NGA-East: a Ground Motion Characterization Model for Central and Eastern North America

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ABSTRACT

In this paper, we introduce the Next Generation Attenuation (NGA) project for Central and Eastern North America (CENA) and summarize its key products. The project, referred to as NGA-East, was tasked with developing a new ground motion characterization (GMC) model for CENA. The project involved several dozens of participating researchers from academia, industry and government and was carried-out as a combination of 1) a scientific research project and 2) a model-building component following the Seismic Senior Hazard Analysis Committee (SSHAC) Level 3 process. The science part of the project led to several products and technical reports while the SSHAC component aggregated the various results into the GMC. The GMC model consists of a set of ground motion models (GMMs) for median and a suite of standard deviation models, each with their associated weights, combined into logic-trees for use in probabilistic seismic hazard analyses (PSHA).

The final NGA-East GMC model consists of 17 median GMMs for pseudo-spectral acceleration (PSA) at 23 frequencies spanning 0.1 to 100 Hz, plus peak ground acceleration (PGA) and velocity (PGV). The models are provided in table form magnitude **M** ranging from 4 to 8.2 and closest-distance R_{RUP} ranging from 0 to 1,500 km. The GMMs are applicable to very hard rock site conditions defined as having a shear-wave velocity V_S = 3000 m/sec and a kappa (κ) of 0.006 sec. Adjustments are provided to account for source depths, hanging wall effects and to represent the lower attenuation of the Gulf Coast Region (GCR) relative to the rest of CENA. Aleatory variability models were developed in a logic tree framework for the between-event standard deviation (τ), single-station within-event standard deviation (φ_{SS}), and site-to-site variability (φ_{S2S}). In turn, these models were combined to develop single-station sigma (σ_{SS}) and ergodic sigma models for CENA.

Keywords: ground motion model, seismic hazard, GMPE, stable continental region, central and eastern North America.

INTRODUCTION

Project Overview

NGA-East is the Next Generation Attenuation (NGA) project for Central and Eastern North America (CENA). The project was tasked with developing a new ground motion characterization (GMC) model for CENA [1]. The project involved a large number of participating researchers from academia, industry and government and was carried-out as a combination of 1) a scientific research project and 2) a model-building component following the Seismic Senior Hazard Analysis Committee (SSHAC) Level 3 process [2, 3]. The science part of the project led to several products and technical reports while the SSHAC component aggregated the various results into the GMC. The GMC model consists of a set of ground motion models (GMMs) for median and standard deviation ground motions and their associated weights, combined into logic-trees for use in probabilistic seismic hazard analyses. This paper provides an overview of the final NGA-East GMC model and briefly documents key elements of its development.

In developing the complete GMC model, NGA-East faced technical challenges related to the relatively small number of recordings available for CENA compared to western North America, for example. To resolve this shortcoming, the project relied on ground motion simulations to supplement the available data. Other important scientific issues were addressed through research projects on topics such as the regionalization of seismic source, path and attenuation of motions and on the re-assessment of reference site conditions and the development of related site effects models. Seven working groups were formed to cover the complexity and breadth of topics in the NGA-East project, each focused on a specific technical area.

Under component (1) of NGA-East, several scientific issues were addressed, including: (a) development of a new database of ground motion data recorded in CENA [4]; (b) development of a regionalized ground-motion map for CENA [5]; (c) definition of the reference site condition [6, 7, 8]; (d) simulations of ground motions based on different methodologies [9, 10]; and (e) development of numerous GMMs for CENA [11, 12] and (f) investigation of aleatory variability [13]. Additional reports addressed issues such as of magnitude scaling [14], site effects corrections [15, 16]. Several of the citations above are for PEER reports available at https://peer.berkeley.edu/peer-reports. Ground motions from the NGA-East database are available at https://peer.berkeley.edu/peer-strong-ground-motion-databases.

The scope of component (2) of NGA-East was to develop the complete GMC. This component was designed as a SSHAC Level 3 study with the goal of capturing the ground motions' center, body, and range of the technically defensible interpretations in light of the available data and models. The SSHAC process involves four key tasks: evaluation, integration, formal review by the Participatory Peer Review Panel (PPRP), and documentation [1].

During the course of the project several innovative technologies were developed and implemented to increase the transparency and repeatability of the GMC building process, and to capture the center body and range of the technically defensible interpretations (CBR of TDI) as required by SSHAC Level 3 process. Furthermore, in developing the median GMM, the evaluation and integration focused on capturing the epistemic uncertainty in ground-motion values as opposed to examining the underlying modeling approaches. This involved using and expanding the original candidate GMM set to define and capture the CBR of TDI of median ground motions. Through this process, epistemic uncertainty could be quantified more objectively than before, and with a process that is repeatable. We also developed a new approach for modeling the aleatory variability that was completely independent of the median GMMs. The development made extensive use of the CENA database but also borrowed data from other parts of the world when relevant, and led to an integrated suite of models that sample the epistemic uncertainty in aleatory variability. The aleatory variability model was developed for appropriate use of reference site condition, favoring the partition of aleatory and epistemic uncertainty in site response through the use of single-station sigma.

Objective and modeling constraints

The NGA-East project objective was: to provide the best estimate of the distribution (median and standard deviation) of RotD$_{50}$ [18] horizontal ground motions for peak ground acceleration (PGA), peak ground velocity (PGV), and 5%-damped pseudo-acceleration response spectra (PSA) for oscillator frequencies ranging from 0.1 to 100 Hz (periods from 0.01 to 10 sec) on "hard-rock" sites located up to 1500 km from future earthquakes in CENA with moment magnitudes in the 4.0–8.2 range, and to provide the epistemic uncertainty associated with this estimate. Figure 1 shows the study region.
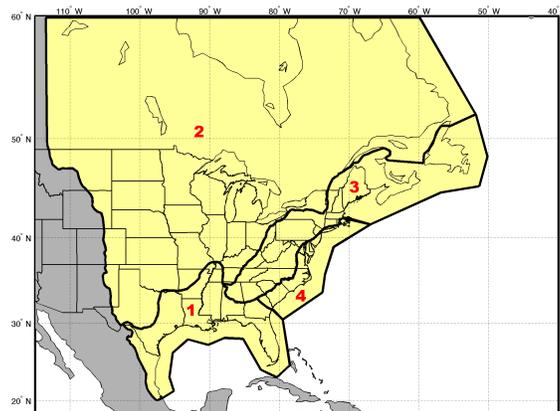

Figure 1. Study area and the four regions defined for CENA. The regions have been numbered as follows: (1) Mississippi Embayment/Gulf Coast Region; (2) Central North America; (3) the Appalachian Province; and (4) the Atlantic Coastal Plain. Together, Regions 2, 3, and 4 form the larger Mid-Continent Region.

The reference site conditions have been defined by the NGA-East Geotechnical Working Group as corresponding to shear-wave velocity V_{S30} = 3000 m/sec and a kappa (κ) of 0.006 sec [6, 7, 8,]. The significance of the reference rock definition is that it represents the site condition for which ground motions will be predicted using GMMs, and it represents the site condition to which site amplification factors are referenced (i.e., site amplification is unity for reference rock).

MODEL FOR MEDIAN GROUND MOTIONS

As with other SSHAC-based projects, we aimed at quantifying the epistemic uncertainty in median ground motions. Most past projects involved the evaluation of different existing GMMs and their integration into a GMC by applying weights to the individual models. NGA-East took a different approach involving the definition of the full range of ground motions, and subsequently creating new GMMs that would span this ground motion space with an attempt to create a set of *mutually exclusive completely exhaustive* set of GMMs. The motivation for this approach is that existing GMMs may not represent the complete range of epistemic uncertainty. On the one hand, GMMs that are similar in terms of development process or assumptions may lead to similar results, eventually getting a large aggregate weight. On the other hand, other viable GMMs may not have been created, but could be just as defensible. The NGA-East process attempts to correct this uneven distribution of ground motions, as represented by GMMs, by removing redundant models and creating new GMMs in between. The process can be summarized in the five steps, which are summarized in the following paragraphs (see Figure 2).

1. Develop a suite of seed GMMs

The seed GMMs were selected following the evaluation of an initial set of 30 candidate models applicable to CENA. To begin the process, the NGA-East Technical Integration (TI) team evaluated the vintage and redundancy of the candidate models, as well as their applicability to the range of magnitudes (M=4-8.2), distances (R=0-1200 km) and frequencies (f=0.1-50 Hz, and PGA) required in the final model. This initial screening found 10 of the candidate models [19] were superseded by the most recent GMMs. The remaining 20 GMMs come from a set created specifically for the NGA-East project by 11 developer groups using various combinations of empirical, hybrid-empirical, and simulation-based approaches [11, 12]. Further evaluation led to the selection of 19 seed GMMs.

2. Develop parameters for continuous distributions of GMMs

The selected seed GMM set was used to generate ground-motion estimates. We then characterized the full ground-motion distribution by estimating the means, variances, and correlations between median values at 374 different (**M**, R_{RUP}) scenarios considered. The covariance model, together with the seed GMMs, defines the continuous distribution describing median ground motions and samples can be drawn from it.
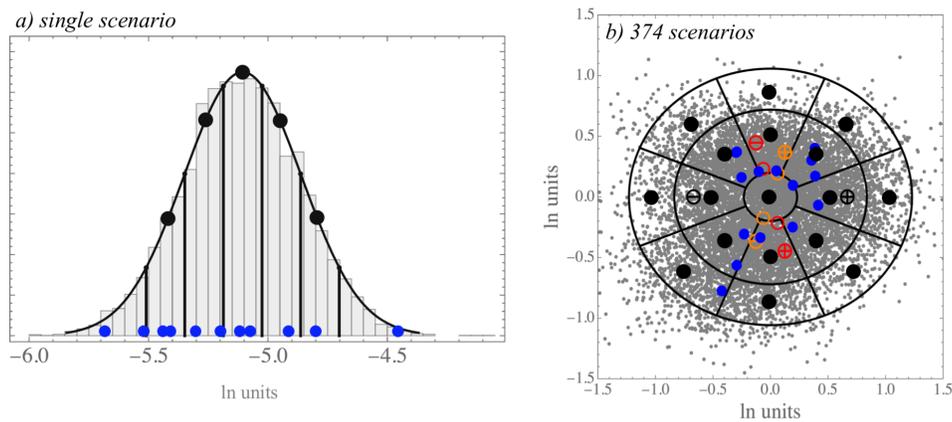

Figure 2. Illustration of the NGA-East median model development process, Steps 1-4 using a more intuitive one dimensional case as a reference. a) single (**M**, R_{RUP}) scenario (one dimensions) and b) 374 (**M**, R_{RUP}) scenarios, projected in two dimensions using Sammon's mapping. Step 1: blue dots represent ground motions from the seed GMMs, additional orange and red dots in b are reference points showing the scaling with **M** and R_{RUP}; Step 2 (visible only in a): black normal probability distribution function (PDF) shows the fit to the blue dots; Step 3 sampled ground motion values: shown as a grey histogram in a and as grey dots in b; Step 4 shows the re-discretization in cells and sampling of representative models in black dots: in a, cells are defined by vertical lines on the PDF and, in b shown as sections of an ellipse.

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3. Visualize the ground-motion space and sample GMMs

A suite of 10,000 ground-motion values were then sampled from the distribution defined above for each of the scenarios. It is impossible to grasp what 10,000 models represent in 374 dimensions, hence the visualization step is critical in the application of the NGA-East methodology. It involved mapping the 374 dimensions of ground motions space to a two-dimensional Sammon map [20, 21].

4. Re-discretize the ground-motion space (final GMMs)

The next step involves the definition of the range in ground-motion space, the partitioning of that range, and the selection of representative sets of GMMs. There are many tasks required to complete this step; please see the final report [1] for details.

5. Assign weights

The last step is to calculate weights for the set of representative models. We have defined four types of weights with two based on the expected and realized distributions of sampled GMMs and two based on the goodness of fit of the models with recorded data (minimizing residuals and favoring high likelihood). We weighted the weighting scheme to come up with an aggregate weight for each of the 17 model at the 25 intensity measures considered (23 PSA frequencies, PGA, PGV). Final models were then smoothed to remove artifacts, when present, with frequency, magnitude and distance.

MODEL FOR ALEATORY VARIABILITY

The model development for the aleatory variability (i.e., standard deviation) of ground motions followed a simpler process, consisting of two key steps: (1) model building, and (2) weight assignment. The model is to be applied to all 17 median models in an identical fashion. The model building part involved analysis of the various components of ground-motion variability using recorded data from CENA. Trends of ground-motion variability with parameters such as magnitude, distance, and V_{S30} were analyzed and compared to trends of ground-motion variability observed in other regions, particularly the Western United States (WUS) using the NGA-West2 dataset and Japan.

The CENA dataset is limited to small-to-moderate magnitudes and in frequency content to frequencies between 1 and 10 Hz due to the bandwidth limitations of the recordings. Therefore, standard deviation models developed using the CENA ground-motion data could not be reliably extrapolated to large magnitudes, hard rock conditions, and to frequencies outside of 1 to 10 Hz. As a result, standard deviation models from other regions such as WUS and Japan were used to inform the extrapolation of CENA standard deviations and overcome data limitations. Models were developed and evaluated in a logic tree framework for the between-event standard deviation (τ), single-station within-event standard deviation (φ_{SS}), and site-to-site variability (φ_{S2S}). In turn, these models were combined to develop single-station sigma (σ_{SS}) and ergodic sigma models for CENA.

SAMPLE RESULTS

In this section we show sample results from the final GMC. Figure 3 shows the 17 median GMMs in three complementary plots showing the scaling with magnitude and distance and showing the final model spectra for a given scenario. Figure 4 shows the final weights for 1 sec (1 Hz) PSA. Figure 5 shows the comparison of the three total ergodic standard deviation models, along with their associated epistemic low and high branches. Finally, Figure 6 shows hazard sensitivity results to the median models by comparing hazard from the seed GMMs relative to the final median GMMs.
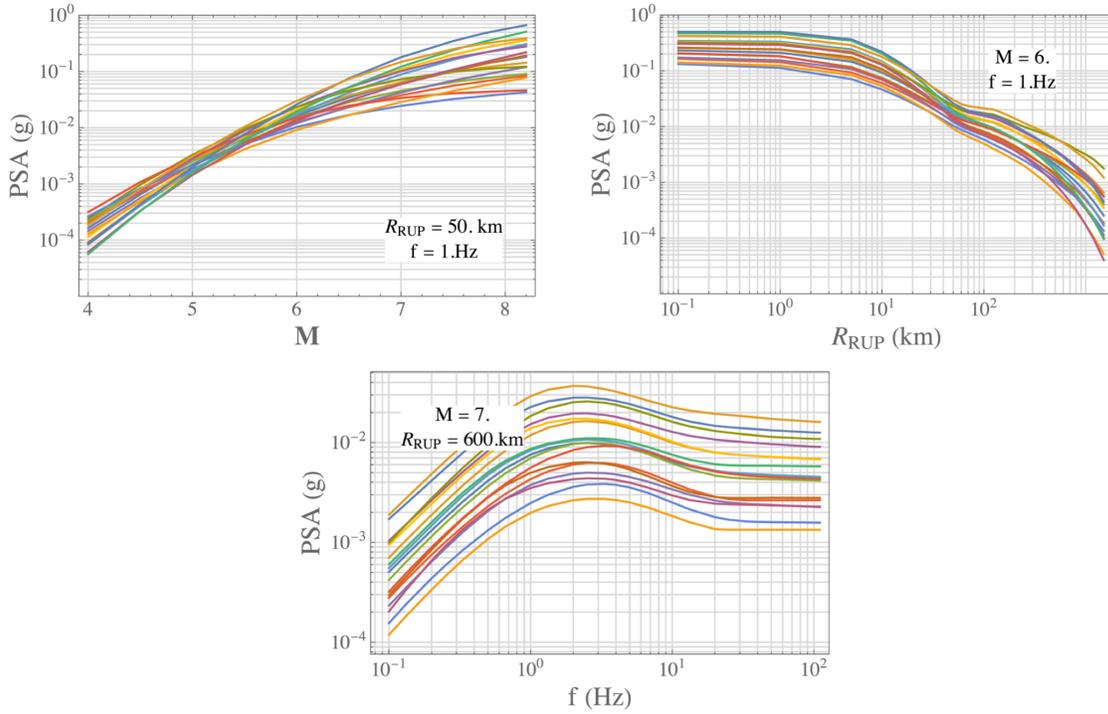
*Figure 3. Sample results show the 17 median models. Top left: magnitude scaling for 1Hz spectral frequency (1 sec period) for a fixed R_{RUP} distance of 50 km. Note the different slopes and the increased uncertainty at large **M**. Top right: Distance scaling for 1 Hz spectral frequency for a fixed M of 6. Note the different slopes and the different levels of Moho bounce effects in the 50-100 km range. Bottom: smoothed spectra of 17 selected models for a single (**M**, R_{RUP}) scenario.*
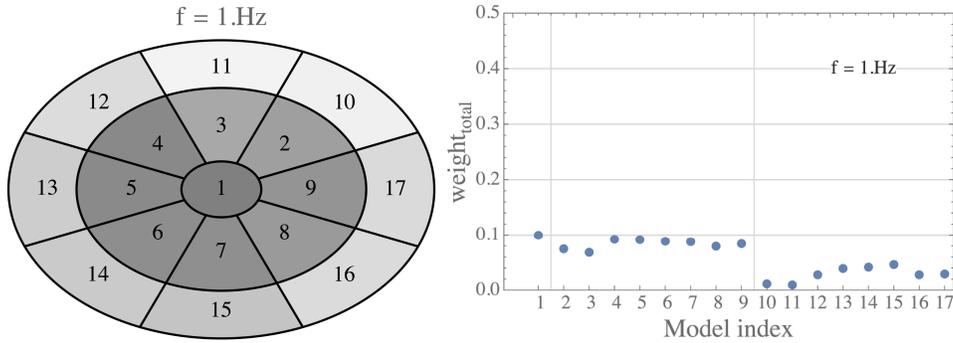

Figure 4. Total weights for the 1 Hz case. Left: model number as defined in the Sammon's maps with shading proportional to the total weight. Right: total weights values corresponding to shading in left figure.
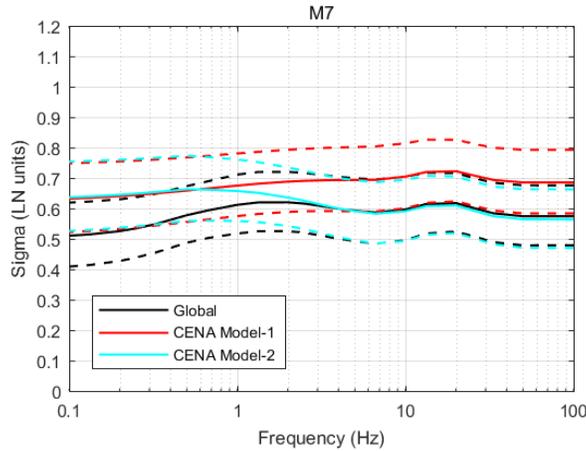
Figure 5. Comparison of ergodic total sigma (σ) models for CENA versus frequency for M = 5.0, 6.0, and 7.0. Solid lines show the central branches. Dashed lines show the low and high branches.
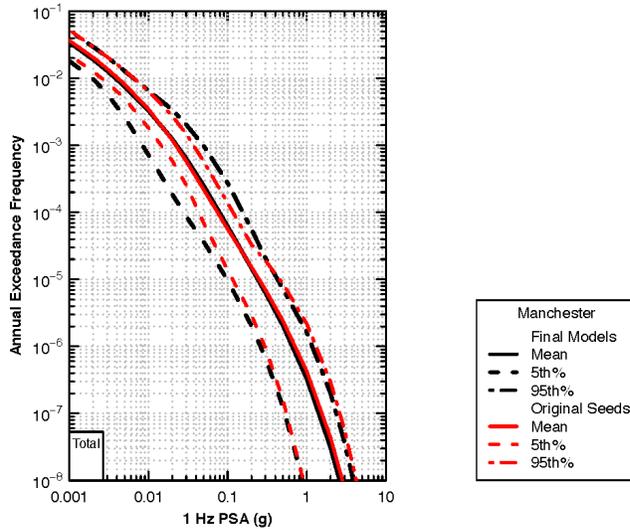

Figure 6. Hazard curves from original weighted seed GMMs using as-is distance measures (R_{JB} or R_{RUP}) and from the final NGA-East GMMs at the Manchester site, 1 Hz. Standard deviation model used is the single branch mean ergodic total sigma. Note in this case a slight difference in mean hazard, but a widening in the epistemic range of ground motions for the final GMMs relative to the seed GMMs.

CONCLUSIONS

NGA-East was a large multidisciplinary community-based research initiative to develop a comprehensive ground-motion database and multiple GMMs for CENA for hard-rock conditions. The final GMC models is applicable to the large CENA region that spans Canada and the USA east of the Rockies. The model provides of RotD$_{50}$ horizontal ground motions for PGA, PGV, and 5%-damped PSA for oscillator frequencies ranging from 0.1 to 100 Hz (periods from 0.01 to 10 sec) on "hard-rock" sites located up to 1500 km from future earthquakes in CENA with moment magnitudes in the 4.0–8.2 range. The model includes 17 median GMMs and alternate standard deviation models with the epistemic uncertainty for both sets captured through logic trees. Additional features not discussed in this paper include models to include source depth effects, hanging-wall effects and a modification of attenuation for the GCR. In addition to the final GMC, NGA-East developed a number of products, including a comprehensive and publicly-available database of CENA ground motion recordings.

ACKNOWLEDGMENTS

REFERENCES

[1] Goulet, C.A., Y. Bozorgnia, N.A. Abrahamson, N. Kuehn, L. Al Atik, R.R. Youngs, and R.W. Graves (2018). "Central and Eastern North America Gound-Motion Characterization - NGA-East Final Report", *PEER Report No. 2018/08*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[2] Budnitz, R.J., G. Apostolakis, D.M. Boore, L.S. Clu, K.J. Coppersmith, C.A. Cornell, and P.A. Morris (1997). "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts." *Report NUREG/CR-6372*, U.S. Nuclear Regulatory Commission, Washington D.C.

[3] NRC (2012). "Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies." *Technical Report NUREG-2117*, U.S. Nuclear Regulatory Commission, Washington D.C.

[4] Goulet, C.A., T. Kishida, T.D. Ancheta, C.H. Cramer, R.B. Darragh, W.J. Silva, Y.M.A Hashash, J. Harmon, J.P. Stewart, K.E. Wooddell, and R.R. Youngs (2014). "PEER NGA-East Database." *PEER Report No. 2014/17*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[5] Dreiling, J., M.P. Isken, W.D. Mooney, M.C. Chapman, and R.W. Godbee (2014). "NGA-East Regionalization Report: Comparison of Four Crustal Regions within Central and Eastern North America using Waveform Modeling and 5%-Damped Pseudo-Spectral Acceleration Response." *PEER Report No. 2014/15*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[6] Hashash, Y.M.A, A.R. Kottke, J.P. Stewart, K.W. Campbell, B. Kim, E.M. Rathje, and W.J. Silva (2014). Reference-Rock Site Conditions for Central and Eastern North America: Part I - Velocity Definition." *PEER Report No. 2014/11*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[7] Campbell, K.W., Y.M.A. Hashash, B. Kim, A.R. Kottke, E.M. Rathje, W.J. Silva, and J.P. Stewart (2014). "Reference-Rock Site Conditions for Central and Eastern North America: Part II – Attenuation Definition." *PEER Report No. 2014/12*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[8] Hashash, Y.M.A., A.R. Kottke, J.P. Stewart, K.W. Campbell, B. Kim, E.M. Rathje, and W.J. Silva (2014). "Reference Rock Site Condition for Central and Eastern North America." *Bull. Seismol. Soc. Am.,* 104: 684–701.

[9] Goulet, C.A., N.A. Abrahamson, P.G. Somerville, and K.E. Wooddell (2014). "The SCEC Broadband Platform Validation Exercise: Methodology for Code Validation in the Context of Seismic-Hazard Analyses." *Seismol. Res. Lett.,* 86 (1): 17–26.

[10] Dreger, D.S., G.C. Beroza, S.M. Day, C.A. Goulet, T.H. Jordan, P.A. Spudich, and J.P. Stewart. (2014). "Validation of the SCEC Broadband Platform V14.3 Simulation Methods using Pseudospectral Acceleration Data." *Seismol. Res. Lett.,* 86 (1): 39–47.

[11] PEER (2015). "NGA-East: Median Ground-Motion Models for the Central and Eastern North America Region." *PEER Report No. 2015/04*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[12] PEER (2015). "NGA-East: Adjustments to Median Ground-Motion Models for Central and Eastern North America." *PEER Report No. 2015/08*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[13] Al Atik, L. (2015). "NGA-East: Ground Motion Standard Deviation Models for Central and Eastern North America." *PEER Report No. 2015/07*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[14] Somerville, P.G. (2014). "Scaling Relations between Seismic Moment and Rupture Area of Earthquakes in Stable Continental Regions." *PEER Report No. 2014/14*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[15] Boore, D.M. (2015). "Adjusting Ground-Motion Intensity Measures to a Reference Site for which V_{S30} = 3000 m/sec," *PEER Report No. 2015/06*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[16] Stewart, J.P., G.A. Parker, J.P. Harmon, G.M. Atkinson, D.M. Boore, R.B. Darragh, W.J. Silva, and Y.M.A. Hashash (2017). "Expert Panel Recommendations for Ergodic Site Amplification in Central and Eastern North America", *PEER Report No. 2015/04*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[17] Hashash, Y.M.A, J.A. Harmon, O. Ilhan, G.A. Parker, and J.P. Stewart (2017). "Recommendations for Ergodic Nonlinear Site Amplification in Central and Eastern North America.", *PEER Report No. 2015/05*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

[18] Boore, D.M. (2010). "Orientation-Independent, Nongeometric-Mean Measures of Seismic Intensity from Two Horizontal Components of Motion." *Bull. Seismol. Soc. Am.*, 100(4): 1830–1835.

[19] EPRI. 2013. "EPRI 2004-2006 Ground-Motion Model (GMM) Review Project 3002000717." Final Report. June 2013, Electric Power Research Institute, Palo Alto, CA.

[20] Scherbaum, F., N.M. Kuehn, M. Ohrnberger, and K. Koehler. (2010). "Exploring the Proximity of Ground-Motion Models Using High-Dimensional Visualization Techniques." *Earthq. Spectra*, 26(4): 1117–1138.

[21] Sammon, J.W. (1969). "A Nonlinear Mapping for Data Structure Analysis." *Trans. Comp.* C13(5): 401-409