI now automatically computes this uncertainty value as part of its product suite as input to ShakeMap. In addition, we are implementing the technique of Worden et al. (2012) to determine uncertainty functions for other macroseismic collection programs such as EMSC in order to systematize the inclusion of their data into ShakeMap. In other countries,

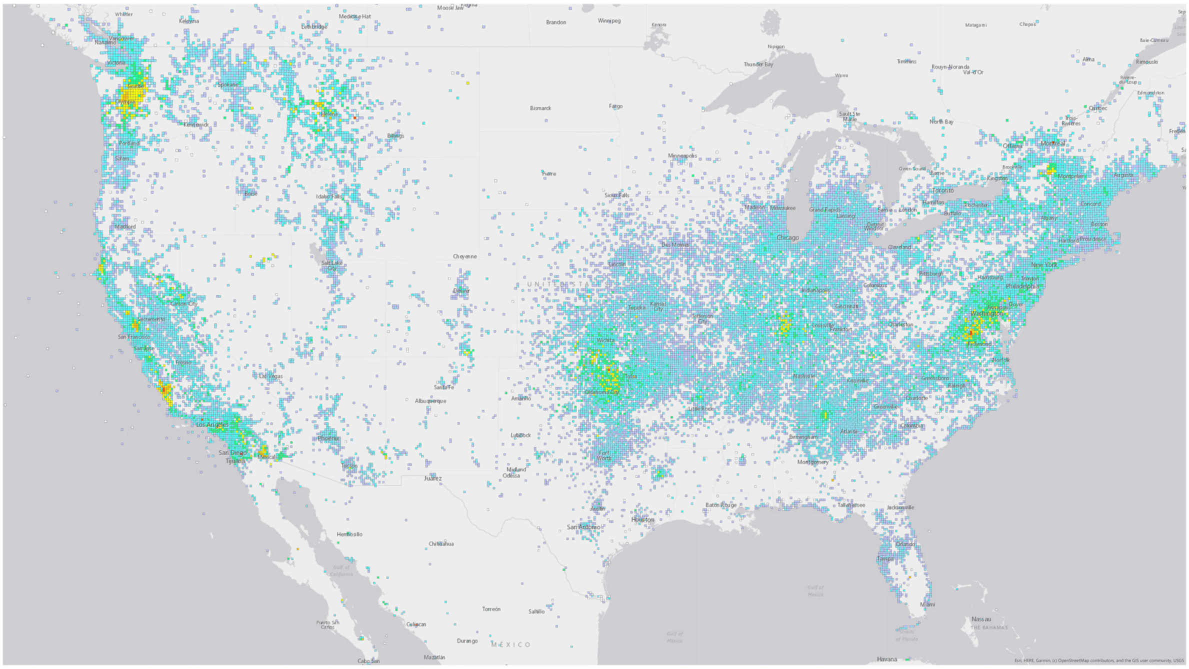


FIGURE 7 | Cumulative maximum DYFI intensities, 10-km geocoded blocks, in the U.S. from 1999 through 2018. Each cell is a 10-km block. Color corresponds to the highest intensity reported in that block among all events in that timespan using the intensity scale shown in **Figure 1**. This map and intensity maps for each year are available online in the Summary Maps section of the DYFI website (Source: U.S. Geological Survey).

DYFI systems or their equivalents are routinely ingested as part of their ShakeMap production; for instance, in Australia (Allen et al., 2019), northwestern Europe (Van Noten et al., 2016), and the French Overseas Territories (A. Schlupp, written communication, 2017).

The ability to incorporate macroseismic data geospatially into ShakeMap serves a very useful purpose. Recall that one attribute of macroseimic data is the connection of the present to the past. Historical macroseismic observations used directly in ShakeMap play a vital role in constraining shaking from significant past earthquakes. In turn, these maps help us elucidate the nature and pattern of shaking behavior, damage, and ground failure that might otherwise remain elusive. With the portfolio of historical macroseismic data and modern DYFI-based MI observations, we have basic constraints on any event that left an impression on the regional population.

New Empirical Relations

Worden et al. (2012) and Caprio et al. (2015) employ DYFI data to derive new relations among a range of peak ground motion parameters and MI data, or ground motion-intensity conversion equations (GMICEs). The development of these relations sets a new standard for ground motion to intensity relations in that the DYFI intensity data used are decimal intensities and inverse relations are provided explicitly. Similarly, DYFI data have been used to derive (IPEs, e.g., Atkinson et al., 2014) to estimate MI directly from magnitude and distance. Both GMICEs and IPEs are important for robust ShakeMap generation (Worden et al., 2018) and hazard evaluations that incorporate historical macroseismic observations, as well as for improved DYFI real-time filtering. In addition, the spatial coverage of DYFI and the precision provided by geocoding allows researchers to study regional amplification effects from intensities to complement instrumental data (e.g., Van Noten et al., 2016).

Induced Earthquakes

One special subset of the DYFI data is the Induced Events Database, which collects all data received for induced seismicity in the Central United States Over 200,000 observations for these events have been collected in the past decade with 22,000 at epicentral distances less than 20 km. These data have been particularly useful in determining the unique characteristics of induced events and evaluating their potential for damage (e.g., Atkinson et al., 2018). We foresee that this catalog will be useful for improving IPEs and GMICEs specifically for areas at risk of induced seismicity. The catalog also includes tools to create specific subsets of events and allows researchers to download intensity data for their own customized datasets.

Social Science and Behavior Studies

The DYFI portal allows for a participatory experience. Users coming to the USGS for information are empowered to become data providers themselves by contributing valuable observations that benefit the USGS as well as the participants, their local communities, and earthquake responders. DYFI also provides an important human perspective on earthquakes, providing sociological documentation of the way people behave and respond, and how they perceive risk (e.g., Celsi et al., 2005; Goltz et al., 2020).

What's more, DYFI seems to provide emotional support to citizens who have just had a frightening or even traumatic experience (e.g., Casey et al., 2018). By allowing citizens to share their experiences and enabling them to contribute their observations toward a general public understanding of the phenomenon they have experienced, DYFI provides many with a form of catharsis at an opportune time. Often, users describe the desire to confirm their experience with their larger community. The DYFI system also educates the public on oft- misunderstood seismological concepts like the geographic variations of shaking intensity and the difference between earthquake magnitude and MI (Celsi et al., 2005).

In addition, the DYFI questionnaire includes questions about contributors' situations, experiences, and behaviors that go beyond the calculation of MI. Hence, the DYFI database is a repository of millions of relevant social science observations that is still largely untapped. Some researchers have started to examine DYFI data in this light. Boatwright and Phillips (2017) explore ZIP code population demographics of "Did You Feel It?" responses in California to correct for potential sampling biases as an effort to better estimate the felt area of moderate earthquakes there. Mak and Schorlemmer (2016) ask, "What makes people respond to "Did You Feel It?" They were concerned mostly with the question of data completeness, but conclude that the number of responses depends not only on population and felt intensity but also social factors such as ethnicity, education, and age. Likewise, Goltz et al. (2020) examine response behaviors of DYFI users in various regions during earthquakes of various magnitudes, emphasizing the need for further study of appropriate response during potentially damaging earthquakes while observing that "studies that specifically address the response of persons during earthquake shaking are few in number."

We hope that the creation of specialized, accessible data subsets such as the Induced Events Database, and increasing the accessibility of DYFI generally, will encourage interest from social scientists and researchers from other fields.

Toward a Common Macroseismic Scale

Several other national government agencies employ DYFI software or use the DYFI questionnaire and intensity algorithm for their domestic macroseismic data collection: Geosciences Australia, New Zealand's GeoNet, Natural Resources Canada, the British Geological Survey, and France's Bureau Central Sismologique Français, among others. Having a common code base throughout multiple countries not only facilitates maintenance; it allows disseminating new techniques and best practices among agencies. More importantly, the use of compatible questionnaires makes possible a larger common dataset for scientific research.

At higher MI values (typically, VIII and greater), neither DYFI intensities nor Modified Mercalli Intensity assignments are particularly well defined. This intensity range primarily describes observed structural damage to buildings (e.g., Musson et al., 2010). Building vulnerability and damage grading play a crucial role in assigning high intensities, and assessing these requires a degree of engineering expertise that most DYFI contributors lack. Tosi et al. (2015) group the higher degrees of EMS-98 (>VII) into a single class, maintaining that direct evaluations by experts are needed for correct assessment.

Other than via DYFI, the USGS no longer maintains dedicated staff to assign traditional MI assignments. The USGS is therefore interested in pursuing MI data collection that combines the advantages of DYFI for crowd-sourced, massive MI data collection for lower MI (<VII, which is >95% of all MI data collected) with professional assignments at higher MI based on the more systematic EMS-98 methodology. We aim to support the development of tools for domestic MI collection that utilize engineering expertise via onsite reconnaissance, remote imagery, and other rapid data-collection strategies. Employing EMS-98 domestically will require its adaptation for United States structures, partnering with professionals to calibrate EMS-98 to United States earthquake damage data and developing outreach materials to facilitate its adoption for future domestic earthquakes. Likewise, efforts are ongoing to employ more uniform data collection strategies, with the goal of harmonizing data collection around the globe (e.g., Goded et al., 2018). Some progress to this end has been made on global macroseismic data harmonization through efforts by the European Seismological Commission's Working Group in Macroseismology (Van Noten et al., 2018). Likewise, continuing efforts to develop a Global Macroseismic Scale (Spence and Foulser-Piggott, 2014) continue from time to time.

The use of uncertainty estimates in the newest version of ShakeMap provides a possible solution to combining disparate intensity scales. Any intensity measure can now be turned into DYFI-like intensity "stations" in ShakeMap, and combined with DYFI and other data, as long as that intensity has a computed uncertainty. Intensities assigned by expert observers could be combined this way as well.

NEW OPPORTUNITIES

Increasing DYFI Data Access

The USGS is developing various ways of facilitating access to earthquake data. DYFI has been fully integrated with other USGS earthquake products available from the National Earthquake Information Center (NEIC). Guy et al. (2015) summarizes the various NEIC systems that support earthquake triggering, data processing, and product delivery. For researchers, DYFI data have been made accessible via the ComCat earthquake archives and database. Users can now replicate, filter, and update aggregated datasets via USGS web services, although individual responses are not accessible (except by special request) given that they contain Personally Identifiable Information (PII). A web service and Python library for ComCat are available for researchers to automate queries for DYFI and other products.

We have replaced or enhanced many of the DYFI static maps and products with dynamic versions using modern web tools such as GIS, GeoJSON, and Leaflet (Smoczyk et al., 2017). Web displays of DYFI data are now zoomable and interactive, allowing users to overlay their choice of layers that include 1- or 10-km geocoded boxes, population density, and ShakeMap contours and stations. Our online products now provide more information by clicking or hovering over different data elements (see **Figures 1–5**). We are also providing annual and cumulative aggregation maps showing the highest intensities reported in every UTM block (e.g., **Figure 7**). We have worked to enable usability of all webpages on smartphones and tablets, which are now the primary means of submitting questionnaire responses and viewing DYFI content.

Event Magnitude and Location With DYFI Data

Often small events, typically less than magnitude 3.5, occur near small population centers where observers quickly report via DYFI. We have developed a grid-search algorithm that employs the first set of incoming entries to determine the best-fitting magnitude and location based on region-specific IPEs (Quitoriano and Wald, 2016). NEIC analysts receive notifications of clusters of felt reports and the estimated location and magnitude from DYFI if the solution is sufficiently well constrained. Oftentimes, these approximate solutions provide a heads-up to NEIC seismic analysts of small events that may otherwise take time to locate. The origin time – needed to find the event in the seismic traces – becomes obvious since the first reported time is typically only a minute or two *after* the event's occurrence.

Developing New Tools and Approaches

We are currently developing a voice-activated DYFI questionnaire (currently for an Alexa Skill for Amazon's Alexa Smart Speaker). The difference in listening to and interacting with the questionnaire verbally, as opposed to a screen, necessitates a "Conversational User Interface" (CUI) that is easier to use than simply reading the questionnaire out loud. Considerable effort, including feedback from test users, went into the CUI to allow for more natural conversations. With proper care in skill development, voice-enabled Internet of Things (IoT) devices may allow people to interact and respond more easily with DYFI during real world events and eliminate some of the technological barriers to entry.

Ultimately, such IOT devices will likely all have accelerometers such that colocated human and instrumental measurements could be commonplace. Gathering colocated accelerometric parameters for joint analyses of instrumental and human observations is a holy grail in human-centric ground motion seismology. As mentioned earlier, anticipating the expansion of earthquake reporting on ubiquitous, lower cost – but limited quality – smartphone and speaker sensors, USGS ShakeMap can now accept uncertainty measures for intensity and ground motion parameters and weigh their contributions accordingly.

As part of the development process of the voice interface, we also designed a DYFI Questionnaire Application Program Interface (API) that allows selected third parties to submit questionnaire entries from their own applications, without going through the online questionnaire. While this raises questions of security and data quality, it also opens the potential of increased participation by partnering and integrating with other data users.

Short Versus Long Form Intensity Questionnaires

The evolution from manual, postal macroseismic questionnaires to emailed forms to internet surveys has been accomplished in many regions of the world. Many countries either maintain a manual approach as the primary strategy or reserve the option to augment their web- based approaches with traditional assignments. Several very successful internet-based macroseismic survey systems are now implemented in many countries or regions (see summaries in Wald et al., 2011 and Goded et al., 2018). One recent trend in the collection of felt reports is the rapid collection of large quantities of observer reports using simple picture-based options, which we refer to as the "short form." These are now used for worldwide events by EMSC and in New Zealand (Goded et al., 2018) as an adjunct to the "traditional" long-form questionnaire.

We agree that short form questionnaires have advantages over the long form. Their ease of use on mobile phone apps allows contributors to fill them much more quickly compared to full questionnaires, potentially increasing coverage and user participation. For example, during the 2016 M7.8 Kaikoura Earthquake (New Zealand), "[GNS] got 15,000 felt rapids in first 30 min. (which is an) order of magnitude more than traditional [questionnaires]" (N. Horspool, written communication, 11/17/2016). We believe that, given sufficient calibration, they might be relatively accurate.

However, we have two concerns with the short form. The first is the lack of precision. Since discerning differences of a single intensity unit from pictures is hard, the intensity scales of these short-form questionnaires are necessarily much coarser than a full questionnaire such as DYFI. Some of this concern may be alleviated by our ongoing efforts to quantify the uncertainty of these systems. Bossu et al. (2017) provide a bias correction for EMSC short-form responses to better align with DYFI intensity values.

A more fundamental problem with short-form questionnaires is that they leave no archival record of the actual effects and observations that are essential to establishing higher intensities. Many historical studies (e.g., Ambraseys and Douglas, 2004; Szeliga et al., 2010; Hough, 2013) have relied on the reevaluation of documented accounts of shaking and earthquake effects. Such studies would be impossible from a purely picture-based dataset.

Allowing short form derived intensities to be used in ShakeMap as long as their uncertainties can be quantified could ameliorate the record issue. For significant earthquakes, we could encourage follow-up responses employing DYFI or additional engineering assessments for archival purposes. For example, the MyShake Earthquake Early Warning platform allows its users to make short-form observations. Pointing those users to the DYFI questionnaire to capture more detailed information about their experience is a possibility.

SUMMARY

In this study, we tried to directly address the questions posited by the Editors of this Special Issue on the Power of Citizen Seismology (slightly edited):

- How much does public involvement help awareness and preparation toward seismic impact, and how does it affect public communication?
- How has the Power of Citizen Seismology made a difference in influencing government agency actions?
- What specific scientific advances have been made through data integration and interoperability between projects/across countries?
- What ethical and other challenges have been encountered?

Fundamentally, DYFI relies on input from the general public, rather than trained citizen-scientists, so more properly, DYFI is citizen-based science, rather than citizen science. In conjunction with ShakeMap, DYFI has substantially facilitated the use of MI throughout the United States, educating millions of citizens who experienced earthquakes to think in terms of the varying intensities produced by an earthquake rather than the poorly understood concept of magnitude. ShakeMap and the citizen-based science of DYFI in particular have played an important role in guiding the media and the public toward a more suitable way to describe the variations of earthquake shaking, and thus to better understand the nature of earthquake shaking hazards and risks more generally. And, given the public's uptake of MI domestically following the advent of DYFI and ShakeMap, the USGS' 2019 public release of Earthquake Early Warning (EEW) in the United States considered intensity to be the most suitable metric for warning the populace of imminent shaking with intensity-based depictions of shaking levels (e.g., Given et al., 2018). The ShakeAlert EEW system, now in operation along the United States West Coast, communicates MI using the Modified Mercalli Intensity scale (MMI) and determines which areas to alert using prescribed MMI thresholds. This strategy is consistent with the long-held approach adopted in Japan, where the Japan Meteorological Society (JMA) seismic intensity scale is very well established and understood within the community, media, and decision-makers (e.g., Doi, 2011), and preferred over magnitude as the main earthquake information delivered.

This reintroduction of the concept and use of MI to the general public has, in turn, allowed numerous federal and state government agencies including the USGS and Federal Emergency Management Agency (FEMA), various non-governmental agencies, and earthquake managers and responders to more widely adopt the depiction and communication of shaking intensity, thus promoting a more intuitive understanding of earthquake shaking hazards. This general promotion of the use of intensity can provide benefits to the general public's understanding of earthquake hazards and risk (Celsi et al., 2005).

As a web-based citizen science tool, the data collected with DYFI data are neither immutable nor perfect. And yet, the IPEs developed from DYFI data are remarkably robust and have proven to be invaluable. We have described our strategies for continued quality control. Robust treatment of the DYFI data lead to robust results. One conceivable ethical issue raised over the two-decade experiment with DYFI data collection is in the potential for manipulation of aggregated intensity values for ulterior motives by contributing spurious data. While this issue is addressed in detail by Wald et al. (2011), we add here that the direct use of DYFI data in ShakeMap can accommodate spurious observations by culling outliers and weighting DYFI data according to their uncertainty, and with a second, failsafe strategy: providing additional ShakeMap layers where DYFI data are not utilized in the computation of the ground motion field. To date, we have few examples of spurious DYFI entries during significant events; a few random entries do occasionally show up during quiet times (Wald et al., 2011). Another issue pertaining to DYFI is with respect to user privacy. Since the data are aggregated into 1- km and 10-km cells, individual users are not recoverable from DYFI products. Whereas individual entries are made available for research purposes, they are anonymized by removing PII and truncating the precision of provided locations.

Operationally, the DYFI data, when integrated directly for use in ShakeMap, allow for better-constrained estimates of shaking for significant earthquakes around the globe (to varying degrees, based on the region's uptake of DYFI). In turn, better-constrained ShakeMaps as input for USGS earthquake impact products such as PAGER and ShakeCast (Lin and Wald, 2008) improve our ability to project useful loss estimates immediately following earthquakes worldwide. In this context, interoperability across nations could be further achieved by the types of analyses described herein where both obvious trends and heteroscedastic uncertainties can be accommodated in ShakeMap. Moreover, we have described a wide array of seismological hazard and risk studies that depend primarily on DYFI data, ranging from response-oriented applications (ShakeMap constraints), to better ground motion estimates of intensity and shaking from induced earthquakes, to social and behavioral science.

DATA ACCESS

"Did You Feel It?" can be found online at the website http://earthquake.usgs.gov/dyfi/. Event queries can be made through the ComCat webpage at https://earthquake.usgs.gov/data/comcat/. Command line tools and the Python API for accessing ComCat are available at https://github.com/usgs/libcomcat. The DYFI Induced Events Database is available online in USGS ScienceBase data archives (https://doi.org/10.5066/F7WM1BPC). Specialized DYFI data requests, including (anonymized) user entries and comments, can be made to the authors upon request for educational or research purposes.

AUTHOR CONTRIBUTIONS

DW wrote the first draft of the manuscript. Both authors wrote or rewrote the sections of the manuscript. Both authors contributed to manuscript revision, read, and approved the submitted version.

REFERENCES

Allen, R. M., Kong, Q., and Martin-Short, R. (2020). The MyShake platform: a global vision for earthquake early warning. *Pure Appl. Geophys.* 177, 1699–1712. doi: 10.1007/s00024-019-02337-7

Allen, T., Carapetis, A., Bathgate, J., Ghasemi, H., Pejić, T., and Moseley, A. (2019). "Real-time community internet intensity maps and shakemaps for australian earthquakes," in *Proceedings of the Australian Earthquake Engineering Society 2019 Conference*, Newcastle, NSW, 13.

Ambraseys, N. N., and Douglas, J. (2004). Magnitude calibration of north Indian earthquakes. *Geophys. J. Int.* 159, 165–206.

Atkinson, G. M., and Wald, D. J. (2007). "Did You Feel It?" Intensity data: a surprisingly good measure of earthquake ground motion. *Seis. Res. Lett.* 78, 362–368. doi: 10.1785/gssrl.78.3.362

Atkinson, G. M., Wald, D. J., Worden, C. B., and Quitoriano, V. (2018). The intensity signature of induced seismicity. *Bull. Seism. Soc. Am.* 108, 1080–1086. doi: 10.1785/0120170316

Atkinson, G. M., Worden, C. B., and Wald, D. J. (2014). Intensity prediction equations for north america. *Bull. Seism. Soc. Am.* 104, 3084–3093. doi: 10.1785/0120140178

Boatwright, J., and Phillips, E. (2017). Exploiting the demographics of "Did You Feel It?" Responses to Estimate the felt area of moderate earthquakes in California. *Seism. Res. Lett.* 88, 335–341. doi: 10.1785/0220160041

Bossu, R., Landès, M., Roussel, F., Steed, R., Mazet-Roux, G., Martin, S. S., et al. (2017). Thumbnail- based questionnaires for the rapid and efficient collection of Macroseismic Data from Global Earthquakes. *Seism. Res. Lett.* 88, 72–81. doi: 10.1785/0220160120

Caprio, M., Tarigan, B., Worden, C. B., Wald, D. J., and Wiemer, S. (2015). Ground Motion to Intensity Conversion Equations (GMICEs): a global relationship and evaluation of regional dependency. *Bull. Seism. Soc. Am.* 105, 1476–1490. doi: 10.1785/0120140286

Casey, J. A., Goldman-Mellor, S., and Catalano, R. (2018). Association between Oklahoma earthquakes and anxiety- related Google search episodes. *Environ. Epidemiol.* 2:e016. doi: 10.1097/EE9.0000000000000016

Celsi, R., Wolfinbarger, M., and Wald, D. J. (2005). The effects of magnitude anchoring, earthquake attenuation estimation, measure complexity, hubris, and experience inflation on individuals' Perceptions of felt earthquake experience and perceptions of earthquake risk. *Earthquake Spectra.* 21, 987–1008.

Dengler, L. A., and Dewey, J. W. (1998). An intensity survey of households affected by the Northridge, California, earthquake of 17 January 1994. *Bull. Seism. Soc. Am.* 88, 441–462.

Doi, K. (2011). The operation and performance of earthquake early warnings by the Japan Meteorological Agency, Soil. Dyn. *Earthquake Eng.* 31, 119–126.

Given, D. D., Allen, R. M., Baltay, A. S., Bodin, P., Cochran, E. S., Creager, K., et al. (2018). *Revised Technical Implementation Plan for the ShakeAlert system—An Earthquake Early Warning System for the West Coast of the United States: U.S. Geological Survey Open-File Report 2018–1155*. Reston, VA: U.S. Geological Survey, doi: 10.3133/ofr20181155

Goded, T., Horspool, N., Canessa, S., Lewis, A., Geraghty, K., Jeffrey, A., et al. (2018). New macroseismic intensity assessment method for New Zealand Web Questionnaires. *Seismol. Res. Lett.* 89, 640–652. doi: 10.1785/0220170163

Goltz, J. D., Park, H., Nakano, G., and Yamori, K. (2020). Earthquake ground motion and human behavior: using DYFI data to assess behavioral response to earthquakes. *Earthquake Spectra*. doi: 10.1177/8755293019899958 [Epub ahead of print].

Grünthal, G. (1998). European macroseismic scale 1998 (EMS-98). *Cahiers Centre Europe'en Geodynamique Seismologie Luxembourg* 15, 1–99.

Guy, M., Patton, J., Fee, J. M., Hearne, M., Martinez, E. M., Ketchum, D., et al. (2015). *National Earthquake Information Center Systems Overview And Integration: USGS Open File Report*. Reston, VA: USGS, 2015–1120. doi: 10.3133/ofr20151120

Hough, S. E. (2013). Spatial Variability of "Did You Feel It?" Intensity data: insights into sampling biases in historical earthquake intensity distributions. *Bull. Seism. Soc. Am.* 103, 2767–2781. doi: 10.1785/0120120285

Lin, K. W., and Wald, D. J. (2008). ShakeCast manual: U.S. *Geol. Surv. Open File Rep.* 200:90.

Mak, S., and Schorlemmer, D. (2016). What makes people respond to "Did You Feel It?"? *Seismol. Res. Lett.* 87, 119–131.

Montalvo-Arrieta, J. C., Perez-Campos, X., Ramirez-Guzman, L., Sosa-Ramirez, R. L., Ruiz-Esparza, M. C., and Leonardo-Suarez, M. (2019). Macroseismic Intensities from the 19 September 2017 7.1 Puebla- Morelos Earthquake. *Seismol. Res. Lett.* 90, 2142–2153. doi: 10.1785/0220190145

Musson, R. M. W., Grünthal, G., and Stucchi, M. (2010). The comparison of macroseismic intensity scales. *J. Seismol.* 14, 413–428. doi: 10.1007/s10950-009-9172-0

Petersen, M. D., Shumway, A. M., Powers, P. M., Mueller, C. S., Moschetti, M. P., Frankel, A. D., et al. (2020). The 2018 update of the US National Seismic Hazard Model: Overview of model and implications. *Earthq. Spectra* 36, 5–41. doi: 10.1177/8755293019878199

Quitoriano, V., and Wald, D. J. (2016). Use of U. S. Geological Survey's "Did You Feel It?" Responses for Near Real-Time Earthquake Location, Seismo. *Res. Lett.* 87:567.

Sbarra, P., Tosi, P., and De Rubeis, V. (2010). Web-based macroseismic survey in Italy: method validation and results. *Nat. Hazards* 54, 563–581. doi: 10.1007/s11069-009-9488-7

Sbarra, P., Tosi, P., and De Rubeis, V. (2014). How observer conditions impact earthquake perception. *Seismol. Res. Lett.* 85, 306–313. doi: 10.1785/0220130080

Smoczyk, G. M., Wald, D. J., Worden, C. B., Thompson, E. M., Quitoriano, V., and Hearne, M. (2017). "Seismology and GIS: USGS near real-time significant earthquake and earthquake scenario GIS feeds," in *Proceedings of the Seismological Society of America 2017 Annual Meeting*, Denver, CO.

Spence, R., and Foulser-Piggott, R. (2014). "The International Macroseismic Scale – extending EMS-98 for global application," in *Proceedings of the Second European Conference on Earthquake Engineering and Seismology*, Istanbul,

Szeliga, W., Hough, S., Martin, S. S., and Bilham, R. (2010). Intensity, magnitude, location, and attenuation in India for felt earthquakes since 1762. *Bull. Seismol. Soc. Am.* 100, 570–584.

Tosi, P., Sbarra, P., De Rubeis, V., and Ferrari, C. (2015). Macroseismic intensity assessment method for web questionnaires. *Seismol. Res. Lett.* 86, 985–990. doi: 10.1785/0220150127

Van Noten, K., de Rubeis, V., Tosi, P., and Sbarra, P. (2018). "Challenges of the new ESC Working Group Macroseismology—Integrating corrective parameters to merge multiple-sourced online macroseismic data," in *Proceedings of the 6th Colloquium on Historical Earthquakes & Paleoseismology Studies, Han-sur-lesse*, Belgium,

Van Noten, K., Lecocq, T., Sira, C., Hinzen, K.-G., and Camelbeeck, T. (2016). Path and site effects deduced from transfrontier internet macroseismic data of two recent M4 earthquakes in NW Europe. *Solid Earth Discuss* 8, 453–477. doi: 10.5194/se-2016-150

Wald, D. J., Earle, P. S., Porter, K., Jaiswal, K., and Allen, T. I. (2008). "Development of the U.S. Geological Survey's prompt assessment of global earthquakes for Response (PAGER) System," in *Proceedings of the 14th World Conference. Earthquake Engineering*, Beijing.

Wald, D. J., Quitoriano, V., Dengler, L., and Dewey, J. W. (1999a). Utilization of the internet for rapid community intensity maps. *Seismol. Res. Lett.* 70, 680–697.

Wald, D. J., Quitoriano, V., Heaton, T. H., Kanamori, H., Scrivner, C. W., and Worden, C. B. (1999b). TriNet "ShakeMaps": rapid generation of peak ground motion and intensity maps for earthquakes in southern California. *Earthquake Spectra* 15, 537–556.

Wald, D. J., Quitoriano, V., Worden, C. B., Hopper, M., and Dewey, J. W. (2011). USGS “Did You Feel It?” Internet- based macroseismic intensity maps. *Ann. Geophys.* 54, 688–709. doi: 10.4401/ag-5354

Worden, C. B., Gerstenberger, M. C., Rhoades, D. A., and Wald, D. J. (2012). Probabilistic relationships between peak ground motion and Modified Mercalli intensity. *Bull Seism. Soc. Am.* 102, 204–221. doi: 10.1785/0120110156

Worden, C. B., Thompson, E. M., Baker, J. W., Bradley, B. A., Luco, N., and Wald, D. J. (2018). Spatial and spectral interpolation of ground motion intensity measure observations. *Bull. Seism. Soc. Am.* 108, 866–875. doi: 10.1785/0120170201

Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the United States Government.

Conflict of Interest: The 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.

Copyright © 2020 Quitoriano and Wald. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

ORIGINAL RESEARCH
published: 29 May 2020
doi: 10.3389/feart.2020.00154

Citizen Seismology in Taiwan: Development, Outreach, and Formative Assessment of Near-Real Time Earthquake Game Competition Activities

*Kate Huihsuan Chen[1], Wen-Tzong Liang[2], Chun-Hung Lin[3] and Leon Yufeng Wu[3]**

[1] Department of Earth Sciences, National Taiwan Normal University, Taipei, Taiwan, [2] Institute of Earth Sciences, Academia Sinica, Nankang, Taiwan, [3] Graduate School of Education, Chung Yuan Christian University, Taoyuan, Taiwan

OPEN ACCESS

Edited by:
Pier Paolo Bruno,
University of Naples Federico II, Italy

Reviewed by:
Elizabeth Cochran,
United States Geological Survey (USGS), United States
Bernhard Maximilian Steinberger,
Helmholtz Centre Potsdam, Germany

***Correspondence:**
Leon Yufeng Wu
leonwu@cycu.edu.tw

Specialty section:
This article was submitted to Solid Earth Geophysics, a section of the journal Frontiers in Earth Science

Received: 02 February 2020
Accepted: 27 April 2020
Published: 29 May 2020

Citation:
Chen KH, Liang W-T, Lin C-H and Wu LY (2020) Citizen Seismology in Taiwan: Development, Outreach, and Formative Assessment of Near-Real Time Earthquake Game Competition Activities. Front. Earth Sci. 8:154. doi: 10.3389/feart.2020.00154

Citizen seismology encourages the public involvement in data collection, analysis, and reporting, and has the potential to greatly improve the emergency response to seismic hazard. We believe in the value of citizen seismology and started with distributing Quake-Catcher Network (QCN) sensors at schools in Taiwan. Unlike most of western countries, Earth Sciences is a required course in junior and senior high schools of Taiwan (Ministry of Education, 2014). Low-cost seismometer is potentially a powerful tool in classrooms to teach earthquake science, which makes school teachers our targeted users. We work closely with school teachers and students to understand how a citizen seismology project can help them to encourage successful engagement. In this study, we establish the achievements gained and problems encountered in different phases of the project since 2013. The main tasks carried out here include (1) refinement of Citizen Seismology Literacy (CSL) into three dimensions: Awareness, and Willingness, and Technology fluency (2) development of an interactive competition platform called the Near-Real Time Earthquake Game Competition (EGCnrt) that allows citizen seismologists to report earthquake information by processing P- and S-wave arrivals, peak ground motion, and first motion of P-waves for every inland $M_L \geq 4$ earthquake in Taiwan; (3) development of the formative assessment for the 1.5 h long, non-lecture-based game activities. Based on 565 student surveys completed after our 2016 summer outreach activity, we found that all three CSL dimensions have an influence on students' score in the training activity. The final score in EGCnrt is also found to significantly correlate with the performance in the training sections. We therefore, propose that the CSL can act as a powerful indicator for the performance and engagement in earthquake learning activities. The game-based, non-lecture-based learning approach can be effective in promoting citizen seismology in the future.

Keywords: citizen seismology, QCN, earthquake game, citizen seismology literacy, formative assessment

HIGHLIGHT

– How to motivate the long-term engagement in citizen seismology remains a global challenge. In this paper we review different phases of citizen seismology in Taiwan since 2013. The highlight of the project is the development of a near-real time earthquake game competition. This competition platform allows citizen seismologist to report earthquake information by processing P- and S-wave arrivals (Finding Earthquakes game), peak ground motion (Measuring Earthquake Shaking and Sizing Up Earthquakes games), and first motion of P waves (Measuring How a Fault Moves game). The users are allowed to process the real data, to estimate the location, seismic intensity, magnitude, and focal mechanism of any magnitude greater than 4 earthquake in Taiwan. Through the formative assessment during the outreach activities, we propose a 1.5 h long, game-based, non-lecture-based learning approach that can be effective in promoting citizen seismology in the future.

PROJECT BACKGROUND

In the past decade, citizen seismology has become more popular due to the rise of internet, the development of social media, and the low-cost sensor technologies that allow for building networks of non-scientists for collecting and analyzing seismic data. The successful projects for rapid earthquake information include DYFI (Did You Feel It) developed by U.S. Geological Survey (Wald et al., 2011), multichannel rapid information system comprising websites developed by European Mediterranean Seismological Centre (EMSC) (e.g., Bossu et al., 2008, 2015, 2018), and other social networking tools (e.g., Twitter, facebook, Instagram, LinkedIn) that allow the citizens to provide the first-hand accounts of ground conditions for situational awareness and emergence response (Earle et al., 2010; Guy et al., 2010). For places where the seismic station coverage is sparse, crowdsourcing approaches also play a crucial role in understanding the shaking level of an earthquake. There exist some projects of citizen seismology that aim at distributing low-cost sensors for early warning or data sharing purposes. With a collection of seismic signals from a denser seismic network, they provide accurate and useful seismic signals for scientific investigation and hazard awareness. For example, QCN and Community Seismic Network provide citizens with micro-electro-mechanical systems (MEMS) accelerometers that are installed at home and school, connected to the computer, and sending continuous data to the server (Cochran et al., 2009). MyShake makes use of the data from phone motion sensors, to provide early warning of earthquakes (Kong et al., 2016; Allen et al., 2019). P-Alert distributes the MEMS sensors at schools that are equipped with P wave alarm technology (Wu et al., 2013). These sensor-based citizen networks provide precise and real-time information, which allow the science community to collect and analyze data. However, the participation of citizens has been minimal due to several reasons: (1) the devices are black-boxes to the users, (2) the recorded signals are difficult for non-seismologists to read and understand, (3) application does not encourage the instant feedback from users, (4) no routine exercises or activities to attract users' attention. How to motivate citizens to participate is a big challenge.

Taiwan is situated at a complicated plate boundary zone between the Eurasian plate (EP) and the Philippine Sea Plates (PSP), which exhibits a unique interaction between the EP and PSP. In northeast Taiwan, the PSP subducts beneath the rifted Eurasian plate margin along the Ryukyu Trench at a rate of 8 cm/yr to the north-west (Seno, 1977; Yu et al., 1977; Seno et al., 1993), whereas in southwest Taiwan, the Eurasian plate subducts underneath PSP along the Malina trench. As a result, approximately 21,000 earthquakes strike the island with an average rate of 39 $ML \geq 5$ events [equivalent to $Mw \geq 4.48$ using Mw – ML relation derived from local seismicity by Huang et al. (2000)] every year (in the past 29 years since 1991). In the next 30 years, the probability of $Mw \geq 6.5$ earthquakes is predicted to be higher than 87% based on probabilistic seismic hazard analysis (PSHA) (Wang et al., 2016). Note that the moment magnitude is used in PSHA to avoid the ML saturation at a large magnitude. To better prepare Taiwanese citizens for future impacts of seismic hazard, it is important that they understand why earthquakes happen, how they occur, and how to best prepare for an earthquake. Citizen seismology in Taiwan was motivated by the need for volunteers to host QCN sensors (Liang et al., 2016). Unlike most western countries, Earth Sciences is a required course in junior and senior high schools of Taiwan (Ministry of Education, 2014). Can QCN be potentially a powerful tool in classrooms for teaching earthquake science? Given that very dense seismic networks in Taiwan (e.g., 5 km spacing for P-Alert network) already existed, our main goal was not to increase the number of sensors. Instead, we work closely with school teachers and students to understand how a citizen seismology project can help them to encourage successful engagement. The key questions are: how to motivate the teachers and their students to interact with the seismograms, how to transform their contribution to useful information, and how to plan a series of activities for a long-term engagement of citizens? In this paper we detail the scopes and tasks since 2013, the result of formative assessment, and the problems encountered in different phases of the project.

PHASE I: QCN NETWORK

Motivated by the collaboration with QCN project (Cochran et al., 2009) for promoting citizen seismology in Asia, the Citizen Seismologists in Taiwan Project (CSTaiwan) was initiated in 2012. The purpose is to build a cloud-based computing service incorporating an earthquake school where the volunteers (teachers and students) can contribute to QCN data collection, analysis, and reporting with the potential of improving the emergency response to earthquakes. Up to 2019, 149 volunteers in total installed QCN sensors with Internet-enabled computers at schools. The population is highest at the places where we had intensive Professional Teacher Development workshops held by Taiwan Rotary club. **Figure 1** shows the current QCN site

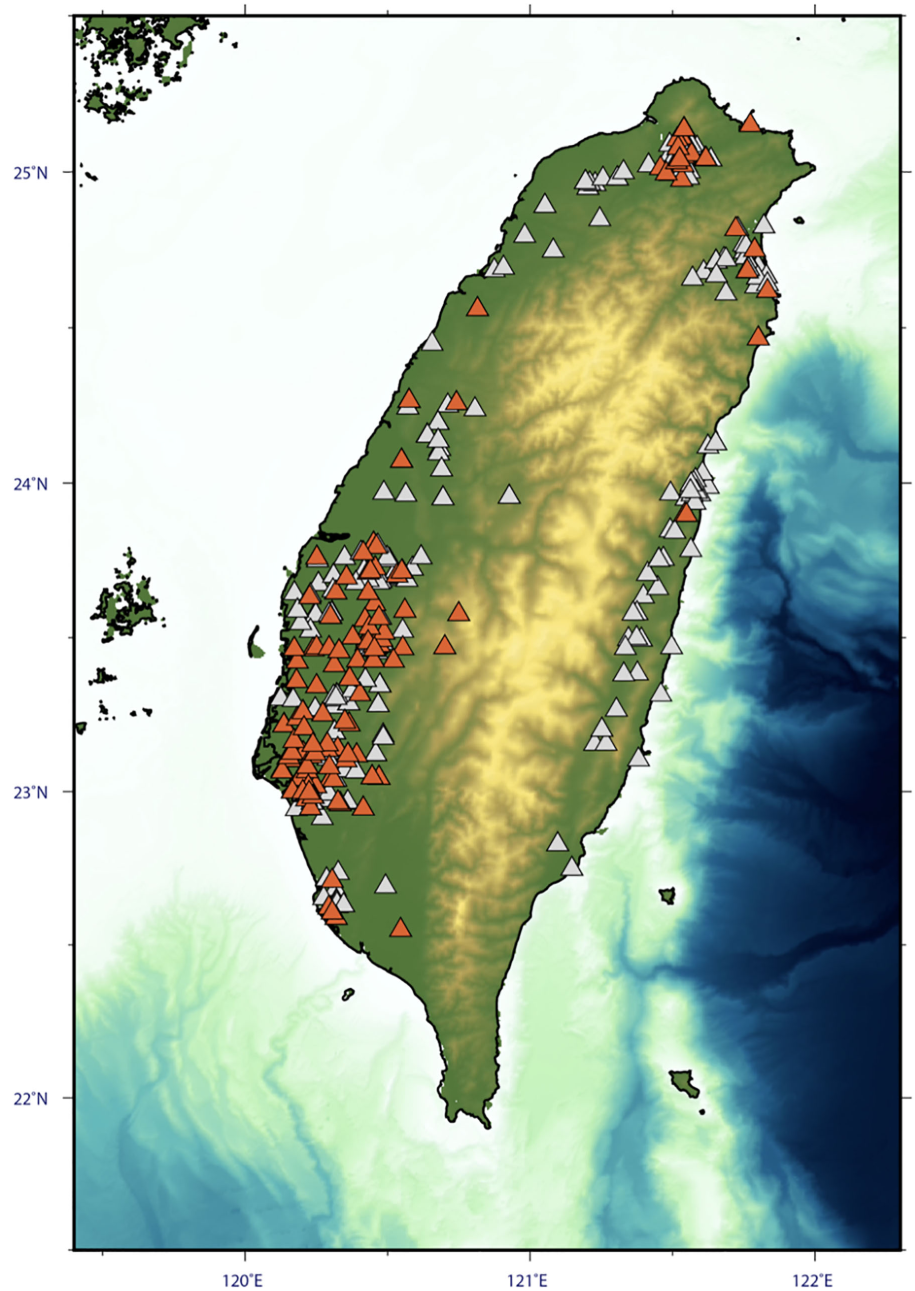


FIGURE 1 | The distribution of QCN in Taiwan. The active stations are indicated by orange, while the inactive stations are shown by white.

distribution in Taiwan. Most of the stations are located in southwestern Taiwan (Tainan and Chiayi counties). The time evolution from 2012 January to 2016 October of active QCN sensors is shown in **Figure 2**. System logs indicate that the sensors are on average active ∼50–60% of the time. Note that to keep the QCN project active (i.e., seismic data can be continuously sent to the servers), the local host needs to check "project manager window" of the BOINC server software from time to time. It is a difficult mission for the hosts who are not familiar with the software in the English interface. Another problem is the switching role of local QCN host. In schools, the QCN sensor is usually hosted by the computer/information system manager, which is a temporary position with only a few years in service. Thus from time to time, the QCN hosts lost contact with the administration server, leading to the low "active" rate.

The recorded waveforms for magnitude greater than 4 earthquakes in Taiwan are shared in the platform of School QCN network (**Figure 3**). The volunteers can view and download the waveforms with Seismic Analysis Code (SAC) format (Goldstein et al., 2003) and further, analyze the seismic signal through

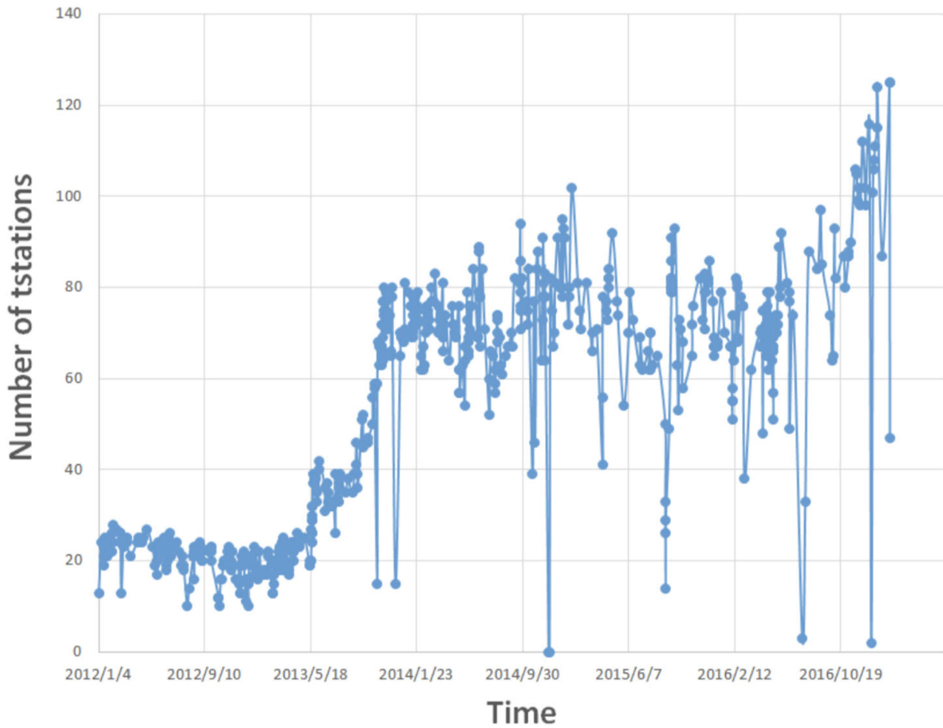


FIGURE 2 | Time history of active QCN in Taiwan since 2012 January to 2016 November. After then the QCN server had encountered an unknown problem leading to an acquisition gap.

the program of Seisgram2K. Continuous signals collected at homes/schools are streamed to Academia Sinica of Taiwan for data archiving. The QCN hosts who make effort to maintain the "active QCN," often request teachable materials on "what the recorded signal means" and "what can be learned from the signals." That's where the next phase began.

PHASE II: NEAR-REAL TIME EARTHQUAKE GAME COMPETITION AND TEACHING RESOURCES

To make the recorded signals useful in classrooms and to allow the citizen to learn basic seismology, we developed an interactive tool called "the Near-Real Time Earthquake Game Competition (EGCnrt)[1]. This platform was announced along with online teaching resources in Nov. 2014. Within 10 min of a M≥4 earthquake event in Taiwan, the near-real time seismic data from the P-alert strong motion network (Wu et al., 2013, 2016) are released and the competition begins. The original purpose of the P-alert network is to provide on-site earthquake early warning and near real-time ground motion intensity measurements. Such island-wide earthquake early warning network could be beneficial for earthquake science learning (e.g., Kong et al., 2016), especially since the P-alert sensors are mostly installed in schools.

[1]http://qcntw.earth.sinica.edu.tw/games/competitionV3/index.php

The EGCnrt competition platform allows citizen seismologists to report earthquake information by processing P- and S-wave arrivals (Finding Earthquakes game), peak ground motion (Measuring Earthquake Shaking and Sizing Up Earthquakes games), and first motion of P-waves (Measuring How a Fault Moves game). A series of simplified certificate games are designed in a training activity, to familiarize beginners with data processing steps. As shown in **Figure 4A**, four different processing skills are required in this training stage: (1) Finding the earthquake – by picking P- and S-wave arrivals at more than 3 stations, the epicenter of the earthquake can be found. (2) Measuring earthquake shaking – by picking the maximum amplitude in three components of seismograms, peak ground motion can be measured. (3) Sizing up earthquake – by picking the maximum amplitude in the horizontal component with the previously defined epicenter, earthquake magnitude can be measured. (4) Measuring how a fault moves – by picking initial motion polarities of P wave first arrival (up or down), the fault type (normal, thrust, or strike slip) can be determined. The certificate games corresponding to the above four components require the processing of at least three, five, ten, and 20 stations, respectively (**Figure 4A**). Once the certificates are achieved, the citizen seismologists can challenge themselves by taking part in the near-real time competition. As shown in **Figure 5**, the three components waveforms in each station can be viewed and processed when the users click the red circles in **Figure 4B**. The processing flow is listed in the left side of **Figure 4B** as (1) picking P and S arrivals at more than 3 stations (2) measuring

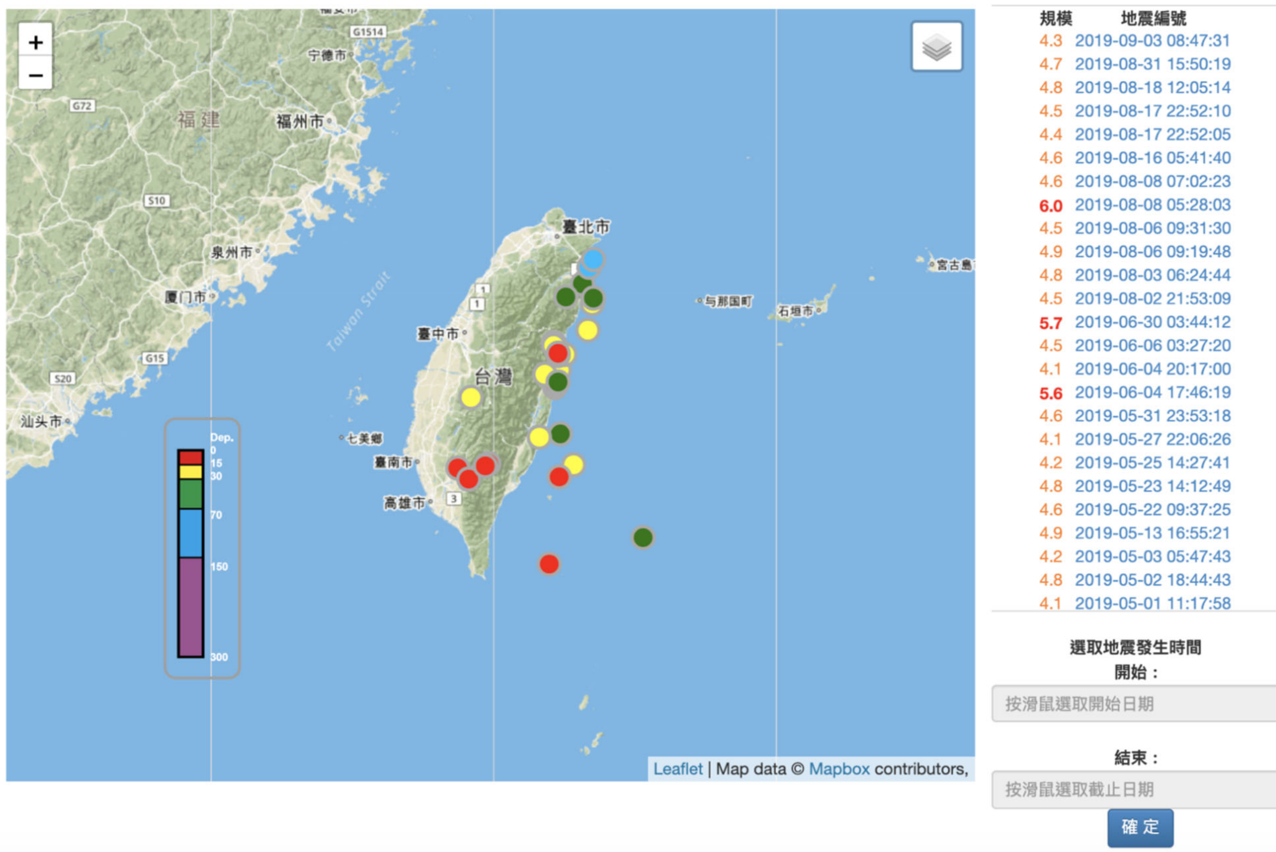


FIGURE 3 | Website of School QCN network. Circles represent the recorded earthquakes colored coded by focal depth. The list of earthquakes on the right panel shows the date and magnitude for $M_L \geq 4$ events, which allows the volunteers to access the waveforms in each QCN site.

peak ground acceleration (PGA) and magnitude at more than 7 stations (3) determining fault plane solution at more than 10 stations (4) creating the shake map at more than 15 stations. One can click the "locating earthquake" function to determine the hypocenter once three stations are processed. The competition steps are in a different order than the training steps. Here the processing of at least seven and ten stations are needed, to determine earthquake magnitude and fault plane solution, respectively. The score of the near-real time game is determined based on the precision of the location of the epicenter, magnitude, and fault plane solution. The algorithms are detailed in Liang et al. (2016) and also briefly summarized below.

1. Score for "Finding Earthquake": ($5 < \text{Score\_1} < 20$)
   X = Epicenter difference = (location determined by the user) – (location announced by Central Weather Bureau)
   Score_1 = $-0.6X + 20$ if $X < 25$ km
   Score_1 = 5, if $X \geq 25$ km
2. Score for "Measuring earthquake shaking" Game: ($5 < \text{Score\_2} < 20$)
   PGA difference Xi = (PGA determined by the user) – (PGA measured by the densest P-alert seismic network)
   Score_2 = $-0.2(\Sigma Xi/n) + 20$ if $(\Sigma Xi/n) < 75$ cm/s^2
   Score_2 = 5 if $(\Sigma Xi/n) \geq 75$ cm/s^2,
   where n is the number of stations processed.
3. Score for "Sizing up earthquake" Game: ($5 < \text{Score\_3} < 20$)
   Magnitude difference X = (Magnitude determined by the user) – (magnitude announced by Central Weather Bureau)
   Score_3 = $-10X + 20$ if $X < 1.5$
   Score_3 = 5 if $X \geq 1.5$
4. Score for "Measuring how a fault moves" Game: ($5 < \text{Score\_4} < 20$)
   Score_4 = 20 if the fault type is the same with the one announced by Real-Time Moment Tensor Monitoring System in Taiwan by Lee et al. (2013)[2].
5. Additional score for number of stations processed: ($5 < \text{Score\_5} < 20$)
   X = Number of stations processed
   Score_5 = $0.2X + 10$ if $X < 50$
   Score_5 = 20 if $X \geq 50$

Note that the final score is computed and accumulated when the above (1)–(4) are completed.

[2]http://rmt.earth.sinica.edu.tw/

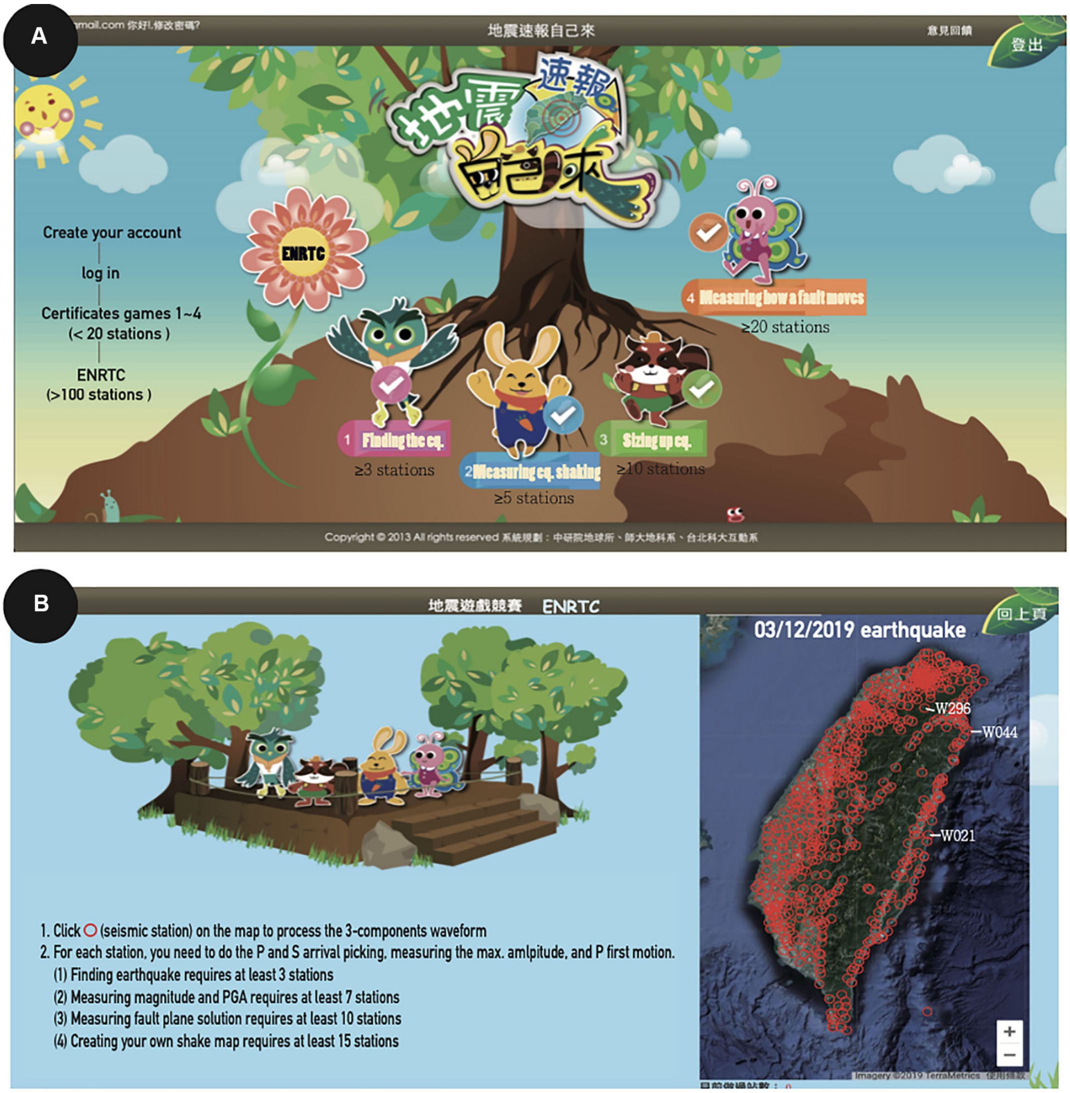


FIGURE 4 | (A) The front page of the near-real-time earthquake games competition website. Each animal represents a different game. Once the certificate is achieved, the user can enter the competition platform (EGCnrt) to contribute to real earthquake information. **(B)** The EGCnrt page for a selected date of March 12, 2019. Station distribution for this event is shown by the red circles. The waveforms examples indicated by text are shown in **Figure 5**.

Six teachable units were also prepared, to closely link with different functions in EGCnrt. The summary of teachable units is listed below. (1) Orphan Tsunami: A story of mysterious tsunami in 1700 that stroke Japan along the coastline over a distance 1000 km without an apparent cause. The parent earthquake was found to locate in the western United States and Canada, in a region that was not known to have experienced an earthquake greater than *Mw* 7.5 in recorded times. Through geological evidence, the students will learn how the magnitude 8 (or higher) earthquake had written its own history. (2) Finding Earthquakes: An introduction to the skills needed for locating earthquakes – picking P- and S-wave arrivals at more than three stations. (3) The 2004 Sumatra Earthquake and Tsunami: A story of how the serious fatalities could happen during a disastrous tsunami, following the 2004 *Mw* 9.3 earthquake that occurred in northern Sumatra. The students will learn what are the precursory signals before a massive tsunami, how the amplitude of the seismic signal correlates with earthquake magnitude, and what information is required for effective tsunami warning. (4) Sizing Up Earthquakes: An introduction to the skills needed for determining earthquake magnitude and intensity – picking the maximum amplitude on three- component seismograms. (5) Forensic Seismology: A story of how the seismic signals help us to discriminate explosion/mine collapse from tectonic earthquake. (6) Making Fault Motions: An introduction to the skill needed for focal mechanism determination – picking the initial motion polarities of the first arrival of the P waves. These teaching materials

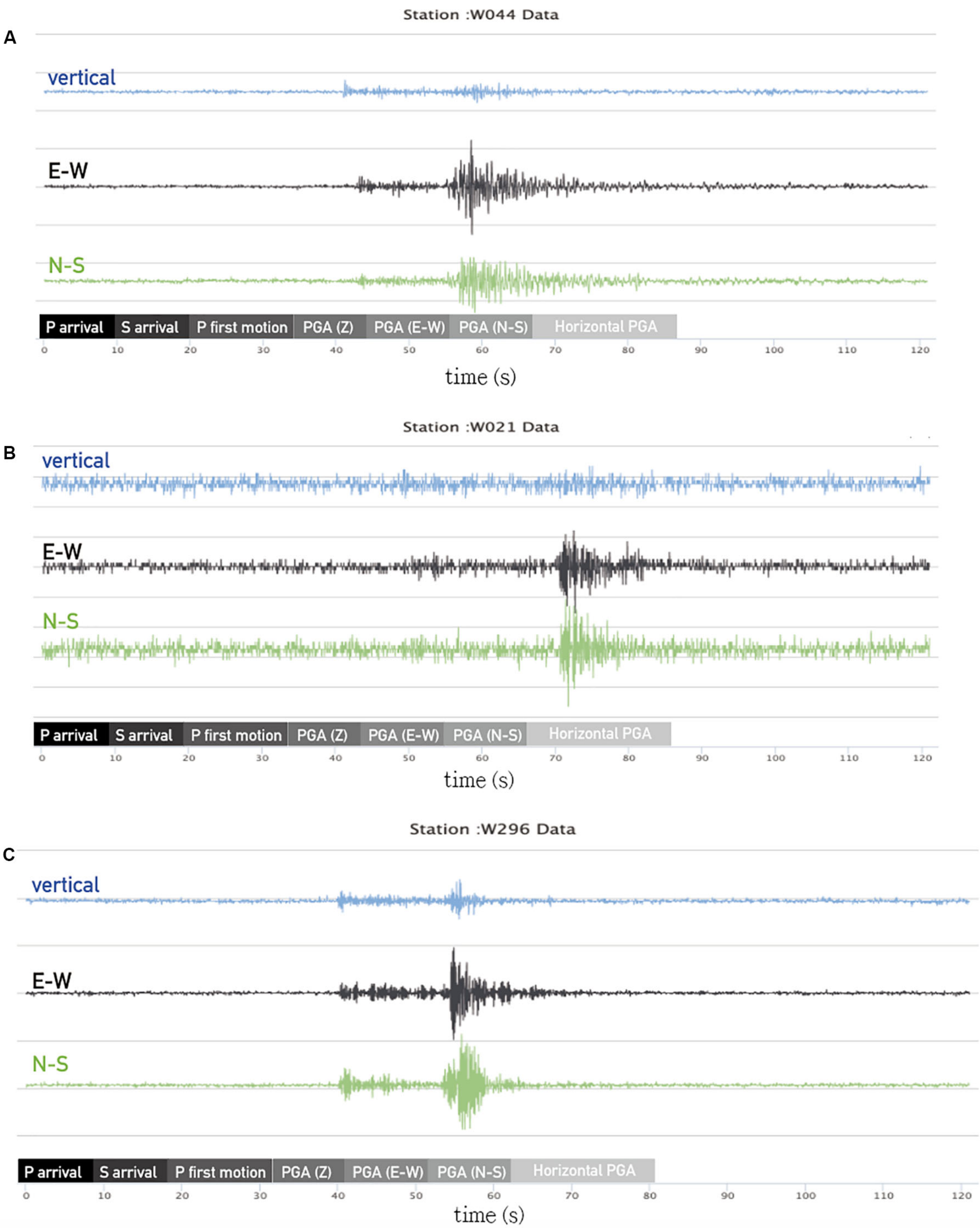


FIGURE 5 | Waveform examples for three selected stations in **Figure 4B**. For each station the process flow is shown in the bottom.

are put into a several-mins-long youtube video, to prepare the citizen seismologist for EGCnrt. The original ppt and video clips are available on the website of https://katepili2003.wixsite.com/future-eq-school (in Chinese). Note that since students' level may vary greatly from third to twelfth grade, the educational materials were designed differently to fit the student's background knowledge. This was done during eight seed-teacher workshops where we worked with teachers from elementary, junior, and senior high schools in October 2013 to July 2014.

PHASE III: TEACHER WORKSHOPS AND DEVELOPMENT OF CITIZEN SEISMOLOGY LITERACY (CSL)

Shortly after Phase II, we introduced the teaching materials in six teacher professional development workshops. With 15–80 participants in each workshop, we reached 121 first- to twelfth-grade teachers across the nation in 2014 and 2015. To collect feedback of the participants for future directions of this project, we developed 49 items to evaluate participants' pre-knowledge, attitude, and skills in earthquake sciences, called Citizen Seismological Literacy (CSL). The CSL is compared with participants' personality categorized into three sub-factors: Conscientiousness (a desire of personality to complete a task well), Intellect/Imagination (the ability of personality to understand or depict abstract ideas) and Grit (perseverance and passion for long-term goals). As detailed in Liang et al. (2017), we found that all three sub-factors in Personality are positively related to CSL dimensions of Attitude and Skills. This indicates that that Conscientiousness, Intellect/imagination, and Grit may have an effect when developing one's seismology literacy and that the CSL can act as a powerful approach to citizens' learning paths for promoting citizen seismology in the future. Using Exploratory Factor Analysis (EFA), we also found some items in CSL questions are redundant. By removing the items with low factor loadings from the original 49 survey items, 15 items were extracted and re-categorized into new dimensions of Willingness, Awareness, and Technology fluency (**Table 1**), referring to the willingness to be educated and trained as contributors, the awareness of earthquakes and disaster prevention, and the self-efficacy on technical proficiency. The reliability can be indicated by Cronbach's alpha that is commonly used to evaluate the internal consistency of the measurements within the same dimension. The value of higher than 0.7 and lower than 0.5 represent acceptable and unacceptable reliability, respectively. Here the alpha is calculated to be 0.756, 0.778, and 0.858 for Willingness, Awareness, and Technology fluency, respectively. The modified CSL model is now embedded in the

TABLE 1 | Items of citizen seismological literacy survey.

CSL dimensions	Sample survey items
Awareness	I often take part in the community outreach for disaster prevention and preparedness
	When the earthquake occurs, I attempt to search for earthquake info due to the potential impact from aftershocks and other natural hazards that may come together.
	I think that citizen scientific literacy is important
	I would like to help with the community outreach plan for disaster prevention and preparedness
	Everybody should be involved with the community plan for disaster prevention and preparedness
Technology fluency	I usually use the computer
	My smart phone and computer can act as the earthquake detector.
	I am familiar with the cloud technology (e.g., social media, cloud service)
	I usually use mobile devices (e.g., laptop, smartphone, iPad)
Willingness	I usually surf the internet to look for answers
	The science education activities provided by the community help me to improve my teaching and scientific literacy
	If possible, I'd like to help such community learning activities
	I love to take part in the community-based education activities
	If possible, I'd like to be trained as seed teacher in community education activities
	The modern technology allows me to upload the recorded seismic data when an earthquake occurs

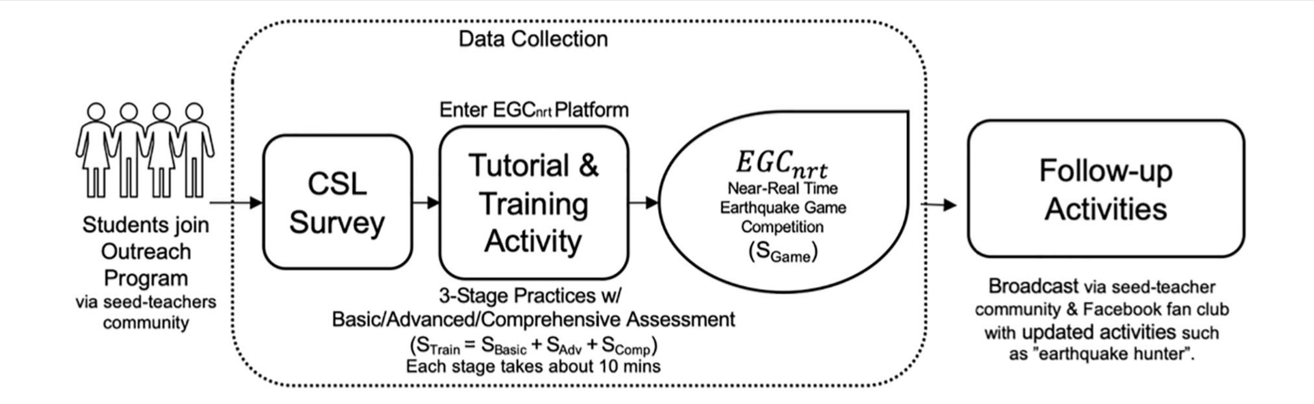
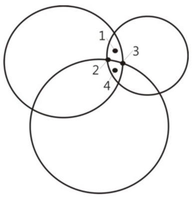
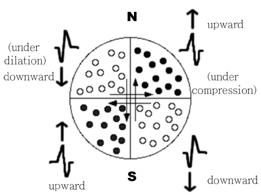
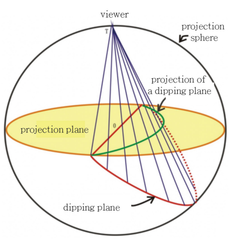


FIGURE 6 | Flowchart of a 1.5 h long EGCnrt program at schools. This program is composed of CSL survey, training activity (four certificate games), and near-real time earthquake game competition. The tutorial in training activity only takes 5 min for introducing the structure and function of the EGCnrt platform.

TABLE 2 | Items in each section of training activity (certificate game).

Section	Items
Basic knowledge (total score = 3) 	1. For a given station, when the P- and S-arrivals are picked for, the circle appears on the map. What does the size of the circle mean? (1) magnitude of earthquake (2) distance between earthquake and station (3) how far the seismic energy can travel. 2. In theory, earthquake occurred at the point where three circles intersect. However, which point you would choose in the practice if the intersect looks like the figure below? 3. In this game the circle can be enlarged or reduced through a function called "velocity parameter." This is because the real speed at which a seismic wave travels to the station is different from the default. Presumably, when you increase the velocity parameter you increase the travel speed. In this case the circles (1) become bigger (2) become smaller (3) remain the same.
Advanced knowledge (total score = 3)	4. What is the main difference between earthquake magnitude and intensity (1) The magnitude can only go up to 7.0 (2) Seismic intensity does not have a unit (3) The location of max. intensity always corresponds to the epicenter (4) Magnitude defines how much energy is released, the value remains the same at different places. 5. The max. amplitude of a seismogram tells us the peak ground motion. In the certificate game, you learned that max. amplitude is NOT controlled by (1) travel distance (2) magnitude (3) particle motion of waves. 6. In this certificate game, you determine the magnitude using the relationship between magnitude, distance, and max. amplitude. However, at the different stations you obtained different magnitude due to (1) different seismometer at different stations (2) that the amplitude is not only controlled by travel distance and earthquake magnitude (3) different elevation for different stations.
Comprehensive knowledge (total score = 3)  	7. If the fault ruptured to the surface, the direction of fault trace (as a line) relative to North is referred as faults strike. The fault trace could be indicated by two straight lines in the figure – either strike N-S or E-W. When the area is compressed during the fault motion (coinciding with the direction of arrows), the P first motion detected is "upward" motion as illustrated by filled circles. On the other hand, dilation coincides with "downward" first motion. Judging from the direction of motion (arrows), the fault is (1) N-S striking, right-lateral (2) N-S striking, left-lateral. 8. Following the above question, the fault could be also (1) E-W striking, right-lateral (2) E-W striking, left-lateral. 9. Through stereographic projection, the fault plane (area encircled by red line) can be projected into an equatorial plane (yellow area) as the green line. This green line is a projection of a fault plane with a dip angle of 45°. If the fault plane has a steep angle of 70°, the projected line will be located to the (1) right or (2) of the current green line.

EGCnrt game, which allows us to collect and analyze the players' demographical information, pre-knowledge of seismology, and personality self-portraits.

In addition, we found that the most efficient learning happens when the participants are engaged in a competitive environment without *a priori* introduction of seismological background, indicating that the EGCnrt itself can be treated as self-learning tool. Despite the excellent learning progress through the EGCnrt, the degree of willingness of the participants to use EGCnrt in their own classrooms is found to be low. The feedback gathered in the individual interviews reveals the lack of confidence in teaching the earthquake science behind the game. The barriers for the teachers to make EGCnrt (with six teachable units) useful in the classroom mainly come from the limited teaching hours in Earth Sciences. In the exam-oriented education system of Taiwan, all the teaching hours are divided into five topics including astronomy, oceanography, atmospheric sciences, geology, and geophysics. The teachers often find it impossible to arrange additional hours to run all the teaching units associated with EGCnrt. We therefore changed our target audiences from teachers to students.

PHASE IV: EGCNRT PROGRAM IN SCHOOLS AND THE IMPACT ASSESSMENT OF EARTHQUAKE GAME COMPETITION

The outreach activities called EGCnrt program were initiated by an online registration system that allows the host teachers to sign in and arrange the time for the EGCnrt program in their classrooms. In summer 2016, we visited 12 schools selected by geographical diversity to run the pilot teaching. We reached 406 citizen seismologists (hereafter referred as players) who successfully participated in the game. Based on the experience in the previous workshops with teachers, the outreach activities were designed to facilitate the learning and thinking. As illustrated by the flowchart in **Figure 6**, the students are assigned to fill

TABLE 3 | Pearson correlations among competition scores and CSL.

		Sgame	Strain	SBasic	SAdv	SCom	CSL
SGame	Pearson Correlation **(r)**	1					
	Sig. (2-tailed) **(p)**						
	N	411					
Strain	Pearson Correlation **(r)**	0.121*	1				
	Sig. (2-tailed) **(p)**	0.015					
	N	404	406				
SBasic	Pearson Correlation **(r)**	0.072	0.754**	1			
	Sig. (2-tailed) **(p)**	0.148	0.000				
	N	404	406	406			
SAdv	Pearson Correlation **(r)**	0.098*	0.805**	0.454**	1		
	Sig. (2-tailed) **(p)**	0.049	0.000	0.000			
	N	404	406	406	406		
SCom	Pearson Correlation **(r)**	0.110*	0.791**	0.364**	0.446**	1	
	Sig. (2-tailed) **(p)**	0.027	0.000	0.000	0.000		
	N	404	406	406	406	406	
CSL	Pearson Correlation **(r)**	0.011	0.048	0.069	0.037	0.011	1
	Sig. (2-tailed) **(p)**	0.817	0.335	0.167	0.452	0.827	
	N	411	406	406	406	406	425

**Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed). In the total number of 425 samples, 14 and 19 went missing due to incorrect coordination with EGCnrt activity and training activity, respectively.*

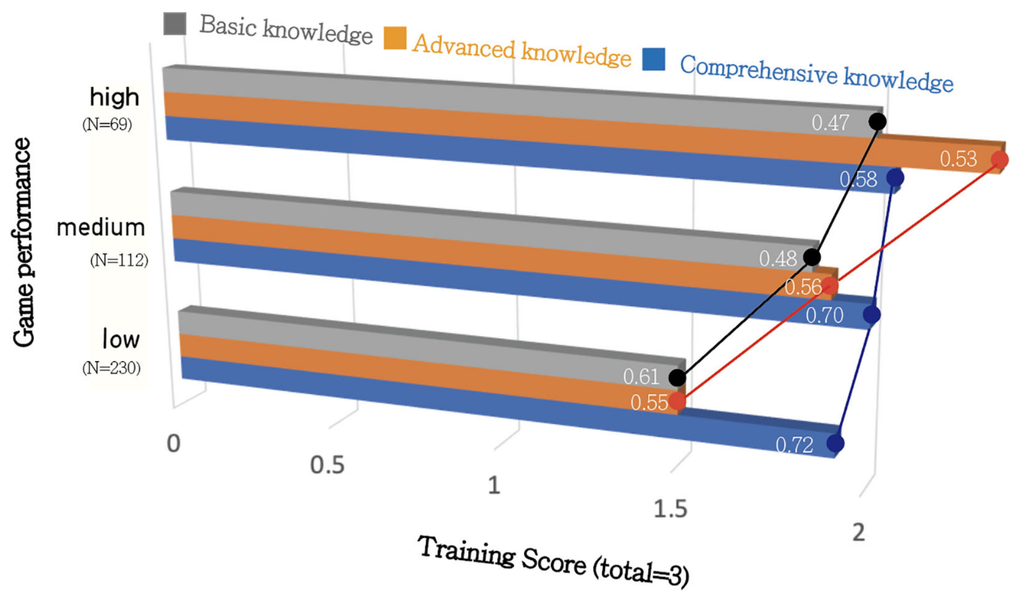


FIGURE 7 | The relationship between training score and EGCnrt game performance. The number of students belonging to groups of low, medium, and high performance in EGCnrt is 230, 112, 69, respectively. In the total number of 425 samples, 14 went missing due to incorrect coordination. The number within each horizontal bar represent the coefficient of variation (the ratio of standard deviation to the mean).

out the CSL survey before entering EGCnrt platform. The 1.5 h long EGCnrt program is composed of half an hour training activity and 1 h EGCnrt activity, as detailed in sections Training Activity (Certificate Game) and EGCnrt Activity.

Training Activity (Certificate Game)

The training activity requires the students to complete the four levels of certificates without lecture. A 5 min tutorial allows the students to (1) login to the system, (2) briefly understand the structure of this platform, and (3) learn how to view and process the seismic signals. Once they successfully got the certificates, nine questions will appear on the screen for bridging the game to some basic earthquake knowledge. Different from CSL, these questions are strongly tied with the knowledge behind the game. They can be classified into three sections: basic, advanced, and comprehensive knowledge. The three questions in each section are listed in **Table 2**. When the three questions

TABLE 4 | Relationships between CSL groups and game performance.

	Low CLS (cov) (*N* = 37)	Medium CSL (cov) (*N* = 170)	High CSL (cov) (*N* = 204)
Sgame	17.77 (0.75)	25.94 (0.94)	24.78 (0.85)

cov represents the coefficient of variation.

are completed after each section, the correct answers will be displayed on the screen.

The section of basic knowledge (S_{Basic}) refers to the recognition of the P and S first arrivals and their association with earthquake location, which is listed in high school curriculum. The section of advanced knowledge (S_{Adv}) refers to an understanding of the relationship between maximum amplitude of seismogram and seismic intensity/earthquake magnitude. Although not listed in the high school curriculum, this concept introduced in this section is straightforward. The section of comprehensive knowledge (S_{Comp}) refers to the determination of fault plane solution using first motion of seismic waves, which requires an integration of seismic source and slip on the fault. It is a section bringing a new concept associating P wave radiation pattern and stereographic projection. The total score in this training activity (S_{train}) is 9, as $S_{Train} = S_{Basic} + S_{Adv} + S_{Com}$. Our experience shows that during the activity, getting the certificates requires only learning a specific skill or set of steps rather than requiring a deeper understanding. The knowledge behind each skill is only introduced in the pop-out questions that requires critical thinking. From our observation, in each classroom there exists only a handful of students who asked questions associated with logical connection between the skill and knowledge. These active learners can be identified during the activity.

EGCnrt Activity

The following 1 h EGCnrt activity requires the skills learned in the training stage to compete with each other using real data. The total score of up to 100 (S_{Game}) is determined by the precision of the location of the epicenter, magnitude, and fault-plane solution. By examining the statistical significance of their correlation, we used Pearson Correlation to measure the linear association of two variables and k-mean clustering analysis to compare the difference between grouped variables.

Table 3 show the result of Pearson Correlation. We found that S_{Game} is better correlated with S_{Adv} and S_{Comp} than with S_{Basic}, as revealed by $r = 0.098$, $p = 0.049$ for S_{Adv}, $r = 0.11$, $p = 0.027$ for S_{Comp}, and $p > 0.05$ for S_{Basic}. Here r and p represent Pearson correlation and statistical significance (*p*-value, > 0.05 means no significant correlation). This suggests that the knowledge gained during the training activity reflect their performance in EGCnrt activity. The performance in EGCnrt activity is also categorized into three groups as low ($S_{Game} = 0$), medium ($0 < S_{Game} < 42$), and high scores ($S_{Game} > 62$) using k-means method, to compare with the scores in training activity. The k-means clustering method is commonly used due to its simplicity (MacQueen, 1967), which minimizes the distance between the cluster center and each point in the data set. As illustrated in **Figure 7**, it appears that the high score group in EGCnrt shows highest score in the training activity, which is consistent with the observation in **Table 3**. The increasing rate

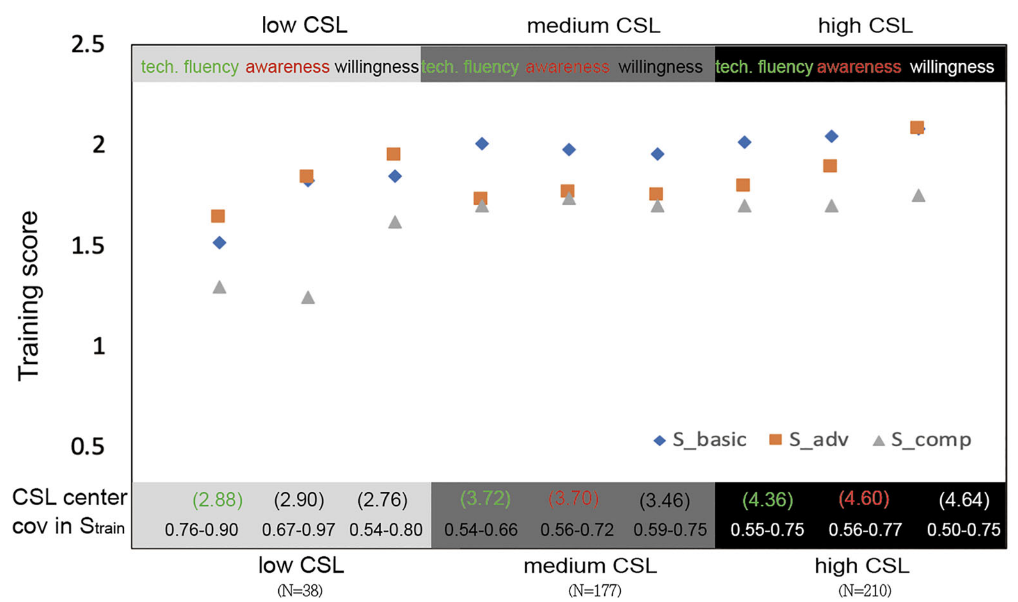


FIGURE 8 | The relationship between the training scores and CSL. Low, medium, and high CSL is now divided into three dimensions (Technology fluency, awareness, and willingness), to correlate with training score. The number of samples that belong to groups of low, medium, and high CSL is 38, 177, and 210, respectively. In the bottom, the numbers in the first row (within the brackets) denote the clusters center for individual CSL group using k-means. The numbers in the second row denote the range of coefficient of variation in Sbasic, Sadv, and Scomp.

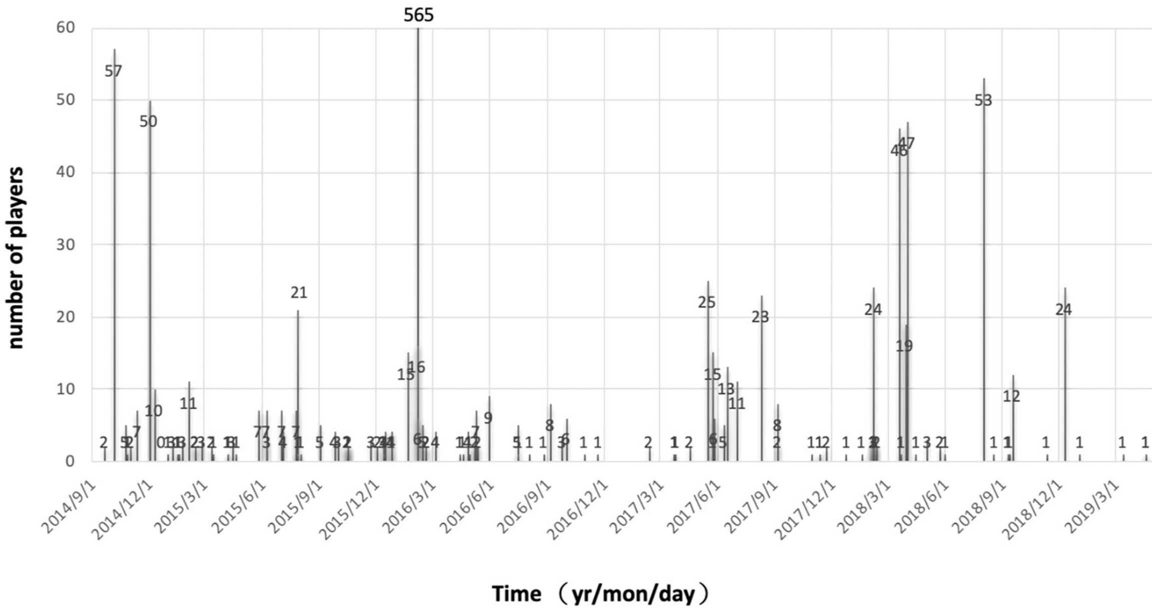


FIGURE 9 | Number of players for the *ML*≥4 inland earthquakes since September 2014. For the 2016/2/6 Meinong earthquake, the number of volunteers reaches 565.

tends to be highest in advanced knowledge (**Figure 7**), which could be due to the fact that the skill learned for S_{Adv} is heavily used in the EGCnrt activity. Note that the S_{Game} is computed and accumulated once enough of stations are processed to obtain the basic earthquake information of location, magnitude, and fault plane solution (minimum requirement is 15 stations). From our observation, the large number of $S_{Game} = 0$ happened when the students failed to stay focused on the EGCnrt activity. The coefficient of variation (cov) is a measurement of precision, smaller cov leads to greater precision. The cov of greater than 1 is considered to be high variance. In **Figure 7**, the largest cov (up to 0.82) appears in low game performance group, suggesting a less precise measure comparing with high and medium S_{Game} group.

Table 3 also shows the impact of EGCnrt on change in knowledge, attitude, and skill in earthquake sciences for students, as represented by CSL. The large *p*-value (0.167–0.827) indicates that the CSL does not reveal significant correlation with S_{Game} and S_{train}. When the CSL is categorized into three levels from low, medium, and high for computing the corresponding S_{Game} in **Table 4**, we found that the low CSL group tends to have lower S_{Game} comparing with high and medium CSL groups. If comparing with the training score using the same CSL groups, the medium and high CSL also tend to show higher training scores, while the difference between medium and high CSL appears to be very small (**Figure 8**). This indicates that the correlation between scores in the EGCnrt activity (S_{Game} and S_{train}) and CSL exists but is unlikely to follow a linear relation. Among three training sections, S_{Comp} and S_{Basic} reveal strong dependency with CSL level, as the training score denoted by blue and gray symbols significantly increases from low CSL to medium/high CSL. S_{Adv}, however, does not show such a tendency, implying that the core knowledge in S_{Adv} may not be discriminable between different level of CSL groups. The effect of different CSL dimensions on the performance in training activity can be also seen in **Figure 8**. We found that when learners' technology fluency and awareness increases, their performance and engagement in basic and comprehensive knowledge increases. The player's willingness may not play an important role in the performance in the training activity, as the training score stands high even for low-willingness. In summary, we found that CSL could be regarded as an important indicator that reflects the students' learning efficiency in seismology. Compared to willingness, technology fluency and awareness appear to play a more important role in the performance of training activity. The advanced knowledge gained during the training activity significantly correlates with the performance in EGCnrt activity, but no correlation with CSL scale is evident. This may be due to the fact that the advanced knowledge is relatively easy, so that even the low CSL group has fairly high training score. The coefficient of variation is found to be large (up to 0.97) in **Figure 8**, as a result of large cov in Scomp (gray triangles in low CSL group). Comparing with the dispersion in Sgame vs. Strain (**Figure 7**), the dispersion in CSL vs. Sgame (**Table 4**) and CSL vs. Strain (**Figure 8**) tends to be relatively large (up to > 0.90). This indicates that the association between CSL and training score/game performance is not as strong as the association between training score and game performance.

DISCUSSION AND CONCLUSION

By attempting to distribute the QCN in schools, the project of "Citizen Seismology in Taiwan" started with developing a near-real time earthquake game competition, followed by preparing the corresponding teachable units, and operating a series of

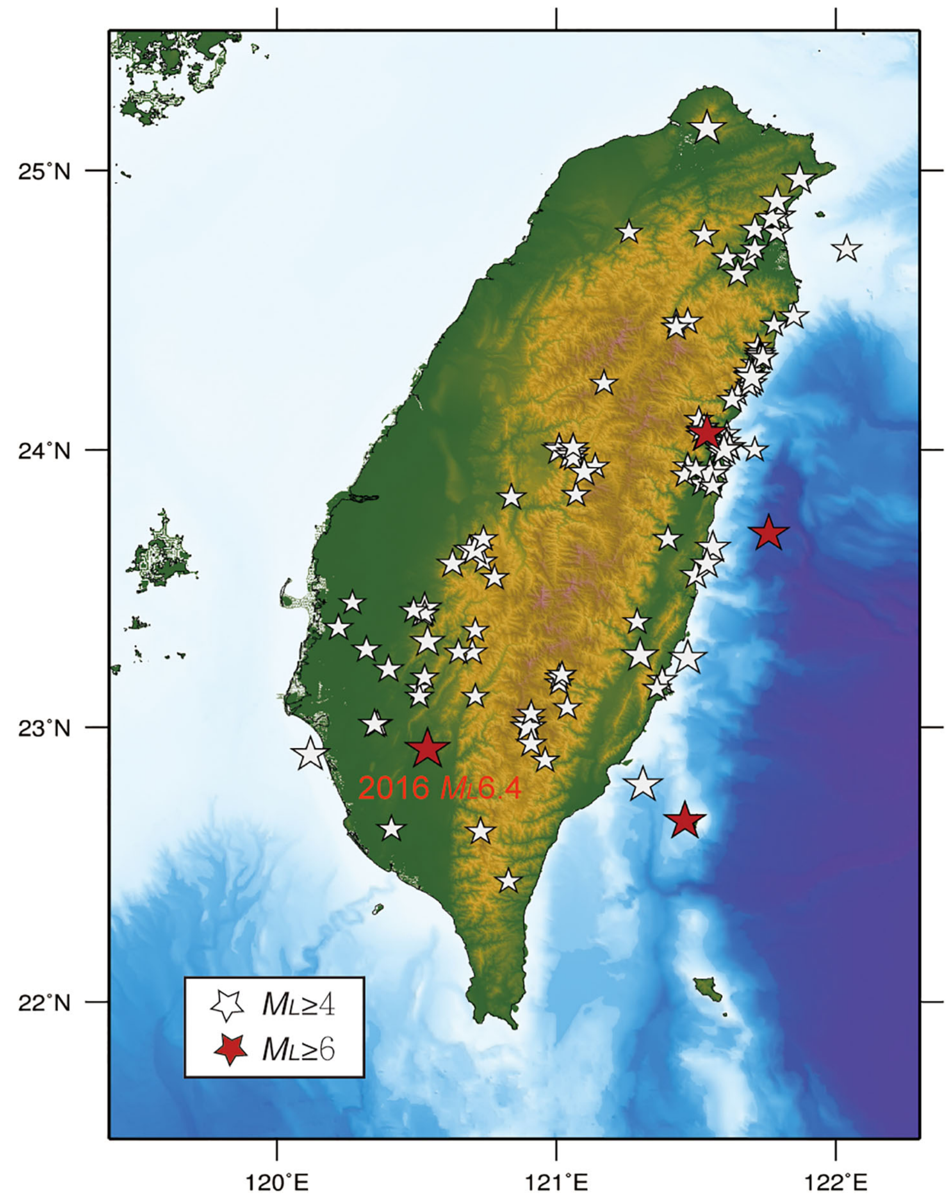


FIGURE 10 | Location of the $M_L > 4$ inland earthquakes in the earthquake game competition (the same events listed in **Figure 9**). White stars indicate events with magnitude greater than 4 but smaller than 6. Red stars indicate events with magnitude greater than 6.

outreach activities with formative assessment. The purposes are to encourage volunteers to interact with the real earthquake data and improve learning outcomes in earthquake science. Through professional development workshops with teachers, we found that teachers tend to lack confidence to run EGCnrt in their own classrooms. The barriers are mainly from the limited teaching hours in Earth Sciences (required course). In the exam-oriented education system in Taiwan, the teaching hours in high school are split into the five core knowledge units of astronomy, oceanography, atmospheric sciences, geology, and geophysics. The teachers often find it impossible to arrange additional hours to run all the teaching units associated with EGCnrt. Therefore, other than collaborating with primary and secondary educators (Liang et al., 2017), we also conducted pilot teaching in high school classrooms. Up to 2019, the total number of players reached 1319 since the EGCnrt was first online in late 2014. The time evolution of the number of players for all $M_L \geq 4$ earthquakes on inland regions of Taiwan is shown in **Figure 9**. The corresponding location of earthquakes is shown in **Figure 10**. The largest number of players, 565, is reached for the 2016 *ML*6.4 Meinong earthquake, which is reinforced by a series of pilot courses intensely conducted during the summer of 2016 (as detailed in section 5), several months after the Meinong mainshock. Although the top-three players are announced real time on the EGCnrt platform and rewarded, only 23 out of 425 players who joined the 2016 summer outreach activities came back to the EGCnrt, to challenge with more earthquake data. These 23 players have an average score of 2, 1.96, and 1.96 for S_{Basic}, S_{Adv} and S_{Comp}, respectively, which are classified into the "high" performance in training activity illustrated by **Figure 7**. This again confirms the strong connection between the performance in training and EGCnrt activities. However, so far the number of players who returned to EGCnrt (outside the classroom) is too small to show a statistically meaningful trend in their CSL scale. In the future, more outreach activities are needed to investigate the personal characteristics for this group of volunteers. It is worthwhile to further study whether the long-term engagement is associated to the attributes proposed for CSL (e.g., awareness technology fluency, and willingness). To increase the return-rate and facilitate the long-term engagement, follow-up activity is necessary (**Figure 6**). We strongly encourage the host teachers/schools to run a "earthquake hunter" competition. For example, hunt for a major earthquake archived in the EGCnrt platform to report how much we know about this event. The nationwide competition with a strategic reward system can be expected as well to raise the public awareness to the EGCnrt platform.

Different from the traditional classroom, the EGCnrt program allows that students interact with each other across the room by discussing the skills needed in the activities and helping each other to get the certificates in training stage. From our observation, the most active discussion occurred when the questions appear on the screen after completing the certificate game(s) in each section. The students often asked around for the meaning of the questions and their connection with the certificate game(s). While the EGCnrt scores and ranking are shown online, a fun and competitive atmosphere can be naturally formed where the players attempt to outdo others and put each other into good humor. With such competition and lighter moments in class, the concentration in EGCnrt usually lasted longer than 30 mins. The host teachers were encouraged to participate in the activity as the observer. The interviews with the host teachers were conducted during and after the activity to learn (1) how do they teach earthquake science in the classroom, (2) what is the general behavior of students toward learning, (3) what is the problem encountered in teaching earthquake science, (4) how do the students behave differently when the competition platform is introduced in the classroom. Based on their observations, those players who showed excellent performance in EGCnrt (i.e., frequently helped others and attempted to understand the meaning of each game) are found to generally achieve low academic grades. Such an observation implies that the EGCnrt program has potential to foster learning and behavioral changes for the students who are less motivated in a traditional instruction classroom. In fact, mounting evidence has supported that the game-based elements in learning activities improve the learners' motivation and engagement in educational environment (Dichev and Dicheva, 2017; Chen et al., 2019; Herrera et al., 2019). In this study, we present a game-based approach that uses real seismic data on an online digital platform, to extract information from students and assess the learning outcomes. This approach is composed of (1) pre-class Citizen Seismology Literacy (CSL) survey (2) half hour training activity with formative assessment (3) 1 h near-real time earthquake game competition (EGCnrt). Through statistical analysis, the above three elements are found to correlate with each other. We found that students with high CSL tend to have higher scores in game performance and training activity (especially for basic and comprehensive knowledge), however, such correlation does not follow a linear pattern. The score in the training activity is found to be more strongly correlated with performance in the EGCnrt, whereby the most significant factor is advanced knowledge. Such a result suggests that the CSL survey has potential to act as an indicator for the learning outcomes in seismology, while training program may efficiently improve the students' performance in EGCnrt activity. In the near future, it is worthwhile to develop more dedicated CSL dimensions that might better depict the long-term engagement in citizen seismology throughout the programs and activities we offer.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements (Center for Research Ethics and Research Ethics Committee in National Taiwan Normal University). The written consent was not required to participate in this study in accordance with the national legislation and the institutional requirement.

AUTHOR CONTRIBUTIONS

W-TL developed the platform of near-real time earthquake game competition (EGCnrt) and maintained the QCN in Taiwan, while LW developed the Citizen Seismology Literacy. C-HL carried out the formative assessment. KC conducted the EGCnrt outreach activities in high schools and wrote the manuscript.

FUNDING

Support for this work was provided by MOST grant 108-2116-M-003-006-MY3 and 108-2511-H-033-003-MY2.

REFERENCES

Allen, R. M., Kong, W., and Martin-Short, R. (2019). The Myshake platform: a global vision for earthquake early warning. *Pure Appl. Geophys.* 177, 1699–1712.

Bossu, R., Laurin, M., Maze-Roux, G., Roussel, F., and Steed, R. (2015). The importance of smartphones as public earthquake-information tools and tools for the rapid engagement with eyewitnesses: a case study of the 2015 Nepal earthquake sequence. *Seismol. Res. Lett.* 86, 1587–1592.

Bossu, R., Mazet-Roux, V., Douet, S., Rives, S., Marin, S., and Aupetit, M. (2008). Internet users as seismic sensors for improved earthquake response. *EOS Trans.* 89, 225–226.

Bossu, R., Roussel, F., and Fallou, L. (2018). LastQuake: from rapid information to global seismic risk reduction. *IInt. J. Dis. Risk Reduct.* 28, 32–42. doi: 10.1016/J.IJDRR.2018.02.024

Chen, C. H., Law, V., and Huang, K. (2019). The roles of engagement and competition on learner's performance and motivation in game-based science learning. *Educ. Technol. Res. Dev.* 67, 1003–1024.

Cochran, E. S., Lawrence, J. F., Christensen, C., and Jakka, R. (2009). The quake-catcher network: citizen science expanding seismic horizons. *Seismol. Res. Lett.* 80, 26–30.

Dichev, C., and Dicheva, D. (2017). Gamifying education: what is known, what is believed and what remains uncertain: a critical review. *Int. J. Educ. Technol. High Educ.* 14:9. doi: 10.1186/s41239-017-0042-5

Earle, P., Guy, M., Buckmaster, R., Ostrum, C., Horvath, S., and Vaughan, A. (2010). OMG earthquake! Can Twitter improve earthquake response? *Seismol. Res. Lett.* 81, 246–251.

Goldstein, P., Dodge, D., Firpo, M., and Minner, L. (2003). "SAC2000: Signal processing and analysis tools for seismologists and engineers, Invited contribution," in *The IASPEI International Handbook of Earthquake and Engineering Seismology*, eds H. WHK Lee, P. C. Kanamori, and J. C. Kisslinger (London: Academic Press).

Guy, M., Earle, P., Ostrum, C., Gruchalla, K., and Horvath, S. (2010). Integration and dissemination of citizen reported and seismically derived earthquake information via social network technologies. *Lect. Notes Comput. Sci.* 6065, 42–53.

Herrera, R. F., Sanz, M. A., Montalban-Domingo, L., Garcia-Segura, T., and Pellicer, E. (2019). Impact of game-based learning on understanding lean construction principles. *Sustainability* 19:5294.

Huang, K. C., Kao, H., and Wu, Y. M. (2000). "The determination of ML – MW in Taiwan," in *Proceedings of the 8th Annual Meeting of Geophysical Society of China*, Oxford 193–201.

Kong, Q., Allen, R. M., Schreier, L., and Kwon, Y. W. (2016). MyShake: a smartphone seismic network for earthquake early warning and beyond. *Sci. Adv.* 2:e1501055. doi: 10.1126/sciadv.1501055

Lee, S. J., Liang, W. T., Cheng, H. W., Tu, F. S., Ma, K. F., Tsuruoka, H., et al. (2013). Toward realtime regional earthquake simulation I: Real-time moment tensor monitoring (RMT) for regional events in Taiwan. *Geophys. J. Int.* 196 432–446. doi: 10.1093/gji/ggt371

Liang, W. T., Chen, K. H., Wu, Y. F., Yen, E., and Chang, C. Y. (2016). Earthquake school in the cloud: citizen seismologists in Taiwan. *Seismol. Res. Lett.* 87:1. doi: 10.1785/0220150061

Liang, W. T., Lee, J. C., Chen, K. H., and Hsiao, N. C. (2017). Citizen earthquake science in Taiwan: from science to hazard mitigation. *J. Disaster Res.* 12, 1174–1181. doi: 10.20965/jdr.2017.p1174

MacQueen, J. B. (1967). "Some Methods for classification and Analysis of Multivariate Observations," in *Proceedings of 5-th Berkeley Symposium on Mathematical Statistics and Probability*, (Berkeley: University of California Press), 281–297. doi: 10.1504/ijdmb.2015.067955

Ministry of Education (2014). *Curriculum Guidelines of 12-Year Basic Education*. Available online at: https://cirn.moe.edu.tw/Upload/file/32077/83646.pdf (accessed December 1, 2019).

Seno, T. (1977). The instantaneous rotation vector of the Philippine Sea Plate relative to the Eurasian plate. *Tectonophysics* 42, 209–226.

Seno, T., Stein, S., and Gripp, A. E. (1993). A model for the motion of the Phillippine Sea plate consistent with NUVEL-1 and geologic data. *J. Geophys. Res.* 98, 17941–17948.

Wald, D. J., Quitoriano, V., Worden, B., Hopper, M., and Dewey, J. W. (2011). USGS "Did you feel it?" internet-based macroseismic intensity maps. *Ann. Geophys.* 54, 688–707.

Wang, Y. J., Chan, C. H., Lee, Y. T., Ma, K. F., Shyu, J. B., Rau, R. J., et al. (2016). Probabilistic seismic hazard assessment for Taiwan. *Terr. Atmos. Ocean. Sci.* 27, 325–340. doi: 10.3319/TAO.2016.05.03.01(TEM)

Wu, Y. M., Chen, D. Y., Lin, T. L., Hsieh, C. Y., Chin, T. L., Chang, W. Y., et al. (2013). A high-density seismic network for earthquake early warning in Taiwan based on low cost sensors. *Seismol. Res. Lett.* 84, 1048–1054. doi: 10.1785/0220130085

Wu, Y. M., Liang, W. T., Mittal, H., Chao, W. A., Lin, C. H., Huang, B. S., et al. (2016). Performance of a low-cost earthquake warning system (P-alert) during the the 2016 ML6.4 Meinong (Taiwan) earthquake. *Seismol. Res. Lett.* 87, 1050–1059. doi: 10.1785/0220160058

Yu, S. B., Chen, H. Y., and Kuo, L. C. (1977). Velocity field of GPS stations in the Taiwan area. *Tectonophysics* 274, 41–59.

Conflict of Interest: The 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.

Copyright © 2020 Chen, Liang, Lin and Wu. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

ORIGINAL RESEARCH
published: 18 June 2020
doi: 10.3389/feart.2020.00180

A Case Study of Highly-Engaged Educators' Integration of Real-Time Seismic Data in Secondary Classrooms

Tammy Bravo[1]*, John Taber[1] and Hilarie Davis[2]

[1] *Incorporated Research Institutions for Seismology, Washington, DC, United States,* [2] *Technology for Learning Consortium, Stuart, FL, United States*

The Incorporated Research Institutions for Seismology (IRIS) Seismographs in Schools (SIS) program has supported teachers in the use of educational seismometers and real-time seismic data in the classroom for the past 20 years. To better understand how the seismographs and seismic data are being used in the classroom, we sent a survey to 770 past or current program participants. The survey asked about their seismometer, seismic data use, software use, the impact of seismic data on their classroom, and what additional seismology-related resources or instruction they provide to their students. Four highly-engaged teachers were then recruited from this larger pool for a case study. The purpose of this study was to better understand these highly-engaged teachers, their experiences with seismic instrumentation, software, and data in the classroom, how and to what degree seismic data has impacted their curriculum and instruction, and their perceptions of the impact of the SIS program on their students' understanding of Earth Science concepts. The case study results show that each of the highly-engaged teachers values data driven instruction, instrument science, and the integration of seismic data into the classroom more than just during their earthquake units. They have made it part of everyday class activities by having students be aware of data coming in, noting earthquakes in the news, and helping students learn more about analyzing data for advanced investigations. While there were differences in their implementations, in all cases a critical feature of their engagement with students was use of a variety of seismology-related resources which connected the seismic data to the rest of the curriculum. Thus, the use of seismic data was just one component of their seismology-related teaching. This study also highlights the value of a local sensor, as all four highly-engaged teachers stressed that students as stewards of the seismometer linked them to the science in an engaging and dynamic way. Thus, while the highly-engaged teachers had a primary responsibility to promote learning, their focus on student engagement is also helping to create young citizen scientists.

Keywords: educational seismology, seismographs in schools, educational seismographs, classroom data analysis, Earth science education

OPEN ACCESS

Edited by:
Remy Bossu,
European-Mediterranean Seismological Centre, France

Reviewed by:
Laure Fallou,
European-Mediterranean Seismological Centre, France
György Hetényi,
Université de Lausanne, Switzerland

Correspondence:
Tammy Bravo
tkb@iris.edu

Specialty section:
This article was submitted to Solid Earth Geophysics, a section of the journal Frontiers in Earth Science

Received: *09 March 2020*
Accepted: *07 May 2020*
Published: *18 June 2020*

Citation:
Bravo T, Taber J and Davis H (2020) A Case Study of Highly-Engaged Educators' Integration of Real-Time Seismic Data in Secondary Classrooms. Front. Earth Sci. 8:180. doi: 10.3389/feart.2020.00180

INTRODUCTION

The Incorporated Research Institutions for Seismology (IRIS) have supported low-cost seismic systems in schools for over 20 years through the Seismographs in Schools (SIS) program. IRIS's SIS program serves teachers across the country and around the world using seismic instruments or real-time seismic data in kindergarten (age 5 years) through undergraduate (ages 19–22 years) classrooms. Additionally, our website (www.iris.edu/earthquake) includes tools to share seismic data in real-time, classroom activities, and technical support documents for seismic instruments. IRIS began the SIS program with the goal of increasing the quality and quantity of Earth science education in the classroom. While that is still the main goal of the program, the rapid advances of technology allowing easier access to real-time seismic data over the past 20 years have allowed the program to expand to reach a wider audience so that students and citizen scientists can be involved globally with or without access to a local seismograph. Since much of the US is not very seismically active, the focus of the program has been on the science and the recording of regional and distant earthquakes rather than promoting local seismic hazards awareness.

IRIS's early program (Braile et al., 2003) grew in collaboration with other educational seismology networks in the US, which included an effort to coordinate activities (Hamburger et al., 2001; Hamburger and Taber, 2003). Educational seismometers were distributed to classrooms across the country after teachers participated in training workshops that included two full days of training about the instrument, seismic data, and seismology concepts. In subsequent years, the distribution of instrumentation expanded to seismographs operating in such venues as libraries and other public places, as well as supporting citizen scientists who operate seismographs privately. Collaborations with international educational networks [e.g., Denton (2008)] also developed during this time. As the program expanded with increased participation, IRIS realized the limitation of requiring an instrument to participate as not all teachers were equipped or interested in operating an educational seismometer or meeting the challenges of equipment maintenance. IRIS believed students could experience the benefits of working with seismic data if we could facilitate easy sharing of data, initially between educational stations and then expanded to sharing real-time research station data. IRIS's focus has slowly shifted to support transferrable data manipulation and analysis skills as part of the process of science. Through software development and data storage and transfer enhancements that built on the original Amaseis software (Jones et al., 2003), IRIS's educational software jAmaSeis (www.iris.edu/hq/jamaseis; Drago et al., 2009) allows teachers to operate an educational seismometer locally and share data, as well as to view and manipulate data from over 3,500 global research quality seismic stations that stream data to the IRIS Data Management Center. The original design goals for the software were to provide an operating system-independent way for schools to display and analyze data from a local sensor, and to compare their data to other educational seismographs. As the software became more widely used, ability was added to be able to stream data from research stations and a wider variety of educational and citizen science sensors.

The types of educational seismometers available on the market has increased since the early days of the program, allowing a growth in the models employed by programs and users. Empirically however, programs often followed a consistent path: steady growth and excitement, plateau of station numbers, and then difficulty maintaining station operation and encouraging interactions/collaborations between stations. As the IRIS SIS network grew, the challenges to support and mentor the growing network became apparent. Regional networks, often with a University lead, became models of success keeping teachers engaged and instruments operating. In summarizing the European experience in educational seismology, Zollo et al. (2014) identified the scientific support and relationship between teachers and researchers as a key to success. However, in the US, calls to action for seismologists to provide support for local teachers often went unanswered, and we learned that while we had a number of exceptional individuals leading regional school networks [e.g., Kafka et al. (2006), Kafka and Fink (2019)], leadership in new areas was not something we could easily recruit.

An inventory of the current status of seismic stations in schools across Europe was completed in 2011 and revealed "many 'wrecks' of former seismic stations, web pages and e-learning experiments" (Zollo et al., 2014). This was also true in the US. After a decade of distributing educational seismometers and training teachers across the country, the US network was struggling with issues of equipment failure or damage, teacher turnover, and the difficulty of retraining new teachers who inherited instruments. What remained consistent was the presence of a small group of successful highly engaged users, which we will refer to as superusers, who have been with the program for many years. These superusers integrate the use of their seismograph and seismic data into their science curriculum in a manner which is far beyond how the typical teacher (from our experience) treats seismology-related topics. In some cases, they have relocated and reinvented their implementations, but they have remained the most visible success stories, examples of the goals that the program is striving to achieve.

The purpose of this study was to better understand these superusers, their experiences with seismic instrumentation, software, and data in the classroom, how and to what degree seismic data has impacted their curriculum and instruction, and their perceptions of the impact of the SIS program on their students' understanding of Earth Science concepts. Our goal was then to attempt to determine characteristics and situations in common across the superusers that supported the long-term successes they have had engaging their students. This information can then be used by our program and other programs to help other teachers be more successful in their use of seismic data with students.

FIGURE 1 | Geographical distribution of zip codes of survey respondents. Map data: Google.

ONLINE SURVEY AND CASE STUDY DESIGN AND METHODS

In 2019, an 11-question survey including multiple choice, Likert-style, and free response questions, was sent to 770 SIS program participants who were currently or had been registered users in the IRIS SIS database. The survey asked about their educational seismometer, seismic data use, software use, the impact of seismic data on their classroom, and what additional seismology-related resources, or instruction they provide to their students (Davis and Bravo, 2020). There were 92 respondents to the survey request geographically distributed between the US and the UK (**Figure 1**). Descriptive statistics were calculated for closed-ended items. Open-ended items were coded using discourse analysis (Gee, 2010).

Four superuser teachers were then recruited from this larger pool for the case study (Stake, 1978), based on their long-term connection to the SIS program as innovative engaged users. Since the IRIS SIS program is based in the US, only US teachers were considered for the case study. The criteria for being considered a superuser included being employed as a teacher, having eight or more years of experience operating educational seismometers, and having regularly used seismic data from educational seismometers in formal classroom instruction. Each superuser took part in an individual ∼ 60-min semi-structured interview conducted via the telephone or skype regarding their experience in the SIS program, how they have used seismic data and the educational seismometer in the classroom, and the effect on their curriculum and students. After the interview, interview notes were summarized and emailed back to the superuser for review and clarifications as needed. The interviews were conducted by an outside evaluator who created subject reports from those interviews. Superusers signed informed consent forms and were not compensated for their participation and were happy to contribute to a better understanding of their integration of seismic data and instrumentation into the classroom.

ONLINE SURVEY RESULTS

About half of the respondents (47%) teach grades 9–12 (ages 14–17), 27% teach 6–8 (ages 11–13), 11% teach K-5 (ages 5–10), 11% teach undergraduate (ages 18–22), and 5% teach graduate school (ages 22+). Key results from the survey include:

- The sources of seismic data teachers use are their classroom seismometer (57%), jAmaSeis (51%), USGS (34%), other (21%), IRIS SIS website (18%), and IRIS DMC (11%).
- Teachers use seismic data in different ways: show the data to the class after an earthquake (83%), use the data to discuss earth science topics (73%), plot recorded earthquakes on a map (45%), encourage students to work with seismic data (42%), calculate distance (40%). calculate magnitude of at least 1 earthquake (28%), and other (21%).
- Teachers report high impact of seismic data on student subject knowledge on a scale of 1–10, with one being no impact and 10 being very high impact (8.2/10), on student learning (8.0/10), and on the quality of their curriculum (8.2/10).
- Teachers would recommend seismic data to another teacher as worthwhile for having students learn to: recognize earthquakes in streaming jAmaSeis data (77%), use jAmaSeis to look at an earthquake (79%), and upload and share data through the SIS website (61%).
- Teachers responded that they would like more instruction on using jAmaSeis (63%), seismometer hardware (61%), how to calculate the magnitude of a recorded earthquake (58%), how to locate the epicenter of a recorded earthquake (49%),

advanced data analysis (46%), information about earthquakes they record (41%), how to determine if a recording is an earthquake (38%), and other (21%) such as calibration instructions, more filtering options, replacement parts, lesson plans for Mars seismic data, how to calculate depth of focus.

Overall, the feedback from this survey came from only 12% of our network, which was disappointing considering this is a dedicated community of users bonded by training and equipment. However, in hindsight the single survey invitation was sent in an email that also contained other news items which could have resulted in it being overlooked. Additionally, delivery failed to 15% of the email addresses we had on file, highlighting the turnover in the program. Those that responded spanned a wide range of grade levels, and even with such a wide age range of students, teachers indicated varied use of seismic data in the classroom and overwhelmingly valued its contribution to their classroom and students. However, only half of those that responded are using our jAmaSeis software and less than half encourage students to work with the data. Thus, there appear to be limitations for some teachers in the use of real seismic data in the classroom, which led us to interview our superusers to try to identify approaches we could employ ourselves or recommend to teachers to increase student engagement.

THE SUPERUSER INTERVIEWS

Our four superusers were all male US school teachers with an average of 12 years participating in our SIS program. Their interviews described below explored their experiences with integrating educational seismology into their classrooms. All of their schools except for western US school near the San Andreas Fault are in regions of low seismic hazard. The percentage of students receiving free/reduced price meals is a means of estimating the socio-economic status of the students in the school. Across the US, ∼50% of public school students are eligible for free/reduced price meals.

SUBJECT 1: MIDDLE SCHOOL IN SUBURBAN MID-ATLANTIC REGION

This superuser heard about IRIS at the National Science Teaching Association's National Conference in 2008, signed up to receive a seismometer, and went to an IRIS run 2-days training workshop. The seismology background from the workshop is still useful and the superuser has gotten refreshers at conferences that IRIS attends. This school serves ∼800 students in grades seven and eight (ages 12 and 13), of which 14% are minority. Test scores at this school are above the state average. Six percent of students receive free/reduced price meals under the Federal School Lunch program. The addition of the seismometer to the classroom created opportunities for students to work with real-time seismic data.

> Eighth graders have a novice view of how science data is collected, used, and analyzed. We're trying to expand that. Having this device in the room, it's real science, so it's messy. Textbooks show perfect curves. Our actual data is messy. That's why seismologists look at multiple data sources. The world is messy—it's not always easy to know what you are looking at, that's important to know. It may be a mystery. You can't always have all the answers.

The seismograph is connected to the school's science network so data from the single instrument is shared with three other science teachers. To reach as many students as possible and the community, a seismogram for the last 24 h is fed to the school website and is updated every 10 min. Making this data available introduces all students to the frequency that earthquake occur.

> I start the plate [tectonics] lesson by showing where earthquakes are.

During the earthquake unit, students make use of seismic data from their educational seismometer. A few students are asked to extract data from previous earthquakes using jAmaSeis. The students then analyze the data by measuring the distance between the *P* and *S* waves and calculating the distance from their seismic station to the earthquake epicenter. Also, in the jAmaSeis software, students are able to use data for a single earthquake from three seismic stations to triangulate an earthquake location. This superuser also uses a number of hands-on curricular resources to explore earthquake concepts, including using the earthquake machine (Hubenthal et al., 2008), to show the buildup of stress leading to earthquake rupture. To demonstrate waves traveling through solids and liquids, 10 students line up with their arms rigid (solid) or slack (liquid) and feel the reaction when someone shakes the person on the end. Student teams also build earthquake towers, using balsa wood and weighted plywood floor plates to simulate the weight of concrete poured flooring, test them on a shake table, adjusting the width and height parameters of the tower based on the feedback from the tests. The addition of a seismometer to the classroom has afforded students multiple opportunities to work with data.

> We use data from the device to connect seismology to data collection and as a current event like weather systems. Snow and wind also affect the ground and the seismograph picks that up. Not a week goes by that we don't talk about it. I have telescopes, weather stations, but the seismometer is the coolest thing ever.

Students in environmental science classes are encouraged to monitor the seismogram and connect what is happening on the seismogram to reports in the news. The seismograph has real science data that is displayed directly to the students all the time. They are now doing a weekly video report for Channel 1 news. When there is a big earthquake, the superuser incorporates another IRIS product into the classroom, Teachable Moments (Bravo and Hubenthal, 2016), slide shows that contain interpreted USGS regional tectonic maps and summaries, computer animations, seismograms, press photos, and other event-specific information. This superuser also follows IRIS on twitter because it is "superb with a constant stream of information" and has reminders about classroom resources. This superuser reports that having the seismometer has helped

COUNCIL ROCK

Teacher applies earthquakes to classroom lessons

A seismograph in [redacted]'s classroom picked up the vibrations from the Haitian and Chilean quakes.

By RACHEL CANELLI
STAFF WRITER

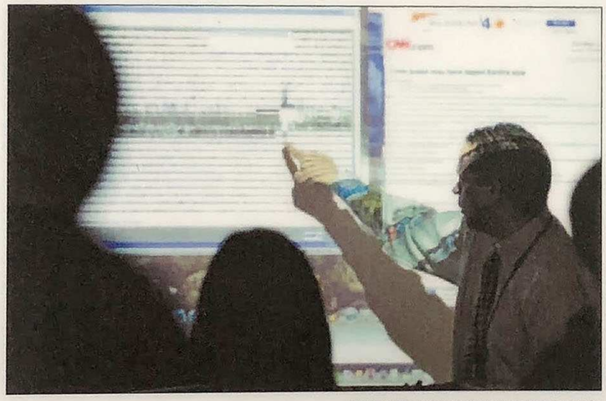
They were the quakes felt 'round the world.

When major tremors shook Haiti and Chile this winter, vibrations made their presence known as far away as Bucks County. A working electronic seismograph in a Council Rock classroom picked up both earthquakes.

So, [redacted], an eighth-grade earth and space science teacher at [redacted] Middle School, put his lesson about rocks on hold this week and shifted the focus to earthquakes to take advantage of the teachable moment.

"It really showed that something major had occurred," [redacted] said as he discussed the quakes' screen graphs, which were playing back in real time across a whiteboard. "Events around the world really do cause the ground to shake where we live … even if we can't feel it."

More than a year ago, [redacted] obtained training and the seismograph, which is an instrument that measures the motions of the ground, through a grant from the Incorporated Research Institutions for Seismology. Since 2000, the Institution has donated more than 200 of the mechanisms to schools across the country.



MATT STANLEY STAFF PHOTOGRAPHER

Teacher [redacted] goes over seismograph readings with students in his earth and space science class at [redacted] Middle School.

The seismograph can sense student movement, a truck driving by in the middle of the night, or even a bird flying into a window. Without that tool, [redacted] and his students wouldn't have known that the upheaval in Chile subtly moved their classroom — kind of like feeling someone walk by if you're sitting still.

"It's really neat that even though we're not there, we could still see and feel it," said 14-year-old Caitlin [redacted]. "It still involves us."

Like the ripple effect of a stone thrown into a pond, or a boat rising and falling on the ocean's waves, it took three hours before the [redacted] school's graph settled down. That's compared to the one hour it took after the Haitian shaking, said [redacted].

See **QUAKE,** Page **B4**

Quake

Continued from Page B1

Although the earthquake in Haiti was devastating, the Chilean trembling was 500 times as intense.

It actually caused the entire planet to ring like a bell, changed the Earth's rotation so much that the globe lost one-millionth of a second, and shifted the world's slightly tilted axis by three inches, he said.

While that probably doesn't seem like much right now, the Earth's tilt is what creates seasons, which could be affected over time, he added.

"It's nice to tie in what we're learning in science with current events, and to be able to understand the terms," said Adam [redacted], 13.

That's [redacted]'s ultimate goal — to apply science by finding it out in the world, in real life. And [redacted] said he knows that nothing captures kids' interest better than showing them how the very ground beneath their feet is shaking.

Rachel Canelli can be reached at 215-949-4191 or rcanelli@phillyBurbs.com.

FIGURE 2 | Example of local media coverage after large earthquakes (Haiti and Chile, 2010) for Subject One and their classroom seismograph display. Article from the Bucks County Courier Times used under a Creative Commons license.

students understand the structure of the Earth and that the Earth is actually moving underneath them. They talk to their parents about it. The local news came in and talked to the students as "local experts" when large earthquakes were in the news (**Figure 2**).

In addition to the classroom, the superuser has supported students wanting to go further with the seismic instrument and data. Over the years, a couple of students have done science fair projects on how their locally recorded data compares with USGS data. Working with the classroom seismometer has inspired students to want to build their own seismometer. One student has been trying to build one that uses a vertical slinky as the spring inside a clear plastic tube. They found the directions online for a design by Channel and van Wijk et al. (2013) that is in use by schools in the US and New Zealand and that the students learned had recorded a recent New Zealand volcanic eruption.

SUBJECT 2: ELEMENTARY SCHOOL ON THE WEST COAST

This technology education superuser received a seismometer in 2005 and has two working seismographs set up in an office off the library. This school serves ∼1,700 students in kindergarten

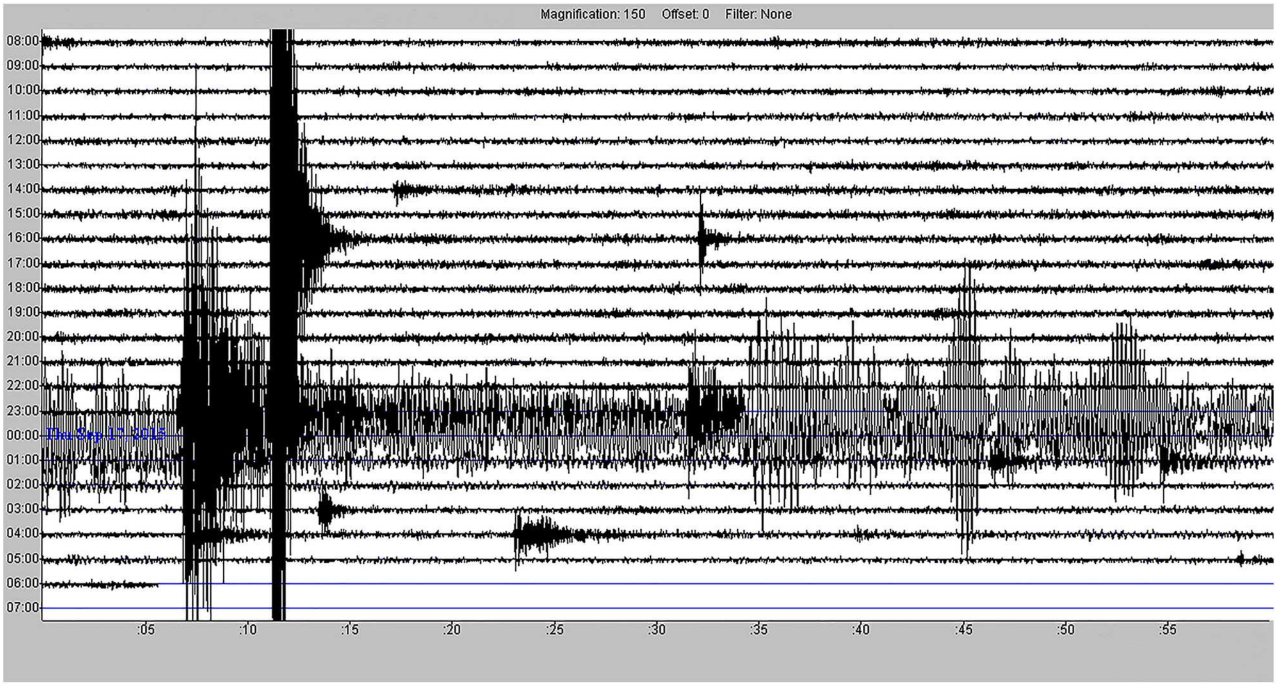


FIGURE 3 | Webicorder display of 24 h of recording from Subject Two's seismograph. The webicorder images are generated automatically by the jAmaseis software and displayed on the IRIS Seismographs in Schools website. This screenshot shows both local short-duration events and a large distant earthquake which generated ground motion at the sensor that was easily visible on the display for over 2 h.

through grade eight (ages five to 13). Minority enrollment is 53% of the student body. Students at this school perform about average on state tests. Fifty-three percent of students receive free/reduced price meals under the Federal School Lunch program. This school's two seismometers have a really clean signal and turn their gain way up so their data is coveted by a lot of other people since they are 17 miles from the San Andreas fault. One of the school counselors keeps an eye on the data from a public safety standpoint. The seismometers increase seismic awareness both in the school and the community.

> We know our data is being used because if there is a power outage the seismometer goes offline and people I don't even know email me to ask what's going on.

This superuser attended an IRIS Seismographs in Schools workshop at Cal State Northridge in 2007. They also keep up with new equipment and software, and noted that jAmaSeis was a big improvement in usability and reliability over the earlier AmaSeis software. The school has their software set up to feed the seismology data to their school website. Instructionally, there is a great deal of potential that is created with access to real-time data.

> We have a great school. I'd like to see more emphasis on data collection in real life in Earth science through operating things like a greenhouse and weather station, as well as our seismology station. I'm so turned on by the idea of kids and data. You can use math to do cool things. You can figure things out and they make sense logically. Another thing is the realization that by having the right tools, you can observe things that you can't observe with your senses. We look at squiggles that you can feel and that you can't feel. The idea is that you don't have to be at the center of the action to study it.

Seismology fits into the curriculum in 4th grade. This superuser has students come to the setup, see how the equipment works, then go online to see the data. They look at three locations and talk about why the earthquake shows up at different times in dispersed locations. They see how the hardware works to detect, amplify, and display seismic signals. In addition, students engage with physical activities to explore earthquake concepts. Using extralong Slinkys, students explore how waves behave. Students are also asked to think about runners running around a track at different speeds to simulate how different waves travel at different speeds and how to determine their starting point. With this background, these young students are able to work directly with seismic data. Students try to pinpoint where a quake happened by looking at the *P* and *S* wave arrival times and drawing a circle around them and two other locations to pinpoint where the earthquake originated. Students are also able to look at the traces to qualitatively see what the event was like (**Figure 3**).

> I say to students, "If you think you felt something locally, go to our site. It will look big—REALLY BIG. The seismograph trace would be so big that the top and bottom of the trace is flattened out. If you feel something and it doesn't show up, it is something else maybe a large truck passing by. Big events happen so seldom, and we haven't had any big events in SoCal in a long time. Not a day

> goes by that we don't see something on there though, sometimes even seismic swarms with 100 s of events.

Seismology helps students understand the Earth just like we can use X-rays and MRIs that see inside the body by having waves pass through it, the waves from an earthquake tell us what's inside the Earth. Having the seismograph helps increase the students' hazard awareness, as they regularly see local earthquakes on their seismograph, which connects them to their regional hazard.

> We have the Great California Shakeout every fall. The whole state at the same time pretends there is an earthquake to make sure the procedures and communications are in place (chain of command, chain of communication). Kids are aware we live in earthquake country but I don't't think they understand that we are "overdue." I think it brings it down to something that is more tangible and accessible to them. They don't remember the ones that did not happen in their lifetimes.

Outside the classroom, even at the elementary school level, seismology captured the interest of a student. A student was interested in what was causing a weak but sustained signal on the seismometers that was lasting around 5 min at fairly regular intervals. The student compared a train schedule to the recorded signal, determining the seismometers were recording train traffic from three miles away from the school.

SUBJECT 3: HIGH SCHOOLS IN THE US SOUTHWEST AND ASIA

This superuser said an IRIS run 2-day seismograph training at the University of Missouri in Kansas City in 2010 was great and allowed him to start on using seismic data with high school students. The Southwest US school serves ∼2,300 students in grades eight through 12 (ages 13 to 18), of which 99% are minority. Students at this school perform above average on state tests. Sixty-eight percent of students receive free/reduced price meals under the Federal School Lunch program. Students enjoy the challenges of working with real data—taking an earthquake, doing triangulation, looking at additional sources, even visiting an area and doing "felt reports" after a quake. In the Southwest, the superuser and a few students worked with a local university after a local earthquake to go into the field for 3 days going door to door in the most damaged areas to create intensity maps and identify the earthquake epicenter. The students who did the field work, then reported out to other students and the college researchers. Awareness of regional seismicity created this unique experience.

> It definitely gave them the skills to be able to do other data collection and analysis. They told me that the research they did on earthquakes made a huge difference in everything else they did.

In the classroom students worked extensively with seismic data. Students learned to recognize *P* and *S* waves, calculate travel-time, triangulate, determine location, and calculate magnitude, then look up USGS information. The superuser values the seismometer as an educational tool to teach a broad range of scientific concepts in subjects like physics and computer science at all grade levels. Incorporating seismic data in the classroom helped students realize the planet is in constant motion through processes like continental drift and plate tectonics, resulting in mountain building, ocean trenches, and mid-ocean ridges.

> The data opens a window to the world! It's not something they are reading in a textbook. It's tangible to the students. It's live, first-hand information. Working with data from jAmaSeis makes students feel like they are part of a larger science research community; that they are contributing to a meaningful endeavor.

The superuser is now in Asia at a STEM-focused international school serving ∼400 students in grades seven through 12 (ages 12 to 18). Tuition is required to attend this school, although there are some scholarships available. At this school his superuser has formed a seismology club. Through this work, students are beginning to understand how earthquakes occur, how they are studied, how they impact people and economies, and better construction techniques. Through IRIS they feel part of a worldwide community of people studying earthquakes. The students thought earthquakes did not occur in Thailand until their seismograph picked up an earthquake on the Laotian border. The students will go on a field trip to the university to the geology and engineering departments to learn more, then eventually do "felt reports" on nearby quakes. The students have studied peer-reviewed article reviews on recent earthquakes for the Pacific Rim to help them understand the geology of the region.

SUBJECT 4: MIDDLE SCHOOL IN SUBURBAN NEW ENGLAND

This superuser is teaching sixth grade Earth science at a school that serves 941 students in grades six through eight (ages 11–13), of which 21% are minority. Students at this school perform above average on state tests. Ten percent of students receive free/reduced price meals under the Federal School Lunch program. The seismograph, received in 2007, is set up in a quiet workroom, connected to a computer in the classroom. This superuser says students are always very engaged with the seismograph data, figuring out what they are seeing, and what it means. Students learn transferable skills like using latitude and longitude to identify places and map them. In mathematics, the GPS vector gives them an understanding of coordinate graphs. This transfers to the study of weather, where they look at relationships in the data of temperature and relative humidity. They develop a clear understanding of what happens with different kinds of waves, why we use the seismograph, why we need to triangulate, and make the geology connection (rock cycle related to the movement of the plates). The seismograph creates a real-time connection to the Earth.

> The neat thing about having it running is that every day the kids are checking it. 1 day a kid yelled out, "We're having an earthquake right now." We all stopped and took a look at it.

This superuser utilizes a range of IRIS animations to introduce students to seismic data including visualizing how *S* and *P* waves travel, why multiple stations are needed to locate an earthquake, and how you can see the subduction zones if you look at the global distribution and depth of earthquakes. Students' progress to working with seismic data, calculating distance from the earthquake to the school, determining the great circle arc, and determining the location of the earthquake. Students advance in working with the seismic data, learning about amplitude and wave periods to calculate magnitude. Students extend their knowledge even more, working with GPS data from all over the world, using vectors to get a sense of Iceland's motion relative to the North American and Eurasian Plate. Students have been able to use data to see the rising of the caldera in Yellowstone. This superuser also incorporates hands on curriculum to explore earthquake concepts. Students build structures with clay and building materials like straws, washers, and rubber bands. By researching modern construction methods, students use the simple materials to make buildings that are stable in an earthquake, then test out their designs on a shake table.

> The students are much more aware of seismic hazards because of constructing their own buildings. At first, they don't know what to do with the rubber bands or washers. Then they learn that in 1906 San Francisco was all leveled and building methods changed to provide more cushioning.

This superuser has supported more activities by students who showed a lot of interest. When the superuser was out on leave, he set up a seismometer at a student's house and supported him in reporting to the class on the data he was seeing and analyzing. Other students have done more with the software as part of the earthquake unit. Overall, hazard awareness has increased among students and even their families.

> Looking back at previous years, they were really connected when we were doing earthquakes and volcanoes. One family changed their April trip to visit a volcano.

REFLECTIONS ON SUPERUSERS

Each of the superusers values data driven instruction, instrument science, and authentic experiences as shown in their use of their seismometer with students, and in other programs that afford students access to data. For superusers, the integration of seismic data into the classroom happens more than just during their earthquake units, they have made it part of everyday class activities by having students be aware of the data coming in, noting earthquakes in the news, and helping students to learn more about how to analyze the data for advanced investigations. Superusers all discussed the observation that utilizing data from across the world gave students a better understanding of earthquakes, how they are studied, and their effects, and allowed students to generate multiple questions to interrogate seismic data. Each superuser emphasized a philosophy of exposing as many students as possible to draw them into thinking like a scientist, and extending activities with those who get excited. All of the superusers appear comfortable with the uncertainty of using messy, real data with their students. One advantage our superusers had is they all applied for and attended a professional development workshop run by IRIS where they learned the basics of seismology along with focused training on the use of their seismograph. They all valued the training they received, and sought out continuing education on concepts and equipment. They also all mentioned the value of ongoing support. Additionally, all of the superusers were highly personally motivated to ensure the technical conditions were met for instrument integration into the classroom.

Each superuser described positive experiences among all their students in their courses, and also extended student involvement outside of the classroom. They described the instrument and data as a tool to reach and encourage interested students to explore concepts further. Students engaged with seismic data, and saw the relevant connection to their lives. There was no doubt on any of their parts that having the seismograph and the software connected students to the world of seismology through getting data from faraway events revealing the structure of the Earth, and allowing students to query the data to learn more. While there was some discussion of collaboration between schools, IRIS could do more to connect students and teachers to facilitate more collaboration and sharing of data, ideas, and experiences within our network.

Among the superusers, there were differences in their implementations. However, in all cases, a critical feature of their engagement with students was to use a variety of seismology-related resources which connected the use of seismic data to the rest of the curriculum. Thus, the use of seismic data was just one component of their seismology-related teaching. Many of the resources are available via the IRIS Education and Public Outreach Program (www.iris.edu/earthquake; Taber et al., 2015), but the superusers also used other resources, and in one case even included students in the collection of felt reports from the community. The grade-level of implementation was more varied than we expected, stretching from 4th grade to 10th grade. Even among this wide age range, students were able to make personal connections to the data and use age-appropriate curriculum to learn about the Earth with seismic data.

The regional seismic hazard of the communities where the superusers were teaching also varied widely, with three of the four teachers working in low seismic hazard regions. What was surprising was that even in the most seismically active area, students didn't have a personal experience or memory of a large event, which created a disconnection from recognizing and understanding their regional seismic hazard. Seismographs in schools have the ability to raise earthquake hazard awareness and preparedness among students which can help communities prepare for future earthquakes (Subedi et al., 2020). In these multiple implementations, students were interested to learn the local impact of their regional seismicity, and were engaged when they realized they could record global seismicity as well. Through this program, students were given the opportunity to speak as local experts, passing on the lessons they were learning to their parents, the community, and even the media.

DISCUSSION AND FUTURE DIRECTIONS

After 20 years of the Seismographs in Schools program, data from both our user survey as well as the in-depth case studies of program superusers, show that integrating seismic data into classroom lessons is engaging students in Earth Science. By collecting and analyzing real data, students experience roles that require technical expertise with instruments, data analysis, teamwork, and other twenty-first century workplace skills (Dede, 2009; National Research Council, 2012). They experience firsthand some ways in which we use data to understand Earth processes in ways that we cannot observe directly. Students seem to easily take ownership of both monitoring and analyzing data, asking their own questions from the data. Their engagement is enhanced by the relationships they develop within the seismology community, as well as the validation they receive from their community. However, the current study has inferred student engagement from surveys and interviews of teachers. A more quantitative analysis of student engagement and learning could be obtained by surveying the students directly.

Both superusers and the sample of users surveyed responded positively to the effect of seismic data on student subject knowledge, student learning, and curriculum quality. Real data from a real instrument of unseen and often unfelt phenomena draw students into thinking more about how an event on the other side of the world can possibly be picked up at their location. What is going on inside the Earth? The fingerprints of waves from the earthquake begin to reveal the structure of Earth's interior. The patterns of earthquakes tell the story of the plates. Students begin to understand how we know about Earth and its phenomena.

Having initial and ongoing access to seismology-focused professional development was one of common factors mentioned by the superusers, and half of the teachers that responded to the initial survey would like additional training on one or more topics such as the software, seismology topics, and seismographs. A lack of adequate professional development was also one of the key barriers cited by teachers interested in using inquiry-based teaching techniques (Fitzgerald et al., 2019). Thus, IRIS could consider whether there are ways of providing broader professional development support for teachers. One way to do this may be to move to more online training. As an initial trial of such an approach, IRIS partnered with the University of Alaska-Fairbanks to run a successful online seismology course for Alaska teachers (Bravo et al., 2017), though scaling up such an initiative to reach large numbers of teachers would require significant resources.

Having insufficient time to cover a particular curriculum topic was highlighted as another barrier to using active learning techniques by Fitzgerald et al. (2019). While we lack quantitative data to show that the superusers spend more time on seismology-related topics than the average teacher, the superusers appear to use a larger number of IRIS resources than the typical workshop attendee, along with spending more time working with seismic data, based on follow-up surveys of teachers who have attended other IRIS professional development workshops. Thus, another superuser characteristic appears to be the ability to flex their school's curriculum to use seismology examples when teaching about other topics. In the US, the curriculum is set at the state and local level, so a teacher's ability to modify the curriculum varies considerably from state to state. However, all of the superusers used their instrument and the data it recorded as a process of science tool, using it to teach about data collection and analysis, thereby incorporating an awareness of global seismicity into students' daily experience. This approach fits well with the new Next Generation Science Standards which are being adopted by many states (National Research Council, 2013). The NGSS focus more on science and engineering practices and cross-cutting concepts than on specific content, so there is more opportunity to weave seismology examples into the curriculum. Providing such examples to other teachers might help them see ways that they could make more use of seismic data.

Reflecting on superusers long-term engagement of their students, it appears to depend both on the use of seismic data to explore concepts of data manipulation and analysis skills, as well as the existence of a local physical sensor, given the value to these superusers of their instrument and local recordings of large earthquakes. This was true in 1998 when a UK teacher explained how recording real data from real events was inspiring students at his school to think about science in a positive and engaging manner (Bullen, 1998). Paul Denton reiterated this observation 10 years later in an evaluation of the UK School Seismology Project (Denton, 2008). This study also shows the value of a local sensor, as all four superusers interviewed stressed that students as stewards of the seismometer links them to the science in an engaging and dynamic way. Thus, while the superusers had a primary responsibility to promote learning, their focus on student engagement is also helping to create young citizen scientists.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Human Subjects Research Review Office Binghamton University. The patients/participants provided their written informed consent to participate in this study. 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

TB, JT, and HD contributed to the design of the research. TB and HD created the online survey and designed the interview protocols. HD conducted the interviews and analyzed both the survey and interview results. All authors contributed to the interpretation, writing, and revision of the manuscript.

ACKNOWLEDGMENTS

This manuscript was greatly improved via comments and suggestions from Michael Hubenthal, and the research was funded by the National Science Foundation's Seismological Facilities for the Advancement of Geoscience (SAGE) Award to IRIS under Cooperative Service Agreement EAR-1851048.

REFERENCES

Braile, L., Hall-Wallace, M., Aster, R., and Taber, J. (2003). The IRIS education and outreach program. *Seismol. Res. Lett.* 74, 503–510. doi: 10.1785/gssrl.74.5.503

Bravo, T., and Hubenthal, M. (2016). Using earthquakes as "teachable moments." *Sci. Teach.* 83:14. doi: 10.2505/4/tst16_083_03_14

Bravo, T. K., Gardine, L., Taber, J., and West, M. E. (2017). "Developing an online seismology course for Alaska," in *GSA Annual Meeting in Seattle* (Washington). doi: 10.1130/abs/2017AM-308093

Bullen, S. (1998). Seismology in schools. *Astron. Geophys. 9*, 4.25–4.26. doi: 10.1093/astrog/39.4.4.25

Davis, H. B., and Bravo, T. (2020). *Seismographs in Schools Survey Summary*. Available online at: www.iris.edu/hq/files/programs/education_and_outreach/Evaluation/SISSurvey19.pdf (accessed May 1, 2020).

Dede, C. (2009). *Comparing Frameworks for 21st Century Skills*. Harvard Graduate School of Education. Available online at: http://sttechnology.pbworks.com/f/Dede_(2010)_Comparing%20Frameworks%20for%2021st%20Century%20Skills.pdf (accessed March 4, 2020).

Denton, P. (2008). Seismology in schools: 10 years on. *Astron. Geophys. 49*, 6.13–6.14. doi: 10.1111/j.1468-4004.2008.49613.x

Drago, J., Ginther, J., Viglione, P., Wicklund, E., and Coleman, B. (2009). "*Amaseis: seismology software meeting the needs of educators,*" in *Midstates Conference for Undergraduate Research in Computer Science and Mathematics* (Milwaukee, Wisconsin).

Fitzgerald, M., Danaia, L., and McKinnon, D. H. (2019). Barriers inhibiting inquiry-based science teaching and potential solutions: perceptions of positively inclined early adopters. *Res. Sci. Educ.* 49, 543–566. doi: 10.1007/s11165-017-9623-5

Gee, J. P. (2010). *An Introduction to Discourse Analysis: Theory and Method. New York, NY: Routledge*. doi: 10.4324/9780203847886

Hamburger, M., Astwood, P., Boone, W., Boyd, T., and Hall-Wallace, M. (2001). *A white paper for the U.S. Educational Seismology Network*. Available online at: http://www.indiana.edu/usesn/about.html (accessed March 4, 2020).

Hamburger, M., and Taber, J. (2003). Towards integration of educational seismology programs: the U.S. *educational seismology network. Seismol. Res. Lett.* 74, 603–604. doi: 10.1785/gssrl.74.5.603

Hubenthal, M., Braile, L., and Taber, J. (2008). Redefining earthquakes and the earthquake machine. *Sci. Teach.* 75, 32–36.

Jones, A. L., Braile, L. W., and Braile, S. J. (2003). A suite of educational computer programs for seismology. *Seismol. Res. Lett.* 74, 605–617. doi: 10.1785/gssrl.74.5.605

Kafka, A. L., Ebel, J. E., Barnett, M., Macherides Moulis, A., Campbell, L., and Gordon, S. E. (2006). Classroom seismographs and the challenge of encouraging a culture of scientific inquiry in K-12 schools. *Seismol. Res. Lett.* 77, 74–86. doi: 10.1785/gssrl.77.6.734

Kafka, A. L., and Fink, K. R. (2019). *Raspberry Shake, EQ1, and Research-Grade Seismographs: Pros and Cons of Different Types of Seismographs for Education, Citizen Science, and Earthquake Monitoring*. New England and Texas. Eastern Section Meeting, Seismological Society of America (Columbus, OH).

National Research Council (2012). *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century. Washington, DC: The National Academies Press.* doi: 10.17226/13398

National Research Council (2013). *Next Generation Science Standards: For States, By States. Washington, DC: The National Academies Press.* doi: 10.17226/18290

Stake, R. E. (1978). The case study method in social inquiry. *Educ. Res.* 7, 5–8. doi: 10.3102/0013189X007002005

Subedi, S., Hetényi, G., Denton, P., and Sauron, A. (2020). Seismology at school in Nepal: a program for educational and citizen seismology through a low-cost seismic network. *Front. Earth Sci.* 8:73. doi: 10.3389/feart.2020.00073

Taber, J., Hubenthal, M., Bravo, T., Dorr, P., Johnson, J., McQuillian, P., et al. (2015). Seismology education and public outreach resources for a spectrum of audiences, as provided by the IRIS consortium. *Leading Edge* 34, 1178–1184. doi: 10.1190/tle34101178.1

van Wijk, K., Channel, T., Viskupic, K., and Smith, M. L. (2013). Teaching geophysics with a vertical- component seismometer. *Phys. Teach.* 51, 552–554. doi: 10.1119/1.4830072

Zollo, A., Bobbio, A., Berenguer, J. L., Courboulex, F., Denton, P., Festa, G., et al. (2014). "The European experience of educational seismology," in *Geoscience Research and Outreach. Innovations in Science Education and Technology, Vol. 21*. ed. V. Tong (Springer, Dordrecht), 145–170. doi: 10.1007/978-94-007-6943-4_10

Conflict of Interest: The 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.

Copyright © 2020 Bravo, Taber and Davis. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

ORIGINAL RESEARCH
published: 07 July 2020
doi: 10.3389/feart.2020.00272

Accurate Locations of Felt Earthquakes Using Crowdsource Detections

István Bondár[1], Robert Steed[2], Julien Roch[2], Rémy Bossu[2,3], Andres Heinloo[4], Joachim Saul[4] and Angelo Strollo[4]*

[1] Kövesligethy Radó Seismological Observatory, Geodetic and Geophysical Institute, Research Centre for Astronomy and Earth Sciences, Budapest, Hungary, [2] European-Mediterranean Seismological Centre, Arpajon, France, [3] CEA, DAM, DIF, Arpajon, France, [4] GFZ German Research Centre for Geoscience, Potsdam, Germany

We present a methodology that uses crowdsourced detections as an initial location to obtain fast and reliable hypocenter parameters for felt earthquakes using arrival-time data from the GEOFON Program. We derive selection criteria for issuing an alert message using a 3-year-long training set from the trial runs at the European-Mediterranean Seismological Centre (EMSC) to identify accurate event locations at a high confidence level. Since an event may have several crowdsourced detections, we also develop a methodology dealing with multiple triggers. We validate the selection criteria using real-time processing of recent data and demonstrate that 95% of the selected events are within 50 km distance from the traditional seismic location published by the EMSC. Since *CsLoc* remains essentially a seismic location algorithm, the selection criteria measure the quality of the seismological network coverage used in the location, not the method itself. We show that our methodology provides accurate locations much faster than those published by conventional seismic methods. On average, the EMSC *CsLoc* service can provide rapid and accurate locations within a minute after the occurrence of a felt earthquake, thus it can provide timely and accurate information on a felt earthquake to the civil protection services and the general public.

Keywords: crowdsource detection, earthquake location, earthquake alert, real time seismology, citizen seismology

OPEN ACCESS

Edited by:
Susanne Buiter,
RWTH Aachen University, Germany

Reviewed by:
Kwang-Hee Kim,
Pusan National University, South Korea
Kostas Konstantinou,
National Central University, Taiwan
Matthew R. Agius,
Universitá degli studi Roma Tre, Italy

****Correspondence:***
István Bondár
bondar@seismology.hu;
ibondar2014@gmail.com

Specialty section:
This article was submitted to Solid Earth Geophysics, a section of the journal Frontiers in Earth Science

Received: *06 February 2020*
Accepted: *15 June 2020*
Published: *07 July 2020*

Citation:
Bondár I, Steed R, Roch J, Bossu R, Heinloo A, Saul J and Strollo A (2020) Accurate Locations of Felt Earthquakes Using Crowdsource Detections. Front. Earth Sci. 8:272. doi: 10.3389/feart.2020.00272

INTRODUCTION

Earthquake crowdsourced detections are based on following eyewitnesses' immediate reactions to felt earthquakes on various social media platforms, such as Twitter (Earle et al., 2011), traffic on the EMSC website (Bossu et al., 2014), and the number of launches of the EMSC smartphone app, *LastQuake* (Bossu et al., 2018). While other crowdsourced approaches in seismology (e.g., Cochran et al., 2009; Minson et al., 2015; Finazzi, 2016; Kong et al., 2016; Cochran, 2018) have focused on using accelerometers in smartphones or dedicated sensors that are maintained by the public, our approach exploits the public's search for information and their online reactions (Steed et al., 2019). In other words, a crowdsourced earthquake detection reflects a public desire for information. Offering a very fast earthquake location is a way to answer this desire. It is also instrumental for rapid engagement of eyewitnesses and to ensure efficient felt report collection from eyewitnesses which are in turn essential for rapid impact assessment (Bossu et al., 2015). It can also be exploited as a “heads-up” for civil protection services which might save lives in a period where every minute counts and this is why seismic networks around the world have been constantly pushing for always faster earthquake information (Kanamori, 2005).

Crowdsourced detections typically appear very fast in social media, almost immediately after the earthquake occurrence in densely populated areas. Hence, they can be used as an initial estimate of the earthquake location. This initial guess triggers our seismic data analysis to obtain a reliable earthquake location with a state-of-the-art event location algorithm. Steed et al. (2019) demonstrated that the crowdseeded location (*CsLoc*) approach produces quicker results than traditional earthquake alert algorithms, and that it can provide reliable locations even with a limited number of seismic phase arrivals.

This paper focuses on the conditions that would allow our method to enter into routine operational service, providing fast, reliable locations of felt earthquakes. This information can then be provided to the civil protection services and disseminated to the public. The public’s appreciation for high accuracy is much less than it’s dislike of false alarms, so one of the crucial aspects of our effort is to minimize the number of events with inaccurate locations whilst providing accurate locations on average. Hence, our objective is to achieve 50 and 80 km location accuracy (measured as the distance from the traditional seismic network location) at the 95 and 98% confidence levels, respectively, while maximizing the number of events that pass the publication criteria. To derive the selection criteria, we use a training set of 3-year data, and validate the results on 4-month data from current real-time processing.

DATA AND METHODS

Crowdsourced Detection

We rely on three different crowdsourced detection methodologies to start a *CsLoc* analysis. Note that they may trigger *CsLoc* independently, therefore several triggers may exist for the same earthquake. *CsLoc* is initiated by the detection of increased traffic at the EMSC website, www.emsc-csem.org (Bossu et al., 2014); the detection of increased number of launches of the EMSC LastQuake smartphone application (Bossu et al., 2018); and the detection from the Twitter Earthquake Detection (TED, Earle et al., 2011) system that follows the keyword “earthquake” in 59 languages in tweets of less than seven words because people tend to react to stressful events such as earthquakes in just a few words. The *TED* system was developed by the United States Geological Survey National Earthquake Information Center (NEIC), and it is currently used in the EMSC crowdsourced detection system.

To detect an event, the number of app launches or website visits are monitored as counts/minute at 5 s intervals and a short-term average/long-term average (STA/LTA) algorithm is applied to these curves to detect peaks in the traffic (Bossu et al., 2019). The latest count/minute is compared to a baseline created from an average of the last half an hour of traffic and if the difference reaches a preset threshold then a peak is declared. Various procedures are used to increase signal to noise and to eliminate false detections (such as those caused by automated scans of IP addresses or the website). For instance, only visitors that have not been seen within 30 min are included in the analysis, as this helps to remove frequent users from the data such as researchers from institutes. We also bin our users by country of origin so that the background noise level is reduced. As the EMSC becomes more known by the public, we will probably need to adjust our triggering system to take account of greater levels of traffic but the current system has worked well for since 2014.

Crowdsourced detections are typically obtained before the first seismic location is made, therefore the *CsLoc* procedure starts without having a location provided by local or regional seismic networks. Once a crowdsourced detection is made, the centroid of the largest cluster of geolocations of the users within 120 s before the detection time and within the country where the detection was made is passed to the *CsLoc* association module (Steed et al., 2019). The cluster centroid and the crowdsourced detection time serves as an initial guess for the earthquake location, and as noted above, several *CsLoc* processes could be initiated for the same event. The system collects arrival picks within 1000 km (for regions with sparse networks up to 2000 km) distance of the crowdsourced initial location from the global GEOFON Program (73 FDSN networks as used in GEOFON Data Centre, 2019; Steed et al., 2019) that includes some 800 stations. The P-wave arrival picks are received in real time from 210 s before until 120 s after the crowdsourced detection time using the GEOFON HTTP Message Bus (Heinloo, 2016).

CsLoc Association and Location

The *CsLoc* association process is optimized for speed and it uses the crowdsourced initial guess as the event hypothesis for finding corroborating arrivals. Hence, *CsLoc* is a seismic location algorithm that exploits the fact that we already know from crowdsourcing that an earthquake occurred, and we have a rough idea where and when the earthquake has struck. We assume that for our spatial range of interest the first P wave arrival is a Pn phase and we search for first-arriving P-phases that given the hypocenter origin hypothesis, providing a reasonably good fit to the *ak135* (Kennett et al., 1995) Pn travel-time curve. Only those arrivals that are within three times the median absolute deviation (MAD) of the Pn travel time curve are passed to the locator.

Using the selected arrivals, we apply the *iLoc* (Bondár and Storchak, 2011; Bondár et al., 2018) location algorithm to locate the event. iLoc accounts for correlated travel time prediction errors due to unmodeled 3D velocity structures (Bondár and McLaughlin, 2009) and thus provides robust location estimates even for unfavorable network geometries. It is an iterative linearized inversion method that obtains an improved hypocenter estimate using a neighborhood algorithm (Sambridge, 1999).

As new data arrives and the location changes, it is necessary to repeat the association and location procedures several times until an acceptable solution is reached. **Figure 1** illustrates the iterative association-location steps for the 2016-08-24, magnitude 6.2 Central Italy event. The crowdseeded location triggered by the EMSC website traffic is some 450 km away from the earthquake epicenter. The association algorithm considers P picks arriving

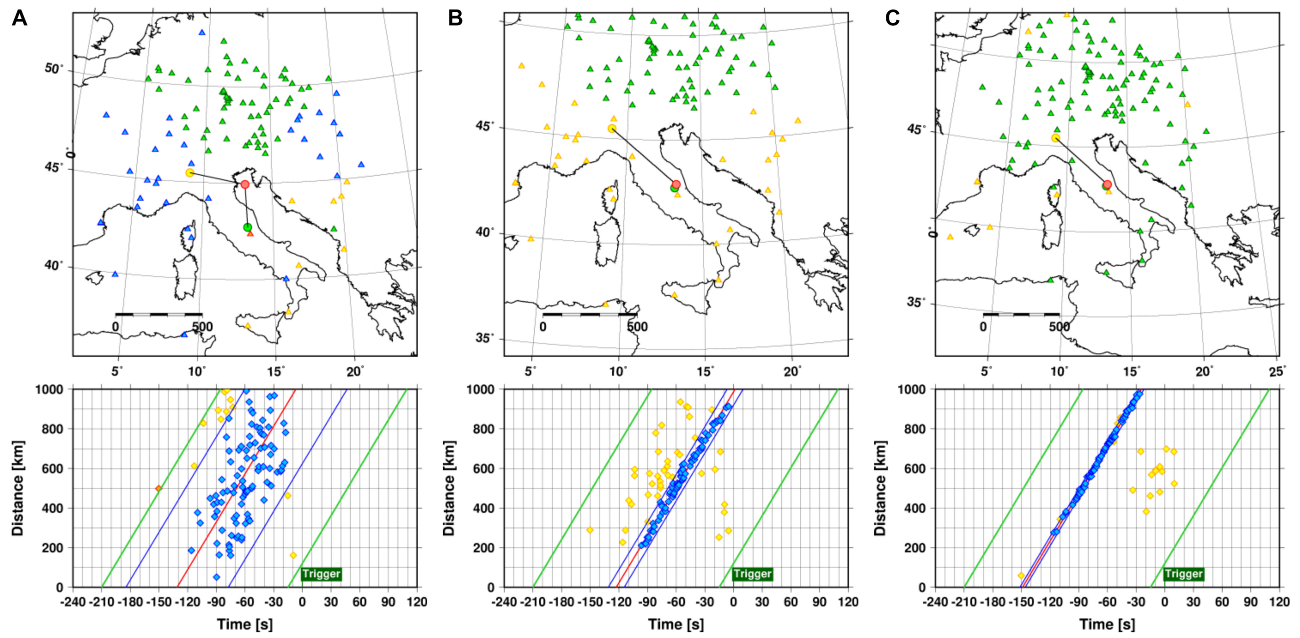


FIGURE 1 | The *CsLoc* association and location cycle, for iterations **(A)** 0, **(B)** 1, and **(C)** 2. Top row: The initial crowdsourced trigger (yellow circle) may be far away from the EMSC seismic location (green circle), but *iLoc* (red circle) converges fast to the traditional seismic location. Yellow, blue and green triangles show the seismic stations considered, associated and used in the locations, respectively. Bottom row: First-arriving P phase picks are considered in a time window (green lines) before the crowdsourced trigger. Those within 3*MAD (blue lines and blue diamonds) of the best fitting travel time curve (red line) with the slope of the ak135 Pn velocity, 8.04 km/s, are passed to *iLoc*.

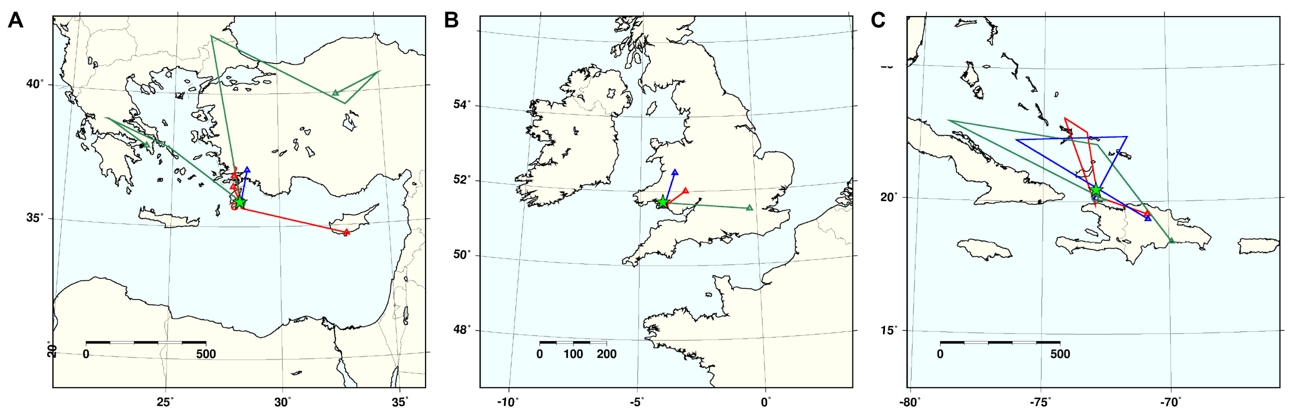


FIGURE 2 | Multiple strains for the same event (star) triggered by various country-based website traffic (green triangle) and *TED* triggers (blue triangle), as well as the *LastQuake* app (red triangle) crowdsourced detections in **(A)** Turkey, **(B)** Great Britain, and **(C)** Haiti. Corresponding color lines show the trajectory of *CsLoc* locations during the iterations. *CsLoc* shows a robust performance against the position of the initial crowdsourced triggers.

in the time interval shown in green lines, and selects those that are within the 3*MAD of the best fitting line with a slope of 8.04 km/s, the ak135 Pn velocity. On the map, green triangles show the seismic stations that *iLoc* used in the location and the *iLoc* solution is shown as a red circle. In the two next iterations, as the *iLoc* solution improves, the 3*MAD interval for the candidate associations shrinks drastically and even after the first iteration the *iLoc* solution is very close to the final EMSC seismic location.

Steed et al. (2019) executed 10 iterations of the association and location cycle with 15-s delays between each step. In this paper we focus on the determination of the set of conditions that will allow us to stop as soon as some quality assurance criteria are met. The selection criteria will also allow us to fully automate the *CsLoc* procedures.

The three types of crowdsourced detections (web traffic, *LastQuake* app, and *TED*) can each trigger the *CsLoc* procedure. For the web triggers the geolocation is based on the user's IP address that varies from country to country and it is often accurate to the city level or less. If the website is accessed via a mobile phone, the geolocation often gives the location where the

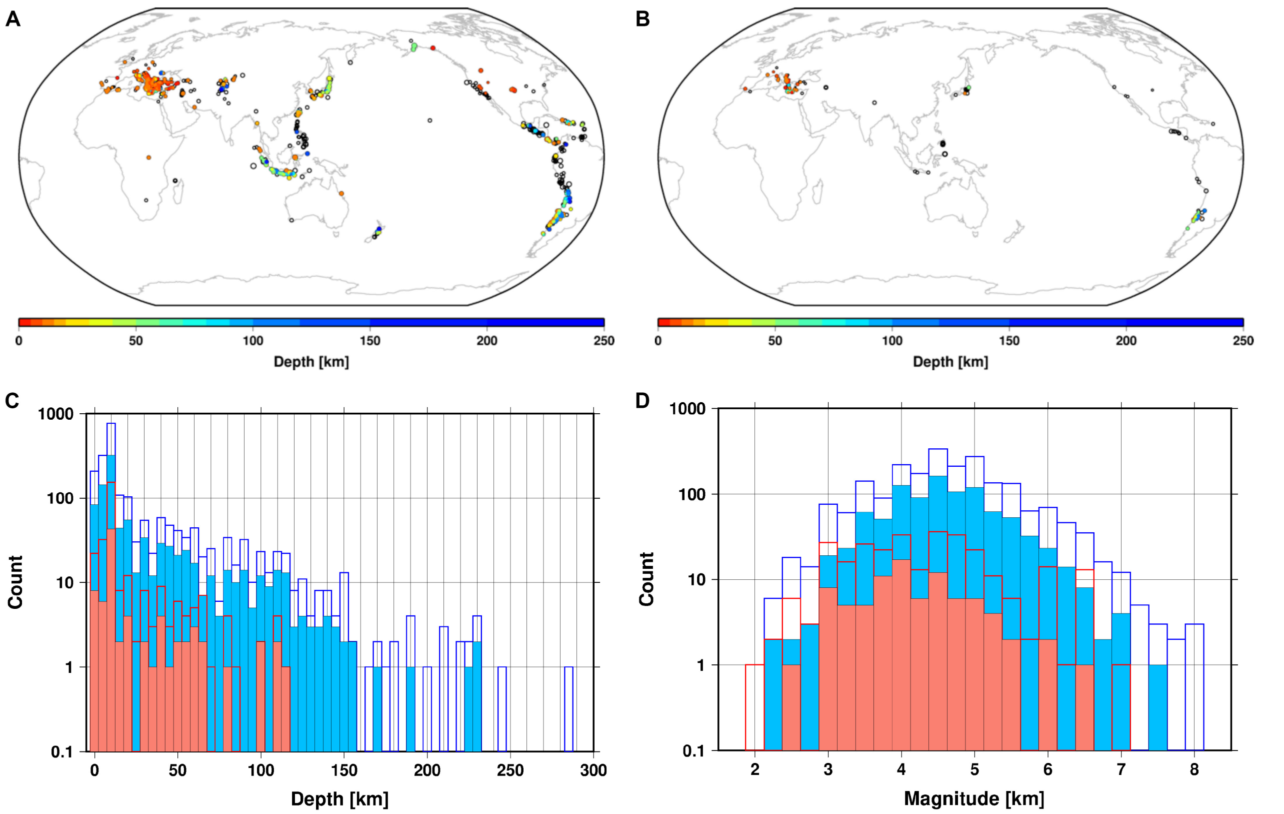


FIGURE 3 | Location map of events in the **(A)** training and **(B)** validation data sets. Circles color coded by depth denote the events that pass the selection criteria described later in the text; empty circles represent the events that did not pass the criteria. **(C)** Histogram of **(C)** depths and **(D)** magnitudes of event in the training (blue) and validation (red) data sets. Filled bars in the histogram represent events that pass the selection criteria.

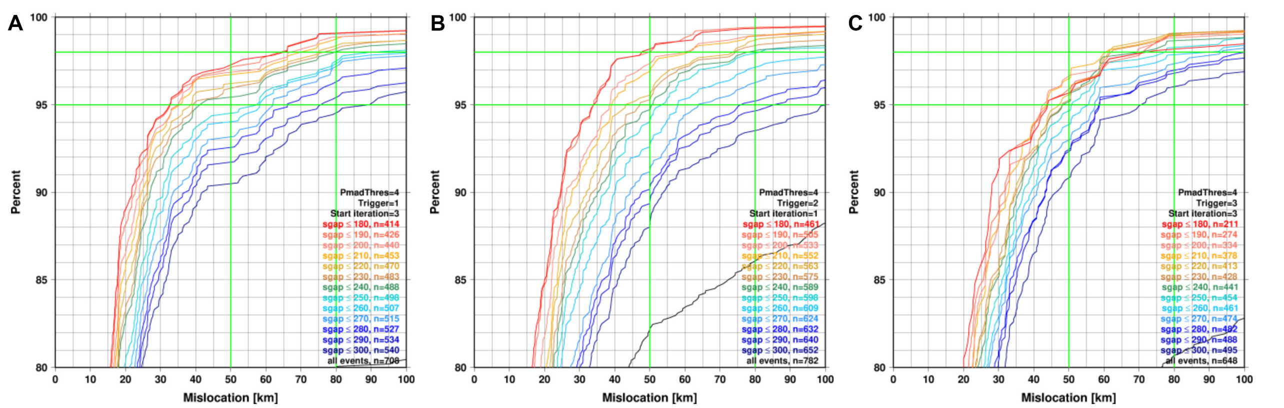


FIGURE 4 | Cumulative distributions of *CsLoc* mislocations from published EMSC solutions for **(A)** web traffic, **(B)** *LastQuake*, and **(C)** *TED* crowdsource triggers with decreasing secondary azimuthal gap thresholds (from black to red curves, with better coverage toward red curves). Green vertical and horizontal lines mark the 95 and 98% confidence levels and the 50 and 80 km location accuracy targets, respectively.

mobile network is connected to the internet. Thus, as **Figures 1**, **2** illustrate, the physical location of the users can be quite inaccurate and often biased by large cities and therefore the centroid of the crowdsourced detections often coincides with a large city, such as Istanbul, Athens, Milan, etc. This is always true for IP locations and tweets.

The *LastQuake* app asks for the user's permission to access their mobile phone's location, otherwise it determines the user's location using triangulation or wifi. Some 80% of users allow the use of location services, therefore the app triggers are considered the most accurate. Furthermore, the website and app detection systems are monitored in each country separately. The Twitter

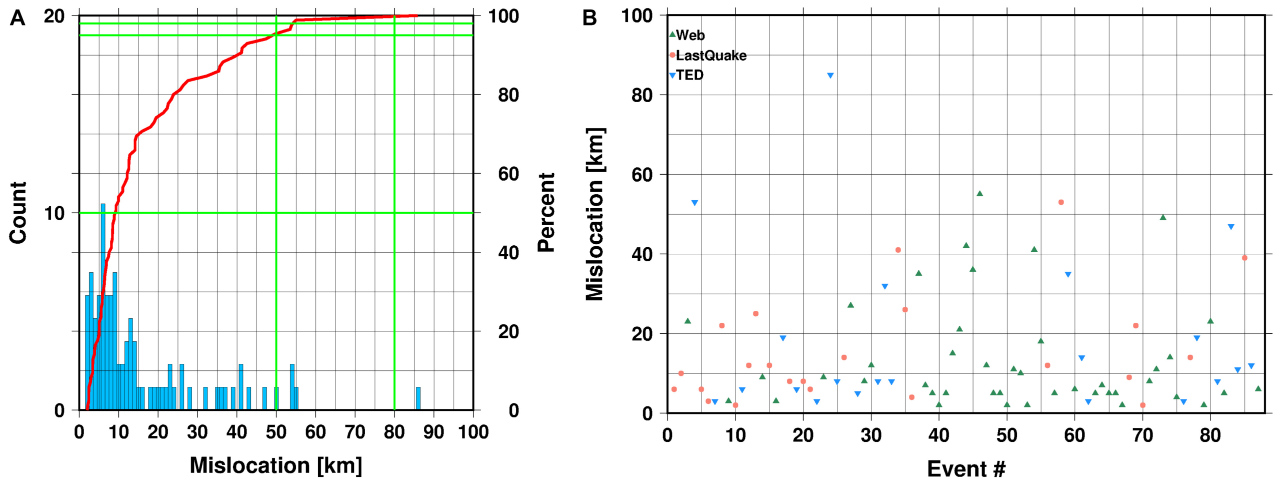


FIGURE 5 | (A) Histogram (blue) and cumulative distribution (red line) of the distance of *CsLoc* locations from published EMSC locations for the validation data set. Green lines mark the 95 and 98% confidence levels and the 50 and 80 km location accuracy targets, respectively. The green line at the 50% confidence level indicates that 50% of the locations are within 10 km from the EMSC location. **(B)** Event mislocation by crowdsource triggers that first satisfied the publication criteria. Only 1 event was located with a larger than 80 km location error.

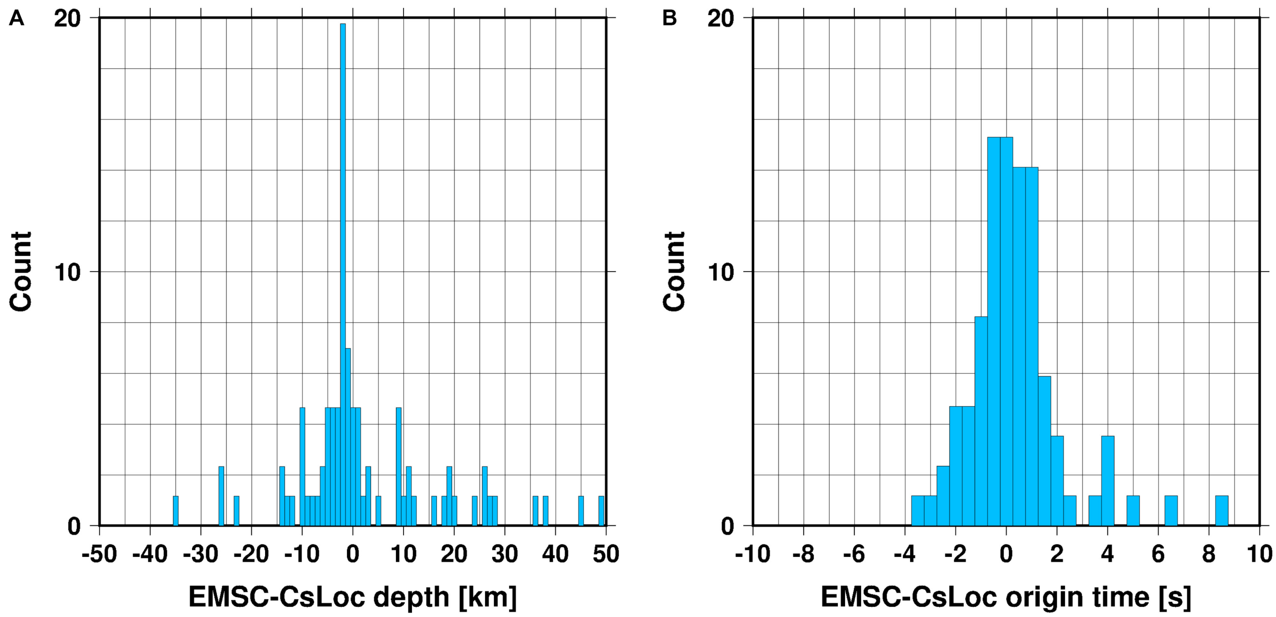


FIGURE 6 | Histogram and cumulative distribution of the deviation of *CsLoc* **(A)** depth and **(B)** origin time determinations from published EMSC values for the validation data set.

detection system determines the location of the user from the profile of the author found in each tweet. It also tries to divine the user's location based on the language used in the tweet. Therefore, the accuracy of *TED* triggers may also exhibit a large scatter.

Because of the various triggers, it is not uncommon that there are several crowdsource detections for the same event. *CsLoc* is robust enough to reach accurate locations, even if the initial location is far off. However, it helps to identify these multiple strains early on. We analyzed our data set to find reasonable criteria to decide if two crowdsourced detections are generated by the same event. We found that events with a large number of seismic arrivals and those with just a few seismic arrivals require separate logic. We rely on the assumption that if two solutions share a fair amount of common seismic arrival picks then the events are likely to be the same. For candidate events for multiple triggers we check the number of common seismic arrivals for each event pair. If the number of common seismic arrival picks is larger than 20, we declare the two events common. For events with just a few picks, we require at least three common seismic arrival picks and that

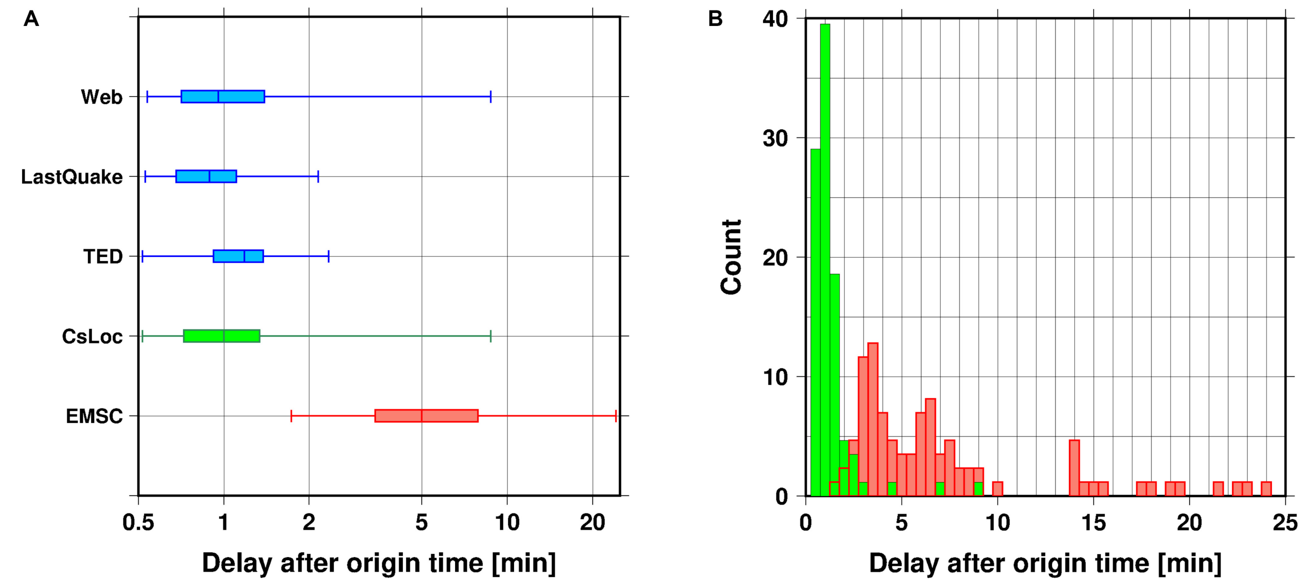


FIGURE 7 | Publication delay after the origin time for the events that satisfied the publication criteria in the validation data set. **(A)** Box-and-whisker plot of publication delay for each crowdsource trigger types (blue), all *CsLoc* locations and the EMSC. **(B)** Histogram of CsLoc (green) and EMSC (red) publication delays. The median publication delay is reduced from 5 min of the EMSC locations to around 1 min for the *CsLoc* locations.

20% of the seismic phases be shared between the events to declare them the same.

Figure 2 shows examples for *CsLoc* event location trajectories starting from several different crowdsourced detection. Recall that the crwodsourced detection is the barycenter of the eyewitness locations. Green trajectories denote web-based triggers, red lines *LastQuake* app triggers and blue trajectories *TED* triggers. One of the major strengths of our method is that regardless of the trigger type and the initial mislocation, *CsLoc* is capable to obtain a final solution that is very compatible to the final EMSC solution of the event.

RESULTS

Steed et al. (2019) executed 10 iterations of the association and location cycle with 15-s delays between each step and developed publication criteria based on the combination of acceptance thresholds of six different parameters. Exploiting the accumulated wealth of data, we aim to simplify the original publication criteria and focus on the determination of the set of conditions that will allow us to stop as soon as some quality assurance criteria are met.

To determine the new selection criteria, we use a training set of crowdsourced detections between January 2016 and May 2019 including 708 events triggered by the EMSC web-site traffic, 782 events triggered by the *LastQuake* app, and 648 events triggered by *TED*. Note that the same earthquake may initiate several triggers and the data set represents 2,138 unique events. To validate the selection criteria, we use the data set between 10 October 2019 and 12 December 2019 that were not used in the creation of the training data set. We consider only those events that produced a location at the last, 10th iteration. The validation data set contains 288 events of which 123 events triggered by the EMSC web-site traffic, 97 events triggered by the *LastQuake* app, and 68 events triggered by *TED*.

Figure 3 shows the location map of the training and validation sets, as well as their depth and magnitude distributions. The training set represents a fairly good representation of global seismicity of felt earthquakes, while the validation data set, owing to its much shorter time window, have events mostly from Europe and South America. Nevertheless, the depth and magnitude distribution of the events in the training and validation sets are quite similar. Note that both sets have subcrustal and intermediate depth events, and the magnitudes span from small to large events.

We consider the secondary azimuthal gap in the network used in the location, and the MAD of the residuals after the *iLoc* location in each iteration. The secondary azimuthal gap is obtained by calculating the largest azimuthal gap when removing one station from the network and it is a good indicator of reliable, accurate locations (Bondár et al., 2004). The MAD of the residuals helps removing outliers due to noisy data or associations from other events, typically aftershocks. We use the distance between the published EMSC location and the *CsLoc* location as the metric to measure the performance of *CsLoc*. These parameters measure of the seismic network coverage that ultimately controls the location accuracy.

Our design goal is to achieve 50 km location accuracy at the 95% confidence level and less than 80 km mislocation at the 98% confidence level while maximizing the number of events that pass the criteria and stop the iterations as soon as possible to facilitate quick but reliable earthquake alert information. This means that only 5 and 2% of the events would have a location error larger than 50 km and 80 km, respectively, all the rest will be much more accurately located. We calculate the metric for a series of secondary azimuthal gap thresholds between 180 and 300 degrees (the smaller the secondary azimuthal gap, the more favorable the network geometry to produce accurate locations) and a MAD residual threshold of 3, 4, 5, and 100 (the latter being no constraint on MAD). We found that setting the MAD threshold to 4 s is a reasonable choice, that excludes obvious outliers while keeping most events.

As noted previously and illustrated on **Figure 2**, the different triggers represent different levels of reliability, therefore we develop the selection criteria for each trigger type separately. The web traffic and *TED* crowdseeded initial locations can be far away from the final solution, and they may need a few iterations for *CsLoc* to close on the right location. On the other hand, the *LastQuake* app crowdseeded location can be quite accurate, therefore the final *CsLoc* solution might be obtained in just one iteration. Thus, we also set thresholds for the minimum number of iterations *CsLoc* has to perform before we apply the selection criteria.

Figure 4 summarizes our results. The figure shows the cumulative distributions of the distance of the *CsLoc* location from the published EMSC solution for each trigger type for the series of secondary azimuthal gap thresholds for MAD *leq* 4. Note that **Figure 4** shows only the upper 20% percentiles, from 80 to 100%, as we focus on location errors in the top 10 percentiles. We found that for the web traffic and *TED* triggers we should execute at least two iterations to allow for the warm-in period for *CsLoc* before testing for the criteria; for the *LastQuake* triggers we can apply the selection criteria right away.

We list our final publication criteria for each trigger types below. Note that these criteria measure the seismic network performance, not the quality of the crowdsource detection. That is only used as the initial guess for the location using observations from seismological stations. Once the selection criteria are met at any iteration after the prescribed number of iterations, the *CsLoc* association – location iteration cycle stops and an earthquake alert can be issued.

- For website traffic triggers after the 3rd iteration accept an event for publication if the secondary azimuthal gap *leq* 240° and the MAD of residuals *leq* 4 s.
- For *LastQuake* triggers after the 1st iteration accept an event for publication if the secondary azimuthal gap *leq* 230° and the MAD of residuals *leq* 4 s.
- For *TED* triggers after the 3rd iteration accept an event for publication if the secondary azimuthal gap *leq* 240° and the MAD of residuals *leq* 4 s.

The selection criteria for the web traffic triggers select 69% (488 out of 708) of the events with a median mislocation of 9.2 km from the EMSC solution and with a location accuracy of 41 and 77 km at the 95 and 98% confidence levels, respectively. For the *LastQuake* app triggers, they select 73.5% (575 out of 782) of events with a location accuracy of 10.4, 47, and 74 km at the median, 95 and 98% percentiles, respectively. For the *TED* triggers, the criteria select 68% (441 out of 648) of events with a mislocation of 13.2, 48, and 65 km at the median, 95 and 98% confidence levels, respectively.

Applied to the validation data set, the publication criteria for web traffic triggers selected 60.2% (74 out of 123) of events with a mislocation of 7.5, 42, and 52 km at the median, 95 and 98% confidence levels, respectively. The publication criteria for the *LastQuake* triggers select 56% (54 out of 97) of events with 8.7, 38, and 40 km mislocation at the median, 95 and 98% confidence levels, respectively. For the *TED* triggers, the publication criteria select 37% (25 out of 68) of events with a location accuracy of 8.5, 51, and 71 km at the median, 95 and 98% percentiles, respectively.

We indicated those events that passed our selection criteria in **Figure 3** as the events color coded by depth. The events that did not pass the selection criteria are shown as empty circles, and concentrate in regions with somewhat poorer station coverage. The depth and magnitude distributions do not show any particular bias for events passing (colored bars) or failing the selection criteria (empty bars) either.

Figure 5 shows the distribution of the *CsLoc* location differences from the published EMSC locations as well as the mislocations by the trigger types that first reached the publication criteria. The green lines show our target design criteria of 50 and 80 km location accuracy at the 95 and 98% confidence level, respectively. They indicate that the validation data set confirms that our publication criteria are indeed able to identify accurate locations for all trigger types that satisfy our design goals of minimizing the number of poorly located events and maximizing the number of accurately located events when issuing an earthquake alert to the public. The selection criteria will also allow us to fully automate the *CsLoc* procedures and the automatic publication of fast and reliable locations even using very limited data sets.

DISCUSSION

Aiming at fast and accurate locations for an operational centre such as the EMSC, the first issue to address is the identification of the single event to trigger among the various triggers for the same event. Thus, we check at each iteration if the event has already satisfied the publication criteria from another trigger, by applying the test for common events. If the event proves to be a common event by an earlier trigger and is already published, we simply abandon the trigger and stop processing the event. While other triggers may later result in slightly more accurate locations, our objective is to issue an alert at the earliest possible time with the stated location accuracy at high, 95 and 98% confidence levels.

Our crowdsourced detections carry no information on event depth, yet with the *CsLoc* procedures we are able to determine the depth with reasonable accuracy. Recall that *CsLoc* employs the *iLoc* location algorithm (Bondár and Storchak, 2011; Bondár et al., 2018) that provides robust depth estimates. In the *CsLoc* procedures the local networks typically provide sufficient resolution for depth determination. **Figure 6** shows the histograms of the deviation of the *CsLoc* depth and origin time from the published EMSC values for the validation data set. The vast majority of *CsLoc* event depths are within 10 km of the EMSC depth, and the origin times are within 2 s from the published EMSC origin time.

In principle, *CsLoc* can also provide magnitude estimates. We plan to publish magnitudes alongside the hypocenters as that would be a fairly trivial task; all we need to do is to get the automatic amplitude measurements along with the first-P arrival picks and calculate the magnitude. Since we collect phase picks up to 1,000 km (for sparse networks up to 2,000 km) this would allow us to calculate local magnitude, ML. However, ML starts saturating relatively early at medium moment magnitudes, therefore for some cases ML would underestimate the magnitude. For these events we will not publish ML at all. Attenuation along the ray path and possible interference with Lg phase poses further problems that might bias the ML estimate. Obviously, we will have to rely on generic attenuation relations the same way as the most popular programs, such as Antelope, SeisComp3 do. Nevertheless, we believe that besides producing rapid, accurate locations for felt earthquakes it is also important to publish magnitudes for small events that may not be recorded at teleseismic distances.

CONCLUSION

We successfully developed a methodology that can be used to identify accurately located events at a high confidence level. The selection criteria are quite robust against the various crowdsource triggers and facilitate the handling of multiple triggers for the same event. The location accuracy is better than 10 km for 50% of the events, which is comparable to the average location error of 9.4 km in the EHB bulletin (Engdahl et al., 1998). The EHB bulletin is the groomed ISC bulletin and it is considered amongst the highest quality global bulletins and thus the preferred source for doing global and regional tomography. The location error is larger than 50 and 80 km or only for 5 and 2% of the events, respectively. Similarly, the *CsLoc* depth and origin time estimates are on average within 5 km and 1 s of the EMSC solution for 50% of the events, and larger than 25 km and 3 s for only 10% of the events.

Our selection criteria for publication allows us to significantly reduce the publication latency times compared to those cited in Steed et al. (2019) as the majority of events can be published right after the third iteration and notably it was never necessary to wait for the full ten iterations. **Figure 7** shows the publication delay after the origin time for the EMSC published hypocenter and the *CsLoc* locations that satisfy the publication criteria. The median delay time for the EMSC is 5.6 min, while the median delay in publication time is reduced to 55, 53, and 72 s for the web traffic, *LastQuake* and *TED* triggers, respectively. Overall, the median delay in publication time for the *CsLoc* locations is reduced to 60 s, hence providing a significant improvement over the 103 s median delay reported by Steed et al. (2019).

The selection criteria allow us to reduce the EMSC publication delay after the event origin time by as much as 4 min on average and publish 75% of the events within 2 min after their occurrence. The performance of the *CsLoc* services depends on both population and station density as well as information timeliness. To further improve the *CsLoc* services we plan to improve the network coverage by complementing the actual real time seismic phases obtained from the GEOFON Program with more openly accessible stations, without significantly increasing the data latency.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

IB developed the phase association algorithm and its code, developed the event acceptance criteria, and also the author of the *iLoc* location algorithm, available for download at https://seiscode.iris.washington.edu/projects/iloc. RS and JR developed the *CsLoc* implementation, and created both the training and the validation data sets. RB formulated the overarching research goals, led and supervised the project, and acquired funding. AH developed the HMB messaging bus. AS and JS provided the feedback during the discussions as well as phase and seismic detection from the GEOFON program both historically and in real time using the HTTP Message Bus (HMB). All authors contributed to the article and approved the submitted version.

FUNDING

This article was partially funded by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement RISE No. 821115 and TurnKey No. 821046. Opinions expressed in this article solely reflect the authors' view; the EU was not responsible for any use that may be made of information it contains.

ACKNOWLEDGMENTS

We thank for the comments from the reviewers that helped to improve the manuscript. Real time data were provided by 73 FDSN networks as used in Steed et al. (2019), via the GEOFON Program (GEOFON Data Centre, 2019) with P-phases arrival times. We thank network operators for making data available.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.00272/full#supplementary-material

REFERENCES

Bondár, I., and McLaughlin, K. (2009). Seismic location bias and uncertainty in the presence of correlated and non-Gaussian travel-time errors. *Bull. Seismol. Soc. Am.* 99, 172–193. doi: 10.1785/0120080922

Bondár, I., Mónus, P., Czanik, C. S., Kiszely, M., Gráczer, Z., Wéber, Z., et al. (2018). Relocation of seismicity in the pannonian basin using a global 3D velocity model. *Seismol. Res. Lett.* 89, 2284–2293.

Bondár, I., Myers, S. C., Engdahl, E. R., and Bergman, E. A. (2004). Epicenter accuracy based on seismic network criteria. *Geophys. J. Int.* 156, 483–496. doi: 10.1111/j.1365-246x.2004.02070.x

Bondár, I., and Storchak, D. (2011). Improved location procedures at the international seismological centre. *Geophys. J. Int.* 186, 1220–1244. doi: 10.1111/j.1365-246x.2011.05107.x

Bossu, R., Laurin, M., Mazet-Roux, G., Roussel, F., and Steed, R. J. (2015). The importance of smartphones as public earthquake information tools and tools for the rapid engagement with eyewitnesses: a case study of the 2015 Nepal earthquake sequence. *Seismol. Res. Lett.* 86, 1587–1592. doi: 10.1785/0220150147

Bossu, R., Lefebvre, S., Cansi, Y., and Mazet-Roux, G. (2014). Characterization of the 2011 mineral, Virginia, earthquake effects and epicenter from website traffic analysis. *Seismol. Res. Lett.* 85, 91–97. doi: 10.1785/0220130106

Bossu, R., Roussel, F., Fallou, L., Landès, M., Steed, R. J., Mazet-Roux, G., et al. (2018). LastQuake: from rapid information to global seismic risk reduction. *Int. J. Disaster Risk Reduct.* 28, 32–42. doi: 10.1016/j.ijdrr.2018.02.024

Bossu, R., Steed, R. J., Roussel, F., Landès, M., Fuenzalida, A., Matrullo, E., et al. (2019). App earthquake detection and automatic mapping of felt area. *Seismol. Res. Lett.* 90, 305–312. doi: 10.1785/0220180185

Cochran, E. S. (2018). To catch a quake. *Nat. Commun.* 9:2508.

Cochran, E. S., Lawrence, J. F., Christensen, C., and Jakka, R. S. (2009). The quake-catcher network: citizen science expanding seismic horizons. *Seismol. Res. Lett.* 80, 26–30. doi: 10.1785/gssrl.80.1.26

Earle, P. S., Bowden, D. C., and Guy, M. R. (2011). Twitter earthquake detection: earthquake monitoring in a social world. *Ann. Geophys.* 54, 708–715.

Engdahl, E. R., van der Hilst, R., and Buland, R. (1998). Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. *Bull. Seismol. Soc. Am.* 88, 722–743.

Finazzi, F. (2016). The earthquake network project: toward a crowdsourced smartphone-based earthquake early warning system. *Bull. Seismol. Soc. Am.* 106, 1088–1099. doi: 10.1785/0120150354

GEOFON Data Centre (2019). *P-Phases Arrival Times Used In Steed et al 2019 for Crowdseeded Seismic Locations (CsLoc)*. Rome: GFZ Data Services.

Heinloo, A. (2016). *The Httpmsgbus General-Purpose HTTP-Based Message Bus*. Rome: GFZ Data Services.

Kanamori, H. (2005). Real-time seismology and earthquake damage mitigation. *Ann. Rev. Earth Planet. Sci.* 33, 195–214. doi: 10.1146/annurev.earth.33.092203.122626

Kennett, B. L. N., Engdahl, E. R., and Buland, R. (1995). Constraints on seismic velocities in the Earth from traveltimes. *Geophys. J. Int.* 122, 108–124. doi: 10.1111/j.1365-246X.1995.tb03540.x

Kong, Q., Allen, R. M., Schreier, L., and Kwon, Y. W. (2016). MyShake: a smartphone seismic network for earthquake early warning and beyond. *Sci. Adv.* 2:e1501055. doi: 10.1126/sciadv.1501055

Minson, S. E., Brooks, B. A., Glennie, C. L., Murray, J. R., Langbein, J. O., Owen, S. E., et al. (2015). Crowdsourced earthquake early warning. *Sci. Adv.* 1:e1500036.

Sambridge, M. (1999). Geophysical inversion with a neighbourhood algorithm—I. Searching a parameter space. *Geophys. J. Int.* 138, 479–494. doi: 10.1046/j.1365-246x.1999.00876.x

Steed, R. J., Fuenzalida, A., Bossu, R., Bondár, I., Heinloo, A., Dupont, A., et al. (2019). Crowdsourcing triggers rapid, reliable earthquake locations. *Sci. Adv.* 5:eaau9824. doi: 10.1126/sciadv.aau9824 doi: 10.1126/sciadv.aau9824

Conflict of Interest: The 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.

Copyright © 2020 Bondár, Steed, Roch, Bossu, Heinloo, Saul and Strollo. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

TECHNOLOGY AND CODE
published: 14 July 2020
doi: 10.3389/feart.2020.00243

The Earthquake Network Project: A Platform for Earthquake Early Warning, Rapid Impact Assessment, and Search and Rescue

*Francesco Finazzi**

Department of Management, Information and Production Engineering, University of Bergamo, Bergamo, Italy

Earthquake Network is a citizen science research project implementing an earthquake early warning system based on smartphone crowdsourcing. People join the project by installing a smartphone application and they receive real time alerts when earthquakes are detected by the smartphone network. Started at the end of 2012, the project has involved more than 5.5 million people and the application currently has around 500,000 active users. This makes Earthquake Network one of the largest citizen science project and an earthquake early warning system operational at the global scale. This paper aims at describing the main features of the project, of the smartphone application and of the data which are made available when an earthquake is detected in real time or reported by the application users.

Keywords: smartphone network, crowdsourcing, citizen science, real time alerts, statistics

OPEN ACCESS

Edited by:
Remy Bossu,
European-Mediterranean Seismological Centre, France

Reviewed by:
Jennifer A. Strauss,
University of California, Berkeley, United States
Ina Cecic,
Slovenian Environment Agency, Slovenia

Correspondence:
Francesco Finazzi
francesco.finazzi@unibg.it

Specialty section:
This article was submitted to Solid Earth Geophysics, a section of the journal Frontiers in Earth Science

Received: *24 February 2020*
Accepted: *04 June 2020*
Published: *14 July 2020*

Citation:
Finazzi F (2020) The Earthquake Network Project: A Platform for Earthquake Early Warning, Rapid Impact Assessment, and Search and Rescue. Front. Earth Sci. 8:243. doi: 10.3389/feart.2020.00243

1. INTRODUCTION

Earthquake Early Warning (EEW) systems are timidly becoming operational in some areas of some seismic countries (Cremen and Galasso, 2020). Despite EEW technology is mature, liability issues about who send the alerts and who is responsible for false/missed detections limit the pace at which EEW are made available to the general public. Additional, the high implementation and operation costs are an obstacle for the diffusion of EEW systems in underdeveloped and developing countries.

In parallel to EEW systems run by government agencies at the national level, the last decade has witnessed the development of “unofficial” platforms providing fast earthquake alerts at the global level. This was possible thanks to smartphone technology and to the crowdsourcing model, with people making their smartphone available in order to receive a useful service in return. Well-known examples are the LastQuake project (Bossu et al., 2018) by the European-Mediterranean Seismological Centre and the MyShake project (Kong et al., 2016) by the UC Berkeley Seismological Laboratory. For LastQuake, a smartphone application (app hereafter) is used to monitor people activity soon after an earthquake. If many people from the same area open the app at the same time, it is likely that an earthquake has just occurred and an alert is sent. For MyShake, a smartphone app is used to continuously monitor the smartphone accelerometer in order to measure earthquakes and possibly send alerts.

This paper is about the Earthquake Network project (Finazzi, 2016) that, despite it has been on the scene long before LastQuake and MyShake, it has only recently gain the attention of the seismological community. As the other two projects, Earthquake Network has its own smartphone app which is used for earthquake detection. In its functioning, the Earthquake Network app is similar to the MyShake app, with the exception that it does not try to make any seismological analysis of the data recorded by the accelerometer and early warnings are issued when many smartphones from the same area detect accelerations above a threshold.

Earthquake Network, however, is more than just EEW and this paper comprehensively describes for the first time all the features of the Earthquake Network platform and of the Earthquake Network app.

2. HISTORY OF THE PROJECT

The Earthquake Network app was first published on the Android Market (now known as Google Play) on 20 December 2012. At that time, the app was only available in Italian and it was designed to work with Android version 2.3.3. With an average of 50 installs per day, it took the network around 5 months to reach the critical mass for detection. The first detection took place in Italy on 8 May 2013 at 00:52:33 UTC. According to the EMSC catalog (ID 315886), a M3.6 earthquake occurred at 00:52:17 UTC with a depth of 8 km. The earthquake was detected by 4 smartphones located at 23 km from the epicenter and an alert was immediately sent to people with the app installed. This was the evidence that smartphones can actually detect earthquakes and this is when the Earthquake Network project officially started.

Since then, more than 5.5 million participants took part to the project, a number higher than the 5.2 million participants of the famous SETI@home project (Anderson et al., 2002) searching for signs of extraterrestrial intelligence since 1999.

Table 1 shows the distribution by country of the 3,130 alerts issued as of 26 May 2020. Note that the first and last alert dates are quite heterogeneous among countries. This is due, on the one hand, on the local seismicity varying with time, and on the other, on the app being installed by the population at different stages of the project life. Usually, people install the app after a strong earthquake hits their area, and the network of smartphones grows up to the point it is able to detect aftershocks and future earthquakes. Similarly, people may loose interest in the project and uninstall the app in periods of "seismic calm," actually jeopardizing future detections in the area. For instance, Nepal had enough users to detect 6 earthquakes in real time in 2015 but it currently only has 150 users with the app installed and new detections are unlikely. The same problem affected Japan and Taiwan for which the two detections are related to aftershocks after large earthquakes. Mainly because the app is not translated into the local languages, however, the smartphone network did not last long.

TABLE 1 | Geographical and temporal distribution of the 3,130 alerts sent by the Earthquake Network platform since 2013.

Country	Alerts	First alert	Last alert	Participants
Chile	952	08 Jan 2014	25 May 2020	801 k
Mexico	770	21 May 2014	24 May 2020	2,200 k
Puerto Rico	728	13 Aug 2014	22 May 2020	181 k
Peru	186	03 Jun 2014	26 May 2020	437 k
Ecuador	147	14 Aug 2014	16 May 2020	567 k
U.S.	109	17 Mar 2014	10 May 2020	272 k
Venezuela	55	23 Nov 2015	11 Mar 2020	40 k
Italy	46	08 May 2013	11 May 2020	487 k
Albania	33	22 Sep 2019	31 Jan 2020	20 k
Croatia	20	22 Mar 2020	23 Apr 2020	12 k
El Salvador	16	11 Apr 2017	09 Feb 2020	18 k
Colombia	10	14 Oct 2015	31 Dec 2019	135 k
Argentina	10	13 Nov 2015	07 Apr 2020	74 k
Costa Rica	8	07 Aug 2014	17 Apr 2019	16 k
Nicaragua	7	11 Apr 2014	24 Mar 2019	33 k
Guatemala	6	22 Jun 2018	19 Apr 2020	30 k
Nepal	6	12 May 2015	22 Jul 2015	27 k
Indonesia	6	22 Aug 2018	15 Nov 2019	20 k
North Macedonia	5	14 Sep 2016	13 Jul 2017	5 k
Panama	5	14 Mar 2019	13 Mar 2020	20 k
Dominican Rep.	3	03 Jun 2018	12 Nov 2018	30 k
Taiwan	1	07 Aug 2019	07 Aug 2019	5 k
Japan	1	04 May 2014	04 May 2014	7 k

The participants column gives the total number of participants (in thousands) by country since the start of the Earthquake Network project.

3. SMARTPHONE APP

The Earthquake Network app is both the instrument to detect an earthquake and to receive the early warning. When the smartphone is charging and unused, the app starts monitoring the accelerometer for detecting vibrations possibly due to an earthquake. If something is detected, a signal is sent to a server that collects signals from all the smartphones. Thanks to a statistical algorithm, the server decides in real time if an earthquake is occurring. If this is the case, an alert is sent to the smartphone users around the epicenter, which may be received before the user experience the shaking.

Earthquake Network, therefore, provides an early warning service to users which are keen to make their smartphones available for detection when the smartphone is not used. On the other hand, the impact of the app on the user daily experience with her/his smartphone is practically zero, nor the app has any impact on battery consumption unless the user interacts with the app.

Figure 1 shows the warning message appearing on the smartphone when the alert is received. If the lead time is greater than zero, a count down and a simulation of the expected location of the P-phase front are displayed.

4. WARNING SYSTEM

The smartphone network sends signals to a server located in Europe for real time detection of earthquakes. The infrastructure is actually based on a total of nine servers which cope with the large number of signals coming from the network and the large number of users opening the app when an earthquake strikes.

Any new signal received by the server infrastructure triggers a statistical algorithm that decides if an earthquake is happening.

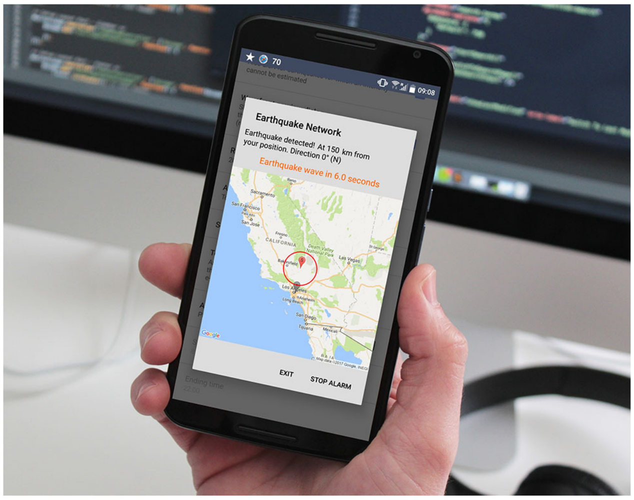


FIGURE 1 | Early warning message as received on smartphones with the Earthquake Network app installed.

The analysis is thus in real time and at the global scale. This implies that multiple earthquakes occurring at different places of the world can all be detected at the same time and separate warnings are issued.

4.1. Statistical Algorithm

On average, only one trigger out of a million is due to an earthquake and adopting a statistical algorithm is the only way to reduce and control the probability of false alarm. Although the algorithm is detailed in Finazzi and Fassò (2017), it is worth describing here the general idea behind its functioning.

The algorithm is based on statistical hypothesis testing which is a statistical inference method for choosing between two hypothesis, one called null hypothesis and the other called alternative hypothesis. The null hypothesis usually describes a favorable condition and, as long as it is true, no action is required. The null hypothesis is thus supposed to be true unless there is enough evidence to reject it in favor of the alternative hypothesis, and evidence is brought by the data.

In this context, the null hypothesis is that no earthquakes are undergoing while the alternative hypothesis is that an earthquake is currently happening and an alert must be sent. Data used for accepting or rejecting the null hypothesis are the triggers send by the smartphones and the number of active smartphones in a given area.

The rule for rejecting the null hypothesis is defined by studying the statistical distribution of the smartphone triggers when no earthquakes are happening. Due to human interaction, smartphones send triggers also when the ground is not actually shaking and the statistical distribution of the number of triggers has a natural variability that mainly depends on the number of active smartphones. Defining the rejecting rule essentially means to set a threshold on the number of triggers, above which an earthquake is claimed. Currently, the minimum value for the threshold is five, meaning that at least six smartphones must be active in the area affected by the shaking and that all of them must send a trigger at around the same time. Below this value, the smartphone network is not reliable. Also note that having six active smartphones does not imply that, in case of an earthquake, six triggers will be received by the server. Smartphones are not seismometers and, for a large number of reasons, they may not send the trigger even if affected by the shaking. This implies that six is a critical mass for detection but also that it is not guaranteed that the detection will occur.

4.2. False Alarms and Missed Detections

When the statistical algorithm is running, two kinds of errors can be made. An earthquake is detected but nothing is happening (false alarm) or the earthquake is happening but the null hypothesis is not rejected (missed detection). There is a trade-off between the probability of false alarm and the probability of missing a detection. Decreasing the former implies to increase the latter and vice-versa.

The choice made by Earthquake Network is to control the probability of false alarm and to fix it at the desired value. Currently, the algorithm is designed to have a nominal false alarm rate of one false alarm per year per country. In practice, this probability is often exceeded due to events which, for the smartphone network, are indistinguishable from an earthquake. These event include explosions, strong thunders, sonic boom and, more rarely, soccer fans celebrating a goal [1].

The probability of missing an earthquake, instead, cannot be easily controlled. While the probability of false alarm is controlled by studying the behavior of the network when no earthquakes are occurring (namely most of the time), the probability of missing an earthquake can only be studied by simulating the response of the smartphone network during that particular earthquake. The response of the network is affected by the spatial distribution of the shaking level, the number of active smartphones, the spatial distribution of the smartphones, the smartphone sensor sensitivity and many other factors which are specific to a given earthquake at a given time.

What is observed is that, when the earthquake epicenter is close to a town with enough smartphones with the app installed, the network is able to detect earthquakes down to magnitude 2. On the other hand, strong earthquakes with epicenter far from any town may not be detected, despite they are mildly felt in different towns. This behavior of the network is currently under investigation.

Additionally, the probability of missing an earthquake is affected by the number of active smartphones at the time of the event. This probability reaches its minimum at around 3 AM when many smartphones are charging while it is maximum at around 2 p.m. Nonetheless, this probability tends to zero when the number of active smartphones increases. When the minimum number of active smartphones, within a town and during the day, is a above 500, the time of day does not matter anymore.

[1]https://www.foxnews.com/tech/soccer-fans-in-peru-celebrate-crucial-goal-trigger-earthquake-alert-app

4.3. Alert Distribution

When an earthquake is detected, the server infrastructure sends the alert to smartphones located in the expected affected area. This is done using the Firebase Cloud Messaging (FCM) messaging platform which allows to send notifications to a large number of smartphones in near real time. The current alert strategy of Earthquake Network is based on the distance between the preliminary epicenter and the smartphones, where the preliminary epicenter is simply the center of gravity of the locations of smartphones that contributed to detect the earthquake.

Smartphones close to the epicenter are thus alerted first. This strategy is not necessarily optimal since smartphones very close to the epicenter cannot be alerted before the shaking and priority should go on smartphones with a lead time greater than zero. Nonetheless, the actual epicenter may be far from the preliminary estimate and the distance-based criterion is the "safest" option under this uncertainty condition.

By default, smartphones receive the alert if located within 300 km from the epicenter but users can change this setting at any time from the app configuration page.

5. USER FELT REPORTS

By simply pushing a button in the app interface, users can report the impact of an earthquake they just felt. Spatial coordinates of the smartphone are automatically sent with the felt report. Contrary to a questionnaire, the app is designed in such a way that the report is sent as fast as possible to the server and the app interface (see **Figure 3**) only allows for three levels of impact: mild (only perceived), strong (fall of objects), and very strong (building collapse).

If many reports are received from the same area at around the same time, a notification is sent to the smartphone users using FCM. In general, users first receive the early warning alert triggered by smartphones and within one minute they receive the notification triggered by users. By clicking on the notification, the user is redirected to a map showing all felt reports. As an example, **Figure 2** depicts the reports collected in Puerto Rico within 60 s after a 3.6 magnitude earthquake. Before any official information was released, app users were aware that the impact of the earthquake was negligible. In general, this kind of information may be useful for civil protection agencies and first responders in order to identify areas where the earthquake had the highest impact on people and things.

Additionally, reports collected in the first few seconds/minutes after the earthquake are useful for providing preliminary estimates of earthquake parameters such as magnitude and depth. Finazzi (2020) shows how a space-time statistical model is trained to provide estimates of the above parameters, uncertainty included, and to update those estimates while new felt report are collected by the server. The statistical model accounts for an information content of the felt reports which increases with time and for the heterogeneity in the people's response across the globe. It is usually the case that people living in low seismicity countries tend to report a strong earthquake despite it is small in magnitude and despite the actual impact is not the one selected through the app user interface.

6. SOCIAL NETWORK

Earthquake Network is also the first social network about earthquakes. With chatrooms in 10 languages, users can share information soon after an earthquake, either in the public space or with private messages. In the public space, order is maintained by chat moderators whose role is to keep the discussion focused on important matters and to block users who behave against the rules. Although secondary with respect to the mission of Earthquake Network, chatrooms actually help people during what can be a shocking experience and, according to their comments, having someone to discuss with is useful to reduce anxiety and the fear of new earthquakes. Moreover, users who join the chatrooms are those who keep the app installed for longer periods, from months to years. User retention is a common problem of citizen science projects and encouraging interaction with the app and other users may increase the user lifetime value.

Earthquake Network is also on popular social networks such as Facebook[2], with nearly 90 k people engaged, and Twitter[3], with around 82 k followers. When an early warning is issued or users report an earthquake, information are published in real time on Facebook and Twitter in order to reach people without the app installed and who will likely join the project.

7. SEARCH AND RESCUE AID

When a strong earthquake hit and causes extensive damage, smartphone technology can be helpful in search and rescue operations allowing missing people to be localized. Earthquake Network is currently testing two strategies for helping localize missing people, one based on statistical modeling of people location and one based on the smartphone geolocation capabilities. Both strategies assume that people and smartphone are located in the same place, which is usually the case.

7.1. Statistical Model of People Location

The Earthquake Network app periodically sends the smartphone location to the server. This information is exploited, on the one hand, for earthquake detection, and on the other, to first alert people close to the epicenter when an earthquake is detected.

Considering all the locations sent by a smartphone during an extended period, a statistical model (Finazzi and Paci, 2019) can be trained to learn the spatio-temporal pattern of the user location along a typical week. Indeed, people tend to exhibit cyclical patterns and to be in the same place at a given time of a given day of the week. If a person is missing after a strong earthquake, the statistical model can provide the expected location(s), uncertainty included, at the time of the earthquake.

[2]https://www.facebook.com/earthquakenetwork
[3]https://twitter.com/SismoDetector

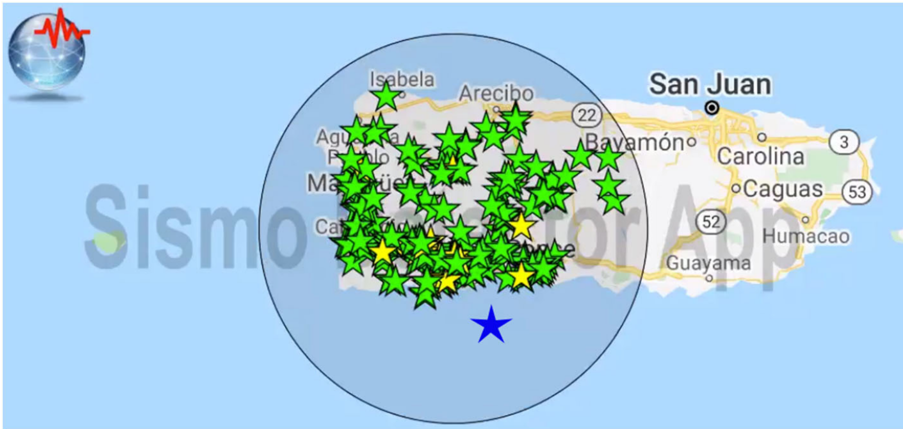


FIGURE 2 | Felt reports sent by users of the Earthquake Network app after a 3.6 magnitude earthquake in Puerto Rico on 26 January 2020, 01:59:26 UTC (EMSC catalog ID 823242) within 60 s from origin time. Blue star is the earthquake epicenter. Green (mild) and yellow (strong) stars are felt reports localized using smartphone spatial coordinates.

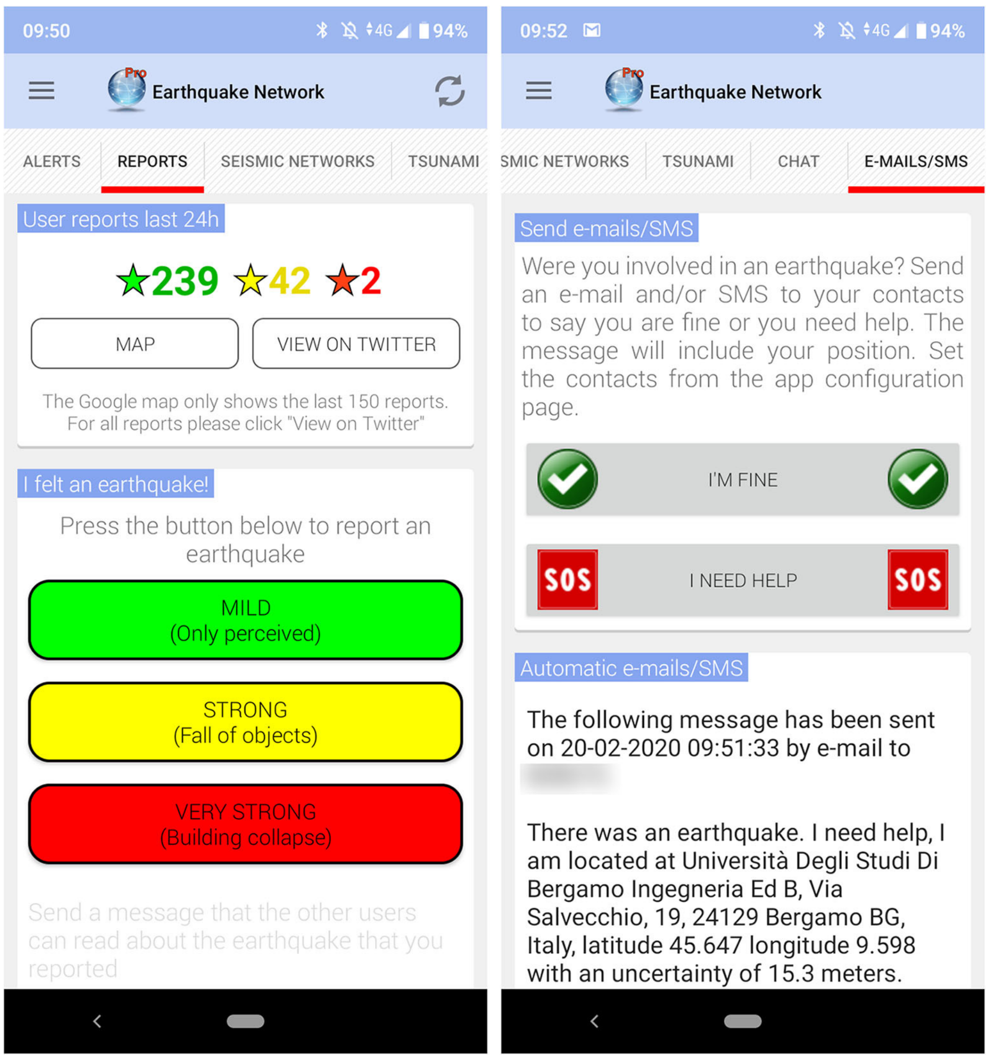


FIGURE 3 | User interface of the Earthquake Network app for sending felt reports **(Left)** and for asking help if involved in an earthquake **(Right)**.

7.2. Real Time Geolocation

The second strategy implemented by the Earthquake Network app is to send the smartphone coordinates by e-mail or SMS to a list of trusted contacts when an alert is received. The idea is that, even in the case of catastrophic earthquakes, the alert is received before the shaking starts and the e-mail/SMS is sent before Internet and/or the phone network are compromised. This solution is more appealing since the uncertainty on the user location is usually much lower if compared with the previous strategy. However, it requires the smartphone to be on at the time of the earthquake.

After the e-mail/SMS is sent, users can update their status by sending a "I'm fine" or "I need help" message to the same contacts. This is done by simply pressing a button in the user interface of the app. The right panel of **Figure 3** shows the user interface for sending messages to contacts and an example of message which is sent by pressing the "I need help" button. Users can opt-in and opt-out this service at any time from the app configuration page, where e-mail addresses and phone numbers of the trusted contacts are also set.

8. IMPLEMENTATION AND OPERATIONAL COSTS

Assessing the implementation costs of an EEW system developed over more than seven years is not an easy task. Nonetheless, the magnitude of some costs can be provided.

Assuming to know all system specifications, developing an app similar to Earthquake Network (for Android and iOS) costs around 40,000 Euros. Implementing the server architecture (hosted by an Internet provider) for the real time detection and able to handle up to one million active users costs around 50,000 Euros. Operational costs, on the other hand, are relatively small. Assuming that the system is stable and does not need major updates, average operational costs are around 250 Euros/month and no human intervention is needed. Currently, these costs are covered by in-app advertising, meaning that the Earthquake Network project is self-sustainable.

Finally, scaling the EEW system requires around 2,000 Euros per million active users. However, smartphone technology may not be the most efficient option for distributing a real time alert to a very large number of people and this cost is meaningful only up to 10 million users globally.

9. USER PRIVACY

Collecting and handling user locations opens some privacy issues. Despite this information is collected anonymously, the user must have a way to delete all personal data (chat messages included) stored on the server. Earthquake Network is compliant with the General Data Protection Regulation on data protection and privacy in the European Union and the European Economic Area. This means that Earthquake Network has a data protection officer who is responsible for handling and deleting personal data upon user request.

10. OPEN PROBLEMS AND CONCLUSIONS

Earthquake Network is widely appreciated in many seismic countries where EEW systems are not available or not yet operational. Despite it releases very preliminary information, it helps to rapidly fulfill the need for information arising among the population soon after an earthquake.

Current main limit of the EEW system implemented by Earthquake Network is that the warning is sent without an accurate information of the earthquake intensity. This means that warnings may also be triggered by mild earthquakes that do not require a warning to be sent. As a consequence, some users may receive the warning but not experiencing any shaking. Although the smartphone is measuring an acceleration, the smartphone acceleration is not easily related to the ground acceleration. Indeed, the smartphone is an object with a relatively small mass that is free to move. Especially during a strong earthquake, the recorded acceleration may be much higher than the ground acceleration. Also, in general, the recorded acceleration may depend on unknown factors such as the object above which the smartphone is located, the floor within the building and so on.

Another intrinsic limit of Earthquake Network is that smartphones are located where people are and the geometry of the network is not necessarily optimized with respect to the known faults. Therefore, it may be useful to integrate the smartphone network data with measurements coming from seismometers.

Thanks to TURNkey[4] and RISE[5] projects financed by the Horizon 2020 programme of the European Commission, Earthquake Network will see improvements both on the real time detection side and on the real time integration of data coming from classing seismic networks. In particular, a statistical approach will be adopted to explore acceleration-free methods for estimating and updating the earthquake intensity/magnitude in near real time, completing the information provided to the population through the Earthquake Network app and through social networks.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

FUNDING

Toward more Earthquake-resilient Urban Societies through a Multi-sensor-based Information System enabling Earthquake Forecasting, Early Warning, and Rapid Response actions TURNkey project has received funding from the European

[4]https://earthquake-turnkey.eu
[5]http://rise-eu.org

Union's Horizon 2020 research and innovation programme under grant agreement No 821046. Real-time Earthquake Risk Reduction for a Resilient Europe RISE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821115.

ACKNOWLEDGMENTS

The author is thankful to two reviewers for very helpful comments that improved the quality of this paper and to Steamware S.R.L. for the great job in designing and implementing the hardware architecture of Earthquake Network.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.00243/full#supplementary-material

REFERENCES

Anderson, D. P., Cobb, J., Korpela, E., Lebofsky, M., and Werthimer, D. (2002). SETI@home: an experiment in public-resource computing. *Commun. ACM* 45, 56–61. doi: 10.1145/581571.581573

Bossu, R., Roussel, F., Fallou, L., Landès, M., Steed, R., Mazet-Roux, G., et al. (2018). Lastquake: from rapid information to global seismic risk reduction. *Int. J. Disast. Risk Reduct.* 28, 32–42. doi: 10.1016/j.ijdrr.2018.02.024

Cremen, G., and Galasso, C. (2020). Earthquake early warning: recent advances and perspectives. *Earth Sci. Rev.* 2020:103184. doi: 10.1016/j.earscirev.2020.103184

Finazzi, F. (2016). The earthquake network project: toward a crowdsourced smartphone-based earthquake early warning system. *Bull. Seismol. Soc. Am.* 106, 1088–1099. doi: 10.1785/0120150354

Finazzi, F. (2020). Fulfilling the information need after an earthquake: statistical modelling of citizen science seismic reports for predicting earthquake parameters in near realtime. *J. R. Stat. Soc. Ser. A*. doi: 10.1111/rssa.12577. [Epub ahead of print].

Finazzi, F., and Fassò, A. (2017). A statistical approach to crowdsourced smartphone-based earthquake early warning systems. *Stochast. Environ. Res. Risk Assess.* 31, 1649–1658. doi: 10.1007/s00477-016-1240-8

Finazzi, F., and Paci, L. (2019). Kernel-based estimation of individual location densities from smartphone data. *Stat. Model.* doi: 10.1177/1471082X17870331. [Epub ahead of print].

Kong, Q., Allen, R. M., Schreier, L., and Kwon, Y.-W. (2016). Myshake: a smartphone seismic network for earthquake early warning and beyond. *Sci. Adv.* 2:e1501055. doi: 10.1126/sciadv.1501055

Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright © 2020 Finazzi. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

ORIGINAL RESEARCH
published: 04 August 2020
doi: 10.3389/feart.2020.00235

Rapid Public Information and Situational Awareness After the November 26, 2019, Albania Earthquake: Lessons Learned From the LastQuake System

Rémy Bossu[1,2], Laure Fallou[1], Matthieu Landès[1], Fréderic Roussel[1], Sylvain Julien-Laferrière[1], Julien Roch[1] and Robert Steed[1]*

[1] European-Mediterranean Seismological Centre, Arpajon, France, [2] CEA, DAM, DIF, Arpajon, France

OPEN ACCESS

Edited by:
Carmine Galasso,
University College London,
United Kingdom

Reviewed by:
Rosemary Fayjaloun,
Bureau de Recherches Géologiques
et Minières, France
Karim Tarbali,
University College London,
United Kingdom

***Correspondence:**
Rémy Bossu
bossu@emsc-csem.org

Specialty section:
This article was submitted to
Solid Earth Geophysics,
a section of the journal
Frontiers in Earth Science

Received: 07 February 2020
Accepted: 02 June 2020
Published: 04 August 2020

Citation:
Bossu R, Fallou L, Landès M, Roussel F, Julien-Laferrière S, Roch J and Steed R (2020) Rapid Public Information and Situational Awareness After the November 26, 2019, Albania Earthquake: Lessons Learned From the LastQuake System. Front. Earth Sci. 8:235. doi: 10.3389/feart.2020.00235

The use of the LastQuake information system, its app, the associated Twitter account, and, to a lesser extent, the EMSC's websites have been analyzed for the 7 days following the November 26, 2019, M6.4 Albania destructive earthquake to evaluate what can be improved and how crowdsourcing of information and monitoring of both use and absence of use of the app can contribute to rapid situational awareness. The mainshock and its numerous felt aftershocks triggered a strong public desire for information, which in turn led to rapid and massive adoption of the LastQuake app by up to 5% of the country's population. The constant flow of new app users created a stress test of the app's crowdsourcing features and led to errors in the association of felt reports with their appropriate earthquake. However, these errors had no identifiable impact, supporting the conclusion that the curation mechanisms currently in place are efficient. The rapid succession of felt aftershocks contributed to these errors by making information related to the mainshock difficult to access within hours of its occurrence, especially for new users who were not attuned to the app, since more recent events pushed older ones down the timeline of presented information. This revealed that prioritization of information within the app layout was lacking and must be an important design objective, especially during aftershock sequences. LastQuake has been shown to be a powerful tool for rapid situational awareness. The possibility of damage was detected within 8 min of the mainshock earthquake by a lack of LastQuake app activity close to the epicenter. This possibility was then gradually strengthened as new data became available and was finally confirmed by the reception of the first geo-located pictures of structural damage and building collapse within 60–70 min. Direct exchanges on Twitter were appreciated by eyewitnesses and seemed to help to reduce their anxiety in some cases (based on the personal reports). Questions mainly focused on the possible evolution of the seismicity. Attempts to debunk prediction claims were difficult. We report on how this could be eased and possibly made more efficient by sharing among the different actors a clear, concise, pre-prepared statement in the local language, that explains the state of scientific knowledge and the difference between prediction, early warning, or forecasts.

Keywords: public earthquake information, crowdsourcing, citizen science, situational awareness, public communication

INTRODUCTION

In 1999, the United States Geological Survey (USGS) developed the "Did You Feel It?" (DYFI) online system to collect felt reports from earthquake eyewitnesses in a standardized manner and to process them automatically (Wald et al., 1999a). It replaced paper questionnaires distributed after earthquakes to collect information about their effects. Such eyewitness reports have always been part of seismology. Preinstrumental earthquakes are primarily—and often exclusively—documented through written evidence (e.g., newspaper clippings, parish bulletin...), this evidence being used by scientists to determine location and magnitude and to extend the historical reach of catalogs for seismic hazard studies (e.g., Musson, 1986). The scientific value of felt reports did not stop with the development of monitoring networks and goes beyond linking past and present earthquake observations. Site effects can be inferred from analysis of historical macroseismic data, which are known to be somewhat subjective and incomplete (e.g., Bossu et al., 2000; Hough and Bilham, 2008). Based on 20 years of DYFI experience, and despite their intrinsic variability, Quitoriano and Wald (2020) list how felt reports contribute to earthquake response and science, from improving Shakemap (Wald et al., 1999b), to social science and behavior studies.

In terms of response, the integration of DYFI data in Shakemap improves shaking estimates, which in turn improves the rapid assessment of the earthquake's impact (Quitoriano and Wald, 2020). In some cases, even an individual eyewitness's observation, a geo-located picture, or a written statement on social media can significantly reduce impact scenario uncertainties by excluding, for example, the possibility of major widespread damage in a specific city (Bossu et al., 2016). Fast crowdsourcing of larger volume of eyewitnesses' observations can then enhance rapid situational awareness and, as such, is a significant development for operational seismology.

Social media and the ubiquity of smartphones have opened new opportunities for fast crowdsourcing and also changed public earthquake communication by allowing instant two-way communication between affected people and institutions/authorities (e.g., Simon et al., 2015; Petersen et al., 2017). This is the basis of the LastQuake multichannel information system, which on the one hand offers rapid earthquake information as well as safety tips to inform and engage with eyewitnesses, and on the other hand crowdsources their observations (felt reports, geo-located pictures, comments) for improved situation awareness and ingestion in new earthquake products (Bossu et al., 2018b).

This article analyzes the use of the LastQuake rapid earthquake information multichannel tools (Bossu et al., 2018b) in the few hours before and up to 7 days after the M 6.4 earthquake, which killed 51 people in the night of November 26, 2019, in Albania, and damaged many buildings in the cities of Durres and Thumane along the Adriatic coast. The aim of this study is two-fold. First, the paper studies whether the LastQuake system correctly addresses the public's need for information. Second, the paper considers what improvements are required for the system to work more optimally during time periods that include foreshocks, a destructive mainshock, an energetic aftershock sequence, and rumors predicting a forthcoming large shock. This is an iterative process that has been carried out after previous large earthquakes, such as Nepal, 2015, Mayotte (France), Lombok, and Palu (Indonesia), 2018 earthquakes (Bossu et al., 2015, 2019a). This article further illustrates how situational awareness can be raised within the first hour through crowdsourcing. It also highlights differences in use of LastQuake app for damaging and non-damaging shaking levels.

Our analysis of the efficacy of the LastQuake system has been derived from qualitative analysis of exchanges on the @LastQuake Twitter timeline and from information collected through the LastQuake smartphone app. Although this reveals only a partial picture, we still believe that there are important lessons here to be learned for the scientific community and for emergency managers in order to exploit the potential of social media for reducing anxiety levels in the population and for seismologists to be better prepared for the recurrent tricky questions that arise about future seismic activity after a damaging earthquake (e.g., Lamontagne and Flynn, 2014; Wein et al., 2016).

After a presentation of the LastQuake system, the studied earthquake sequence, and its background, the LastQuake app adoption and its crowdsourcing performances are analyzed in the context of this destructive earthquake as well as its benefits in terms of improving rapid impact assessments. Strengths and weaknesses of rapid communication disseminated through both the app and Twitter feed are also identified via feedback from its audience before a discussion on a specific earthquake prediction hoax and the possible ways for the seismological community to limit the impact of such rumors in the future.

MATERIALS AND METHODS

This study is based on data collected through the LastQuake information system following the M 6.4 earthquake that struck Albania on November 26, 2019. This data includes LastQuake app launches, crowdsourced felt reports, open comments, and geo-located pictures as well as message exchanges on the @LastQuake Twitter account.

The LastQuake Multichannel Earthquake Information System

LastQuake is a multichannel automatic earthquake information system (for a general presentation, see Bossu et al., 2018b) including a Twitter quakebot, websites (one for desktops and one for mobile devices) and a smartphone app targeting global earthquake eyewitnesses. It is operated by the European Mediterranean Seismological Center (EMSC). It aims to provide rapid earthquake information, engage with eyewitnesses, and initiate crowdsourcing of felt reports (i.e., reports describing shaking and/or damage level), open comments, and geo-located pictures and videos. In turn, crowdsourced information is merged together to create new information products that bring valuable constraints to rapid impact scenarios (Bossu et al., 2016). Crowdsourced data is integrated with other sources of information under the ARISTOTLE project, contributing to rapid (3 h) situation reports for the 24/7 Emergency Response Coordination Center (ERCC) unit of the European Union (EU) Civil Protection Mechanism who coordinates the delivery of assistance to disaster-stricken countries. The ERCC also makes these situation reports available to EU national civil protection agencies (Michelini et al., 2017).

LastQuake utilizes visual communication to erase language and literacy hurdles: felt reports are collected through a set of cartoons describing different shaking and damage levels, each cartoon representing an intensity level of the European Macroseismic Scale 1998 (Grünthal, 1998; **Figure 1**). This approach has been validated by comparing it with the USGS's DYFI macroseismic questionnaire system as well as with independently and manually derived macroseismic datasets (Bossu et al., 2017). Note that felt reports corresponding to intensity 11 and 12 are considered as unreliable and excluded from analyses. Cartoons are also used to offer guidance through safety tips after strong shaking or during a tsunami threat (Fallou et al., 2019). LastQuake is the only information system providing information for only felt earthquakes, regardless of their magnitude. Felt earthquakes are automatically identified through what is called "crowdsourced earthquake detections," which detect eyewitnesses' information-seeking behaviors through their digital footprint immediately after shaking (Bossu et al., 2018b). Three independent sources of crowdsourced detections are in operation, based on rapid changes, respectively, in the number of users accessing EMSC websites (Bossu et al., 2012), of tweets (messages posted on the microblogging Twitter site) containing the keyword "earthquake" in various languages (Earle et al., 2012), and of users launching the LastQuake app (Bossu et al., 2019b). They are complementary with more than two-thirds of felt earthquakes being identified only by a single method, they are fast with detections typically within 20 to 90 s of earthquake occurrence, and they generally precede seismic detections. Crowdsourced detections are published as a rolling banner on websites, as an automatic tweet and on the LastQuake app (without notification). Users are informed about the possibility of a felt earthquake in a given region, and eyewitnesses are invited to confirm the existence of the shaking by providing felt reports (**Figure 1**). When the earthquake responsible has been seismically located, it is associated with related crowdsourced detections, which occurs typically within a few to 20 min depending on earthquake location and magnitude.

The principal objective of the @LastQuake Twitter quakebot is to automatically share rapid earthquake information with its users and encourage those who felt an earthquake to turn to our websites or app to share their felt experience in a structured manner. Structured data collection is essential for automatic processing, for quality checks, and for ingestion into other data products.

For a non-damaging-felt earthquake, there are typically seven automatic tweets published by LastQuake: the first published tweet concerns the crowdsourced detection, then follows the preliminary seismic magnitude and map, the preliminary felt report map (see an example in **Figure 5**), a link to the comments, then a revised seismic magnitude and map, revised felt reports map, and finally, 45 min after the earthquake occurrence, an estimate of the number people who felt the shaking. However, the number of automatically published tweets can increase up to 20 in the same time frame, depending on parameters such as the severity of the earthquake, whether it has been preceded by another shock during the previous days, the existence of a tsunami threat, the volume of crowdsourced data, or whether earthquake parameters (magnitude and/or location) had to be revised. For example, earthquake safety tips are published in the case of a potentially damaging shaking level and tsunami safety tips in the case of a tsunami threat (Fallou et al., 2019).

Alongside automatic tweets, we answer questions left on our Twitter feed and publish and retweet key information related to the earthquake (e.g., scientific information, information on its impact. . .). We also answer remarks and questions on the app stores. We do not answer questions that may appear in the open comments visible on the app and websites. In early September 2019, there were 440,000 LastQuake app users (2,800 in Albania), and the @LastQuake Twitter feed had 109,000 followers.

M 6.4 Earthquake on November 26, 2019

On November 26, 2019, at 03:54 local time, a M 6.4 earthquake occurred a few kilometers north of the port city of Durres (Albania) killing 51 people and injuring 600 others. Several buildings collapsed in the cities of Durres and Thumane, and many were damaged as well as in Tirana, the capital city 30 km from the epicenter[1]. The death toll was probably limited thanks to five felt foreshocks, especially a M 4.4, and a M 3.1, which occurred, respectively, 67 and 35 min before the mainshock, leading many people to leave their buildings before the mainshock (**Figure 2**).

The same region had already been shaken by an earthquake 2 month before. On September 21, 2019, at 16:04 local time, a M

[1]https://balkaninsight.com/2019/12/02/albania-probes-illegal-buildings-after-earthquake-devastation/

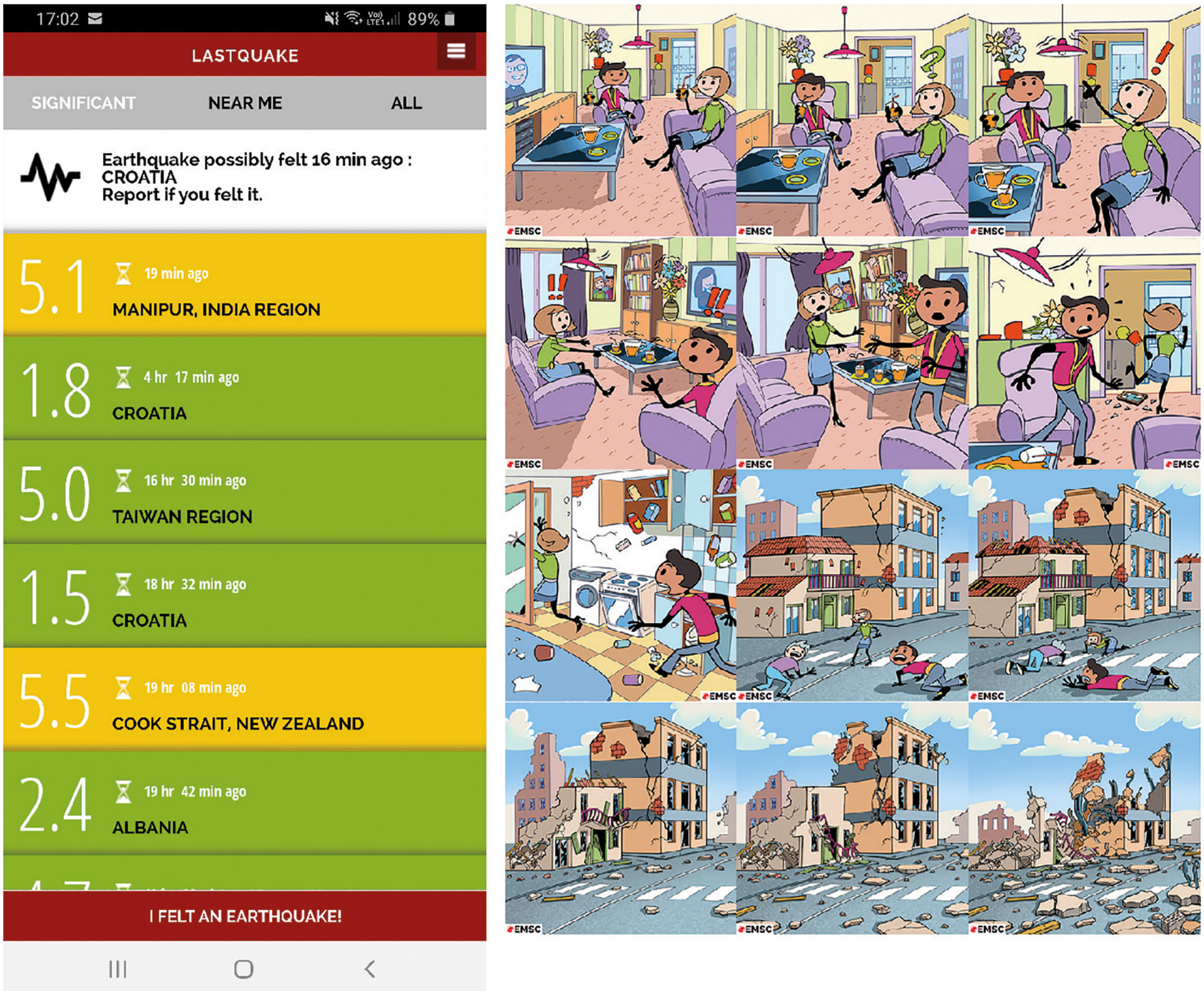


FIGURE 1 | The LastQuake app screen (left) contains the latest felt earthquakes with colors from green to red representing different expected impact (from felt by a limited number of persons to heavily damaging earthquake) and crowdsourced detections (white) not yet confirmed by a seismic location. Felt reports are collected by choosing one of the 12 cartoons (right) presenting different shaking and damage levels. There are two ways for a LastQuake app user to report a felt experience, either by clicking first on the causal event (earthquake or crowdsourced detections) and then accessing the cartoons, or by accessing cartoons directly by clicking on "I felt an earthquake" section of the landing page (left). In the first case, the association between felt reports is performed by the user, while in the second one, it is the EMSC team that will try to perform *a posteriori* this association using a simple magnitude-distance relationship.

5.6 event whose epicenter was within a few kilometers of the M 6.4 mainshock (i.e., within location uncertainties) damaged about 500 buildings, causing no recorded fatalities. As in November, the September M 5.6 earthquake was also preceded 127 min before by a M 3.2 felt foreshock (**Figure 2**). Both September M 5.6 and November M 6.4 were felt throughout the whole country. In both cases, the majority of the seismically recorded aftershocks—down to M 2—were felt by locals according to the felt reports collected by EMSC. Even those earthquakes considered as not felt in these two sequences were close in time with other events (**Figure 2**), and we believe that when aftershocks follow each other within minutes, eyewitnesses may have difficulties selecting the causing earthquake and may tend to choose the event presenting the larger magnitude. In other words, one cannot exclude that some of the aftershocks labeled as not-felt may have indeed been felt. However, this does not affect the results of this study.

RESULTS

Number of LastQuake App Users and Efficiency of Felt Report Crowdsourcing

As observed in other regions of the world, the main driver for LastQuake app installation is widely felt earthquakes, especially rapid successions of felt earthquakes (Bossu et al., 2015). In Albania, the number of users rose from 2,800 to 25,000 in September and exceeded 146,000 7 days after the M 6.4 November earthquake for a population of about 2.8 million inhabitants, i.e., 5% of the population and an average density of $5/km^2$ (**Figure 3**).

People adopt the LastQuake app to get rapid earthquake information. The way they use it is then informative of their information-seeking behaviors. As usual, one can see that large spikes in the rate of app launches correlate with widely felt earthquakes (**Figure 4**). The mainshock was thus detected through the surge in app launches it generated in 73 s. Still, the app launch rate remained high during the daytime, even in the absence of felt earthquakes (**Figure 4**). This indicates that

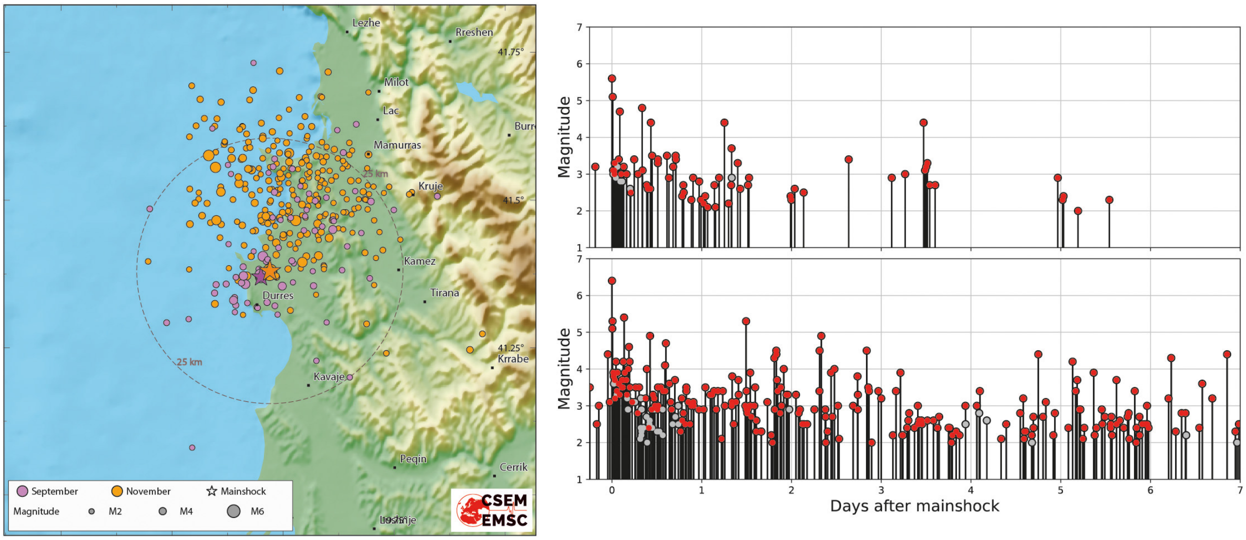


FIGURE 2 | Seismicity map for Albania immediately before and after the September 21, 2019, M 5.6 shock (purple) and November 26, 2019, M 6.4 earthquake (orange) (Left); time evolution of this seismicity before and after the September 21, 2019, M 5.6 shock (Right); and November 26, 2019, M 6.4 earthquake (Right, bottom). For the sake of comparison, figures share the time duration, starting 6 h before the respective mainshock and ending 7 days (168 h) after. Earthquakes in red are the ones known to have been felt, that is, for which felt reports were crowdsourced. Only earthquakes within 100 km of M 6.4 earthquake are shown. Both aftershock sequences were energetic with six aftershocks greater than M 4 for the September 21 M 5.6 event and four aftershocks greater than M 5 for the November 26 M 6.4 event. There were 77 and 271 aftershocks recorded, among them 68 and 234 were reported as felt, respectively.

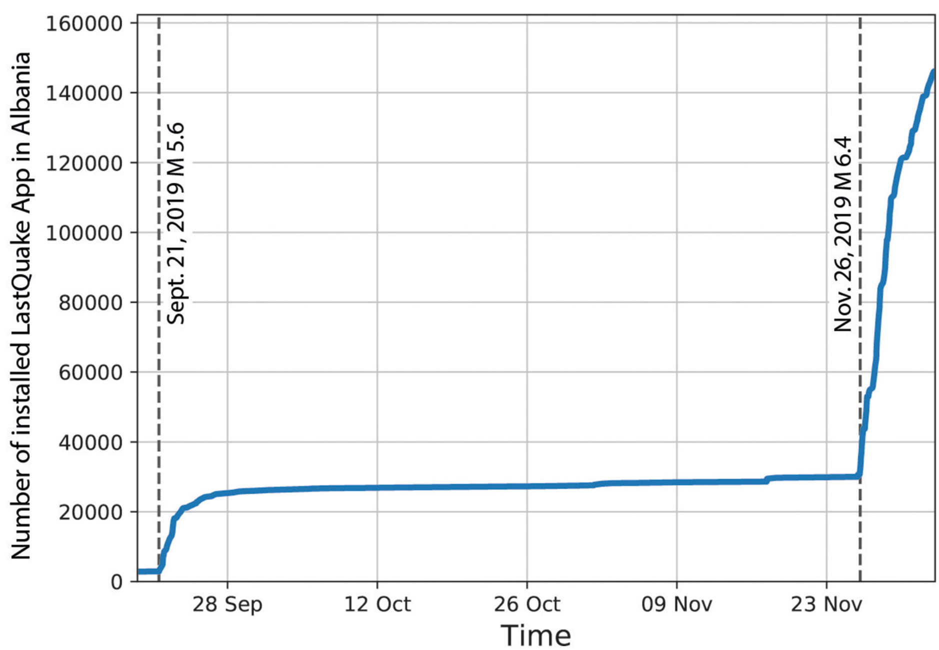


FIGURE 3 | Time evolution of the number of LastQuake app users geo-located in Albania. This estimate contains users who installed the app corrected by the ones known to have deleted it at the time of the estimate. Felt earthquakes led to rapid LastQuake app installations.

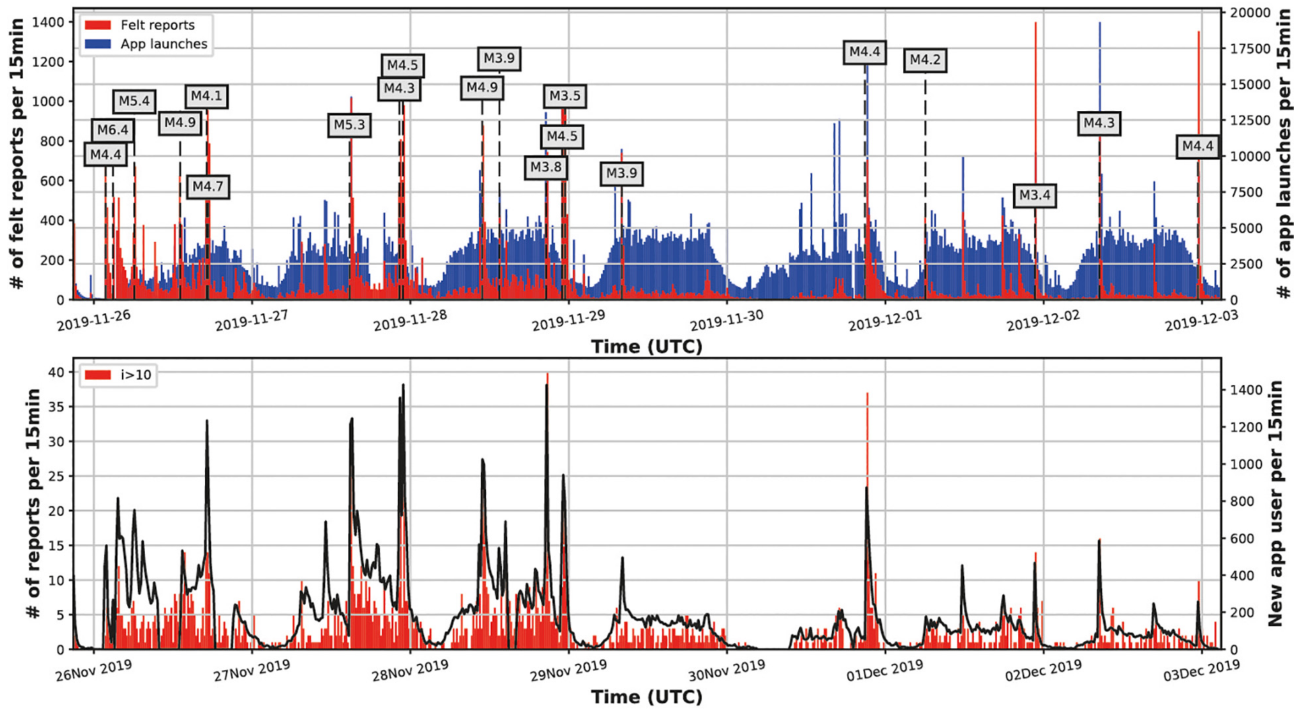


FIGURE 4 | Top: Time variations of individual app launches (blue) and felt report collection (red) within 150 km of the mainshock. The 2.3 M app launches exhibited a strong day/night variation over the whole sequence, showing significant information seeking behaviors even in the absence of felt earthquakes. Some app launch peaks like on November 30 are not correlated with located earthquakes or a surge in felt report collection; **Bottom:** time variations of collected intensities 11 and 12 (red) and LastQuake app installations (black) (below) in 15-min windows during the M 6.4 Albania November period. The strong correlation between the number of intensities 11 and 12 reports and the number of new users suggests that these unrealistically high-intensity values are mainly caused by new users testing the app.

during an aftershock sequence, information-seeking periods are not limited to the immediate follow-up of a tremor but that a significant proportion of users are repeatedly checking for updates, possibly reflecting a high emotional state, a behavior that has been reported on Twitter (see **Figure 4**). For example, the 5% most-active Albanian users launched the app more than 46 times during the studied period.

The LastQuake app is the main crowdsourcing tool of the LastQuake system (Bossu et al., 2015, 2018b), and the number of app users greatly influences both the number of collected felt reports and the sensitivity of felt earthquake identification: the higher the density of app users, the more likely a small magnitude weakly felt earthquake will be reported. In the November period, there were 58,125 collected felt reports within 150 km of the M 6.4 epicenter. For comparison, in the same area, 15,780 were collected in the September period. Intensity in this area was greater than 4 for the former and greater than 3 for the latter. In the period in November, despite our services being inaccessible due to high traffic for 5 h—and very slow after several widely felt aftershocks—there was an average collection of about 6/min. The maximum collection rate was observed for a M 3.4 aftershock on December 1 at 180/min, while it was only 100/min for the mainshock (**Figure 4**), illustrating the impact of the growing number of users (**Figure 5**).

Increasing the number of app users not only impacted the rate of collection but also the volume of crowdsourced data per earthquake. For earthquakes of similar-and-greater-than-3 magnitude, the number of felt reports increased with the number of app users, while for lower-magnitude earthquakes, felt reports were mainly collected once the number of app users exceeded 100,000, illustrating the correlation of the sensitivity of the crowdsourcing system to the density of users (**Figure 5**).

The rate of unassociated felt reports of 22% (12,749) in the November time period is high compared to the 12% (1,825) of the September period. A large number of new app users in conjunction with an energetic aftershock sequence where felt events were sometimes within minutes of each other (**Figures 2**, **3**) probably caused some difficulties and errors in the association of individual felt reports to the causative earthquake. Difficulty in report association likely was amplified by the setup of the LastQuake app, which by default displays the last 25 felt earthquakes. As a consequence of the energetic aftershock sequence, the Albanian mainshock disappeared 4 h 36 min after its occurrence from the default screen of LastQuake app. This may have left new users in a practical difficulty to associate their felt experience, since information about the mainshock was only visible by scrolling down to download older earthquakes.

Errors in report association are illustrated by the M 5.4 earthquake in Bosnia and Herzegovina, which happened 6 h 25 min after the Albanian mainshock (which by then had disappeared from the default screen of LastQuake app) and 250 km away. Although this earthquake was widely felt in

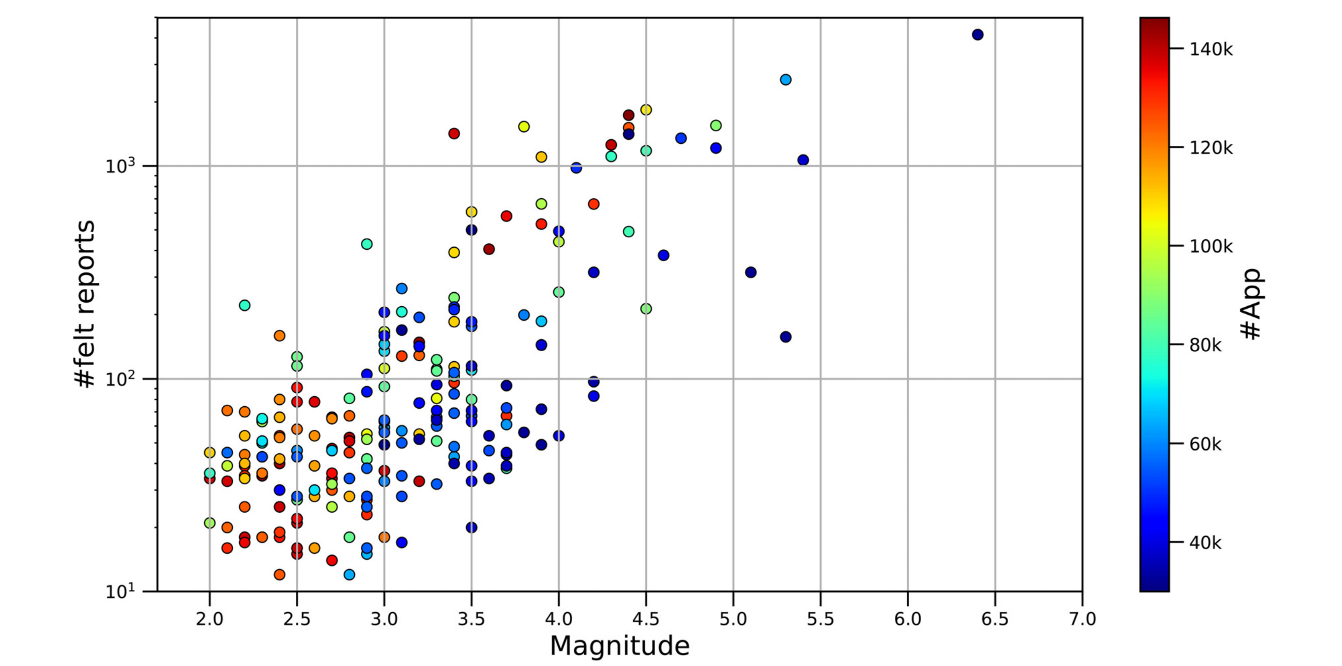


FIGURE 5 | Number of collected felt reports per earthquake as a function of their magnitude for the 228 felt earthquakes of the November 26 studied period (see **Figure 1**) with at least 10 felt reports. The number of LastQuake app users in Albania at the time of each earthquake occurrence is shown via marker color. For a given magnitude greater than three, overall, the larger the number of app users, the larger the number of collected reports. For the earthquakes below magnitude three, felt reports were mainly collected when the number of users was large, reflecting the increasing sensitivity of the crowdsourcing system with growth in the number of app users.

Albania, it did not cause strong or damaging shaking in this country contrary to what was reported by some users (**Figure 6**). The fact that these reported damages were localized along the Durres-Thumane area of the Adriatic coast where actual damage from the Albanian mainshock occurred points to an association error rather than fake felt reports (**Figure 6**). We surmise that some new users may have been confused and reported their experience of the Albanian mainshock via other earthquakes (such as the Bosnian one) due, at least partly, to an inadequate prioritization of information within the LastQuake app.

There is another indication that for new users, at least some of them, may need time and/or tests to discover the app's functionalities and how to share their experience. This is revealed by the strong correlation between the number of new users and the number of intensities 11 and 12 collected (**Figures 1**, **4**). As mentioned before, these intensities values are automatically excluded during data processing because crowdsourcing is highly unlikely to work under such extreme circumstances, and so they are considered to result from tests or jokes (Bossu et al., 2018a). Although some users influenced by high emotional state may have reported such values in good faith, it reaffirms that these reports are not reliable enough to be integrated in situation maps (Bossu et al., 2017).

Crowdsourced Pictures and Videos

Eyewitnesses are also invited to share geo-located pictures and videos. These are manually validated before publication to ensure that they are not related to a previous earthquake or subject to copyright (by checking their possible indexation on the internet, as well as their shooting and location dates), that effects are consistent with expected shaking level at the location, and that they are informative (e.g., a close-up of a crack is not validated) and respect human dignity. There were 1,788 collected pictures, and 361 (available on an interactive map here[2]) were validated and published during the November period. The first picture to be validated was submitted 44 min after the earthquake, the first one to show structural damage in 64 min and the first collapse in 77 min (**Figure 7**). There were 32 validated pictures within 2 h of the mainshock occurrence and more than 200 within 24 h.

This shows that when building collapses are localized (rather than generalized over a whole city or region) and the communication network remains active, first pictures of interest for rapid impact assessment can be crowdsourced within a couple of hours even for an earthquake happening during the night, and the majority are collected within few tens of hours. After a couple of days, submitted files include a majority of selfies or family pictures. It could be part or an extension of a "witnessing culture" with these pictures simply saying, "I lived through this earthquake" (Koliska and Roberts, 2015).

From Crowdsourced Data to Situational Awareness

Crowdsourced information can be a cost-effective alternative to a dense real-time accelerometric network for reducing

[2]https://www.emsc-csem.org/Earthquake/Gallery/maps.php?id=807751

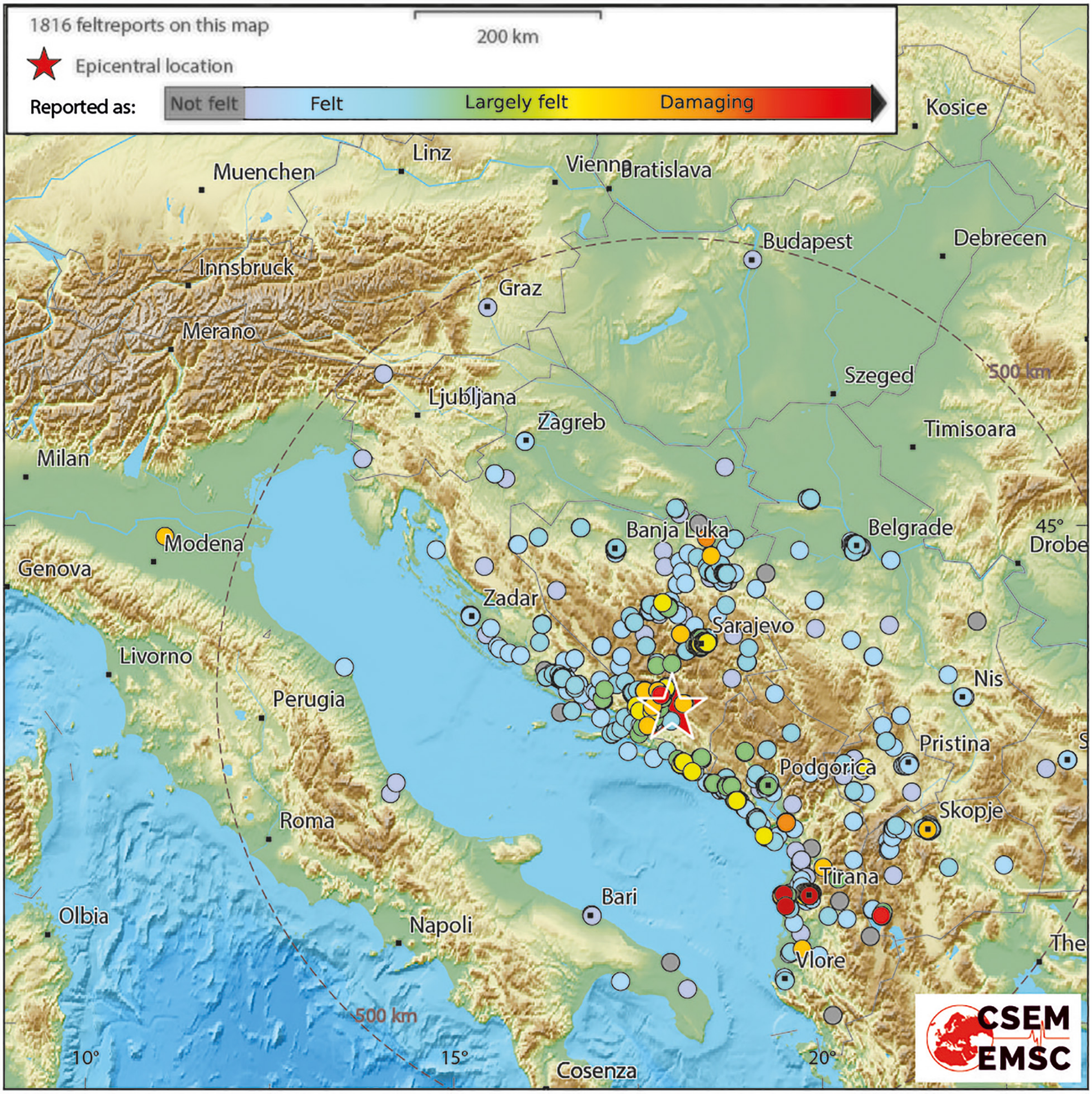


FIGURE 6 | Individual felt reports for the M 5.4 Bosnia and Herzegovina earthquake, which happened 6 h 25 min after the Albanian mainshock. Damaging intensities (in red) are reported along the Adriatic coast where the main damage caused by the M 6.4 earthquake lies but which could not have been incurred by this earthquake. Higher intensity reports are plotted over other reports to illustrate the association issue. However, they are too few to influence the intensity vs distance curve for this earthquake (see an example **Figure 9**) derived from all the felt reports https://www.emsc-csem.org/Earthquake/earthquake.php?id=807844#map.

intrinsic uncertainties of rapid earthquake damage scenarios (Bossu et al., 2016). A schematic pattern, named the "doughnut effect," has been statistically identified for data collected by the EMSC where damaged zones are free or almost free of felt reports and app launches, or at least the local ratio of app launches amongst the locally installed apps is much lower for the same earthquake in damaged areas than in areas affected by lower shaking levels (Bossu et al., 2018a). While the absence of such a pattern is proof of the absence of significant damage, its existence is not a proof on its own of damage and can be due to local communication issues (Bossu et al., 2018a).

The "doughnut pattern" was observed following the M 6.4 Albania earthquake where despite more than 1,000 app users within the first 10–20 km of the epicenter where damage occurred, there were only a few of them launching the app, with

FIGURE 7 | The first crowdsourced picture exhibiting structural damage (left) was collected 64 min after the mainshock and located in Tirana, 30 km from epicenter. The first collapse (right) was collected 77 min after the mainshock and taken in Durres, less than 10 km from the epicenter.

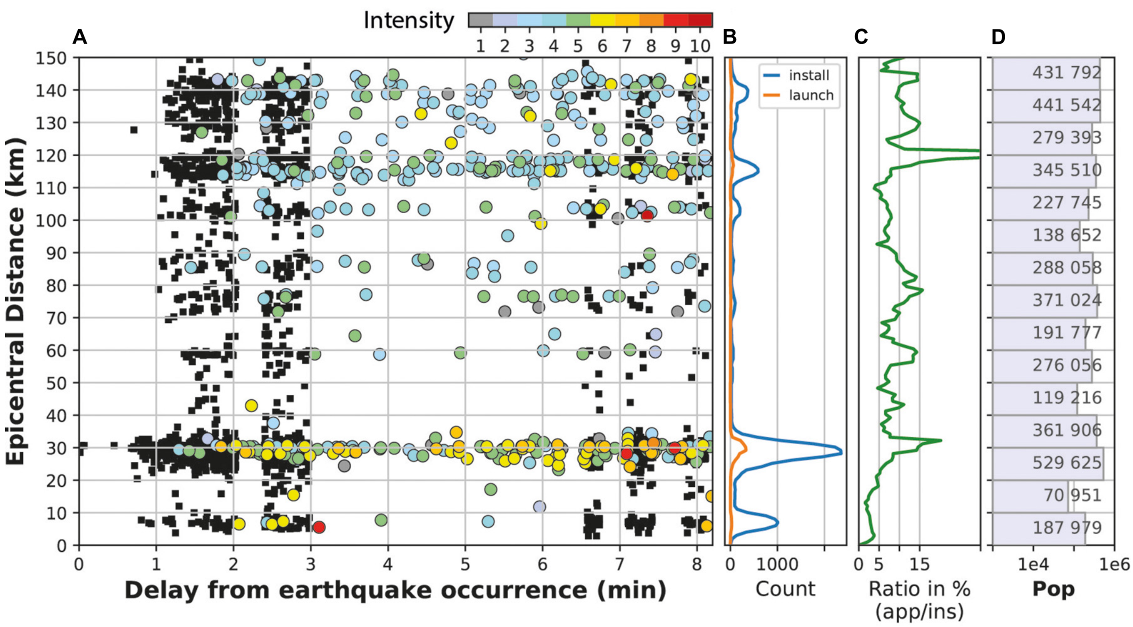


FIGURE 8 | Time-distance distribution of app launches (black square) and felt reports (colored circles) for the M 6.4 Albania earthquake occurrence until the app notification—8 min after the earthquake occurrence—that is, when app users react to the shaking rather that the notification The apparent absence of app launches in different time intervals (e.g., from 3 to 6 min) is an artifact due to technical issues during the data collection process due to the high level of internet traffic to the EMSC servers **(A)**; only a minority of installed apps (blue curve) are launched (orange curve) in this time window **(B)**; still, the ratio (green curve) of app launches to app's locally installed decreases below 5% within 20 km of the epicenter indicating the possibility of damage in this area (curves are smoothed with a 2.5 km space window) **(C)**; and population in 10-km intervals are indicated **(D)**.

a ratio below 5% in the first 8 min (**Figure 8**). It was the first indication of the likely existence of damage.

The second indication resulted from Earthquake Qualitative Impact Assessment, a software used internally at EMSC, calibrated on past earthquakes where impact is estimated by comparing expected ground motion with the number of inhabitants (Bossu et al., 2009; Julien-Laferrière, 2019a,b). Its first automatic estimate based on preliminary earthquake parameters was available 10 min after the earthquake, immediately after the first preliminary earthquake parameters were available. It was updated 15 min later once earthquake parameters had been manually reviewed. Both qualitative impact assessments predicted significant damage in the epicentral region. Likely damage was further supported by the automatic analysis of felt reports, which indicated an intensity eight (severe damage) within 1 h of the quake within 13 km of the epicenter (**Figure 9**). After an hour, the existence of damage within 10–20 km of the epicenter could be established with high certainty supported by impact scenario data (Earthquake Qualitative Impact Assessment results), statistical analysis of felt reports (**Figure 9**), and eyewitnesses' digital footprints (**Figure 8**). It was further confirmed with the first crowdsourced geo-located pictures of damage (**Figure 7**).

Collected Open Comments

During the November period, 34% of the felt reports associated with an earthquake were also associated with an open comment, a proportion similar to that observed for other earthquakes. We do not currently exploit these comments for situational awareness. They are generally shared by eyewitnesses to express emotions (anxiety, fear...) and/or felt experience in plain words. They are visible on EMSC's websites and on the app where users can vote in favor or against a comment through a system of up and down arrows. Reading other eyewitnesses' experiences is an appreciated feature of the app often mentioned as such on the IOS and Android app stores. Moderation is minimal due to language barriers, and the volume of comments typically no more than a few comments are deleted per earthquake, with special attention on comments with significant negative votes. Moderation, which is explicitly mentioned in the terms of service of the app, concerns offensive comments, earthquake prediction claims, proselytism comments, fake news (e.g., fake death toll), or comments including phone numbers, Internet links, and social media handles. Some comments were removed after being reported to us by email.

Alongside its main objective of sharing emotions and earthquake experience in plain words and although one cannot directly answer a comment, this feature has been exploited during the November period by some as a social platform, for example, posting ads to sell cars, furniture, dating messages, and many for humoristic remarks as well as political comments. This new usage of the comments as a sort of social network was later observed following the destructive Elazig, Turkey, M 6.8 earthquake of January 24, 2020. Although this earthquake was not felt in Albania (1,600 km away), some Albanian users shared felt reports and comments such as "Pray for Turkey" comments, which were among the most voted for. This further illustrates that, at least for some Albanian users, the role of comments expanded from its initial objective of sharing experience to more direct discussion. Such an extension of use was not unanimously approved; comments not related to the earthquake led to new comments complaining about what their authors perceived as inappropriate behavior in the face of a disaster.

We received emails and messages on Twitter asking for more stringent moderation. Beyond the difficulty and resources needed for moderating comments in foreign languages, we consider it difficult to draw a precise line between what is and is not acceptable, especially in terms of humor or political statements because it is highly cultural. From our perspective, the fact that this feature is commonly used argues that its overall benefits outweigh possible negative impact. Being appreciated by users, it may contribute to the adoption and/or retention of the app and in turn to its crowdsourcing efficiency.

Earthquake Communication on Twitter

The aims of the @LastQuake Twitter account are to broadcast rapid information about felt earthquakes, attract more app users, and better understand public expectations after earthquakes. Publications comprise of automatic tweets (a quakebot) conveying rapid earthquake information as well as manual ones. The latter cover general solid earth science. They also share external information and resources about damaging earthquakes, and they include systematic—or nearly systematic—direct answers to questions. The increase in the number of followers on Twitter was far more modest than the one observed for LastQuake app users, moving from 109,000 at the beginning of September to 124,000 at the end of the November period. There is no way to evaluate the proportion of these new followers from Albania.

During the November period, there were 14.2 million cumulated views of the 2,272 @LastQuake tweets. The most viewed was our dedicated Twitter moment with 238,000 views (a compilation of tweets gathering key information on the earthquake and its effects) and which was pinned (i.e., remained the first message of the @LastQuake timeline) during the duration of the November period. The second most popular with 140,000 views was our first tweet published on November 26, explaining that earthquake prediction does not exist and should not be trusted (**Figure 10**).

On November 26, the day of the mainshock, there were 586 tweets published, mainly automatic ones, relating to the numerous felt earthquakes in Albania (**Figure 1**). This was too high a number of publications to be easily followed. Furthermore, information about the mainshock had been rapidly replaced by new tweets, and so the Twitter moment had to be put in place to correct this and make the mainshock data accessible. Beside the volume of tweets, a common situation was the intertwining of automatic tweets from different events since automatic tweets continue to be published up to 45 min after an earthquake (**Figure 1**). This lack of clarity can create potential confusion, especially during a rapid succession of aftershocks when users may be nervous and tense. In conclusion, the current publication strategy of the LastQuake twitter quakebot is not suitable for an energetic aftershock sequence. It will be revised in order to hierarchize the information, that is, first to ensure the information about the mainshock remains easily accessible, and second to reduce the number of tweets about small magnitude aftershocks and shorten the time window of publication.

Although this analysis is purely qualitative, exchanges with Twitter followers illustrate the high level of anxiety among at least in part of the population (**Figure 10**). Some report how they constantly check for updates on the LastQuake app (**Figure 10**), a behavior that likely contributed to the large number of app launches even in the absence of felt earthquakes (**Figure 4**). Despite slow services due to high traffic after widely felt earthquakes, users found information useful and somehow comforting, illustrating the public desire for information during an earthquake and why it is important for the seismological community to fulfill this need (**Figure 10**).

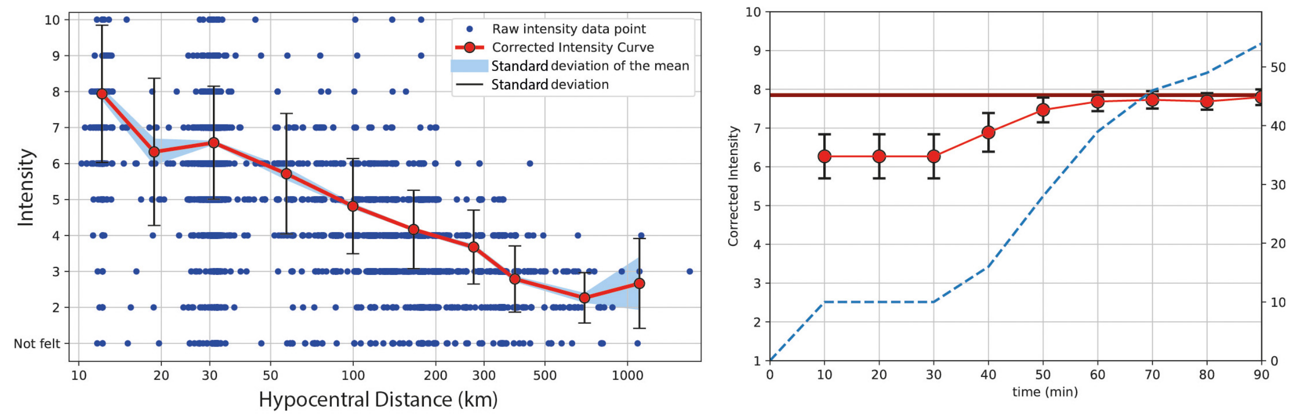


FIGURE 9 | Right: Time evolution of the intensity derived from felt reports within 13 km of the epicenter (red). The increase of number of felt reports (blue dashed) and the estimated intensity after 30 min translates the doughnut effect. The intensity moved from 6 (slightly damaging) to 8 (heavily damaging) between 30 and 60 min after the earthquake. The final intensity is shown as a horizontal dark red line. Left: Final intensity vs distance curve (red) derived from collected felt reports (blue dots). If individual reports at the same epicentral distance exhibit significant variability (as measured by the standard deviation), averaging allows accurate estimation of the mean intensity (as measured by the standard deviation of the mean). Intensities are corrected following procedures presented in Bossu et al. (2017).

The Question of Earthquake Prediction and Evolution of the Earthquake Sequence

The central question raised on Twitter was about the possible evolution of the seismicity after the mainshock, whether the aftershock rate was normal, whether one should expect a new damaging shock, and whether earthquake prediction can be trusted. We explained the best we could, without jargon and with empathy (Bartel and Bohon, 2019), that a new damaging shock was not the most likely scenario but could not be totally ruled out and that the aftershock rate decreases with time but will last for weeks and months. Despite the lack of certainty, these answers were generally accepted, and Twitter users appreciated our effort to provide them with answers, even incomplete and non-actionable (**Figure 10**).

Earthquake prediction is another recurrent question after a strong earthquake. Following similar experience during the Lombok (Indonesia) 2018 earthquake sequence (Bossu et al., 2019a), we systematically publish a message on Twitter after a damaging earthquake explaining that earthquake prediction does not exist as of today and that such a claim should not be trusted (**Figure 10**). We also systematically blocked Twitter accounts associating prediction claim to our Twitter account in an attempt to make it visible to our followers. This stringent policy aims at reducing possible adverse consequences of earthquake prediction rumors. An example of such a negative consequence was observed in Albania on September 22, 2019, when large-scale panicked evacuations were reported following a prediction about an imminent earthquake published online[3]. A similar rumor spread via the messaging app Whatsapp on November 27, maybe also with panicked evacuations, although this is disputed[4]. In the latter case, the audio message was a deliberate attempt to create panic by claiming that the prediction was based on confidential military information and explicitly inviting people to leave the area. We published several tweets in an attempt to counter this claim. However, some answers and new questions showed there can be confusion between early warning, aftershock forecast, and prediction and that we lacked a clear, simple, and complete statement in the local language to explain what science can and cannot offer today.

[3]https://shqiptarja.com/lajm/ministria-e-mbrojtjes-sqaron-lajmi-per-termet-te-fuqishem-ne-2330-i-pavertete-fajtoret-do-mbajne-pergjegjesi

[4]https://shqiptarja.com/lajm/nje-audio-ne-italisht-shperthen-panikun-ne-durres-por-eshte-false

DISCUSSION AND LESSONS LEARNED

We analyzed the use of the LastQuake multichannel information system in the aftermath of the deadly M 6.4 Albania earthquake of November 26, 2019, to identify its strengths and weaknesses in answering public desire for earthquake information, as well as how the data it collects from eyewitnesses can contribute to rapid situational awareness. We acknowledge that since this study is focused on a single country, Albania, the cultural context, risk perception, and technological culture are likely playing a role, but we still believe there are lessons to be learned. This earthquake is of specific interest because the number of LastQuake app users in Albania was significant (25,000) when the mainshock struck thanks to a previous M 5.6 earthquake, which affected the same region on September 21, 2019. It reached 5% of the country population 7 days after the mainshock and after more than 200 felt events represents the highest adoption rate we can realistically expect for this app. Rather than representing the average expected performances for any global earthquake, this study then likely illustrates the current best-case scenario.

This analysis confirms two important lessons learned from past earthquakes, such as the M 7.8 2015 Gorkha Nepal earthquake (Bossu et al., 2015). First, that felt earthquakes trigger a public desire for information and the adoption of LastQuake app (**Figure 1**). Second, while the app is the most efficient and

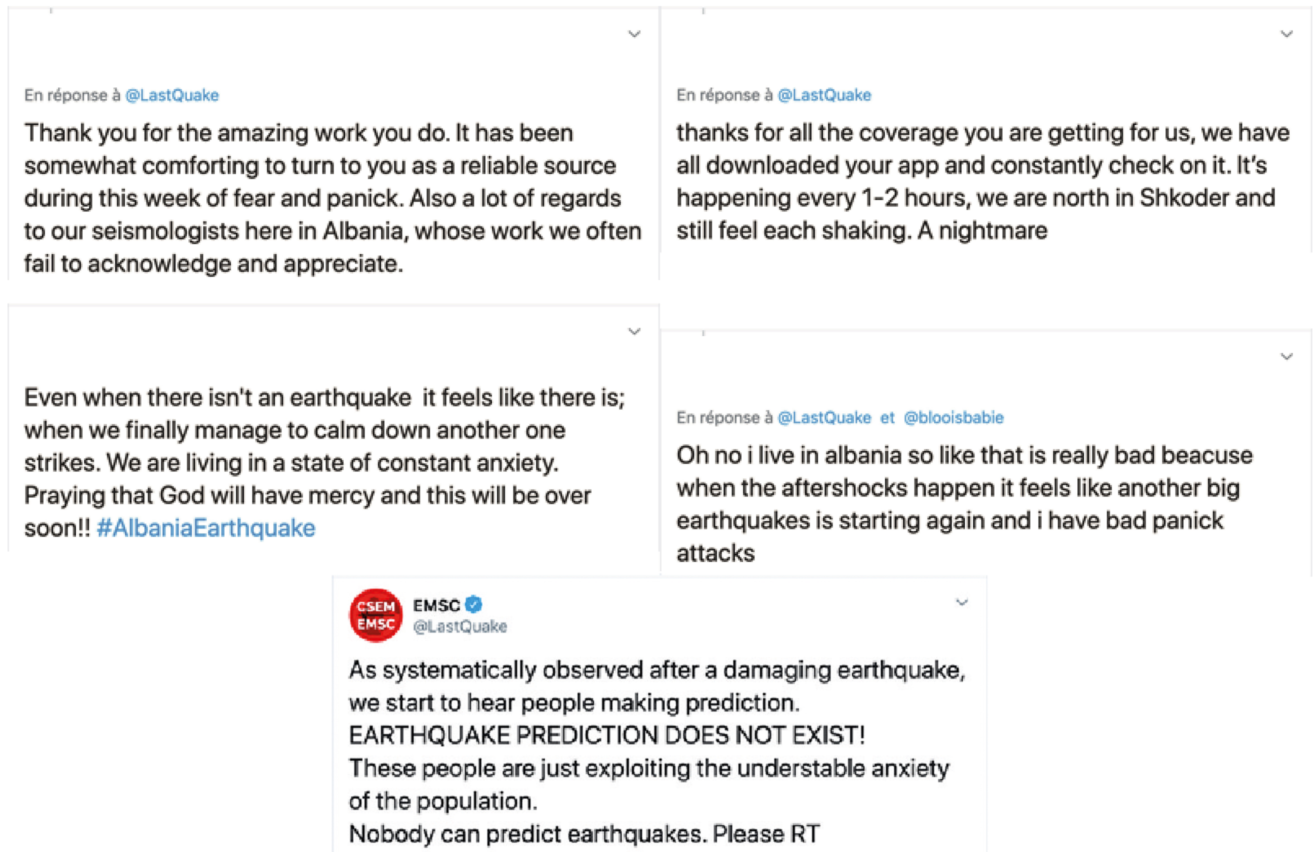


FIGURE 10 | Examples of tweets exchanged following M 6.4 earthquake in Albania. EMSC systematically reminds its audience after damaging earthquakes that earthquake prediction does not exist to date. Followers express their anxiety, compulsive need for information and appreciation of @LastQuake information. Some report possibly phantom earthquake effects.

rapid crowdsourcing tool yielding 96% of the felt reports collected in the first 10 min of the mainshock, websites remain essential in terms of reach with an average of 1 million daily unique visitors during the 7-day studied period, with one-third originating from Albania. App launches were also significant even in the absence of located felt earthquakes (**Figure 4**). It cannot be excluded that some $M < 2$ aftershocks (M2 being the smallest reported aftershocks) caused some app launch activity because the aftershocks were located in a populated area and could have been felt. However, that is also consistent with a behavior identified by Wein et al. (2016) via focus group studies where some members of the public try to relieve anxiety by "endlessly seeking scientific information when emotional support is actually needed." Another possible explanation could be "phantom earthquakes" when some people report feeling tremors that cannot be confirmed by any seismic data after a large earthquake (e.g., Takayama, 2017; Hapsari et al., 2019). Both phantom earthquake phenomena and unreported small-magnitude felt aftershocks could explain why fake crowdsourced earthquake detections caused by high traffic during the studied period were regularly confirmed by several individual felt reports. Whatever the cause, we should consider strengthening earthquake detection criteria during aftershock sequence to restrict crowdsourced detections to larger app launch surge and to avoid contributing to any phantom earthquake phenomena.

In the studied case, new users were shown to be more likely to report unrealistically high-intensity values (11 and 12) and to make mistakes in associating their felt reports with the correct causative earthquake. Intensities 11 and 12 resulted either from tests of new users or from overinflated reports (potentially due to high emotional state) but also possibly due to a lack of distinction between the different cartoons representing high intensities (**Figure 1**). On the cartoons, intensities 8–12 mainly differ through the level of damage to the same couple of buildings (**Figure 1**), while the definition of the EMSC 98 scale, includes a different class of building vulnerability and different proportion of damaged buildings. If building vulnerability cannot be easily estimated by laypersons—and even less through a simple system of cartoons—cartoons could better represent a different proportion of collapsed buildings that range from intensity 8 to 12 from a few to most/all. More precise and distinctive cartoons could help an eyewitness observing a couple of collapsed buildings in an otherwise unscathed neighborhood not choose intensity 11 or 12. Until such changes are developed, tested, and implemented, our analysis confirms previous studies that intensities 11, 12 have to be excluded from automatic processing (Bossu et al., 2017).

Errors in felt report association with the causative earthquake are not specific to the LastQuake system, and Quitoriano and Wald (2020) noted that "DYFI contributors tend to select the most recent earthquake displayed on the USGS website." However, they were likely amplified by the current setup of the app where, due to the lack of information prioritization, information about the mainshock was difficult to access within hours of its occurrence. A similar prioritization issue was identified with the Twitter quakebot. They will need to be corrected to ensure both on the app and on Twitter that essential information, such as reports related to the mainshock, remains easily accessible during an appropriate time window and also to limit information overload due to multiple aftershocks, notably by reducing the number of tweets automatically published for small-magnitude aftershocks. Despite slow and sometimes disrupted app services due to the high demand on the EMSC's internet infrastructure and the lack of an Albanian language version of the LastQuake app (which was only released in January 2020) the overall satisfaction was large with a rating for Albania of 4.8/5 (based on 504 ratings on January 24, 2020) in the IOS store where statistics per country are available.

A second important result concerns rapid situation awareness. This study confirms that when the number of users is significant in the epicentral region, when communication networks remain operative and building collapses remain localized rather than widespread over a whole city, the LastQuake system can confirm the existence of significant damage suspected from impact scenarios within about an hour thanks to independent corroborating information. The first cue about the existence of damage was derived within 8 min (i.e., when the first preliminary seismic location was available) of the earthquake occurrence through the lack of app users' reactions within 20 km of the epicenter (**Figure 8**). This was then supported by a rapid impact scenario, then by a felt report analysis, and (**Figure 9**) finally through the first crowdsourced geo-located pictures of structural damage and collapse (**Figure 7**). Although today comments are not exploited for situational awareness, there is, however, a potential here too with the first comment in English reporting damage from Durres 48 min after the mainshock: "*It was scary. A five-story building fell in front of my eyes. People were hurt. Communication shut till now. Stay safe Albanians.*" These results indicate that rapid impact assessment can directly benefit from improved public interaction by fast cost-effective collection of valuable information and data on earthquake impact while better fulfilling strong public desire for information after widely felt earthquakes. Put together with a recent work by Steed et al. (2019) demonstrating that the combined analysis of crowdsourced and seismic data improves seismic network location performances at marginal costs, the current work further illustrates that operational seismology can benefit from crowdsourced data.

Open comments are an appreciated feature of the app. They have been exploited by the users in Albania not only to share experience and emotions in plain words but also more as a type of social platform with comments answering each other and topics not always related to earthquakes. We do not know whether this is specific to the affected country or a change of expectations and needs during an aftershock sequence or a type of behavior that only emerges with a large density of users. It will be monitored during future earthquakes, and if necessary, our moderation policy will be updated.

Exchanges on Twitter @LastQuake reflect anxiety among the population and the desire from the affected people for direct interactions. Exchanges being in English and the number of Twitter followers having not dramatically surged during the studied period (and the geographical origin of followers being difficult to identify), the potential impact of such exchanges should not be overevaluated. Although this may not be true for the whole affected population, LastQuake followers on Twitter from Albania reported that service and information offered tend to reduce their anxiety (**Figure 10**). Same effects were reported by LastQuake Twitter followers during other earthquake sequence, such as 2018 Lombok (Indonesia) or in Mayotte (France) (Fallou and Bossu, 2019) and consistent with study underlining the importance of information during crisis to reduce uncertainty and comfort affected population (Saathoff and Everly, 2002; Boyle et al., 2004).

Questions were often about possible evolution of the seismicity and the trustworthiness of prediction claims. The lack of certainty in our answers about possible sequence evolution, where we systematically mentioned that an earthquake as strong or even stronger than the mainshock was unlikely but could not be totally excluded, was accepted and positively received. Focus then shifted more specifically on earthquake prediction after such a claim spread on the messaging app WhatsApp. Because such claims, observed after many significant earthquakes around the globe can have advert consequences such as panic evacuations, we believe that both EMSC but also the seismological community should be better prepared to debunk them by communicating rapidly with the public. We thus advocate for the establishment of a clear, concise statement on this topic, explaining differences between prediction, aftershock forecast, or early warning, a statement that ideally would be endorsed and shared by the seismological community and made available in multiple languages. EMSC and other actors could then automatically publish it after large earthquakes both on Twitter but also on the LastQuake app. An informal international working group has been set up to prepare such a statement. Although it will not be a panacea, such a document made rapidly and widely available after destructive earthquakes in an easy-to-understand format could contribute to reducing unnecessary confusion and anxiety among the population at a time of high emotional state. This communication issue about prediction is part of a wider effort in seismology to adapt rapid direct public communication to time-varying hazard products, such as aftershock forecast or earthquake early warning (e.g., Jordan et al., 2014; Lamontagne and Flynn, 2014; Wein et al., 2016; Allen et al., 2018; Allen and Melgar, 2019; McBride et al., 2020) in a consistent way.

CONCLUSION

This article demonstrates that a multichannel earthquake information system such as LastQuake aiming to satisfying eyewitnesses' information needs can efficiently engage with them and collect, at least in some cases, essential information about the damage caused by an earthquake with 60–70 min of its occurrence and then reduce uncertainties of the damage scenario and improve rapid situational awareness. It also identifies some weaknesses in the LastQuake system that will need to be addressed.

More fundamentally, it shows that earthquake predictions, which tend to flourish after a damaging earthquake, could be better debunked by having a clear and concise consensual statement available in various languages about what science can and cannot offer today in terms of time evolution of seismicity. Although it will not eradicate on its own all possible advert consequences of every pseudo-prediction, it would facilitate communication and possibly encourage more actors, individual seismologists, seismological observatories, or civil protection agencies to engage with the public on social media before and after earthquakes to contribute to raising awareness, improving earthquake literacy, and reducing public anxiety.

DATA AVAILABILITY STATEMENT

Felt reports can be found through the web service, https://www.seismicportal.eu/testimonies-ws/. The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

RB formulated the overarching research goals, led and supervised the project, and acquired funding. LF and ML had major contributions in the analysis of the results. FR, SJ-L, JR, and RS have contributed in LastQuake system development and operation as well as in data preparation and provided feedback during the discussions. All authors contributed to the article and approved the submitted version.

FUNDING

This article was partially funded by the European Union's Horizon 2020 Research and Innovation Program under grant agreement RISE No. 821115 and grant agreement TurnKey No. 821046. Opinions expressed in this article solely reflect the authors' views; the EU is not responsible for any use that may be made of information it contains.

ACKNOWLEDGMENTS

Rapid earthquake locations are collated from different seismological institutes contributing to the EMSC earthquake information system. We thank them for their support with a special thanks to the Institute of Geosciences, Energy, Water, and Environment (IGEWE) of Albania.

REFERENCES

Allen, R. M., Cochran, E. S., Huggins, T. J., Miles, S., and Otegui, D. (2018). Lessons from Mexico's earthquake early warning system. *EOS Earth Space Sci.* 99. Available online at: https://eos.org/features/lessons-from-mexicos-earthquake-early-warning-system

Allen, R. M., and Melgar, D. (2019). Earthquake early warning: advances, scientific challenges, and societal needs. *Annu. Rev. Earth Planet. Sci.* 47, 361–388. doi: 10.1146/annurev-earth-053018-060457

Bartel, B., and Bohon, W. (eds) (2019). "The hazards of hazard communication: importance, rewards, and challenges of science in the public sphere: a white paper summary of presentations from session," in *Proceedings of the PA23B at the 2018 Fall Meeting of the American Geophysical Union*, Washington, DC.

Bossu, R., Fallou, L., Julien-Laferrière, S., Landès, M., Roch, J., Roussel, F., et al. (2019a). *How to Improve Rapid Public Earthquake Information? Listen to Eyewitnesses!*. Available online at: https://blogs.egu.eu/divisions/sm/2019/05/08/how-to-improve-rapid-public-earthquake-information-listen-to-eyewitnesses/

Bossu, R., Gilles, S., Mazet-Roux, G., Roussel, F., Frobert, L., and Kamb, L. (2012). Flash sourcing, or rapid detection and characterization of earthquake effects through website traffic analysis. *Ann. Geophys.* 54, 716–727.

Bossu, R., Landès, M., Roussel, F., and Steed, R. (2018a). Felt reports for rapid mapping of global earthquake damage: the doughnut effect? *Seismol. Res. Lett.* 89, 138–144. doi: 10.1785/0220170129

Bossu, R., Landès, M., Roussel, F., Steed, R., Mazet-Roux, G., Martin, S. S., et al. (2017). Thumbnail-based questionnaires for the rapid and efficient collection of macroseismic data from global earthquakes. *Seismol. Res. Lett.* 88, 72–81. doi: 10.1785/0220160120

Bossu, R., Laurin, M., Mazet-Roux, G., Roussel, F., and Steed, R. (2015). The importance of smartphones as public earthquake-information tools and tools for the rapid engagement with eyewitnesses: a case study of the 2015 Nepal earthquake sequence. *Seismol. Res. Lett.* 86, 1587–1592. doi: 10.1785/0220150147

Bossu, R., Merrer, S., and Mazet Roux, G. (2009). *Applications and Utilization of ELER Software. Evaluation of the Level 0 Approach*, 38. Available online at: http://www.neries.eu.org/main.php/JRA3_D5EMSCImpactEstimationJRA3_V3.pdf?fileitem=10272797

Bossu, R., Roussel, F., Fallou, L., Landès, M., Steed, R., Mazet-Roux, G., et al. (2018b). LastQuake: From rapid information to global seismic risk reduction. *Int. J. Disaster Risk Reduct.* 28, 32–42. doi: 10.1016/j.ijdrr.2018.02.024

Bossu, R., Steed, R., Roussel, F., Landès, M., Fuenzalida, A., Matrullo, E., et al. (2019b). App earthquake detection and automatic mapping of felt area. *Seismol. Res. Lett.* 90, 305–312. doi: 10.1785/0220180185

Bossu, R., Scotti, O., Cotton, F., Cushing, M., and Levret, A. (2000). Determination of geomechanical site effects in France from macroseismic intensities and reliability of macroseismic magnitude of historical events. *Tectonophysics* 324, 81–110. doi: 10.1016/s0040-1951(00)00112-8

Bossu, R., Steed, R., Mazet-Roux, G., Roussel, F., Etivant, C., Frobert, L., et al. (2016). "The key role of eyewitnesses in rapid impact assessment of global earthquakes," in *Earthquakes and Their Impact on Society*, ed. S. D'Amico (Cham: Springer), 601–618. doi: 10.1007/978-3-319-21753-6_25

Boyle, M. P., Schmierbach, M., Armstrong, C., McLeod, D. M., Shah, D. V., and Pan, Z. (2004). Information seeking and emotional reactions to the September 11 terrorist attacks. *J. Mass Commun. Q.* 81, 155–167. doi: 10.1177/107769900408100111

Earle, P. S., Bowden, D. C., and Guy, M. (2012). Twitter earthquake detection: earthquake monitoring in a social world. *Ann. Geophys.* 54:6.

Fallou, L., and Bossu, R. (2019). *Taking into Account the Cultural Context to Improve Scientific Communication – Lessons Learned from*

Earthquakes in Mayotte. EGU Blog for Seismology. Available online at: https://blogs.egu.eu/divisions/sm/2019/03/08/taking-into-account-the-cultural-context-to-improve-scientific-communication-lessons-learned-from-earthquakes-in-mayotte/

Fallou, L., Petersen, L., Bossu, R., and Roussel, F. (2019). "Efficiently allocating safety tips after an earthquake – lessons learned from the smartphone application LastQuake," in *Proceedings of the 16th International Conference on Information Systems for Crisis Response And Management*, eds Z. Franco, J. J. González, and J. H. Canós (Spain: Iscram).

Grünthal, G. (1998). *European Macroseismic Scale 1998*. Bruyères-le-Châtel: European Seismological Commission (ESC).

Hapsari, A. D., Hutagalung, F. D., Harsono, Y. T., Puspitasari, D. N., and Azzahra, T. A. (2019). *Psychoeducation: Psychological First Aid After Disaster (earthquake) at Sekarbela Region*. Lombok: Southeast West Nusa.

Hough, S. E., and Bilham, R. (2008). Site response of the Ganges basin inferred from re-evaluated macroseismic observations from the 1897 Shillong, 1905 Kangra, and 1934 Nepal earthquakes. *J. Earth Syst. Sci.* 117, 773–782. doi: 10.1007/s12040-008-0068-0

Jordan, T. H., Marzocchi, W., Michael, A. J., and Gerstenberger, M. C. (2014). Operational earthquake forecasting can enhance earthquake preparedness. *Seismol. Res. Lett.* 85, 955–959. doi: 10.1785/0220140143

Julien-Laferrière, S. (2019a). *Earthquake Qualitative Impact Assessment (EQIA): Improvements and New Performance Evaluation, SERA JRA6 Report*, 62. Available online at: http://www.sera-eu.org/export/sites/sera/home/.galleries/pdfs/Improvement_EQIA.pdf

Julien-Laferrière, S. (2019b). *Earthquake Qualitative Impact Assessment (EQIA): Performance Evaluation, SERA JRA6 Report*, 43. Available online at: http://www.sera-eu.org/export/sites/sera/home/.galleries/pdfs/Performance_analysis_EQIA.pdf

Koliska, M., and Roberts, J. (2015). Selfies: witnessing and participatory journalism with a point of view. *Int. J. Commun.* 9, 1672–1685.

Lamontagne, M., and Flynn, B. W. (2014). Communications in the aftermath of a major earthquake: bringing science to citizens to promote recovery. *Seismol. Res. Lett.* 85, 561–565. doi: 10.1785/0220130118

McBride, S. K., Llenos, A. L., Page, M. T., and van der Elst, N. (2020). #EarthquakeAdvisory: exploring discourse between government officials, news media, and social media during the 2016 bombay beach swarm. *Seismol. Res. Lett.* 91, 438–451. doi: 10.1785/0220190082

Michelini, A., Wotawa, G., and Arnold-Arias, D. (2017). "ARISTOTLE (all risk integrated system towards the holistic early-warning)," in *Proceedings of the EGU General Assembly Conference Abstracts*, Munich.

Musson, R. M. (1986). The use of newspaper data in historical earthquake studies. *Disasters* 10, 217–223. doi: 10.1111/j.1467-7717.1986.tb00591.x

Petersen, L., Fallou, L., Reilly, P., and Serafinelli, E. (2017). "Should CI operators use social media to communicate with the public during crisis situations?: lessons learned from a pilot study in Oslo Harbour," in *Proceedings of the 2017 4th International Conference on Information and Communication Technologies for Disaster Management (ICT-DM)* (Piscataway, NJ: IEEE), 1–6.

Quitoriano, V., and Wald, D. J. (2020). USGS" Did you feel it?"-science and lessons from twenty years of citizen science-based macroseismology. *Front. Earth Sci.* 8:120. doi: 10.3389/feart.2020.00120

Saathoff, G., and Everly, J. G. (2002). Psychological challenges of bioterror: containing contagion. *Int. J. Emerg. Mental Health* 4, 245–252.

Simon, T., Goldberg, A., and Adini, B. (2015). Socializing in emergencies—A review of the use of social media in emergency situations. *Int. J. Inform. Manag.* 35, 609–619. doi: 10.1016/j.ijinfomgt.2015.07.001

Steed, R. J., Fuenzalida, A., Bossu, R., Bondár, I., Heinloo, A., Dupont, A., et al. (2019). Crowdsourcing triggers rapid, reliable earthquake locations. *Sci. Adv.* 5:eaau9824. doi: 10.1126/sciadv.aau9824

Takayama, K. (2017). Disaster relief and crisis intervention with deaf communities: lessons learned from the Japanese deaf community. *J. Soc. Work Disabil. Rehabil.* 16, 247–260. doi: 10.1080/1536710x.2017.1372241

Wald, D. J., Quitoriano, V., Dengler, L., and Dewey, J. W. (1999a). Utilization of the internet for rapid community intensity maps. *Seismol. Res. Lett.* 70, 680–697. doi: 10.1785/gssrl.70.6.680

Wald, D. J., Quitoriano, V., Heaton, T. H., Kanamori, H., Scrivner, C. W., and Worden, C. B. (1999b). TriNet "ShakeMaps": rapid generation of peak ground motion and intensity maps for earthquakes in southern California. *Earthquake Spectra* 15, 537–556.

Wein, A., Potter, S., Johal, S., Doyle, E., and Becker, J. (2016). Communicating with the public during an earthquake sequence: improving communication of geoscience by coordinating roles. *Seismol. Res. Lett.* 87, 112–118. doi: 10.1785/0220150113

Conflict of Interest: The 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.

Copyright © 2020 Bossu, Fallou, Landès, Roussel, Julien-Laferrière, Roch and Steed. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

ORIGINAL RESEARCH
published: 06 August 2020
doi: 10.3389/feart.2020.00321

Citizen Scientists Help Detect and Classify Dynamically Triggered Seismic Activity in Alaska

Vivian Tang[1]*, *Boris Rösler*[1], *Jordan Nelson*[2], *JaCoya Thompson*[1,3], *Suzan van der Lee*[1,4,5], *Kevin Chao*[1,4] *and Michelle Paulsen*[5]

[1] Department of Earth and Planetary Sciences, Northwestern University, Evanston, IL, United States, [2] Department of Chemistry, Northwestern University, Evanston, IL, United States, [3] Department of Computer Sciences, Northwestern University, Evanston, IL, United States, [4] Northwestern Institute on Complex Systems, Northwestern University, Evanston, IL, United States, [5] Center for Interdisciplinary Exploration and Research in Astrophysics, Northwestern University, Evanston, IL, United States

In this citizen science project, we ask citizens to listen to relevant sections of seismograms that are converted to audible frequencies. Citizen scientists helped identify local seismic events whose recorded signals are much smaller than those associated with the surface waves that have triggered these local events. The local events include small earthquakes as well as tectonic tremor. While progress has been made in understanding how these events might be triggered by surface waves from large teleseismic earthquakes around the world, there is no consensus on its physical mechanism. The aim of our project is to engage the help of citizen scientists to increase general knowledge of triggered seismic events that may or may not occur during transient strain changes, such as from propagating surface waves. A better understanding of triggered seismic events is expected to provide important clues toward a fundamental understanding of how earthquakes nucleate and the physical mechanisms that connect different earthquakes and other slip events. From the volunteers' classifications we determined that citizen scientists achieve a higher reliability in detecting earthquakes and noise than in detecting tremor or other signals and that citizen scientists more accurately identify earthquake signals than a trained machine-learning algorithm. For tremor classifications we currently depend entirely on humans as no machine has yet learned to detect triggered tremor.

Keywords: earthquake detective, citizen sciences, triggered seismic events, machine-learning algorithm, audible pitches, Alaska

OPEN ACCESS

Edited by:
Kate Huihsuan Chen, National Taiwan Normal University, Taiwan

Reviewed by:
Chi-Chia Tang, China University of Geosciences, China
Wen-Tzong Liang, Academia Sinica, Taiwan

***Correspondence:**
Vivian Tang
vivian@earth.northwestern.edu; viviantang2015@u.northwestern.edu

Specialty section:
This article was submitted to Solid Earth Geophysics, a section of the journal Frontiers in Earth Science

Received: *12 February 2020*
Accepted: *09 July 2020*
Published: *06 August 2020*

Citation:
Tang V, Rösler B, Nelson J, Thompson J, van der Lee S, Chao K and Paulsen M (2020) Citizen Scientists Help Detect and Classify Dynamically Triggered Seismic Activity in Alaska. Front. Earth Sci. 8:321. doi: 10.3389/feart.2020.00321

INTRODUCTION

Surface waves generally have the longest duration and largest displacement of all seismic waves. When they pass through a seismically active region, surface waves from distant earthquakes may locally trigger an earthquake or tremor (Miyazawa and Mori, 2005; Gomberg et al., 2008; Rubinstein et al., 2009; Chao et al., 2012; Ide, 2012). Determining the frequency and conditions under which triggered seismic events occur will lead to a better understanding of the dynamic triggering of earthquakes (Peng and Gomberg, 2010; Brodsky and van der Elst, 2014). Seismometers continuously record ground motion at stations around the world, including seismic waves of small events which may be detected at one or at multiple instrument locations. Due to the large number of seismometers, the available seismograms are too numerous to be examined by seismologists (Liang et al., 2016). With *Earthquake Detective*, we utilize the Zooniverse platform to engage citizen scientists in an experiment to test if many human ears and eyes can replace the process of a professional seismologist in identifying dynamically triggered seismic events. We focus on data from seismic stations in Alaska, including USArray stations of EarthScope. Our approach has three advantages: (1) The human ear naturally performs a time-frequency analysis and is capable of discerning a wide range of different signals (Zwicker, 1961), (2) many human ears listening to the same data provides statistics that rank seismograms in order of their likelihood to contain a recording of a local event, which is helpful to researchers' analysis of this data (Kilb et al., 2012), and (3) part of the citizen scientists' responses can be compared to the results of a machine-learning algorithm to assess their performance.

Different seismic events can be classified by citizen scientists when listening to the audio data alongside the visual graphs. When sufficient data is classified, seismologists and data scientists can use it to train a machine-learning algorithm (an example of artificial intelligence) to automate the classification of seismograms (Xing et al., 2003; Perol et al., 2018; Tang et al., 2020). From there, seismic models for how, where, when, and why earthquakes happen may be refined by seismologists. The work citizen scientists put into this project contributes to the fundamental understanding of our planet that will allow a more sustainable society by allowing professionals to better assess hazards from future seismic events. An electronic supplement provides details on interface diagrams of the project and portions of data utilized.

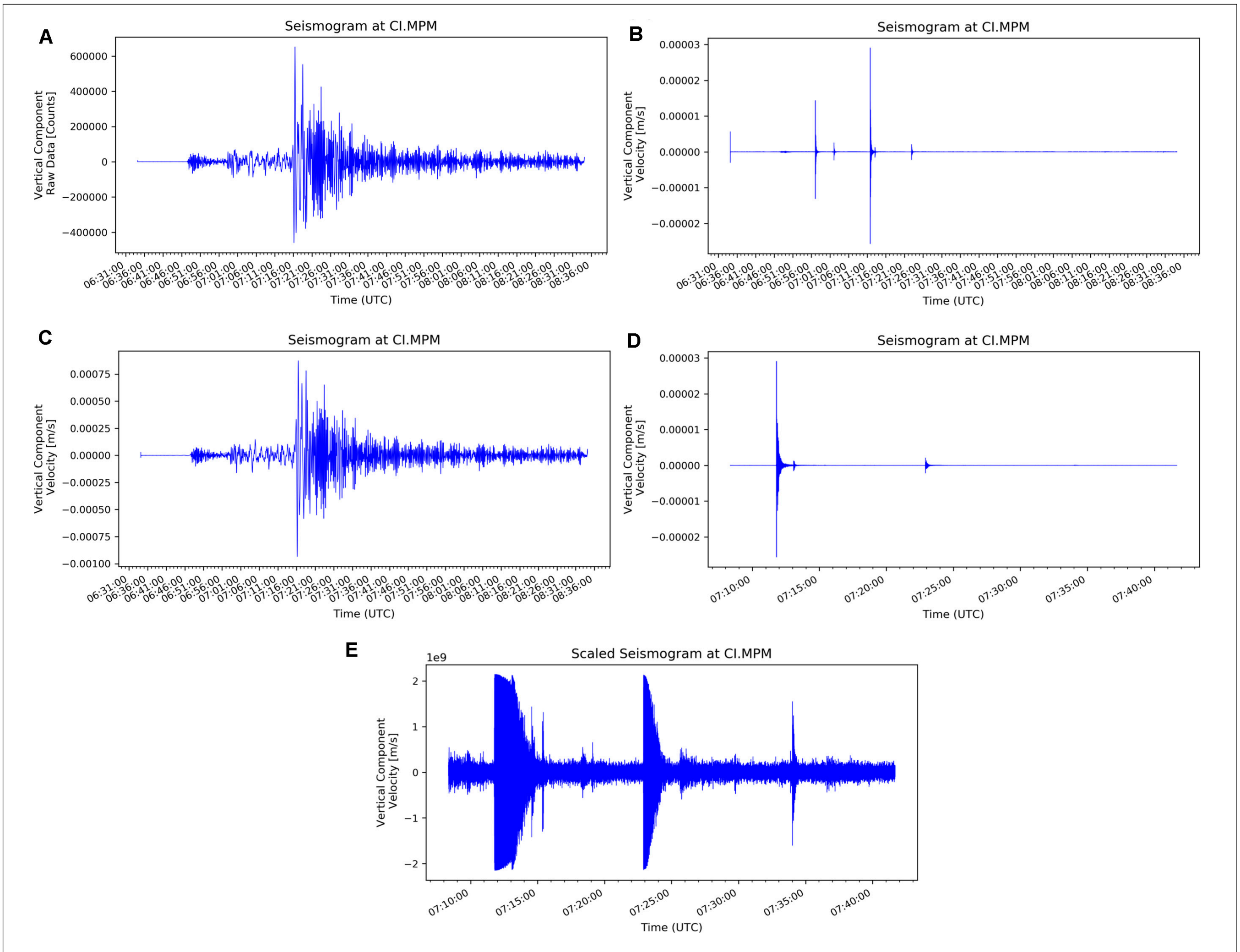


FIGURE 1 | Data processing. **(A)** Raw seismogram from MPM station following the February 27, 2010 Chile earthquake with M_w8.8. **(B)** Seismogram converted to velocity by removing the instrument response. **(C)** Seismogram after applying a filter from 2 to 8 Hz. **(D)** Seismogram is cut for the surface-wave interval. **(E)** Generating audio files by speeding up the time series and scaling the amplification.

MATERIALS AND METHODS

Far-field surface waves of large magnitude earthquakes can dynamically trigger seismic events such as small, local earthquakes (Prejean et al., 2004) and tectonic tremor (Peng and Gomberg, 2010). Here, we address results from the citizen scientists' classifications of data from USArray (TA) and the Alaska Regional Network (AK), which were recorded in the US from 2013 to 2018 (see section "Acknowledgments and Data" for details). The seismic waveforms presented to citizen scientists are downloaded from the IRIS (Incorporated Research Institutions for Seismology) Data Management System (DMS) (see section "Acknowledgments and Data"). The downloaded waveforms (**Figure 1A**) have a start time of 60 minutes before and an end time of 180 minutes after the origin times of selected large earthquakes with moment magnitude (M_w) greater than 7.5 (**Table 1**; Aiken and Peng, 2014; Chao and Obara, 2016). Waveforms were converted to ground velocity by deconvolving the instrument response from the recorded waveforms, and rotated to radial, transverse and vertical components (**Figure 1B**). The waveforms are then band-pass filtered between 2 and 8 Hz (**Figure 1C**) to remove Rayleigh waves from the radial and vertical components and Love waves from the transverse component. After determining the beginning of the surface-wave window for each station based on its distance from the epicenter and using a group velocity of 4.5 km/s, we selected the first 2000 s of the time series after this start time (**Figure 1D**). We generated audio files by speeding up the time series by a factor of 800 and applying an arctangent function to the amplitudes for dynamic-range compression (**Figure 1E**). This provides improved audibility for signals with smaller amplitude while preventing events with larger amplitude signals from excessive loudness. Waveforms with either gaps in the time series, calibrations or re-centering signals, or other glitches were discarded before presenting the data to citizen scientists on the largest people-powered research platform, "Zooniverse" (**Supplementary Figures S1–S3**). With this platform, we were able to provide tutorial and practice sessions for training our citizen scientists to identify "earthquakes," "tremor," and "noise" signals. Citizen scientists are asked to choose "none of the above" when the seismic signals do not clearly fall in one of the other categories or more than one different signal is present in the data (**Supplementary Figures S4, S5**).

TABLE 1 | Teleseismic earthquakes used in this study.

No.	Date	Longitude (°)	Latitude (°)	Depth (km)	Magnitude (M_w)
1.	2013-02-06T01:12:26	165.114	−10.799	24.0	8.0
2.	2013-04-16T10:44:19	61.996	28.033	80.0	7.7
3.	2013-11-17T09:04:56	−46.4011	−60.2738	10.0	7.7
4.	2014-04-01T23:46:47	−70.7691	−19.6097	25.0	8.2
5.	2014-04-03T02:43:14	−70.4931	−20.5709	22.4	7.7
6.	2014-04-12T20:14:38	162.1481	−11.2701	22.56	7.6
7.	2014-04-19T13:28:00	155.0241	−6.7547	43.37	7.5
8.	2014-06-23T20:53:09	178.7352	51.8486	109.0	7.9
9.	2015-03-29T23:48:31	152.5623	−4.7294	41.0	7.5
10.	2015-04-25T06:11:26	84.7314	28.2305	8.22	7.8
11.	2015-05-05T01:44:04	151.8751	−5.4624	55.0	7.5
12.	2015-05-30T11:23:02	140.4931	27.8386	664.0	7.8
13.	2015-09-16T22:54:32	−71.6744	−31.5729	22.44	8.3
14.	2015-10-26T09:09:42	70.3676	36.5244	231.0	7.5
15.	2016-03-02T12:49:48	94.3299	−4.9521	24.0	7.8
16.	2016-04-16T23:58:36	−79.9218	0.3819	20.59	7.8
17.	2016-07-29T21:18:26	145.5073	18.5429	196.0	7.7
18.	2016-11-13T11:02:59	173.054	−42.7373	15.11	7.8
19.	2016-12-08T17:38:46	161.3273	−10.6812	40.0	7.8
20.	2016-12-17T10:51:10	153.5216	−4.5049	94.54	7.9
21.	2016-12-25T14:22:27	−73.9413	−43.4064	38.0	7.6
22.	2017-01-22T04:30:22	155.1718	−6.2464	135.0	7.9
23.	2017-01-22T04:30:22	155.1718	−6.2464	135.0	7.9
24.	2017-07-17T23:34:13	168.857	54.4434	10.0	7.7
25.	2017-09-08T04:49:20	−93.8993	15.0222	47.39	8.2
26.	2018-01-10T02:51:31	−83.52	17.4825	19.0	7.5
27.	2018-08-19T00:19:40	−178.153	−18.1125	600.0	8.2
28.	2018-09-06T15:49:14	179.3502	−18.4743	670.81	7.9
29.	2018-09-28T10:02:43	119.8462	−0.2559	20.0	7.5
30.	2018-12-05T04:18:08	169.4266	−21.9496	10.0	7.5

Seismic waves that are caused by the displacement of tectonic plates along a fault are known as earthquake signals. They are caused by the sudden release of seismic energy, making them short in duration and resembling the sound of a slamming door. Tremors have a longer duration and are generated by a slow release of acoustic and seismic energy. Sped up to audible frequencies, tremor can sound like a train darting over railroad tracks.

The Earth is in constant motion under the influence of forces from atmosphere, hydrosphere (e.g., ocean currents and waves), and biosphere, including anthropogenic activity, generated by traffic or industry, for example. Therefore, every seismogram contains relatively steady noise, even in the absence of seismic signals or distinct noise events, which converts to a slowly varying, white noise "baseline" for the sound file. These noise signals sound like whistling wind, crinkling aluminum foil, or radio static.

Earthquakes and tremors as well as natural and anthropogenic sources generate seismic signals that may or may not exceed the baseline noise level of a seismogram. These different sources can be distinguished by the sound of their signals.

RESULTS

Of 2467 seismograms recorded by the AK network, 1103 seismograms were classified as earthquakes by citizen scientists, 141 as tremor, 770 as noise, and 228 were labeled as to pertaining to none of these categories. The distribution of classifications in the four categories (**Figure 2**) indicates that earthquakes (74% of all classifications on seismograms identified as earthquakes are made for this category) and noise (66%) were identified with more certainty by

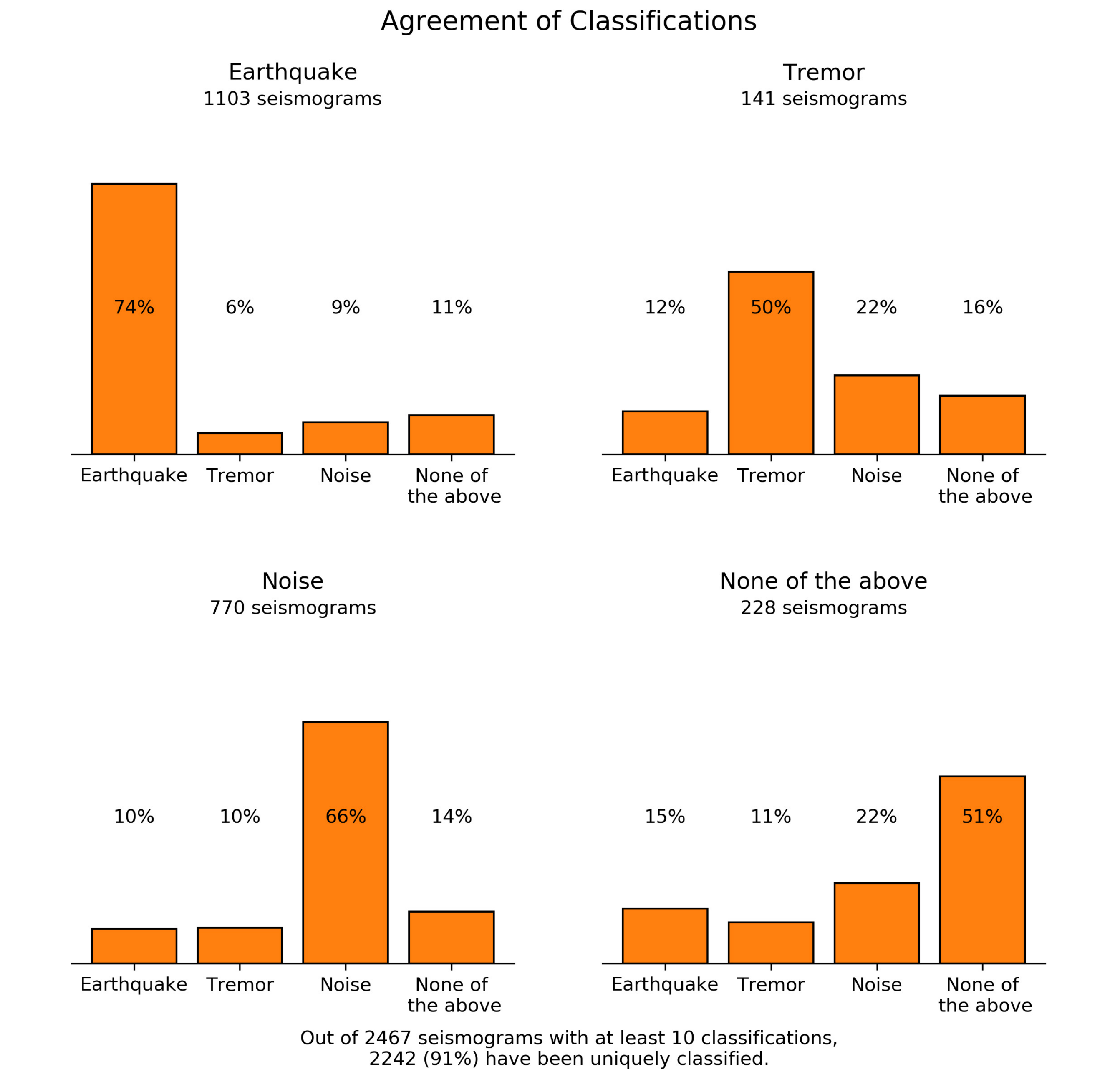


FIGURE 2 | Histograms for each classified category. The four categories contain seismograms which have received a majority classification for one category and show the average of the classifications made for the seismograms contained in this category.

citizen scientists than tremor (50%) and other, unclear events (51%). Hence, citizen scientists were able to classify earthquakes and noise more consistently than tremor and other events.

For one M_w7.5 earthquake on December 5, 2018, seismologists independently classified the seismograms for which 7 of 10 citizen scientists agreed, in order to assess the accuracy of the project volunteers. For comparison, we applied a machine-learning (ML) algorithm, trained to detect earthquake signals only (Tang et al., 2020), and compared its output with our expert labels as well. Assuming that the expert labels are "true," citizen scientists' labels were 85% accurate in classifying earthquakes and did not mislabel any seismogram without earthquakes though 23% of all earthquakes remained undetected by citizen scientists (**Figure 3**). **Figure 4** shows results from ML as projections into two-dimensional spaces via the PCA (Principal Component Analysis) of 10-dimensional embeddings. PCA is a non-parametric statistical technique (George and Vidyapeetham, 2012) used for dimensionality reduction in machine learning and the principal components

Volunteers (7/10 agree)	
True Positives 43	False Negatives 13
False Positives 0	True Negatives 28

Machine Learning	
True Positives 47	False Negatives 9
False Positives 11	True Negatives 17

FIGURE 3 | Confusion matrices for citizen scientists' and the machine-learning algorithm's classifications.

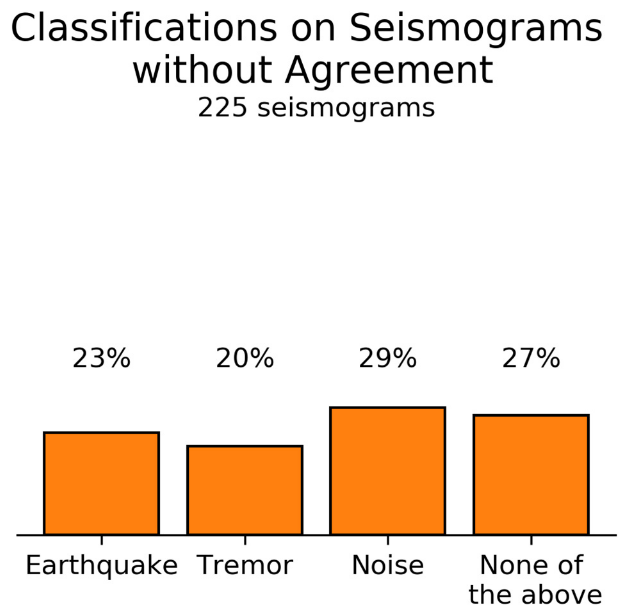


FIGURE 5 | Histograms for classifications made on seismograms without conclusive label. The seismograms contained in this category have received the same amount of classifications for at least two different categories with less classifications for the other categories.

are the coefficients of orthogonal linear combinations of the variables in the dataset. Contours indicate the distributions of the training dataset and the symbols represent the testing dataset. The machine-learning algorithm achieved only 76.2% accuracy in classifying earthquakes in the same dataset, a score nearly 10% lower than citizen scientists (**Figure 4**).

DISCUSSION

Seismograms are retired after having been classified by 10 different users on Zooniverse. Of 2467 seismograms, 2242 have received a conclusive label, meaning that the number of classifications made for one category is not reached for any other category as shown by a narrow distribution. There was a larger level of agreement between volunteers

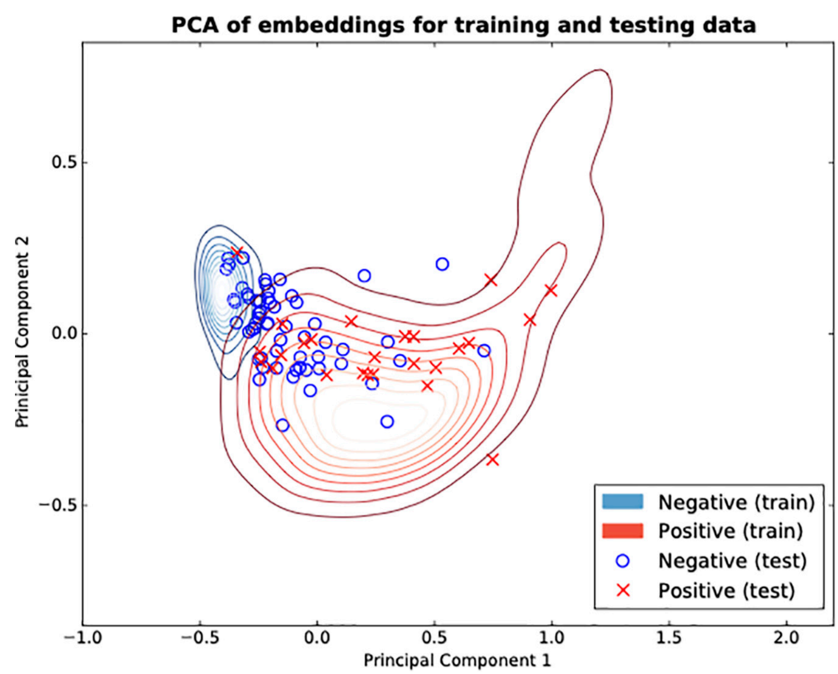


FIGURE 4 | The convolutional neural network for classifying the training dataset (contour maps) and the test dataset (symbols) from the December 5, 2018 M_W7.5 teleseimic earthquake. Shown in red are seismograms with an earthquake, seismograms without earthquakes are shown in blue.

when the seismographs contained either earthquakes or noise (**Figure 2**). Citizen scientists agree less on which seismograms contain tremor and other signals as shown by a wider distribution of classifications (**Figure 5**). We assume that the degree of agreement of classifications between citizen scientists reflects the collective confidence of citizen scientists in identifying the seismic signals. We found that earthquakes and noise have characteristic waveforms and associated audio signals that make it easy to distinguish them from other seismic signals. Citizen scientists are directed to classify seismic signals as not pertaining to any of the other categories when the seismograms contain several different signals or have unclear waveforms or audio signals. In these situations the seismograms are often classified as an earthquake or tremor. It is therefore unsurprising that the agreement of classifications made on seismograms in the category "none of the above" is lower than on seismograms in the other categories.

The 225 seismograms which have not received a conclusive label (**Figure 5**), meaning that the highest amount of classifications has been reached for more than one category,

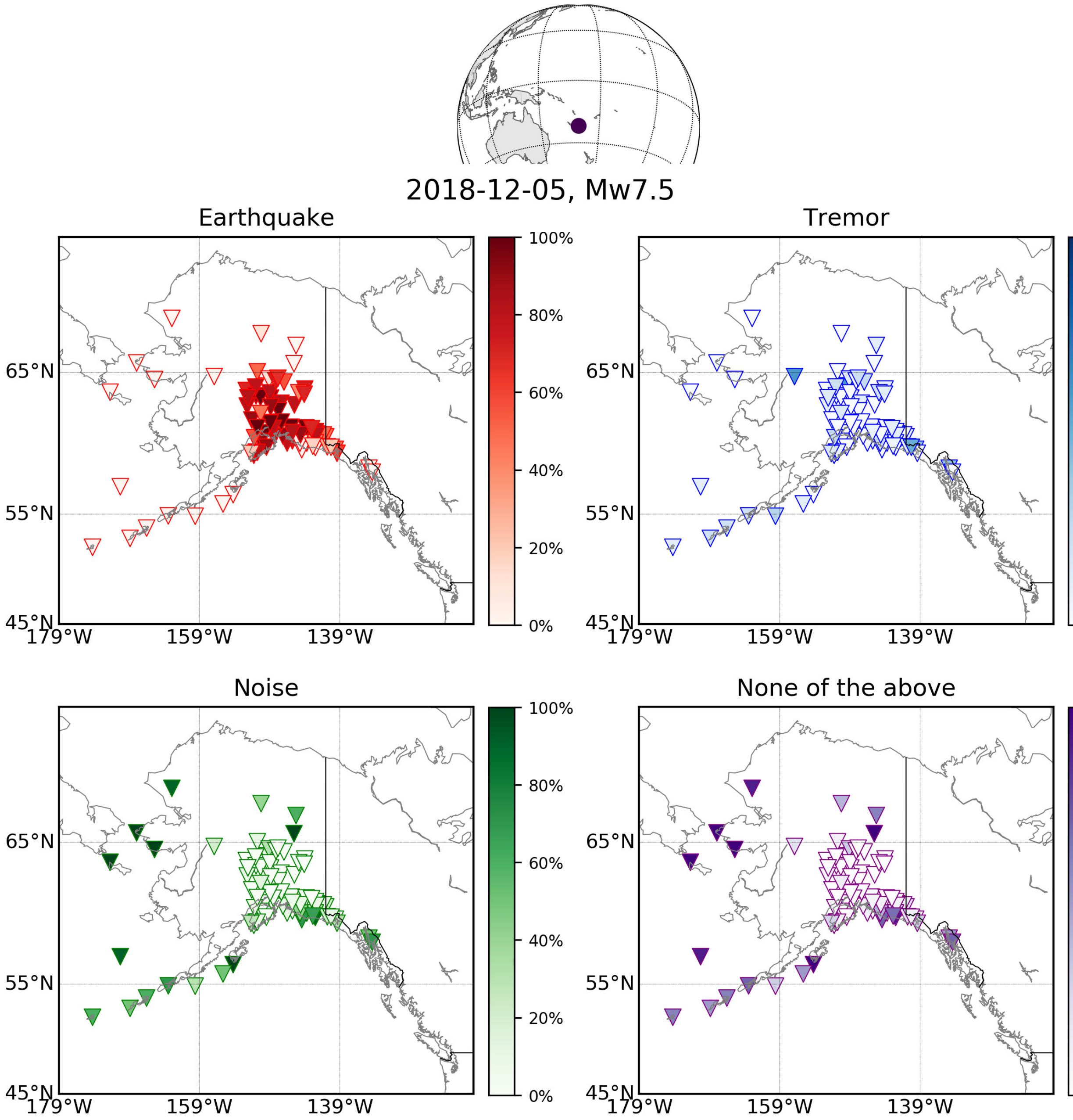


FIGURE 6 | Map of stations showing the location of recordings of triggered earthquake for different teleseismic earthquakes.

amount to only 9% of all seismograms. Unsurprisingly, the distribution of classifications made on these seismograms shows no clear preference for any of the categories. However, it stands out that classifications for tremor and "none of the above" are more numerous than for earthquakes and noise, reflecting that these seismic signals are more difficult to identify and confirming the affirmations made for seismograms with a conclusive label. This may bias citizen scientists (Hart et al., 2009; Swanson et al., 2016) to classify seismograms with "none of the above" events as earthquakes, tremor or noise. These "none of the above" events reflect that seismograms within the surface wave intervals may contain instrument signals, and signals of anthropogenic and natural sources (Smith and Tape, 2019).

The classifications made by citizen scientists of Zooniverse make it possible to locate the stations with additional seismic signals that occurred during the passage of surface waves of teleseismic earthquakes in the AK network (**Figures 6–8**). Surface waves from the earthquake on December 5, 2018 with M_w 7.5 southeast of the Loyalty Islands triggered local earthquakes within 300 km north of Anchorage, (**Figure 6**). During the passage of surface waves from the September 8, 2017 M_w 8.2 Mexico earthquake, tremor occurred in central Alaska (**Figure 7**). The signals recorded during the passage of surface waves from the September 28, 2018 M_w 7.5 Sulawesi earthquake (**Figure 8**) show a random mix of classifications by citizen scientists, implying that signals are present, but are ambiguous in nature.

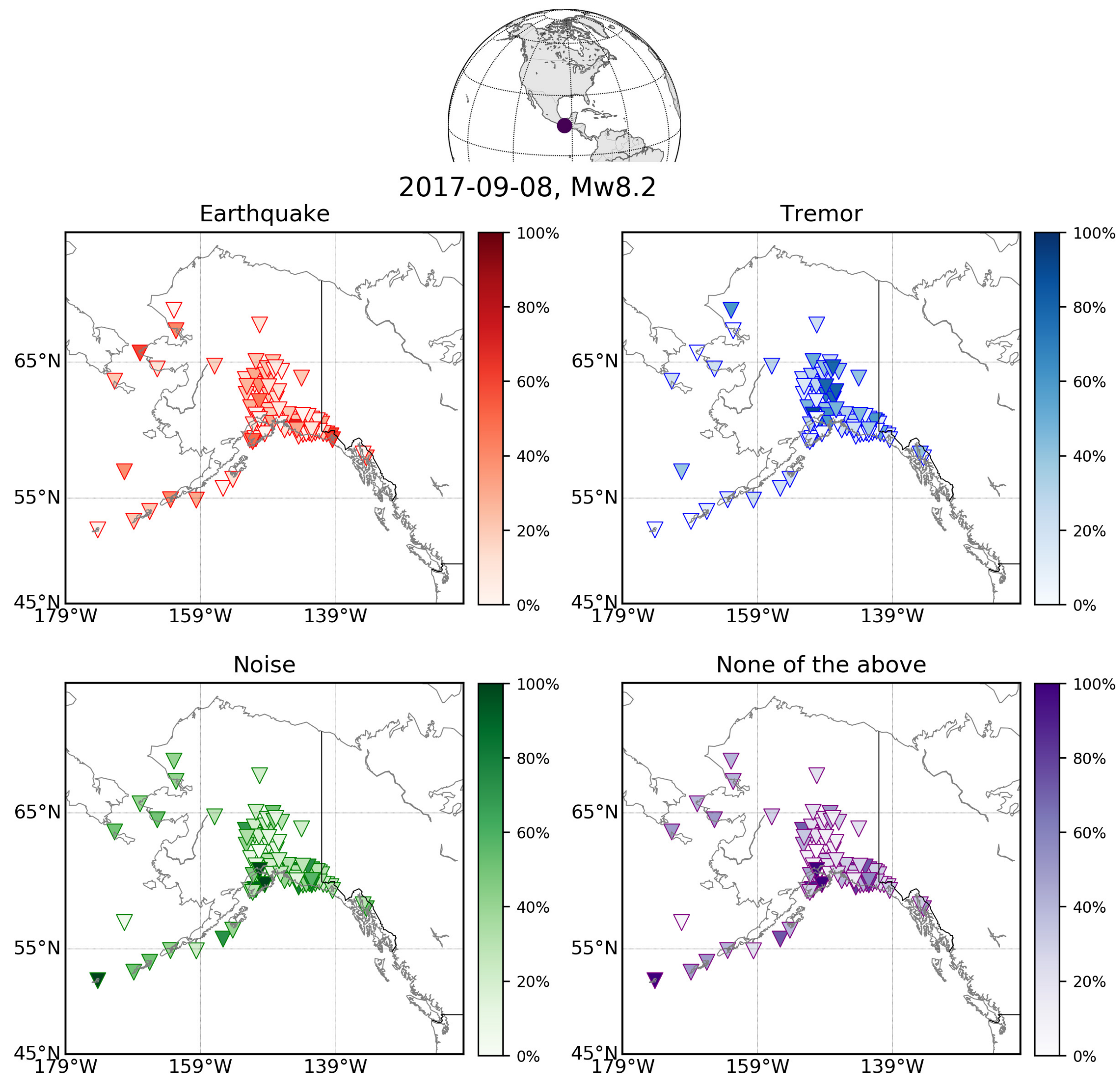


FIGURE 7 | Map of stations showing the locations of recordings of triggered tremor for different teleseismic earthquakes.

The focus on this study has been on harnessing the intelligence of citizen scientists to identify triggered seismic events. In the subtask of detecting triggered earthquakes, we compared the results of citizen scientists to an existing machine-learning algorithm (Tang et al., 2020). The confusion matrices in **Figure 3** show that the machine-learning algorithm misidentified 11 of the expert-labeled non-earthquake signals as earthquake signals and missed 9 of the expert-labeled earthquakes, while correctly labeling 47 earthquake and 17 non-earthquake signals. On the other hand, citizen scientists correctly identified 43 earthquakes and missed 13 earthquake signals, while correctly labeling 28 non-earthquake signals. From the above results, both methods can successfully identify triggered earthquakes, but citizen scientists can detect non-earthquake signals better than the machine-learning algorithm. Citizen scientists are more successful at identifying non-earthquake signals because we encourage them to classify seismograms without clear earthquake signals as "none of above," and the same standard used by seismologists to label the data. However, the machine-learning algorithm may identify triggered earthquakes hidden by high background noise as positive examples (**Figure 9**). Hence, the algorithm detects 11 more earthquake signals than seismologists.

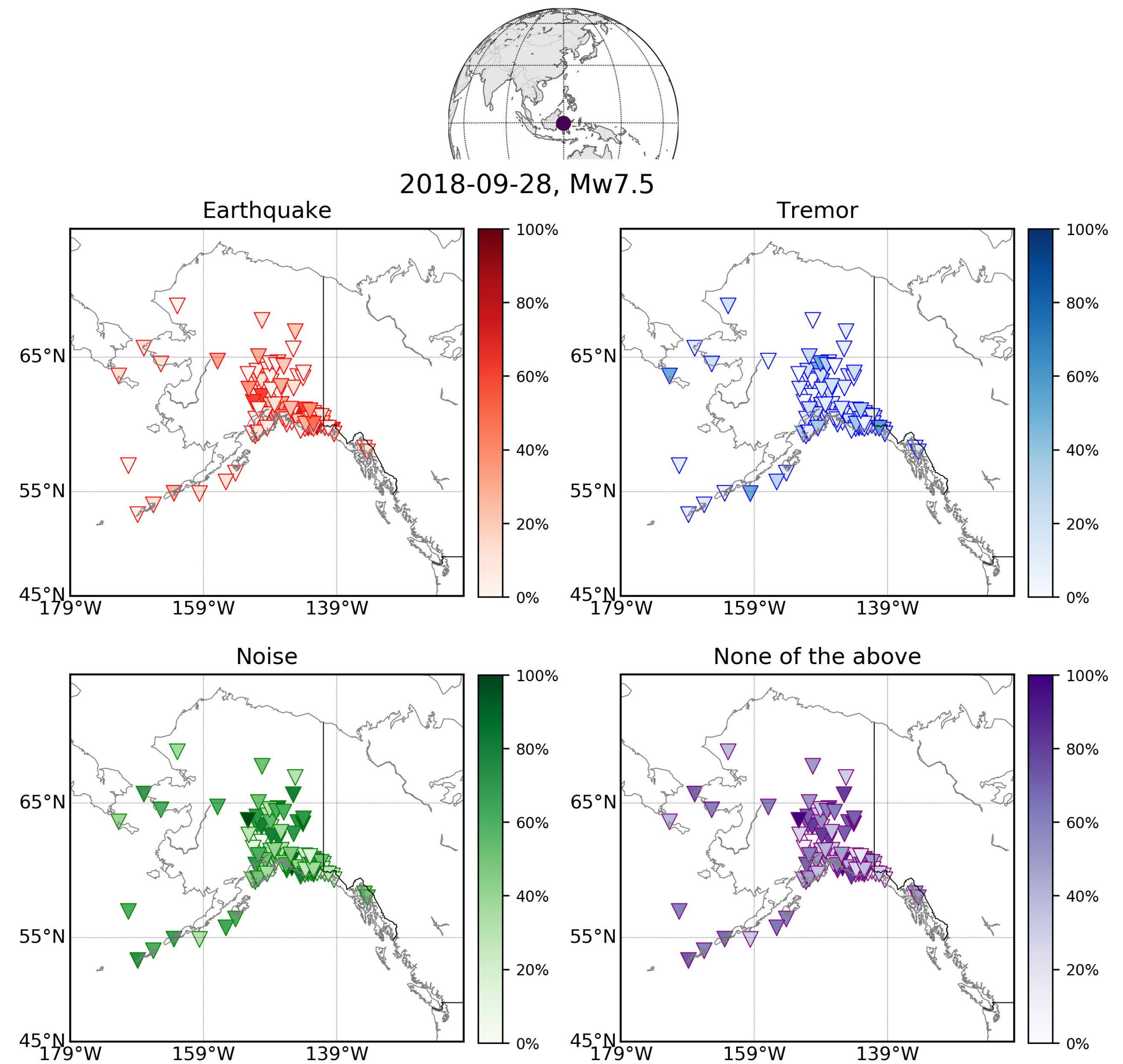


FIGURE 8 | Map of stations showing the locations of recordings where no triggered seismicity (noise) occurred for different teleseismic earthquakes.

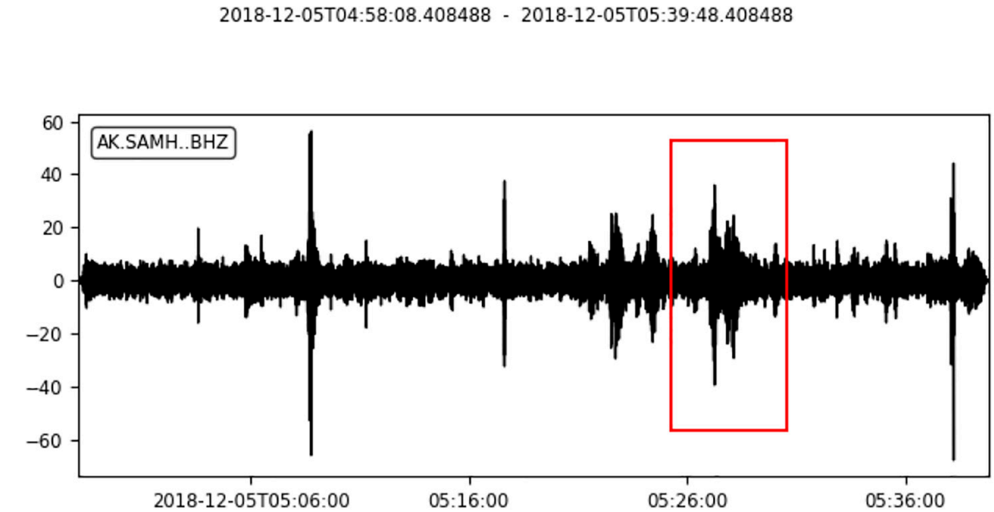


FIGURE 9 | Example seismogram with a triggered earthquake (red box) hidden in high background noise.

CONCLUSION

Over 2000 citizen scientists helped classify more than 2000 seismograms from 30 large worldwide earthquakes with magnitudes over 7.5 in the citizen science project "*Earthquake Detective*" on Zooniverse. Citizen scientists generally agree more with each other when identifying (1) seismograms with earthquake signals and (2) the absence of distinct signals (noise) than when identifying tremor or other signals. A subset of data we also classified by experts (seismologists among the authors) and a machine-learning algorithm trained to detect triggered earthquakes (Tang et al., 2020). We compared these classifications from a machine-learning algorithm, citizen scientists and seismologists with each other and with the earthquake classifications of citizen scientists. We found that citizen scientists did not misidentify seismograms without an earthquake (no false positives) but missed 13 earthquake signals in seismograms (false negatives), while correctly labeling 43 earthquake and 28 non-earthquake signals. The machine-learning algorithm misidentified 11 non-earthquake signals and failed to detect 9 earthquake signals in seismograms, while correctly labeling 47 earthquake and 17 non-earthquake signals. Both the citizen scientists and the machine-learning algorithm perform well in identifying earthquakes, but the citizen scientists outperformed the machine-learning algorithm in labeling non-earthquake signals. Earthquake Detectives and a machine-learning algorithm experience similar degrees of difficulties for example in identifying other seismic signals, which are more challenging and requires more intelligence than identifying earthquakes, even though citizen scientists are currently better at both.

AUTHOR'S NOTE

All seismic data were downloaded through the IRIS web service (https://service.iris.edu/irisws/) using ObsPy (https://docs.obspy.org), including the following seismic networks (http://ds.iris.edu/mda): USArray (2003) and Alaska Earthquake Center (1987). The ANSS (Advanced National Seismic System) earthquake catalog can be accessed at https://earthquake.usgs.gov/data/comcat/.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

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 from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

VT, BR, and SL conceived and designed the project. VT organized the database of seismic data. VT, BR, JN, and SL developed the project. JT and MP contributed miscellaneous support for project development, management, presentation, and strategy. KC contributed to data collection and critical discussions of triggered seismic events. VT, BR, and SL wrote the first draft of the manuscript and figures. All authors contributed to the revision of the manuscript, read and approved the submitted version.

FUNDING

This research was funded by the Integrated Data-Driven Discovery in Earth and Astrophysical Sciences (ID^{3}EAS) program under National Science Foundation grant NSF-NRT 1450006.

ACKNOWLEDGMENTS

We thank Zhigang Peng and Laura Trouille for critical discussions. We also sincerely thank over 2,000 citizen scientists for important contributions to Earthquake Detective on Zooniverse.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.00321/full#supplementary-material

REFERENCES

Aiken, C., and Peng, Z. (2014). Dynamic triggering of microearthquakes in three geothermal/volcanic regions of California. *J. Geophys. Res. Solid Earth* 119, 6992–7009. doi: 10.1002/2014jb011218

Brodsky, E. E., and van der Elst, N. J. (2014). The uses of dynamic earthquake triggering. *Annu. Rev. Earth Planet. Sci.* 42, 317–339. doi: 10.1146/annurev-earth-060313-054648

Chao, K., and Obara, K. (2016). Triggered tectonic tremor in various types of fault systems of Japan following the 2012 Mw8. 6 Sumatra Earthquake. *J. Geophys. Res. Solid Earth* 121, 170–187. doi: 10.1002/2015jb012566

Chao, K., Peng, Z., Fabian, A., and Ojha, L. (2012). Comparisons of triggered tremor in California. *Bull. Seismol. Soc. Am.* 102, 900–908. doi: 10.1785/0120110151

George, A., and Vidyapeetham, A. V. (2012). Anomaly detection based on machine learning: dimensionality reduction using PCA and classification using SVM. *Int. J. Comput. Appl.* 47, 5–8. doi: 10.5120/7470-0475

Gomberg, J., Rubinstein, J. L., Peng, Z., Creager, K. C., Vidale, J. E., and Bodin, P. (2008). Widespread triggering of nonvolcanic tremor in California. *Science* 319, 173–173. doi: 10.1126/science.1149164

Hart, W., Albarracín, D., Eagly, A. H., Brechan, I., Lindberg, M. J., and Merrill, L. (2009). Feeling validated versus being correct: a meta-analysis of selective exposure to information. *Psychol. Bull.* 135, 555–588. doi: 10.1037/a0015701

Ide, S. (2012). Variety and spatial heterogeneity of tectonic tremor worldwide. *J. Geophys. Res. Solid Earth* 117:B03303.

Kilb, D., Peng, Z., Simpson, D., Michael, A., Fisher, M., and Rohrlick, D. (2012). Listen, watch, learn: SeisSound video products. *Seismol. Res. Lett.* 83, 281–286. doi: 10.1785/gssrl.83.2.281

Liang, W. T., Chen, K. H., Wu, Y. F., Yen, E., and Chang, C. Y. (2016). Earthquake school in the cloud: citizen seismologists in Taiwan. *Seismol. Res. Lett.* 87, 177–185. doi: 10.1785/0220150061

Miyazawa, M., and Mori, J. (2005). Detection of triggered deep low-frequency events from the 2003 Tokachi-oki earthquake. *Geophys. Res. Lett.* 32:L10307.

Peng, Z., and Gomberg, J. (2010). An integrated perspective of the continuum between earthquakes and slow-slip phenomena. *Nat. Geosci.* 3, 599–607. doi: 10.1038/ngeo940

Perol, T., Gharbi, M., and Denolle, M. (2018). Convolutional neural network for earthquake detection and location. *Sciencances* 3:e1700578. doi: 10.1126/sciadv.1700578

Prejean, S. G., Hill, D. P., Brodsky, E. E., Hough, S. E., Johnston, M. J. S., and Malone, S. D. (2004). Remotely triggered seismicity on the United States west coast following the Mw 7.9 Denali fault earthquake. *Bull. Seismol. Soc. Am.* 94, S348–S359.

Rubinstein, J. L., Gomberg, J., Vidale, J. E., Wech, A. G., Kao, H., Creager, K. C., et al. (2009). Seismic wave triggering of nonvolcanic tremor, episodic tremor and slip, and earthquakes on Vancouver Island. *J. Geophysics. Res.* 114:B00A01.

Smith, K., and Tape, C. (2019). Seismic noise in central Alaska and influences from rivers, wind, and sedimentary basins. *J. Geophys. Res. Solid Earth* 124, 11678–11704. doi: 10.1029/2019jb017695

Swanson, A., Kosmala, M., Lintott, C., and Packer, C. (2016). A generalized approach for producing, quantifying, and validating citizen science data from wildlife images. *Conserv. Biol.* 30, 520–531. doi: 10.1111/cobi.12695

Tang, V., Seetharaman, P., Chao, K., Pardo, B. A., and van der Lee, S. (2020). Automating the detection of dynamically triggered earthquakes via a deep metric learning algorithm. *Seismol. Res. Lett.* 91, 901–912.

Xing, E. P., Jordan, M. I., Russell, S. J., and Ng, A. Y. (2003). “Distance metric learning with application to clustering with side-information,” in *Advances in Neural Information Processing Systems*, 521–528.

Zwicker, E. (1961). Subdivision of the audible frequency range into critical bands (Frequenzgruppen). *J. Acoust. Soc. Am.* 33, 248–248. doi: 10.1121/1.1908630

Conflict of Interest: The 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.

Copyright © 2020 Tang, Rösler, Nelson, Thompson, van der Lee, Chao and Paulsen. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Communication

ORIGINAL RESEARCH
published: 12 August 2020
doi: 10.3389/fcomm.2020.00049

Citizen Seismology Without Seismologists? Lessons Learned From Mayotte Leading to Improved Collaboration

Laure Fallou[1]*, *Rémy Bossu*[1,2], *Matthieu Landès*[1], *Julien Roch*[1], *Frédéric Roussel*[1], *Robert Steed*[1] and *Sylvain Julien-Laferrière*[1]

[1] EMSC (Euro-Mediterranean Seismological Centre), Arpajon, France, [2] CEA, DAM, DIF, Arpajon, France

OPEN ACCESS

Edited by:
Tarla Rai Peterson,
The University of Texas at El Paso,
United States

Reviewed by:
Wei Peng,
National Taiwan Normal
University, Taiwan
György Hetényi,
University of Lausanne, Switzerland

***Correspondence:**
Laure Fallou
fallou@emsc-csem.org

Specialty section:
This article was submitted to
Science and Environmental
Communication,
a section of the journal
Frontiers in Communication

Received: 07 February 2020
Accepted: 16 June 2020
Published: 12 August 2020

Citation:
Fallou L, Bossu R, Landès M, Roch J, Roussel F, Steed R and Julien-Laferrière S (2020) Citizen Seismology Without Seismologists? Lessons Learned From Mayotte Leading to Improved Collaboration. Front. Commun. 5:49. doi: 10.3389/fcomm.2020.00049

Starting the 10th May 2018, a series of earthquakes has hit Mayotte, a French island in the Indian Ocean. Facing a lack of seismic data, scientific information and communication from the authorities, the inhabitants took advantage of social media to develop, on their own, a citizen seismology group, composed of more than 10,000 people. Due to a particular cultural context, this was carried out mainly without the seismologist community. While some citizens did share seismological information (and eventually volcanology information when it was discovered that the earthquakes were caused by a new-born, undersea volcano), the lack of seismologists in the group also lead to the emergence of misinformation and even conspiracy theories. This mistrusting atmosphere had negative consequences for the way various seismological organizations were perceived, including LastQuake, a crowdsource-based earthquake information app which allows eyewitnesses to share information about earthquakes they felt, combined with seismic data. However, due to the lack of seismic data for these earthquakes, some were not displayed in the app. This lack of information and understanding of how the system functioned led to additional mistrust toward this citizen seismology tool. This paper combines sociological observations with an empirical approach. First, a sociological analysis of this independent citizen science network enables an identification of the reasons for its creation and the pitfalls caused by the absence of collaboration with the scientific community. Then, an empirical case study of the LastQuake system exposes how it has been improved to offer information, while admittedly more incomplete, is nevertheless closer to citizens' needs. It concludes that citizen seismology requires a stronger collaboration between citizens' and scientists' communities in order to be more efficient. It also advocates for scientific communication that takes into account cultural context from the beginning.

Keywords: citizen science, seismology, science communication, crisis communication, misinformation, conspiracy theory, risk culture, social media

INTRODUCTION

Within citizen science, seismology holds a special place as earthquakes are not only a fascinating phenomenon, but also a potentially deadly risk. Thus, involving citizens in seismology has been impacting the way it is made and disseminated as a science, and has also contributed to reducing risk (Khan et al., 2018). Citizen seismology is here defined as any project, formalized or not, involving citizens around earthquake related themes, aiming at increasing scientific and risk knowledge, either for the scientific community or the involved citizens.

Citizens have long been an essential part of the way seismology is made. Amateurs and eyewitnesses were relied upon for observations before the development of measuring tools (Ferreira, 2019) and after their introduction, to compensate for a lack of data or to complement it. Indeed, their testimonies have contributed to mapping the effects of earthquakes (Aronova, 2017). However, the way citizens take part in seismology is evolving, especially with the rise of new technologies, including smartphones and new types of seismic sensors.

The spectrum of actors involved in citizen seismology is broadening. While only amateur seismologists or eyewitnesses used to be involved, it tends to grow beyond age and universally, including also children in schools (Liang et al., 2016; Subedi et al., 2020), and entire communities (Calais et al., 2018), implying that prior knowledge and interest levels may be relatively low. Furthermore, new and more independent actors have since appeared in the field. For instance, the Earthquake Network app uses smartphones' accelerometers to detect earthquakes (Finazzi, 2016) and the Euro-Mediterranean Seismological Center (EMSC), with the LastQuake project (Bossu et al., 2011) uses crowdsourcing to detect felt earthquakes and inform the public about them. Operating worldwide, these projects face specific challenges associated with gathering citizen observation.

Starting as passive observers, citizens have become more and more involved. They can now report earthquakes or damages (Wald et al., 2012), help with measurements or computation, learn how to locate earthquakes or take an active role in risk reduction activities (Liang et al., 2017). Recent projects also study the opportunity to engage citizens in order to augment data at little cost, in both Haiti (Calais et al., 2018) and at a global scale (Finazzi, 2016; Bossu et al., 2018). Citizens' attributed role depends on the purpose of the project. If historically it has been a way to improve scientific knowledge about earthquakes, it is now also a way to raise interest about earthquakes within society, increase citizens' understanding of seismic phenomena and contribute to risk reduction (Coen, 2012), thus demonstrating that citizens' interest must be taken into account alongside those of scientists (Scolobig et al., 2015). It also implies the need to reflect on the mutual relationship between citizens and seismologists and how they interact. Mutual trust, as well as communication, is an essential part of citizen science (Aronova, 2017).

In most citizen seismology projects found in the literature, scientists are taking the lead to build and guide them. This does not hold true in the case of Mayotte. In May 2018, this French island located in the Indian Ocean was hit by a series of, at the time, unexplained earthquakes. To date, the swarm has not stopped yet. Seismic data and explanations for the phenomenon were lacking at the beginning of the swarm. In the face of an information vacuum and a high level of mistrust toward the authorities and the scientific community, the population looked for ways to satisfy their informational and emotional needs. Not only did they turn to existing citizen science projects (such as the LastQuake app) but they also created their own citizen seismology network through a Facebook group called STTM, ("Soutien Tremblement de Terre Mayotte"), standing for "Earthquake support Mayotte." In both of these solutions, conversation with seismologists was limited and relevant seismological information was not readily available. This paper reviews how citizen seismology is made when citizens take the lead in a context of an information vacuum. It evaluates how existing citizen seismology projects, such as LastQuake, can evolve to support citizens, meet their information needs, avoid misinformation and rebuild trust. It does so by first describing the Mayotte case study, which includes an analysis of the seismic and cultural context, a description of the Mayotte citizen science project and of its outcomes. It then presents the LastQuake crowdsourced detection system and how a questionnaire was set up to understand the Mayotte users' needs and improve the LastQuake system to better take them into account in the EMSC citizen science project.

MATERIALS AND METHODOLOGY

This article is based on a two step-methodology. First, we analyse the situation in Mayotte, based on a sociological approach. We focus on citizens' perspective, considering their perception of the events and the related communication. Indeed, not only the risk or the actual communication matter, but also how they are perceived (Wray et al., 2006). Observations of the Facebook group were made from its creation on May 13th 2018 to the end of November 2019, with a specific focus on the first year of the event. Observations were made possible by one of the authors joining the Facebook group as a passive observer, only in the bystander role, paying attention not to modify interactions and thus, not creating bias (Ditchfield and Meredith, 2018)[1]. Interactions between members, shared information, reactions and content evolutions were analyzed qualitatively. This was supplemented by a series of 10 semi-structured interviews (Edwards and Holland, 2013)[2] with people living in Mayotte, in August 2018. The interviews aimed at getting insights on how citizens in Mayotte experienced the seismic activity and assess their satisfaction level regarding their information needs. Questions targeted citizens' perception of seismological actors and authorities, which were not primarily mentioned by the interview leader in order to identify the perceived legitimate

[1] As it is common on Facebook, the group was composed of active members posting content and discussing it, along with more passive one (Bastard et al., 2017), therefore being a passive observer, researcher do not modify the interaction.

[2] Semi-structured interview is a common method of research within social sciences in which the set of questions is open and can evolve depending on what the interviewee says (Edwards and Holland, 2013).

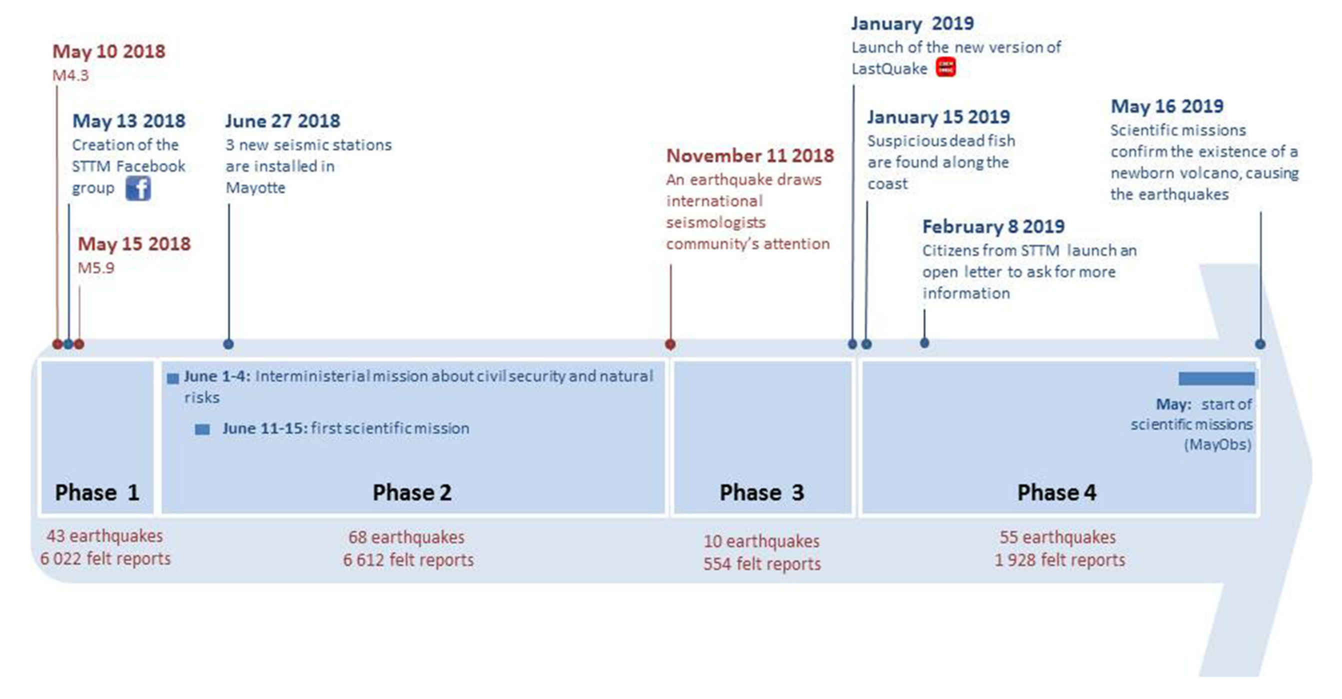


FIGURE 1 | Seismo-sociological phases of Mayotte case study. Number of earthquakes corresponds to M>4 events displayed on LastQuake. Many more earthquakes were felt by the population but due to lack of sensors, no data was available. For phase 4, 20 additional earthquakes were displayed with no magnitude or location, thanks to the new version of the app. Felt reports correspond to testimonies left by eyewitnesses on EMSC's services, including LastQuake.

actors. The panel of interviewees is composed of a variety of profile in terms of geographical origin (born in Mayotte or in mainland France), age, gender and social background. It also includes a local journalist and an imam. Results have been pseudonymized; therefore, names have been changed. Consent to the publication of their quotes and indirectly identifiable data was obtained from the participants. All interviews were led in French. Interviewees were canvassed on social media, based on volunteering and on recommendations from other interviewees. This constitutes a bias as most interviewees are therefore globally more educated than the general population of Mayotte. Nevertheless, as part of a qualitative approach the study is not aiming to provide a representative picture of the situation, but to contribute to identifying key aspects of the context.

The second step is empirical. EMSC launched an online questionnaire, targeting its own users in Mayotte in order to better understand what information they need and improve its services. This questionnaire was sent to LastQuake users in Mayotte who had indicated an e-mail address in the app. It was also promoted on Twitter and Facebook. Four hundred and sixty-eight responses were collected between 22 June 2018 and 17 July 2018. Only available in French and requiring an internet access and digital literacy skills, the questionnaire did not aim to collect responses from a representative sample of the population, nor from LastQuake users. It still provides an overview of the anxiety level and information needs among respondents. Following the questionnaire results, LastQuake information system was improved in order to disseminate additional information.

MAYOTTE SEISMIC AND CULTURAL CONTEXT AS AN EXPLANATION FOR INFORMATION NEEDS

Mayotte Seismic Context and the 2018 Swarm

The Mayotte sequence can be divided into 4 seismo-sociological phases, which are based on seismic activity, scientific research, communication activities and citizens' reactions (**Figure 1**).

Phase 1 starts on May 10th 2018 when a M4.3 earthquake was felt in Mayotte during the evening. The event was surprising to the public, as the island is known for having only moderate seismicity. The International Seismological Center (ISC) catalog lists 22 earthquakes with a magnitude <4 between 1964 and 2010, within a radius of 300 km around the island (**Figure 2**) (International Seismological Centre, 2020). This May 10th event was followed by high seismic activity with between 10 and 30 felt earthquakes per day during the following few weeks (Lemoine et al., 2019). On May 15, the strongest earthquake ever recorded in the region (M5.8) hit the island (**Figure 3**).

The earthquakes were found to be mostly located about 50 km east of the island. Many happened at night, waking up citizens, increasing their anxiety level. During the 21 first days of phase 1, EMSC displayed 43 M>4 earthquakes on LastQuake. A month after the beginning of the swarm, 1,400 earthquakes had been detected by local seismic networks, 140 with M>4 and more than 20 M>5 (Lemoine et al., 2019). Some dwellings have been weakened (cracks and fractures could be observed),

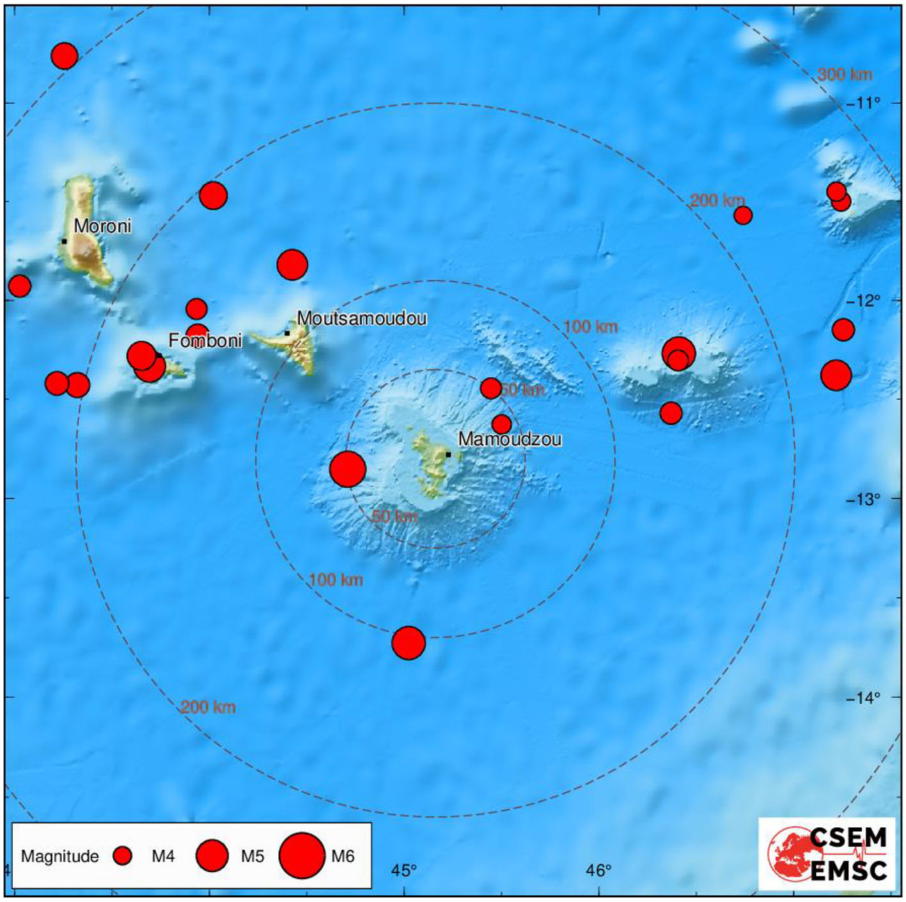


FIGURE 2 | Historic seismicity map near the Mayotte island using the ISC catalog for M> = 4 earthquakes (1964–2010). Largest event reaches magnitude 5.3.

yet, no casualties have been reported. Due to the lack of seismic sensors in the region, the surge of moderate-size earthquakes was left unexplained initially and many small earthquakes were not detected at all. This intense seismic activity left everyone, scientists, authorities and the population, puzzled.

Phase 2 runs from beginning of June to November 11. During this period, seismic activity continued but at a lower rate. LastQuake was able to display 68 M>4 earthquakes in the app during this phase. Seismologists and authorities set up an interministerial mission[3] to ensure that a reliable organization and logistical means would be operational in the event of a worsening of the seismic crisis. It was complemented by a scientific mission in order to explain the phenomenon. However, many citizens' questions remained unanswered. Indeed, despite the installation of three new seismic stations, data was often lacking on felt earthquakes and scientists needed time to conduct research. This was not well-understood by citizens.

On November 11, the Mayotte case started to draw the attention of scientists in international communities, starting phase 3 of this analysis. On that day, global networks registered low frequency signals, which could correspond to volcanic tremor that is likely associated with rising magma (Lemoine et al., 2019; Cesca et al., 2020). This raised the interest of the global geoscientist community along with many questions among citizens who still perceived scientific and institutional communication as insufficient.

Finally, phase 4 started in January 2019 and ended in May 2019. It marks a turning point in the case study, not because of the seismic activity but rather due to specific efforts in communication activities toward the public. Messages about the ongoing situation, research activities and safety measures to take were regularly spread on traditional and social media. Research also made important progress, scientists discovered that the cause of this active earthquake swarm is a new-born submarine volcano located ~50 km from the island (Lemoine et al., 2019; Cesca et al., 2020).

At the time of this paper, the swarm has yet to stop and earthquakes are still being detected and felt by citizens. For instance, in March 2020, seven earthquakes were detected (between M3 and M3.4), including two that were felt by the population.

[3]https://la1ere.francetvinfo.fr/mayotte/mission-gouvernementale-seismes-est-attendue-ce-vendredi-594683.html

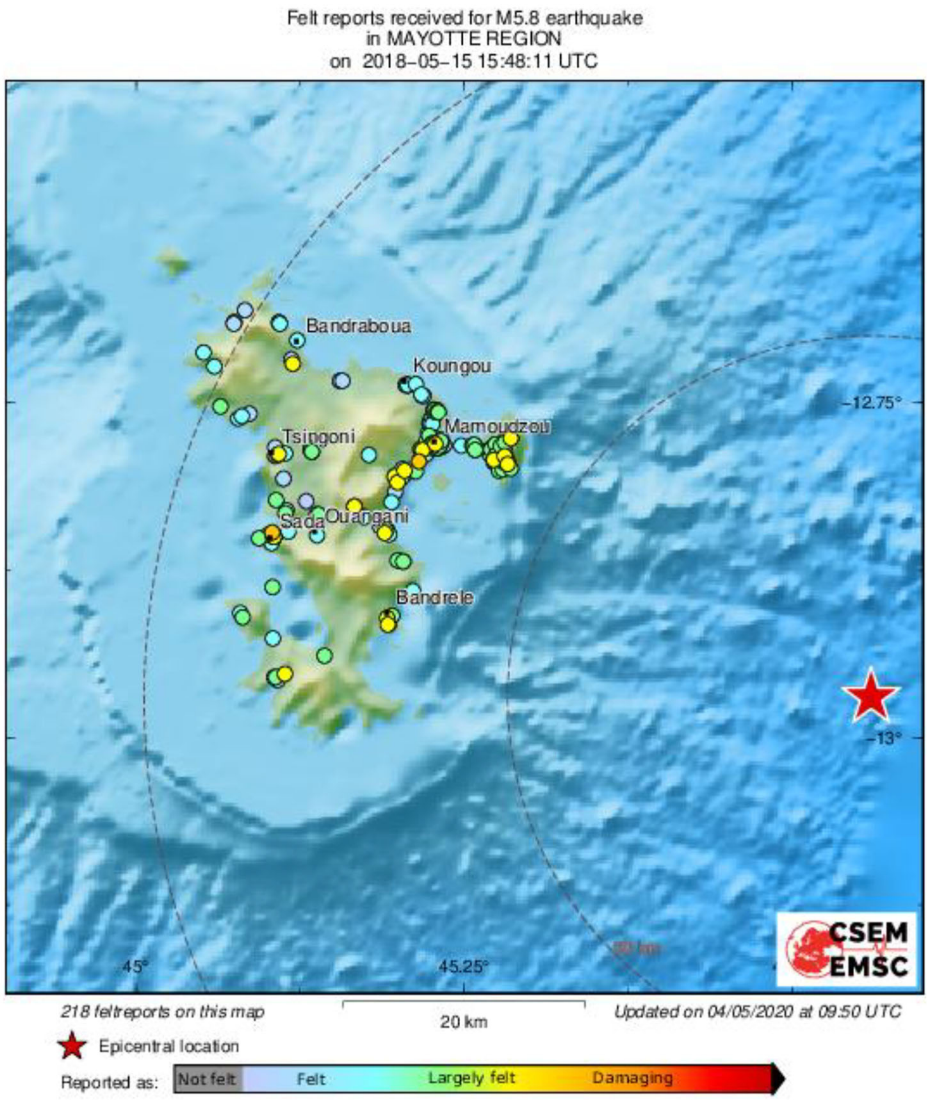


FIGURE 3 | Felt map for the M5.8 earthquake (2018-05-21). Each dot represents a felt report collected by EMSC, color corresponds to the felt shaking intensity reported by citizens.

Mayotte Socio-Cultural Context

In addition to the unusual seismic activity, cultural factors and context must also be taken into account to understand the full situation in Mayotte (Fallou and Bossu, 2019). The island, inhabited by more than 256,000 people (INSEE, 2017), has a very particular cultural setting despite being part of the French territory (Dauphin and Thibault, 2011). The population suffers more from poverty and illiteracy than on mainland: 84% of the population lives beneath the poverty threshold and in 2000 35% of men and 40% of women were considered as illiterate, while it is only 7% are among French citizens as a whole[4]. Insecurity feeling is at high level. Mayotte is the French department with the highest delinquency rate. The island is particularly in the lead for burglaries, reaching, in 2016, 19.1 burglaries per 1,000 dwellings, compared to 7.1 in metropolitan France (InterStats, 2017). Socio cultural differences also include religion, as 95% of people in Mayotte are Muslims[5], compared to 6% of the general French population[6], and a significant part of the inhabitants have animist beliefs (Barthès, 2003). Moreover, in 2007, only 63% of people aged 14 or older were found to be able to speak French, the official language, demonstrating the importance of the two native languages (Shimaore and Kibushi). Lastly, people in Mayotte have an ambivalent relationship with the authorities, due to the administrative history of the island (Mayotte became

[4]https://www.nouvelobs.com/rue89/rue89-mayotte/20111020.RUE5109/non-non-non-mayotte-ce-n-est-pas-la-france.html

[5]http://www.outre-mer.gouv.fr/mayotte-culture

[6]https://www.pewforum.org/interactives/muslim-population/

a French department through a local referendum in 2009), the geographical and cultural distance to mainland France. Findings from the interviews show that on the one hand they have strong expectations for the government to take specific measure to improve the socio-economic situation, but on the other hand they have little hope that they will be taken into account. Suspicion and mistrust are therefore high. In Mayotte as in every French department, the *prefecture* is the institution which represents the State at a local level, and as such, citizens' expectations are centered around it.

Beyond these cultural characteristics, people in Mayotte were also found to have a low risk culture[7], especially regarding earthquakes. Indeed, citizens were not used to seismic activity. Few had impacted the territory and earthquakes were not perceived as a risk by the inhabitants. Oral tradition can identify damaging earthquakes in 1606, 1679, and 1788 (Hachim, 2004) and the most recent significant earthquake associated with moderate damage, besides the 2018–2019 crisis, occurred in 1993 (Lambert, 1997). During the interviews most people expressed this perceived lack of preparedness, for themselves but also more generally among the population. For instance, Baptiste, a journalist, declared that not only the population but also the emergency services were not ready to face a major catastrophe. Nadine, a teacher who has been on the island for over 15 years also stated "We were not ready. I had never been told about earthquakes in Mayotte. They didn't exist. When we were doing drills with the kids it was for fire or terrorist attacks, but never for earthquakes. [...] And now the problem for the people is to know whether they should risk a burglary or an earthquake" *(Nadine, 60 years old, teacher).*

Overall, given the seismic history and cultural context, the population, along with the authorities and to a certain extent the scientific community, was unprepared to face such a seismic crisis.

Citizens' Information Needs and Anxiety Level

Unsatisfied Information Needs

According to the interviews and observations on social media, when the first earthquake hit the island, citizens wanted to get a confirmation that what they felt was an earthquake, know the magnitude and location of the earthquake. They also needed to know how to react in case of an earthquake and how to secure their houses. These are common queries when it comes to a large ground shaking event (Wein et al., 2016). As the earthquakes continued, information needs increased to include explanations for the phenomenon, insights on when would be the next one, what was the largest magnitude that could occur, when would the swarm finally stop and an assessment of tsunami risk.

Depending on various cultural factors, explanations were looked for in different rationality spheres (Boudon, 2001) and from different actors as expressed by Lucile, a teacher born in mainland France but who's family in law is from Mayotte: "Personally, I understood that the BRGM[8] didn't know what was going on and that they couldn't know it. But here it's different, first people looked for a religious explanation. They though it was God's will. In their reasoning, scientific explanations come after, in second or third position. But in a way, people still had high expectations toward scientists. They really needed an explanation, and they trusted them to bring this explanation quickly. So... they're waiting, especially now that they've come to the island... and they don't understand why nobody has told them anything" *(Lucile, 36 years old, teacher).*

Lucile's testimony gives insights on the importance of religious beliefs as an explanation for the earthquakes in Mayotte. Comments left on social media confirm this first sphere of explanation for many people in Mayotte. During the first 6 months, after each earthquake, many comments were posted on Facebook, stating that it was another warning, if not punishment, from God. This is consistent with social science research on the role of religious beliefs in popular explanations for seismic activity, including for Muslims (Severn, 2012; Sibley and Bulbulia, 2012; Chester et al., 2013; Stephens et al., 2013). However, in Mayotte, God's will and other religious beliefs appeared to be insufficient to explain earthquakes, especially when the earthquake activity lasted too long to calm the nerves by religious reason alone. According to most testimonies, including Icham's, an influential Imam, most of the citizens in Mayotte initially thought earthquakes were caused by God, or at least divinities, given the strong Muslim and animist cultural background. He stated that he was himself was looking for other explanations: "I've done a lot of research to know better what the Koran says about earthquakes, and I keep on doing my research. It is said in the Quran that the earth will shake and people will get scared. It does not mean it is the end of the world. So... I'm researching also about what everyone says. My role is to find an explanation to calm people down. So, I'm very interested in what seismologists say" *(Icham, 57 years old, imam)*. Thus, both secular and religious people then turned to scientists in order to get an explanation for the phenomenon.

In the first month of the earthquake swarm, the understanding of where, how big, and why earthquakes occurred is very limited due to several reasons. First, a lot of seismic data went missing due to the lack of station coverage. Many earthquakes felt by citizens were thus not recorded and no data was available to identify them from a scientific point of view. Additionally, scientists were unable to understand the nature and cause of the swarm as it was an unusual and rare case (Lemoine et al., 2019; Cesca et al., 2020). Secondly, information expectations about the prediction of earthquakes and the swarm's end were unsatisfied because they were unrealistic. Indeed, to date, no method of prediction (specifying when and where an earthquake will occur) has been scientifically demonstrated and, at first, scientists were

[7]Following Cornia et al.'s work, the concept of risk culture is used to explain "how groups and communities share common ways of perceiving risk, common knowledge about how to deal with disaster, common beliefs about who should be blamed for the disaster consequences, common feelings of trust or mistrust towards authorities and similar informative behaviours to be adopted in case of crisis situations" (Cornia et al., 2016).

[8]BRGM stands for Bureau of Geological and Mining Research. It is the national French Geological Service.

not able to explain the nature and causes of the swarm nor indicate when the swarm would end.

Despite the technical and scientific incapacity to provide this information, expectations toward seismologists remained very high among the population. A widespread image of scientists was that of powerful, nearly omniscient scientists who knew everything about earthquakes. On Facebook, many expressed their incredulity facing the lack of explanations from the seismologist community. Jean also stated: "It's unbelievable that they don't know anything. We feel earthquakes and they don't know anything about them. They are not even capable to explain them, but it's their job!" (*Jean, 60 years old, policeman*).

These unrealistic expectations can be partially explained by the lack of knowledge about seismology's limits. One could argue that it may be a matter of education. Indeed, among highly educated interviewees, some of them understood the limits of seismologists' knowledge such as Lucile quoted above or Joel, an engineer working for the departmental council: "I quickly understood that they wouldn't be able to tell us what was going on…It will take time for them to research this. But of course, I would love to know what's going on. But for the moment I just have to be patient… and hope it will stop soon" *(Joel, 47 years old, engineer)*. However, education and information about these limits may not be sufficient as these expectations were found to be enhanced by anxiety. For instance, Marie, a lawyer originally from Paris stated her own "irrationality," explaining that even though she knew the BRGM could not yet explain the seismic phenomenon she still needed to understand and they expected the seismologists to find an answer. A need that was increased by her anxiety. Such cognitive errors about seismologist work has been found in other case studies (Celsi et al., 2005).

All interviewees reported a perceived lack of communication from both the authorities (especially the prefecture) and the scientific community, particularly concerning why they failed to provide sufficient information. As far as the scientific community is concerned, interviews and observations demonstrate that people in Mayotte hold high expectations on the BRGM, as it is the national institute. Officially, BRGM's role is to monitor and collect geological, geodetic, and geophysical data to prevent natural hazards and to help decision making. Regarding seismic risk, BRGM is in charge of "regular information when earthquakes are felt, characterization of the risk of liquefaction under school buildings and implementation of a "Seismology for schools" program[9]". In France other institutions such as BCSF (Central Bureau of French Seismicity) or IPGP (Paris Institute of Earth Physics) are also partly responsible for seismic information and observation. However, BRGM was quickly identified by the local population as the main interlocutor and became the center of most of the expectations from citizens in Mayotte. Despite this, people also looked for information from additional sources such as the USGS (United States Geological Survey) or EMSC, demonstrating their urgent need for understanding.

Overall, an absence of science communication and risk communication can be identified. Interviewees noted that they would have understood better if the knowledge limits had been explained shortly after the first earthquake. Moreover, they expected the communication to be accessible to all, which implies to be done on various channels, including social media, and in all languages, not only French. Some complained that the authorities and scientific institutions didn't understand their needs. Nadine for instance stated: "I called the mayor's office and the prefecture but they didn't give me any information. They just gave me the number for psychologists for help… but that's not what I needed. I needed an explanation!" *(Nadine, 60 years old, teacher)*. Additionally, interviewees also reported a lack of information in the local media, but they attributed it to the general lack of information they felt the BRGM should be responsible for.

During the first phase of Mayotte swarm, citizens" needs were neither sufficiently managed nor satisfied. This had two consequences: it increased anxiety level, which was already high, and it opened up the space for the propagation of misinformation.

An Anxiety Level Raised by a Lack of Information

Due to the stress and fatigue induced by a large number of earthquakes, combined with little previous experience of seismic activity in the region, anxiety was very high among people. Marie for instance reports that: "At some point, and it's not only me but everyone I know, we were doing everything depending on the earthquakes. We were thinking… "Do I have time to shower?" or "Maybe I should wait before going to the bathroom because there may be another earthquake, it may be too dangerous". And it lasted for weeks" *(Marie, 26 years old, lawyer)*.

Another interviewee also told that he was so anxious that he slept with a machete to break the wall between his bedroom and his daughter's in case of an emergency. Many earthquakes occurred at night, leading people to sleep outside. Baptiste, a journalist for a local newspaper remembers how they made a special edition one night at 4 a.m. "People were sleeping on the streets, the mosques were calling on people to get out, to evacuate the houses... because they were announcing an aftershock after the tremor that had been recorded at more than [M]6[10]" (*Baptiste, 31 years old, journalist*).

Anxiety was found to be enhanced by the perceived lack of information. Many testified that not knowing the causes or how long it would last increase their anxiety. This is consistent with previous work demonstrating that information can partially cure anxiety (Saathoff and Everly, 2002). A poignant example of the effect of a lack of information was found in Joel's interview when he stated with strong emotion in his voice, somewhere between distraught and anger: "NOTHING! We had NOTHING, neither from the prefecture, nor from the BRGM, NOTHING. While everyone could see that it was shaking, that at the moment... We were upstairs, between 20 and 30 people, and everyone could see, when we were at work, that it was shaking at the same time... We're not liars! It happened! But there was nothing!" *(Joel, 47 years old, engineer)*.

[9]https://www.brgm.fr/regions/reseau-regional/mayotte.

[10]Baptiste talks here about the M5.8. His mention of ≪ M6 ≫ refers to the fact that magnitude estimation can fluctuate after an earthquake, and collective minds can recall higher magnitudes that are then revised.

As a whole, in the Mayotte case, in the first few months of the crisis, citizens suffered from a perceived lack of scientific and crisis related information. These needs were increased by anxiety, which in turn, increased their anxiety, in a vicious circle.

Information Vacuum Increased Misinformation and Mistrust

While scientific understanding of the Mayotte earthquake swarm was limited, numerous scientifically unsound theories arose. Marc, a retired man who has lived on the island for over 30 years reported: "We've heard everything! There were crazy rumors about a volcano that was going to rise from the sea[11], secret petroleum drills were causing the earthquakes, and also the cow, buried alive, was moving its head, making the earth shake… But there were no scientific explanations, so people turned to other beliefs" (*Marc, 66 years old, retired*). Icham also expresses his personal doubts about theories he heard: "Everyone has theories, I personally don't know exactly so I'm waiting to get information. It is said that people looked for evidence of oil and gas drilling. Everyone has their own imagination. Maybe some of them are right and have the right explanations, but I don't believe it. From what I analyzed it's not the cow either. But still, I can't explain" (*Icham, 57 years old, imam*).

The theories were of different natures. Some were religious or spiritual, such as God's wrath, others were linked to animist beliefs and oral traditions such as a cow or zebu that had been buried and was moving its head beneath the ground. The existence of a submarine volcano or of secret oil drills were commonly believed. While the set of explanations have been in turn believed, researched, explained, mocked and ridiculed, all were taken under debate among citizens, including on the Facebook group. Further research would be needed to assess to what extent inhabitants of the island believed in one, or several, of these explanations. However, the way people exchanged their ideas of what caused the active earthquake swarm demonstrates a certain level of interest and illustrates the importance of constructing an explanatory frame of reference to citizens.

However, citizens not only had to find an explanation for the earthquakes, but also for the silence of the authorities and scientists. This led to an increase of mistrust toward the institutions that were seen as hiding the truth from the population. Joël, for instance, declared: "We need to know the truth. It's not possible… they're hiding the truth from us. Why? So, either we're just kids, underage who aren't told the truth... Or they're worried; the administration is worried and doesn't want to share the information. But it's no better. We don't know why they won't tell us!" This testimony is a typical example of the suspicious atmosphere in Mayotte during that time, which led to an increased mistrust toward institutions. Baptiste even noted that "At some point a theory was even explaining that the government created the earthquake swarm to prevent people from going on strike again, because they had done so during the previous 2 months" (*Baptiste, 31 years old, journalist*). This explanation falls under conspiracy theories, stimulated by emotional fatigue and mistrust toward the institutions. It appeared satisfactory to some members of the community as it provided an explanation both for the seismic phenomenon and for the information vacuum. Media may have also played a role. For instance, on January 17th 2019, an article in Mayotte la 1ère[12], a local newspaper, reported that Paul Allen, an American billionaire, may have observed the birth of a volcano from his yacht "the Octopus" Beyond the facts, the author uses the lexical field of mystery, which may have reinforced already existing doubts and suspicion in the reader's mind.

In order to cope with the situation, reduce their anxiety and meet their needs for understanding the earthquakes (why, when, and how they happened), citizens turned to existing citizen seismology projects, and also created their own network.

STTM, A SELF-STRUCTURED CITIZEN SEISMOLOGY COMMUNITY

Citizen Seismology for Citizens, by Citizens

STTM ("Soutien Tremblement de Terre Mayotte"), standing for "Earthquake support Mayotte" is a Facebook group[13] made up of more than 10,000 members. It was created a few days after the first earthquakes with the goal of gathering information about the situation.

Facebook is a major part of information and technology culture in Mayotte. Many interviewees describe how things can and must be done through this social media, such as booking an appointment with the aesthetician, checking a doctor's schedules or road traffic conditions. The road traffic condition page is indeed a popular one in Mayotte, gathering more than 49,000 users with on average of 230 posts per day according to Facebook data. After the first earthquake many started to discuss about it on the road traffic group. One of the group administrators thus decided to create a group dedicated to earthquakes for more consistency. According to some interviewees who know him, this man, who did not wish to be interviewed, has no specific knowledge about earthquakes. He just aimed at making users' navigation easier with an identified page for traffic and one for earthquakes.

The group was created by a citizen for citizens, in order for them to exchange what they know and feel about earthquakes. The group is public and anyone with a Facebook account can join it. It is moderated by a few volunteers who can decide of the rules of the group and exclude members who do not comply with them. Data is insufficient to get a precise overview of the sociological characteristic of the group and of these moderators. However, from what could be observed, messages were posted, commented and got reactions from both men and woman, in French and Shimaore.

After a felt earthquake citizens usually post messages to say where and when they felt it, and sometimes ask for complementary information such as magnitude (**Figure 4**, left). They also ask for and show emotional support, comment on each

[11]It is here to note that what was considered as a crazy theory revealed partly true as the earthquake swarm is indeed linked to a volcanic activity.

[12]https://la1ere.francetvinfo.fr/mayotte/naissance-volcan-au-large-mayotte-670649.html

[13]https://www.facebook.com/groups/312080469323937/?ref=bookmarks

FIGURE 4 | On STTM Facebook group, a citizen wonders about the magnitude of an earthquake he just felt (Left). Citizens also use humor to describe earthquakes they felt. “21H31, heavy stuff guys, I thought Mbappé had scored again!” (Right).

others’ questions and posts. Some of them post in Shimaore. If, at first, they shared their anxiety about an unknown and unexplained phenomenon, the tone became lighter as they became partly used to it. Once members of the group became less anxious or frightened by the earthquakes, they also made great use of humor, in order to play down the situation. For instance, following an earthquake occurring during the football world cup (30th of June 2018), users compared earthquakes to shakings provoked by supporters after Mbappé, a French player, scored (**Figure 4**, right). As such STTM could be seen as a barometer for social emotions on the islands, relative to the seismic situation.

Most interviewees mentioned the STTM Facebook group spontaneously. One of the first functions of the group was to create a feeling of community, to be part of a shared experience. For Marie, “It was very reassuring to know that others had felt earthquakes in Mayotte, and that I was not crazy” (*Marie, 26 years old, lawyer*) and Lucile felt the same: “As soon as I feel an earthquake, I’m going on this page to check that it really was an earthquake. And I also check for damage. If something happened it’s mentioned on this group, for sure. Everyone posts pictures of cracks or trees on the roads. And I can also check where it was felt, in which part of the island” (*Lucile, 36 years old, teacher*).

Many users in this Facebook group also discuss the potential causes of the earthquakes. Nadia for instance stated “I had basic knowledge of seismology; I knew what I learnt at school, but no more. When the earthquakes started, I made further research because there was no information. I wanted to know about the faults in the regions etc. I looked on the internet but also on this Facebook group, because there was a lot of information” (*Nadia, 40 years old, nurse*). Icham, imam on the island, also took part in the group to get more information and share his findings: “I’m doing research… I’m not sure yet why there are all these earthquakes. Some will say it’s God punishing us but I think it’s more complicated than that. Maybe God is warning us about something; it still has to be studied. And that’s why I’m in this group, to learn and share what I discovered” (*Icham, 57 years old, imam*).

Through this Facebook group, citizens thus launched a form of citizen seismology, as they shared knowledge and information about earthquakes they had felt as well as about the phenomenon. And they did so without the help from the seismologist community.

Seismology Without Seismologists

Initially, the group was not thought of as a citizen science tool, it was simply created to meet emotional and informational needs. No member of the scientific community per se took the lead of this group, and no seismic institution or authority member has officially contributed to its development.

Nevertheless, due to the length of the seismic crisis and to its initially unexplained cause, the group has taken a more and more scientific direction. Some members, those more interested in seismology or in this seismic phenomenon, took the lead and shared information in an understandable way for their fellow citizens. Information was related to felt earthquakes, as well as to seismology in general. Information about possible earthquake causes was shared and discussed. Basic seismological concepts such as magnitude and intensity were explained in a pedagogical way. Comparisons with other earthquake swarms were made. Historical data about Mayotte seismicity was documented along with information about seismological knowledge limits, and safety measures to take. Citizens thus took the lead on collecting data and reviewing the existing scientific literature which they had access to.

In addition, they also started to *produce* collated forms of knowledge, as one of the members started to list all felt earthquakes declared on the group and compare it to BRGM's seismic reports. Moreover, a few months after the beginning of the crisis, a user suggested launching a crowdfunding operation in order to equip the island with Raspberry Shakes. Raspberry Shakes are relatively affordable seismic sensors that can be installed easily in schools or in citizens' homes and that are used in many citizen seismology projects (Calais et al., 2018; Subedi et al., 2020). The crowdfunding project has not actually been implemented in Mayotte; however, it demonstrates a certain commitment level as well as an understanding of the lack of sensors and data issue.

Finally, in January 2019, a few members collected questions from the whole group and organized them in an open letter[14] addressed to scientific institutions and authorities. During the first phase of the crisis that was observed, neither the BRGM nor the prefecture publicly engaged with the STTM page. Information was progressively made available on Prefecture's social media account and BRGM's website. Some active members of the group were invited to a meeting by the prefecture in October 2019 (a year and half after the beginning of the crisis) in order to discuss citizens' expectations, future research developments and measures to take.

The citizen seismology community was formed and self-organized through STTM Facebook group. Without direct interactions with seismologists, the active members in this group took a role in leading the discussion. Some members also relayed rumors, conspiracy theories and explanations that would not be considered as scientific, however, these were debated or fought against with humor. As a result, the general tone on the group became more and more scientific. It led to a perceived increase of global knowledge and interest for seismological matters among members of the group, from what could be observed. This could not be quantified and further study would be necessary.

Along with the STTM experience, another citizen response to the information vacuum was for them to turn to the LastQuake app to get timely information and leave their testimonies. However, seismic data was also lacking for EMSC's system to run efficiently and it had to be adapted.

LASTQUAKE, A CITIZEN SCIENCE PROJECT EVOLVING WITH CITIZENS

An Innovative Citizen Seismology Project, Popular in Mayotte

LastQuake is an innovative earthquake detection and information system developed by the EMSC. It is a multichannel system composed of a Twitter bot (@LastQuake), a mobile site and a free and ad-free mobile application. Its main goals are to provide information for the public as well as to collect data via crowdsourcing. It detects peaks in web traffic and app launches that are characteristics of felt earthquakes. Indeed, when citizens feel an earthquake, they tend to look for information, quickly launching the LastQuake app, finding EMSC's website or tweeting about earthquakes. When launching the app, they are then asked to provide a testimony of how intensely they felt the event and can add a comment and/or a picture. This set of crowdsourced data is then merged with seismic data coming from partners' institutes. Originally, if after 15 min no seismic location had confirmed the crowdsourced detection, the event disappeared from the app as it was suspected of being a false detection (Bossu et al., 2018). Operating globally, it enables users to get timely information about felt earthquakes, being useful to eyewitnesses who want to get information or to share some (**Figure 5**), as well as to people interested in seismology or members of impacted communities located in other area. LastQuake also provides post-earthquake visual safety tips in order to contribute to risk reduction and help users adopting safe behaviors after an earthquake (Fallou et al., 2019). LastQuake's strategy of using visual content helps to address the challenges linked to its global distribution. Indeed, being used all over the world, the content must be as universally understandable as possible, regardless of language, cultural background, or literacy level.

LastQuake is a pioneering citizen seismology project that uses digital technologies, especially social media. As the system uses crowdsourcing to detect felt earthquakes, citizens are placed at the core of its system (Bossu et al., 2011). It was and continues to be developed by seismologists, however, in order to efficiently develop these citizen science tools, users feedback is crucial (Bossu et al., 2019).

Few weeks after the beginning of the seismic activity, more than 1% of the population in Mayotte had downloaded LastQuake, which is another sign of citizen's information needs[15]. Despite the popularity of the app on the island, users reported that not all needs were met, especially because some earthquakes that they had felt were not displayed in the app, or disappeared after they had left a testimony. In the comments section as well as on the app store and social media, users expressed ambivalent feelings toward the app. On the one hand it was helping them cope with the situation when information was available and they could share their experience, but on the other hand it often created frustration or suspicion when it wasn't. As with many other seismological institutes, EMSC received criticisms for the lack of information. EMSC thus launched a questionnaire in order to collect testimonies from users in Mayotte, to understand their specific information needs and improve LastQuake. Methodology for the survey is described in the Materials and Methodology section.

Lessons Learned From Lastquake Users in Mayotte

Information as a Necessity

Through an open question about users' experience during the earthquakes, results confirmed that information can cure anxiety.

[14] Accessible at: https://www.change.org/p/m-le-pr%C3%A9fet-de-mayotte-plus-d-informations-et-de-communication-sur-les-s%C3%A9ismes-%C3%A0-mayotte

[15] 2,744 people on 2018/06/18.

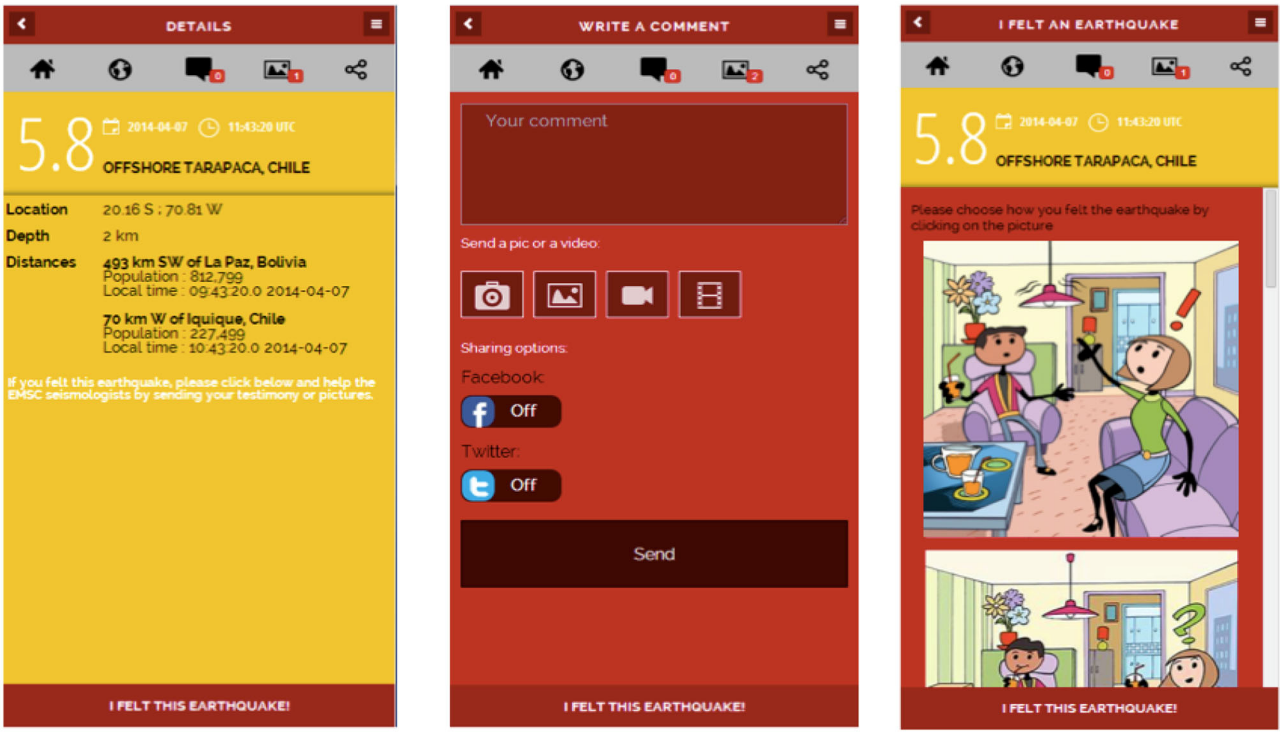


FIGURE 5 | LastQuake app enables users to get information about felt earthquakes (screenshot on the left), leave comments and pictures about earthquakes they felt (screenshot in the middle) and provide information about the intensity they experienced through a set of visuals (screenshot on the right).

Amongst all the answers, the following two illustrate well this phenomenon:

> "Anxiety and disturbed sleep for the first 15 days. Since then, I have been interested in the phenomenon scientifically and I have learned a lot about it. I have adapted to daily life; I now know how to react in the case of tremors."

> "I lived for a week with fear in my stomach, but after I knew that you can't predict earthquakes and tsunamis, I started to get a little better but I will still be attentive."

However, information needs are of diverse types and are not always possible to meet.

Missing Information and Mistrust

Overall, 18% of the respondents declared to be "very satisfied" and 43% "satisfied" with the LastQuake app. This suggests room for improvements. Through an open question, users were encouraged to provide suggestions to make LastQuake more useful to them. Two hundred and ninety-seven respondents took this opportunity and made propositions. Among them, nearly one third left a comment related to the necessity to report all felt earthquakes in the app. Further, some mentioned their lack of understanding linked to the fact that earthquakes of small magnitudes were reported in other regions of the world (better equipped with sensors) but not in Mayotte.

29% requested higher precision in the magnitude and location of earthquakes, and 15% to improve the rapidity of information sharing. Other popular suggestions also targeted the need for general information about the causes of the earthquakes (11%), and the explanation of why seismic data was not available (8%).

This is consistent with what was found in the semi-directive interviews. For instance, Nadia stated that "The app is information served on a platter... But on the other hand, on the app I am not told that information will only be given from M4 onwards. And we constantly experienced ground shaking. We had about twenty earthquakes during the day and no information because it was below M4. So, for me the threshold to trigger the notifications was too high" (*Nadia, 40 years old, nurse*). Her statement actually reveals that she didn't understand that no information was provided not because of a threshold but because of a lack of seismic data. A similar frustration is presented by Nadine: "As soon as there was an earthquake, I would directly check my application, and then I was not happy because we had a lot of the earthquakes we felt that were not marked… whereas I had the M2.5 from Hawaii. I had felt more than M2.5 and I didn't care about the M2.5 in Hawaii. [...] You feel like you've been forgotten" *(Nadine, 60 years old, teacher).*

This added to the suspicion held by many users, as evidenced by some comments on the app. For instance, after a M4.6 event on 26th August 2018, among the 37 eyewitnesses comments, there are many questions regarding the absence of data for other felt earthquakes: "10 earthquakes felt today in Mayotte with an increasing intensity and duration… why don't you[16] tell about them?," some even mention conspiracy suspicion: "Is it over? You no longer count the tremors in Mayotte? Government order?"[17].

Comments on LastQuake along with questionnaire and interview results, reveal the frustration and mistrust created by the fact that some felt earthquakes were not displayed in the app, and by the lack of understanding of the way the system operated.

The Ambivalent Relationship to Magnitude

Both the questionnaire and interviews demonstrate that citizens attach great importance to magnitude even though they don't always understand it and sometimes confuse it with intensity[18]. This is consistent with Celsi et al. (2005) findings. In their research they demonstrate the cognitive anchoring process which leads people to compare their felt earthquake experience to the reported magnitude size of the earthquake, regardless of how far from the epicenter they were and other seismic parameters. This anchoring effect can be alleviated by scientific knowledge and understanding of seismicity (Celsi et al., 2005).

Providing the information of earthquake magnitude enables citizens to measure how much damage should be expected: "Magnitude is important… it tells me if I should worry or not. Under M5 I know it's ok, I don't have to be scared. But more than 5… it scares me. I remember well the M5.8 that occurred in May. I was alone at home and I was very very scared" stated Nadine. The same idea was expressed by Marie: "I'm very interested in magnitude, it's a point of reference. Now I know what a M4 can do in terms of damage. If I see a magnitude 6 or 7 on TV then I also know" (*Marie, 26 years old, lawyer)*. However, her statement reflects a possible confusion between magnitude and intensity.

More interestingly, associating a magnitude to an earthquake was also found to be a way to legitimize the event, to give it a name and a certain form of existence. Providing a magnitude objectifies the earthquake. "When we get the magnitude, we know it's real, that someone in a lab has said "yes there was an earthquake" So yes, I'm really waiting for the magnitude. […] And also, the magnitude it's nearly the name of the earthquake, when we discuss about it it's always "oh did you feel the 4.6 yesterday? And the 4.3?" We always use the magnitude, but sometime it varies so…" (*Nadia, 40 years old, nurse*).

Jean's view complements Nadia's as he stated that getting a magnitude not only enables confirmation of the fact that it was indeed an earthquake, but also confers a special status to those who felt it, which seemed important to him: "at least when you have the information [of magnitude], when they release it, it gives you the victim status. You know it was something, it really shook and you went through this. And you probably don't realize it, but it's important" (*Jean, 60 years old, policeman*). In other words, magnitude, being officially and publicly provided by an institution, certifies that an earthquake has been felt and, legitimizes the emotions experienced by eyewitnesses.

Citizens realized that a social validation of the seismic characteristic of what they felt was already an achievement and could alleviate anxiety. "Of course, magnitude is very important, but if there is at least the event in the app, it's already something. It would make me feel like we're not forgotten" *(Lucile, 36 years old, teacher).* This is supported by the fact that the Facebook group was created in order to share experience about felt earthquakes and get a confirmation that had also felt it. his is consistent with what we observed from STTM Facebook group that, the more citizens learn about the earthquake, the less anxious they feel. This suggests that with or without the complete seismic data, it is important for people to share and talk about their experience in an interactive platform (e.g., social media, app, and so on).

Overall, the results of the questionnaire and of the interviews suggested that citizens involved in the project needed to get information about earthquakes, even when it was incomplete, and also to understand how the detection system worked. This had two implications for LastQuake. First a new type of event with no associated magnitude or location was created, and secondly a communication effort was made to explain the system behind the app to citizens.

LastQuake Improvements

Following the questionnaire and interviews results which are essential tools used by EMSC to gain a return on experience and improve their tools, EMSC decided to create a new type of events in its app: incomplete events. Included in the LastQuake system at the beginning of January 2019, they are launched when a crowdsourced detection occurs and 8 felt reports, close in time and space, are left by eyewitnesses. This guarantees that a seismic event has indeed happened, even though it has not yet been associated with a magnitude or location. They turn into a regular event if/when they are finally associated with a magnitude and location thanks to official seismic data. During phase 4 of the case study (**Figure 1**), 28 events of this types appeared on the app, including 8 that were eventually completed with seismic location and magnitude.

These events have been designed in a way that underlines their specificity and their incomplete nature. They also follow the constraint that they must be understood at a global scale, regardless of cultural factors, language or literacy level. The term "earthquake" has been chosen from the beginning in order to stay simple and limit text in the app to keep it as universal as possible. However, if in most cases these events are indeed earthquakes, LastQuake can also detect felt shaking issued by sonic booms or meteors[19]. EMSC will then consider replacing "earthquake" by "shaking" in the event description, which would require translation in every language available in the app. They appear in brown in the app, whereas events with complete seismic information are represented in a range of colors from green to red depending on their intensity and impact. When associated with a magnitude and location they turn from brown

[16]≪ you ≫ here targets EMSC.

[17]Comments available at: https://www.emsc-csem.org/Earthquake/Testimonies/comments.php?id=715233

[18]Seismic magnitude scales are used to describe the energy released by an earthquake, while intensity represents the strength of the shaking at a given location. An earthquake has one magnitude, but impacts different locations with different intensities.

[19]See for instance: http://novilist.hr/Vijesti/Hrvatska/Kod-Ucke-u-atmosferi-izgorio-meteor-Vidjela-se-jarka-svjetlost-i-trag-dima

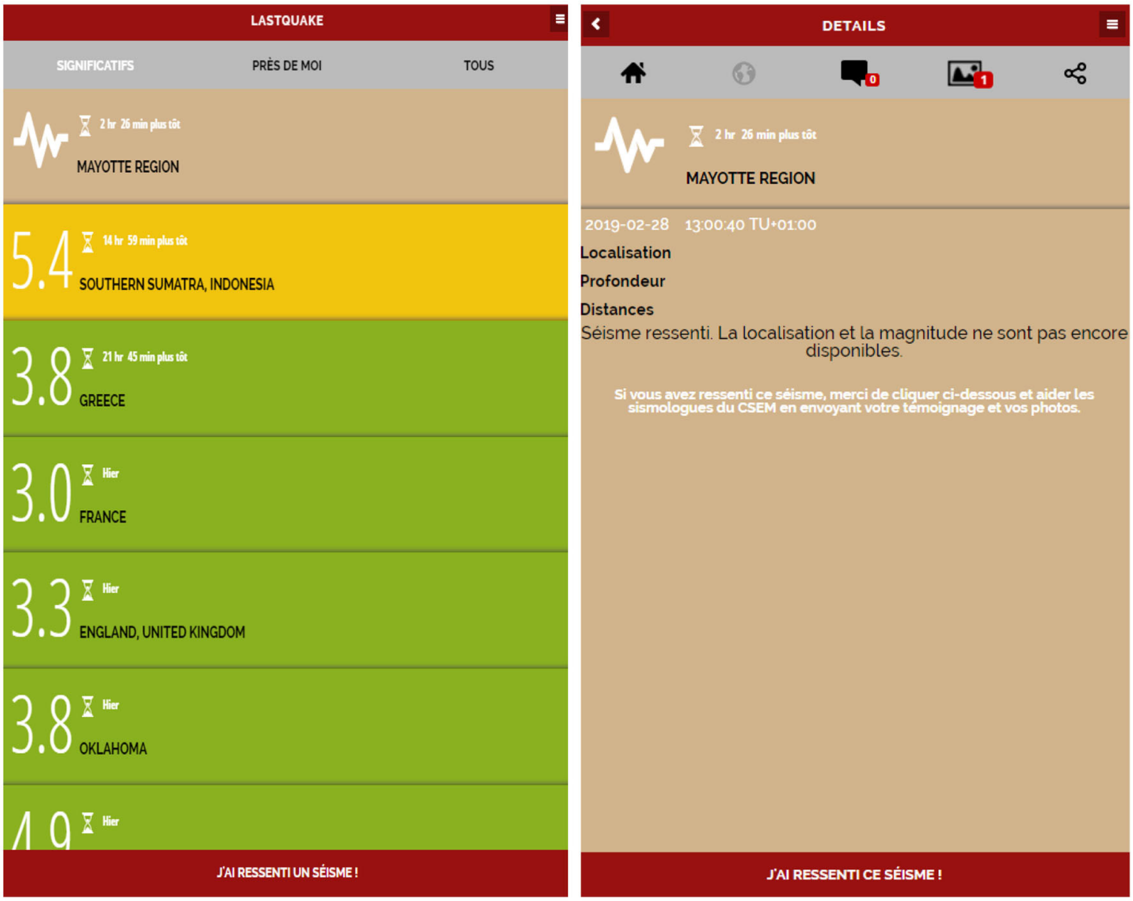


FIGURE 6 | A new type of event has been implemented in LastQuake (in brown). Though incomplete, the presence of some information has been found to be essential to users.

to their associated color. A seismic wave symbol is displayed instead of the magnitude to indicate the incomplete nature of the information (**Figure 6**).

When clicking on this new type of event, users access the event page, stating that the earthquake has been felt, but that magnitude and location are not available yet (**Figure 6**). This implies that information will be updated when and if possible. Textual contents were translated into all languages available in the app. As for any event, users can contribute and share their experience, stating how intensively they felt it. They are also encouraged to send photos and can access comments left by others, and a map of testimonies.

This new type of events was designed to respond to citizens' need for a validation that what they felt was really shaking and possibly an earthquake. This information, though incomplete (as no magnitude or location is associated) is essential for reducing anxiety levels. By providing all information available at a given time, assuming its incompleteness and publishing updates when available, EMSC guarantees a transparent information process. Based on comments collected through the app, social media and the application stores EMSC also observed that trust-based relationship with its users has been restored. It highlights that during a seismic crisis information needs must be hierarchized and prioritized. Even though magnitude and mapping effects were found to be important information, they appeared secondary compared to the confirmation of the seismic nature of what eyewitnesses had just experienced.

Additionally, EMSC's communication strategy has been revised in order to include materials explaining the nature of the detection system. Indeed, as LastQuake relies on the one hand on crowdsourcing and on the other hand on seismic data, citizens have to understand that not only are they a crucial part of the detection system, but also that no complete data can be published if sensors are lacking in a given region. This was made through a motion design video posted on social media and available on EMSC's website[20]. It is accessible easily on Twitter as it is the @LastQuake pinned post on Twitter. The video was designed in order to be universally understood by users, using no text or voice over.

[20]https://www.emsc-csem.org/service/application/

DISCUSSION

Citizen Seismology Without the Seismologists

This Mayotte case-study shows that when information is not available to them, citizens will seize or create tools that meet their needs, and that they can do so without seismologists, as was the case for the Facebook group.

STTM, the Facebook group, was originally created, at least in part, in opposition to the seismologists' community who did not succeed in meeting nor managing their information needs. While it was not originally perceived as a citizen seismology tool, it slowly became one. The group, composed uniquely of citizens slowly became a full-fledged citizen-seismology group as they discussed not only their own earthquake experiences, but also causes and potential consequences of the swarm. Gathering more than 10,000 members, the group was not anecdotal and even took on a political dimension (in a broad sense) when they published an open-letter asking for political action and scientific responses. The number of members provides a certain form of legitimacy, even though expression on social media is still controversial and cannot be considered as representative. Their legitimacy was further raised by the prefecture who invited authoritative representatives of the Facebook group for a meeting to discuss information needs along with political and scientific actions.

STTM members' relation with scientists remained ambivalent. On the one hand the STTM members had strong expectations on scientists, and on the other hand they showed a lack of trust toward them. While citizens were debating on Facebook, scientists were gathering on Twitter, another social media, to discuss explanations for this seismic phenomenon (Lacassin et al., 2019). Both citizen and researcher communities were thus discussing about the same topic, but on different social media. Questions were formulated on Facebook by citizens while answers started to emerge on Twitter. This can be explained by technological culture as well as by socio-technical design of the platforms. Indeed, in Mayotte, Facebook is more commonly used by individuals for daily and personal uses, while Twitter has become a useful tool for researchers to exchange ideas, collaborate and share preliminary results.

On the whole, members of the groups appeared to have learnt about the situation and about seismology in general. However, citizen seismology initiatives like this one would benefit from the expertise of seismologists, especially to avoid mistrust, misinformation and conspiracy theories. Seismologists, providing information in an understandable way could contribute to the success of such citizen seismology enterprises, and thus to raise risk awareness, scientific knowledge and finally, to improve risk reduction. However, this represents a major challenge for all parties.

Science Communication and Risk Communication for Citizen Seismology

Citizen seismology lies between many disciplines that include not only seismology but also sociology to understand citizens' needs, science communication, and risk communication. Therefore, geoscientists need to investigate both fields when communicating with the public. Lamontagne and Flynn (2014) have already shown that in the aftermath of earthquakes, geoscientists have a key role to play in communication. They can contribute to reduce anxiety and promote recovery by sending messages that "provide a sense of safety, calming, self- and community efficacy, connectedness, and hope" (Lamontagne and Flynn, 2014). All these elements are important for citizens to feel reassured and cared for. However, information needs to be prioritized. Right after the earthquake, the main point of communication is to establish a public statement about the seismic event, and in a second time but in a timely manner, to provide seismic data such as magnitude, felt intensity, shaking map. This, along with post-earthquake safety tips will contribute to reduced anxiety. Furthermore, the Mayotte case demonstrates that during long-lasting seismic swarms, and when information is lacking, there is a need to communicate about the way seismology is done in order to limit the cognitive errors and unrealistic information expectations.

However, this requires that geoscientists are ready to communicate with the public. This does not only imply that they have special training but also that they identify themselves as responsible for communicating to the public. In Mayotte, in the first couple of days of the earthquake swarm, BRGM was expected to communicate with citizen and deliver more earthquake information. However, this institution is not always the official communicating actor for seismic hazards in France. Assessing public communication expectations and responsibilities beforehand is thus necessary, not only in terms of information to be provided but also of perceived legitimate actor to carry out the communication (Petersen et al., 2017).

Understanding Information Needs and Cultural Background

The example of both the STTM Facebook group and of LastQuake users' show that seismologists need to acknowledge citizens' questions and efforts in order to lead successful citizen seismology projects. Even though the public's expectations may not be realistic they can be managed. Seismologists could help leverage expectations by explaining the way they work, their constraints and what type of data they need. Re-asserting that, as of today, earthquakes cannot be predicted or that aftershocks will occur may be useful.

In order to communicate efficiently, information needs must be assessed locally as they vary depending on cultural factors as well as previous knowledge and experience. Research has found that the type of information, the legitimate and trusted actor, as well as the way the public want to receive it will vary depending on risk culture, technology culture, gender roles, age or religion for instance (Tagliacozzo and Magni, 2016; Appleby et al., 2019; Becker et al., 2019). This implies that scientific communication is an essential part of citizen science projects. As far as seismology is concerned this applies to both science communication and risk communication. Assessing needs and cultural context will also enable organizations to set up an inclusive communication (Canfield et al., 2020).

Assessing information needs is also essential for designing efficient citizen science tools. Indeed, citizens will use technologies that meet their needs, especially in case of disaster (Appleby et al., 2019). This confirms that citizen seismology projects should set up ways to obtain user feedback on a regular basis and co-build the tools. Doing so enabled EMSC to understand that incomplete information was still valuable, and even essential to citizens. The simple fact of stating that an earthquake has been felt by other users can already contribute to reducing anxiety and avoiding suspicions.

Avoiding Misinformation and Conspiracy Theories

In the Mayotte case study, misinformation and conspiracy theories were partly fuelled by an information vacuum and increased by the pre-existing mistrust. Interviews revealed that citizens were seduced by conspiracy theories when they had to find an explanation for both the seismic events and the perceived silence of the scientific community and the authorities. Scientists thus have a key role to play, along with the authorities, in order to provide the reasons why the information is not available. Research takes time and citizens may not realize it, especially under high level of anxiety (Lamontagne and Flynn, 2014). Misinformation after a disaster or during a crisis is likely to spread and social media constitutes one of the ways (though not the only one) which it quickly expands (Keim and Noji, 2011; Rajdev and Lee, 2015). Thus, in order to limit the spread of misinformation, a proactive communication approach from scientists is required. This would help prevent rumors about earthquake prediction, anxiety and misinformation. However, science and risk communication require specific skills. Scientists can be trained to communicate with citizens better. This decision depends on many elements including personal proficiency and appetence, hazard context, as well as financial aspects. However, it must be addressed and scientists need to take part in the communication process.

However, the Mayotte case also reveals the importance of building a trust-based relationship beforehand, as part of a preparedness phase. This can include communicating about researchers' activities, or meeting the public for instance. No precursory sign could have warned the scientists in this case. However, given the duration of the situation, scientists from BRGM and other institutes have learnt to communicate more about their research activity on social media and in the press for instance. BRGM created a special page on their website[9], and report research activity through press conferences and interviews. This seems to have contributed to an increase in trust among STTM, where members often share this content.

Toward an Active Collaboration

Overall, the Mayotte case study demonstrates the importance of an active collaboration between all actors, including citizens, seismologists, and authorities. Citizens have shown that they were willing to take an active role in order to meet their own information needs, especially when they perceive an information vacuum. Of course, not all of them have the same instruments in the project. Influential and motivated citizens stepped in to play an ambassador role for their community. This echoes the issue explored in the introduction. While more and more citizens get involved in citizen science projects, partly thanks to technology and social media, not all have the same level of engagement.

Collaboration between citizens and scientists is challenging as it requires common interests and mutual understanding. For instance, more interested and engaged citizens can be used as relays to spread information as was the case when a few members of the group were received by the prefecture and then passed the key messages on STTM[21]. These users were found to be not only seismology amateurs, but also influential on the group as many of others members are addressing directly to them. Efficient communication must then include a collaboration with interested and influential users (Kotras, 2012; Chong and Kim, 2016). The LastQuake example shows that integrating feedback is a key part of the process, in order to better meet citizen's information needs. Co-building citizen seismology tools is essential to ensure their use and efficiency (Fallou et al., 2019). This collaboration must also be done as a long-term process by taking advantage of teachable moments (Schwarz, 2004) which enables the community to remain active in between earthquakes. In Mayotte, citizens have already partly been more involved through an initiative from the prefecture who launched a process in August 2019 to have the volcano named by the pupils in Mayotte.

CONCLUSION

To date, earthquakes in Mayotte have fascinated seismologists around the world for nearly 2 years. Due to an initial lack of data and understanding of the phenomenon, information had been scarce at the beginning of the crisis. In this very specific seismic and cultural context, citizens, experiencing a high level of anxiety, expressed high information needs and expectations toward the scientific community. Facing an information vacuum, they seized the opportunity to use already existing citizen seismology tools such as LastQuake. They also launched their own network through Facebook. Due to a certain level of mistrust toward seismologists and communication failures, they created a community of citizen seismologists, without initially conceptualizing it as such. The reasons for the creation of such a group should call to mind seismologists as well as all citizen seismology actors, including authorities. It shows that citizen seismology projects must take cultural background into account as this shapes citizens' information needs in terms of type, form and media. Citizens in Mayotte have proven that they were willing to take on an active role on delivering correct and useful information associated with the earthquakes. It thus also demonstrates that when it comes to earthquakes, all citizens, not only amateurs may be involved in citizen science projects and that cooperation is essential to their success. Co-creating and co-developing citizen science tools will help to increase citizen knowledge about seismology, raise their interest in seismic technologies, raise risk awareness and contribute to

[21] https://la1ere.francetvinfo.fr/mayotte/envoyes-du-groupe-facebook-sttm-recus-prefecture-737386.html

risk reduction. Finally, the existence of this autonomous citizen initiative further proves that improving communication related to earthquakes requires actions from all actors. Citizens need to clearly express their information needs to the perceived legitimate institution(s), while this institution should consider and address this need in a comprehensive way. In cases involving a lack of data or explanations, communication must explain the reasons for this vacuum, in an educational and empathic way.

The Mayotte case is very unique as it is linked to an unusually long-lasting seismic activity, enabling the local community to develop and strengthen, becoming a key actor in crisis management. Despite the specificities of this case-study, it demonstrates that citizens, seismologist and authorities could already greatly benefit from collaboration. This should not remain wishful thinking, and represents a strong challenge as it requires that people with different cultural backgrounds and interests work together, with a long-term perspective. This is also part of the major challenge for earthquake early warning systems that are developing, which require an efficient communication system, and thus a strong collaboration between scientists, citizens and authorities (Allen et al., 2018). Technologies such as disaster apps and social media represent an astounding opportunity to build bridges between researchers and citizens and animate communities in between seismic sequences, making citizen science projects not only useful and accessible but attractive to all.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LF led the research, conducted the interviews, did the social media observations, created the questionnaire, analyzed the results and wrote the manuscript. LF, RB, ML, JR, and FR analyzed users' needs and contributed to designing the new type of events, implemented by FR in LastQuake system. ML provided data about seismic events and edited maps. RS and SJ-L have provided feedback during the discussions and writing process. All authors contributed to the article and approved the submitted version.

FUNDING

This article was partially funded by the European Union's Horizon 2020 research and innovation programme under grant agreement RISE No 821115 and grant agreement TurnKey No. 821046. Opinions expressed in this paper solely reflect the authors' view; the EU was not responsible for any use that may be made of information it contains.

ACKNOWLEDGMENTS

The authors thank interviewees and respondents to the questionnaire.

REFERENCES

Allen, R. M., Cochran, E. S., Huggins, T. J., Miles, S., and Otegui, D. (2018). Lessons from Mexico's earthquake early warning system. *EOS* 99. doi: 10.1029/2018EO105095

Appleby, S., Brockdorff, N., Fallou, L., and Bossu, R. (2019). Truth, trust, and civic duty: cultural factors in citizens' perceptions of mobile phone apps and social media in disasters. *J. Contingencies Cris. Manag.* 1, 1–13. doi: 10.1111/1468-5973.12282

Aronova, E. (2017). Citizen seismology, stalinist science, and vladimir mannar's cold wars. *Sci. Technol. Hum. Values* 42, 226–256. doi: 10.1177/0162243916687643

Barthès, C. (2003). *L'Etat et le monde rural à Mayotte*. Paris: Karthala.

Bastard, I., Cardon, D., Charbey, R., and Cointet, J. (2017). What do we do on facebook? Activity patterns and relational structures on a social network. *Sociologie* 1, 57–82. doi: 10.3917/socio.081.0057

Becker, J. S., Potter, S. H., McBride, S. K., Wein, A., Doyle, E. E. H., and Paton, D. (2019). When the earth doesn't stop shaking: how experiences over time influenced information needs, communication, and interpretation of aftershock information during the canterbury earthquake sequence, New Zealand. *Int. J. Disaster Risk Reduct.* 34, 397–411. doi: 10.1016/j.ijdrr.2018.12.009

Bossu, R., Fallou, L., Julien-Laferriere, S., Landès, M., Roch, J., Roussel, F., et al. (2019). *How to Improve Rapid Public Earthquake Information? Listen to Eyewitnesses!* EGU Blogpost. Available online at: https://blogs.egu.eu/divisions/sm/2019/05/08/how-to-improve-rapid-public-earthquake-information-listen-to-eyewitnesses/ (accessed July 16, 2020).

Bossu, R., Gilles, S., Mazet-Roux, G., and Roussel, F. (2011). "Citizen seismology: how to involve the public in earthquake response," in *Comparative Emergency Management*, eds D. M. Miller and J. Rivera (Boca Raton, FL), 235–257. doi: 10.1201/b10974-15

Bossu, R., Steed, R., Roussel, F., Landes, M., Fuenzalida, A., Matrullo, E., et al. (2018). App earthquake detection and automatic mapping of felt area. *Seismol. Res. Lett.* 90, 1–22. doi: 10.1785/0220180185

Boudon, R. (2001). La rationalité du religieux selon max weber. *L'Année Sociol.* 51, 9–50. doi: 10.3917/anso.011.0008

Calais, E., Etienne, G. P., Prépetit, C., Boisson, D., Courboulex, F., Deschamps, A., et al. (2018). Can a raspberry shake seismic network complement a national seismic network? A case study in Haiti. *EarthArXiv* Preprint. doi: 10.31223/osf.io/nyp7h

Canfield, K. N., Menezes, S., Matsuda, S. B., Moore, A., Austin, A. N. M., Dewsbury, B. M., et al. (2020). Science communication demands a critical approach that centers inclusion, equity, and intersectionality. *Front. Commun.* 5:2. doi: 10.3389/fcomm.2020.00002

Celsi, R., Wolfinbarger, M., and Wald, D. (2005). The effects of earthquake measurement concepts and magnitude anchoring on individuals' perceptions of earthquake risk. *Earthq. Spectra* 21, 987–1008. doi: 10.1193/1.2099047

Cesca, S., Letort, J., Razafindrakoto, H. N. T., Heimann, S., Rivalta, E., Isken, M. P., et al. (2020). Drainage of a deep magma reservoir near mayotte inferred from seismicity and deformation. *Nat. Geosci.* 13, 87–93. doi: 10.1038/s41561-019-0505-5

Chester, D. K., Duncan, A. M., and Dhanhani, H. A. G. (2013). Volcanic eruptions, earthquakes and Islam. *Disaster Prev. Manag. Int. J.* 22, 278–292. doi: 10.1108/DPM-04-2013-0079

Chong, M., and Kim, H. M. (2016). "#Pray for paris with celebrities: the social role of influentials in a twitter network," in *Bridging Asia and the World: Global Platform for Interface Between Marketing and Management* (Hong Kong), 1688–1689. doi: 10.15444/GMC2016.12.01.05

Coen, D. R. (2012). Introduction: witness to disaster: comparative histories of earthquake science and response. *Sci. Context* 25, 1–15. doi: 10.1017/S0269889711000275

Cornia, A., Dressel, K., and Pfeil, P. (2016). Risk cultures and dominant approaches towards disasters in seven European countries. *J. Risk Res.* 19, 288–304. doi: 10.1080/13669877.2014.961520

Dauphin, S., and Thibault, F. (2011). Mayotte : les spécificités du 101e départelent français. *Rev. des Polit. Soc. Fam.* 106, 94–97. doi: 10.3406/caf.2011.2656

Ditchfield, H., and Meredith, J. (2018). "Collecting qualitative data from facebook: approaches and methods," in *The Sage Handbook of Qualitative Data Collection*, ed U. Flick (Sage: London), 496–510. doi: 10.4135/9781526416070.n32

Edwards, R., and Holland, J. (2013). *What is Qualitative Interviewing?* London: A & C Black.

Fallou, L., and Bossu, R. (2019). *Taking into Account the Cultural Context to Improve Scientific Communication – Lessons Learned from Earthquakes in Mayotte*. EGU blogpost. Available online at: https://blogs.egu.eu/divisions/sm/2019/03/08/taking-into-account-the-cultural-context-to-improve-scientific-communication-lessons-learned-from-earthquakes-in-mayotte/ (accessed July 16, 2020).

Fallou, L., Petersen, L., Bossu, R., and Roussel, F. (2019). "Efficiently allocating safety tips after an earthquake – lessons learned from the smartphone application LastQuake," in *Proceedings of the 16th ISCRAM Conference* (Valencia), 263–275. Available online at: http://idl.iscram.org/files/laurefallou/2019/1943_LaureFallou_etal2019.pdf (accessed July 16, 2020).

Ferreira, T. (2019). "Two seismological approaches to the benavente earthquake (1909): from the network of citizens to the network of instruments," in *Web of Knowledge: A Look into the Past, Embracing the Future* (Évora).

Finazzi, F. (2016). The earthquake network project: toward a crowdsourced smartphone-based earthquake early warning system. *Bull. Seismol. Soc. Am.* 106, 1088–1999. doi: 10.1785/0120150354

Hachim, S. (2004). *Catastrophes: Mayotte perd sa mémoire ! Catastrophes naturelles et mémoire collective à Mayotte*. Montpellier: Université Paul Valéry.

INSEE. (2017). INSEE Focus n° 105, Montrouge. Available online at: https://insee.fr/fr/statistiques/3286558#consulter (accessed July 16, 2020).

International Seismological Centre (2020). *Online Bulletin Board*. Available online at: http://www.isc.ac.uk/iscbulletin/search/ (accessed July 16, 2020).

InterStats (2017). *Insécurité et délinquance en 2016: premier bilan statistique*. InterStats.

Keim, M. E., and Noji, E. (2011). Emergent use of social media: a new age of opportunity for disaster resilience. *Am. J. Disaster Med.* 6:47. doi: 10.5055/ajdm.2011.0044

Khan, A., Denton, P., and Bossu, R. (2018). Engaging citizen seismologists worldwide. *Astron. Geophys.* 59, 4.15–4.18. doi: 10.1093/astrogeo/aty190

Kotras, B. (2012). *Des opinions qui (se) comptent. Influence, visibilité et hiérarchisation des opinions sur le web*. Available online at: http://socialmediaclub.fr/2013/12/smc-research-awards-les-laureats-du-concours/ (accessed July 16, 2020).

Lacassin, R., Devès, M., Hicks, S. P., Ampuero, J., Bossu, R., Bruhat, L., et al. (2019). Rapid collaborative knowledge building via twitter after significant geohazard events. *Geosci. Commun.* 3, 129–146. doi: 10.5194/gc-2019-23

Lambert, J. (1997). *Contribution au relevé de la sismicité historique des îles de la Réunion, de Maurice et des Comores*. BRGM R39736, 56. BRGM:Orléans.

Lamontagne, M., and Flynn, B. W. (2014). Communications in the aftermath of a major earthquake: bringing science to citizens to promote recovery. *Seismol. Res. Lett.* 85, 561–565. doi: 10.1785/0220130118

Lemoine, A., Bertil, D., Roullé, A., and Briole, P. (2019). The volcano - tectonic crisis of 2018 east of Mayotte, Comoros Islands. *EarthArXiv* 1–33. Available online at: https://eartharxiv.org/d46xj?fbclid=IwAR2UugfcV1d25RrtCzNEgbvGuO_9YoDQS6b4BxIZNVe5juuL_X_4BO-fSg0 (accessed July 16, 2020).

Liang, W. T., Chen, K. H., Wu, Y. F., Yen, E., and Chang, C. Y. (2016). Earthquake school in the cloud: citizen seismologists in Taiwan. *Seismol. Res. Lett.* 87, 177–185. doi: 10.1785/0220150061

Liang, W. T., Lee, J. C., Chen, K. H., and Hsiao, N. C. (2017). Citizen earthquake science in Taiwan: from science to Hazard mitigation. *J. Disaster Res.* 12, 1174–1181. doi: 10.20965/jdr.2017.p1174

Petersen, L., Fallou, L., and Serafinelli, E. (2017). "Public expectations of social media use by critical infrastructure operators in crisis communication," in *Proceedings of the 14th ISCRAM Conference* (Albi).

Rajdev, M., and Lee, K. (2015). "Fake and spam messages: detecting misinformation during natural disasters on social media," in *Proceedings - 2015 IEEE/WIC/ACM International Joint Conference on Web Intelligence and Intelligent Agent Technology, WI-IAT* 2015 (Singapore), 17–20. doi: 10.1109/WI-IAT.2015.102

Saathoff, G., and Everly, G. (2002). Psychological challenges of bioterror: containing contagion. *Int. J. Emerg. Ment. Heal.* 4, 245–252.

Schwarz, S. (2004). Cyberseismology and teachable moments. *Seismol. Res. Lett.* 75, 749–750. doi: 10.1785/gssrl.75.6.749

Scolobig, A., Prior, T., Schröter, D., Jörin, J., and Patt, A. (2015). Towards people-centred approaches for effective disaster risk management: balancing rhetoric with reality. *Int. J. Disaster Risk Reduct.* 12, 202–212. doi: 10.1016/j.ijdrr.2015.01.006

Severn, R. T. (2012). Understanding earthquakes: from myth to science. *Bull. Earthq. Eng.* 10, 351–366. doi: 10.1007/s10518-011-9312-0

Sibley, C. G., and Bulbulia, J. (2012). Faith after an earthquake: a longitudinal study of religion and perceived health before and after the 2011 christchurch New Zealand earthquake. *PLoS ONE* 7:e49648. doi: 10.1371/journal.pone.0049648

Stephens, N. M., Fryberg, S. A., Markus, H. R., and Hamedani, M. Y. G. (2013). Who explains hurricane katrina and the chilean earthquake as an act of god? The experience of extreme hardship predicts religious meaning-making. *J. Cross. Cult. Psychol.* 44, 606–619. doi: 10.1177/0022022112454330

Subedi, S., Hetényi, G., Denton, P., and Sauron, A. (2020). Seismology at school in Nepal: a Program for educational and citizen seismology through a low-cost seismic network. *Front. Earth Sci.* 8:73. doi: 10.3389/feart.2020.00073

Tagliacozzo, S., and Magni, M. (2016). Communicating with communities (CwC) during post-disaster reconstruction: an initial analysis. *Nat. Hazards*. 84, 2225–2242. doi: 10.1007/s11069-016-2550-3

Wald, D., Wald, D. J., Quitoriano, V., Worden, C. B., Hopper, M., and Dewey, J. W. (2012). USGS "Did you feel it?" Internet-based macroseismic intensity maps. *Ann. Geophys.* 54, 688–707. doi: 10.4401/ag-5354

Wein, A., Potter, S., Johal, S., Doyle, E., and Becker, J. (2016). Communicating with the public during an earthquake sequence: improving communication of geoscience by coordinating roles. *Seismol. Res. Lett.* 87, 112–118. doi: 10.1785/0220150113

Wray, R., Rivers, J., Whitworth, A., and Clements, B. (2006). Public perceptions about trust in emergency risk communication: qualitative research findings. *Int. J. Mass Emerg. Disasters* 24, 45–75.

Conflict of Interest: The 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.

Copyright © 2020 Fallou, Bossu, Landès, Roch, Roussel, Steed and Julien-Laferrière. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

ORIGINAL RESEARCH
published: 25 September 2020
doi: 10.3389/feart.2020.542654

A Socio-Seismology Experiment in Haiti

Eric Calais[1,2], Dominique Boisson[3], Steeve Symithe[3], Claude Prépetit[4], Bétonus Pierre[4], Sophia Ulyse[4], Laennec Hurbon[5], Alain Gilles[5], Jean-Marie Théodat[6], Tony Monfret[2], Anne Deschamps[2], Françoise Courboulex[2], Jérôme Chèze[2], Fabrice Peix[2], Etienne Bertrand[2], Jean-Paul Ampuero[2], Bernard Mercier de Lépinay[2], Julien Balestra[2], Jean-Luc Berenguer[2], Remy Bossu[7,8], Laure Fallou[7] and Valérie Clouard[9]*

[1] École Normale Supérieure, Université PSL, Paris, France, [2] Université Côte d'Azur, Centre National de la Recherche Scientifique, Institut de Recherche pour le Développement, Observatoire de la Côte d'Azur, Géoazur, France, [3] Faculté des Sciences, Laboratoire URGéo, Port-au-Prince, Haiti, [4] Bureau des Mines et de l'Énergie, Port-au-Prince, Haiti, [5] Faculté des Sciences Humaines et Sociales, Port-au-Prince, Haiti, [6] École Normale Supérieure, Port-au-Prince, Haiti, [7] European-Mediterranean Seismological Center, Arpajon, France, [8] Commissariat à l'Energie Atomique, Direction des Applications Militaires, Ile de France, Arpajon, France, [9] Observatoire Midi-Pyrénées, Laboratoire Géosciences Environnement Toulouse, Toulouse, France

OPEN ACCESS

Edited by:
Jenni Barclay, University of East Anglia, United Kingdom

Reviewed by:
Kiran Kumar Singh Thingbaijam, Institute of Seismological Research, India
Max Hope, Leeds Beckett University, United Kingdom

***Correspondence:**
Eric Calais
eric.calais@ens.fr

Specialty section:
This article was submitted to Geohazards and Georisks, a section of the journal Frontiers in Earth Science

Received: 13 March 2020
Accepted: 04 September 2020
Published: 25 September 2020

Citation:
Calais E, Boisson D, Symithe S, Prépetit C, Pierre B, Ulyse S, Hurbon L, Gilles A, Théodat J-M, Monfret T, Deschamps A, Courboulex F, Chèze Jô, Peix F, Bertrand E, Ampuero J-P, Mercier de Lépinay B, Balestra J, Berenguer J-L, Bossu R, Fallou L and Clouard V (2020) A Socio-Seismology Experiment in Haiti. Front. Earth Sci. 8:542654. doi: 10.3389/feart.2020.542654

Earthquake risk reduction approaches classically apply a top-down model where scientific information is processed to deliver risk mitigation measures and policies understandable by all, while shielding end-users from the initial, possibly complex, information. Alternative community-based models exist but are rarely applied at a large scale and rely on valuable, but non-scientific, observations and experiences of local populations. In spite of risk reduction efforts based on both approaches, changes in behaviour or policies to reduce earthquake risk are slow or even non-existent, in particular in developing countries. Here we report on the initial stage of a project that aims at testing, through a participatory seismology experiment in Haiti—a country struck by a devastating earthquake in January 2010—whether public or community involvement through the production and usage of seismic information can improve earthquake awareness and, perhaps, induce grassroots protection initiatives. This experiment is made possible by the recent launch of very low-cost, plug-and-play, *Raspberry Shake* seismological stations, the relative ease of access to the internet even in developing countries such as Haiti, and the familiarity of all with social networks as a way to disseminate information. Our early findings indicate that 1) the seismic data collected is of sufficient quality for real-time detection and characterization of the regional seismicity, 2) citizens are in demand of earthquake information and trust scientists, even though they appear to see earthquakes through the double lens of tectonics and magic/religion, 3) the motivation of seismic station hosts has allowed data to flow without interruption for more than a year, including through a major political crisis in the Fall of 2019 and the current COVID19 situation. At this early stage of the project, our observations indicate that citizen-seismology in a development context has potential to engage the public while collecting scientifically-relevant seismological information.

Keywords: earthquake, Haiti, seismic network, risk perception, citizen science

INTRODUCTION

Over the past 50 years, earthquakes have cost about US$ 800 billions, mostly in developed countries, and 1.3 million human lives, mostly in developing countries (Bilham, 2013; EM-DAT, 2020). Faced with these figures, which show no sign of inflection over time, the classic and rational approach to reduce earthquake risk is "top-down" (e.g., UNISDR, 2015). It consists in formulating a scientific discourse—an explanation of the natural phenomenon—then in translating it to the public and decision-makers while adapting the wording to these audiences in order to develop risk awareness and trigger protective measures. In a complementary way, community-based, "bottom-up" approaches are more and more common, but are rarely applied at a large scale. They rely on valuable, but non-scientific, observations and experiences of local populations (e.g., Fischer, 2000; Sim et al., 2017). One would like to believe that these approaches would lead, over time, to changes in behaviour, or even in policies, so that people and property are better protected against a threat that is often known and quantified. However, each major earthquake puts us face to face with the obvious: these changes are slow, or even non-existent. Why?

Disaster risk reduction studies have shown that it is difficult for stakeholders—individuals, their governing bodies, the private sector, etc.—to feel directly concerned by a threat that they do not perceive as immediate (e.g., UNISDR, 2014)—an attitude similar to the one we may have toward death (Théodat, 2013; Théodat et al., 2020). "*The philosopher is the one who learns to die*" says a Michel de Montaigne. Since earthquake disasters occur rarely, the time interval between them within a given territory, a time often longer than a human life, establishes a disconnect between stakeholders and the seismic threat that constantly surrounds them (Moon et al., 2019). The scientific discourse on the reality of the threat—while the Earth is calm!—is listened to passively, even though with sincerity and interest. This holds particularly true in areas where the culture of seismic risk is low—such as Haiti before the devastating earthquake that struck its capital region in 2010 (Bilham, 2010; Desroches, 2011).

Here we report on the initial stage of a participatory seismology project in Haiti (**Figure 1**) that aims at testing whether public involvement can improve earthquake awareness and grassroots protection initiatives. The project investigates under which conditions a community of citizen-seismologists, in a development context, can collect and share information about earthquakes while producing data that is useful for seismologists. Eventually, one could envision a symbiotic relationship between citizen and scientists where it is recognized that one needs the other to reach their goals. The expected project outcomes are the conditions under which such a relationship is reachable and sustainable.

In this paper, we describe the seismic instrumentation put in place and the results of a first survey aimed at collecting information on the perception of earthquakes and on the expectations of citizens in terms of earthquake information.

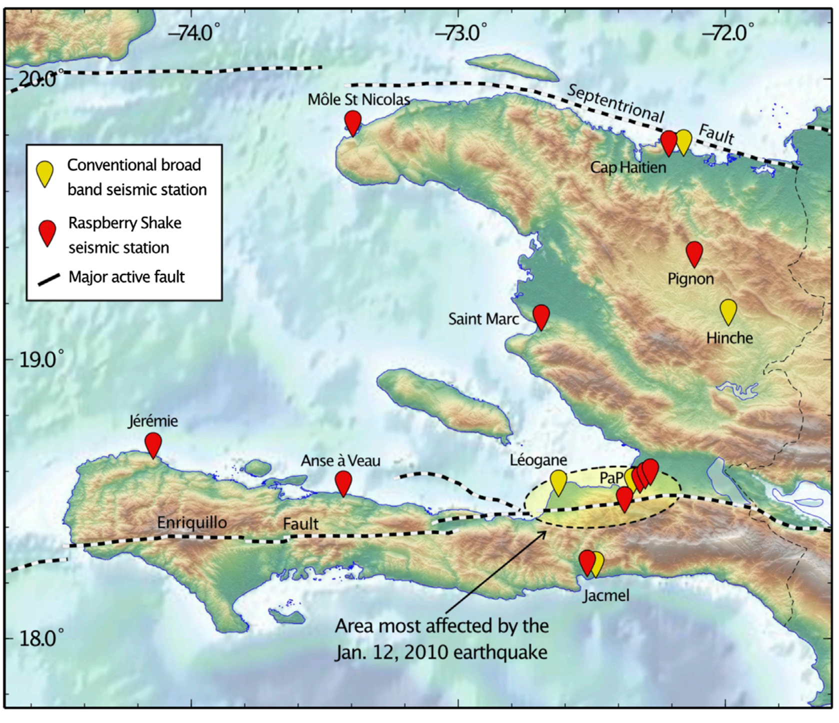


FIGURE 1 | Map of Haiti showing the main active faults (dashed lines), the area most affected by the M7.1, January 12, 2010, earthquake, the location of conventional broadband seismic stations, and the location of Raspberry Shake seismic stations installed to date in the framework of the project described here.

These first steps are key to ensure that 1) the seismic instruments provide data of sufficient quality to produce reliable seismological information, and 2) the information extracted from these data is adapted to the needs and demands of the general public.

CONTEXT

Any geoscientist engaged in research with developing countries knows their chronic difficulty, despite their heightened vulnerability, in maintaining observation networks of environmental variables for the benefit of protecting societies and citizens from natural threats. Complex technology networks are difficult to maintain there because they require sustained technical and financial capacity. This applies to seismic networks, which are expensive mechanical and electronic systems that rely on complex communication protocols. Without constant funding and maintenance, they tend to rapidly fail, so that the information that scientists can provide to the public or to decision-makers may become minimal or even inexistent. These failures, in turn, perpetuate the notion that these networks are, apparently, of little use.

The lack of earthquake information raises the risk of a misunderstanding of what science can do, and perhaps even a public denial of science, which may appear useless since it does not provide a concrete answer to questions as common as "when will the next earthquake take place?". On the other hand, the public is placed in a situation of passivity with regard to the scientific information. Its knowledge of earthquakes progresses little and the threat remains a theoretical possibility not integrated into daily life. Finally, this situation of under-information and/or information provided only by "official" national seismological institutes is conducive to the spread of rumours, false information, and even conspiracy theories. In the end, decision-making in the face of seismic risk may use the rational in a rather limited way. During the 2019 seismic sequence in Mayotte, for example, the lack of communication from the scientific community and the authorities, added to the local socio-cultural context, led citizens to consider false information and conspiracy theories as the only rational explanations in the face of unexplained seismic events and the silence of these authorities. By organizing themselves on the Facebook social network, citizens compiled information and developed their own expertize (Fallou and Bossu, 2019; Fallou et al., 2020).

In developing countries exposed to earthquakes, which are also the most vulnerable to that threat, relying on official institutions for information production and communication has limitations for financial reasons (the state and its donors have limited resources that they must direct to short-term objectives: elections, hunger, poverty, etc.), for reasons of continuity (very fast turn-over within institutions, little or no planning, lack of long-term vision, etc.), and for political reasons (earthquakes are too rare to affect anyone's election, protection is expensive, etc.). Relying only on the scientific community has limitations for financial reasons as well (maintaining networks is expensive and resources are scarce), but also because technical capacity in seismology may be limited, because the available scientific discourse is not suited to public expectations, or because national and international institutions may not be keen on listening about earthquakes when climate change, for instance, appears to be a much more pressing issue.

The situation described above is exacerbated in Haiti, a country affected on January 12, 2010, by one of largest seismic disasters known. In the late afternoon, a Mw7.0 earthquake struck the capital region of Port-au-Prince, killing more than 100,000 people,[1] leaving more than 1.5 million homeless, and destroying most governmental, technical, and educational infrastructure. The event caused an estimated $ 8 billion in damage, equivalent to about 120% of the country's Gross Domestic Product (Haiti Earthquake PDNA, 2010). No earthquake of such moderate magnitude had ever caused so many causalities and such extensive damage (Bilham, 2012). Before that dramatic event, the culture of seismic risk in Haiti was essentially inexistent, even though initiatives from the Civil Protection Agency were in place and scientific information on the hazard level was available (e.g., Manaker et al., 2008). The previous earthquake disaster had occurred 168 years earlier, in 1842, striking the northern part of the country and killing close to half of the population of Cape Haitian (Scherer, 1912).

Following the 2010 event, a national seismological network was set up, maintained by a governmental institution (Bureau of Mines and Energy, BME), which currently operates five broadband seismic stations (**Figure 1**; Bent et al., 2018). On October 7, 2018 an earthquake of magnitude 5.9 in the north-western part of the country killed 17 people and caused significant structural damage. None of the Haitian seismic stations was functional at the time. As a result, the national civil protection agency and the population had to rely on information from the U.S. Geological Survey, which only reports on events of magnitude greater than 4–4.5 in the region. This illustrates the difficulty of maintaining the operability of such a system and to provide quick and independent information to the public.

It is essential that seismologists monitor earthquakes with high-quality—though expensive—sensors located at carefully chosen sites where environmental noise is minimal, and try to ensure constant real-time data communication, for instance *via* satellite links. However, in the age of social media and participatory science, complementary ways to produce reliable and actionable earthquake information through the involvement of citizens and/or communities are emerging (e.g., Bossu et al., 2018a; Hicks et al., 2019) that warrant further investigation.

The concept of citizen-science has emerged in part as a consequence of the use of professional expertize in the fields of environmental science, and of the tension that arises between expertize and democratic governance (Fischer, 2000). Indeed, analyzing and finding solutions to most environmental issues—seismic hazard being one of them—require training or time that is beyond what most citizens can afford, while the

[1]Estimates vary between 225,000 (SNGRD, 2010), 137,000 (Daniell et al., 2013), 159,000 (Kolbe et al., 2010), and 46,000–8,500 (Schwattz et al., 2017), see also Corbet (2014).

technical expertize required is more and more often perceived by citizens as biased toward risky solutions designed to the advantage of the business and political elites. The participation of citizens in the production of scientific information and in its usage to influence policies is, in theory, a way to reconcile these two propositions, but there is no ideal model for applying this apparently straightforward concept.

For instance, Irvin (1995) argues that the public views on environmental risks is largely overlooked and describes a participatory, dialogical approach where citizens are given a prominent role in environmental risk management—though his argument addresses mostly the social aspects of this issue. Other workers, in particular from development and political economy perspectives, are more sceptical. For instance, Hickey and Mohann (2004) argue that, even though the collection of environmental data by citizens or communities may be of some superficial use, participation approaches in international development practices have not led to much transformative and sustainable progress for marginal peoples because "politics matter." Indeed, environmental issues are dynamically linked to socio-economic ones such as political decision making, poverty reduction, enhancing local democracy, social justice, gender inequalities, etc.

It is only recently that researchers from the broad field of "geosciences," defined here as "physics and chemistry of our planetary environment," have embraced the concept of participatory-, or citizen-science. They have been largely absent from the debate described above, as they also are largely absent from the scene of international development. In seismology, early efforts to bridge basic research with the broader public in a systemic way took place in the framework of education programs in primary and/or high schools (e.g., Cantore et al., 2003; Levy and Taber, 2005; Courboulex et al., 2012). These programs paved the way for the design of affordable and low-maintenance seismic instruments, as well as for the realization of the scientific value of the data they produce (e.g., Anthony et al., 2018; Calais et al., 2019; Schlupp et al., 2019). But the contextualization of such efforts in the broader scheme of risk perception and management, of socio-economic development, or of public policies is rarely accounted for in seismology-driven projects.

The experiment described here aims at using affordable and low-maintenance seismic instruments to go one step further by 1) involving seismologists in development science, taking advantage of the fact that they are—by design!—interested in long-term (>10 years) observations, as opposed to the short-term nature of most international development projects, and 2) using *Raspberry Shake* (RS) instruments as a sort of "alibi" to probe how citizens of a developing country perceive their seismological environment and how to best work with them in order to build a mutually-beneficial relationship between (seismological) science and society.

That community participation in data or knowledge production enhances risk perception—although it is a tenant of most citizen-science projects—is of course not granted. Enhancing risk perception continues to be at the core of international efforts to reduce environmental risks as increasing public understanding should develop a "culture of risk" (e.g., UNISDR, 2015) and stimulate individuals and communities to take appropriate protective actions (Twigg, 2004). However, this apparently simple logics must face the highly variable values and priorities of people and communities exposed to environmental hazards across cultures, socio-economic classes, genders, etc. (Löfstedt and Frewer, 1998).

For instance, there are evidence that higher-income countries tend to be more sensitive to risks arising from human actions (nuclear, pollution, etc.) while they also tend to underestimate the risks of natural hazards (Johnston et al., 2013; Yamori, 2013). In low-income countries, most poor and vulnerable people live in permanent risk and uncertainty—economic, political, social, etc.—and therefore struggle to determine a future. But if there is no future—ultimately no real world—then the very notion of risk disappears (Hurbon, 2014). In Bangladesh, a country particularly exposed to flooding, Jabeen and Johnston (2013) show that "people do not distinguish between hazards and other life stresses, but instead prepare for a range of possible negative events" and have developed a range of simple coping strategies that allow them to continue living in highly exposed areas.

Cultural influences also play an important role (Solberg et al., 2010) as risk perception is a matter of choice and interpretation of reality rather than open-page reading in a world of unambiguous codes (Théodat, 2010). In Haiti, the pervasive presence of vodoo likely affects risk perception, though in ways that have not yet been investigated (Hurbon, 2014). One may forecast the coexistence of an objective register—where the earthquake is a telluric reality—with a magical and religious one—where scientific reality is absent but that nevertheless provides other ways to cope with hazards and uncertainties.

Clearly, the factors that shape hazard perception are multiple—lack of awareness of infrequent high impact events, poverty, gender inequality, political and economic stresses, etc. The project described in this paper will attempt to better understand the multiplicity of those factors and the interactions between them, using low-cost seismic stations as a way to engage citizens in a dialog with scientists. As this early stage of the project, this paper aims at describing its motivations and setup, as well as the results of a first a baseline survey on earthquake and risk perception.

METHODOLOGY

Our objective is to test, through a participatory seismology experiment, whether citizen or community involvement through the production and usage of seismic information can improve earthquake awareness and, perhaps, induce grassroots protection initiatives. This experiment is made possible by 1) the recent launch of very low cost seismological stations with minimal maintenance (RS,[2]), 2) the relative ease of access to the internet, even in developing countries such as Haiti, 3) the

[2]https://raspberryshake.org.

possibility to distribute information through simple smartphone applications that anyone can handle, 4) the existence of social networks as a way to share and disseminate information. A similar initiative using RS instruments is on-going in Nepal, focused on schools (Subedi et al., 2020, submitted).

This project[3] is exploratory in nature as we are embarking on a direction that has not yet been systematically investigated. Indeed, if several hundreds of these very low-cost seismological stations exist in the world, there is not yet an integrated scientific study of their impact both on regional seismological knowledge or on the perception of seismology and seismic risk amongst their hosts. It is different from a classic community-based approach to risk reduction because it includes a significant scientific element through the usage of RS seismometers. Putting citizens at the core of a scientific project, while placing scientists in a position of support, is not a natural process. There is no guarantee that this strategy will gain support amongst the public, especially in a development context, but it is important to learn from it both on the standpoint of the usability of the RS instruments and of the perception of risk. Addressing such issues implies research at the boundary between seismology and social/behavioural sciences.

The seismology part of the project consists in installing RS stations in collaboration with citizens, collecting and processing the resulting data, and making information on earthquake locations and magnitudes available to the public in quasi-real time. The sociology part of this project was intended to capitalize on the availability of RS stations for a low price and of this quasi-real time information on earthquakes. We had envisioned to constitute two groups of individuals, one equipped with RS instruments and duly informed of their significance, the other group unequipped and uninformed. This would allow us to evaluate, over time, the impact of using the RS and receiving privileged information on the perception of earthquake and the associated risk. We identified two groups around Léogâne (very much affected in 2010) and Cap Haïtien (high risk but no recent earthquake), to be surveyed by master students from the Faculty of Social Sciences of Port-au-Prince. Unfortunately, the deplorable political and security situation in Haiti from September to December 2019, almost directly followed by the COVID19 sanitary crisis, did not allow students to travel to the provinces. We therefore decided to set up an alternative methodology in order to obtain a minimum of sociological data usable for our project. We put together, distributed, and analyzed an online questionnaire (in French and in Creole) in order to collect quantitative information on the perception of earthquakes and the citizens' information expectations. The form was built collaboratively by seismologists and sociologists—the first tangible interdisciplinary collaboration within the project.

Online surveys have indeed become increasingly prevalent in research inquiries, though they should comply with "good practices" in order to be efficient, useful, and ethical (e.g., Buchanan and Hvizdak, 2009; Alessi and Martin, 2010; McInroy, 2016). The online methodology we used considered the most likely platform to be available/easy to use for respondent (a simple Google form). We made sure that the questions would be understandable by the broadest audience by first testing them on a pilot sample of students from all disciplines. We optimized the content through a series of iterations on the list of questions and their specific wordings between the sociologists and seismologist of the project. In order to maximize response rates, we used the 10th anniversary of the January 12, in 2020, earthquake to disseminate information about the questionnaire as widely as possible. We did so by using the main national media as well as social platforms such as Facebook and WhatsApp, which are the two most widely used ones in Haiti. We made sure that the survey format was simple and usable on a simple smartphone, without photos or videos that would affect the respondents' bandwidth, and that it could be answered in less than 15 min. As the January 12, 2020, earthquake has been—and remains—traumatic for a number of Haitians, we introduced as a first question "*I do not wish to answer this questionnaire because I am still too affected by January 12, 2010*." Finally, the survey was designed to be entirely anonymous.

We are well aware that such an online survey necessarily samples the Haitian population in a biased manner, as it favours a social class that has easy access to the internet, is literate and urban, and is motivated enough to respond. Indeed, the literacy rate in Haiti is 53%, the unemployment rate 41%, and the percentage of the population below the poverty line (living with less than US$ 3/day) 51%. We tried to reduce the sampling bias by administering the questionnaire in the streets of Port-au-Prince during the week of January 12, 2010, targeting popular neighbourhoods.

FIRST RESULTS

Seismology

Interacting with citizens requires that we are able to use the information they produce to determine earthquake locations and magnitudes in near-real time on the Haitian territory. This is especially important when events are felt by the population. Since it was unrealistic to try and convince individuals to acquire a RS station and become part of a project that had not even started, we purchased 15 RS4D seismic stations that we installed at private homes across the country (**Figure 1**). The only required condition was access to electricity and internet, though we prioritized some locations in order to optimize the network geometry. Given that the objective of the project is to test a citizen seismological network, we did not make much efforts to ensure that the site noise conditions were optimal. The stations are placed on the ground floor of the house, often in the living room, in a place as far as possible from environmental noise disturbances (**Figure 2**). We deliberately did not provide training to the hosts, as we hope to observe if/how the presence of a RS stations may lead them to spontaneously requests more information earthquakes, preparedness, etc., and under what format.

So far, the hosts are volunteers known to the project participants. We aim at diversifying the host population in order to increase the number of stations, but also the number

[3]"Socio-Seismology of earthquake Risk in HAIti," acronym "S2RHAI."

FIGURE 2 | Example of a Raspberry Shake (RS) station installed in Jérémie (**Figure 1**) with its host on the right, M. Guild Mézile, a local farmer. The instrument is placed on the ground floor of his home, with good access to electricity—thanks to a local generator—and to the internet. Steeve Symithe is pointing at the RS station, with the internet modem on the floor just behind the host. This station has been up and running 75% of the time since it was installed on September 11, 2019. Written informed consent was obtained from the individuals for the publication of any potentially identifiable images or data included in this article.

of individuals with whom we can interact—or who can interact with each other *via* social media. In order to stimulate this interaction, we created a WhatsApp group dedicated to the hosts, as this media is one of the most prominently used in Haiti. The group, with currently 30 participants, is intended to share information produced by hosts and other citizens that can be verified and certified by scientists. We have observed that this generally quiet group becomes very active as soon as an earthquake is felt, with immediate requests for information. On the other hand, there is little activity in the absence of a felt earthquake. How to best use this down-time to keep hosts—and eventually the general public—engaged is a yet unsolved question, part of our upcoming research objectives.

We developed an automated system for rapid and automatic earthquake detection and location/magnitude determination. The system, called "Ayiti-séismes" is portable and meant to be transferred to Haiti. It is based on developments implemented at the Géoazur laboratory[4] to display regional earthquake information in the south-east of France. First, we developed a VPN software that we installed on each RS station in order to allow for real-time data recovery *via* the "seedlink" protocol. The data still also flows to the open-access OSOP server, the default procedure for RS stations worldwide, but our additional link ensures a better control of the data flow. Second, we implemented a server that aggregates data flows in real time from 11 RS stations, 3 broadband stations in Haiti, and 14 regional stations in the Dominican Republic, Jamaica, Cuba, Bahamas, and Puerto Rico whose data are publicly available. Third, we configured an automated near-real-time detection system based on the SEISCOMP3 software (Weber et al., 2007). Automatic detection can be quite complex with RS stations, whose noise level can vary significantly from one station to another as well as during the course of a day. We are continuing to investigate how to optimally parameterize this system in the context of Haiti.

Finally, we installed a web server for disseminating the information through a simple, interactive, map interface where earthquake locations and magnitudes are readily visible[5]. This interface also provides quantitative information to seismologists such as visualization of the seismic traces and statistics on the quality of detections. This server has been continuously operational since August 1, 2019. Each earthquake detected and automatically characterized first appears as "not yet confirmed." It is then checked and validated, or rejected, by a seismologist.

We used the August 1 to December 31, 2019, time interval for an initial assessment of the performance of Ayiti-séismes by comparing its location and magnitude (M) determinations with those of the Haitian seismological network (BME) and of the Loyola Polytechnic Seismological Observatory (OSPL) in the Dominican Republic (**Figure 3**). The latter is mainly focused on the south-eastern part of the island (Rodriguez et al., 2018). Within the "Haiti" region (17.04–1.41°N; 71.48–76.31°W), the

[4]http://sismoazur.oca.eu.

[5]http://ayiti.unice.fr/ayiti-seismes/.

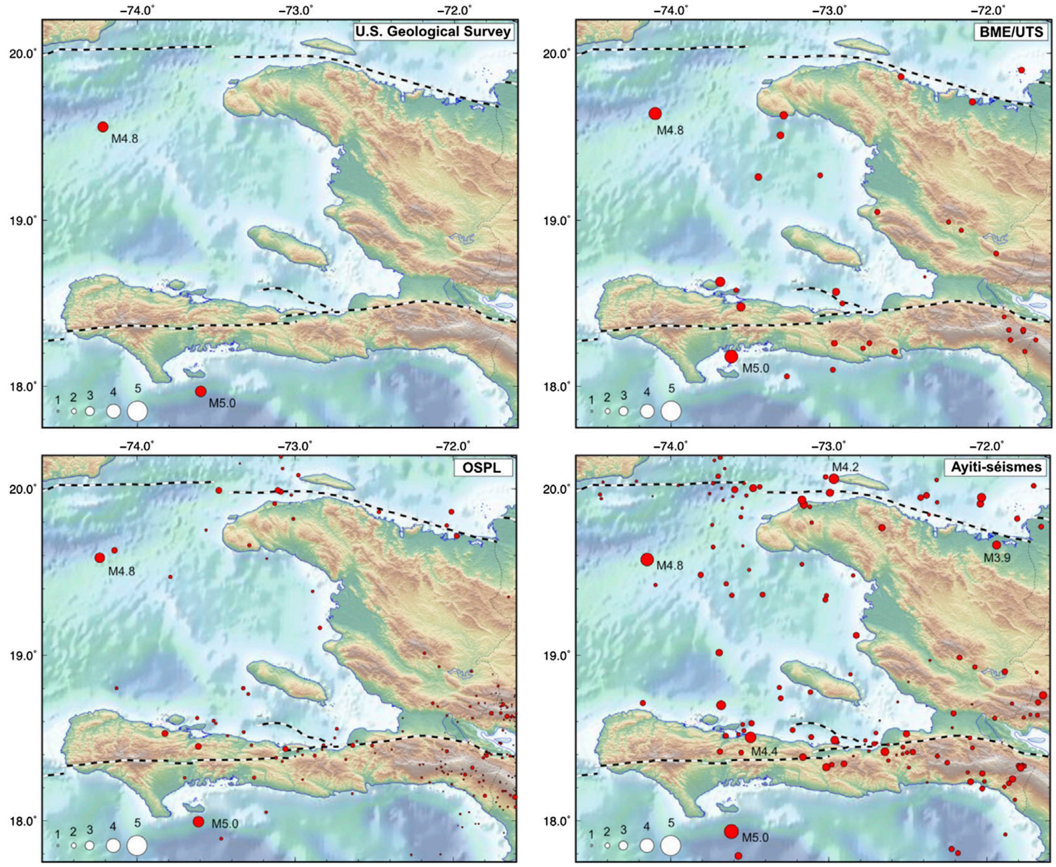


FIGURE 3 | Comparisons of earthquake locations for the August 1, 2019 to December 31, 2019 time interval. Top right: the U.S. Geological Survey uses a global distribution of seismic stations and, for the Haiti region, reports events with magnitude greater than 4–4.5. Top left: the Haiti Bureau of Mines and Energy uses its broadband stations (**Figure 1**) and several other regional stations. During the time interval considered here, their operations were severely affected by the political crisis in Haiti, which limited the number of events they could detect. Bottom-left: the Loyola Polytechnic Seismological Observatory (OSPL) in the Dominican Republic uses their own stations in the southern part of their country, which explains the larger number of detections in the south-eastern corner of the map. Bottom right: Ayiti-séismes uses Raspberry Shake and broadband stations in Haiti, as well as 20 other regional stations. Its magnitudes may be slightly overestimated, as discussed in the text.

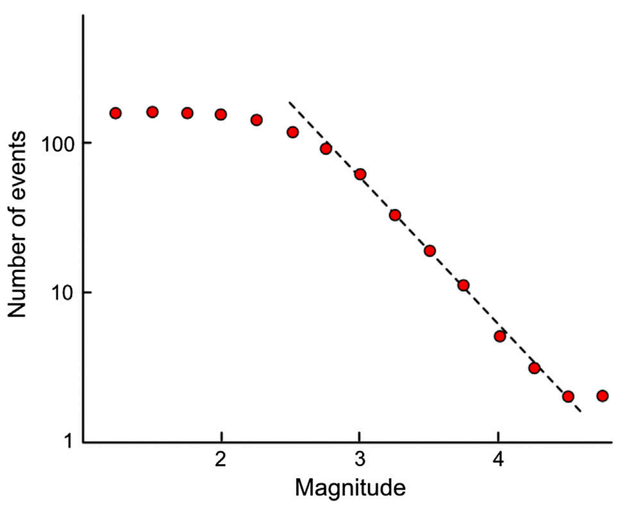


FIGURE 4 | Number of Ayiti-séismes determinations as a function of magnitude illustrating a completeness magnitude between 2.5 and 3 Mlv.

BME reported 33 events (2.2 < M < 4.8), OSPL 246 events (0.6 < M < 4.4), and Ayiti-séismes 146 events (1.5 < M < 5.0). Of the 33 BME events, 31 were detected by the OSPL and 29 by Ayiti-séismes. During the same time interval, the U.S. Geological Survey reported only two events (M4.8 and M5.0).

The difference between the OSPL and Ayiti-séismes catalogues concerns, 89% of the time, events of magnitude 0.5–2.25 that are located in the southernmost part of the Dominican Republic, where the OSPL seismological stations are concentrated. These earthquakes are currently undetectable by Ayiti-séismes. Event locations are consistent within 25 km between Ayiti-séismes and OSPL, but can differ from those of the BME by up to 90 km. As both Ayiti-séismes and BME use the IASPEI91 global seismic velocity model, whereas OSLPL uses a more suitable regional model (Rodriguez et al., 2018), we assume that the location differences with BME are the result of the smaller number of seismic stations they use. We also observed that the Ayiti-séismes magnitudes are systematically larger than those of OSPL. Resolving this issue requires discussions with network operators to ascertain the instrumental responses and attenuation equations they use.

In summary, the installation of RS stations in Haiti, coupled with permanent regional seismic stations and the implementation of an automated, quasi-real time, earthquake detection and characterization system provide rapid seismological information for any earthquake of magnitude greater than ~2.5 (**Figure 4**), down to events of magnitude 1.5–2.0 under certain conditions. The current limitations of this system are the small number of RS stations currently in operation and the discontinuous availability of broadband station data from the Haitian seismic network (**Figure 1**). Regarding the former issue, it is not trivial to find hosts who can provide continuous electricity and internet everywhere in Haiti. In addition, road conditions and insecurity prevented repairing internet access at some stations or installing instruments at locations where hosting had been established. Some of these difficulties are shared with conventional seismic networks, but in several cases of RS misfunction it only took an email to the host to reboot the RS and solve the issue—an advantage of using plug-and-play technology and involving hosts in station management.

Earthquake Awareness and Vulnerability

The on-line survey described above received a total of ~1,000 responses, most of them within a week of the questionnaire being announced. We gathered an additional ~200 responses from administering the questionnaire in the streets. Again, we acknowledge the bias introduced by the on-line sampling methodology, but as no previous similar survey has been performed in Haiti, to our knowledge, its results nevertheless provides important elements that will help us—and perhaps other similar projects elsewhere—better understand the perception of earthquake risk, at least within the section of the Haitian population sampled here. We summarize hereafter the preliminary findings of this survey.

A Trauma Still Present

Field investigators reported that a significant number of citizens contacted on the streets did not wish to answer the questionnaire. This is partly explained by a lack of time, but also by a desire not to plunge back into the past trauma. This is corroborated by the fact that 2% of the respondents answered the first question "I do not wish to answer this questionnaire because I am still too affected by January 12, 2010," thus interrupting their participation. One percent refused to answer for "other reasons." We can hypothesize that a larger number of people refused to answer the questionnaire altogether for that same reason, without even going through this first question. Despite the trauma still present, interest in the subject is noticeable among the respondents, with more than 90% answering that they are "interested in better understanding earthquakes." This interest was also reported by the field investigators who noted that the respondents were eager to speak about earthquakes. This is confirmed by the length of the write-ups in the open questions.

Lessons Learned From the January 12, 2010 Earthquake

Ninety one percent of the respondents experienced the January 12, 2010, earthquake. While 53% declared that they understood that it was an earthquake, a large percentage did not understand what was going on. Some thought of "the end of the world" (11%), "a divine punishment that had befallen us" (3%), or that "our contract with Earth had ended" (2%). This latter answer was meant for vodou believers, for whom there is an actual contract between mankind and nature, brokered by the vodou spirits (or "loas"). The profile of the respondents and the mode of survey may underestimate the importance of such religious beliefs.

When asked about the cause of earthquakes, 92% of the respondents chose "the movement of tectonic plates," 15% "American military experiments," 6% "oil drilling," and 5% "divine anger." The responses also point to alternative explanations that fall either in the mystical or conspiracy areas. Sometimes plate tectonics and an alternative explanation were answered together by the same respondent. There is therefore a certain level of ambivalence in the understanding of the seismic phenomenon.

Sixty five percent of the respondents believe that the likelihood of an earthquake similar to that of 2010 during their lifetime is "very high" (42%) or "high" (23%). Only 9% consider it "low" or "very low." This awareness is confirmed by the fact that earthquakes are perceived as one of the main risks in Haiti, together with insecurity and violence, political instability, health risks, and cyclones. The vast majority of the respondents answer that they know better than before the 2010 event the safety instructions to follow before, during and after an earthquake. This knowledge seems mainly disseminated by the scientific community and the media, not by political, educational or religious institutions. All in all, it appears that the January 12, 2010, earthquake significantly raised the awareness of seismic risk and understanding of earthquakes in Haiti.

A Need for Information

Consistent with the risk awareness improvement noted above, 93% of the respondents want more information about earthquakes. They prioritized customized, actionable information such as earthquake-resistant construction rules, what to do during an earthquake, or which areas are the most at risk. Such information can indeed be applied directly by individuals in order to implement protection measures for their own safety. It is unclear whether such information would actually be put to use by individuals, but this suggest that they may consider acting to reduce their own risk. When it comes to information after an earthquake, the most popular requests are in the categories of "where to get help," and "how to help." Information on the earthquake itself or the aftershocks are not the priority. Here again, the need for actionable information dominates over the need for scientific information.

When asked about the means they would use to find information in the case of an earthquake, the respondents show voluntarism, declaring that they would not only use traditional means [radio (54%), TV (59%), press (54%)] but also social networks (29% for Facebook and Twitter) and WhatsApp (40%), making themselves not only consumers but also producers of information.

Distrust Toward the Authorities

When asked which sources of information they trust most, the respondents rank "scientists" and "the Bureau of Mines and

Energy" at the top, with, respectively, 78 and 68% of "confidence" or "total confidence." The Government of Haiti only comes in 7th place, after civil protection, international organizations, relatives, and journalists, with 44% or distrust 29% of trust, the remainder being neutral. This is also expressed in numerous open comments that criticize the inaction of the authorities. This distrust in the government is a key element of the political situation in Haiti, caused in part by the weak reaction of the authorities after the 2010 earthquake and an unaccomplished reconstruction phase (Hurbon, 2014) but also, more recently, by a multi-billion dollars corruption scandal and heightened insecurity throughout the country. This permanent turmoil is currently leading to a feeling of chaos amongst the Haitian civil society.

In spite of this, from the respondents' point of view, the solutions to be provided must be national. Eighty percent would like more Haitian scientists to be trained—while only 22% think that more international experts are needed—and 71% want more "measuring devices" to be installed on the national territory. But the respondents also think that "earthquake prediction research" (16%), or "learning how to interpret the signs of nature" (27%) can contribute to understanding earthquakes.

The Place of Religion?

Religious institutions appear not to be trusted very much either. For example, only 6% of the respondents declare to trust or totally trust the vodou associations, with similar numbers for catholic or protestant churches. This result is however likely biased by the survey method, as mentioned above, which did not allow us to properly sample social groups that are more inclined to trust religious institutions. Directive or semi-directive interviews are needed to shed more light on the role of religion and faith in risk perception and understanding. Survey answers show, in a significant number of cases, answers that are dual: there is a scientific explanation, but also a divine one. Understanding how individuals may be able to juxtapose these two views without conflict is an interesting topic for future research.

This juxtaposition of faith and science also happens in places where magic or fiction can lead people to react in a way that can worsen vulnerability. For instance, during the cholera epidemic of late 2010, close to 50 vodou priests were killed by mobs on the accusation that they were using "black magic" to spread diseases.[6] That cholera had been brought to Haiti by Nepalese UN soldiers (Frerichs et al., 2012) was suspected, but not yet demonstrated at the time.

The Place of Women?

Women represent only 35% of the respondents. At this stage of our research, it is unclear why this number is so much lower than men. They were subjected to a higher risk of post-traumatic symptoms (Nemethy, 2010) which may have detracted them from answering the questionnaire. In particular, beyond the earthquake itself, one must account for the sexual trauma endured by a number of them in refugee camps. This should not be underestimated in our future research. In addition, interviews in the streets indicated that they often were less available than men, perhaps because of their role to ensure that daily family logistics is achieved in the Haitian society. A more detailed analysis of their responses to the questionnaire is needed to reveal differences in perception or needs for information. Interviews to come may be an opportunity to establish a more secure framework for collecting their views.

DISCUSSION AND CONCLUSION

As we initiated this project, it was not clear how easy or difficult it would be to find hosts for RS stations and to maintain their interest over many months, or possibly years. We were also unsure of the benefit of RS stations for earthquake locations and magnitude determination in a variety of noise environments. Although access to electricity and internet can be a serious issue in Haiti, we found a significant number of volunteers motivated to host a RS instrument, even though there is no financial support from our side. The seismological analysis of the RS data shows that more stations would be useful, and that redundancy is important: several RS in the same city, for instance, is not a waste as they may not all be operational at the same time. Also, during the difficult months of October and November 2019, when political instability and insecurity locked-up the country causing schools, universities, and most governmental institutions to close—hence official seismic data streams to stop—data from citizen seismometers were flowing at rate no different from the 6-month average. Citizen seismology can therefore be a viable means to alleviate such difficulties and provide continuity in seismological information even under duress.

As for the usefulness of RS stations to complement the existing—but hard to operate and maintain—broadband seismic network, the above analysis demonstrates that they bring valuable information for real-time detection and characterization of the regional seismicity. We also better understand their limitations in terms of sensitivity, as well as the limitation of having only one velocimetric component in high noise environment and with interrupted data flow. With an automatic detection system that is operational, portable to Haiti, and scalable to hundreds of stations (RS and other types), we can now start thinking of how to best interface that information with RS hosts, as well as with the general public, beyond a simple web interface with a seismicity map. Designing such a system will require joined efforts from seismologists and sociologists, informed by more in-depth surveys and interviews.

The online survey, in spite of the bias and limitations discussed above, indicates that the January 12, 2010 earthquake raised seismic risk awareness and the level of understanding of earthquakes amongst the population surveyed. Future directive and semi-directive interview are needed to explore this further, but one may hypothesize that this results from the numerous interventions of trusted scientific figures in the national media in

[6]https://www.bbc.com/news/world-latin-america-12073029; https://www.lemonde.fr/ameriques/article/2010/12/23/cholera-en-haiti-les-autorites-inquietes-de-lynchages-a-mort_1456914_3222.html.

the wake of the event. Indeed, the survey reveals an overall trust of scientists, an information that seismologists should use to further develop opportunities to convey basic earthquake information and seismic risk protection messages. However, the survey also reveals a first-order need for practical and actionable information—protection measures, where to seek help, etc.—whereas scientific information—magnitudes, aftershocks, etc.—is not favored by the respondents. This may be a bit disappointing to seismologists, but likely reflects the fact that what is learned by studying aftershocks or small unfelt earthquakes is too theoretical and remote from the priorities of most citizens. However, the appetite for information on earthquake protection measures is an indication that, if that information was properly packaged and distributed—it is available, but on the internet pages of government institutions—then it may have a better chance of having an impact.

The survey highlights the need for information through internet platforms and tools, which is to be expected in this current day and age. Seismological products (quasi real-time earthquake locations and magnitudes, information on protective measures, etc.) must obviously be disseminated that way, but more work is needed to understand the specific expectations of citizens and communities, in the Haitian context, so that information perceived as relevant is conveyed with an optimal chance of motivating grassroots risk reduction efforts.

The distrust toward the authorities and the government, understandable in the Haitian context, is an indication that government-only initiatives are likely to be insufficient for efficient disaster risk reduction. That respondents point at the inaction of the state is an indication that there may be a place for informed citizen action. In an economic and governance situation such as Haiti, imposing the "building back better" principle systematically and at a large scale is difficult. Increasing awareness through initiatives such as the one described here may create a public demand for more effective policies, and, perhaps more usefully, instigate grassroots initiatives to build better.

The survey highlights other interesting points that cannot be further discussed without directive or semi-directive surveys, such as the juxtaposition of faith and science. We anticipated that the earthquake would be seen through the double lens of tectonics and magic/religion. Our survey provides a hint of this, though its limited social sampling, as well as the methodology used here, likely underestimate this element. In Haiti, the weak state leaves a vacant space—as noted by survey respondents—which is heavily occupied by religious movements. In fact, any social reflection must take into account patterns of thought where rationality can vary significantly from one individual to another, from one group to another. How to insert earthquake science as yet another element, without conflicting or negating other representations of one's environment, remains an open question.

The gender ratio of respondents remains to be understood, especially in a society where women play a structuring role in most families. Interviews in the streets indicate that they often were less available than men, perhaps because of their role to ensure that daily family logistics is achieved. A more detailed analysis of their responses to the questionnaire is needed to reveal differences in perception or needs for information. Interviews to come may be an opportunity to establish a more secure framework for collecting their views.

Our preliminary observations indicate that citizen-seismology in a development context has potential to engage the public while collecting scientifically-relevant seismological information. However, the actual impact of the experiment on risk perception and, in turn, the stimulation of individuals and communities to take protective actions remains be determined. At this early stage of the project, and because of the recent political situation in Haiti, our interaction with target populations and communities have been limited so that measures of success or failure are not yet available. Many questions remain open—Will there be a sustained engagement of citizens in hosting RS stations? How much involvement from seismologists will be needed to develop and maintain interest? How to anchor the potential achievements of a citizen-seismology into long-term policy goals? How should the citizen-seismology model described here should evolve to better fulfill its objectives?

Finally, a citizen-based source of seismological data in Haiti also has the potential for being used in teaching programs. Educational seismic network experiences have shown that local seismic datasets improve the impact of teaching about earthquakes. They also increase the awareness of seismic risk among students who live in a seismically area, especially when events are detected close by, even though those events may not be felt (Courboulex et al., 2012). The ability to detect and report close-by events may have a similar impact on volunteer citizens.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study containing human participants in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

The project concept was developed by EC, with input from all co-authors. The Ayiti-séismes system was developed by JC and FP. The daily verification and relocation of earthquakes has been performed by TM, AD, and FC. The educational aspects of the project are carried out by JB and J-LB. The survey analysis was carried out by LF and LH. The preparation of the manuscript and figures was done by EC. All authors discussed the results, and contributed to the final manuscript.

FUNDING

This research was funded through the CNRS-MITI/IRD program "Risques Naturels," the "Interreg Caraïbe" program of the European Union through the PREST project, and the URGéo "Jeune Equipe Associée de l'IRD" (JEAI) at the Haiti State University supported by the Institut de Recherche pour le Développement (IRD). EC acknowledges support from the Institut Universitaire de France.

ACKNOWLEDGMENTS

We deeply thank the individuals and organizations that are currently hosting RS stations in Haiti, they make a difference! We thank the master students from the Faculté des Sciences Humaines et Sociales of Port-au-Prince, Haiti, for carrying out the survey in the streets of Port-au-Prince. We thank Branden Christensen and the OSOP team for their efficient technical support. We are grateful to two reviewers for their comments that significantly helped improved the original version of the paper.

REFERENCES

Alessi, E. J., and Martin, J. I. (2010). Conducting an internet-based survey: benefits, pitfalls, and lessons learned. *Soc. Work Res.* 34, 122–128. doi:10.1093/swr/34.2.122

Anthony, R. E., Ringler, A. T., Wilson, D. C., and Wolin, E. (2018). Do low-cost seismographs perform well enough for your network? An overview of laboratory tests and field observations of the OSOP Raspberry Shake 4D. *Seismol. Res. Lett.* 90, 1–10. doi:10.1785/0220180251

Bent, A. L., Cassidy, J., Prépetit, C., Lamontagne, M., and Ulysse, S. (2018). Real-time seismic monitoring in Haiti and some applications. *Seismol. Res. Lett.* 89, 407–415. doi:10.1785/0220170176

Bilham, R. (2010). Lessons from the Haiti earthquake. *Nature* 463, 878–879. doi:10.1038/463878a

Bilham, R. (2013). Societal and observational problems in earthquake risk assessments and their delivery to those most at risk. *Tectonophysics* 584, 166–173. doi:10.1016/j.tecto.2012.03.023

Bossu, R., Roussel, F., Fallou, L., Landès, M., Steed, R., Mazet-Roux, G., et al. (2018a). LastQuake: from rapid information to global seismic risk reduction. *Int. J. Disaster Risk Reduct.* 28, 32–42. doi:10.1016/j.ijdrr.2018.02.024

Buchanan, E. A., and Hvizdak, E. E. (2009). Online survey tools: ethical and methodological concerns of human research ethics committees. *J. Empir. Res. Hum. Res. Ethics* 4, 37–48. doi:10.1525/jer.2009.4.2.37

Calais, E. (2017). *Science et conscience dans la Post-urgence du Séisme d'Haïti*. Paris, France: L'Harmattan, 98.

Calais, E., Boisson, D., Symithe, S., Momplaisir, R., Prepetit, C., Ulysse, S., et al. (2019). Can a Raspberry Shake seismic network complement a national seismic network? A case study in Haiti. Eos, 100. doi:10.1029/2019eo123345

Calais, E., Freed, A., Mattioli, G., Amelung, F., Jonsson, S., Jansma, P., et al. (2010). Transpressional rupture of an unmapped fault during the 2010 Haiti earthquake. *Nat. Geosci.* 3 (11), 794–799. doi:10.1038/ngeo992

Cantore, L., Bobbio, A., Di Martino, F., Petrilio, A., Simini, M., and Zollo, A. (2003). The EduSeis project in Italy: an educational tool for training and increasing awareness of seismic risk. *Seismol. Res. Lett.* 74, 596–602. doi:10.1785/gssrl.74.5.596

Corbet, A. (2014). "Invisibles omniprésents. Les morts du séisme, in Catastrophes et environnement, Haïti, séisme du 12 janvier 2010," in *Editions de l'EHESS*. Editors L. Hurbon, Collection « Cas de figure », 29–58. doi:10.4000/books.editionsehess.7320

Courboulex, F., Berenguer, J. L., Tocheport, A., Bouin, M. P., Calais, E., Esnault, Y., et al. (2012). SISMOS à l'Ecole: a worldwide network of realtime seismometers in schools. *Seismol. Res. Lett.* 83 (5), 870–873. doi:10.1785/0220110139

Daniell, J. E., Khazai, B., and Wenzel, F. (2013). Uncovering the 2010 Haiti earthquake death toll. *Nat. Hazards Earth Syst. Sci. Discuss.* 1, 1913–1942. doi:10.5194/nhessd-1-1913-2013

Desroches, R., Comerio, M., Eberhard, M., Mooney, W., and Rix, G. J. (2011). Overview of the 2010 Haiti earthquake. *Earthq. Spectra* 27 (1), S1–S21. doi:10.1193/1.3630129

EM-DAT, Centre for research on the epidemiology of disasters (CRED), School of Public Health, Université Catholique de Louvain, Belgium (2020). Available at: https://www.emdat.be (AccessedMarch 12, 2020).

Fallou, L., and Bossu, R. (2019). Taking into account the cultural context to improve scientific communication—lessons learned from earthquakes in Mayotte. EGU blogpost. Available at: https://blogs.egu.eu/divisions/sm/2019/03/08/taking-into-account-the-cultural-context-to-improve-scientific-communication-lessons-learned-from-earthquakes-in-mayotte/.

Fallou, L., Bossu, R., Landes, M., Roch, J., Roussel, F., Steed, R., et al. (2020). Citizen seismology without seismologists? Lessons learned from Mayotte leading to improved collaboration. *Front. Commun.* 5, 49. doi:10.3389/fcomm.2020.00049

Fischer, F. (2000). *Citizens, experts, and the environment: the politics of local knowledge*. Durham, NC: Duke University Press.

Frerichs, R. R., Keim, P. S., Barrais, R., and Piarroux, R. (2012). Nepalese origin of cholera epidemic in Haiti. *Clin. Microbiol. Infect.* 18 (6), E158–E163. doi:10.1111/j.1469-0691.2012.03841.x

Haiti Earthquake Post Disaster Needs Assessment (2010). Assessment of damage, losses, general and sectoral needs. Available at: http://siteresources.worldbank.org/INTLAC/Resources/PDNA_Haiti- 2010_Working_Document_EN.pdf.

Hickey, S., and Mohan, G. (2004). *Participation – from tyranny to transformation? Exploring new approaches to participation in development*. London, UK: Zed Books.

Hicks, A., Barclay, J., Chilvers, J., Armijos, M. T., Oven, K., Simmons, P., et al. (2019). Global mapping of citizen science projects for disaster risk reduction. *Front. Earth Sci.* 7 (165), 226. doi:10.3389/feart.2019.00226

L. Hurbon (2014). "Catastrophes et environnement, Haïti, séisme du 12 Janvier 2010, collective work under the direction of L. Hurbon," in *Editions de l'EHESS*, Collection « Cas de figure ».

Irwin, A. (1995). *Citizen science: a study of people, expertise and sustainable development*, London, UK: Psychology Press.

Jabeen, H., and Johnson, C. (2013). "Perceptions of climate variability and coping strategies in informal settlements in dhaka, Bangladesh," in *Cities at risk. Advances in natural and technological hazards research*. Editors H. Joffe, T. Rossetto, and J. Adams (Dordrecht, Netherlands: Springer), Vol. 33. doi:10.1007/978-94-007-6184-1_9

Johnston, D. M., Becker, J., McClure, J., Paton, D., McBride, S., Wright, K., et al. (2013). "Community understanding of, and preparedness for, earthquake and tsunami risk in Wellington, New Zealand," in *Cities at risk: Living with perils in the 21st century*. Editors H. Joffe, T. Rossetto, and J. Adams (Berlin, Germany: Springer Science & Business Media), 131–148.

Kolbe, A. R., Hutson, R. A., Shannon, H., Trzcinski, E., Miles, B., Levitz, N., et al. (2010). Mortality, crime and access to basic needs before and after the Haiti earthquake: a random survey of Port-au-Prince households. *Med. Confl. Surviv.* 26 (4), 281–297. doi:10.1080/13623699.2010.535279

Levy, G., and Taber, J. (2005). Shake up your community with the IRIS, seismographs in schools program. *Earth Sci.* 21 (2), 28–29.

Löfstedt, R., and Frewer, L. (1998). *The Earthscan reader in risk and modern society*. London, UK: Earthscan/James & James.

Manaker, D. M., Calais, E., Freed, A. M., Ali, S. T., Przybylski, P., Mattioli, G., et al. (2008). Interseismic plate coupling and strain partitioning in the northeastern Caribbean. *Geophys. J. Int.* 174, 889–903. doi:10.1111/j.1365-246x.2008.03819.x

McInroy, L. B. (2016). Pitfalls, potentials, and ethics of online survey research: LGBTQ and other marginalized and hard-to-access youths. *Soc. Work. Res.* 40, 83–94. doi:10.1093/swr/svw005

Moon, J., Hwang, H., and Chung, J. (2019). Factors affecting awareness of preparedness after moderate earthquakes: an analysis of the Pohang earthquake in Korea. *Disaster Prev. Manag.* 29 (3), 405–420. doi:10.1108/dpm-07-2019-0209

Nemethy, K. (2010). Mental illness and resilience following the Haiti earthquake: an initial assessment. MSc thesis. Paris (France): École des Hautes Études en Santé Publique, 33.

Rodriguez, R. Y., Havskov, J., Sørensen, M. B., and Santos, L. F. (2018). Seismotectonics of south-west Dominican Republic using recent data. *J. Seismol.* 22 (4), 883–896. doi:10.1007/s10950-018-9738-9

Scherer, J. (1912). Great earthquakes in the island of Haiti. *Bull. Seismol. Soc. Am.* 2 (3), 161–180.

Schlupp, A., Chavot, P., Grunberg, M., Bes-De-Berc, M., Jund, H., Ajak, F., et al. (2019). SeismoCitizen: a project combining seismology and human science approaches based on a deployment of a dense low-cost seismic network hosted by citizens. *Geophys. Res. Abstr.* 21.

Schwartz, T. T. (2017). *The great Haiti humanitarian aid swindle*. Scotts Valley, CA: CreateSpace Independent Publishing Platform, 508.

Sim, T., Dominelli, L., and Lau, J. (2017). A pathway to initiate bottom-up community-based disaster risk reduction within a top-down system: the case of China. *Int. J. SAFE* 7, 283–293. doi:10.2495/safe-v7-n3-283-293Google Scholar

SNGRD(Système national de gestion des risques et des désastres – National Risk and Disaster Management Agency) (2010). SNGRD Situation Report 16. Bulletin d'Information du Gouvernement Haïtien – 8 au 12 Mars 2010 (Information Bulletin of the Haitian Government spanning 8th–12th March).

Solberg, C., Rossetto, T., and Joffe, H. (2010). The social psychology of seismic hazard adjustment: re-evaluating the international literature. *Nat. Hazards Earth Syst. Sci.* 10, 1663–1677. doi:10.5194/nhess-10-1663-2010

Théodat, J. M. (2010). Haïti 2010: les leçons d'une catastrophe. *EchoGéo*, 1–5. doi:10.4000/echogeo.11682,Google Scholar

Théodat, J. M. (2013). Port-au-Prince en sept lieux. *Outre Terre* 35–36, 123–150.

Théodat, J. M., Simoens, P. J. M., Sobczak, F., and Cornut, P. (Forthcoming 2020). La perception du risque sismique à Canaan: Haïti 2019. *Revue Haïtienne d'Histoire et de Géographie*.

Twigg, J. (2004). *Disaster risk reduction: mitigation and preparedness in development and emergency programming*. London, UK: Overseas Development Institute (Humanitarian Practice Network, Good Practice Review #9).

UNISDR (United Nations International Strategy for Disaster Reduction) (2014). *Progress and challenges in disaster risk reduction: a contribution towards the development of policy indicators for the post- 2015 framework on disaster risk reduction. Summary and main findings*. Geneva, Switzerland.

UNISDR (United Nations International Strategy for Disaster Reduction) (2015). Sendai framework for disaster risk reduction 2015–2030. Available at: https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030 (Accessed March 11, 2020).

Weber, B., Becker, J., Hanka, W., Heinloo, A., Hoffmann, M., Kraft, T., et al. (2007). SeisComP3-automatic and interactive real time data processing. *Geophys. Res. Abstr.* 9, 09219, 2007 ,General Assembly European Geosciences Union.

Yamori, K. (2013). "A historical overview of social representation of earthquake risk in Japan: fatalism, social reform, scientific control and collaborative risk management," in *Cities at risk: living with perils in the 21st century*. Editors H. Joffe, T. Rossetto, and J. Adams (Berlin, Germany: Springer Science & Business Media), 73–92

Conflict of Interest: The 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.

Copyright © 2020 Calais, Boisson, Symithe, Prépetit, Bétonus, Ulyse, Hurbon, Gilles, Théodat, Monfret, Deschamps, Courboulex, Chèze, Peix, Bertrand, Ampuero, de Lépinay, Balestra, Berenguer, Bossu, Fallou and Clouard. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). . The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

frontiers in Earth Science

METHODS
published: 15 October 2020
doi: 10.3389/feart.2020.00315

Knowledge-Building Approach for Tsunami Impact Analysis Aided by Citizen Science

Eric Yen[1], Simon C. Lin[1], Tso-Ren Wu[2], Yu-Lin Tsai[2] and Meng-Ju Chung[2]*

[1] *Institute of Physics, Academia Sinica, Taipei, Taiwan,* [2] *Graduate Institute of Hydrological and Oceanic Sciences, National Central University, Taoyuan City, Taiwan*

Even though the impact from large tsunamis are limited to coastal areas, these events are still devastating. Knowledge is crucial in minimizing the losses from natural disasters, as it can aid in creating better and more proactive preparation. Focusing on natural hazards' mitigation in Asia, a collaboration between 10 Asian and two European countries, based on a deeper understanding approach, has been conducted since 2015. Deeper understanding aims to discover the physical mechanisms and drivers behind a hazard event. Innovative models and simulation facilities are developed correspondingly to achieve more accurate numerical simulations of the whole lifespan of the target event. An application framework composed from the knowledge, data, simulation facility, software tools, and case studies is designed to provide an advanced estimation of hazard risk and would be evolved progressively with more case studies and observation data. For tsunamis, based on the COMCOT (COrnell Multi-grid Coupled Tsunami Model), the simulation portal (iCOMCOT) implementing parallelized tsunami wave propagation calculation over distributed clouds had been established. The iCOMCOT system finished the simulation of the whole lifecycle of the 2011 Great East Japan Earthquake Tsunami in 1 min. In this regional collaboration, case studies on historical events and tsunami impact analysis were conducted. The goal is to capture the physical characteristics of the tsunami as much as possible, such as tsunami wave propagation, tsunami refraction, and tsunami run-up on land, as well as their drivers and root causes. The whole processes of the tsunami, from its initiation to its impacts in selected locations, then could be simulated accurately by iCOMCOT based on the scientific explorations and the quantitatively revised models. The Sulawesi Tsunami (2018) case is presented to demonstrate the processes of the deeper understanding approach and how to achieve the capacity building. At the same time, ways to take advantage of citizen science are also explored. The citizen science model is valuable in supporting data collection, such as data of run-up height, inundation range, flow depth, disruption information, impact area, from publication, news reports, and interviews from local people. According to experiences on case studies, suggestions to simplify and optimize the integration of the citizen science model with the deeper understanding approach to result in a lower operation cost are provided.

Keywords: tsunami, disaster mitigation, citizen science, numerical simulation, distributed cloud, open platform

OPEN ACCESS

Edited by:
Kate Huihsuan Chen,
National Taiwan Normal University,
Taiwan

Reviewed by:
Yong Wei,
University of Washington,
United States
Robert Lovas,
Computer and Automation Research
Institute (MTA), Hungary

***Correspondence:**
Eric Yen
Eric.Yen@twgrid.org

Specialty section:
This article was submitted to
Solid Earth Geophysics,
a section of the journal
Frontiers in Earth Science

Received: *30 January 2020*
Accepted: *03 July 2020*
Published: *15 October 2020*

Citation:
Yen E, Lin SC, Wu T-R, Tsai Y-L and Chung M-J (2020) Knowledge-Building Approach for Tsunami Impact Analysis Aided by Citizen Science. Front. Earth Sci. 8:315. doi: 10.3389/feart.2020.00315

INTRODUCTION

Knowledge of the ever-changing earth is the foundation of effective hazard preparedness and mitigation. For example, significant progress in the fast determination of fault parameters and earthquake early warning signs based on discoveries of the physics and complexity of earthquakes in the past few decades have contributed to hazard mitigation (Kanamori, 2008). Tsunamis caused more casualties than other type of disaster in the past 30 years. The Indian Ocean tsunami in 2004, which is the deadliest tsunami in history, took the lives of over 230,000 people (Lay et al., 2005; Meltzner et al., 2006). The 2011 Tohoku tsunami, induced by the magnitude 9.0 undersea megathrust earthquake in Tohoku Japan, caused around 20,000 people to be killed (Fujiwara et al., 2011; Goto et al., 2011). Although tsunamis cannot be prevented, the impact of a tsunami can be alleviated through enhancement of knowledge, early warning, education, and adaptation.

After the largest and most damaging tsunami disasters, such as the 1960 Chile tsunami (Cisternas et al., 2005) and 1964 Alaska tsunami (Brocher et al., 2014), the international tsunami hazard community focused on hazard assessment and early warning systems based on numerical models in the 1970s (Vastano and Reid, 1967; Hwang and Divoky, 1970; Hwang et al., 1972). Stimulated by the 2004 Indian Ocean tsunami, tsunami hazard mapping and comprehensive risk understanding were improved significantly with the help of better numerical models, computational resources, and simulations (Spahn et al., 2010; Strunz et al., 2011). The extension of quantitative understanding of the vulnerability of various types of facilities on land due to tsunamis were intensified after the 2011 Japan tsunami (Suppasri et al., 2013; Muhari et al., 2015).

Discoveries of the physical mechanisms behind each tsunami event led directly to improved hazard preparedness and mitigation strategies after each disastrous tsunami (Løvholt et al., 2019). Unfortunately, tsunamis are quite rare. Only 11.32 tsunami events happen worldwide annually on average.[1] In addition to their rarity, there are a few more obstacles to advancing the knowledge of hazards from detailed case studies. These obstacles include: (1) a limited period of consistent observations for large natural variability; (2) limited knowledge on the drivers and root causes of a disaster event; (3) the difficulty of performing experiments to understand the processes of a hazard on a similar scale; (4) the difficulty in transforming knowledge into simulation models and sharing this data.

The Disaster Mitigation Competence Centre (DMCC), supported by EGI-Engage[2] (2015–2017) and EOSC-Hub[3] (2018–2020), aligned with the UND project (deeper Understanding of Natural Disaster)[4] (2018–2020), led by Academia Sinica and National Central University in Taiwan, adopt deeper understanding approaches to support regional disaster mitigation, including tsunamis, in collaboration with partners in nine Asian countries. The aim of DMCC is to achieve humanity's sustainable development in Asia by reducing the impact of natural disasters. Centered on the primary barrier of disaster mitigation, DMCC aims to build up the capacity of disaster risk analysis through deeper understanding approaches. Deeper quantitative understanding and reproductions of the whole lifecycle of target hazards contribute directly to more accurate hazard risks analysis and could enhance prevention and mitigation strategies. DMCC has conducted case studies on tsunamis, storm surges, floods, forest fire monitoring, and dust transportation in partner countries and demonstrated the advantages of deeper understanding approaches using advanced numerical simulations. Additionally, local scientists and user communities were engaged in each case study collaboratively. A regional collaboration framework based on well-proved distributed computing infrastructure and technologies is enhanced in response to the requirements from case studies.

Based on the strategy to estimate potential risks quantitatively using what and how historical events happened, the collaboration platform supporting case study, numerical simulation, and information and knowledge sharing had been established. With the goal to push forward the knowledge and risk analysis capability of natural hazards, DMCC focuses on extending collaborations with more case studies, more partners, more types of hazards, and more observation data, as well as more analysis tools and methods based on local requirements. The open collaboration platform also targets the openness of the whole research lifecycle, such as open data, open access, open tools, and open standards, etc. The open science (Couch et al., 2019) principles and approaches will be adopted gradually. In order to foster the engagement of various local communities and to encourage good practice through collaborations with diverse parties, the citizen science (Blake et al., 2018) model has been incorporated to assist case studies, simulations, and training.

This paper is organized as follows. The deeper understanding approach and Sulawesi Tsunami case study are described in the next section. The citizen science model experiments from the collaboration platform for tsunami hazard risk analysis is explained in section "Application and Integration of Citizen Science Model." Summary and future perspectives are wrapped up in the last section.

DEEPER UNDERSTANDING APPROACHES FOR IMPROVING HAZARD RISK ANALYSIS

The goal of this study is to gather more data on disaster mitigation through the deeper understanding approach in the Asian region. Tsunamis are a target hazard since they are one of the primary common concerns in this region. Based on the deeper understanding approach, capacity development is implemented by case study, knowledge (root cause) discovery, and accurate simulation of the target hazard. Through the research on each case study, the hazard dynamics and science behind the event are explored. According to the discoveries, a

[1] Global Historical Tsunami Database: https://www.ngdc.noaa.gov/hazard/tsu_db.shtml.

[2] EGI-Engage: https://wiki.egi.eu/wiki/EGI-Engage:Main_Page.

[3] EOSC-Hub: https://www.eosc-hub.eu.

[4] UND Project: http://und.twgrid.org.

more accurate numerical simulation is developed and the whole lifecycle of this event can be reproduced.

Tsunami Hazard Risk Analysis Through the Deeper Understanding Approach

The deeper understanding approach focuses on discovering the root causes and physical processes of target events. Simulation portals for tsunamis and meteorology-oriented processes are available for case studies in this collaboration. Case studies also allow researchers to learn from a specific historical event. Through deeper understanding activities, key factors to the simulation accuracy are investigated according to the lessons learned from each case study. As a direct outcome, processes of the whole life cycle of the target hazard could be reproduced more accurately. Both the enhanced simulation facility and the knowledge gained from case studies are shared through the application framework. The learning process and knowledge repository are key components of knowledge transformation and reuse. The application framework including those data, knowledge, workflow, simulation, and analysis facility, together with the configurations of each case study, becomes the foundation of an open collaboration platform for hazard risk analysis.

The typical case study workflow based on the deeper understanding approach starts from investigations of the root causes by the scientist group when the target case is confirmed. In order to reproduce the whole lifecycle of a target event accurately, the numerical model and parameterization will be fine-tuned according to the identified physical mechanisms. The expected outcome is not just more numerically accurate simulations but also optimized simulation procedures as well as observation data and initial and boundary conditions. Good quality observation data is crucial to the simulation process design and its results. New simulation portals will be developed accordingly, or the simulation facility would be revised following the requirements from case studies. The whole process will be carried out efficiently using scalable high-throughput computing schemes over the regional distributed cloud infrastructure. The workflow of tsunami event case studies based on the deeper understanding approach is depicted in **Figure 1**.

iCOMCOT[5] (Lin et al., 2015), which is based on the well-known COMCOT tsunami model (COrnell Multi-grid Coupled Tsunami Model) (Liu et al., 1998), is a tsunami simulation portal to support scalable and high-performance tsunami risk analysis over the cloud. Typically, when the earthquake source parameters (nine parameters: strike, dip, rake, focal depth, etc.) are confirmed and bathymetry data is in place, the initial free surface elevation could be evaluated by iCOMCOT in a few seconds. Afterwards, the whole processes of tsunami wave propagation are able to be efficiently simulated and the maximum tsunami wave height, tsunami arrival time, inundation, and the predicted time-history of the tsunami in certain locations will be generated in a few minutes. For example, in the case of the 2011 Japan earthquake, the iCOMCOT system with the spatial domain coverage of almost the whole Pacific Ocean can finish the simulation within 2 min. The impact analysis could be updated quickly whenever there is any change to the seismic source parameters, observation data, or bathymetry. The iCOMCOT simulation workflow and user interfaces, exemplified by an experimental case of the 2004 Indian Ocean earthquake and tsunami, is shown in **Figure 2**. The simulation results of iCOMCOT is also demonstrated in **Figure 3**.

iCOMCOT provides quantitative understanding of the vulnerability of tsunamis. The whole risk analysis workflow, platform (including the numerical simulation model and facility), and collaborations are improved progressively with more case studies, knowledge, and observation data. For each case study, facts (such as academic and government reports, news clips, videos, images, etc.) and observation data are collected. An accurate simulation facility is provided based on the deeper understanding approaches. The event itself is able to be reproduced and reinvestigated through the simulation portal. The numerical modeling and analysis methodology tool could be revised according to new findings and requirements. The ecosystem to investigate the tsunami event is available for applications of various aspects of disaster mitigation and preparedness, including education, awareness building, and communication, as well as coastal area planning and protection.

Sulawesi Tsunami (2018) Case Study

The 2018 Sulawesi Tsunami case study was conducted using DMCC collaborations because of the complexity in source identification and characterization. A very fast tsunami after a Mw 7.5 earthquake[6] killed 4,340 people in northern Sulawesi. It is unusual that such a deadly tsunami was generated following a Mw 7.5 strike-slip earthquake rather than resulting from a big earthquake that happened in a long and straight trench. After confirming the capability of iCOMCOT from those disastrous tsunamis, it is a good opportunity for this collaboration to extend the deeper understanding approach to a different type of tsunami event.

Based on water-level records at the gauge station of Pantoloan, the tsunami propagated to the port of Pantoloan in just a few minutes after the mainshock and caused signals with higher frequency than the tides. The location of Pantoloan can be seen in **Figure 4A**. The Butterworth high-pass filter with the cutoff frequency of 6 h is adopted on the observed water-level data at Pantoloan to remove the tide effect. As can be seen from the de-tidal signal in **Figure 4B**, the tsunami amplitude reached 1.6 m at the port of Pantaloan. Based on video clips from the Internet,[7] the tsunami waves arrived after about 3 min of the earthquake. For a seismogenic catastrophic tsunami, the wave is not possible to propagate to the city of Palu Bay within 3 min after the earthquake. More video analysis for the 2018 Sulawesi tsunami event can be found in Sunny et al. (2019) and Takagi et al. (2019).

According to the COMCOT simulation, the earthquake itself could only create a small tsunami with about 0.7 m wave height

[5] iCOMCOT Simulation Portal: http://icomcot.twgrid.org.

[6] 2018 Sulawesi Earthquake information from USGS: https://earthquake.usgs.gov/earthquakes/eventpage/us1000h3p4/dyfi/intensity.

[7] For example, a CCTV record at Palu Bay from YouTube, https://www.youtube.com/watch?v=8qaP7BCN87M.

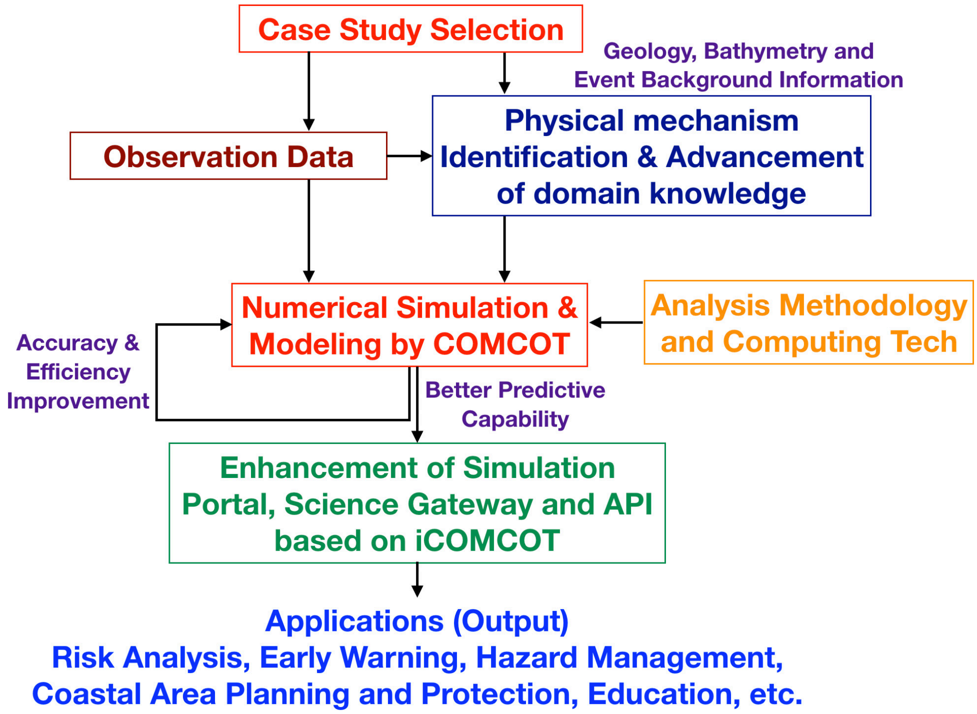


FIGURE 1 | Typical workflow of a tsunami event case study based on the deeper understanding approach. The deeper understanding approach aims to advance the knowledge of the target hazard and develop an accurate numerical simulation model accordingly. The whole lifecycle of the event could be reproduced more accurately than before. All the data, numerical models, simulation portals, and the event simulation are the open accessible outcome of each case study. The numerical simulation model and results could be updated whenever there is new knowledge to the event, new observation data, and new applicable computing technologies.

at Pantoloan and 0.65 m at Palu. Heidarzadeh et al. (2019) used a tsunami ray-tracing method to find out the locations of potential landslides, according to the discrepancy between observation data and simulations. Omira et al. (2019) conducted field surveys along the Palu Bay in the aftermath of the tsunami and identified several locations of the coastal landslides inside the bay. According to the scenario studies, we concluded tentatively that there are two tsunami sources in this event. A strike-slip earthquake tsunami dominates the impact outside the Palu Bay. Inside the Palu Bay, a landslide is one possible source. However, the locations of landslides are still under debate.

In this case study, the computational domain of COMCOT is (119.6–119.95 E) and (−1.0 to −0.2 N), as shown in **Figure 4A**. The nonlinear shallow water equations with the bottom friction are solved on the spherical coordinate. The Manning formula is used to model the bottom friction, and the Manning's coefficient is 0.013, according to the analysis of Garzon and Ferreira (2016). In order to maintain numerical stability, the Courant–Friedrichs–Lewy (CFL) condition needs to be fulfilled. In COMCOT, the grid size is 0.05 arc-minutes (about 100 m) and the time step is set as 0.05 s. The bathymetry data used in the simulation is from the BATNAS data bank of Badan Informasi Geospasial (BIG), Indonesia. The resolution of BATNAS is 6 arc-seconds (0.1 arc-minutes).

The initial free surface elevation for the proposed scenario of a landslide tsunami at the mouth of Palu Bay is depicted in **Figure 5**. The landslide is assumed to move offshore because the crest of the tsunami waves arrived first, and were followed by the trough according to the observed tsunami signals at Pantoloan. The length and width of the uplift of the water surface disturbances are 4 and 8 km, respectively. The depression of the water surface has the same dimension as the uplift – 3 m uplift of water surface disturbances and – 4 m depression.

The snapshots of computed tsunami propagation are shown in **Figure 6**. In the first 1–3 min after the earthquake, the leading negative tsunami waves propagate into Palu Bay. After 4 min of the mainshock, the tsunami wave front arrives in Pantoloan. Later, after 6 min of the mainshock, the positive tsunami waves arrive at Pantoloan.

Results of the simulated maximum free surface elevation is shown in **Figure 7a**. Near Pantoloan, the maximum free surface elevation caused by the proposed landslide tsunami is 3.0 m. Inside Palu Bay, the largest maximum free surface elevation is 3.8 m which occurs at the end of Palu Bay. In comparison to the observation data in Pantoloan, as shown in **Figure 7b**, the numerical results capture very well the first trough of the tsunami waves arriving at Pantoloan after 5 min of the mainshock. After 7 min of the earthquake, the simulation gives a good prediction on the first crest of the tsunami waves. At about 10 min, the simulated results give a faster prediction on the second trough, around 2 min faster than observed tsunami. Similar patterns can be found after 10 min.

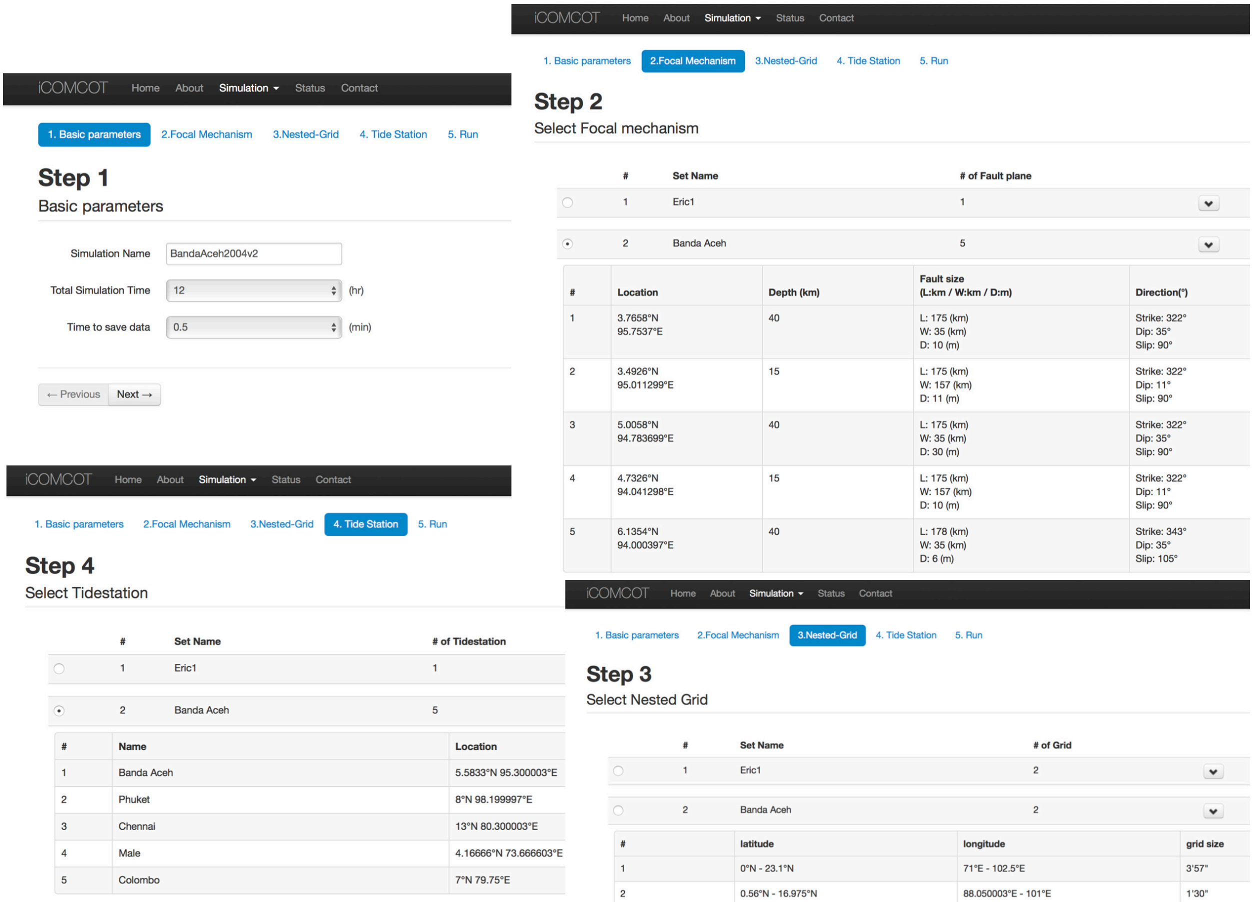


FIGURE 2 | iCOMCOT simulation workflow exemplified by an experiment case of the 2004 Indian Ocean earthquake and tsunami. Before running the simulation, four configurations have to be defined in advance. Step 1 is to initialize the task by naming and defining the duration of the simulation time (in hours) and time interval (elapsed time between two saved simulation data). Step 2 is to set up focal mechanism parameters of the earthquake, including the epicenter location (latitude and longitude), depth, fault Size (length, width and depth in kilometer), and direction (strike, dip and rake in angles). Step 3 is to determine the nested grid domains of the simulation. Step 4 is to designate the observation sites (tidal stations).

An accurate and timely forecast of a hazard is the most practical solution to minimize potential losses. Development of the early warning system for the Indian Ocean tsunami had also kicked off in our collaborations with partner countries around the region. Based on the experiences of tsunami risk assessment (Wu and Huang, 2009; Wu, 2013) and early warning system development for the South China Sea (Lin et al., 2015), the large-scale trench-typed tsunami threats sources in the Indian Ocean will be explored carefully. Historical tsunami events in the Indian Ocean will be analyzed quantitatively. Potential sources, especially in the Java Trench, will be identified and their rupture length and width, the scale of seismic moment, the slip, and as the dip angle, etc., will be elaborated as well. iCOMCOT will be applied to simulate tsunami propagation, run-up, and inundation with multi-nested grids for a complete simulation of the process of a tsunami from the beginning to the inundation.

The deeper understanding approach has been advancing the knowledge of natural hazards and supporting more accurate risk analysis on selected case studies using simulation portals. Moreover, all the analysis is reproducible with shared data, knowledge, event background information, and analysis tools. All these cases could be further reinvestigated with innovative numerical models and updated data whenever they are available. Both the awareness of hazard risk and the capacity for disaster mitigation could be upgraded from all these outcomes through new case studies, education, communication, and better planning and adaption.

APPLICATION AND INTEGRATION OF CITIZEN SCIENCE MODEL

The practical framework for hazard risk evaluation based on the deeper understanding approach has been built and verified by several case studies of various types of hazards in different countries. The framework keeps on evolving progressively with more cases, including tsunami hazards, using iCOMCOT in this regional collaboration (Yen et al., 2018). New observation

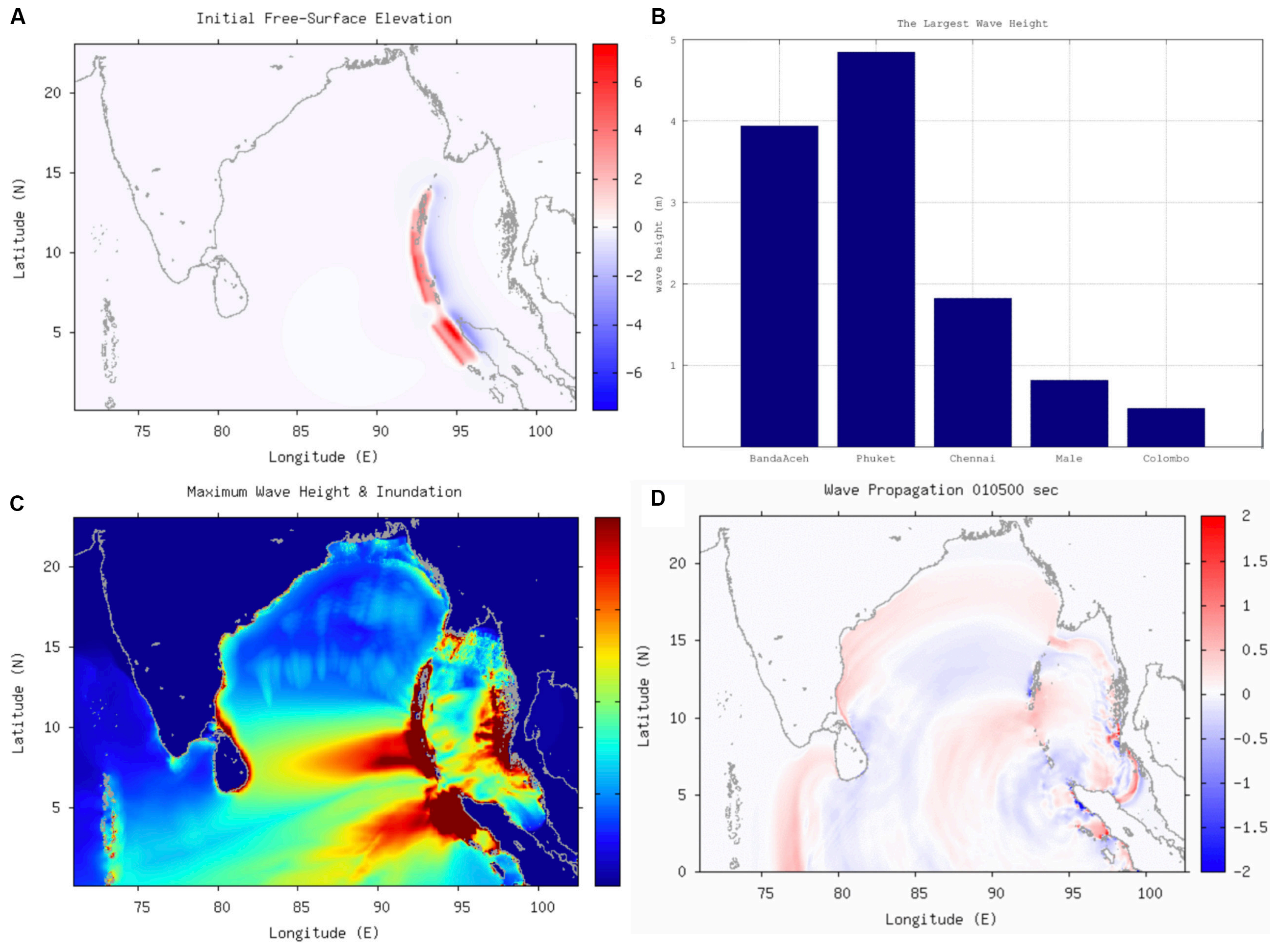


FIGURE 3 | iCOMCOT simulation results of the experiment on the 2004 Indian Ocean earthquake and tsunami simulation experiment: **(A)** initial free surface elevation; **(B)** largest wave heights; **(C)** maximum wave height and inundation; **(D)** wave propagation animation.

data and knowledge of the tsunami impacts and tsunami source characteristics will lead to the innovation of numerical models, risk estimation workflow, and analysis facility. Efficiency and functionality will also be advanced by user experiences and by adopting new information and communication technologies.

The collaboration takes advantage of the collective intelligence paradigm, such as the citizen science model, to extensively collect data of diversified data types and locations for tsunami case studies. In order to reduce the losses from future tsunamis, impact analysis and protection of local focus need to be enhanced from the lessons of historical events. Additionally, validation of impact analysis, education, early warning development, test of the workflow and functionality, and locally focused case studies all could benefit from the citizen science model. The framework integrating the deeper understanding approach and citizen science model is illustrated in **Figure 8**.

In accordance with the deeper understanding approach and the example of the Sulawesi Tsunami, basic steps of a case study include: (1) data collection, (2) source characterization, (3) simulation and verification, (4) impact analysis, (5) reproducibility test, and (6) training. The citizen science model is usually deployed to fill resource gaps or to extend participation and awareness. Observation data of gauges and local monitoring systems, bathymetry data, official reports and announcements, news, videos clips, information from social media, and field survey data from many countries are collected by partners in different countries since the impact region of a big tsunami, including both the near-field and far-field area, are very large. Based on the lessons learned from case studies, every partner could reproduce the tsunami hazard using iCOMCOT by focusing on different local impacts and local environments repeatedly. For instance, it could encourage intensified protection of important facilities, such as nuclear power plants, near the coastline and coastal region community planning. Influences of strong currents and floating debris from the possible wave height and inundation from a tsunami also have to be inspected seriously. Another example is the tsunami-induced coastal changes as proposed by the Indonesian partners. Volunteers around the world are able to learn the details of tsunami events or to validate the simulation results using iCOMCOT with the local data. The scientist group will review the report and initiate a new investigation task force if there are any significant new findings.

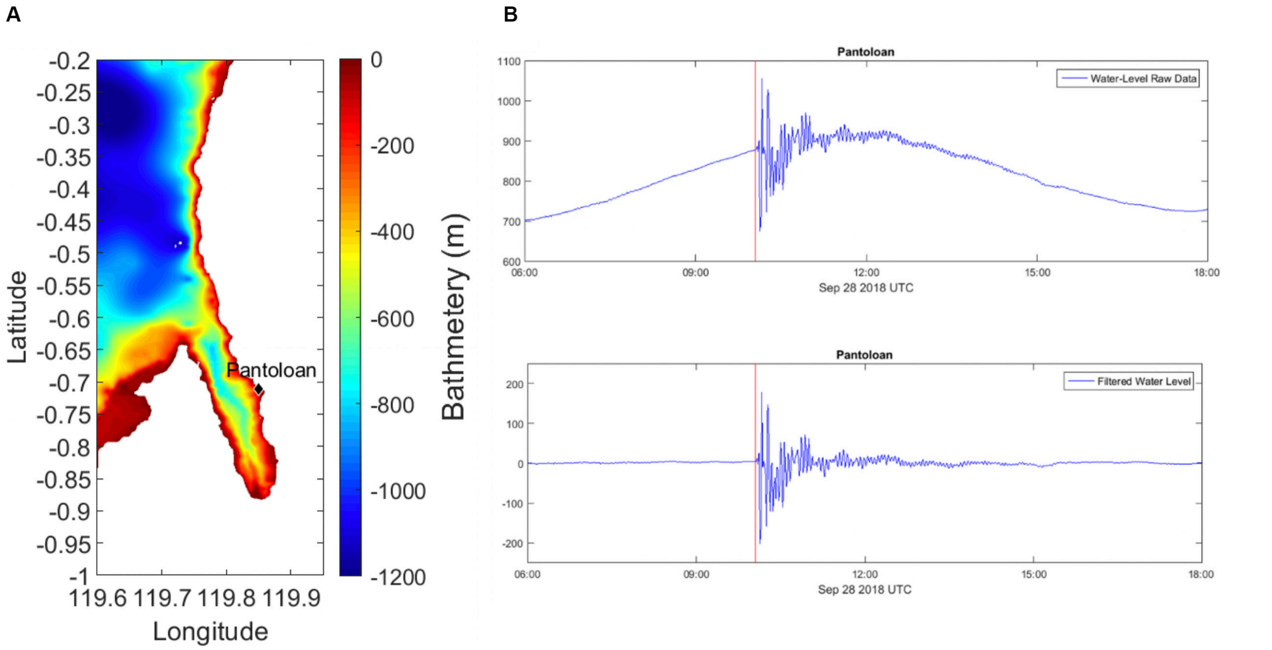


FIGURE 4 | (A) Location of Pantoloan and the computational domain of COMCOT. The color shading depicts the water depth in meters. The station of Pantoloan located at (−0.7120 °E, 119.8554 °N) is labeled by the solid black diamond. The bathymetry data is from the BATNAS data bank of Badan Informasi Geospasial (BIG), Indonesia. **(B)** Upper panel: the observed wave level at Pantoloan in cm; lower panel: the time series of tsunami signal at Pantoloan by Butterworth high-pass filter with the cutoff frequency of 6 h in cm. The red line indicates the time of the mainshock of the earthquake (10:02 UTC, September 28, 2018).

Numerical simulations and case studies are very practical for the education of tsunami hazard mitigation in understanding the possible impacts and the processes. Partners also delivered knowledge of tsunamis through customized experiment designs using the numerical simulations. Training on using iCOMCOT to find out the possibilities of tsunami hazards according to the local environment and concerns are also a common use case in education by partners. Straight-forwardly, workflow and functions of the numerical simulation and risk analysis process could be improved from those various applications. Partners are encouraged to develop new analysis tools or applications and integrate these into the framework according to their local requirements.

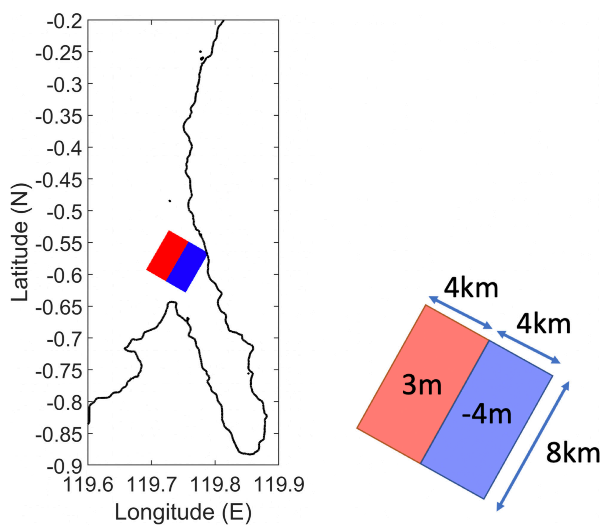


FIGURE 5 | The initial free surface elevation for the proposed potential submarine landslide tsunami off the mouth of Palu Bay. The color shading indicates the water surface disturbances by the landslide: red – the uplift of the water surface disturbance; blue – the depression of the water level disturbance. The dimension of the initial free surface elevation is shown in the right panel.

Furthermore, all these outcomes, including education materials, new case studies, local simulations and experiments, new observation data, test results, new tools, and feed-back from local people, will be compiled into the collaboration platform by design. All materials in the platform will be shared based on the FAIR principle: findable, accessible, interpretable, and reusable.

The citizen science model is helpful in extending capacity, gaining popularity, and strengthening the practices of hazard mitigation from the experiences of the regional collaborators led by DMCC. Many hazard mitigation tasks could benefit from the citizen science model, but different strategies and implementation approaches are necessary. The citizen science model could be implemented by limited partners or volunteers instead of the general public only according to the goals and stages. For the deeper understanding approach in our collaborations, many tasks could be reinforced by the citizen science model in numerous forms, including data collection, impact analysis validation, education, early warning development support, testing, and local focused analysis. To develop the

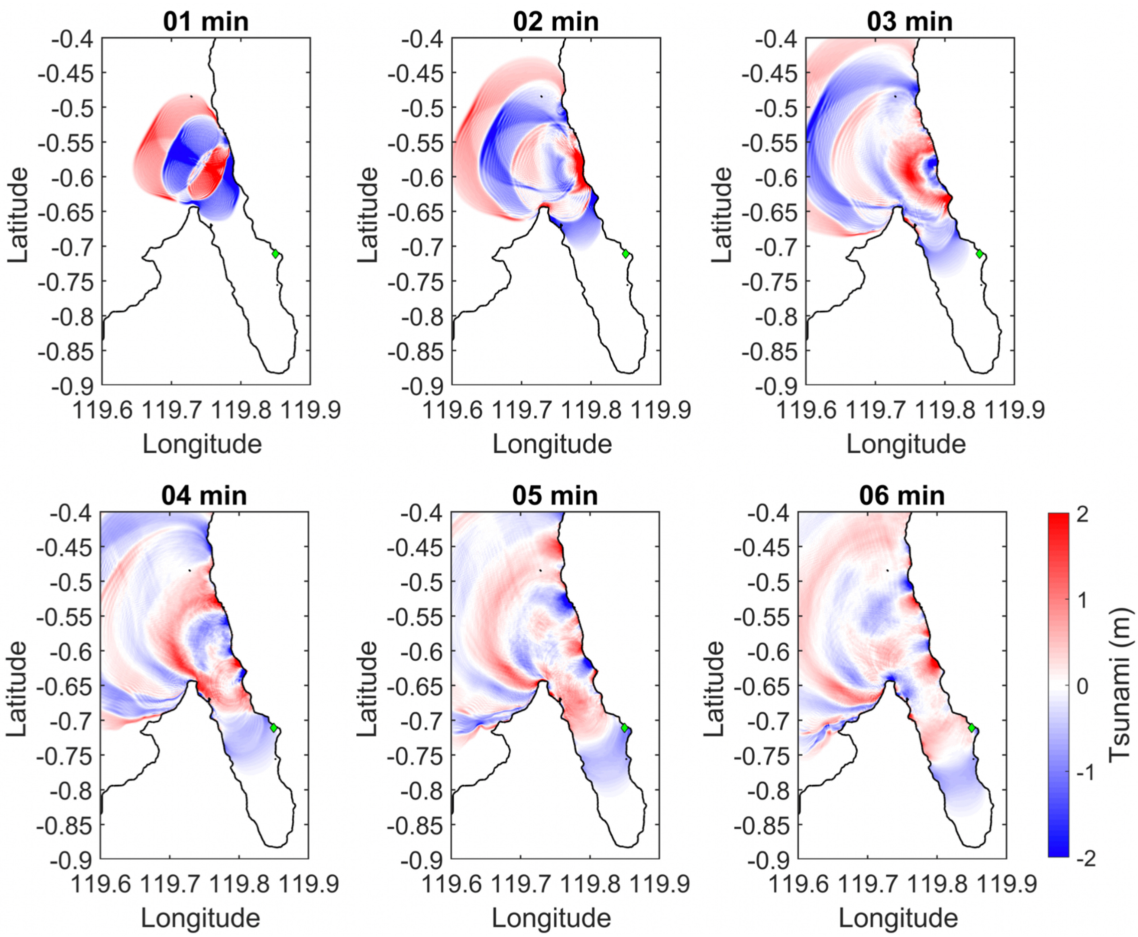


FIGURE 6 | The snapshots of the tsunami propagation. The color shading indicates the free surface elevation in meters. The green diamond indicates the location of Pantoloan. The time depicts the instants after the mainshock of the earthquake (10:02 UTC, September 28, 2018).

capacity, the collaboration initiated several representative or disastrous case studies of each selected hazard type using the simulation portals and collaboration platform. Subsequently, the collaboration is able to support more partners to carry out their own case studies using the platform. The subject matter is to engage local communities to initiate more case studies focusing on the local environment. With the strong motivation and obligations in our collaborations, the partners could achieve high quality in each task and take the roles as local coordinators of local groups and collaboration networks as well as dissemination and training events. On the other hand, the citizen science model was extended to trained volunteers on those exemplar case studies to further enrichment of the case studies. Trained volunteers are not just able to support new case studies but could also extend the capacity and strengthen the practices.

In terms of indicators for citizen science model implementation on tsunami hazard mitigation, such as the best achievable quality, it is suggested to extend the model to the general public step by step, from collaboration partners to trained volunteers first. Moreover, collaboration frameworks, simulation tools, well-defined workflow and guidelines, and clear goals for each task have to be in place before widely calling for volunteers. In the public volunteer level of citizen science model, the first issue is the quality of work is irregular even when all the previous mentioned prerequisites are available. Revalidation of contributions from public volunteers are required, although they are helpful in supporting data collection, local surveys, testing, and compilation of education materials. In coping with these, tools such as auto-checker, smart filter, error reduction assistance according to common faults, validation schemes, and intelligent tests are valuable to enhance the quality of citizen science model applications. Standard operation procedures, atomic task items, and intelligent error detection and error correction tools based on experiences are all necessary supporting tools. For the case study designed through our collaborations, the partner-only model is a special case of citizen science instances. Trained partners motivated by common goals could achieve expected throughput under constraints of cost and time. Applications could define indicators of the citizen science model according to their goals and limitations. Experiences and suggestions of implementing the citizen science model on tsunami hazard mitigation through our collaborations is summarized in **Table 1**.

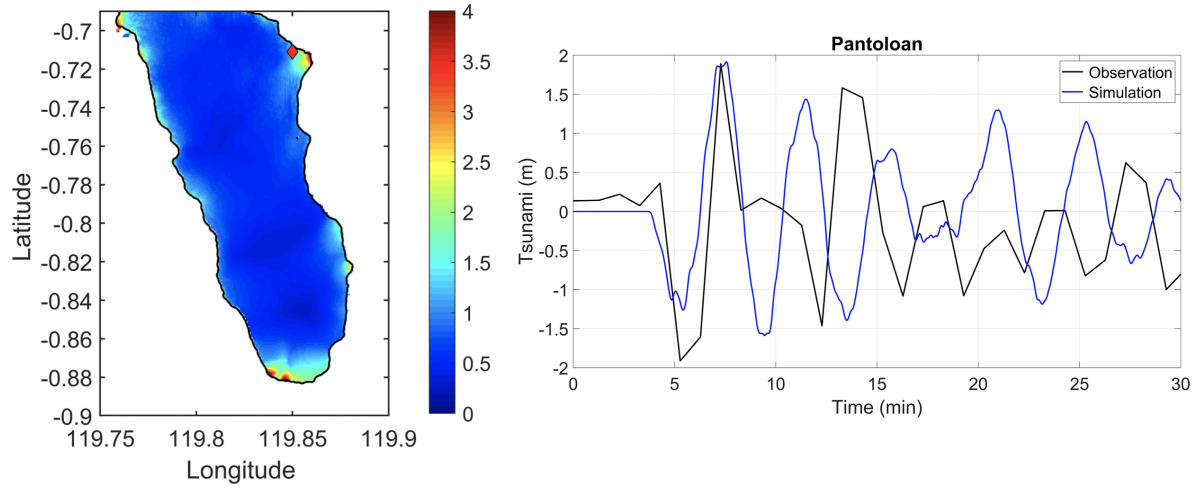


FIGURE 7 | (Left panel) The computed maximum free surface elevation. The color shading indicates the maximum free surface elevation in meter. This plot has been zoomed in from the original computational domain to the regions of Palu Bay. The solid red diamond indicates the location of Pantoloan. **(Right panel)** The comparison between the simulated tsunami and the observed tsunami at Pantoloan. The blue line indicates the numerical results of COMCOT, and the black line indicates the observed tsunami. Note that the observed tsunami has been filtered by the high-pass filter with the 6-h cutoff frequency. The *y*-axis indicates the time after the mainshock of the earthquake (10:02 UTC, September 28, 2018).

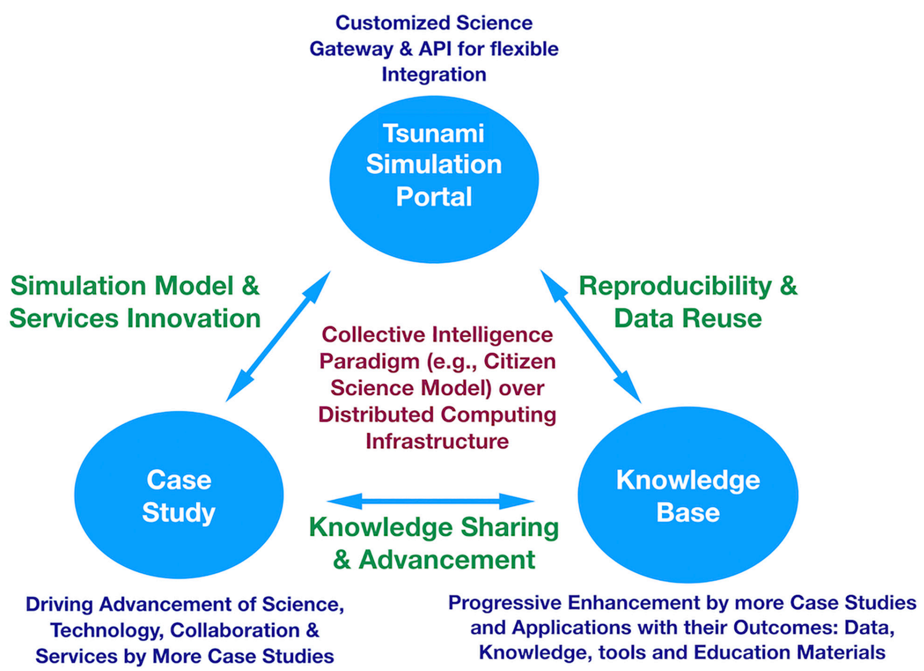


FIGURE 8 | Framework integrating the deeper understanding approach and the citizen science model.

Except for the purposes of science, hazard mitigation, including tsunamis, should attract many contributions from volunteers because of its significance for sustainability and public welfare. In our collaborations, all partners are trained to conduct more case studies according to their local needs using the collaboration platform. By learning from case studies, partners could develop their own customized collaboration model implementing the deeper understanding approach over the platform. The collaboration platform is a distributed computing infrastructure and will be advanced based on the requirements of applications and experiences of case studies. The citizen science model is applicable because people are eager to contribute to the safety and sustainability of their own community. In general, with a clear defined workflow, supporting tools, and training, the citizen science model could aggregate a lot of helpful input, test results, and even innovations to the local needs from knowledge advancement and risk assessments to the adaptation.

In general, the citizen science model is useful for enriching science with participants' know-how and allowing for new points of view in addition to sharing time-consuming and labor-intensive tasks. It also makes science more open and encourages trust in and use of knowledge-based decision making. The deeper understanding approach and the collaboration platform are prepared to integrate contributions from broader types of participants in the production of tsunami disaster mitigation knowledge using the citizen science model. To the better advantage of the citizen science model, our strategy is to extend communication and complement this with extensive communities through education, discussion, and case studies over the distributed cloud platform with the iCOMCOT simulation portal.

SUMMARY AND FUTURE PERSPECTIVES

In this study, the integration of the citizen science model to the deeper understanding approach using the 2018 Sulawesi Tsunami case study is demonstrated. Based on the goal of capacity building, the ecosystem (domain experts, supporting infrastructure, application providers, and collaboration platform) and good projects should be established first. Utilizing the citizen science model for disaster mitigation allows for the enhancement of communication and for support to be gained in the production of scientific knowledge with wider communities. Educating participants on a broader understanding of the scientific process and the nature of science through case studies could lead to a better quality and production of scientific workflow. Mutual learning between scientists and the public is essential in establishing trust with the scientific community. Effectiveness of disaster mitigation could also be improved from making people excited about science through citizen science projects. Opening the data, methodologies, outcomes, tools, projects, and labs, etc. are valuable ways to enable the transformation of science and research and facilitate innovations.

Based on the experiences gained from the collaboration, it has become apparent that a deeper understanding of the tsunami source characteristics, the whole process during its lifecycle, and its impacts especially in light of local environments, is essential to tsunami hazard mitigation. Extensive risk analysis and reinvestigation according to the new knowledge of the tsunami source and new observation data are necessary to update the risk assessment and preparedness in time. The citizen science model is one of the most feasible ways to motivate and aggregate intelligence from volunteers collectively.

To ensure the citizen science model could be implemented effectively, those necessary and supporting components have to be available first. In this regional collaboration, the citizen science model is implemented from partners only in the beginning, because the case study workflow and data policy have to be confirmed and the collaboration platform has

TABLE 1 | Summary of the citizen science model on tsunami hazards mitigation.

Citizen Science Model	Tasks	Data Collection	Impact Analysis Validation	Education	Early Warning Development	Test of Workflow and Analysis Functions	Local Focused Analysis
	Focus	All kind of data required for case study, validation and mitigation planning	Validate the experiment design and analysis results	Understanding potential risks and how it will happen; tsunami science; how to conduct case study	Based on potential risk, develop effective warning actions (societal and cultural perspectives)	Risk analysis workflow and functions of collaboration platform	Mitigation and adaptation strategy, Local environment
Collaboration Partners Only		Best due to strong motivation and obligation	Best due to strong motivation and obligation	Target to conduct new case study and train more local partners	Best, due to the knowledge or local environment	Best, expect to design test items, report, and methodology	Best, due to the aim is to be realized by local partners
Trained Volunteers		Good, very helpful to support local partners on all tasks in good quality as well as extend capacity and strengthen practices					
Public Volunteers		Irregular	Revalidation required	Very good for education material validation and compilation	Best for test and validation	Good	Best for test and feedback collection
Suggested Actions		Smart filter and auto checker	SOP and error reduction tools	Evaluation schemes have to be in place	Identify priorities and verify by case studies	Intelligent test and validation	Survey, review and reorientation are necessary whenever there is update to knowledge and strategy

to be in place at first. Using the citizen science model for data collection (including observation data, geological data, multimedia data from the mass media and social media, etc.) is very helpful. However, data quality requirements have to be clarified in the beginning. For example, data quality and evaluation methodology (including data inconsistency resolution), credibility, legality (licensing, ownership, privacy, liability and copyright), sustainability of the system or project must be established before the project begins. Citizen science could also be deployed for the validation of impact analysis, education, early warning development, testing of the workflow and functionality, and locally focused case studies according to the pilot experiments of our collaborations together with our Asian partners.

The deeper understanding approach has been proven to be able to advance the knowledge of hazards and to build up a better capacity of natural hazard risk analysis from case studies. In this regional collaboration, the goal of capacity building based on the deeper understanding approach is then implemented mainly on the basis of the following pillars: (1) improvement of numerical simulations through the integration of root cause discovery, (2) improvement of risk analysis by accurate numerical simulation, (3) capability to conduct a new case study from each partner, (4) case study reproduction using the simulation portals and collaboration platform, and (5) sharing of knowledge from case studies. Collective intelligence mechanisms could be integrated in the workflow of each perspective. The collaboration platform will grow with more case studies and more contributions from partners and volunteers from data, tools, analysis methodology, and knowledge.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author. The bathymetry data of BATNAS and the tide-gauge data at Pantoloan belong to Badan Informasi Geospasial (BIG), Indonesia. BATNAS data is publicly available on http://tides.big.go.id/DEMNAS/ and the information of Pantoloan tidal gauge can be referred to http://tides.big.go.id:8888/dash/.

AUTHOR CONTRIBUTIONS

EY, SL, and T-RW designed the research and coordinated the collaborations. T-RW, Y-LT, and M-JC conducted the tsunami case studies and result analysis. EY and SL coordinated the development of iCOMCOT and data analysis. EY and Y-LT wrote the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

The Disaster Mitigation Competence Centre (DMCC) is partially supported by the EGI-Engage Project (co-funded by the European Union Horizon 2020 Programme under grant number 654142 during 2015 and 2017) with partners in the Philippines, Malaysia, Indonesia, and coordinated by the Academia Sinica Grid Computing Centre in Taiwan. DMCC+ is partially supported by the EOSC-Hub project (funded by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No. 777536). The Deeper Understanding of Natural Disaster – Instrumental to Disaster Mitigation (UND) project is funded by Asi@Connect under grant agreement No. Asi@Connect-18-066. All these projects are supported by the Academia Sinica and National Central University in Taiwan.

ACKNOWLEDGMENTS

We thank all the partners who provided event data and work together on the case studies and collaboration platform. We also gratefully acknowledge Dr. Veerachai Tanpipat of Hydro-Informatics Institute (HII), Ministry of Higher Education, Science, Research, and Innovation (MHESI) in Thailand for his coordination of observation data collection on the 2018 Sulawesi Tsunami event; Dr. Philip L.-F. Liu and Dr. Pablo Higuera for advices on bathymetry data and the environment of the Palu Bay; and Dr. Xiaming Wang and Dr. Tung-Cheng Ho for discussions of data post-processing on the observation data of Pantaloon.

REFERENCES

Blake, D., Johnston, D., Leonard, G., McLaren, L., and Becker, J. (2018). A citizen science initiative to understand community response to the Kaikoura Earthquake and tsunami warning in Petone and Eastbourne, Wellington, Aotearoa/New Zealand. *Bull. Seismol. Soc. Am.* 108, 1807–1817. doi: 10.1785/0120170292

Brocher, T. M., Filson, J. R., Fuis, G. S., Haeussler, P. J., Holzer, T. L., Plafker, G., et al. (2014). The 1964 Great Alaska Earthquake and tsunamis-A modern perspective and enduring legacies: U.S. *Geological. Surv. Fact Sheet* 6, 2014–3018. doi: 10.3133/fs20143018

Cisternas, M., Atwater, B. F., Torrejón, F., Sawai, Y., Machuca, G., Lagos, M., et al. (2005). Predecessors of the giant 1960 Chile earthquake. *Nature* 437, 404–407. doi: 10.1038/nature03943

Couch, J., Theisz, K., and Gillanders, E. (2019). "Engaging the Public: Citizen Science," in *In Strategies for Team Science Success*. eds K. Hall, A. Vogel, and R. Croyle (Berlin: Springer).

Fujiwara, T., Kodaira, S., No, T., Kaiho, Y., Takahashi, N., Kaneda, Y., et al. (2011). The 2011 Tohoku-oki earthquake: displacement reaching the trench axis. *Science* 334:1240. doi: 10.1126/science.1211554

Garzon, J. L., and Ferreira, C. M. (2016). Storm surge modeling in large estuaries: sensitivity analyses to parameters and physical processes in the Chesapeake Bay. *J. Mar. Sci. Engin.* 4:45. doi: 10.3390/jmse4030045

Goto, K., Chagué-Goff, C., Fujino, S., Goff, J., Jaffe, B., Nishimura, Y., et al. (2011). New insights of tsunami hazard from the 2011 Tohoku-oki event. *Mar. Geol.* 290, 46–50. doi: 10.1016/j.margeo.2011.10.004

Heidarzadeh, M., Muhari, A., and Wijanarto, A. B. (2019). Insights on the source of the 28 September 2018 Sulawesi tsunami, Indonesia based on spectral analyses and numerical simulations. *Pure Appl. Geophys.* 176, 25–43. doi: 10.1007/s00024-018-2065-9

Hwang, L.-S., Butler, H. L., and Divoky, D. J. (1972). Tsunami model: Generation and open-sea characteristics. *Bull. Seismol. Soc. Am.* 62, 1579–1596.

Hwang, L.-S., and Divoky, D. J. (1970). Tsunami generation. *J. Geoph. Res.* 75, 6802–6817.

Kanamori, H. (2008). Earthquake physics, and real-time seismology. *Nature* 451, 271–273. doi: 10.1038/nature06585

Lay, T., Kanamori, H., Ammon, C., Nettles, M., Ward, S., Aster, R., et al. (2005). The Great Sumatra-Andaman Earthquake of 26 December 2004. *Science* 308, 1127–1133. doi: 10.1126/science.1112250

Lin, S. C., Wu, T. R., Yen, E., Chen, H. Y., Hsu, J., Tsai, Y. L., et al. (2015). Development of a tsunami early warning system for the South China Sea. *Ocean Eng.* 100, 1–18. doi: 10.1016/j.oceaneng.2015.02.003

Liu, P. L.-F., Woo, S. B., and Cho, Y. S. (1998). *Computer programs for tsunami propagation and inundation*. New York, NY: Cornell University.

Løvholt, F., Fraser, S., and Salgado-Gálvez, M. (2019). Global trends in advancing tsunami science for improved hazard and risk understanding. *Contributing Paper to GAR*, University of Hamburg: Germany doi: 10.1007/978-3-642-27737-5_642-1

Meltzner, A. J., Sieh, K., Abrams, M., Agnew, D. C., Hudnut, K. W., Avouac, J.-P., et al. (2006). Uplift and subsidence associated with the great Aceh-Andaman earthquake of 2004. *J. Geophys. Res.* 111:B02407. doi: 10.1193/1.2201969

Muhari, A., Charvet, I., Futami, T., Suppasri, A., and Imamura, F. (2015). Assessment of tsunami hazard in port and its impact on marine vessels from tsunami model and observed damage data. *Natural Hazards* 78, 1309–1328. doi: 10.1007/s11069-015-1772-0

Omira, R., Dogan, G. G., Hidayat, R., Husrin, S., Prasetya, G., Annunziato, A., et al. (2019). The September 28th, 2018, Tsunami In Palu-Sulawesi, Indonesia: A Post-Event Field Survey. *Pure Appl. Geophys.* 176, 1379–1395. doi: 10.1007/s00024-019-02145-z

Spahn, H., Hoppe, M., Vidiarina, H. D., and Usdianto, B. (2010). Experience from three years of local capacity development for tsunami early warning in Indonesia: challenges, lessons and the way ahead. *Natural Hazards Earth Sys. Sci.* 10, 1411–1429. doi: 10.5194/nhess-10-1411-2010

Strunz, G., Post, J., Zosseder, K., Wegscheider, S., Mück, M., Riedlinger, T., et al. (2011). Tsunami risk assessment in Indonesia. *Nat. Hazards Earth Syst. Sci.* 11, 67–82. doi: 10.5194/nhess-11-672011

Sunny, R. C., Cheng, W., and Horrillo, J. (2019). Video Content Analysis of the 2018 Sulawesi Tsunami, Indonesia: Impact at Palu Bay. *Pure Appl. Geophys.* 176, 4127–4138. doi: 10.1007/s00024-019-02325-x

Suppasri, A., Mas, E., Charvet, I., Gunasekera, R., Imai, K., Fukutani, Y., et al. (2013). Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami. *Natural Hazards* 66, 319–341. doi: 10.1007/s11069-012-0487-8

Takagi, H., Pratama, M. B., Kurobe, S., Esteban, M., Aránguiz, R., and Ke, B. (2019). Analysis of generation and arrival time of landslide tsunami to Palu City due to the 2018 Sulawesi earthquake. *Landslides* 16, 983–991. doi: 10.1007/s10346-019-01166-y

Vastano, A. C., and Reid, R. O. (1967). Tsunami response for islands: verification of a numerical procedure. *J. Mar. Res.* 25, 129–139.

Wu, T. R. (2013). "Tsunami Risk Assessment in Taiwan after the Event of 2011 Tohoku Tsunami," in *The Twenty-third International Offshore and Polar Engineering Conference* (California: ISOPE).

Wu, T. R., and Huang, H. C. (2009). Modeling tsunami hazards from Manila trench to Taiwan. *J. Asian Earth Sci.* 36, 21–28. doi: 10.1016/j.jseaes.2008.12.006

Yen, E., Lin, S. C., Tsai, Y. L., Wu, T. R., and Lin, C. Y. (2018). "Open Application Framework for Disaster Mitigation Based on Deeper Understanding Approach," in *2018 5th International Conference on Information and Communication Technologies for Disaster Management* (New Jersey, NJ: IEEE).

Conflict of Interest: The 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.

Copyright © 2020 Yen, Lin, Wu, Tsai and Chung. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Advantages of publishing in Frontiers

OPEN ACCESS
Articles are free to read for greatest visibility and readership

FAST PUBLICATION
Around 90 days from submission to decision

HIGH QUALITY PEER-REVIEW
Rigorous, collaborative, and constructive peer-review

TRANSPARENT PEER-REVIEW
Editors and reviewers acknowledged by name on published articles

Frontiers
Avenue du Tribunal-Fédéral 34
1005 Lausanne | Switzerland

Visit us: www.frontiersin.org
Contact us: info@frontiersin.org | +41 21 510 17 00

REPRODUCIBILITY OF RESEARCH
Support open data and methods to enhance research reproducibility

DIGITAL PUBLISHING
Articles designed for optimal readership across devices

FOLLOW US
@frontiersin

IMPACT METRICS
Advanced article metrics track visibility across digital media

EXTENSIVE PROMOTION
Marketing and promotion of impactful research

LOOP RESEARCH NETWORK
Our network increases your article's readership