The 2018 update of the US National Seismic Hazard Model: Ground motion models in the central and eastern US



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Abstract

The United States Geological Survey (USGS) National Seismic Hazard Model (NSHM) is the scientific foundation of seismic design regulations in the United States and is regularly updated to consider the best available science and data. The 2018 update of the conterminous US NSHM includes major changes to the underlying ground motion models (GMMs). Most of the changes are motivated by the new multi-period response spectra requirements of seismic design regulations that use hazard results for 22 spectral periods and 8 site classes. In the central and eastern United States (CEUS), the 2018 NSHM incorporates 31 new GMMs for hard-rock site conditions $(V_{sso} = 3000 \text{ m/s})$, including the Next Generation Attenuation (NGA)-East GMMs. New aleatory variability and site-effect models, both specific to the CEUS, are applied to all median hard-rock GMMs. This article documents the changes to the USGS GMM selection criteria and provides details on the new CEUS GMMs used in the 2018 NSHM update. The median GMMs, their weights, epistemic uncertainty, and aleatory variability are compared with those considered in prior NSHMs. This article further provides implementation details on the CEUS site-effect model, which allows conversion of hard-rock ground motions to other site conditions in the CEUS for the first time in NSHMs. Compared with the 2014 NSHM hard-rock ground motions, the weighted average of median GMMs increases for large magnitude events at middle to large distance range, epistemic uncertainty increases in almost all situations, but aleatory variability is not significantly different. Finally, the total effect on hazard is demonstrated for an assumed earthquake source

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model in the CEUS, which shows an increased ring of ground motions in the vicinity of the New Madrid seismic zone and decreased ground motions near the East Tennessee seismic zone.

Keywords

National Seismic Hazard Model, ground motion models, NGA-east, multi-period response spectra, site effects

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Introduction

The National Seismic Hazard Model (NSHM), developed by the United States Geological Survey (USGS) for the United States and its territories, has long been the scientific foundation of seismic design regulations in the United States. Among other applications, in the past several decades these models have been used to compute design ground motions for the National Earthquake Hazard Reduction Program (NEHRP) Recommended Seismic Provisions for New Buildings and Other Structures (NEHRP Provisions, e.g. Building Seismic Safety Council (BSSC), 2015, 2020). For the conterminous United States (i.e. lower 48 states; CONUS), the 1996 USGS NSHM (Frankel et al., 1996) was the first model adopted by the NEHRP Provisions in 1997. This model was updated by Frankel et al. (2002) and adopted by the 2003 NEHRP Provisions. The previous two updates of the USGS NSHM for CONUS were in 2008 (Petersen et al., 2008) and 2014 (Petersen et al., 2014, 2015), which were adopted by the 2009 and 2015 NEHRP Provisions, respectively. From 2017 to 2019, the USGS updated the NSHM for CONUS to incorporate the latest available science and data, resulting in the 2018 NSHM, an overview of which is presented in Petersen et al. (2020). This latest update has been influenced by and accepted for adoption in the 2020 NEHRP Provisions (BSSC, 2020), as described below.

The USGS used the 2018 NSHM to perform probabilistic seismic hazard analyses (PSHAs) on a 0.05° by 0.05° grid spanning CONUS for the 2020 NEHRP Provisions. Two fundamental components of an NSHM are inputs to a PSHA: (1) seismic source models, including earthquake fault and background or smoothed seismicity models, which forecast the occurrence rates and magnitudes of potential seismic events and (2) ground motion models (GMMs), which provide estimates of the ground shaking for a given seismic event. Both PSHA inputs are updated in the 2018 NSHM as summarized by Petersen et al. (2020). This article focuses on the latter and further elaborates on the update of GMMs in the central and eastern United States (CEUS), including comparisons and implementation details that were not presented in Petersen et al. (2020). Selection of GMMs for the 2018 NSHM was not only influenced by the best available scientific modeling and seismic data, but also by the interests of earthquake engineers, which are summarized below.

The NEHRP Provisions specify procedures for computing design ground motions from USGS NSHMs. The BSSC Provisions Update Committee (PUC) develops these procedures, with funding for meetings from the Federal Emergency Management Agency (FEMA). Prior to the current update, the design ground motion maps of the NEHRP Provisions only required mean hazard values at three spectral periods (i.e. 0, 0.2, and 1 s) and one reference site condition (i.e. soft rock with a 760 m/s time-averaged shear-wave

velocity from the surface to a depth of 30 m; hereafter V_{s30}). The USGS therefore developed prior NSHMs primarily to permit computation of mean-hazard ground motions at the reference site condition for the peak ground acceleration (PGA) and pseudo spectral accelerations (SAs) at periods of 0.2 and 1 s for the average horizontal component (i.e. geometric mean or an approximate equivalent) at a 5% damping ratio. As a result, the USGS GMM selection criteria were limited to the performance of models at the three mentioned periods and one reference site condition; other periods and site classes were also available in reports and at the USGS website over the past several cycles of updates (e.g. Shumway et al., 2018); however, these were not considered in the NEHRP provisions.

Project 17, a joint committee of BSSC-organized engineers and USGS researchers, was formed as part of the 2020 NEHRP Provisions update cycle to improve the procedures for development of the next generation of seismic design values (BSSC, 2019). One of the recommendations of Project 17 was to incorporate multi-period and multi- V_{s30} response spectral values (collectively referred to as multi-period response spectra (MPRS)) and make use of USGS hazard results at more periods and site conditions. This recommendation was made to improve the design response spectrum of the NEHRP Provisions and avoid potentially dangerous underestimation of design forces for long period structures on soft site conditions (Kircher et al., 2019; Rezaeian and Luco, 2019). As a result, for the 2018 NSHM update, only GMMs that are applicable for (or can be reasonably extrapolated to) all periods and site conditions of interest are selected.

The geology, tectonics, and earthquake potential represented in the NSHM source model is diverse, ranging from active tectonic regions and subduction zones in the western United States (WUS) to the stable continental regions in the CEUS. The NSHM requires GMMs that capture the propagation effects of each tectonic setting. It selects from the collection of all published GMMs, which represent various modeling choices (i.e. epistemic uncertainty), and weights them according to various criteria (Rezaeian et al., 2015). Similar to the 2008 and 2014 NSHMs, the GMMs used in the 2018 NSHM consist of four groups, those applicable to earthquakes in (1) stable continental regions of the CEUS, (2) the Cascadia subduction zone interface in the Pacific Northwest, (3) the Cascadia subduction zone interfaces may be added in the future to allow for improved regionalization. This article focuses on the first group. The GMMs for the other three groups in the WUS are discussed in Powers et al. (2021).

In the following, we first discuss updates to the USGS GMM selection criteria that stem from the recommendation of Project 17 to use multi-period response spectra. This article is the only 2018 NSHM publication where these updates are formally documented. Petersen et al. (2020a) presented only a summary of the CEUS GMM updates, which included comparisons of the 2018 weighted median GMMs to the 2014 NSHM and an overview of the aleatory variability (GMM standard deviation) and site-effect models. In this article, we discuss the CEUS GMM updates and implementation in the 2018 NSHM in detail. These updates consist of (1) 31 new GMMs, including the state-of-the-art Next Generation Attenuation relationships for central and eastern North America (NGA-East) (Goulet et al., 2018, 2017, 2021; Pacific Earthquake Engineering Research Center (PEER), 2015a), (2) an associated model of aleatory variability (based on Al Atik, 2015; Goulet et al., 2017; Stewart et al., 2019), and (3) a new site-effect model (for amplification or deamplification) specific to the CEUS (Hashash et al., 2020; Stewart et al., 2020). In the following, we discuss the individual GMMs in terms of their medians, assigned weights,

weighted averages, attenuations with distance (not discussed in Petersen et al., 2020), and epistemic uncertainty. We also elaborate on the aleatory variability and site-effect models and provide details on their implementation in the 2018 NSHM. Whenever possible, we compare each of these GMM components with those considered in prior NSHMs, specifically, the 2008 and 2014 NSHMs (Rezaeian et al., 2015), both of which are still in use for various engineering and risk assessment applications. Finally, we discuss the impact of the 2018 GMM updates on hazard relative to previous NSHMs for an assumed earthquake source model in the CEUS.

GMM selection criteria

GMMs (formerly referred to as attenuation relationships, or ground motion prediction equations, GMPEs) are models that describe the probability distribution of ground motion intensities in relation to parameters that represent the earthquake source, the seismic wave propagation path, and local site characteristics. A comprehensive model specifies the center, body, and range of this distribution (Budnitz et al., 1997). A typical GMM provides an equation for the median value of horizontal SA, assuming a lognormal distribution, and an equation for estimating its standard deviation (or aleatory variability). Most recent models provide the RotD50 component (Boore, 2010) of horizontal SA, which represents the 50th-percentile horizontal ground motion for all possible rotation angles and is independent of the orientation of the recording instrument. These equations are functions of spectral period, earthquake magnitude, source-to-site distance, $V_{S_{30}}$, and other parameters. Differences in model parameters and functional forms depend on the type of earthquake, its tectonic setting, the properties of the path and site, and various modeling choices. For example, in active tectonic settings such as the WUS, where recordings from past earthquakes are relatively plentiful, we can better define the seismic source inventory, and GMMs include additional parameters that further characterize the source and path, such as faulting style or a hanging-wall indicator; where data from well-defined sedimentary basins are available, GMMs better reflect expected local site effects. Aleatory variability represents the natural variability seen in ground motion intensities, in contrast to epistemic uncertainty that represents differences in modeling choices due to limitations in knowledge and data. The model of aleatory variability is typically assumed to be a constant for a given spectral period, sometimes dependent on earthquake magnitude, distance, or V_{S30} .

Background: the GMM selection criteria in the 2014 NSHM

As part of the 2014 NSHM update, the USGS formally introduced a set of 16 GMM selection criteria to vet available published GMMs and select those most appropriate for use in the NSHM (see p. 109–110 of Petersen et al., 2014, and p. S61–S62 of Rezaeian et al., 2015, for the full list of criteria). These criteria were designed to be general and flexible to accommodate the continued growth and evolution of GMMs. The criteria consisted of four categories: (1) general requirements, (2) database scope, (3) parameters and applicability range, and (4) functional form and modeling procedure. Two of these 16 criteria (items 1 and 10, shown below) were included specifically to ensure that the 2014 NSHM met minimum seismic design requirements. In particular, GMMs had to support hazard calculations at PGA, 0.2-, and 1-s spectral periods, and at a reference site condition of $V_{s30} = 760 \text{ m/s}$ (soft-rock site condition, NEHRP site class boundary BC, Table 1):

	2014 and prior NSHMs	2018 and future NSHMs ^a
Period (s)	0 (PGA), 0.2, I	0 (PGA), 0.01, 0.02, 0.03, 0.05, 0.075, 0.1, 0.15, 0.2 0.25, 0.3, 0.4, 0.5, 0.75, 1, 1, 5, 2, 3, 4, 5, 7,5, 10
$\pmb{V}_{_{S30}}$ (m/s) (site-class description)	760 (BC-soft rock)	 1500 (A—hard rock) 1080 (B—medium hard rock) 760 (BC—soft rock) 530 (C—very dense soil or hard clay) 365 (CD—dense sand or very stiff clay) 260 (D—medium dense sand or stiff clay) 185 (DE—loose sand or medium stiff clay) 150 (E—very loose sand or soft clay)

Table 1. Minimum requirements for spectral periods and site classes

PGA: peak ground acceleration.

^aSee Shumway et al. (2020) for more details on the selection of the given periods and site classes.

1. Basic Requirement (Petersen et al., 2014: 109–110)—The GMM must provide, as a minimum, equations for the median and aleatory uncertainty of the horizontal component for peak ground acceleration and spectral acceleration at 0.2- and 1-second spectral periods (5-hertz and 1-hertz frequencies). The GMM must be applicable to one of the tectonic regions relevant to the United States.

10. Site Condition Requirement (Petersen et al., 2014: 109–110)—GMMs must include a term for V_{s30} (currently for WUS GMMs), or be accompanied by other relations that transfer their equations to a V_{s30} of 760 meters per second (m/s) (currently for CEUS and subduction interface and deep intraslab GMMs). For use in softer soil hazard maps, GMMs should account for nonlinear soil effects.

Update: changes to the GMM selection criteria in the 2018 NSHM

Given the recommendation of Project 17 (BSSC, 2019) to use multi-period response spectra, the BSSC PUC and USGS have selected 22 periods and 8 V_{s30} values that represent the centers of site classes defined for the 2020 NEHRP Provisions. These periods and site classes are described in Shumway et al. (2020) and shown in Table 1. They span PGA, a range of periods from 0.01 to 10 s, and a range of site classes from hard rock (site class A) to very loose sand or soft clay (site class E). The 2018 NSHM provides hazard results for all these periods and site classes, and because future NSHMs are also expected to do the same, items 1 and 10 in the USGS GMM selection criteria have been updated as follows:

1. Basic Requirement (2018)—The GMM must provide, as a minimum, equations for the median and aleatory variability of the horizontal component for peak ground acceleration (PGA) and spectral accelerations at periods from 0.01 to 10 seconds, specifically the 21 periods 0.01, 0.02, 0.03, 0.05, 0.075, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.75, 1, 1.5, 2, 3, 4, 5, 7.5, and 10 seconds. If equations are not provided for all 22 periods (including 0 seconds for PGA), the GMM must be reasonably extrapolated or interpolated to them. The GMM must be applicable to one of the tectonic regions relevant to the United States and its territories.

10. Site Condition Requirement (2018)—The GMM must include a term for V_{s30} or be accompanied by one or more site-effect models that adjust the GMM to, at a minimum, the eight V_{s30} values of 1500, 1080, 760, 530, 365, 260, 185, and 150 meters per second (m/s), representing NEHRP Site Classes A, B, BC, C, CD, D, DE, and E, respectively. If the GMM does not include all eight V_{s30} values, it must be reasonably extrapolated or interpolated to them. For use in softer soil hazard models, the GMM should account for nonlinear soil effects.

2014 NSHM CEUS GMMs: (stable continental region)	Abbreviation	Weight ^a	Period range	Site classes or V ₅₃₀ (m/s)		
Atkinson and Boore (2006, 2011) Atkinson (2008), Atkinson	AB06' A08'	0.22 0.08	PGA to 5 s PGA to 5 s	A, BC (A to E) A, BC (A to E)		
and Boore (2011) Campbell (2003) Frankel et al. (1996)	C03 F96	0.11	PGA to 2 s (4 s) PGA to 2 s	A, BC ^b A_BC		
Pezeshk et al. (2011) Silva et al. (2002)	PII S02	0.15	PGA to 5 s (10 s) PGA to 5 s (10 s)	A, BC ^b A BC ^b		
Somerville et al. (2001) Tavakoli and Pezeshk (2005)	S01 TP05	0.10	PGA to 2 s (4 s) PGA to 4 s	A, BC ^b A, BC ^b		
Toro et al. (1997), Toro (2002)	T02	0.11	PGA to 2 s	A, BC ^b		

Table 2. CEUS ground motion models in the 2014 NSHM. Parentheses for periods and site classes indicate the published range when a different range is supported in the USGS codes

NSHM: National Seismic Hazard Model; CEUS: central and eastern United States; PGA: peak ground acceleration. ^aDifferent weights used for grid sources and distances larger than 500 km, Rezaeian et al. (2015).

^bAvailable through conversion factors described in Rezaeian et al. (2015).

While it would be possible to select different suites of GMMs for different periods and site classes, our updated selection criteria above for the 2018 NSHM are designed to result in the same set of GMMs for all periods, in order to achieve a smooth spectral shape that has no discontinuities with respect to period. Furthermore, the selection criteria also maintain GMM consistency across all site classes. However, future research or observations may reveal that a GMM is not acceptable at a particular site class (e.g. site class E), but is necessary to represent epistemic uncertainty at other site classes. If such variation across periods and/or site classes is allowed in a future version of the NSHM, USGS GMM selection criteria would require revision.

CEUS GMMs in the 2014 NSHM

In the stable continental regions of the CEUS, USGS hazard models calculate ground shaking from earthquake sources up to a distance of 1000 km with moment magnitudes (hereafter "magnitude") between 4.7 and 8.0. Therefore, CEUS GMMs must be applicable to this range of magnitudes and distances. Typical CEUS GMMs are relatively simple with only two input parameters, magnitude and distance, at any given spectral period. These models are not as well constrained as the WUS GMMs due to the lack of recorded data from large magnitude events at close distances in the CEUS. As a result, representation of uncertainties is extremely important and challenging. This is especially true for epistemic uncertainty, which is typically represented by logic tree branches and weights in PSHA and accounts for redundant models as well as missing models.

In the 2014 NSHM, the nine CEUS GMMs in Table 2 were incorporated (Rezaeian et al., 2015). To represent epistemic uncertainty in GMMs, logic tree weights were assigned based on model type (i.e. single-corner models, dynamic-corner models, hybrid models, reference-empirical models, and full-waveform simulation-based models) and categorization of near-source geometric spreading (i.e. R^{-1} , $R^{-1.3}$, or otherwise, where *R* represents distances less than about 50–70 km). The logic tree weights were assigned to avoid redundancy by grouping similar models and to give more weight to models in which experts have greater confidence. Although this approach is well established, it is subjective. The nine

2014 CEUS GMM median predictions are shown in Figure 1 as a function of period and distance for a magnitude 7 event and a very hard rock site condition (the original site condition for which each model was developed, with a $V_{_{530}}$ of about 2000 m/s). The standard deviations are shown in Figure 2 as functions of period; unlike the median models, the standard deviation models do not depend on distance.

Figure 1a shows the medians as a function of period at an example distance of 50 km. Although several of these GMMs were available beyond 2 s (Table 2), their validity was never examined by the USGS beyond this threshold (Shumway et al., 2018). Figure 1b shows the medians at a 0.2-s spectral period and demonstrates their attenuations with distance. The models are color coded to represent different geometric spreadings and model types. The two models with $R^{-1.3}$ geometric spreading attenuate faster compared with the R^{-1} models and received more weight in the 2014 NSHM compared with the 2008 NSHM, as new studies showed increased confidence in the $R^{-1.3}$ models. In Figure 1, the weighted average of the medians is also shown based on the 2014 NSHM logic tree weights listed in Table 2, details of which can be found in Rezaeian et al. (2015).

Limitations of the 2014 CEUS GMMs in terms of period and V_{sso}

The 2014 NSHM GMMs in the CEUS are not applicable or adjustable through reasonable extrapolations for all periods and site conditions of interest in the 2018 NSHM. As an interim computation, Shumway et al. (2018) extended the 2014 NSHM hazard results to a subset of the 22 periods and 8 site classes shown in Table 1, namely, to 7 periods and 2 site classes in the CEUS. They were unable to provide the full suite because of the limited applicability of CEUS GMMs, shown with respect to period and site class in Table 2. Most of these GMMs are not available for spectral periods beyond 4 s and very few are available for site classes softer than BC. Furthermore, all nine GMMs listed in Table 2 were developed a decade, or more, ago. Considering their period and site class limitations, and the fact that new or updated GMMs have recently become available via NGA-East (Goulet et al., 2018, 2017, 2021; PEER, 2015a, 2015b; Youngs et al., 2021) and other modelers (e.g. Hashash et al., 2020; Stewart et al., 2020), all nine CEUS GMMs are replaced in the 2018 NSHM with new models that not only satisfy the Project 17 requirements of extended periods and site classes, but also better represent the epistemic uncertainty, as described in the following sections.

CEUS GMMS in the 2018 NSHM for very hard rock

In 2010, the PEER center initiated a multidisciplinary research project, NGA-East, to evaluate and improve ground motion characterization in central and eastern North America. The NGA-East project developed a uniformly processed database of empirical ground motion recordings and simulations (Goulet et al., 2014). The recorded ground motions were primarily from small magnitude events but included some moderate magnitude events. The simulations were developed for moderate to large magnitude events to supplement the recorded motions. The NGA-East database, available at the time of the 2014 NSHM development, aided in the GMM selection and logic tree weight assignments for that NSHM update through residual analyses (Rezaeian et al., 2015). PEER provided this database to a group of ground motion modelers to either update their previously published GMMs (Table 2) or to develop new GMMs. This resulted in a set of 20 new empiricaland/or simulation-based GMMs for the median (i.e. RotD50) component of horizontal ground motion (PEER, 2015b). These models were then adjusted by the NGA-East project



Figure 1. The nine 2014 NSHM GMMs in the CEUS for a magnitude 7 event on a very hard rock site: (a) median ground motions versus period at a distance of 50 km and (b) median ground motions versus distance at a 0.2-s spectral period. Model abbreviations and logic tree weights used to compute the weighted average are given in Table 2.



Figure 2. Standard deviations of the nine 2014 NSHM GMMs in the CEUS for a magnitude 7 event on a very hard rock site versus spectral period. Model abbreviations are given in Table 2.

team (PEER, 2015a) to be applicable to a uniform range of distances and spectral periods. These adjustments included extrapolations to small distances less than 10 km and large distances up to 1500 km, and spectral shape adjustments at high frequencies to ensure the GMMs are applicable to the entire range of PGA to 10 s. Of these 20 new adjusted GMMs, 19 GMMs['] are referred to as the "adjusted seed" models because the NGA-East project then used them as input seed models in a process to develop GMMs representative of a continuous distribution of all possible GMMs (Goulet et al., 2018, 2017, 2021; Youngs et al., 2021). The goal of this process was to better and more objectively sample the ground motion distribution by accounting for redundancies in the seed models and capturing potentially missing models. NGA-East utilized the Sammon's mapping process (Sherbaum et al., 2010) to project the input seed models onto a two-dimensional ground motion space in order to visualize the underlying epistemic uncertainty of GMMs. The space was then resampled to develop a manageable number of new, representative GMMs and associated period-dependent weights. These sampled models constitute the final 17 NGA-East GMMs (Goulet et al., 2018) and, as expected, provide a broader range and better representation of epistemic uncertainty.

As summarized in Petersen et al. (2020), the 2018 NSHM update uses two suites of CEUS GMM medians: (1) 14 updated seed GMMs with a collective weight of 0.333, which are an updated subset of the NGA-East adjusted seed models as described in the following section and (2) the 17 NGA-East GMMs with a collective weight of 0.667. These group weights, like all USGS NSHM logic trees, are based on a consensus-building process that assigns weights to a range of expert opinions. Table 3 and Figure 3 show these two main logic tree branches and their collective weights. The decision to update to NGA-East GMMs over the 2014 GMMs is also supported by the residual analysis of McNamara et al. (2019), which showed that the NGA-East GMMs provide a more accurate

CEUS GMMs (Acronyms)	Authorship	Weight
I4 Updated Seed GMMs (used by L	0.333	
B-bcallOd	Boore	0.02209
B-ab95	Boore	0.00736
B-bs11	Boore	0.00736
2CCSP	Darragh-Abrahamson-Silva-Gregor	0.01841
2CVSP	Darragh-Abrahamson-Silva-Gregor	0.01841
Graizer I 6	Graizer	0.01813
Graizer 17	Graizer	0.01813
PZCT15-MISS	Pezeshk-Zandieh-Campbell-Tavakoli	0.01813
PZCT15-M2ES	Pezeshk-Zandieh-Campbell-Tavakoli	0.01813
SP16	Shahjouei-Pezeshk	0.03626
YA15	Yenier-Atkinson	0.03736
HA15	Hassani-Atkinson	0.03736
Frankel15	Frankel	0.03737
PEER-GP	Hollenback-Kuehn-Goulet-Abrahamson	0.03850
Other NGA-East Adjusted Seed GM	0	
B-a04	Boore	0
B-ab14	Boore	0
B-sgd02	Boore	0
ICCSP	Darragh-Abrahamson-Silva-Gregor	0
ICVSP	Darragh-Abrahamson-Silva-Gregor	0
SPI5 (replaced with SPI6 by USGS)	Shahjouei-Pezeshk	0
Graizer (replaced with Graizer 16 &	Graizer	0
Graizer 17 by USGS)		
PEER-EX	Hollenback-Kuehn-Goulet-Abrahamson	0
ANCI5 (see Note I)	Al Noman Cramer	0
17 NGA-East GMMs (used by USG	0.667	
Models I to 17	NGA-East Project	Period-dependen ^a

Table 3. CEUS ground motion models in the 2018 NSHM

CEUS: central and eastern United States; USGS: U.S. Geological Survey; NSHM: National Seismic Hazard Model. ^aSee Figure 6 for example weights at periods PGA, 0.2, 1, 2, and 5 s.

representation of the distribution (both median and standard deviation) of the observed instrumental ground motion data in stable tectonic environments than GMMs used in the 2014 NSHM. All the models in Table 3 and Figure 3 are applicable to the 22 periods requested by Project 17, but they are only valid for very hard-rock site conditions corresponding to $V_{s30} = 3000 \text{ m/s}$ and $\kappa = 0.006\text{s}$ (see Campbell, 2009; Hashash et al., 2014 for the definition of κ , a term that reflects site attenuation, and more information on site conditions). A site-effect model was developed and applied to these GMMs for conversion to different site conditions that will be described in the site-effect model section in this article.

Although the final NGA-East GMMs and associated weights are intended to represent the entire epistemic uncertainty by quantifying the center, body, and range of the underlying distribution in an objective way, in the 2018 NSHM update we also include a logic tree branch for the updated seed GMMs. This decision was made because some participating experts at the 2018 NSHM workshop (Petersen et al., 2020) made the case that incorporating both suites of GMMs is necessary to accurately represent the epistemic uncertainty. They argued that seed GMMs are more informed by physics, as opposed to the outcome of the Sammon's mapping process in the NGA-East approach that results in models which



Figure 3. A logic tree showing the grouping of updated seed GMMs by geometric spreading and model type, as well as the weights assigned to all CEUS GMMs in the 2018 NSHM. Relative weights for each group or model are given in parentheses.

are not interrogated by individual modelers in the same way that has been customary for GMM development. Therefore, seed GMMs should be incorporated directly in the NSHM to capture any physical features that may not be represented by GMMs derived via Sammon's mapping. An example of such a physical feature is a strong reflection of seismic waves from the Mohorovičić discontinuity, the boundary between the crust and the mantle in the Earth that can change the velocity and composition of seismic waves, (hereafter referred to as the Moho reflection) that is seen in the attenuation of most seed GMMs at a distance of around 60 to 100 km, but is somewhat subtle in the final NGA-East GMMs. Another example is the higher correlations seen between the NGA-East GMMs, with respect to distance, compared with the seed GMMs, which may not affect the mean hazard substantially at an individual site, but is suspected to influence uncertainty analyses and applications that aggregate the hazard, for example, portfolio risk assessments. Both examples are discussed in detail in this article. Given that the current primary output of the USGS NSHM is the mean hazard at individual sites, and to reflect the high confidence of most workshop participants in the Sammon's mapping process, the

set of final NGA-East GMMs is assigned double the weight (0.667) of the updated seed GMMs (0.333).

The weighted medians calculated separately for the updated seed and the NGA-East GMMs, assuming hypothetical group weights of 1 for each suite, were compared with each other in Petersen et al. (2020, their Figure 3). In general, the NGA-East GMMs result in larger weighted medians compared with the updated seed GMMs for large magnitude events. Hypothetical hazard maps, also assuming group weights of 1 for each suite of GMMs, are compared in Petersen et al. (2019) to understand the sensitivity of hazard values to each suite of models. In the following, we first present the two suites of 14 updated seed and 17 NGA-East median GMMs. We discuss the behavior of each suite in terms of attenuation with distance and representation of epistemic uncertainty. We then compare the combined weighted median of the two GMM suites, using their final group weights of 0.333 and 0.667, to the weighted GMM medians from prior NSHM cycles.

Updated seed GMMs and weights

For the 2018 NSHM update, we performed our own review of the 19 NGA-East adjusted seed GMMs (PEER, 2015a) and selected 13 models based on our GMM selection criteria. We replaced two of the adjusted seed models with three updated versions from Graizer (2016, 2017) and Shahjouei and Pezeshk (2016), which were published after the NGA-East report on adjusted seed models was completed. We refer to these final selected 14 seed models as the "updated seed GMMs." All adjusted seed models are listed in Table 3 with their assigned weights. If an adjusted seed model was not selected or was replaced in the set of 14 updated seed GMMs, its assigned weight is zero.

Logic tree weights are assigned to the updated seed GMMs using the same method as in the 2014 NSHM. The CEUS GMM logic tree and final weights are illustrated in Figure 3. We generally consider equal weights across different geometric spreading categories and model types and split weights between multiple models developed by a single team who assumed alternative input parameters. In the end, the individual model weights are low and are very similar to one another. These weights were discussed with the NGA-East team and the NSHM Project Steering Committee and found to be reasonable. Other weighting methodologies could be chosen that would also lead to reasonable assessments of mean hazard. During an early sensitivity analysis, two alternative weighting methodologies were considered, which resulted in at most a 10% difference in the total mean hazard, with smaller differences at shorter periods, and larger differences at longer periods.

As shown in Figure 3, the updated seed GMMs are separated into three categories based on their geometric spreading: (1) R^{-1} models, (2) $R^{-1.3}$ models, and (3) other models, with each group receiving almost equal weight (0.33, 0.33, and 0.34, respectively). The models are then grouped by model type, which are different from those used in the 2014 NSHM due to improvements made to previous models and new modeling approaches. Within each branch for a given model type, weights are distributed based on a number of considerations that consist of expert opinions (including those of the modelers when multiple models are available from the same developer team), residual studies, magnitude and distance scaling of the models, and examination of their spectral shapes.

The R^{-1} models are grouped into two types: (1) point-source models (B_bca10d, B_ab95, B_bs11, 2CCSP, and 2CVSP) with a group weight of 0.67, and (2) empirical-factor models (Graizer16 and Graizer17) with a group weight of 0.33. More weight is

given to the first group because more models of this type are available from two independent developer teams and because this type of model has been used and tested for a longer time in the NSHMs. These models can be summarized as follows:

- B_bca10d, B_ab95, B_bs11: six seed GMMs were developed by Boore (2015), using point-source stochastic simulations with a single-corner source spectral shape. Each model is based on different anelastic attenuation (often expressed as seismic quality factor, Q) and geometric spreading factors. Based on recommendations from the author (D. Boore, *written communs.*, 2018), we selected B_bca10d as the preferred model, assigned a relative weight of 0.3 in its group, and B_ab95 and B_bs11 as the next two preferred models with relative weights of 0.1 (Figure 3).
- 2CCSP and 2CVSP: four seed GMMs were developed by the Darragh-Abrahamson-Silva-Gregor (DASG) team (Darragh et al., 2015), based on singlecorner (1C) or double-corner (2C) point-source stochastic simulations, using both constant (CSP) and variable (VSP) stress models. We selected the two doublecorner models with both types of stress models. Each is assigned a relative weight of 0.25 in its group.
- Graizer16 and Graizer17: these two models are based on applying spectral shapes that are developed for the WUS and then empirically adjusted to the CEUS, and therefore, are referred to as empirical-factor models in Figure 3. These types of models were not used in previous NSHM cycles. Graizer16 (Graizer, 2016) was published as an update to the "Graizer" seed model of NGA-East (PEER, 2015b, chapter 9). Graizer17 (Graizer, 2017) is an alternative, using a more physically justified approach, to Graizer16. Based on recommendations from the author (V. Graizer, *oral and written communs.*, 2018), we used both models with equal weights to replace the original seed model.

The $R^{-1.3}$ models are categorized into three types: (1) hybrid empirical (PZCT15_M1SS and PZCT15_M2ES), (2) hybrid empirical and broadband (SP16), and (3) stochastic equivalent point-source (YA15). Each of these three groups is assigned almost equal weights. These models can be summarized as follows:

- PZCT15_M1SS and PZCT15_M2ES: these are two models from the same developer team, Pezeshk–Zandieh–Campbell–Tavakoli (Campbell, 2014; Pezeshk et al., 2015). They are based on a hybrid empirical method that defines the WUS as the host region and the CEUS as the target region, then develops host-to-target adjustments. The two different models have different large-magnitude scaling, one based on stochastic simulation scaling (SS) and the other based on empirical scaling (ES). Both versions are used and assigned equal weights.
- SP16: this model is developed by Shahjouei and Pezeshk (2016) and is an update to SP15, an original seed GMM for NGA-East (PEER, 2015b, chapter 7). This model is based on a hybrid empirical method like the two models above, but unlike those models, it also incorporates hybrid broadband simulations with both stochastic and deterministic components for both host and target regions.
- YA15: this model is developed by Yenier and Atkinson (2015b) and is a regionally adjustable generic model, based on equivalent point-source simulations. The model is adjusted to the CEUS based on empirical observations (also see Yenier and Atkinson, 2014, 2015a)

There are three models (HA15, Frankel15, and PEER_GP) with geometric spreading other than R^{-1} or $R^{-1.3}$. Each are assigned almost equal weight and are summarized as follows:

- HA15: this is a referenced empirical model by Hassani and Atkinson (2015) (also see Hassani and Atkinson, 2014) and is similar in methodology to YA15. However, it uses WUS GMMs as the base, and therefore, the geometric spreading is different from the other CEUS GMMs and more similar to WUS GMMs.
- Frankel15: this model is developed by Frankel (2015), using finite-fault simulations that are enhanced by stochastic simulations at short periods. The R^{-1} geometric spreading is used for stochastic simulations below 70 km, but because of the mixed use of finite-fault simulations, it is placed in its own category of geometric spreading.
- PEER_GP: two seed GMMs were developed by the Hollenback–Kuehn–Goulet– Abrahamson developer team (Hollenback et al., 2015) based on different simulation models (GP and EX, Table 3). Based on recommendations from the authors and simulation model developers (e.g. R. Graves, *oral communs.*, 2018), we selected the PEER_GP as the preferred model and excluded the PEER_EX model. The PEER_GP model is based on the finite-fault simulations of Graves and Pitarka (2015).

The 14 updated seed models described above are shown in Figure 4 for a magnitude 7 event on a very hard-rock site condition ($V_{s30} = 3000 \text{ m/s}$), along with the 9 CEUS GMMs of the 2014 NSHM (but with $V_{s30} = 2000 \text{ m/s}$ as they are not available for 3000 m/s). Note that although the 2014 and 2018 GMMs consider different V_{s30} values for very hard rock, the differences in predicted ground motion values are typically very small for the two site conditions. The updated seed GMMs show complexity in distance scaling (Figure 4). The "flat" segment in Figure 4b, around 60–100 km, is prominent in many of the seed GMMs. This flattening is likely due to the Moho reflection and is typically seen in physics-informed GMMs (e.g. Frankel15). Furthermore, the updated seed GMMs have varying distance-scaling slopes, with little to no correlation between models with respect to distance (models cross each other in Figure 4b).

NGA-East GMMs and weights

The NGA-East project team adjusted the seed models, developed by individual modelers, and used them as inputs to a Sammon's mapping procedure (Sherbaum et al., 2010), a statistical tool that aids in visualizing the probability distribution of the input seed GMMs. The procedure then resamples the ground-motion space to select an evenly distributed set of GMMs and weights that better represent the underlying continuous distribution (or epistemic uncertainty) than the set of input seed GMMs. The evenly distributed set avoids redundant GMMs and fills out the predicted space of possible GMMs. The resulting NGA-East GMMs are tabulated values (i.e. not equations) for given magnitudes, distances, and spectral periods.

Three early versions of the NGA-East models based on Sammon's mapping were considered for use in the 2018 NSHM update: (1) a suite of 29 GMMs; (2) a suite of 13 GMMs; and (3) a suite of 17 GMMs (referred to as "NGA-East for USGS," Goulet et al., 2017, with an addendum, referenced in Petersen et al., 2020). After each version, the



Figure 4. The 14 updated seed CEUS GMMs in the 2018 NSHM for a magnitude 7 event on a very hard rock site: (a) medians versus period at a distance of 50 km and (b) medians versus distance at 0.2-s spectral period, superimposed on the nine CEUS GMMs from the 2014 NSHM of Figure 1. Model abbreviations and weights are defined in Table 3 and Figure 3.

USGS provided feedback to the NGA-East modelers for improving the final set, but the overall variation in mean hazard was minor, reflecting robustness of the Sammon's mapping process regardless of sampling density. After the completion of 2018 NSHM, the



Figure 5. Medians of the 17 NGA-East GMMs in the 2018 NSHM for a magnitude 7 event on a very hard rock site: (a) medians versus period at a distance of 50 km and (b) medians versus distance at 0.2-s spectral period, superimposed on the nine CEUS GMMs from the 2014 NSHM in Figure 1. Vertical bars and arrows indicate the range of ground motions at different spectral periods and distances for the two groups of GMMs and are referenced in Figure 11.



Figure 6. Period-dependent weights for the final 17 NGA-East models. The upper left ellipse defines the model number corresponding to each cell.

suite of 17 GMMs was republished by NGA-East for assessing seismic safety of nuclear facilities and was called the "NGA-East final" suite (Goulet et al., 2018). Hence, the 2018 NSHM uses the NGA-East final suite of GMMs by incorporating the Goulet et al. (2017) report with the addendum.

The final 17 NGA-East GMMs are shown in Figure 5 for a magnitude 7 event on very hard-rock site conditions ($V_{sso} = 3000 \text{ m/s}$), with the nine CEUS GMMs of the 2014 NSHM for comparison. In this figure, the line type is different for GMMs with less (dotted lines) and more (dashed lines) than about 5% weight to show which GMMs have more weight in the ground motion space. As shown in Figure 6, the weights are period dependent. To calculate the weighted average in Figure 5a, weights are approximated by taking the average of the weights across all periods. The 17 NGA-East GMMs show less complexity in distance scaling compared with both the 2014 NSHM (Figure 5b) and the 14 updated seed (Figure 4b) GMMs. The Moho reflection resulting in the "flat" segment around 60–100 km is very subtle in NGA-East GMMs (Figure 5b). The lack of this strong "flattening" feature in the NGA-East GMMs is an important consideration in giving the updated seed GMMs some weight in the 2018 NSHM. Furthermore, the NGA-East GMMs exhibit higher correlations between models with respect to distance and are almost subparallel compared with the updated seed GMMs (Figures 4b and 5b). Figure 5b also suggests that the NGA-East GMMs exhibit a geometric spreading with slower attenuation that is better associated with R^{-1} models and higher stress drops. This could be an unintentional result of Sammon's mapping or due to more representation of such models in the input seed GMMs (recall that our updated seed GMMs exclude/replace some input seed GMMs, Table 3); more studies are required to understand this feature.

Additional figures that directly compare the two suites of updated seed GMMs and NGA-East GMMs (without the 2014 GMMs) are provided in an electronic supplement (Figures A3 and A7 for magnitude 5 and 7 events, respectively). Although the above

conclusions are based on a large magnitude 7 event and for attenuation with distance at a 0.2-s period (Figures 4b and 5b), they are also true for smaller magnitude events (electronic supplement, Figures A1b and A3b) and for a 1-s period (electronic supplement, Figures A5c and A7c).

Figure 5 also shows vertical cross sections at three periods and two distances, indicating the range of ground motions for the two suites of GMMs. These vertical lines show that for a large magnitude event, the range of ground motion from the NGA-East GMMs is significantly larger than that spanned by the nine 2014 GMMs. In contrast, Figure 4 shows that the updated seed GMMs span a similar range as the 2014 GMMs. The updated seed and NGA-East GMMs are compared directly in the electronic supplement Figure A7. This increased range of NGA-East ground motion values demonstrates an increase in epistemic uncertainty. In addition to the range of ground motions, epistemic uncertainty also depends on the distribution of weights assigned to each GMM.

The NGA-East project team assigned period-dependent weights to each of the 17 GMMs based on two considerations: (1) the weight for each final GMM should reflect the likelihood of that GMM with respect to the distribution of input seed GMMs and (2) GMMs that better fit the available data should receive higher weights (Goulet et al., 2017, 2018). Different weights are given to the two approaches at different periods based on their relative merits at that period. These weights are typically displayed in an ellipse that can be thought of as a two-dimensional projection of the ground motion space and can be used to visualize the epistemic uncertainty. Figure 6 shows examples of these period-dependent weights for PGA, 0.2, 1, 2, and 5 s, which are used directly in the USGS hazard analyses. Each cell in an ellipse is the ground motion space represented by one of the final NGA-East GMMs. Therefore, the weight of a GMM representing an individual cell reflects the contribution of that cell in the total ground-motion space.

GMM weights for grid sources and distances beyond 500 km

For grid or background seismicity sources that include smaller magnitude events and for distances beyond 500 km, the 2014 CEUS GMM weights were different than those for fault-based and repeating large-magnitude earthquake (RLME) sources such as the New Madrid and Charleston, SC source zones. While nine GMMs were used for RLME sources within 500 km, only eight were used for grid sources because S01 was not applicable to small magnitude events (Table 2). Between 500 and 1000 km, only five GMMs that could be reasonably extrapolated to large distances were used. In contrast, the 2018 CEUS GMM weights are the same for all source types and for all distances up to 1000 km because the 2018 GMMs are all applicable for the entire magnitude and distance range of interest.

Weighted average of medians

Figures 7 and 8 show the weighted averages of CEUS GMM medians as functions of spectral period and distance, respectively, for two magnitude scenarios: 5.5, typical of areas with high background or gridded seismicity rate (e.g. the East Tennessee seismic zone), and 7.5, typical of fault-based or RLME sources (e.g. the New Madrid seismic zone). Both figures also include the weighted combinations of medians from the 2014 and 2008 NSHMs. Note that the increases and decreases in these figures are not exact representations of changes in the final hazard because PSHA is not a linear process; it first calculates



Figure 7. Weighted averages of CEUS GMM medians from the 2018 NSHM, 2014 NSHM (RLME), and 2008 NSHM (RLME) versus period for magnitude 5.5 and 7.5 events at 10, 50, and 300 km distances for hard rock representing the original site conditions of the models (about 2000 m/s in 2008 and 2014 NSHMs, 3000 m/s in 2018 NSHM).



Figure 8. Weighted combinations of CEUS GMM medians from the 2018 NSHM, 2014 NSHM (RLME), and 2008 NSHM (RLME) versus distance for magnitude 5.5 and 7.5 events at (a) 0.2 s and (b) 1 s. These plots are made for hard rock representing the site conditions of the original models (2000 m/s in the 2008 and 2014 NSHMs, 3000 m/s in the 2018 NSHM).

the hazard (annual rate or probability of exceedance) for a given GMM median and its standard deviation, and then combines the hazard based on logic tree weights rather than combining the ground motion values. However, weighted averages of GMM medians are a good proxy for what happens to the final estimated mean hazard when they are combined with uncertainties discussed in the following sections.

Figure 7 shows the ground motions at three distances of 10, 50, and 300 km. The median 2018 GMMs at 0.2 and 1 s periods are slightly lower than the median 2014 GMMs for small magnitude events (e.g. around East Tennessee), but are noticeably larger than the median 2014 GMMs for large magnitude events (e.g. around New Madrid) at larger distances. At short distances, the differences are negligible. The increase for large magnitudes at larger distances could be due to the higher weight that is given to the NGA-East GMMs and their larger values due to their slower attenuation with distance beyond 60 km compared with the updated seed and the 2014 GMMs. As will be shown in the maps at the end of this article, this causes a ring of increased ground motion values around, but not in the immediate vicinity of the New Madrid seismic zone. In Figure 7, median 2008 GMMs are also shown, which also used physics-informed GMMs, but with more weight on R^{-1} models (GMMs with slower attenuation) compared with the 2014 GMMs. The 2008 GMM median is closer to the 2018 GMM median for large magnitude events and middle to large distances. In most cases, the changes in GMM medians from 2014 to 2018 are more significant compared with the previous cycle (from 2008 to 2014), stemming from the use of an entirely new set of GMMs in the 2018 cycle.

Figure 8 shows the attenuation of 0.2 and 1-s ground motions with distance, plotted in the linear distance scale unlike Figures 4b and 5b to show a different perspective and to be comparable to similar figures in previous NSHM publications. Observe that the medians for hard rock slightly decrease from the 2014 to the 2018 cycle for small magnitude events but increase for large magnitude events. Note that for large magnitudes, the increase from 2014 to 2018 accelerates around 60–80 km (where Moho reflection happens), and is relatively constant beyond about 80 km. The 2008 GMM medians are also shown in Figure 8. Note that,



Figure 9. Epistemic uncertainty of NGA-East GMMs and 2014 GMMs represented by the range and distribution of ground motion medians at vertical cross sections of Figure 5, for a magnitude 7 event on hard rock (i.e. $V_{ss0} = 3000$ m/s) at (a) a 50-km distance and three periods, PGA, 0.2, and 1 s; and (b) two distances, 10 and 100 km, at a 0.2 s period.

as we also observed in Figure 7, for large magnitude events, the 2018 GMMs are closer to the 2008 GMMs than the 2014 GMMs at middle to large distances, and the changes from 2014 to 2018 are more significant compared with the changes from 2008 to 2014.

Epistemic uncertainty of medians

Epistemic uncertainty accounts for variability due to lack of knowledge and modeling choices and is represented by logic tree branches and weights associated with different models. Replacing the 9 2014 CEUS GMMs with the 31 2018 CEUS GMMs increases the epistemic uncertainty significantly. Figure 9 demonstrates the increase of epistemic uncertainty in NGA-East GMMs by showing the range of median ground motion values and their assigned weights for the 17 NGA-East relative to the 9 2014 GMMs. Figure 10 makes the same comparison for the 17 NGA-East relative to the 14 updated seed GMMs. Both figures show values at three periods for a distance of 50 km, and at two distances for a 0.2-



Figure 10. Epistemic uncertainty of NGA-East GMMs and updated seed GMMs represented by the range and distribution of ground motion medians at vertical cross sections of Figures 4 and 5, for a magnitude 7 event on hard rock (i.e. $V_{s30} = 3000$ m/s) at (a) a 50 km distance and three periods, PGA, 0.2, and 1 s and (b) two distances, 10 and 100 km, at a 0.2 s period.

s period for a magnitude 7 event on hard-rock site conditions. Note that the vertical scale is logarithmic in these figures and the range of vertical axes, while different, is similar in the order of magnitude in all subplots for easy comparison. The dotted lines show weighted averages of median ground motions. The solid lines on the vertical axes in Figure 9 are the same as the vertical cross sections in Figure 5 and indicate the range of ground motion values in each suite of GMMs. These ranges are a good representation of epistemic uncertainty (larger range = larger uncertainty), but the distribution of assigned weights, shown in Figures 9 and 10 as stem plots, is also important. These figures show that the ground motion values for all three suites of models (2014 GMMs, 2018 NGA-East GMMs, 2018 updated seed GMMs) cover a broad epistemic uncertainty range: about a factor of 2 for the 2014 and the 2018 updated seed GMMs, and about a factor of 10 for the 2018 NGA-East GMMs, for a magnitude 7 event with variations depending on distances and periods.

As expected, for a magnitude 7 event, epistemic uncertainty of the 17 NGA-East GMMs is much larger and more similar to a continuous normal probability distribution than those of the 2014 GMMs (Figure 9) and the updated seed GMMs (Figure 10) as a result of the NGA-East approach of utilizing Sammon's mapping process and resampling the ground motion space. For smaller magnitude events, the range of the 17 NGA-East GMMs are closer to those of the 2014 and the updated seed GMMs (electronic supplement, Figures A2 and A4). We attribute this to the availability of more small magnitude data and therefore a more similar representation of the ground motion space by different modeling approaches. However, even for smaller magnitude events, the epistemic uncertainty of NGA-East GMMs still provides a better representation of a continuous normal distribution.

Figures 9 and 10 illustrate that the NGA-East GMM weights more closely resemble a normal distribution with higher weights in the middle and lower weights at the highest and lowest ground motion values. The peripheral, lower weighted models are commonly those in the outer rings of the Sammon's maps shown in Figure 6. In contrast, the weights of the 2014 GMMs and the updated seed GMMs are random and asymmetric reflecting the inherent subjectivity of the underlying GMM selection and weighting procedures. Although the NGA-East process may expand the range of GMMs and provide a more complete representation of the ground motion space, it may also have shortcomings that require further studies. For example, in Figures 9 and 10, note that at 0.2 s and 100 km, where the physics-informed seed GMMs show less variability compared with 10 km, possibly due to the flattening effect of Moho reflections discussed earlier (Figures 4b and 5b), the NGA-East GMMs show much more variability that is similar in the order of magnitude to that of 10 km. It is also worth noting that the weighted average of the NGA-East GMMs is at the upper end of the 2014 and the updated seed GMM values. Without observed data for large magnitude events in the CEUS, it is difficult to make a conclusion about the accuracy of the two sets of models. However, these considerations are reflected in the collective weights of 0.333 and 0.667, given, respectively, to the updated seed and NGA-East GMMs, based on a range of expert opinions and their confidence in each suite of models.

Whereas USGS NSHMs have historically focused on the mean hazard, or the center, with underlying logic trees of GMMs representing the body, the NGA-East GMMs expand on prior model distributions to better represent the full "range" of possible ground motions. This feature will prove important as the USGS moves toward complementing mean hazard results with estimates of uncertainty in future NSHMs.

Aleatory variability

Aleatory variability (GMM standard deviation) accounts for the random variability that is naturally present in ground shaking for a given magnitude, distance, and site condition. Unlike the 2008 and 2014 NSHMs, for which each GMM was assigned a different independently developed standard deviation, the 2018 NSHM uses the same standard deviation model for all GMMs. The NGA-East GMMs included a logic tree of standard deviation models (Al Atik, 2015), the most heavily weighted branches of which are largely based on ground motion observations from the richer dataset available in the WUS. The lower weight branches considered data from small to moderate magnitude earthquakes, large-magnitude simulations, and the potential for greater variability in site response in the CEUS for sites with similar V_{s30} values. The CEUS standard deviations are generally larger



Figure 11. The two CEUS aleatory variability models ("2018 Updated EPRI" and "2018 Working Group"), used for all 31 GMMs in the 2018 NSHM, and their SRSS combination ("2018 NSHM"), superimposed on standard deviation models of the nine 2014 GMMs for a magnitude 7 event on hard rock ($V_{sso} = 2000$ or 3000 m/s).

than those associated with the WUS GMMs because fewer predictive characteristics are considered (e.g. no style of faulting) and because the limited ground shaking observations suggest more variability in the CEUS source and path effects. The independently developed adjusted seed GMMs do not include standard deviation models. The three updated seed GMMs (Graizer16, Graizer17, and SP16) that were developed after the conclusion of the NGA-East project do include standard deviation models.

The 2018 NSHM does not use the NGA-East (Al Atik, 2015), Graizer16, Graizer17, or SP16 recommended standard deviation models, but rather uses a modified version of the NGA-East recommended model as described in Petersen et al. (2020) and shown in Figure 11. Figure 11 also shows standard deviation models of the nine 2014 GMMs for comparison. Note that the 2018 model falls in the middle of the range, indicating little overall change to aleatory variability relative to 2014. Petersen et al. (2019) show the sensitivity of hazard values to the 2014 and 2018 aleatory variability models, demonstrating that they are not significantly different. The 2008 standard deviation models were largely identical to the 2014 models and are not shown in Figure 11.

In the NGA-East for USGS report, Goulet et al. (2017) recommend an updated version of the Electrical Power Research Institute (2013) aleatory variability model. This model consists of the final published total inter-event, τ , and intra-event, ϕ , aleatory variability terms of NGA-West2 with CEUS adjustments (Al Atik, 2015). However, concerns arose at the 2018 NSHM workshop that we should consider additional site-to-site variability, ϕ_{S2S} , arising from lack of knowledge of site conditions in the CEUS and from V_{s30} being a less effective proxy for site effects in the CEUS relative to the WUS (Hassani and Atkinson, 2016; Parker et al., 2019). The USGS therefore requested a working group to develop a model of ϕ_{S2S} for the CEUS (Stewart et al., 2019). The resultant model gives due consideration to site dependence of uncertainty terms, regional differences (WUS vs CEUS), and magnitude effects on ϕ_{S2S} . To integrate the ϕ_{S2S} model into a model of total aleatory variability, the USGS used the NGA-East τ and the single-station within-event standard deviation, ϕ_{SS} , terms as described in Goulet et al. (2017). The τ and ϕ_{SS} terms are presented as logic trees of global, constant, and magnitude-dependent models. The global models, also magnitude-dependent, are derived from NGA-West2 models of aleatory variability, whereas the latter two consider CEUS data. Limitations of the available data ultimately led Goulet et al. (2017) to assign the CEUS models zero or very low weight; as a result, the 2018 NSHM only considers the global branches of the NGA-East τ and ϕ_{SS} terms.

The final standard deviation model incorporated in the 2018 NSHM consists of a logic tree of the NGA-East recommended model with 0.8 weight (Goulet et al., 2017, denoted "2018 Updated EPRI" in Figure 11), and an alternate model that includes the working group site-to-site variability term, ϕ_{S2S} , with 0.2 weight (denoted "2018 Working Group" in Figure 11). Petersen et al. (2019) explores the sensitivity of hazard values to each of these models, assuming hypothetical weights of 1 for each model. The final USGS implementation of this logic tree computes hazard for all pairings of CEUS median GMMs and the two aleatory variability models. As shown in Figure 11, the "2018 Working Group" model is higher at short periods and lower at long periods compared with the WUS-based "2018 Updated EPRI" model. The main reason for the higher short-period values is the relative preponderance of short-period resonances in the CEUS compared with the WUS sites. Because these effects are observed in available CEUS data, but are not taken into account in the V_{sso} -based site-effect model (described in the following section and used in conversion of data to hard-rock site conditions), the high dispersion in the site-effect model results in higher standard deviations. The lower values at long periods are supported by the available CEUS data, whereas the 2018 Updated EPRI model is based on WUS data.

Goulet et al. (2017) consider additional epistemic uncertainty on τ and ϕ_{SS} terms and provide period-dependent coefficients for each. The working group model did not include such branching, and we therefore elected to use only the central branches of the τ and ϕ_{SS} terms in the final model. Sensitivity studies show that this has little effect on the mean hazard.

The final standard deviation model in the 2018 NSHM is a function of period, magnitude, and V_{s30} (Figure 12). In Figure 12, the standard deviation models are plotted as functions of magnitude and V_{s30} for two periods of 0.2 and 5.0 s. While the 2018 Working Group model is much larger at shorter periods, the 2018 Updated EPRI model is larger at longer periods, resulting in little difference between the final standard deviations at 0.2 and 5.0 s for the 2018 NSHM. The magnitude dependence is more significant at 0.2 s. The V_{s30} dependence is only influential for very hard-rock site conditions where the standard deviation is lower.

Site-effect model

Prior to the 2018 update, NSHMs were only required to support hazard calculations at one reference site condition defined by $V_{s30} = 760$ m/s. In the CEUS, this was achieved by using GMMs developed for hard-rock site conditions (typically $V_{s30} = 2000$ m/s) and applying either the Frankel et al. (1996) or Atkinson and Boore (2011) conversion factors described in Rezaeian et al. (2015) to scale ground motions to $V_{s30} = 760$ m/s (Table 2). Due to the absence of site-effect models for stable continental regions capable of supporting the site classes listed in Table 1, the USGS funded a working group to develop a model for the CEUS that is a function of V_{s30} (Hashash et al., 2017, 2020; Stewart et al., 2020, 2017). This working group included many of the NGA-East authors with extensive experience in the CEUS ground motion data and modeling. The recommended working group



Figure 12. Standard deviation models used in the 2018 NSHM plotted versus magnitude at spectral periods of (a) 0.2 s and (b) 5.0 s, and versus $V_{_{530}}$, also at (c) 0.2 s and (d) 5.0 s. All plots are at a 50-km distance. The magnitude plots are for a soft-rock site condition ($V_{_{530}} = 760$ m/s) and the $V_{_{530}}$ plots use a magnitude 7 event.

model consists of three additive components, each with associated epistemic uncertainty: (1) a linear, simulation-based term for converting very hard rock with $V_{s30} = 3000 \text{ m/s}$ ground motion to the reference site condition with $V_{s30} = 760 \text{ m/s}$, F_{760} ; (2) a linear, empirically constrained V_{s30} scaling term relative to $V_{s30} = 760 \text{ m/s}$, F_V ; and (3) a non-linear, magnitude- and distance-dependent, simulation-based scaling term relative to $V_{s30} = 760 \text{ m/s}$, F_{NL} .

In the 2018 NSHM implementation, uncertainties associated with each model term are assumed to be independent and the total site-effect standard deviation, σ , is the square root of the sum of the squares (SRSS) of the component standard deviations. Prior to computing hazard, the epistemic uncertainty branches $(\pm 1\sigma)$ are applied as linear adjustments to median ground motion using symmetric weights (0.185, 0.63, 0.185). Figure 13 shows the application of the site-effect model and its uncertainty on the weighted average of the 2018 GMM medians with implementation adjustments as described below.

Subsequent to initial publication of the linear model terms (Stewart et al., 2017), exchanges between the USGS and the working group led to a variety of model improvements, including (1) providing coefficients for peak ground velocity (PGV) and additional spectral periods (consistent with the intensity measures supported by the final NGA-East GMMs (Table 1), (2) adjustments to the V_{s30} scaling term to achieve consistency at hard rock sites, and (3) decomposition of the F_{760} term into a V_{s30} -dependent logic tree of impedance, F_{760_i} , and gradient, F_{760_g} , soil profile terms (Stewart et al., 2020). The impedance and gradient models reflect differences in the soil profiles measured in the CEUS sites with V_{s30} around 760 m/s. The impedance model assumes a soil rock impedance contrast that leads to a site resonance and corresponding spectral peak at about 0.1 s. As shown in Stewart et al. (2020), this spectral peak is also observed in the CEUS data for stiff sites with $V_{s30} > 400m/s$. The gradient model assumes a gradient of V_s with depth and does not



Figure 13. Response spectra for a magnitude 7 earthquake at 50 km, using the weighted average of the 2018 GMM medians at (a) the reference site condition of $V_{_{530}} = 760$ m/s, showing the published Stewart et al. (2020) site-effect median and uncertainty models ("Original") and the USGS smoothed version as implemented in the 2018 NSHM ("Smoothed"), and (b) a range of site classes; dotted lines mark published site-effect models. The dotted lines at 0.1 s illustrate the strong peak of the Stewart et al. (2020) model for soft to hard rock sites. From about 0.4 to 1.5 s, the alternate nonlinear Hashash et al. (2020) model, indicated by dotted lines, suggests lower ground motions at softer sites but is not incorporated in the 2018 NSHM.

produce a resonance spectral peak, consistent with observed spectral shapes for softer site conditions. Considerations were given to assigning (1) symmetric weights of 0.9 and 0.1 at $V_{s30} \ge 600 \text{ m/s}$ and 0.1 and 0.9 at $V_{s30} \le 400 \text{ m/s}$ to the impedance and gradient models, respectively, and (2) equal weights to the two models at $V_{s30} \ge 600 \text{ m/s}$. The final F_{760} term includes both weighting approaches in a logic tree with consensus-based weights of 2/3 and 1/3 such that the term F_{760_g} gets 0.23 weight at $V_{s30} \ge 600 \text{ m/s}$, 0.9 weight at $V_{s30} \le 400 \text{ m/s}$, and linearly interpolated weights in between.

Despite evidence for the 0.1 s peak in stiff CEUS site ground motions and the modeling framework giving greater weight to the gradient-based model for softer sites, the NSHM team and Steering Committee expressed concern about the strong peak in the simulationbased F_{760_i} term between 0.075 and 0.15 s. We examined the effect of interpolating F_{760_i} and associated uncertainty at 0.1 s, using the values of the neighboring periods (0.075 and 0.15 s, see Table 1) in order to avoid the strong peak at 0.1 s. We found the smoothed model to be well within the $\pm 1\sigma$ envelope (Figure 13a). The effect of the 0.1-s interpolation is strongest at sites with $V_{530} \ge 760$ m/s and decreases at softer sites as the weight of the F_{760_g} term increases (Figure 13b). The smoothed F_{760_i} and associated σ terms at 0.1 s are used in the final 2018 NSHM implementation. Overall, amplifications from 3000 m/s to softer soils are greater than 1 at all periods; the amplification is more significant for 760 m/s at short periods due to nonlinear effects for softer soils, whereas it is more significant for 365 and 260 m/s at 0.2 s and longer periods.

Subsequent to initial publication of the nonlinear model, Hashash et al. (2020) proposed alternate interpretations for the soft soil "1 s shoulder" in the response spectra, which can be seen in Figure 13b as dotted lines around 0.4–1.5 s for site classes D, DE, and E. This "1 s shoulder" feature is caused by nonlinear de-amplifications for strong

shaking at periods shorter than about 1 s and can either be a physical period-dependent resonant effect, or a modeling artifact and due to the cutoff period of the nonlinear deamplification model. Given that it may be a modeling artifact, Hashash et al. (2020) compute a set of adjusted coefficients and recommend a final model that gives half-weight to each interpretation (dotted and solid lines near 1 s in Figure 13b). This recommendation was not available in time for inclusion in the 2018 NSHM but will likely be considered in future updates.

Other implementation details

When computing hazard, the USGS truncates the distribution of ground motions at 3 standard deviations to avoid unacceptably large ground motions at shorter periods, where the peak of the spectrum is usually observed (Frankel et al., 1996, 2002; Petersen et al., 2008, 2014). In the CEUS, the USGS has historically also capped the median ground motion at 1.5g for PGA and 3g for 0.2-s spectral acceleration, and further truncated the distribution of ground motion at 3g for PGA and 6g for 0.2-s spectral acceleration when these values are less than the 3 standard deviation cutoff. The capping and truncation also recognized that the ground motion values from point-source simulations were not as reliable for magnitude 8 earthquakes at very short distances less than about 20 km (Frankel et al., 1996). This practice was maintained from the 1996 NSHM up through the 2014 NSHM.

For the 2018 NSHM, due to the addition of spectral periods and site classes, we revisited this practice. Prior NSHMs were only concerned with producing mean hazard at three spectral periods for which this capping and truncation practice ensured that ground motions were less than about 2g for a 2% in 50-year return period (the primary return period of concern for building codes of the time). However, this came at the expense of collapsing the upper end of the underlying epistemic uncertainty distribution; multiple GMMs were restricted to the same median, yielding flat-topped response spectra. With the replacement of all CEUS GMMs in the 2018 NSHM, this practice is discontinued for several reasons. First, the NGA-East and updated seed GMMs include a magnitude saturation effect that limits large ground motions as magnitude increases. Second, continuing the practice would necessitate adapting the capping and truncation rules to shorter spectral periods (the peak usually happens below 0.2 s in the CEUS). Third, with an increased focus on quantification of uncertainty by the USGS moving forward, it does not make sense to apply modifications that collapse the uncertainty distribution.

Implications of GMM changes on hazard

This section shows the combined effects of changes in GMM medians, epistemic uncertainty, and standard deviations on hard-rock site conditions over the last two NSHM cycles. We calculated uniform hazard maps for 2% probability of exceedance in 50 years for the CEUS for 0.2- and 1-s spectral periods using the 2014 NSHM source model. One map uses the 2008 GMMs and the other uses the 2014 GMMs. Figure 14 shows the difference and ratios between these two maps at the two spectral periods. Figure 15 shows the same comparison, using the 2014 NSHM source model but paired with the 2014 GMMs and the 2018 GMMs. Note that these maps are not representative of the total change in hazard given the use of the same source model; they only show the effects of GMM updates discussed in this article. Petersen et al. (2019) provide maps that show the total changes in hazard, including source model updates. Difference and ratio maps for more



Figure 14. Differences and ratios in ground motions with 2% probability of exceedance in 50 years hazard level, using the 2008 and 2014 CEUS GMMs (both using the 2014 NSHM source model). Maps are provided for 0.2 and 1 s spectral periods on a uniform hard rock site condition: (a) differences between 2014 and 2008 GMMs at 0.2 s, (b) ratios between 2014 and 2008 GMMs at 0.2 s, (c) differences between 2014 and 2008 GMMs at 1 s, and (d) ratios between 2014 and 2008 at 1 s.

common site classes in the CEUS are not presented because such maps were not developed in the 2008 and 2014 NSHMs due to site class limitations of CEUS GMMs in those cycles (Table 2).

In the 2014 NSHM update, the primary changes to the 2008 CEUS GMMs were the addition or update of three GMMs and the use of a different weighting methodology (Rezaeian et al., 2015). More weight was given to models that attenuate faster with distance ($R^{-1.3}$ geometric spreading). Furthermore, models not applicable to very large distances were removed beyond 500 km. No significant changes were made to epistemic uncertainty or standard deviations. These changes resulted in a decrease in ground motions around the New Madrid seismic zone and slight increases at very large distances compared with the 2008 NSHM, as demonstrated in Figure 14.



Figure 15. Differences and ratios in ground motions with 2% probability of exceedance in 50 years hazard level, using the 2014 and 2018 CEUS GMMs (both using the 2014 NSHM source model). Maps are provided for 0.2 and 1 s spectral periods on a uniform hard rock site condition: (a) differences between 2018 and 2014 GMMs at 0.2 s, (b) ratios between 2018 and 2014 GMMs at 0.2 s, (c) differences between 2018 and 2014 GMMs at 1 s, and (d) ratios between 2018 and 2014 GMMs at 1 s.

In contrast to the 2014 NSHM update, the 2018 NSHM update incorporates significant changes to the median ground motion values (lower for small magnitude events and higher for large magnitude events at middle to large distances; Figures 7 and 8), epistemic uncertainty (higher in all cases but much greater for large magnitudes and middle to large distances; Figures 5b and 9), and aleatory variability (not significantly different; Figure 11). The overall effects of these changes on hazard are shown in Figure 15 for the two periods of 0.2 and 1 s. Ground motions increase in a ring around the New Madrid seismic zone due to the increase in median ground motions and epistemic uncertainty at middle to large distances (60–100 km), but a negligible change in median ground motion at short distances for large magnitude events. The median increase at middle to large distances is

partly due to the updated seed GMMs, but mainly due to the larger NGA-East GMMs as a result of slower attenuations with distance and their subtle representation of Moho reflections (Figures 5b and 9b). The epistemic uncertainty increases for large magnitude events at all distances, resulting in some increase in mean hazard everywhere; but because this increase is even greater at distances of about 100 km (Figures 5b and 9b), it further contributes to the ring around the New Madrid seismic zone. The outer boundary of the ring could be a result of the New Madrid source being less dominant at larger distances. On the contrary, the ground motions in the vicinity of the East Tennessee seismic zone decrease. This is due to the high rate of smaller magnitude events that control the hazard in this region. For smaller magnitudes, the median ground motion is slightly lower than the 2014 NSHM (Figures 7 and 8), and the epistemic uncertainty does not increase as much as it does for large magnitude events. Likewise, in the areas outside of the New Madrid seismic zone, where background gridded seismicity with lower magnitude events control the hazard (e.g. Oklahoma, Virginia, New York), ground motion decreases due to the changes in 2018 CEUS GMMs.

Future work

Starting with the 2018 NSHM, the USGS is putting noteworthy effort into quantifying and publishing the uncertainty in the model. Doing so is aided by improved characterization of epistemic uncertainty like that provided by the NGA-East GMMs. To improve future updates of the NSHM, the NGA-East approach of attempting to represent a continuous distribution of GMMs and its adoption in PSHA should be studied beyond the CEUS. More studies are required to understand the reason for NGA-East GMMs being higher in terms of both medians and epistemic uncertainty at distances greater than 60 km for large magnitude events compared with the 2014 and the updated seed GMMs. Finally, more research is necessary to understand whether the slower attenuations with distance, the subtle representation of the Moho reflections, and the large epistemic uncertainty at middle to large distances are real physical features that should be preserved or unintentional consequences of the NGA-East approach that should be modified.

As also noted by the site-effect model working group, it is preferable to coordinate the development of GMMs and site-effect models in future updates of the NSHM (Stewart et al., 2020). This was not possible in the time frame leading up to publication of the 2018 NSHM. Moving forward, the USGS encourages coordinated development of median ground motion, aleatory variability, and site-effect models. Although the site-effect model presented in this article was a significant improvement in the CEUS, more studies are required to improve this model for future NSHM updates. Examples include considering additional site parameters such as resonant frequency, regionalization of the model for Atlantic and Gulf coastal plains, and inclusion of non-ergodic models.

In the next update of the NSHM, other CEUS considerations include support for additional intensity measures such as PGV, improvements to the nonlinear site-effect model by Hashash et al. (2020), and as always, additions or modifications to existing median GMMs, epistemic uncertainty, aleatory variability, and site-effect models.

Summary

The USGS NSHMs are used in building design applications, which traditionally have been based on ground motions from three spectral periods at one reference site class. The 2018

NSHM update is influenced by the new MPRS recommendations of Project 17 for future generations of building design regulations that call for hazard results from 22 spectral periods and 8 site classes defined by their $V_{_{S30}}$ values. As a result, the USGS GMM selection criteria are updated for the 2018 NSHM and two new suites of GMMs that consider the latest available data and science and are applicable for all periods and site classes of interest are used in the CEUS. These two suites of GMMs are both based on the NGA-East project and result in 31 new GMMs for very hard-rock site conditions. One-third total weight is given to the 14 updated seed GMMs; relative weights for each model are assigned mainly based on the model type and geometric spreading properties. Two-thirds total weight is given to the final 17 NGA-East GMMs, developed based on the NGA-East approach of representing the ground motion space by objectively resampling a continuous probability distribution, using representative seed GMMs as input to a Sammon's mapping process; relative weights for each model are period dependent and are assigned considering the underlying continuous distribution of GMMs. The one-third and two-third weights reflect the range of expert opinions and their confidence in the two suites of models. As a result of this weighting and compared with the previous 2014 NSHM, for large magnitude events, the weighted average of median ground motion increases at middle to large distances but slightly decreases at very short distances (Figure 8). The epistemic uncertainty is better represented and increases everywhere, but is even greater at larger magnitudes and at large distances about 100 km (Figures 9 and 10). A CEUS aleatory variability model is applied to all GMMs, which consists of two different models. Implementation details for the aleatory variability are discussed in this article. Overall, the aleatory variability model is not significantly different from the previous 2014 NSHM (Figure 11). A newly developed site-effect model for the CEUS is used to convert ground motions from very hard rock to other site conditions. Implementation details for this model are provided in this article. Finally, for hard-rock site conditions, the collective effects of changes in the GMM medians, epistemic uncertainty, and aleatory variability on hazard values are illustrated in Figure 15, comparing the 2018 with the 2014 CEUS GMMs. These changes cause an increased ring of ground motions around the New Madrid seismic zone in the 2018 NSHM. In contrast, for small magnitude events, because the median ground motion decreases slightly with little change to uncertainties, ground motions decrease in the vicinity of the East Tennessee seismic zone and other areas where there is a higher rate of smaller magnitude events.

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Additional resources

An electronic supplement is provided with this manuscript that contains additional Figures (A1–A8) for interested readers. The code used to perform PSHA, including GMM calculations that are used to develop many of the figures in this article, is available as part of the *nshmp-haz* software and associated web services and applications at https://doi.org/10.5066/F7ZW1K31 (Powers, 2017).

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Supplemental Material

Supplemental material for this article is available online.

Note

1. Excluding ANC15 (Al Noman and Cramer), which was 1 of the 20 candidate GMMs (see Table 1.2 of PEER, 2015a), but was not recommended as a seed model because of bias in magnitude scaling at low frequencies due to the use of intensity data, particularly at shorter distances (see Table 3.14 in Goulet et al., 2018). It is also noted for ANC15 that the fixed *h* term (the finite fault factor) does not extrapolate well with magnitude.

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