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NRC Staff Evaluation of the Next Generation Attenuation for Central and Eastern North America Project (NGA-EAST) Ground Motion Model Characterization

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Research Information Letter
Office of Nuclear Regulatory Research

DISCLAIMER

FOREWORD

This research information letter (RIL) is in response to the New Reactor Office, Division of Licensing, Siting and Environmental Analysis' (DLSE)[1] request to the Office of Research (RES), Division of Engineering (DE) for technical assistance in the review of the Next Generation Attenuation for Central and Eastern North America Project (NGA-East) Ground Motion Characterization Model (GMC) (ML19037A460). This RIL documents the review of the NGA-East GMC model by RES staff to ensure that the model is suitable for siting evaluations of nuclear power plants in the central and eastern United States (CEUS). This report summarizes the recently published NGA-East GMC model and describes details of the sensitivity analyses performed by RES staff in order to support the licensing office's decision to endorse and justify the adequacy and technical accuracy of the new GMC model.

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[1] The Division of Licensing, Siting and Environmental Analysis was previously part of the NRC's Office of New Reactors (NRO) and is now part of the Office of Nuclear Reactor Regulation (NRR) known as the Division of Engineering and External Events (DEX).

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ABBREVIATIONS AND ACRONYMS

CENA	Central and Eastern North America
DOE	Department of Energy
EPRI	Electric Power Research Institute
GMC	ground motion characterization
GMM	ground motion model
GP	Gaussian process
$\boldsymbol{M}$	moment magnitude
MECE	mutually exclusive collectively exhaustive
NRC	Nuclear Regulatory Commission
PGA	peak ground acceleration
PGV	peak ground velocity
PPRP	participatory peer review panel
PSHA	probabilistic seismic hazard analysis
RIL	research information letter
$\boldsymbol{R}_{RUP}$	rupture distance
SSC	seismic source characterization
SSHAC	Senior Seismic Hazard Analysis Committee
USGS	United States Geological Survey

EXECUTIVE SUMMARY

The Central and Eastern North America Ground-Motion Characterization Model is the final product of the next Generation Attenuation for Central and Eastern North America (NGA-East) project. NGA-East was a 10-year multidisciplinary project initiated in 2008 and coordinated by the Pacific Earthquake Engineering Research Center at the University of California and jointly sponsored by the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI), and the U.S. Geological Survey (USGS). The NGA-East Project was conducted in a manner consistent with the Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 framework to develop a new ground-motion characterization (GMC) model to be used in probabilistic seismic hazard analyses (PSHAs) for Central and Eastern North America (CEUS).

In February 2019 the Division of Licensing, Siting and Environmental Analysis (DLSE)[1], Office of New Reactors, requested technical assistance from the Office of Research (RES), Division of Engineering (DE) for the review of the NGA-East GMC model (ML19037A460). RES staff, in conjunction with then the NRO staff, first studied the NGA-East report to determine both the technical adequacy of the model and how well the development of the model satisfied the objectives and requirements for a SSHAC Level 3 study. Upon completion of this review, RES staff determined that, due to the uniqueness and complexity of the resulting GMC model, certain analyses should be performed to both validate the unique approaches used in the development of the median and standard deviation ground motion model(s) and inform the regulatory staff on the stability of the new GMC model.

This report provides a summary of the NGA-East report along with detailed description of the GMC model development and highlights the sensitivity analyses performed by the staff on the unique approaches used in estimating the median GMC models and their standard deviations. The results of the sensitivity analyses performed by the staff show that the NGA-East GMC model is robust and captures the epistemic uncertainty in ground motions for the CEUS and that the model captures the center, body, and range of technically defensible interpretations as prescribed by the SSHAC process. Furthermore, the staff's sensitivity analyses demonstrate that the NGA-East GMC model provides regulatory stability for siting evaluations of nuclear facilities in the central and eastern United States (CEUS).

1 Introduction

10 CFR 100.23, paragraph (d)(1), “Determination of the Safe Shutdown Earthquake Ground Motion,” requires that uncertainty inherent in estimates of the SSE be addressed through an appropriate analysis, such as a probabilistic seismic hazard analysis (PSHA). A PSHA has been identified in 10 CFR 100.23 as a means to address the uncertainties inherent in the determination of the SSE. Furthermore, the rule recognizes the nature of uncertainty and the need to account for uncertainties. The NRC has previously recognized the influence of subjective, expert judgement on the results of PSHA studies and proposed methodologies for addressing the potential biases that exist in expert judgement as captured in the report of the Senior Seismic Hazard Analysis Committee (SSHAC) (NUREG/CR-6372 and NUREG-2117).

The Next Generation Attenuation for Central and Eastern North America (NGA-East) project was a multidisciplinary research effort led by the Pacific Earthquake Engineering Research Center (PEER), at the University of California and jointly sponsored by the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI), and the U.S. Geological Survey (USGS). The project extended over a 10-year time period.

The objective of the NGA-East project was to develop a new ground-motion characterization model (GMC) for Central and Eastern North America (CENA) to inform probabilistic seismic hazard analyses (PSHA) conducted in this region. The GMC model consists of a set of new ground-motion models (GMMs) for the median and standard deviation of predicted ground motions and their associated weights to be used in PSHAs for seismic hazard characterizations of critical facilities.

The NGA-East project had two components: (1) a set of scientific research tasks, and (2) a model-building component which followed the framework of the Seismic Senior Hazard Analysis Committee (SSHAC) Level 3 (NUREG/CR-6372 and NUREG-2117). Under component (1), several scientific issues were addressed, including:

a) Development of a new database of ground motion data recorded in CENA

b) Development of a regionalized ground-motion map for CENA

c) Definition of the reference site condition

d) Simulations of ground motions based on different methodologies

e) Development of candidate GMMs for CENA.

The scientific tasks of NGA-East were documented as a series of PEER reports (https://peer.berkeley.edu/research/nga-east/products). The scope of component (2) of NGA-East was to develop the complete GMC model. This later component was conducted as a SSHAC Level 3 study (NUREG-2117) with the goal of capturing the center, body, and range of the technically defensible interpretations in light of the available data and models. The SSHAC process involved four key tasks: evaluation and integration by the technical integration (TI) team, formal review by the Participatory Peer Review Panel (PPRP), and documentation of the final SSHAC report (https://peer.berkeley.edu/news/new-peer-report-201808-central-and-eastern-north-america-ground-motion-characterization-nga).

The final NGA-East GMC model includes a set of 17 median GMMs for the horizontal component of ground motion (5%-damped pseudo-acceleration response spectra) for 23 oscillator periods between 0.01 and 10 seconds as well as peak ground acceleration and peak ground velocity (PGA and PGV). The median GMMs predict spectral acceleration values as a function of earthquake magnitude and source-to-site distances and are applicable to hard-rock sites in CENA in the moment magnitude range of 4.0 to 8.2 and covering source-to-site distances up to 1500 km. Standard deviation models for each of the spectral periods, which depend on earthquake magnitude, are also provided for site-specific analysis (single-station standard deviation) and for general PSHA applications (ergodic standard deviation). Adjustment factors are provided for source-depth effects and hanging-wall effects, as well as for hazard computations at sites in the Gulf Coast region.

The purpose of this report is to support the request for technical assistance (ML19037A460) in the review of the Next Generation Attenuation for Central and Eastern North America (NGA-East) Ground Motion Characterization Project. This report provides a summary of the NGA-East report along with a description of the GMC model development and highlights the sensitivity analyses performed by the RES staff on the unique approaches used in NGA-East for the median and standard deviation GMMs. This report is comprised of 5 sections: Section 1 introduces the NGA-East project. Section 2 summarizes the content of the NGA-East final report. Section 3 details the median and standard deviation GMC models developed by the NGA-East project. Section 4 describes the sensitivity analyses performed to validate the appropriateness of the unique approaches used in the development of the median GMC model. Finally, Section 5 summarizes the staff’s conclusions.

2 Summary of the NGA-East Report

The final NGA-East project report contains 14 chapters, which are briefly summarized below.

- Chapter 1 provides an overview of the NGA-East project, its objectives and limitations, and describes the relationship of the science-based component and the formal SSHAC Level 3 study. This chapter formally defines: the geographic limits of the Study Region (Central and Eastern North America or CENA), reference site conditions, the magnitude and distance range of applicability, the ground motion intensity measures of interest, and the interface with the Central Eastern U.S. Seismic Source Characterization (CEUS-SSC) model (NUREG-2115).

- Chapter 2 provides a brief overview of the SSHAC process (NUREG/CR-6372 and NUREG-2117), the organization of the NGA-East project under the SSHAC Level 3 framework as well as the various participants in the studies. Additional detail is provided in the Project Plan (Goulet et al. 2011).

- Chapter 3 provides a summary of the CEUS-SSC model and describes the basis for selection of the range of magnitudes and distances for which the NGA-East GMC and the individual GMMs were developed. This chapter also describes the existing EPRI (2013) GMM model which was considered as part of the SSHAC evaluation process.

- Chapter 4 presents an overview of the investigations conducted to assess the need for regionalization of ground motions and near-surface attenuation within the CENA project area. Several proponent regionalization models are summarized and evaluated (PEER Report Nos. 2014-12 and 2014-15).

- Chapter 5 summarizes the databases available for the NGA-East project. A key component of the chapter is to summarize the development of the empirical NGA-East ground-motion database of events recorded in CENA. The NGA-East database was used by numerous working groups, and individual researchers and practitioners who worked on various aspects of the NGA-East project. The chapter also summarizes the NGA-West2 global database as well as a database of ground motion simulations, which were made available to the NGA-East researchers and participants. A key conclusion of the database development process was that the available data for CENA is very limited for hazard significant magnitude and distance ranges and is also limited in frequency.

- Chapter 6 presents a summary of the conceptual methodology used by the NGA-East project for capturing the epistemic uncertainty in ground-motion characterization in CENA. It begins by summarizing the approaches used to capture epistemic uncertainty in a number of recent state-of-the-art studies. It then summarizes the process selected for quantifying the epistemic uncertainty in the median ground motion estimate (an essential part of the SSHAC process). This is described in more detail in Section 3 of the present report as part of the RES staff confirmatory analyses.

- Chapter 7 describes the evaluation of existing GMPEs that were considered for use for the next step as “seed” GMMs in populating the median ground-motion space. The NGA-East TI Team concluded that none of the existing GMPEs were appropriate for use the project. This resulted in the development of new GMMs some of which were developed by the members of the NGA-East GMM working group, others by invited experts (documented in PEER Reports Nos. 2015-04 and -08). Site correction issues are also discussed in this chapter.

- Chapter 8 elaborates on the process involved in the three steps in the NGA-East methodology, (a) development of continuous distributions of GMM using the "seed" models from Chapter 7, (b) visualization of the ground-motion space via Sammon's maps (Sammon 1969), and (c) re-discretization of the ground-motion space.

- Chapter 9 describes development of the median ground-motion logic tree, which consists of 17 branches, each corresponding to a unique GMM. This chapter describes the development of, and results for, the weights of the final 17 median models.

- Chapter 10 presents the current framework for characterizing the aleatory variability in observed ground motions. The chapter describes how the total aleatory variability can be decomposed into event-to-event and site-to-site variability. This facilitates the development of a partially non-ergodic aleatory variability term if a site-specific ground response analysis is to be performed. Application of this approach prevents the double-counting of the variability due to inclusion of the site-to-site variability in hazard calculations. The section then reviews and evaluates candidate proponent ground-motion aleatory variability models and provides the framework used to develop standard deviation models for CENA. In addition to evaluating existing aleatory variability models based on global data, the project developed a new, CENA-specific candidate aleatory variability model based on the NGA-East CENA database.

- Chapter 11 presents the integration of the candidate models for the between event variability, the single-station within-event variability, and the site-to-site variability (τ, ϕ_{SS}, and ϕ_{S2S}, respectively). Logic trees are then developed for each of τ, ϕ_{SS}, and ϕ_{S2S}, from which either fully ergodic or partially non-ergodic aleatory variability terms can then be derived. The basis for the resulting weights in each logic tree are then presented. Based on the potential complexity in hazard calculations due to the number of branches in the logic trees, a simplified representation of the trees is then developed.

- Chapter 12 compares PSHA results for seven test sites using the NGA-East GMC as compared to those computed using the EPRI (2013) GMC. Additionally, the EPRI (2013) GMMs were used as "seed" models for the NGA-East methodology and the resulting GMMs were then compared with those of the NGA-East GMC and EPRI (2013).

- Chapter 13 presents the development of adjustment models to be applied to the 17-final median GMMs to address: (1) adjustments for the Gulf Coast region and (2) source-depth adjustments; and discusses hanging-wall adjustments.

- Chapter 14 presents the implementation of the Gulf Coast Region and source-depth effects in PSHA calculations, provides implementation guidance for practitioners, and compares PSHA results computed with the full NGA-East GMM to those computed using the EPRI (2013) GMM for several test sites.

- Appendices: A number of appendices are used to further document the work described in the various chapters. Of particular interest to the NRC staff were (i) Appendix A which documented the interactions between the TI Team and the PPRP, and the PPRP comments on various workshops as well as on the final report, and (ii) Appendix H which contains the Hazard Input Document or HID which contains relevant results in tabular format as well as guidance on implementation of the model.

3 Median and Standard Deviation Ground Motion Characterization

The epistemic uncertainty in median ground motions is often the largest contributor to the total epistemic uncertainty in probabilistic seismic hazard analyses (PSHA). In past practice, the epistemic uncertainty in future ground motions has been captured using a number of alternative ground motion models (GMMs) with weights applied (often based on subjective judgements). Typically, a logic tree is used to propagate the alternative GMMs into the PSHA calculations to produce a suite of weighted hazard curves which are then used to compute the mean hazard and fractiles.

As described in Section 6.2 of the NGA-East report, the mathematical formulation behind the logic-tree representation uses the axioms of probability such that, at a node of the tree, each branch must contribute information that aims to, at least conceptually, make the set of branches at that node mutually exclusive and collectively exhaustive (MECE). However, adherence to MECE is problematic. Alternative GMMs derived from overlapping datasets using similar conceptual models results in model redundancy that violates the mutually exclusive condition (Bommer and Scherbaum 2008). The collectively exhaustive condition is violated due to a finite number of GMMs used to capture the ground motion distribution resulting in intermediate ground motion amplitudes being artificially excluded and the unjustified exclusion of tail values from the ground motion distribution. Thus, the epistemic uncertainty in median ground motions may not necessarily be fully captured. To overcome this, the technical integration (TI) team of the NGA-East project elected to capture the median ground motions through discrete sampling of a multi-dimensional, continuous ground motion space in order to capture the center, body and range of technically defensible interpretations consistent with the objective of NUREG 2117.The following subsections outline the approaches used in NGA East for the above-mentioned median and standard deviation ground motion models for a better understanding of sensitivity analyses performed by RES staff in Section 4 of this report.

3.1 Parameters for a Continuous Distribution of Ground-Motion Models

The NGA-East approach to median ground motions is based on the principle that their associated epistemic uncertainty can be described as a continuous distribution where the general assumption is that both the marginal and conditional distributions are normally distributed. Therefore, the joint distribution of median ground-motion estimates at different magnitude (***M***) and distances between the site and the inferred rupture plane ($\boldsymbol{R}_{RUP}$) scenarios can be modeled as a multivariate normal distribution:

$$P(Y) \sim N(\mu, \Sigma) \quad \text{3-1}$$

Where $Y = \{Y_1, \ldots Y_{N_D}\}$ is a vector of random median ground-motion values for N_D different ($\boldsymbol{M}$,$\boldsymbol{R}_{RUP}$) scenarios, μ is a vector of period dependent expected median values informed by a set of seed GMMs for each ($\boldsymbol{M}$,$\boldsymbol{R}_{RUP}$) scenario, and Σ is the covariance matrix between the median ground-motion estimates at different ***M*** and $\boldsymbol{R}_{RUP}$ scenarios defined as:

$$\Sigma_{i,j} = \rho_{i,j}\sigma_i\sigma_j \quad \text{3-2}$$

Where σ_i and σ_j are the standard deviation of the ground-motion distribution for the i^{th} and j^{th} ($\boldsymbol{M}$, $\boldsymbol{R}_{RUP}$) scenarios and $\rho_{i,j}$ describes the correlation between the i^{th} and j^{th} ($\boldsymbol{M}$, $\boldsymbol{R}_{RUP}$) scenarios. For a sufficiently large number of ($\boldsymbol{M}$, $\boldsymbol{R}_{RUP}$) scenarios, a random sample from Equation 3-1 can be considered a continuous function of ***M*** and $\boldsymbol{R}_{RUP}$ and therefore individual samples selected from

Equation 3-1 are considered representative GMMs. The range of $\boldsymbol{M}$ and $\boldsymbol{R}_{RUP}$ scenarios used in NGA-East are:

$\boldsymbol{M}$ = 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 7.8, 8, 8.2

$\boldsymbol{R}_{RUP}$ = 0,1, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120,130, 140, 150, 175, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800,1000, 1200,1500 km

The above combinations for $\boldsymbol{M}$ and $\boldsymbol{R}_{RUP}$ were selected to capture both the $\boldsymbol{M}$, $\boldsymbol{R}_{RUP}$ scenarios that most influence seismic hazard results and account for the important trends in magnitude and distance scaling as identified in Chapter 1 of the NGA-East Report. For magnitudes less than 7.5 observed ground motions follow a linear trend; therefore, magnitude bins of 0.5 were deemed sufficient. However, for magnitudes above 7.5, the trend in scaling is non-linear therefore, magnitude bin sizes were reduced to capture changes in slope due to magnitude saturation.

The change in observed ground motions with distance is greatest in two zones: 0 km to 50 km where near source saturation and geometric spreading effects are strong and 70 km to 150 km near the Mohorovicic discontinuity (MOHO) bounce. Thus, bin sizes of 10 km or less were selected for distances less than 150 km to capture changes in slope. For distance greater than 150 km, bin sizes were allowed to increase due to trends in distance scaling becoming more linear with increased distance. In total, 374 $\boldsymbol{M}$ and $\boldsymbol{R}_{RUP}$ scenarios inform the covariance matrix in Equation 3-2.

3.2 Visualization of Ground Motion Space

As discussed in Section 3.1 , the joint distribution of median ground-motion estimates at different $\boldsymbol{M}$ and distance $\boldsymbol{R}_{RUP}$ scenarios can be modeled as a multivariate normal distribution. Random samples of Equation 3-1 are a continuous function of $\boldsymbol{M}$ and $\boldsymbol{R}_{RUP}$ and therefore considered to be representative GMMs of the ground motion space. However, the result of randomly sampling Equation 3-1 is multi-dimensional (374 $\boldsymbol{M}$ and $\boldsymbol{R}_{RUP}$ combinations x 19 seed GMMs) and must be projected to two dimensions if discretization of the ground motion space is to be achieved. The TI team's approach to reducing the high dimensional ground motion space to a lower dimension is known as Sammons mapping (Sammon 1969). Sammons mapping is a nonlinear dimension reduction technique that maps the distance distribution of points from a higher dimension to that of a lower dimension by minimizing the Sammons stress E defined as

$$E = \frac{1}{\sum_{i<j} d_{i,j}^{*}} \sum_{i<j} \frac{\left(d_{i,j}^{*} - d_{i,j}\right)^{2}}{d_{i,j}^{*}} \qquad \text{3-3}$$

where $d_{i,j}^{*}$ is the distance between samples i and j in high dimensional space and $d_{i,j}$ is the distance between samples i and j mapped into lower dimensional space. Since random samples from Equation 3-1 are considered representative GMMs, Sammons mapping is used to map the distance distribution of the sampled GMMs in high dimensional space into two dimensions where discretization of the ground motion space can be achieved. Inserting the sampled GMMs into Equation 3-3 results in

$$E = \frac{1}{\sum_{i<j} \Delta_{GM_{i,j}}} \sum_{i<j} \frac{\left(\Delta_{GM_{i,j}} - \Delta_{MAP_{i,j}}\right)^2}{\Delta_{GM_{i,j}}} \qquad 3\text{-}4$$

Where $\Delta_{GM_{i,j}}$ is the difference in the predicted ground motion between sampled GMMs i and j in high dimensional space and $\Delta_{MAP_{i,j}}$ is the difference in predicted ground motion between sampled GMMs i and j in a two-dimensional space.

An example of a Sammons map is shown in Figure 3.1 for 10,000 randomly sampled GMMs (grey dots) from Equation 3-1 projected in two dimensional space where the red dots represent the location in ground motion space of the seed GMMs that informed the distribution of Equation 3-1. The outer ellipse on the map bounds 95% of the ground motion space and is partitioned by two inner rings and linear lines that are used to discretize the ground motion space and discussed further in Section 3.3 . A key observation made from Figure 3.1 is that the range of the ground motion space may not necessarily be fully captured by the seed GMMs alone and if these seed models were used without subsequent sampling of the ground motion space, then the epistemic uncertainty in predicted ground motions would be highly underestimated.

3.3 Discretization of Ground Motion

The projected two-dimensional ground motion space resulting from Sammons mapping, as discussed in Section 3.2 , is a representation of the center, body and range of the ground motion distribution in Equation 3-1. To capture the center, body and range of the ground motion space and develop a finite number of representative GMMs, the TI team chose an ellipse to capture the space. The TI Team chose the size of the ellipse to capture 95% of the ground motion space which approximates a range of two standard deviations for a normal distribution.

In order to discretize the range into a manageable number of representative GMMs, the space inside the range was first partitioned in two smaller ellipses; a center ellipse capturing 10% of the ground motion space and an outer ellipse capturing 75% of the ground motion space. Thus, the final range of ground motion space was partitioned into a central ellipse with two outer rings representing the center, body and range of ground motion estimates. The outer rings were further partitioned by the TI Team into eight cells resulting in the ground motion space being partitioned into a total of 17 cells (Figure 3.1). For each cell, the TI Team determined a median GMM from the population of GMMs (grey dots) that fall within that cell. The result is 17 median models that characterize the center, body and range of the full multidimensional ground motion space at each spectral period as well as PGA and PGV. The TI team investigated several alternative discretization schemes and ultimately decided on the 17-cell structure because it not only provides a manageable number of representative GMMs, it also afforded the TI team to capture the epistemic uncertainty in magnitude and distance scaling inherent in the seed GMMs.

3.4 Standard Deviation Models

In addition to developing 17 median models, the NGA-East TI team developed standard deviation models to be incorporated with the median models. The TI Team decoupled the median GMM from the standard deviation models. This approach has been used for central and eastern North America (CENA) GMMs previously. In 2006, EPRI performed an evaluation of CENA GMM standard deviation models. The EPRI 2006 study concluded that western

United States standard deviation models associated with an active tectonic region were applicable to CENA with some minor modifications. The validity of the TI team decision to decouple the standard deviation model from the median GMM was also confirmed by analyses that showed no correlation between the ground motion standard deviation and the median predicted ground motion. Development of the standard deviation models considered existing CENA models, evaluating the NGA-East CENA ground-motion dataset, and data sets and models from the western U.S and Japan.

CENA GMMs such as the updated EPRI 2004/2006 GMMs (EPRI 2013) employ the ergodic assumption. When employing the ergodic assumption, the standard deviation in ground motion obtained from evaluating data across many sites is used as the standard deviation of ground motion for a specific site over time (Anderson and Brune, 1999). However, applying the ergodic assumption can lead to overestimates in seismic hazard, if the site-specific component of variability is not first removed. Studies over the last 5 to 10 years, such as Rodriguez-Marek et al. 2013 and Rodriguez-Marek et al. 2014, have demonstrated how to remove epistemic uncertainty associated with site specific differences in ground motion amplification from the total ergodic standard deviation. This results in a partially non-ergodic standard deviation. The standard deviation is partially non-ergodic because some epistemic uncertainty associated with source and path effects is still included in the standard deviation. Both ergodic and partially non-ergodic approaches were used in developing the NGA-East standard deviation models. Aleatory variability models were developed for the single-station within-event residual and the between event residual. These standard deviations are denoted as ϕ_{ss} and τ. These standard deviations are combined to obtain the partially non-ergodic single station standard deviation, σ_{SS}. The single-station within-event standard deviation, ϕ_{ss}, does not include the epistemic uncertainty associated with site to site differences in site amplification. When implementing the NGA-East GMM with a partially non-ergodic standard deviation, the GMM must be adjusted using a median site-to-site term, δ_{S2Ss}, along with the epistemic uncertainty in this term which is characterized by the standard deviation ϕ_{S2S}. The δ_{S2Ss} term quantifies the systematic deviation of site-specific ground motion from the event corrected GMM. When developing an ergodic variability model, ϕ_{SS} and ϕ_{S2S} are combined to obtain ϕ.

GMM standard deviations, such as the within-event and between event standard deviations, are obtained as part of the GMM development process. Therefore, a CENA GMM must be used to obtain a standard deviation model from CENA data. The TI team developed a median ground motion model for the sole purpose of evaluating ground motion variability using the CENA data. The TI Team used recordings from sites where at least three events were recorded to obtain ϕ_{SS} and ϕ_{S2S}. These evaluations were limited to a frequency range between 1 and 10 Hz. Analyses were performed with the NGA-West 2 data to obtain single-station within-event and median site-to-site terms and associated standard deviation for sites with V_{S30} ranging from 200 to 600 m/s. Japanese data was used by the TI Team as a basis for adjusting ϕ_{S2S} to hard rock conditions with V_{S30} = 3000 m/s.

Because there is epistemic uncertainty associated with each of the standard deviation terms, A set of logic trees were developed by the TI Team for τ, ϕ_{ss}, and ϕ_{S2S}. These logic trees were combined by the TI Team to obtain an ergodic sigma logic tree. The logic trees generally have a set of branches for the approach used to develop the standard deviation term (e.g. NGA-West/Global standard deviation model) and a set of branches to capture statistical uncertainty. The model logic tree for τ consists of a single branch based on a global model, which is the average of the NGA-West 2 τ models. Statistical uncertainty is then captured from a chi-squared distribution to obtain 5th, central, and 95th percentile τ values. The model logic tree for ϕ_{ss} utilizes a global model and two models based on the analysis of CENA data, magnitude independent and magnitude dependent models. Again, the TI Team used three branches for statistical uncertainty developed from a chi-squared distribution. The model logic tree for ϕ_{S2S} has only one branch based on an evaluation of CENA data and three branches for statistical uncertainty based on a chi-squared distribution. When multiple models are included in the logic tree, the TI Team assigned most of the weight to the global model.

In addition to developing logic trees for the standard deviation terms, a logic tree was also developed by the TI Team to incorporate both log-normal and mixture model distributions with the ground motion model for ergodic and single station standard deviations. Mixture models are used to account for observations that show non-normal distribution of ground motion.

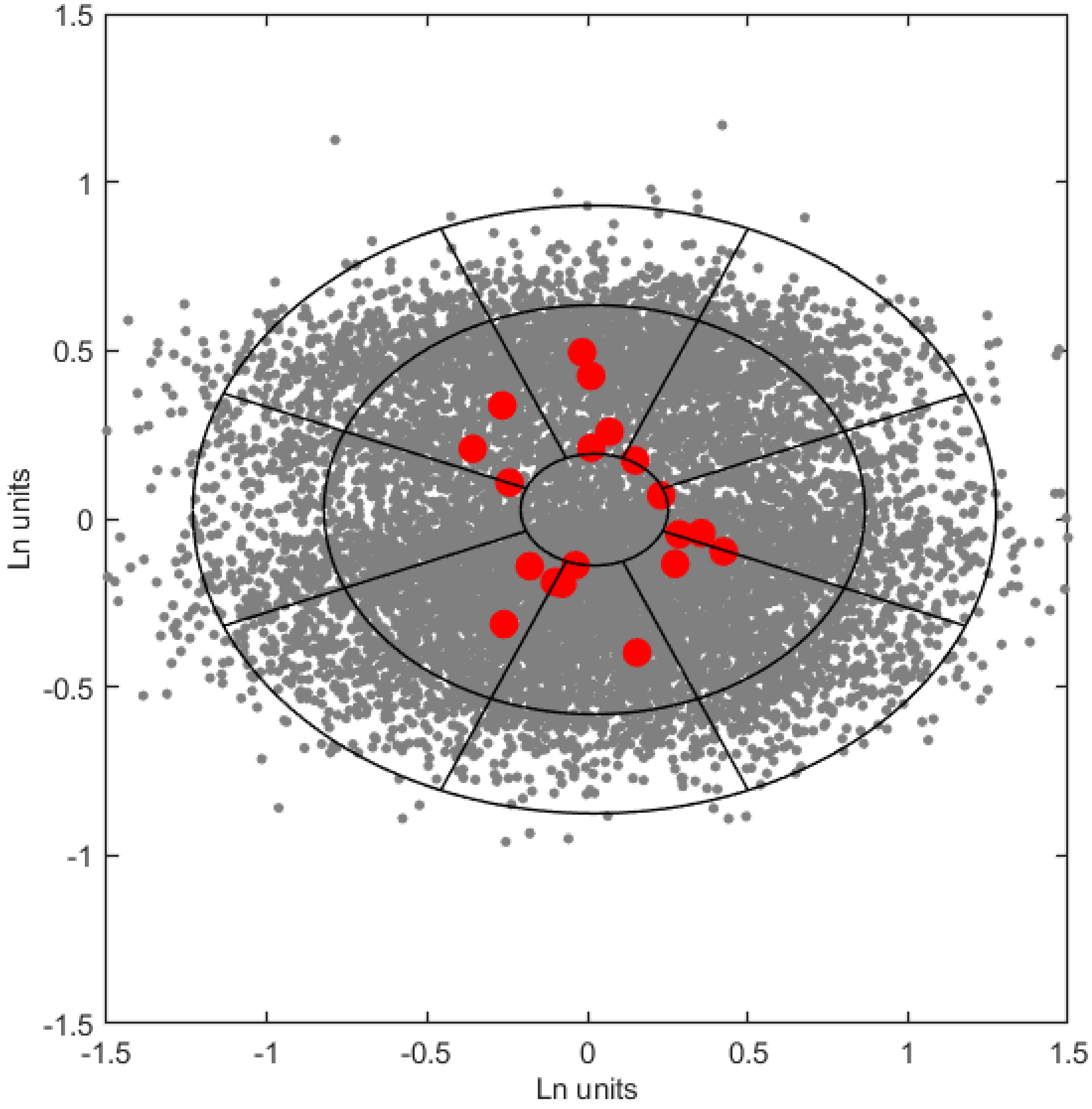

Figure 3.1. Two-dimensional Sammons map of the 5 Hz sampled ground motion space. Each grey dot represents a sampled GMM for all *M* and R_{RUP} scenarios, Red dots represent seed models that informed the ground motion distribution of Equation 3-1 and solid black lines represent the discretized ground motion space where the inner, middle and outer circles capture 10%, 75% and 95% of the ground motion distribution respectively.

4 Sensitivity Analyses Performed on Median GMC Model

The following subsections describe the sensitivity analyses performed by RES Staff on the unique approaches used in NGA-East for characterizing median ground motions estimates. Specifically, analyses were performed to analyze the effects on ground motion distribution from:

- The Gaussian process regression used in defining the ground motion correlation model.
- The selection of magnitude (***M***) and rupture distance ($\boldsymbol{R}_{RUP}$) scenarios used to capture the epistemic uncertainty in median ground motions.
- Updates to and replacement of the seed models that inform GMC model development (Regulatory stability of the NGA-East GMC).

In order to address the above, RES developed computer code to both reproduce the NGA-East GMC model and develop alternative GMC models for its sensitivity analyses. For each of the sensitivity analyses described in the following subsections, the GMC models were developed by the staff using 10,000 random GMMs generated from a multivariate distribution for which Sammons mapping was applied and discretization of the ground motion performed (Section 3). While analyses were performed by the staff at each hazard frequency for all ***M*** and $\boldsymbol{R}_{RUP}$ scenarios, the results shown below are for a small number of frequencies, with magnitudes and distances that commonly have the largest influence on seismic hazard for nuclear power plants.

4.1 Correlation Model

By assuming the median ground motions (in log space) follow a multivariate distribution (Section 3.1), a derivation of the variance and correlation model of Equation 3-2 can be achieved (Section 8.1 of NGA-East) and random models generated to quantify the epistemic uncertainty. However, as described in Section 8.1.2 of the NGA-East report and shown in Figure 5.1 - Figure 5.3 (top left), the correlation between seed GMMs is not smooth over the full range of magnitude and distance pairs. This result can lead to randomly generated models that do not behave in a physically realistic way. To overcome this, the TI Team used Gaussian Process (GP) regression (Rasmussen and Williams. 2006) to model the correlation in Equation 3-2. Figure 5.1 - Figure 5.3 (top) show the correlation of the seed GMMs before and after applying a GP regression (Equation 8-9 of NGA-East). The advantage of applying the GP regression process is that it produces a smoother correlation from which reliable models can be generated. It should be noted that applying a GP regression to the seed GMM correlation model is not necessarily required. Reliable models can be generated using the seed GMM correlation. However, consequences of sampling the seed GMM correlation model are

1. A significantly larger number of generated models are rejected due to not meeting the physicality constraints established by the TI team and described in Section 8.3.2 of NGA-East. Figure 5.1-Figure 5.3 (bottom) show how implementing a Gaussian process regression to the correlation model can greatly reduce the number of models being rejected.

2. A narrowing of the ground motion distribution can occur due to lack of physically realistic models being sampled from the tails of distribution.

What was not clear to RES staff, is whether implementing GP regression on the seed GMM correlation results in a distribution of ground motions consistent with the seed models. Therefore, sensitivity analyses were performed by the RES staff to determine the appropriateness of the GP regression correlation model by comparing the resulting ground motion distributions of the seed GMM correlation model and the GP regressed correlation model. The resulting ground motion distributions using the models in Figure 5.1 - Figure 5.3 are shown in Figure 5.4 - Figure 5.6. No significant change in the mean of the distributions occurs between correlation models; however, there is a slight increase in the variance using the GP regressed correlation model. The increase in variance can be explained by the fact that the GP regressed model is smoother with changes in magnitude and distance. Thus, models generated from samples drawn near the tails of the distribution are more likely to produce physically reliable models. Similar results were found for all magnitude and distance scenarios across all seismic hazard frequencies. As a result, the staff concludes that the TI team's use of Gaussian process regression not only produces ground motion distributions consistent with the seed models but also allows for a broader range of the epistemic uncertainty in ground motion estimates to be captured.

4.2 Selection of Magnitude and Distance Scenarios

Section 8.4 of NGA-East describes the selection of the ***M*** and $\boldsymbol{R}_{RUP}$ scenarios (listed above in Section 3.1) used to capture the epistemic uncertainty in median ground motions. The TI team decided that distances out to 1500 km were required for sites in regions of low seismicity where ground motions from large-distant earthquakes contribute significantly to site hazard. What was not clear to RES staff was if truncating the maximum $\boldsymbol{R}_{RUP}$ distance of 1500 km to a shorter distance typically used in probabilistic seismic hazard analyses (PSHA) for high seismicity zones would affect the resulting ground motion distributions. In other words, was the TI teams decision to use distances out to 1500 km where most GMMs are not necessarily reliable have an adverse effect on the resulting ground motion distributions.

Therefore, RES staff performed sensitivity analyses by truncating the maximum $\boldsymbol{R}_{RUP}$ distance to 800 km and comparing the resulting ground motion distributions to those of the NGA-East maximum $\boldsymbol{R}_{RUP}$ distance of 1500 km. The results show an increase in the variability for the ***M*** 5, $\boldsymbol{R}_{RUP}$ 25 km scenario with the increased variability diminishing with larger $\boldsymbol{R}_{RUP}$ as shown in Figure 5.7-Figure 5.9. The increase in variability with a decrease in $\boldsymbol{R}_{RUP}$ is consistent across all ***M*** and most pronounce for small magnitudes <= 5. This effect can be explained by the combination of a reduction in the number of dimensions sampled and the sparseness of ground motions for larger $\boldsymbol{R}_{RUP}$. The truncation of $\boldsymbol{R}_{RUP}$ results in a multivariate distribution of ground motion with 33 less dimensions to be sampled. This reduction allows for a more refined sampling of the ground motion space that is coupled by higher resolution of ground motions at shorter $\boldsymbol{R}_{RUP}$. RES staff considered the above results and concluded that there would be essentially no impact on the final mean hazard from decreasing the maximum $\boldsymbol{R}_{RUP}$ distance to 800 km. In addition, because only a limited number of the total ***M*** and $\boldsymbol{R}_{RUP}$ scenarios are affected, there will be no significant effects on the resulting epistemic uncertainty in the median ground motions.

4.3 Regulatory Stability

Due to the prolonged effort of the NGA-East project, RES staff was unsure if updating the seed GMMs would significantly change the final 17 median NGA-East GMMs developed by the TI

Team for each spectral period. If updating the seed GMMs had an impact on the final NGA East GMMs, then the regulatory stability of the final models would be a potential issue. Ground motion models applicable to CENA are frequently updated by their developers and the seed GMMs used in the NGA-East GMC where developed prior to the start of the project in 2006.

Traditionally the above-mentioned concerns would be addressed by either simply replacing the existing seed GMMs in the logic tree of a PSHA with their updated/replacement models or simply removing them entirely if they have been determined to be no longer valid. However, due to the unique approaches used by NGA-East for the development of the GMC model (Section 3) it was not clear to RES staff how the ground motion distributions would be effected from changes in the seed GMMs that inform the final GMC model.

Therefore, sensitivity analyses were performed by RES staff using a set of alternative updated seed GMMs in order compare the original NGA-East median models to the models produced using updated seed GMMs. Specifically, RES staff used the original NGA-East seed GMMs with the Graizer model replaced with the updated G16 and G16V2 models and the B04 and BAB95 models removed. For a detailed description of the seed GMMs see Chapter 7 of the NGA-East report.

Figure 5.10 - Figure 5.12 compare the resulting ground motion distributions from both the NGA-East model and the alternative GMC model described above. The results show the distribution of ground motion resulting from the alternative GMC model to be only slightly different from that of the NGA-East model with no significant change in the mean or standard deviation. Similar results were found for all magnitude and distance scenarios across all hazard significant frequencies. As a result, RES Staff is confident in the regulatory stability of the NGA-East GMC for use in future PSHAs for nuclear power plants.

5 Conclusions

The sensitivity analyses described above were performed by RES Staff to address specific issues with the modeling approaches used by the TI Team for developing the NGA East GMC model and, specifically, to determine if the TI Team adequately captured the epistemic uncertainty in median ground motions.

RES Staff expressed concern with the Gaussian Process regression used to smooth the ground motion correlation that informs the selection of the median models. Sensitivity analyses were performed by RES Staff to compare the resulting ground motion distributions from both the seed and GP regressed correlation models. The results show that the GP regression approach used by the TI Team is an effective approach for sampling the ground motion space while preserving the ground motion distribution associated with the seed GMMs (Section 4.1).

RES Staff also expressed concern with the maximum $\boldsymbol{R}_{RUP}$ distance of 1500 km used in the NGA-East GMC compared to shorter distances typically used in PSHAs. The TI team selected the larger distance to account for regions of low seismicity where larger-distant events control hazard. Sensitivity analyses performed by RES Staff compared the ground motion distributions from both the NGA-East GMC model, which uses a maximum $\boldsymbol{R}_{RUP}$ distance of 1500 km, and an alternative GMC model with a maximum $\boldsymbol{R}_{RUP}$ distance of 800 km. The results show that the reduction in the maximum $\boldsymbol{R}_{RUP}$ produces a small increase in ground motion variability for small magnitudes at short distances; however, RES Staff concludes that there would be essentially no impact on the mean hazard since only a limited number of the total $\boldsymbol{M}$ and $\boldsymbol{R}_{RUP}$ scenarios are effected (Section 4.2). Therefore, RES Staff concludes that the NGA-East GMC model is appropriate for regions of both high and low seismicity and that the maximum $\boldsymbol{R}_{RUP}$ distance of 1500 km is not an issue.

Lastly, due to the prolonged effort of the NGA-East project, RES Staff examined the stability of the final NGA-East GMC model by updating the set of seed GMMs to determine the impact on the final median models. Sensitivity analyses performed by RES Staff compared the resulting ground motion distributions using both the NGA-East set of seed models and a set of alternative set of updated seed models. The results show no significant change in the ground motion distributions from the alternative sets of seed GMMs. This result leads RES Staff to conclude that the NGA-East GMC model provides a stable and robust estimate of median ground motions for use in PSHAs for CENA sites.

As a result of RES Staff's confirmatory evaluations performed in this RIL, the NRC now has the ability to continually update the impact of new GMMs on the NGA-East GMC model to determine the viability of the model in the future.

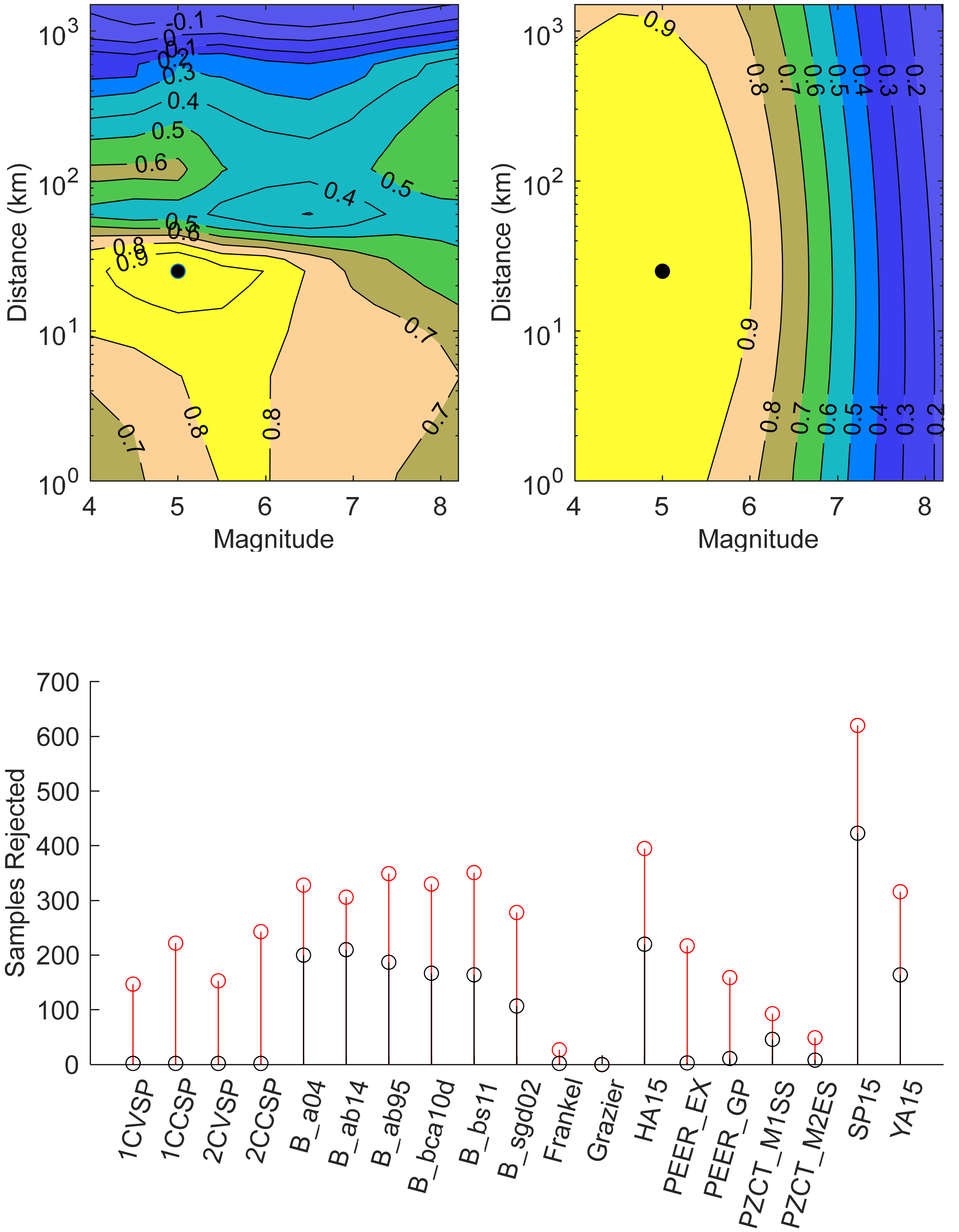

Figure 5.1. PGA Correlation model for Magnitude 5 and rupture distance (*R_{RUP}*) of 25 km. Top left shows correlation resulting from seed models. Top right shows NGA-East modeled correlation. Bottom shows number of models from seed correlation (red) and modeled correlation (black) rejected due to physicality requirements.

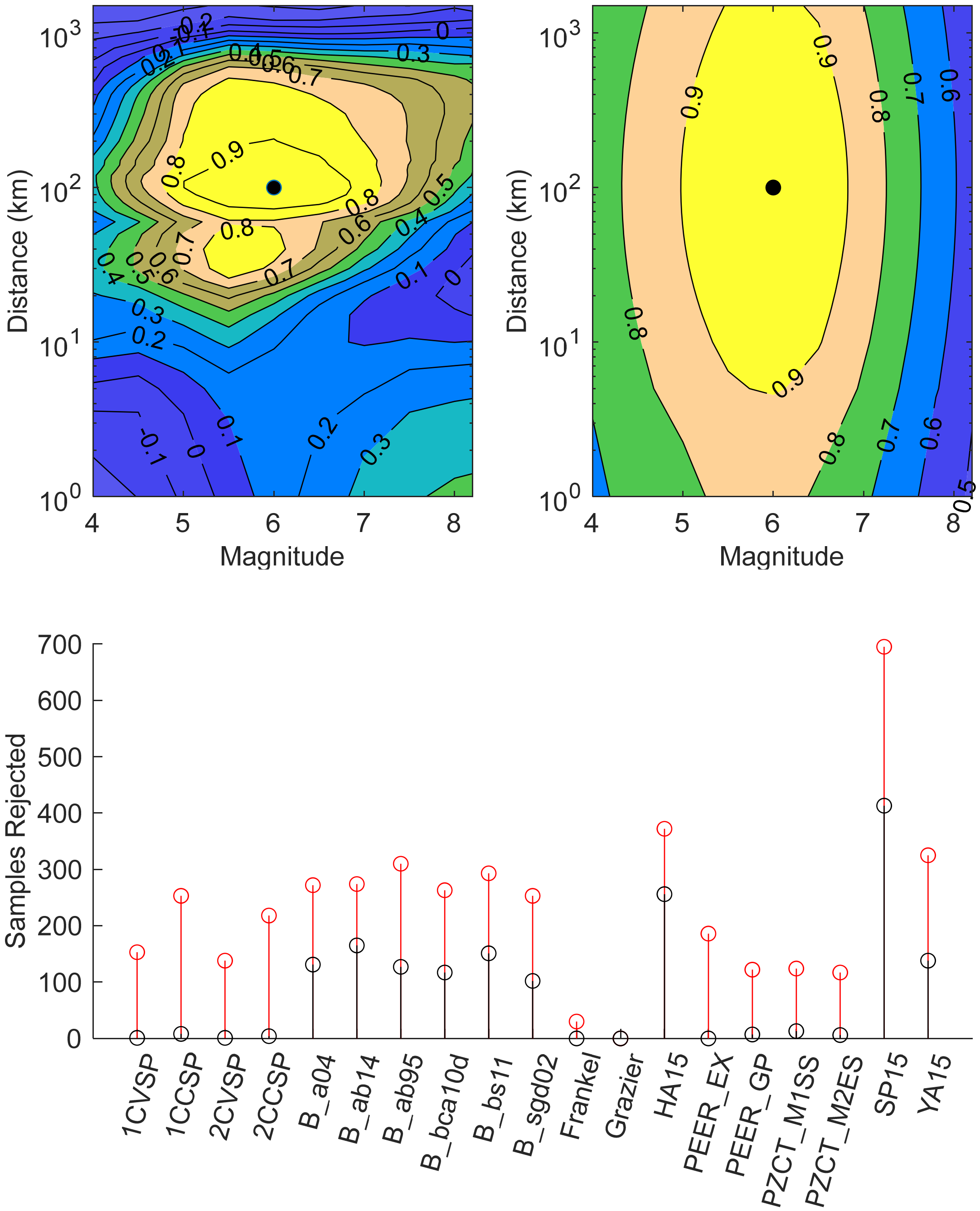

Figure 5.2. 10 Hz Correlation model for Magnitude 6 and rupture distance (*R_{RUP}*) of 100 km. Top left shows correlation resulting from seed models. Top right shows NGA-East modeled correlation. Bottom shows number of models from seed correlation (red) and modeled correlation (black) rejected due to physicality requirements.

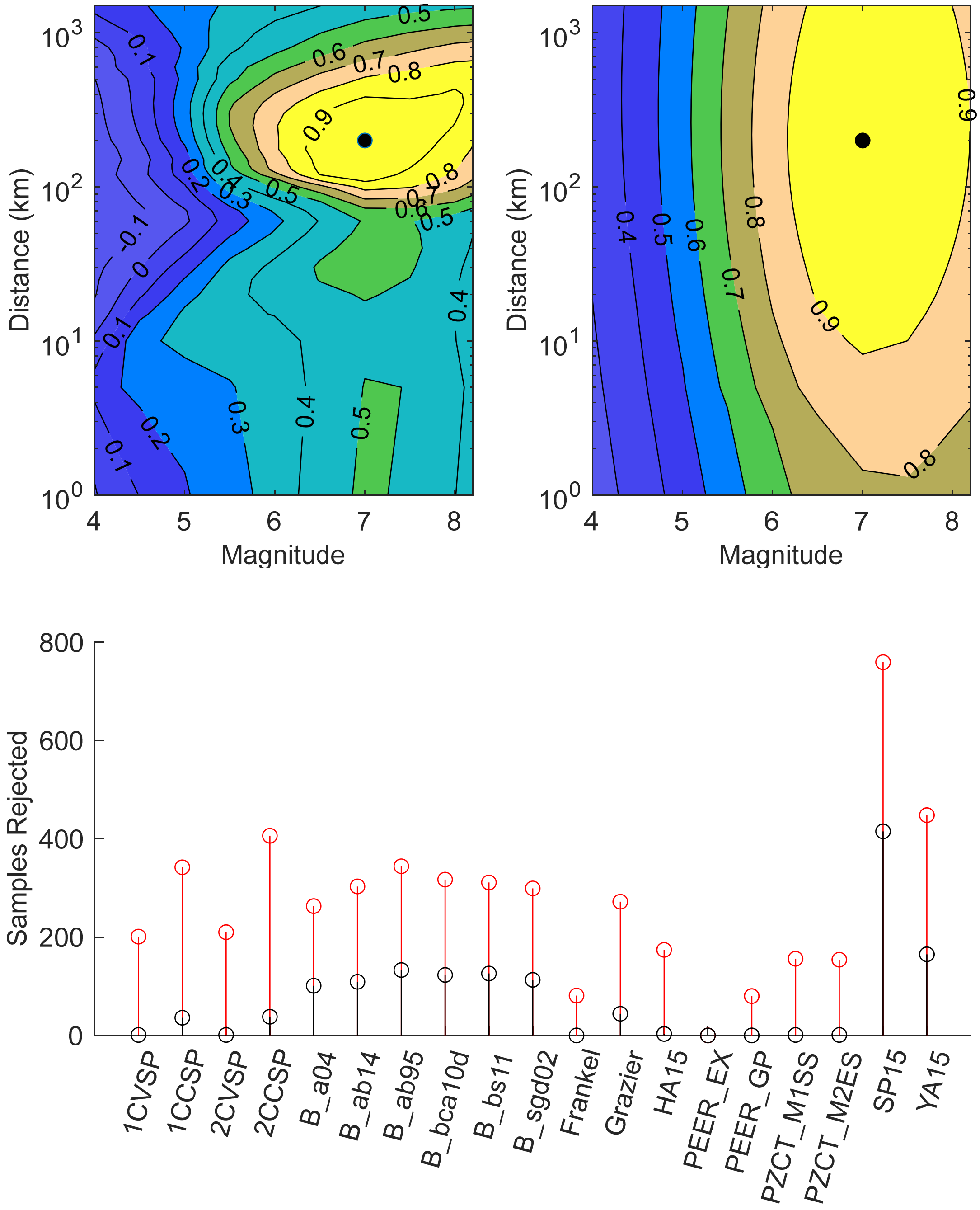

Figure 5.3. 1 Hz Correlation model for Magnitude 7 and rupture distance (R_{RUP}) of 200 km. Top left shows correlation resulting from seed models. Top right shows NGA-East modeled correlation. Bottom shows number of models from seed correlation (red) and modeled correlation (black) rejected due to physicality requirements.

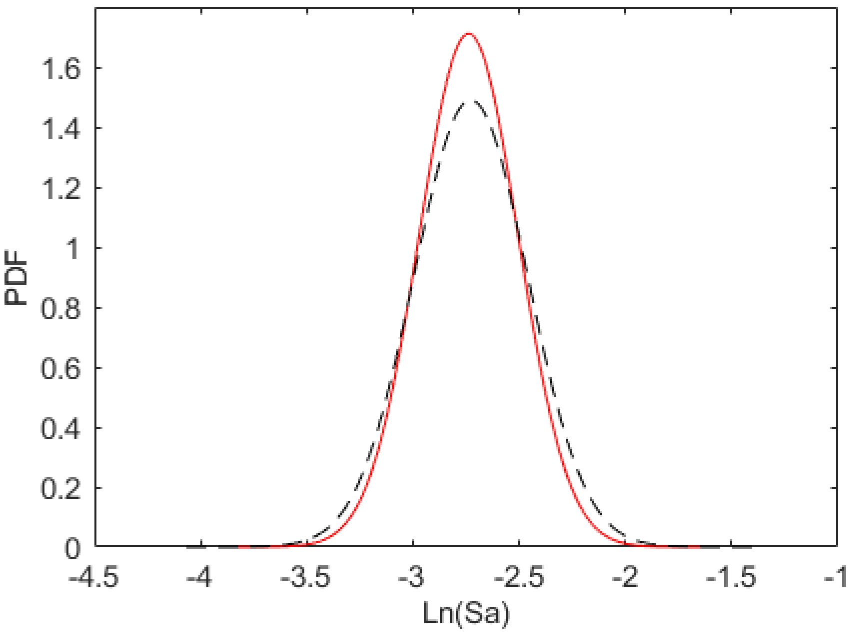

Figure 5.4. Comparison of peak ground motion distributions between seed modeled (red) and GP modeled (black dashed) correlation (M = 5 and R_{RUP} = 25 km)

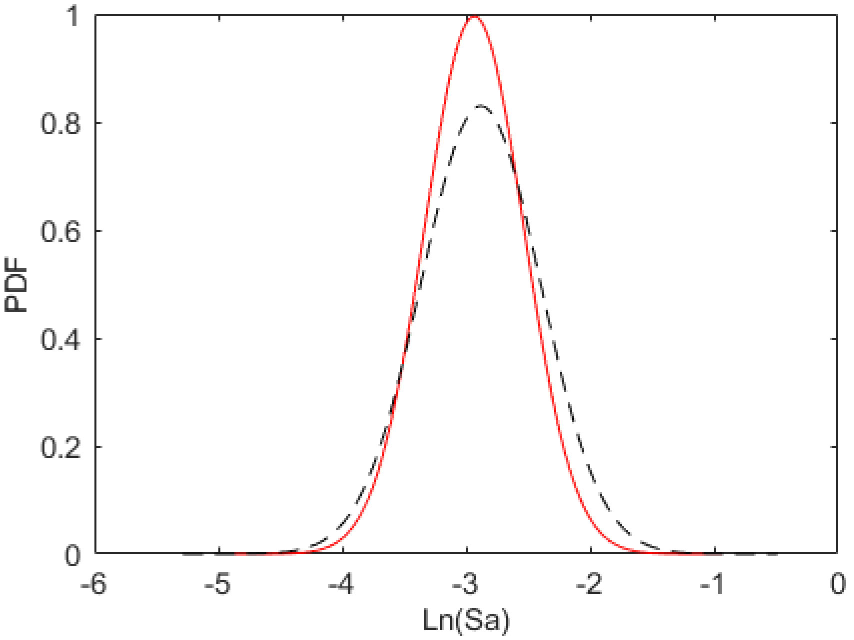

Figure 5.5. Comparison of 10 Hz ground motion distributions between seed model (red) and GP modeled (black dashed) correlation (M = 6 and R_{RUP} = 100 km)

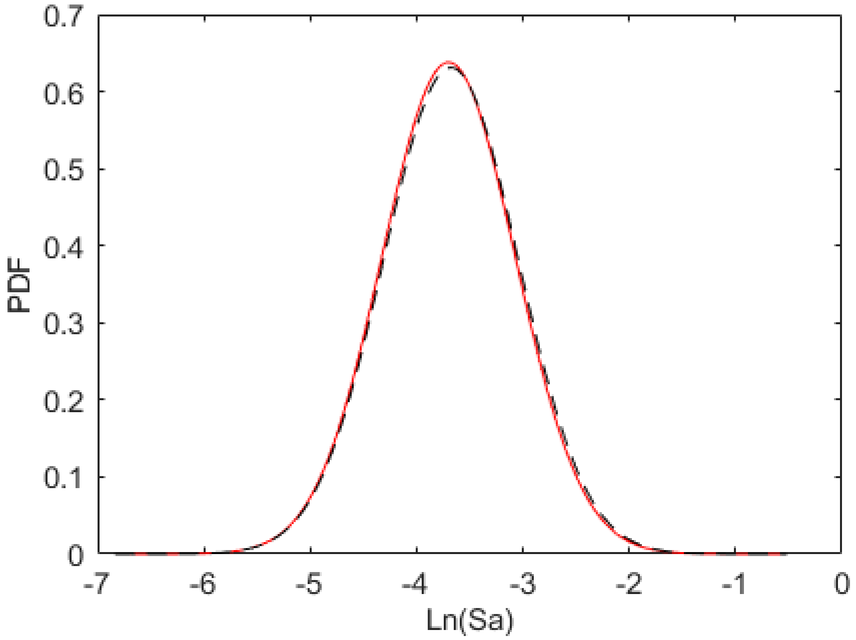

Figure 5.6. Comparison of 1 Hz ground motion distributions between seed model (red) and GP modeled (black dashed) correlation (M = 7 and R_{RUP} = 200 km)

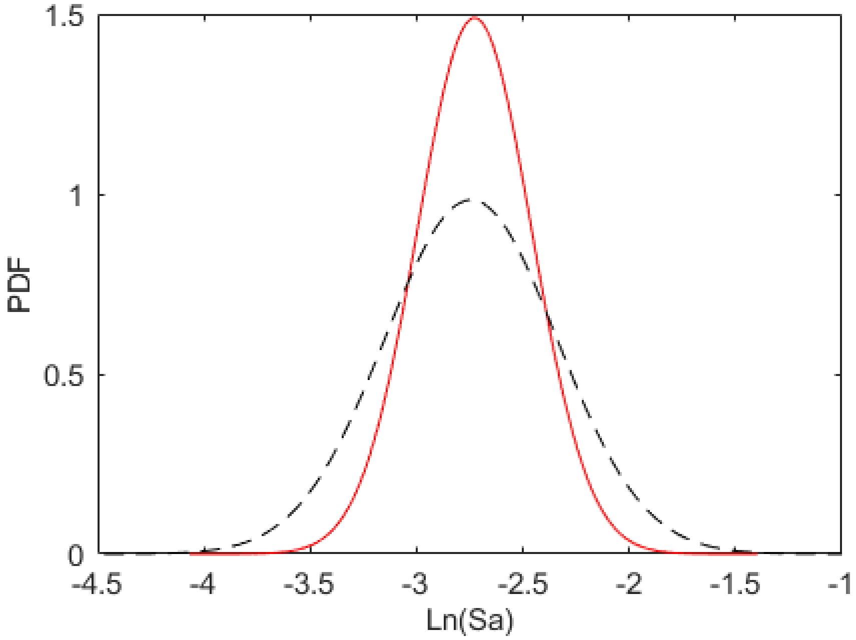

Figure 5.7. Peak ground motion distributions for M = 5 and R_{RUP} = 25 km sampled from multivariate distribution informed by R_{RUP} vector with maximum values of 1500 km (red) and 800 km (black dashed) respectively.

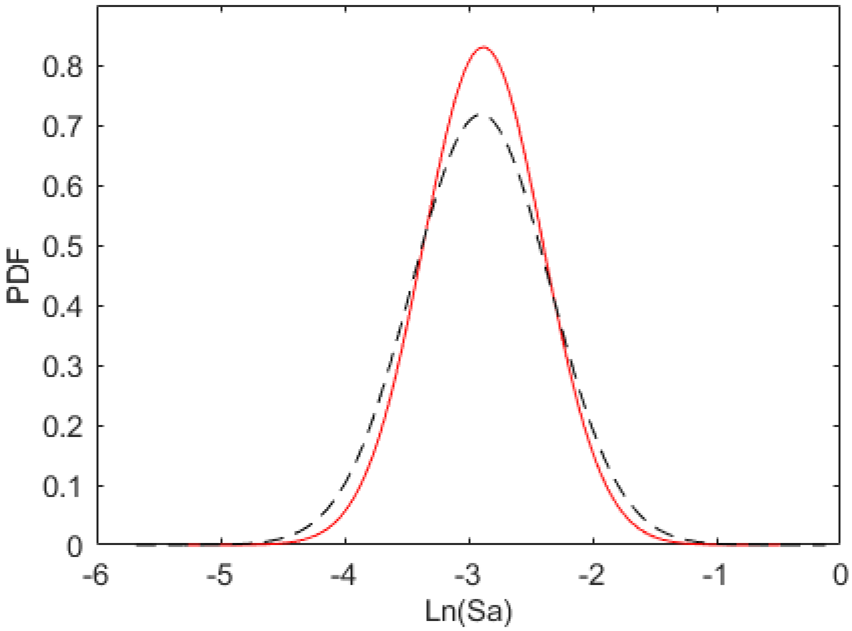

Figure 5.8. 10 Hz ground motion distributions for $M = 6$ and $R_{RUP} = 100$ km sampled from multivariate distribution informed by R_{RUP} vector with maximum values of 1500 km (red) and 800 km (black dashed) respectively

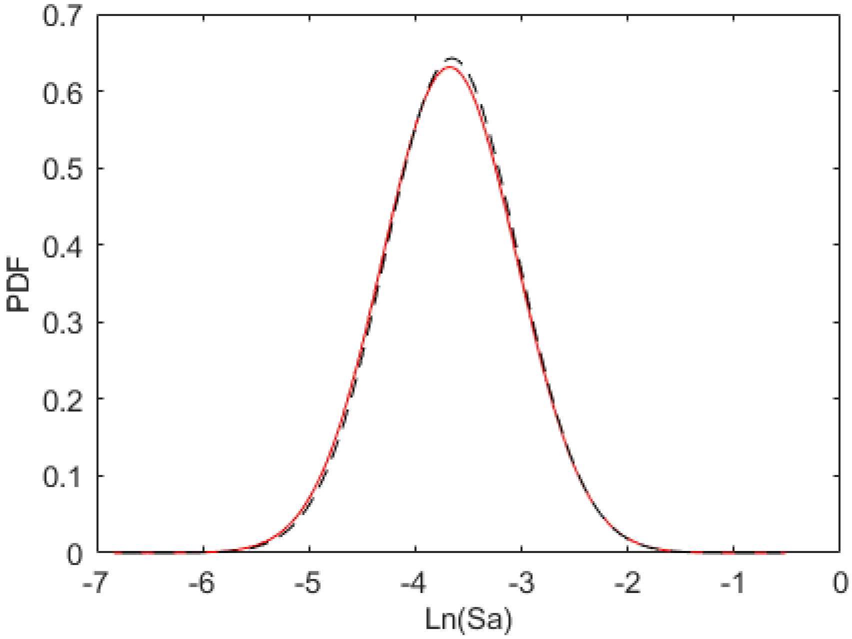

Figure 5.9. 1 Hz ground motion distributions for $M = 7$ and $R_{RUP} = 200$ km sampled from multivariate distribution informed by R_{RUP} vector with maximum values of 1500 km (red) and 800 km (black dashed) respectively

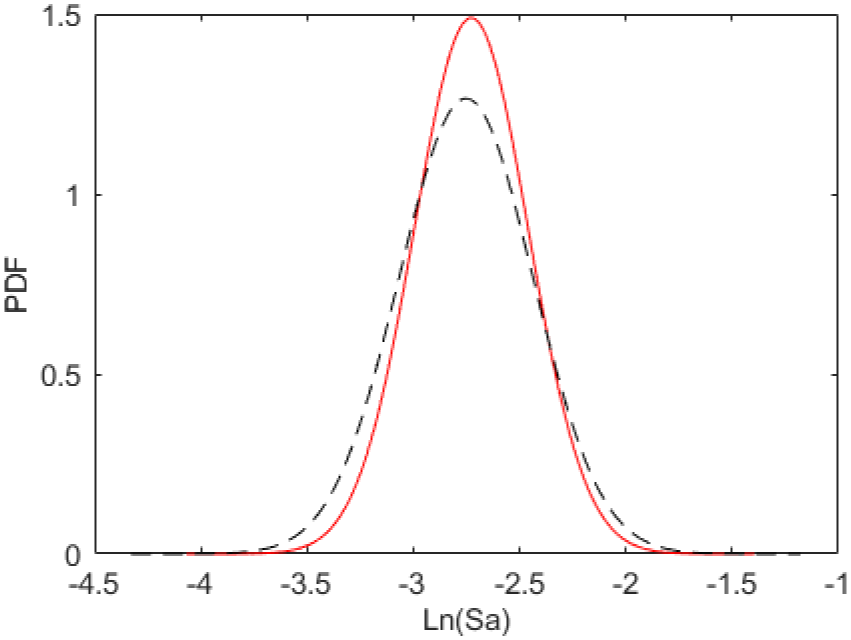

Figure 5.10. Peak ground motion distributions for M = 5 and RRUP = 25 km sampled from multivariate distribution informed by NGA-East seed models (red) and updated/removed models (black dashed) respectively.

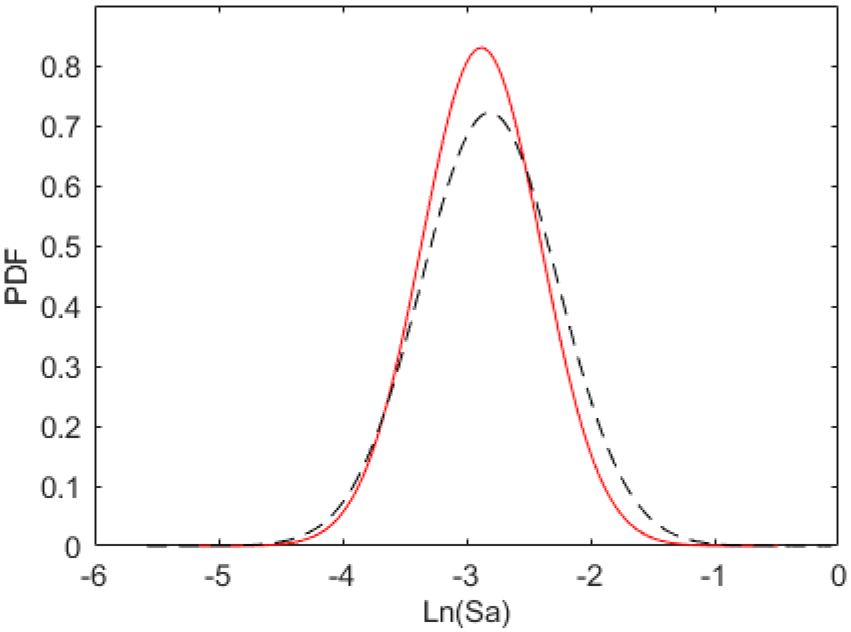

Figure 5.11. 10 Hz ground motion distributions for M = 6 and RRUP = 100 km sampled from multivariate distribution informed by NGA-East seed models (red) and updated/removed models (black dashed) respectively.

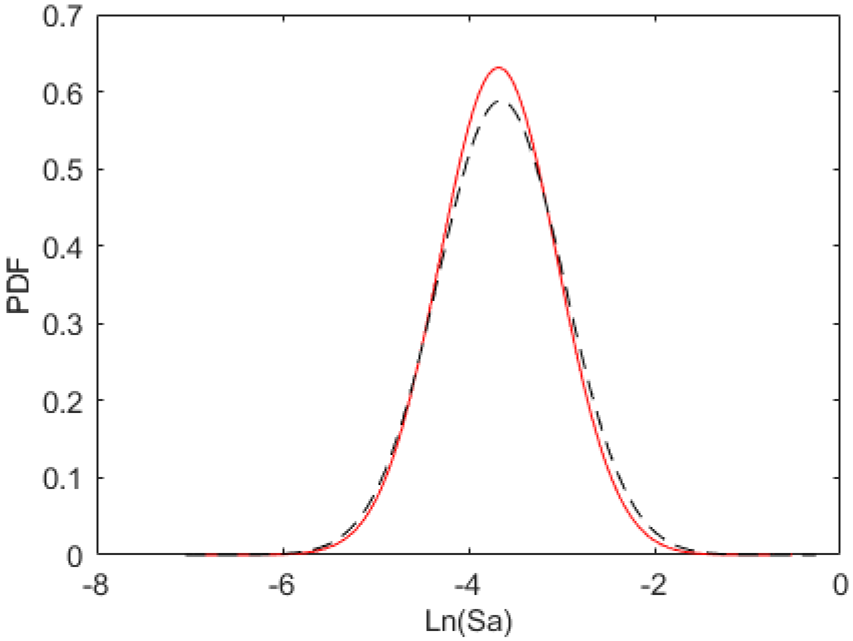

Figure 5.12. 1 Hz ground motion distributions for *M* = 7 and R_{RUP} = 200 km sampled from multivariate distribution informed by NGA-East seed models (red) and updated/removed models (black dashed) respectively.

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