# Supplementary Material

**Appendix I) The Most Salient Characteristics of the Selected Near-field and Far-field Record Pairs for this Study**

The selected near-field (NF) record pairs have the following characteristics: moment magnitude, , between 6.0 and 7.6; site class C or D according to the NEHRP classification; the closest distance from the recording site to the ruptured area, , between 0.9 km and 12.0 km; peak ground acceleration (PGA) between 0.19 g and 0.24 g; peak ground velocity (PGV) between 0.35 m/s and 1.34 m/s; the pulse period between 1.1 s to 6.0 s with mean and median values of 3.53 s and 3.35 s, respectively. Supplementary Table 1 shows the most salient characteristics of the selected NF record pairs. The faulting mechanism for record pairs No. 1, 7, 9-11, and 17 is of the reverse type; for pairs No. 6, 14-16, and 20 is of the reverse oblique type; for pair No. 4 is of the normal type; and for the other eight pairs is of the strike-slip type. The selected ground motion record set encompasses a wide range of NF ground motion intensity, distance from the fault, pulse period, and pulse amplitude. This record set can capture a large enough sample of strong ground motions to permit the calculation of record-to-record variability.

1. The characteristics of the 20 original (unrotated and unscaled) near-field record pairs selected from the PEER NGA database.

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| Pair No. | NGA Seq. No. | Event name | Recording station name | Year |  | (km) | (m) | (m/s) | (g) |
| 1 | 77 | San Fernando | Pacoima Dam | 1971 | 6.6 | 1.8 | 0.39 | 1.14 | 1.24 |
| 2 | 170 | Imperial Valley | EC County Center | 1979 | 6.5 | 7.3 | 0.48 | 0.73 | 0.24 |
| 3 | 173 | Imperial Valley | El Centro Array #10 | 1979 | 6.5 | 8.6 | 0.35 | 0.51 | 0.23 |
| 4 | 285 | Irpinia Italy | Bagnoli Irpinio | 1980 | 6.9 | 8.1 | 0.14 | 0.35 | 0.19 |
| 5 | 723 | Superstition Hills | Parachute Test Site | 1987 | 6.5 | 0.95 | 0.46 | 1.34 | 0.43 |
| 6 | 766 | Loma Prieta | Gilroy Array #2 | 1989 | 6.9 | 11.1 | 0.18 | 0.40 | 0.37 |
| 7 | 828 | Cape Mendocino | Petrolia | 1992 | 7.0 | 8.2 | 0.33 | 0.89 | 0.66 |
| 8 | 879 | Landers | Lucerne | 1992 | 7.3 | 2.2 | 1.14 | 1.33 | 0.79 |
| 9 | 982 | Northridge | Jensen Filter Plant Admin. Bldg. | 1994 | 6.7 | 5.4 | 0.45 | 1.11 | 0.62 |
| 10 | 1085 | Northridge | Sylmar-Converter Sta East | 1994 | 6.7 | 5.2 | 0.34 | 1.21 | 0.85 |
| 11 | 1086 | Northridge | Sylmar-Olive View Med FF | 1994 | 6.7 | 5.3 | 0.32 | 1.29 | 0.84 |
| 12 | 1114 | Kobe Japan | Port Island | 1995 | 6.9 | 3.3 | 0.39 | 0.91 | 0.35 |
| 13 | 1161 | Kocaeli Turkey | Gebze | 1999 | 7.5 | 10.9 | 0.41 | 0.45 | 0.26 |
| 14 | 1244 | Chi-Chi Taiwan | CHY101 | 1999 | 7.6 | 9.9 | 0.74 | 1.09 | 0.40 |
| 15 | 1510 | Chi-Chi Taiwan | TCU075 | 1999 | 7.6 | 0.89 | 0.97 | 1.10 | 0.33 |
| 16 | 1511 | Chi-Chi Taiwan | TCU076 | 1999 | 7.6 | 2.7 | 0.43 | 0.60 | 0.43 |
| 17 | 3744 | Cape Mendocino | Bunker Hill FAA | 1992 | 7.0 | 12.2 | 0.39 | 0.68 | 0.21 |
| 18 | 4040 | Bam Iran | Bam | 2003 | 6.6 | 1.7 | 0.34 | 1.24 | 0.81 |
| 19 | 4100 | Parkfield | Parkfield - Cholame 2WA | 2004 | 6.0 | 3.0 | 0.12 | 0.64 | 0.62 |
| 20 | 8119 | Christchurch NZ | Pages Road Pumping Station | 2011 | 6.2 | 2.0 | 0.40 | 0.97 | 0.67 |

Twenty ordinary record pairs without velocity pulses, denoted as far-field (FF), are also selected from two different databases. The first database considered is a record suite including 22 ground motion pairs used in FEMA P695 (2009). These ground motions were denoted as FF in FEMA P695 because the distance of their recording sites from the fault was greater than 10 km. As shown in Anajafi and Medina (2018), in the acceleration response spectra of many of these records relatively large ordinates are observed for periods greater than 1.0 s, which can be considered potential evidence of the forward directivity (FD) effects. Among the 22 record pairs of this database, only seven pairs do not exhibit the mentioned large spectral acceleration responses, and hence, are selected as FF records for this study. The remaining 13 FF record pairs are selected from the CESMD (Center for Engineering Strong Motion Data) database. A total of 500 ground motions available in this database with a PGA greater than 0.15 g are examined, and 13 Ground motion pairs that are not suspicious of the FD effects are selected. The moment magnitude () of the 20 FF ground motion record pairs selected for this study is between 6.5 and 7.0; these ground motions were recorded either on site class C or D according to the NEHRP classification; their distance to the rupturing fault ranges from 5.9 km to 55.0 km; their PGA is between 0.15 g and 0.82 g; and their PGV varies from 0.12 m/s to 0.62 m/s (see Supplementary Table 2).

1. The characteristics of the 20 original (unscaled) far-field record pairs selected from the CESMD or PEER NGA database

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| Pair No. | CESMD St. No. | Event name | Recording station name | Year |  | (km) | (m) | (m/s) | (g) |
| 1 | 24231 | Northridge | LA 7-story UC Math/Sci | 1994 | 6.7 | 13.3 | 0.09 | 0.25 | 0.28 |
| 2 | 24322 | Northridge | Sherman Oaks 13-story Bldg. | 1994 | 6.7 | 5.9 | 0.18 | 0.56 | 0.45 |
| 3 | 24332 | Northridge | LA 3-story Commercial Bldg. | 1994 | 6.7 | 15.8 | 0.24 | 0.30 | 0.33 |
| 4 | 24370 | Northridge | Burbank 6-story Bldg. | 1994 | 6.7 | 16.6 | 0.14 | 0.25 | 0.30 |
| 5 | 24464 | Northridge | North Hollywood 20-story Hotel | 1994 | 6.7 | 15.2 | 0.07 | 0.35 | 0.31 |
| 6 | 24468 | Northridge | LA 8-story CSULA Admin. Bldg. | 1994 | 6.7 | 34.4 | 0.02 | 0.12 | 0.16 |
| 7 | 24567 | Northridge | LA 13-story Office Bldg. | 1994 | 6.7 | 29.1 | 0.04 | 0.17 | 0.18 |
| 8 | 24579 | Northridge | LA 9-story Office Bldg. | 1994 | 6.7 | 28.3 | 0.03 | 0.17 | 0.16 |
| 9 | 24601 | Northridge | LA 17-story Residential Bldg. | 1994 | 6.7 | 28.8 | 0.04 | 0.23 | 0.26 |
| 10 | 24602 | Northridge | LA 52-story Office Bldg. | 1994 | 6.7 | 28.1 | 0.04 | 0.12 | 0.15 |
| 11 | 24643 | Northridge | LA 19-story Office Bldg. | 1994 | 6.7 | 15.7 | 0.05 | 0.22 | 0.32 |
| 12 | 24652 | Northridge | LA 6-story Univ. Office Bldg. | 1994 | 6.7 | 27.6 | 0.05 | 0.21 | 0.24 |
| 13 | 57562 | Loma Prieta | San Jose 3-story Office Bldg. | 1989 | 7.0 | 20.5\* | 0.09 | 0.20 | 0.20 |
| 14 | 89770 | Ferndale | Eureka 4-story Hospital | 2010 | 6.5 | 54.7\* | 0.07 | 0.30 | 0.29 |
| Pair No. | NGA Seq. No. | Event name | Recording Station name | Year |  | (km) | (m) | (m/s) | (g) |
| 15 | 1602 | Duzce, Turkey | Bolu | 1999 | 7.1 | 12.0 | 0.23 | 0.62 | 0.82 |
| 16 | 174 | Imperial Valley | El Centro Array #11 | 1979 | 6.5 | 12.6 | 0.19 | 0.42 | 0.38 |
| 17 | 960 | Northridge | Canyon Country-WLC | 1994 | 6.7 | 12.4 | 0.13 | 0.45 | 0.48 |
| 18 | 1111 | Kobe, Japan | Nishi-Akashi | 1995 | 6.9 | 7.08 | 0.11 | 0.37 | 0.51 |
| 19 | 68 | San Fernando | LA - Hollywood Stor | 1971 | 6.6 | 22.8 | 0.12 | 0.19 | 0.21 |
| 20 | 1116 | Kobe, Japan | Shin-Osaka | 1995 | 6.9 | 19.2 | 0.09 | 0.38 | 0.24 |

\* The parameter *R*rup for record pairs No. 13 and 14 is the epicentral distance, and for other records pairs is the closest distance to the fault rupture plane.

**Appendix II) Decomposing the Near-field Record Pairs into Forward Directivity and Parallel Components**

Ground motions are usually recorded at two arbitrary orientations that are not necessary the orientations of the strongest (FD) and weakest (PD) pulses. In this study, each NF pair is rotated to derive its FD and PD components, as discussed next. Assume that the accelerograms A and B measured ground motions in two arbitrary orientations, and , respectively. The acceleration in the FD and PD directions can be determined using the following transformation equations:

where and are the azimuths of the instrument axes, and is the orientation of the strongest observed pulse (FD component) as shown in Supplementary Figure 1.

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| 1. The reference axes for the fault and the accelerograms with relevant angles. |

Supplementary Table 3 illustrates the values of , and , for the selected NF excitations. The values are adopted from the study conducted by Shahi and Baker (2012).

1. The orientation of the accelerograms and and the strongest observed pulse (in degrees clockwise from the north) along with the pulse period for the selected NF record pairs.

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| Event No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|  | 164 | 2 | 50 | 0 | 225 | 0 | 0 | 260 | 22 | 11 | 90 | 0 | 0 | 0 | 0 | 0 | 360 | 0 | 360 | 180 |
|  | 254 | 92 | 320 | 270 | 315 | 90 | 90 | 345 | 292 | 281 | 360 | 90 | 270 | 90 | 90 | 90 | 270 | 270 | 90 | 270 |
|  | 189 | 75 | 79 | 72 | 242 | 66 | 287 | 270 | 49 | 37 | 20 | 332 | 33 | 6 | 109 | 125 | 245 | 277 | 67 | 135 |
| (s) | 1.6 | 4.4 | 4.5 | 1.7 | 2.4 | 1.7 | 3.0 | 5.1 | 3.2 | 3.5 | 2.4 | 2.8 | 6.0 | 5.3 | 5.0 | 4.7 | 5.4 | 2.0 | 1.1 | 4.8 |

**Appendix III) Finite Element Modeling**

The primary analyses are conducted using OpenSees (McKenna et al. 2000). Independent modeling is carried out in SAP2000® (Computers and Structures Inc. 2019) for verification purposes. Nonlinear Direct Integration (NLDI) approach is used for the response history analyses. Unless otherwise noted, the same assumptions are used for the finite element modeling in the two software.

In OpenSees, the lead rubber bearings (LRBs) are modeled using parallel zero-length springs attached between the piers/abutments and the deck. In this software, the rubber and lead materials are defined with elastic uniaxial and elastic-perfectly plastic models, respectively; the Parallel Material command is utilized to model the composite behavior of the LRBs. In SAP2000®, the Rubber Isolator element (a nonlinear link element) is used to define the LRBs. The bridge piers are modeled with the nonlinear Fiber element and nonlinear Shell element in OpenSees and SAP2000®, respectively. The concrete material of the bridge piers is defined using the parametric Mander model with the Takeda hysteresis behavior. In this model, the tensile strength of the concrete is neglected. Hence, the concrete tensile cracking (i.e., modifying the flexural stiffness) is automatically considered in nonlinear analysis. The rebar material is defined based on the Multilinear Kinematic Hardening model. The bridge deck and the pier cap-beams are modeled with the elastic Beam-Column element. The conducted nonlinear analyses illustrate that for all considered models, the shear force demand resulting from the flexural plastic hinging at the bottom of the piers is quite below the shear capacity provided by the transverse shear reinforcement (i.e., the shear force corresponding to the column overstrength moment resistance is smaller than the shear capacity). Therefore, the piers are assumed to remain elastic in shear. Because deep piles support the pier foundations, the soil-structure-interaction is neglected.

For all nonlinear response history analyses, 2.5% viscous damping is assumed. A few previous studies illustrated that the traditional use of viscous damping (i.e., Rayleigh damping based on the initial stiffness of a structure) in inelastic structures could lead to fictitiously large damping forces underestimating the seismic responses significantly (Zareian and Medina 2010; Anajafi et al. 2019). To prevent this phenomenon in isolated models, zero viscous damping is assigned to the isolator elements and 2.5% to other structural elements, as recommended in Anajafi et al. (2019). For the non-isolated models developed in OpenSees, Rayleigh damping is assigned based on the current (tangent) stiffness of the structure to prevent the development of the mentioned large damping forces. In SAP2000®, when an NLDI method is used, Rayleigh damping can be assigned only based on the initial stiffness of the structure. In this case, problems associated with modeling viscous damping can be mitigated by transferring stiffness proportional damping term from the Load Case, general to the entire structure, to the material of individual objects that undergo inelastic actions (Computers and Structures Inc., 2019).

A reasonable agreement is observed between the results obtained from the two software. As an example, Supplementary Figure 2 presents the results of the nonlinear response history analyses for the isolated long-pier (ILP) model subjected to an FF record pair from the 1990 Manjil earthquake (PEER NGA ID 1633). Supplementary Figure 2(a) illustrates the hysteresis loops for the LRB pair located above piers in the longitudinal and transverse directions obtained from the two software. Supplementary Figure 2(b) depicts the time history of the deck displacement at the location of pier in the longitudinal and transverse directions. As seen, the seismic responses, especially the peak values, obtained from the two software packages are in good agreement.

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| (a) | (b) |
| 1. (a) The hysteresis loops for the LRB pair; (b) the time history of the deck displacement responses; at the location of pier P7 for the ILP model subjected to an FF record pair. | |

**Appendix IV) Contribution of the Individual Components of Far-field and Near-field Record Pairs to Resultant Seismic Responses**

At least, one study in the past illustrated that for isolated structures under the NF excitations, the maximum displacement in the fault normal direction occurs at a different time than that in the fault parallel direction. Therefore, these maximum responses do not need to be added vectorially to obtain the maximum resultant isolator displacement (Jangid and Kelly 2001). In this context, “resultant response” is the square root of the sum of the squares of the responses in the transverse and longitudinal directions. This section corroborates and extends the validity of such behavior for the substructure responses of the isolated structures and also for long-period non-isolated structures.

The contributions of the individual components of the FF and NF record pairs to the maximum resultant deck displacement and base shear responses are evaluated next. To this end, the response histories in the longitudinal and transverse directions are normalized to the maximum resultant response. A response ratio (normalized response) closer to unity implies a higher contribution of a component to the resultant response. Supplementary Figure 3 illustrates the time histories of the deck displacement ratios at pier P7 for different bridge models under a representative NF excitation. In this example, the FD component is applied to the longitudinal direction and the PD component to the transverse direction. Supplementary Figure 4 depicts similar results for a representative FF excitation. An evaluation of Figure 3 illustrates that for the isolated and non-isolated long-pier models subjected to the NF record pair, the maximum values of the displacement responses in the longitudinal and transverse directions do not occur at the same time instants. It is observed that the maximum displacement in the direction of applying the FD component is fairly close to the maximum resultant displacement. On the contrary, Supplementary Figure 4(a)-(d) illustrates that for all bridge models subjected to the FF record pair, the maximum absolute displacement responses of the two principal directions occur at the same time instants. Results of similar evaluations for the other NF and FF record pairs reveal that for most NF record pairs, the maximum responses of the two components do not coincide, whereas, a consistent trend is not observed for the FF record pairs.

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| 1. The time history of the displacement ratios of the deck at the location of pier P7 for the FD (longitudinal) and PD (transverse) components of an NF record pair from the 1979 Imperial Valley. | |

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| 1. The time history of the displacement ratios of the deck at the location of pier P7 for the NS (longitudinal) and EW (transverse) components of an FF record pair from the 1979 Imperial Valley. | |

Supplementary Table 4 presents the median value of the maximum displacement ratios at pier P7 and also the base shear ratios for different models subjected to the FF and NF excitations (assuming LC1). In this table, the indices and are the maximum absolute displacement and base shear responses, respectively; the indices FD and PD stand for the forward-directivity and its parallel components for the NF record pairs, respectively; NS and EW refer to the north-east and east-west components of the FF record pairs, respectively; the subscript *R* stands for the resultant response. As seen, for all models subjected to the FF excitations, the maximum response ratios for both components of the FF excitations are significant, and none of the two components is markedly dominant with respect to the other one. This statement is true across all models and all structural responses considered. For the NF records, different trends are observed in the responses of different bridge models. For the non-isolated short-period (NSP) model, which has a relatively short fundamental period, the two components of the NF excitations almost equally contribute to the resultant response as the two components are analogous in the short period region of the response spectra previously shown in Figure 1(a)-(b) in the main body of the manuscript. As of the long-period models subjected to the NF excitations, the contribution of the FD components significantly overweighs that of the PD components. For example, for the ILP model, the median value of the ratio is 0.99, whereas this statistic for is only 0.33.

1. Median values of the ratio of the maximum responses of the two components of the FF and NF record pairs (assuming LC1).

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|  | Far-field excitations | | | | Near-field excitations | | | |
| Model |  |  |  |  |  |  |  |  |
| NLP | 0.94 | 0.78 | 0.72 | 0.94 | 0.99 | 0.51 | 0.96 | 0.60 |
| ILP | 0.88 | 0.85 | 0.78 | 0.80 | 0.99 | 0.58 | 0.99 | 0.33 |
| NSP | 0.86 | 0.80 | 0.82 | 0.74 | 0.88 | 0.83 | 0.89 | 0.80 |
| ISP | 0.90 | 0.89 | 0.76 | 0.77 | 1.00 | 0.50 | 0.99 | 0.32 |

Overall, 40 NF and 40 FF response history analyses are conducted on each bridge model. Therefore, the above-mentioned normalization approach results in 40 normalized displacement values for a bridge model under each ground motion set. These normalized values are used to determine the probability of exceedance of the contribution of the component that dominates the resultant displacement response from a given value. Supplementary Figures 5(a) and (b) illustrate such probability graphs for different bridge models under the FF and NF excitations, respectively. The results illustrate that, for example, the probability that the maximum response of the dominant component of the NF records exceeds 90% of the maximum resultant response for the NLP, ILP, NSP, and ISP models is 73%, 98%, 45%, and 98%, respectively. As of the FF excitations, this probability for the NLP, ILP, NSP, and ISP models is 0.48%, 33%, 33%, and 30%, respectively, implying that in the FF excitations none of the two components is dominant.

These observations imply that, for a long-period structure subjected to the NF excitations, the resultant response can be reasonably obtained from a two-dimensional analysis with the FD component only.

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| (a) | (b) |
| 1. Probability of exceedance of the contribution of the component that dominates the maximum resultant deck displacement responses from a given value under (a) FF excitations; (b) NF excitations. | |

**References**

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