New versus Previous ASCE 7-16 Earthquake Loads for 500 Overseas Locations

Zachary Kortum
Civil Engineer, U.S. Geological Survey, Golden, Colorado, U.S.A.

Nicolas Luco
Research Civil Engineer, U.S. Geological Survey, Golden, Colorado, U.S.A.

Manuela Villani
Senior Hazard Specialist, Global Earthquake Model Foundation, Pavia, Italy, and Associate, Arup, London

Kendra Johnson
Seismic Hazard Scientist, Global Earthquake Model Foundation, Pavia, Italy

Marco Pagani
Hazard Team Coordinator, Global Earthquake Model Foundation, Pavia, Italy and Adjunct Professor Institute of Catastrophe Risk Management, Nanyang Technological University, Singapore

ABSTRACT: The American Society of Civil Engineers (ASCE) Earthquake Loads Overseas (AELO) project is an ongoing collaboration between the U.S. Geological Survey (USGS) and the Global Earthquake Model (GEM) Foundation to compute Risk-targeted Maximum Considered Earthquake (MCE_R) and other design ground motions for locations outside of the United States. The project enables overseas application of the ASCE 7 Standard for design of new buildings and other structures, as well as the ASCE 41 Standard for evaluation and retrofit of existing buildings. The ground motions are derived from the GEM Global Mosaic of Seismic Hazard Models in the same way that those inside of the United States are based on the USGS National Seismic Hazard Model. This paper compares ASCE 7-16 ground motions, derived by the AELO project, for approximately 500 overseas sites with previous design values provided by the U.S. Department of Defense and U.S. Department of State. Approximately two-thirds of the newly computed design ground motions are more than +/-20% different from the previous values. Most of the changes are at locations where the previous values were *not* directly based on site-specific or regional Probabilistic Seismic Hazard Analysis (PSHA). On average, the new design ground motions are less than the previous ones, in part because of differences in the risk-targeted calculations.

1. INTRODUCTION

The U.S. Department of State (DoS) and U.S. Department of Defense (DoD) use the American Society of Civil Engineers (ASCE) 7 and ASCE 41 standards for seismic design and evaluation of buildings outside of the United States. As these standards only provide ground motion values for locations within the United States and its territories, DoD and DoS had previously computed ASCE 7-16 (ASCE, 2016) ground motions for approximately 500 overseas sites.

As part of the ASCE Earthquake Loads Overseas (AELO) project, the Global Earthquake Model Foundation (GEM) and U.S. Geological Survey (USGS) have updated the previously computed Risk-targeted Maximum Considered Earthquake (MCE_R) spectral accelerations and Maximum Considered Earthquake Geometric Mean (MCE_G) peak ground accelerations (PGAs). This paper summarizes the computations of the previous and new ASCE 7-16 MCE_R and MCE_G ground motions and compares them. Where the new and previous values differ significantly, possible causes of these differences are investigated.

2. PREVIOUS DESIGN VALUES

DoD provided 200 triplets of previous ASCE 7-16 MCE_R spectral accelerations (S_S and S_1 at periods of 0.2 and 1.0 seconds) and MCE_G PGA values. DoS provided 92 triplets of previous S_S, S_1, and PGA values, and an additional 196 pairs of previous S_S and S_1 values. All the new design values summarized in the next section are based on regional Probabilistic Seismic Hazard Analysis (PSHA) results from an update of the GEM Global Mosaic of Seismic Hazard Models (Pagani et al., 2020), whereas the previous values provided by DoD and DoS were derived from a variety of sources.

Among the 288 DoS pairs of previous S_S and S_1 values,

- 196 (68%) were roughly approximated from previously assigned Uniform Building Code (UBC) (International Conference of Building Officials, 1997) seismic zones of 1, 2A, 2B, 3, and 4;
- 65 (23%) were based on site-specific PSHA results for PGA but applied rough factors to approximate S_S and S_1, typically 2.5*PGA and 1.0*PGA; and
- 27 (9%) were based on site-specific PSHA results for PGA, S_S , and S_1.

Among the 200 DoD triplets of PGA, S_S, and S_1 values, 180 (90%) were roughly approximated from mid-1990s Global Seismic Hazard Assessment Program (GSHAP) (Shedlock et al., 2000) values of 10%-in-50yr PGAs, and the remainder were derived from regional PSHAs, by McGowan et al. (2014).

3. NEW DESIGN VALUES

As mentioned in the preceding section, the new design ground motions compared in this paper are directly derived from the results of PSHA (e.g., the methodology described in Cornell (1968) and Baker et al. (2022)). More specifically, resulting hazard curves of ground motion intensity levels versus return period are used to calculate probabilistic MCE_R and MCE_G values (see Section 3.1), and resulting disaggregations are used to derive deterministic MCE_R and MCE_G values (see Section 3.2).

The PSHA results were computed from the aforementioned GEM Global Mosaic of Seismic Hazard Models, herein called the Mosaic. The Mosaic is a collection of PSHA models that together achieve near-global coverage. Maintained by GEM, the Mosaic includes models contributed by national agencies, cooperative projects, the literature, and the GEM Secretariat.

Several changes were made to the GEM Mosaic for the purposes of this project. These include homogenization of the minimum magnitude used for the seismic source characterization across the PSHA models of the Mosaic, and updates to the ground motion models used in the Mosaic.

3.1. Probabilistic MCE_R and MCE_G Ground Motions

The probabilistic design ground motions were computed following the site-specific procedures (Chapter 21) of ASCE 7-16. For the probabilistic MCE_R spectral response, hazard curves computed from the Mosaic were first converted from geometric mean to maximum horizontal response using the same scale factors used for the MCE_R maps of ASCE 7-16: 1.1 for the spectral acceleration at 0.2 s, and 1.3 for the spectral acceleration at 1.0 s. Then, the spectral accelerations at 0.2 and 1.0 s expected to achieve a 1% probability of collapse within a 50-year period were computed using a Python implementation of the USGS Risk-Targeted Ground Motion (RTGM) Calculator (https://earthquake.usgs.gov/designmaps/rtgm/). This ensures uniform structural performance in terms of collapse risk, as described in ASCE 7-16 and Luco et al. (2007). In addition to the full ground motion hazard curve from the Mosaic, the RTGM calculation requires a notional fragility curve for structural collapse specified by ASCE 7-16.

For the probabilistic MCE_G PGAs, values are directly taken for a probability of exceedance of 2% in 50 years.

3.2. Deterministic MCE_R and MCE_G Ground Motions

ASCE 7-16 (ASCE, 2016) states that the deterministic spectral response acceleration at each period (for MCE_R) or deterministic PGA (for MCE_G) shall be calculated as the largest 84th-percentile ground motions for the characteristic earthquakes on all known active faults within the region, subject to a deterministic lower limit (discussed below).

Because characteristic earthquakes are no longer universally defined in the seismological community (e.g., Working Group on California Earthquake Probabilities, 2013), ASCE 7-22 (ASCE, 2022) now defines deterministic ground motions using disaggregation of the probabilistic ground motion hazard to identify scenario earthquakes. The largest 84th-percentile ground motion calculated for all the scenario earthquakes is used, still subject to a deterministic lower limit.

According to ASCE 7-16 and ASCE 7-22, the deterministic ground motion needs to be calculated only for those sites where the probabilistic ground motion is larger than the deterministic lower limit (DLL). For the reference site condition of the design ground motion compared in this paper (Vs30 = 760 m/s, i.e., the Site Class B/C boundary), these deterministic thresholds are 0.5g for the MCE_G PGA, and 1.5g and 0.6g for the MCEr spectral accelerations at 0.2 and 1.0 s, respectively.

Based on the above thresholds, we performed deterministic analyses for a total of 66 DoS sites and 38 DoD sites. We elected to use the ASCE 7-22 rather than ASCE 7-16 method to avoid the subjectivity of defining characteristic earthquakes.

3.3. Governing MCE_R and MCE_G Ground Motions

As defined in ASCE 7-16 (ASCE, 2016), the governing MCE_R and MCE_G ground motion values are given by the lesser of the probabilistic ground motions described in Section 3.1 and the deterministic ground motions (subject to the DLLs) described in Section 3.2. Accordingly, when the probabilistic value is lower than the DLL, the former is adopted. Note that in the following sections, S_S and S_1 refer to the governing MCE_R value at 0.2s and 1.0s, respectively, and PGA refers to the governing MCE_G value.

4. COMPARISON OF PREVIOUS AND NEW DESIGN VALUES

The previous versus new DoD and DoS ASCE 7-16 values (PGA, S_S, and S_1) described above are compared in Figures 1 and 2. Each subplot shows how many of the new values would, if adopted, represent more than a +/-20% change from the previous values, and the counts are summarized in Table 1. We highlight +/-20% changes because, in the United States and its territories, ASCE 7-16 requires that site-specific ground motions be larger than 80% of the corresponding mapped values. In other words, ASCE 7-16 considers a change of more than 20% to be significant. However, at low ground motion levels (e.g., S_S=0.11g), the absolute differences corresponding to a +/-20% change are typically not significant. Hence, in Figures 1 and 2 and Table 1 we also consider how many of the new values represent changes in the FEMA P-154 (Federal Emergency Management Agency, 2015) "seismicity region," which discretizes the S_S and S_1 values into low, moderate, moderately high, high, and very high seismicity. In particular, we consider changes from/to the "low/moderate/moderately high" to/from "high/very high" seismicity regions, across the S_S and S_1 boundaries of 1g and 0.4g, respectively.

4.1. DoD Values

As seen from the first three rows of Table 1 and the three subplots of Figure 1, approximately two-thirds of the new DoD PGA, S_S, and S_1 values are more than +/-20% different from the previous values. The numbers of significant increases and decreases are approximately the same for PGA, whereas for S_1 there are approximately six times more decreases than increases, and the proportion for S_S falls in between these. On average, across all sites, the result is a decrease of 7% for the PGA values, 24.5% for S_S, and 52% for S_1. A similar pattern is seen for the DoS S_S and S_1 values discussed in the following paragraphs.

4.2. DoS Values

As seen from the last three rows of Table 1 and the three subplots of Figure 2, approximately two-thirds of the new DoS S_S, S_1, and PGA values are more than +/-20% different from the previous values, similar to the new DoD values. Approximately one-half of all the S_S and S_1 changes result in different FEMA P-154 seismicity regions. Only about 15% of the S_S and S_1 changes cross the aforementioned seismicity-region boundaries of 1g and 0.4g, respectively.

Among the DoS S_S and S_1 changes that cross the 1g and 0.4g seismicity-region boundaries, from the last two subplots of Figure 2 we see that most are decreasing (i.e., most are in the lower-right quadrant rather than upper-left), particularly for S_1. Further, most of these changes are at locations where the previous DoS values were not based on site-specific PSHA for S_S and S_1 (directly). In fact, the same can be said for all the changes shown in the S_S and S_1 subplots. In contrast, most of the changes at the site-specific PSHA locations do not cross the seismicity-region boundaries of interest (i.e., most are in the lower-

Table 1: Numbers (and percentages amongst the 200 DoD or 288 DoS locations) of new design values representing more than +/-20% changes with respect to the previous values or changes in FEMA P-154 seismicity region. Note: DoS PGA percentages are amongst the subset of DoS locations with previous PGA values (89 locations).

Design Parameters	**# (%) of decreases more than -20%**	**# (%) of increases more than +20%**	**# (%) of changes in seismicity region**	**# (%) of changes across S_S=1g or S_1=0.4g**
DoD PGA	71 (34%)	69 (33%)	n.a.	n.a.
DoD S_S	88 (42%)	59 (28%)	77 (37%)	15 (7%)
DoD S_1	121 (58%)	19 (9%)	101 (48%)	17 (8%)
DoS PGA	44 (49%)	15 (17%)	n.a.	n.a.
DoS S_S	170 (57%)	40 (13%)	158 (53%)	40 (13%)
DoS S_1	195 (66%)	11 (4%)	157 (53%)	48 (16%)

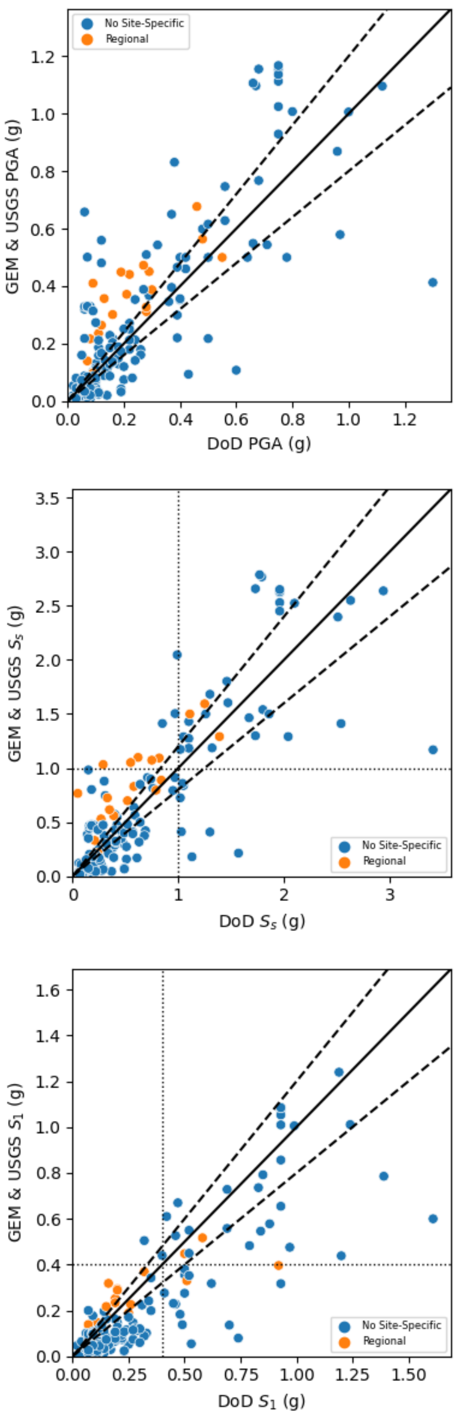

Figure 1: Comparison of new AELO (GEM & USGS) and previous DoD values derived via rough approximations from GSHAP values (not site-specific PSHA, in blue) or from regional PSHA (orange). The dashed lines represent +/-20% boundaries, while the dotted lines represent seismicity region boundaries.

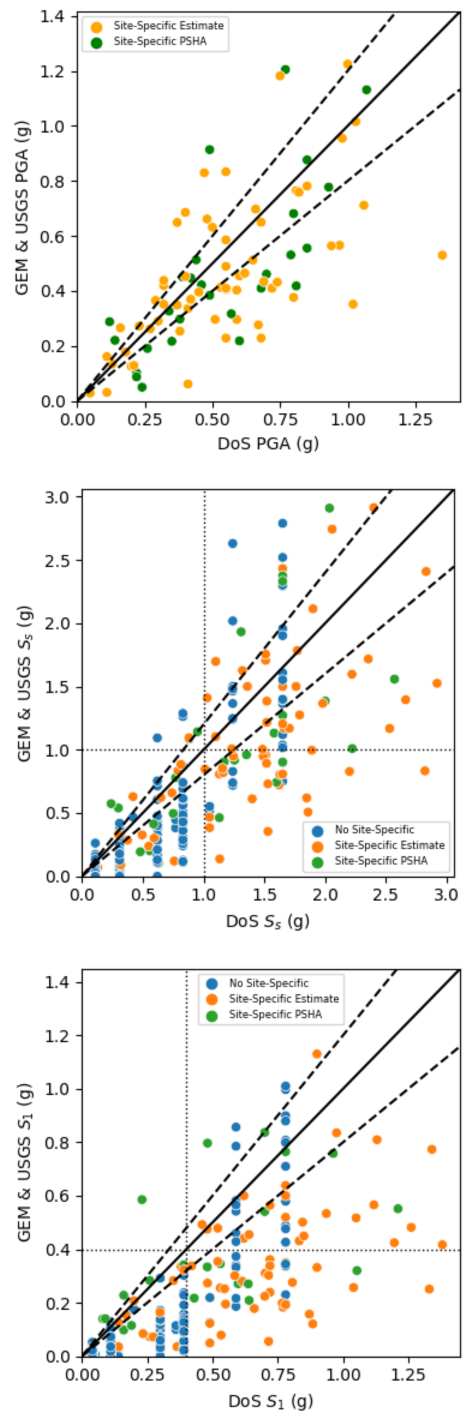

Figure 2: Comparison of new AELO (GEM & USGS) and previous DoS values derived from site-specific PSHAs for S_S and S_1 directly (green), site-specific estimates of S_S and S_1 from PSHAs for PGA (orange), and previously assigned UBC zones (blue).

left and upper-right quadrants). All together, these observations indicate that the previous DoS values not from site-specific PSHA for S_S and S_1 (directly) are biased high, as investigated further in the next subsection.

For PGA, all of the previous DoS values are directly from site-specific PSHA (i.e., none are roughly approximated from previously assigned UBC zones). Even so, the first subplot of Figure 2 and the fourth row of Table 1 reveal that these previous PGA values, like their S_S and S_1 counterparts, are also larger than the new AELO values, on average. This indicates that the S_S and S_1 decreases described in the preceding paragraph are, in part, attributable to differences between the site-specific PSHAs and the GEM Mosaic.

4.3. Spectral Shape Factors

Of the 288 DoS sites, 65 had previous values that were calculated from a site-specific PSHA for PGA only, and then used rough factors to approximate S_S and S_1, typically 2.5*PGA and 1.0*PGA, respectively. Using the newly calculated values, which include probabilistic risk-targeted values for PGA, S_S, and S_1, we can calculate the "true" ratios of S_S/PGA and S_1/PGA, and compare them to the factors used in the site-specific reports. Figure 3 shows the ratios of S_S/PGA and S_1/PGA for all of the newly calculated values for both DoS and DoD sites. The average ratio of S_S/PGA for the new values is 2.24, and the average ratio of S_1/PGA is 0.64. This indicates that the 2.5 and 1.0 factors used in many of the site-specific reports are likely somewhat conservative. This conservatism contributes to the reduction in ground motion level seen between the previous and new values for the sites that used these factors to calculate S_S and S_1.

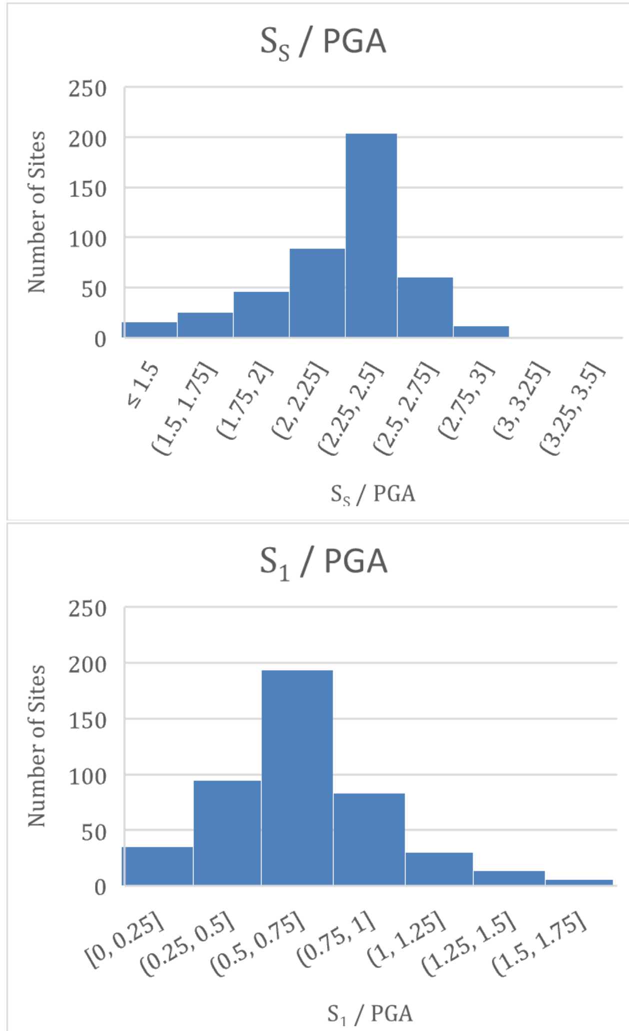

Figure 3: Distribution of spectral shape factors for S_s and S_1 for both DoS and DoD sites.

4.4. Effects of Risk-Targeting

One systematic difference between the newly calculated MCE_R values and those provided by DoS is that the previous probabilistic ground motions are uniform-hazard values, whereas the new probabilistic ground motions are risk-targeted values. Uniform-hazard ground motions achieve a uniform probability of exceeding the spectral acceleration (in this case a 2% chance of exceedance in 50 years), whereas risk-targeted ground motions aim to achieve a uniform probability of structural collapse (in this case a 1% chance of collapse in 50 years). Figure 4 shows the distribution of risk coefficients, defined as the ratio of the risk-targeted ground motion to the uniform-hazard ground motion, for the newly calculated values for all DoS and DOD sites and both S_S and S_1. The risk coefficients for the new values are almost all less than one, indicating that risk-targeting is tending to reduce the ground motion levels. The average risk coefficient across all sites is 0.925 for S_S and 0.922 for S_1. Thus, on average, nearly 10% of the reduction in ground motion levels between the new and the previous DoS values can be explained by the effects of risk-targeting.

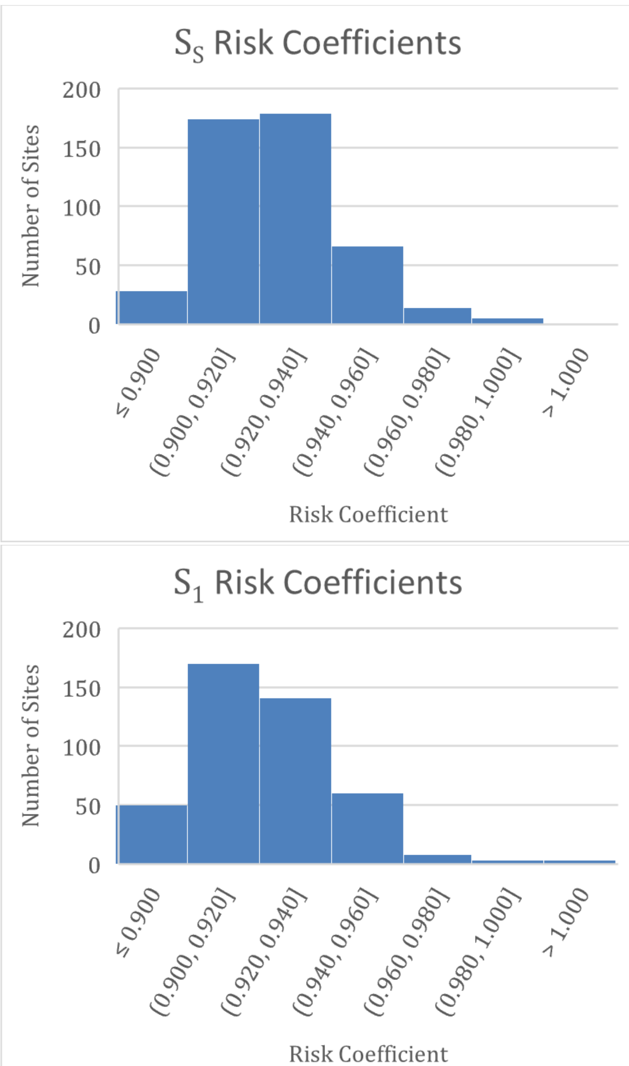

Figure 4: Distribution of risk coefficients for S_S and S1 for both DoS and DoD sites.

5. CONCLUSIONS

This paper summarizes the calculation of updated ASCE 7-16 ground motion values for approximately 500 sites overseas and compares these newly calculated values to the previous design values.

Approximately two-thirds of the new ground motions are more than +/-20% different from the previous values; the corresponding FEMA P-154 seismicity regions are different for approximately one-half of the values. Most of these changes are at locations where the previous design values are not directly based on site-specific or regional hazard models (for all three design parameters). On average, these “indirect” previous values appear to be biased high. The changes with respect to previous ground motions that are directly based on site-specific and regional hazard model are attributable to differences in the PSHA earthquake source models, the PSHA ground motion models, and the effects of risk-targeting. As part of the ongoing work of the AELO project, many sites showing large differences in ground motion values are being investigated more closely to understand specific causes of these differences. Recommendations as to which values to use for design purposes can be made once these more detailed investigations are completed.

6. ACKNOWLEDGEMENTS

This work was supported by funding from the U.S. Department of Defense and the U.S. Department of State.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

7. REFERENCES

American Society of Civil Engineers (ASCE). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE/SEI 7-16*. 2016.

American Society of Civil Engineers (ASCE). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures, ASCE/SEI 7-22*. 2022.

Baker, J.W., Bradley, B.A., and Stafford, P.J. *Seismic Hazard and Risk Analysis*, Cambridge University Press. 2022.

Cornell C.A. Engineering seismic risk analysis. *Bulletin of the Seismological Society of America*, Vol. 58(5), pp. 1583-1606. 1968.

Federal Emergency Management Agency (FEMA). *Rapid visual screening of buildings for potential seismic hazards: Supporting documentation*. Government Printing Office. 2015.

International Conference of Building Officials. *Uniform Building Code*. 1997.

Luco, N., Ellingwood, B.R., Hamburger, R.O., Hooper, J.D., Kimball, J.K., and Kircher, C.A. Risk-targeted Versus Current Seismic Design Maps for the Conterminous United States. *Proceedings of the Structural Engineers Association of California 76th Annual Convention*, Lake Tahoe, California. 2007.

McGowan, S.M., Rezaeian, S., and Luco, N. USGS update of earthquake loading data provided in 2013 edition of unified facilities criteria 3-301-01: Structural engineering. *Proceedings of 10th U.S. National Conference on Earthquake Engineering*, Anchorage, Alaska. 2014.

Shedlock, K.M., Giardini, D., Grunthal, G., and Zhang, P. The GSHAP Global Seismic Hazard Map. *Seismological Research Letters*, Vol. 71(6), pp. 679-686. 2000.

Pagani, M., Garcia-Pelaez, J., Gee, R., Johnson, K., Poggi, V., Silva, V., Simionato, M., Styron, R., Viganò, D., Danciu, L., Monelli, D., and Weatherill, G. The 2018 version of the Global Earthquake Model: Hazard component. *Earthquake Spectra*, Vol. 36, pp. 226–251. 2020.

Working Group on California Earthquake Probabilities (WGCEP). *Uniform California earthquake rupture forecast, v. 3 (UCERF3)–The time-independent model*. USGS Open File Report 2013-1165. 2013.