

The 2018 update of the US National Seismic Hazard Model: Ground motion models in the western US

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Abstract

The U.S. 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 continuous U.S. NSHM includes significant changes to the underlying ground motion models (GMMs), most of which are necessary to enable the new multi-period response spectra (MPRS) requirements of seismic design regulations that use hazard results for 22 spectral periods and eight site classes. This article focuses on the GMMs used in the western United States (WUS) and is a companion to a recent article on the GMMs used in the central and eastern United States (CEUS). In the WUS, for crustal and subduction earthquakes, two models used in previous versions of the NSHM are excluded to provide consistency over all considered periods and site classes. To more accurately estimate ground motions at long periods in the vicinity of Los Angeles, San Francisco, Salt Lake City, and Seattle, the 2018 NSHM incorporates deep sedimentary basin depth from local seismic velocity models. The subduction GMMs considered lack basin depth terms and are modified to include an additional scale factor to account for this. This article documents the WUS GMMs used in the 2018 NSHM update and provides detail on the changes to GMM medians, aleatory variability, epistemic uncertainty, and site-effect models. It compares each of these components with those considered in prior NSHMs and discusses their total effect on hazard.

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Introduction

The National Seismic Hazard Model (NSHM), developed by the U.S. 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, 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, for example, Building Seismic Safety Council (BSSC), 2020) over the past several decades. For the conterminous United States (lower 48 states; CONUS), the 1996 USGS NSHM (Frankel et al., 1996) was the first model adopted by the NEHRP Provisions in 1997. The most recent development of the USGS NSHM for CONUS started in 2017 and was completed in 2019, resulting in the 2018 USGS NSHM (Petersen et al., 2020), which was influenced by and accepted for adoption in the 2020 NEHRP Provisions (BSSC, 2020).

In a companion paper, Rezaeian et al. (2021) present a brief history of adopting USGS NSHMs in the NEHRP Provisions and provide details on how the needs of the 2020 NEHRP Provisions (BSSC, 2020) influenced the 2018 USGS NSHM. For development of the 2018 USGS NSHM, the most significant requirement of the 2020 NEHRP Provisions was to incorporate multi-period and multi- V_{S30} (the time-averaged shear wave velocity in the top 30 m of the soil) spectral values (collectively referred to as multi-period response spectra, MPRS). This recommendation was made by Project 17 (BSSC, 2019), a joint committee of BSSC-organized engineers and USGS researchers, to improve the design response spectrum of the NEHRP Provisions and avoid potentially dangerous underestimation of design forces for long-period structures on soft soil site conditions (Kircher et al., 2019; Rezaeian and Luco, 2019). The MPRS depend directly on hazard values of the peak ground acceleration (PGA) and 21 response spectral periods (from 0.01 to 10 s) and eight site conditions (from hard rock, $V_{S30} = 1500$ m/s, to very loose sand or soft clay, $V_{S30} = 150$ m/s), compared with PGA and 2 spectral periods (0.2 and 1 s) and one reference site condition (soft rock, $V_{S30} = 760$ m/s) used in previous cycles of the NEHRP Provisions.

The USGS uses NSHMs to compute probabilistic seismic hazard over 0.05° spaced grids spanning the CONUS. The two fundamental components of an NSHM are (1) seismic source models, which include finite fault and background or smoothed seismicity models that forecast the occurrence rates and magnitudes of potential seismic events, and (2) ground motion models (GMMs), which provide estimates of the ground shaking (i.e. median ground motions and their uncertainties) for a given seismic event. Both components are updated in the 2018 NSHM; this article focuses on the second component, the GMMs, including comparisons and implementation details not covered in Petersen et al. (2020). For details of the 2018 source model, see Boyd et al. (2015), Frankel et al. (2015), Moschetti et al. (2015), Powers and Field (2015), and Petersen et al. (2020). The USGS uses a set of GMM selection criteria to vet published GMMs and select those most appropriate for use in each NSHM update. In response to the Project 17 recommendation that

the NSHM support development of MPRS, the USGS modified the selection criteria for the 2018 update.

The geology, tectonics, and earthquake potential represented in the NSHM CONUS source model are diverse, ranging from the stable continental setting of the central and eastern United States (CEUS) to the active tectonic setting, including subduction zones, in the western United States (WUS). Similar to previous NSHMs for the CONUS, the GMMs used in the 2018 NSHM consist of four groups: those applicable to earthquakes in (1) the stable craton and margin of the CEUS, (2) the active shallow crust of the WUS (including that of the Pacific Northwest), (3) the Cascadia subduction zone interface in the Pacific Northwest, and (4) the Cascadia subduction zone intraslab setting. Rezaeian et al. (2021) elaborate on the CEUS GMM updates in the 2018 NSHM. Here, we focus on the changes made to the other three GMM groups in the WUS and the influence these changes have on seismic hazard.

The new MPRS requirements and advances in our understanding and ability to quantify long-period ground motions in deep sedimentary basins required the USGS to consider including such effects in the 2018 update (Petersen et al., 2020). Whereas basin effects are often negligible at soft rock reference site conditions and short periods, they can more than double ground motions at soft soil sites and long periods (e.g. Frankel et al., 2002; Hartzell et al., 1997). The 2018 NSHM therefore incorporates, for the first time, spatially varying basin depth data to better estimate basin effects for long-period ($T \geq 1$ s) ground motion due to the reflecting, refracting, and focusing of seismic waves in basin structures. The 2018 update considers basin depth when computing hazard at periods greater than 0.5 s in the vicinity of Los Angeles, San Francisco, Salt Lake City, and Seattle, for which sufficiently developed shear wave velocity models exist.

The 2018 NSHM update did not consider new GMMs for use in the WUS. Although new subduction zone models were available in time for inclusion in the NSHM (e.g. Abrahamson et al., 2018; Zhao et al., 2016a, 2016b), the BSSC has recently adopted a more compressed update schedule (4–5 years instead of the usual 6 years between prior updates), and the NSHM project decided to forego updating the subduction GMMs until the 2023 update when the NGA-Subduction GMMs will be available (Bozorgnia, 2020).

In this article, we briefly review updates to the GMM selection criteria (Rezaeian et al., 2021) that stem from the recommendation of Project 17 to use MPRS and discuss limitations of previous WUS GMMs in terms of period and V_{S30} . We then review resultant changes to the structure and implementation of both shallow crustal and subduction GMMs considered in the WUS for the 2018 NSHM update. Each section includes discussion of (1) the removal of GMMs from the NSHM logic tree, (2) the implications of these changes in the context of the individual GMM medians, their weighted combinations, standard deviations, and epistemic uncertainty, and (3) the consideration of deep basin effects, including modifications to crustal GMMs that have built-in basin-effect terms for all periods and depths, and the addition of scale factors to subduction GMMs that lack basin-effect terms. We conclude with an evaluation of the impact of these GMM changes on estimated hazard relative to the previous 2008 (Petersen et al., 2008, 2014) NSHMs (Petersen et al., 2014, 2015), which are still in use by various building codes and guidelines.

GMM selection criteria

GMMs (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). GMMs typically provide equations for (1) the median value of horizontal pseudo-spectral acceleration (SA) assuming a lognormal distribution and (2) an estimate of the standard deviation (or aleatory variability). These equations are functions of spectral period, source parameters such as earthquake magnitude, path parameters such as source-to-site distance, and local site parameters such as V_{S30} . Differences in model parameters and functional forms depend on the type of earthquake, its tectonic setting, and the properties of the path and site. For example, in active tectonic settings such as the WUS, where recordings from past earthquakes are relatively plentiful, the seismic source inventory is well-defined, and GMMs include a number of parameters to characterize source and path effects, such as faulting style or a hanging wall indicator. Where data from well-defined sedimentary basins are available, some GMMs characterize the expected local site effects using basin depths in addition to V_{S30} . Aleatory uncertainty represents the natural variability in ground motion intensities for a given set of model parameters, in contrast to epistemic uncertainty that represents uncertainty in modeling choices due to limitations in knowledge and data (Toro et al., 1997). The model of aleatory uncertainty can be a constant for a given spectral period, or in some cases it is dependent on earthquake magnitude, and in very few cases a function of distance or V_{S30} . The NGA-West2 GMMs (Bozorgnia et al., 2014), used for crustal earthquake sources in the 2014 and 2018 updates of the NSHM in the WUS, provide models for the RotD50 component of horizontal SA (Boore, 2010), which represents the 50th-percentile horizontal ground motion for all possible rotation angles independent of the orientation of the recording instrument. The GMMs used for subduction sources in the NSHM provide models for the GMRotI50 component of horizontal SA, or geometric mean (Boore et al., 2006). Both intensity measures are averages and are therefore used interchangeably, as in previous NSHMs.

The USGS GMM selection criteria were formally published as a part of the 2014 NSHM update (see Petersen et al., 2014: 109–110; Rezaeian et al., 2015: S61–S62) and are designed to be general and flexible to accommodate the continued evolution of GMMs. There are 16 criteria, grouped into four categories: (1) general requirements, (2) database scope, (3) parameters and applicability range, and (4) functional form and modeling procedure. Given the new MPRS requirement of the 2020 NEHRP Provisions, it was necessary to update these criteria for development of the 2018 NSHM (Rezaeian et al., 2021). Specifically, 2 of the 16 criteria were updated: (1) the *Basic Requirement* was updated to specify support for PGA and 21 response spectral periods, up from PGA and two periods in 2014; and (2) the *Site Condition Requirement* was updated to specify support for a minimum of eight V_{S30} values spanning the range of NEHRP site classes, up from one site class in 2014 (Rezaeian et al., 2021). As a result of these updates, only GMMs that are applicable or that can be reasonably extrapolated to all periods and site classes of interest are selected for the 2018 NSHM CONUS update. The updated spectral period and site class requirements are outlined in Table 1; we refer the reader to Rezaeian et al. (2021) and Shumway et al. (2021) for more thorough discussions of the changes.

Table 1. Minimum requirements for spectral periods and site classes

	2014 and prior NSHMs	2018 and future NSHMs*
Periods (s)	0 (PGA), 0.2, 1	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
V_{S30} , m/s (NEHRP 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)

PGA: peak ground acceleration; NEHRP: National Earthquake Hazard Reduction Program.

*See Shumway et al. (2021) for more details on the selection of additional periods and site classes.

Limitations of 2014 WUS GMMs in terms of period and V_{S30}

For the 2018 NSHM update, it was important to select GMMs that are applicable or that can be reasonably extrapolated to all periods and site conditions of interest shown in Table 1. The list of WUS GMMs selected for the 2014 and 2018 NSHM updates, along with their references, acronyms, applicability ranges with respect to period and V_{S30} , and logic tree weights, are given in Table 2. For the 2018 update, consideration of deep basin effects at long periods necessitated the use of GMMs that include a basin-effect term; for those GMMs without an explicit basin-depth term, we apply an appropriate scale factor.

Rezaeian et al. (2014) reviewed the five 2014 NSHM GMMs for active crustal earthquakes in the WUS. As shown in Table 2, the I14 GMM used in the 2014 NSHM is not applicable to site classes CD or softer ($V_{S30} \leq 450$ m/s, Table 1), whereas the other four GMMs could be reasonably extrapolated to all site classes. In addition, although Rezaeian et al. (2014) found I14 to scale reasonably with distance out to 300 km, I14, as published, only recommends the model be used out to 150 km. I14 also lacks a native basin-effect term. The I14 GMM is therefore removed from the 2018 update and its weight is redistributed evenly among the other four GMMs as was done in an interim update to the 2014 NSHM by Shumway et al. (2018).

Rezaeian et al. (2015) reviewed the 2014 NSHM GMMs for subduction earthquakes in the WUS. As shown in Table 2, all of the AB03 GMMs used in the 2014 NSHM are not applicable to periods beyond 3 s. The models were also found to decay too slowly with distance for interface events at periods above 1 s and distances greater than 100 km (Shumway et al., 2018). Moreover, the AB03-CAS model underestimates ground motions at short periods and distances less than 100 km, which has practical consequences for Seattle and other urban centers of the Pacific Northwest. For these reasons, the AB03 models are removed from the 2018 NSHM and the weights of the remaining GMMs are adjusted. This leaves three GMMs for interface and two GMMs for intraslab earthquakes. Furthermore, because none of the subduction GMMs has a basin-depth term, modifications are made using crustal amplification factors and guided by simulations such as the Cascadia M9 project (Frankel et al., 2018).

Table 2. Ground motion models in the 2014 and 2018 NSHMs

2014 NSHM WUS GMMs	Abbreviation	Period range	Site class or V_{S30} (m/s)	2014 Weight	2018 Weight
WUS active shallow crustal GMMs					
Abrahamson et al. (2014)	ASK14	PGA–10 s	180–1000	0.22	0.25
Boore et al. (2014)	BSSA14	PGA–10 s	150–1500	0.22	0.25
Campbell and Bozorgnia (2014)	CB14	PGA–10 s	150–1500	0.22	0.25
Chiou and Youngs (2014)	CY14	PGA–10 s	180–1500	0.22	0.25
Idriss (2014)	I14	PGA–10 s	450–1200	0.12	0
WUS subduction interface GMMs					
Abrahamson et al. (2016)	BCHydro12	PGA–10 s	180–1500 [†]	0.30	0.3334
Atkinson and Boore (2003)—Global	AB03-GL	PGA–3 s	BC, C, D, E	0.10	0
Atkinson and Macias (2009)	AM09	PGA–10 s	180–1300*	0.30	0.3333
Zhao et al. (2006)	Zhao06	PGA–5 s	BC, C, D	0.30	0.3333
WUS subduction intraslab GMMs					
Abrahamson et al. (2016)	BCHydro12	PGA–10 s	180–1500 [†]	0.333	0.5
Atkinson and Boore (2003)—Cascadia	AB03-CAS	PGA–3 s	BC, C, D, E	0.1665	0
Atkinson and Boore (2003)—Global	AB03-GL	PGA–3 s	BC, C, D, E	0.1665	0
Zhao et al. (2006)	Zhao06	PGA–5 s	BC, C, D	0.334	0.5

NSHM: National Seismic Hazard Model; WUS: western United States; PGA: peak ground acceleration.

*Model delegates to Boore and Atkinson (2008).

[†]Based on the relevant crustal amplification model and the distribution of V_{S30} in the BC Hydro database (written communication with BCHydro12 authors, 17 April 2020).

Although Zhao06 supports a more limited range of site classes and spectral periods up to 5 s, the 2018 NSHM preserves this GMM to avoid reducing the intraslab GMM logic tree (epistemic uncertainty) to a single model. We found Zhao06 to reasonably extrapolate to longer periods and maintain that the Zhao06 site-effects implementation is adequate as long as other GMMs are also considered (see section “2018 Update of WUS Subduction GMMs” below). The consequences of eliminating I14 and AB03 are discussed, crustal GMMs are scrutinized for various basin depths, and modifications to subduction GMMs for deep basin effects are documented in the following section.

2018 update of WUS crustal GMMs

For shallow crustal earthquakes in the active tectonic setting of the WUS, the five NGA-West2 GMMs (Bozorgnia et al., 2014) were used in the 2014 NSHM (Rezaeian et al., 2014) for sources up to 300 km from a site and spanning magnitudes from 5 to 8.3 (Moschetti et al., 2015; Powers and Field, 2015). Four GMMs—ASK14, BSSA14, CB14, and CY14—were assigned an equal weight of 0.22; the fifth, I14, received a lower weight of 0.12 for reasons described in Rezaeian et al. (2014). The 2018 NSHM drops I14, as previously discussed, to maintain consistency across all site classes and assigns an equal weight of 0.25 to the remaining models.

The range of applicable V_{S30} does not extend to site classes E ($V_{S30} = 150$ m/s) and A ($V_{S30} = 1500$ m/s) for all four crustal GMMs (Table 2). ASK14 is not recommended for

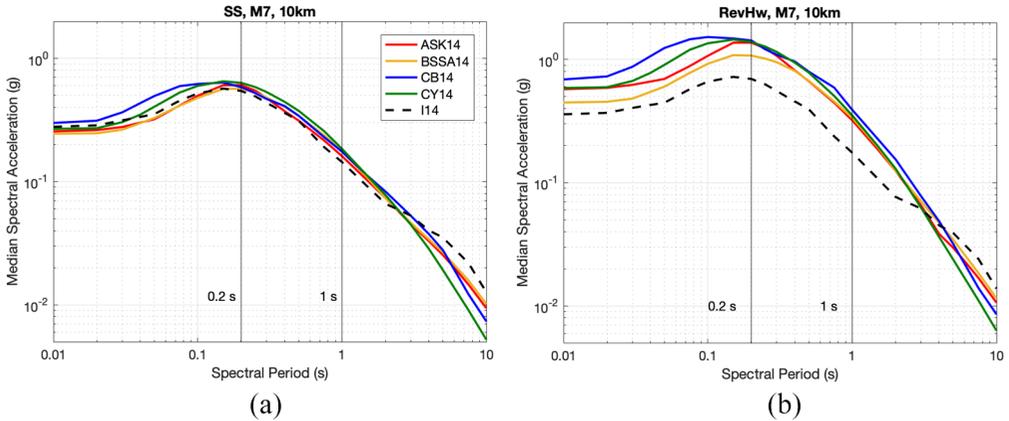


Figure 1. Median GMMs used in the 2014 and 2018 NSHMs for a magnitude 7 event on a soft rock site ($V_{S30} = 760$ m/s; default basin effect; $Z_{tor} = 1$ km) at a distance of 10 km (a) for a strike-slip (SS) fault with 90° dip, and (b) over the hanging wall side of a reverse fault with 45° dip (RevHw). Vertical lines indicate 0.2- and 1-s spectral periods.

site classes E or A, and CY14 is not recommended for site class E. Since these site classes are very rare in the WUS, after discussions with experts and BSSC engineers, it was decided to extrapolate all four crustal GMMs and use them when calculating hazard for site classes E and A until better models become available. Further site response validation studies are recommended, which may lead to changes in future NSHM updates.

Consequences of removing I14

For a soft rock site ($V_{S30} = 760$ m/s) near a strike-slip fault (rake = 0° , dip = 90°), median values of I14 are in line with the other four GMMs, as shown in Figure 1a for a magnitude 7 event at 10-km epicentral distance. However, at short distances and large magnitudes over a reverse fault (rake = 90° , dip = 45°) and at short to moderate periods, I14 exhibits considerably lower ground motion owing to a smaller hanging-wall effect as shown in Figure 1b. One reason for this is that the other four NGA-West2 hanging-wall terms are conditioned on either or both R_{JB} (the distance from the surface projection of a fault) and R_χ (the perpendicular distance from the surface trace of a fault), whereas I14 applies a uniform scale factor irrespective of distance for reverse faults that decreases to zero at long periods. This results in more refined modeling of near-field, hanging-wall terms by the other four models and the increases in ground motions, relative to I14, illustrated in Figure 1b. In further consideration of removing I14, the use of I14 for large magnitudes, short distances, and site classes DE and below can lead to up to a factor of 2 increase in ground motion at short periods (not shown in this article).

The 2018 and 2014 weighted combinations of median GMMs at 0.2 and 1 s versus distance for a magnitude 7 event are plotted in Figure 2. Figure 2 also includes the combined 2008 GMMs (three NGA-West1 GMMs; Petersen et al., 2008) and shows that the changes from 2008 to 2014 were much more significant compared to the changes from 2014 to 2018 for soft rock site conditions. Removal of I14 in the 2018 NSHM causes little change in weighted average median ground motion at sites near strike-slip faults and leads to small increases in near-field ground motion over reverse faults for soft rock site conditions

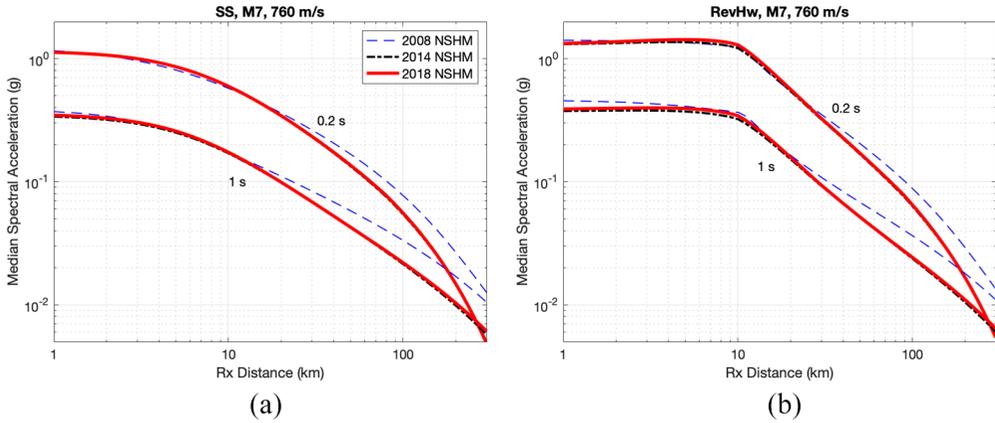


Figure 2. Weighted combinations of 0.2- and 1-s median WUS crustal GMMs in the 2018, 2014, and 2008 NSHMs for a magnitude 7 event on a soft rock site ($V_{S30} = 760$ m/s; default basin effect; $Z_{cor} = 1$ km) for (a) a strike-slip fault and (b) over the hanging wall side of a reverse fault with 45° dip (RevHw).

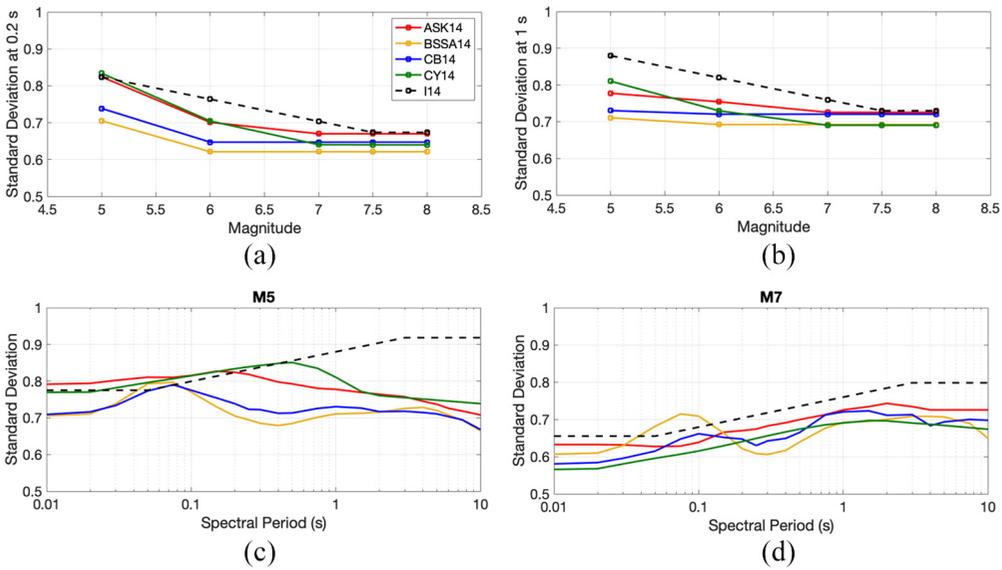


Figure 3. Standard deviations in natural log units of WUS crustal GMMs used in the 2014 and 2018 NSHMs plotted versus magnitude for (a) 0.2-s and (b) 1-s periods, and versus period for (c) a magnitude 5 and (d) a magnitude 7 event. The plots are for a strike-slip fault at 10 km on a soft rock site (Table 1).

(Figure 2). These changes are specific to a soft rock site condition, and if softer site classes were considered in the 2014 NSHM, removal of I14 from the 2018 NSHM would have had a more significant impact on design ground motions.

The I14 standard deviation is generally higher than that of the other four models at most periods and site classes, as shown in Figure 3, and is much higher at smaller magnitudes and longer periods. In probabilistic hazard calculations, increases in average median

ground motions near reverse and normal faults is balanced by the decrease in average standard deviations of the four crustal GMMs arising from the removal of I14.

Epistemic uncertainty for crustal GMMs

Epistemic uncertainty characterizes the range of plausible alternative input model assumptions and parameterizations given limitations in knowledge; these alternatives are represented by logic trees of GMMs and their associated weights. In hazard space, the epistemic uncertainty in GMMs yields a suite of hazard curves with a weighted average value that is typically adopted in forward applications such as the USGS hazard maps. Consistent with the 2008 NSHM (NGA-West1 GMMs) and 2014 NSHM (NGA-West2 GMMs), an additional magnitude- and distance-dependent epistemic uncertainty term is added to the WUS crustal GMMs in the 2018 NSHM (see Table 3 in Rezaeian et al., 2014). The 2008 NSHM assumed a 50% increase in ground motion (i.e. 1.5 scale factor, equivalent to $\ln(1.5) = 0.4$ additive factor in log-space) due to the application of largely California-based GMMs to the Pacific Northwest and interior WUS. The NGA-West crustal GMMs include little or no strong motion data for very large earthquakes outside California, and one could claim that additional epistemic uncertainty is also needed within California for sources that have not yet been recorded, for example, a large magnitude 7.8 San Andreas earthquake. The 2014 NSHM followed the same assumption for the least populated magnitude-distance bin (magnitudes greater than 7 and distances less than 10 km) and reduced the factor for other bins proportional to the number of available earthquakes. In the 2018 NSHM, similar to the 2014 NSHM, this additional epistemic uncertainty scales with the sparseness of the NGA-West2 database (larger values at short distances and large magnitudes) and also accounts for the close interactions between the four NGA-West2 modeling groups. Note the similarity of the models in the response spectra of Figure 4, except at long periods where they diverge. At softer soil sites, there is greater variability between the NGA-West2 GMMs due to differences in site-effect models, as discussed later in the section “Deep Sedimentary Basin Effects in WUS Crustal GMMs.”

The additional epistemic uncertainty is modeled as a three-point distribution about the mean with symmetric weights [0.2, 0.6, 0.2]. It is shown in Figures 4 and 5 to yield an average factor of 4 increase in the range of ground motion (pink bars relative to dark blue bars). Note that the vertical scale is logarithmic in Figure 5 and that the range in each subplot, while different, spans a similar order of magnitude for easy comparison; the dashed lines show weighted averages of median ground motions. Application of this symmetric distribution (in log space) of median ground motions in the NSHM yields an increase of 2%–3% in uniform hazard. For reference, Figures 4 and 5 also show the range of ground motion spanned by the GMMs used in the CEUS for the 2018 NSHM (see similar figures for CEUS in Rezaeian et al., 2021), which is a factor of 3–4 greater than that spanned by the epistemic uncertainty branches of the WUS GMMs (light blue bars relative to pink bars). The WUS crustal GMMs span a much smaller range of ground motion, as expected, owing to a richer WUS earthquake catalog and thereby less epistemic uncertainty as compared to CEUS. Note the steps in ground motion at 10 and 30 km in Figure 4b due to the distance dependence in the epistemic uncertainty logic tree branches.

Deep sedimentary basin effects in WUS crustal GMMs

Long-period ground motion is highly sensitive to basin depth at soft sites. Ground motion observations and three-dimensional (3D) simulations demonstrate that deep sedimentary

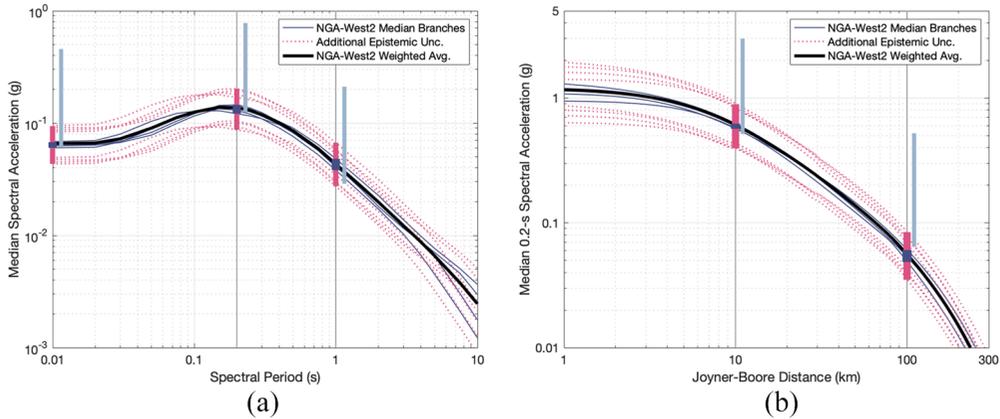


Figure 4. Medians of the four WUS crustal GMMs in the 2018 NSHM for a magnitude 7 event on a soft rock site ($V_{S30} = 760$ m/s; default basin effect) (a) versus period at a distance of 50 km, and (b) versus distance at 0.2-s spectral period. In both figures, the NGA-West2 GMMs as published are shown in dark blue, and the models that consider additional magnitude- and distance-dependent epistemic uncertainty are shown as pink dotted lines. Vertical dark blue and pink bars indicate the range of ground motion at different spectral periods and distances for the two populations of GMMs and are referenced in Figure 5. For reference, both (a) and (b) also show the range of epistemic uncertainty in median ground motion in the NSHM CEUS GMMs with light blue bars (Goulet et al., 2018; Rezaeian et al., 2021) also for a magnitude 7 event on a soft rock site.

basins amplify long-period ground motions due to the reflecting, refracting, and focusing of waves trapped within the basin structure (e.g. Aagaard et al., 2008; Frankel et al., 2002, 2018; Graves et al., 2011; Hartzell et al., 1997; Moschetti et al., 2017; Stephenson et al., 2006). The WUS crustal GMMs account for such basin effects with terms that are parameterized by either Z_1 or $Z_{2.5}$ (the depth to a shear-wave velocity of 1 or 2.5 km/s). These parameters are roughly correlated with depth to bedrock and depth to crystalline basement, respectively; ASK14, BSSA14, and CY14 use Z_1 , and CB14 uses $Z_{2.5}$.

The WUS crustal GMM basin-effect terms were developed using empirical data from northern and southern California with very high scatter. Each term is conditioned on V_{S30} and provides a function relating V_{S30} to an expected, or default, basin depth. In the absence of an estimated basin depth value, the site term of each GMM (a function of V_{S30} , not including Z_1 or $Z_{2.5}$) is assumed to capture average basin effects. When a basin depth is known, however, the basin-effect term is expressed as an adjustment to the default V_{S30} -based site term. The basin scale factors of each of the four GMMs (dashed lines) and the USGS modified models (solid lines) at 5-s spectral period, where basin effects are expected to be significant, are shown in Figure 6. The Z_1 -based models apply amplification or de-amplification relative to the V_{S30} -scaling depending on whether the basin depth is deeper or shallower, respectively, than the default V_{S30} -based value. CB14 uses a fixed-depth scaling model (i.e. there can be amplification or de-amplification in the default site term) with no scaling between 1 and 3 km (dashed, gray line in Figure 6). But, like the Z_1 -based models, CB14 computes any basin-effect scaling relative to the V_{S30} -based default.

In the 2018 NSHM, spatially varying Z_1 and $Z_{2.5}$ values from local seismic velocity models are used as inputs to the GMMs. This was done in four urban regions with deep basins for which detailed velocity models exist: Los Angeles (Lee et al., 2014), San Francisco

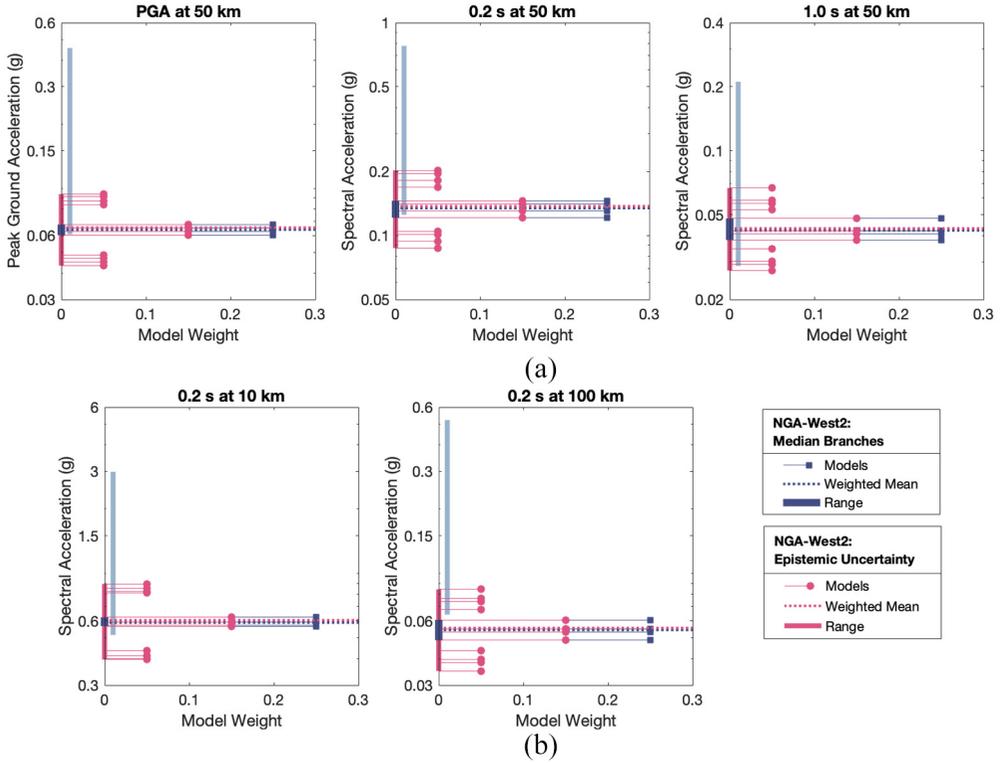


Figure 5. Epistemic uncertainty for the four WUS crustal GMMs represented by the range and distribution of ground motions at vertical cross sections of Figure 4 for (a) three example periods, PGA, 0.2 and 1 s, at 50 km and (b) two example distances, 10 and 100 km, at 0.2-s period, both for a magnitude 7 event on a soft rock site ($V_{S30} = 760$ m/s; default basin effect). For reference, (a) and (b) also show the range of epistemic uncertainty in median ground motion in the NSHM CEUS GMMs with light blue bars (Goulet et al., 2018; Rezaeian et al., 2021) also for a magnitude 7 event on a soft rock site.

(Aagaard et al., 2008), Salt Lake City (Magistrale et al., 2008), and Seattle (Stephenson, 2007; Stephenson et al., 2017); see Rukstales and Petersen (2019) for consolidated values. However, the WUS crustal GMM basin-effect terms were regressed on a velocity structure representative of California. This causes problems in Seattle where Z_1 values from the local velocity model are generally less than 500 m due to the presence of shallow, stiff glacial tills (Stephenson et al., 2017), and the Z_1 -based GMMs predict, at most, weak amplification from the Seattle basin. On the contrary, $Z_{2.5}$ more accurately describes the deep sedimentary structure in the greater Seattle region. To address this, we regress for an effective depth, $Z_{1,eff}$, which is a function of $Z_{2.5}$ using two databases: (1) the NGA-West2 site database (Ancheta et al., 2014; all stations and denoted A14) and (2) basin depths from a recent southern California seismic velocity model (Lee et al., 2014; denoted L14). The relations are as follows:

$$Z_{1,A14} = 0.1146Z_{2.5} + 0.2826 \quad (1)$$

$$Z_{1,L14} = 0.0933Z_{2.5} + 0.1444 \quad (2)$$

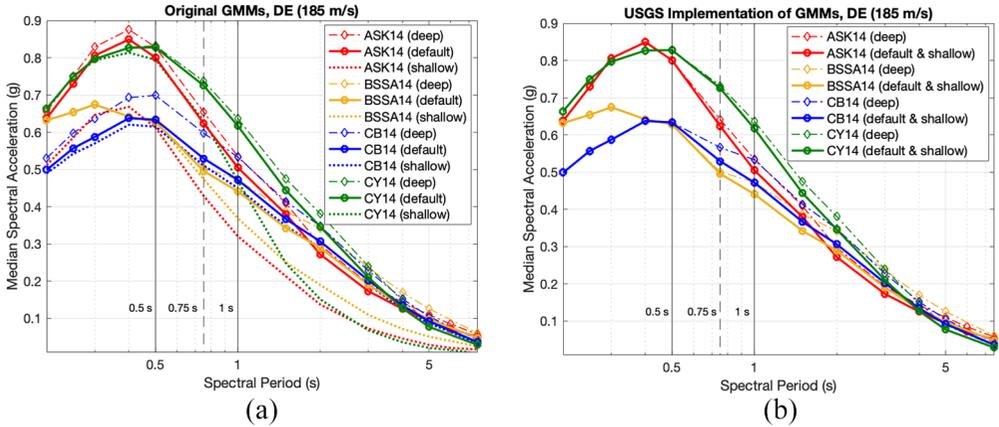


Figure 7. Median ground motion from the four WUS crustal GMMs at a DE site class for (a) the models as published and (b) the 2018 USGS implementation, considering the different basin depths listed in Table 3. The ground motion shown is for a magnitude 7 event on a strike-slip fault at a distance of 10 km.

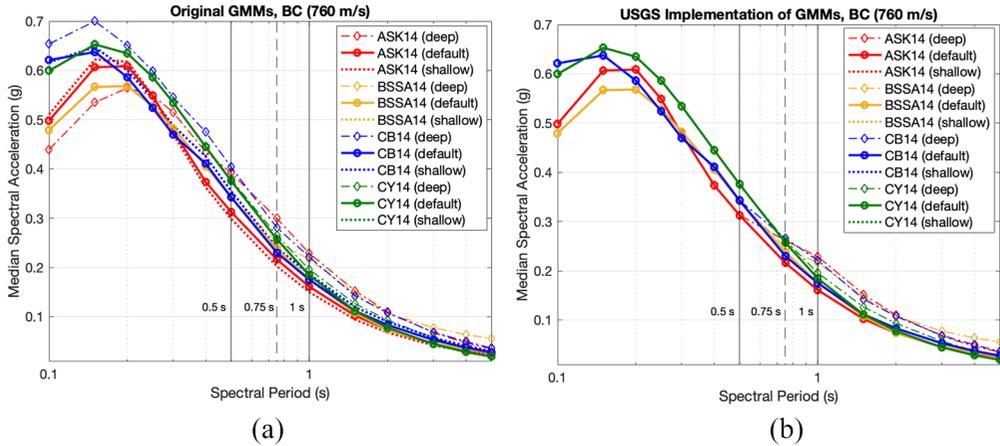
models contrasts with observations of basin-edge amplification due to shear wave focusing and basin-edge generated surface waves (see Petersen et al., 2020, for examples). The 2018 NSHM therefore defines “deep” basins as $Z_{2.5} \geq 3.0$ km when applying CB14 and its approximate equivalent $Z_1 \geq 0.5$ km when applying ASK14, BSSA14, and CY14 (Equations 1 and 2). Basin depths derived from local seismic velocity models are used only if $Z_{2.5}$ is deeper than 3 km (with a linear depth taper between 1 and 3 km) or Z_1 is deeper than 0.5 km (with a linear depth taper between 0.3 and 0.5 km), above which the 100% weight is given to the V_{S30} -based default basin term. For sites with shallow depths and everywhere outside the regions where depth data are considered, the V_{S30} -based default basin effect is used, thereby providing a smooth transition between the basin and surrounding regions (see Figure 7 in Petersen et al., 2020, and Figures 1 and 7 in Shumway et al., 2021, for basin polygon maps).

The USGS basin-effect model is also only applied to spectral periods ≥ 1 s, with a scaled value at 0.75 s to maintain a smooth spectrum between 0.5 and 1 s. This limited and conservative depth- and period-dependent modeling approach was guided by available observations and results from simulations in Seattle and southern California (e.g. Frankel et al., 2002, 2018). In developing the model, we considered applying a basin amplification-only effect when basin depths were deeper than the V_{S30} -based default values, but ultimately preferred a model that was independent of V_{S30} . Note that the USGS model results in minor de-amplification at softer site classes (Figure 6, solid lines) over the depth taper zone. The period dependence of the USGS model is consistent with BSSA14 and CY14 that both suppress any additional basin-effect scaling at short periods.

In the 2014 NSHM and in regions outside of the deep basins considered in the 2018 NSHM, the Z_1 and $Z_{2.5}$ terms are treated as unknowns, which for the target site class of $V_{S30} = 760$ m/s, correspond to Z_1 depths of 0.048 (ASK14), 0.041 (BSSA14), 0.041 (CY14) km, and $Z_{2.5}$ depths of 0.607 (CB14) km (first row in Table 3). Figures 7 and 8 show response spectra for a magnitude 7 event at a distance of 10 km for the different combinations of site class and basin depth that are listed in Table 3. Two site classes BC

Table 3. Site class and basin-depth combinations for plots in Figures 7 and 8

“Site Class-Basin” scenarios	V_{S30} (m/s)	Z_1 (km) (ASK14, BSSA14, CY14)	$Z_{2.5}$ (km) (CB14)
BC-default basin (V_{S30} -based)	760	(0.048, 0.041, 0.041)	0.607
BC-deep basin (Long Beach)	760	0.704	3.83
BC-shallow basin (San Francisco)	760	0.025	0.85
DE-default basin (V_{S30} -based)	185	(0.497, 0.513, 0.513)	3.06
DE-deep basin (Long Beach)	185	0.704	3.83
DE-shallow basin (San Francisco)	185	0.025	0.85

**Figure 8.** Median ground motion of the four WUS crustal GMMs at a BC site class for (a) the models as published and (b) the 2018 USGS implementation, considering the different basin depths listed in Table 3. The ground motion shown is for a magnitude 7 event on a strike-slip fault at a distance of 10 km.

and DE (Table 1), representative of soft rock and a soft site, respectively, are considered. The three selected basin depths for each site class correspond to the V_{S30} -based default values, an example of a basin deeper than default values for site class DE (based on a location in Long Beach, CA), and an example of a basin shallower than default values for site class DE (based on a location in San Francisco, CA).

Figure 7 shows site class DE, for which significant default basin effects are expected; Figure 8 shows site class BC, for which basin effects are expected to be much lower. The broader distribution of ground motions in Figure 7a relative to Figure 8a again shows that the site amplification models of the NGA-West2 GMMs exhibit greater epistemic uncertainty than do the median models for soft rock sites.

Figures 7b and 8b show the USGS modified crustal GMMs for site classes DE and BC, respectively, where ground motions are the same for “default” and “shallow” depths but amplified for “deep” basins at long periods. Although the USGS model restricts basin effects to long periods to maintain a smooth spectral shape, basin effects are suppressed at 0.5 s and below, given a log-period interpolated weight (≈ 0.5) at 0.75 s, and are fully considered at 1 s and above (note the vertical lines in Figures 7 and 8 that mark these three periods). Note also that in Figures 7a and 8a, BSSA14 and CY14 both exhibit no

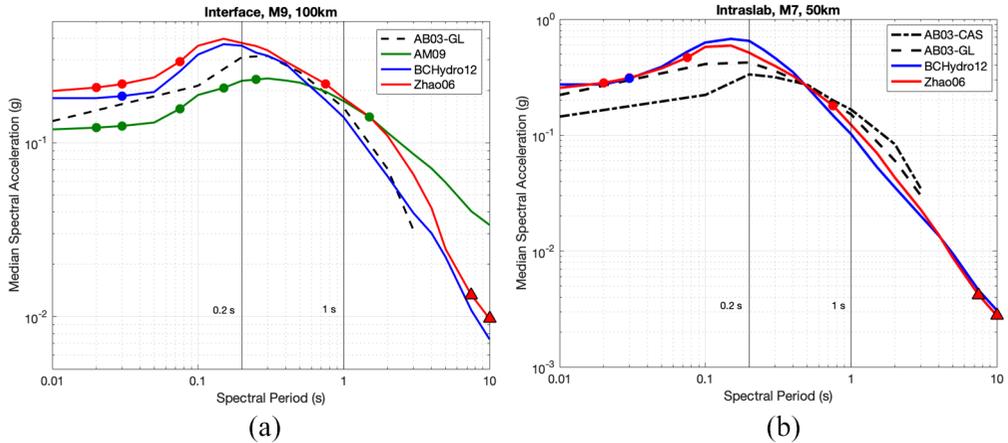


Figure 9. Median ground motion for WUS subduction GMMs versus period at a soft rock site ($V_{S30} = 760$ m/s) for (a) a magnitude 9 interface event at 100-km rupture distance, R_{RUP} , and (b) a magnitude 7 deep intralab event at 50-km rupture distance, R_{RUP} . Dots mark spectral periods computed via interpolation of adjacent periods; triangles indicate extrapolated periods.

variation from the default V_{S30} -based depth due to the deliberate suppression of basin effects at short periods.

2018 update of WUS subduction GMMs

Four GMMs were used in the 2014 NSHM to estimate ground shaking for both subduction interface events up to 1000 km from a site and magnitudes as high as 9.34, and deep subduction intralab events up to 300 km from a site and magnitudes up to 7.95 (Table 2; Frankel et al., 2015; Rezaeian et al., 2015). As published, the AB03 GMM, which was used for both event types, is only applicable to periods up to 3 s and cannot be reasonably extrapolated to longer periods, among other issues discussed in the section “Limitations of 2014 WUS GMMs in Terms of Period and V_{S30} .” After consulting with the modelers, this GMM was removed as was also done in an interim update to the 2014 NSHM (Shumway et al., 2018). The Zhao06 GMM is also limited in its applicable period range; it is missing coefficients for 0.02, 0.03, 0.075, and 0.75 s and is only applicable up to 5 s SA. The Zhao06 site-effect model, as published, is also limited in the range of site classes it supports. The model, as implemented in past and present NSHMs, is a step function of V_{S30} that reflects the period-dependent coefficients for site classes BC, C, and D. The Zhao06 site term is therefore constant over ranges of V_{S30} spanning each supported site class. For missing short periods, we log–log interpolate SAs from adjacent periods. For the long periods, 7.5 and 10 s, we extrapolate median ground motion and aleatory variability using the ratio of Zhao06 to the other GMMs considered at 5 s period. AM09 and BCHydro12 are also limited in their support of some short spectral periods. AM09 does not include coefficients for 0.02, 0.03, 0.075, 0.15, 0.25, and 1.5 s SA, and BCHydro12 does not include 0.03 s SA. Medians and sigmas for missing periods for these models are also computed via log–log interpolation of SAs from adjacent periods. The AM09 site-effect model uses that of the Boore and Atkinson (2008) NGA-West1 GMM. For consistency with

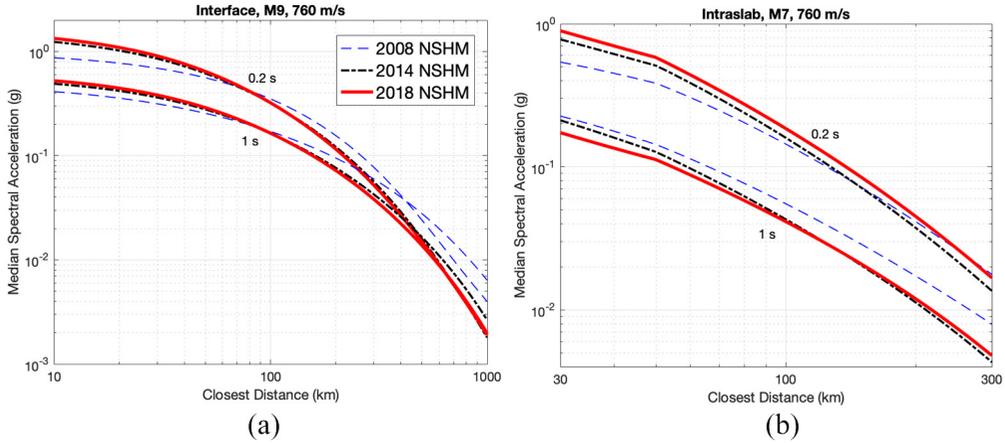


Figure 10. Weighted combination of median WUS subduction GMMs versus rupture distance, R_{RUP} , at a soft rock site ($V_{S30} = 760$ m/s) for (a) a magnitude 9 interface event and (b) a magnitude 7 deep intraslab event at 50-km hypocentral depth (Z_{HYP}).

prior NSHMs and to avoid depleting the subduction GMM logic trees, the 2018 NSHM preserves the Zhao06 and AM09 implementations.

Consequences of removing AB03

The interface variant of the AB03-GL GMM is fairly similar in response spectral shape to the other GMMs considered in the 2014 NSHM (Figure 9). For a magnitude 9 interface event at a distance of 100 km, Figure 9a shows AB03-GL to be centered among the other GMMs except at long periods. At shorter distances, however, AB03-GL is lower than the other GMMs, and at distances greater than 100 km, it is higher. This behavior is consistent for both short and long spectral periods as illustrated in Figure 10a by the crossover in ground motion at about 100 km between the weighted combinations of the 2014 and 2018 subduction interface GMMs. Note also that AM09 median ground motion is significantly higher at long periods, possibly due to the use of stochastic simulations to model low-frequency shaking.

For intraslab events, predicted ground motions of the AB03-CAS and AB03-GL models are significantly lower at short periods and somewhat higher at long periods relative to other GMMs (Figure 9b). This behavior is consistent across all distance ranges as illustrated in Figure 10b by the increase in the 2018 weighted combination of deep intraslab GMMs, relative to the 2014 values, at 0.2 s. An overall decrease at 1-s spectral period is observed at short distances. For both interface and intraslab events, the change in ground motion from 2014 to 2018 is significantly less than that arising from comparison with the 2008 NSHM GMMs, which included the Youngs et al. (1997) GMM and higher magnitude saturation thresholds for the intraslab AB03 GMM (Rezaeian et al., 2015).

Aleatory variability for AB03 is generally lower than for the other subduction GMMs; although at long periods, standard deviation of the AB03-GL interface is about the same as the other interface GMMs (Figure 11). Removal of AB03, therefore, results in increases to standard deviation for subduction interface and intraslab events in the 2018 NSHM.

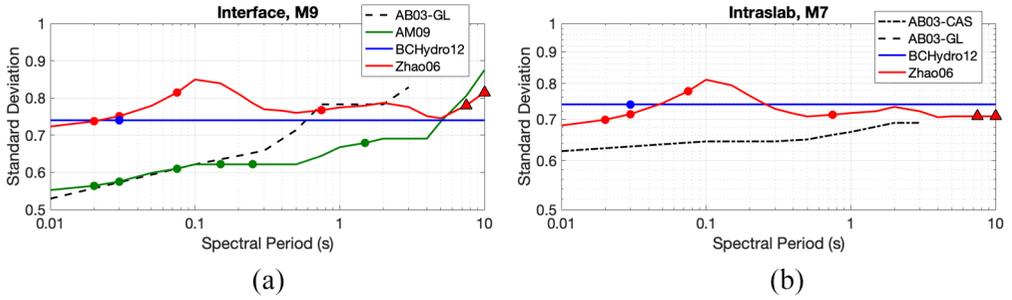


Figure 11. Standard deviations of subduction GMMs for (a) a magnitude 9 interface event and (b) a magnitude 7 deep intraslab event. Dots indicate spectral periods computed via interpolation of adjacent periods; triangles indicate extrapolated periods.

When combined with increases in median ground motion observed for interface events at short distances and intraslab events at short periods, we expect commensurate increases in ground motion and hazard.

Epistemic uncertainty for WUS subduction GMMs

The distribution of epistemic uncertainty for WUS subduction GMMs has historically been very narrow relative to both WUS crustal GMMs in active tectonic settings and CEUS GMMs in stable continental regions, as reflected in the logic trees for the 2014 and 2018 NSHMs (Table 2) and Figure 12. Although removal of AB03 in the absence of alternative GMMs further reduces the number of models considered, median ground motions do not change significantly. There is, however, considerable room for improvement. The tectonic and geologic characteristics of Cascadia are quite different from other, young, high convergence rate and seismically productive subduction zones, recordings from which are the basis for the majority of subduction GMMs (Bozorgnia, 2020). Little data for Cascadia and none for subduction interface events indicate a much broader representation of epistemic uncertainty or an increase in the aleatory variability of the GMMs should be considered in the NSHM. Future updates of the CONUS NSHM are expected to consider epistemic and aleatory uncertainty more thoroughly.

Deep sedimentary basin effects added to subduction GMMs

None of the subduction GMMs considered in the 2018 NSHM include basin-effect terms. Because basin amplifications are critical for estimating long-period ground motions on soft site classes, the 2018 NSHM includes adjustments to subduction GMMs to include additional basin-effect scale factors. Chang et al. (2014) conclude that $Z_{2.5}$ is a better estimator of basin depth in Seattle. $Z_{2.5}$ as a predictor variable is also less correlated with V_{S30} , making it more appropriate for use as an independent scale factor in the subduction GMMs that already include V_{S30} -based site-effects terms. Of the four crustal GMM basin-effects models, CB14 is the only one that uses $Z_{2.5}$, and it also yields the highest ground motion increases over deep basins, making it the most consistent with the factor of 2–3 increases observed in recent 3D simulations of Cascadia M9 earthquakes (Frankel et al., 2018; Petersen et al., 2020). The 2018 NSHM therefore uses the CB14 basin-effect scale factor to directly scale WUS subduction GMM medians.

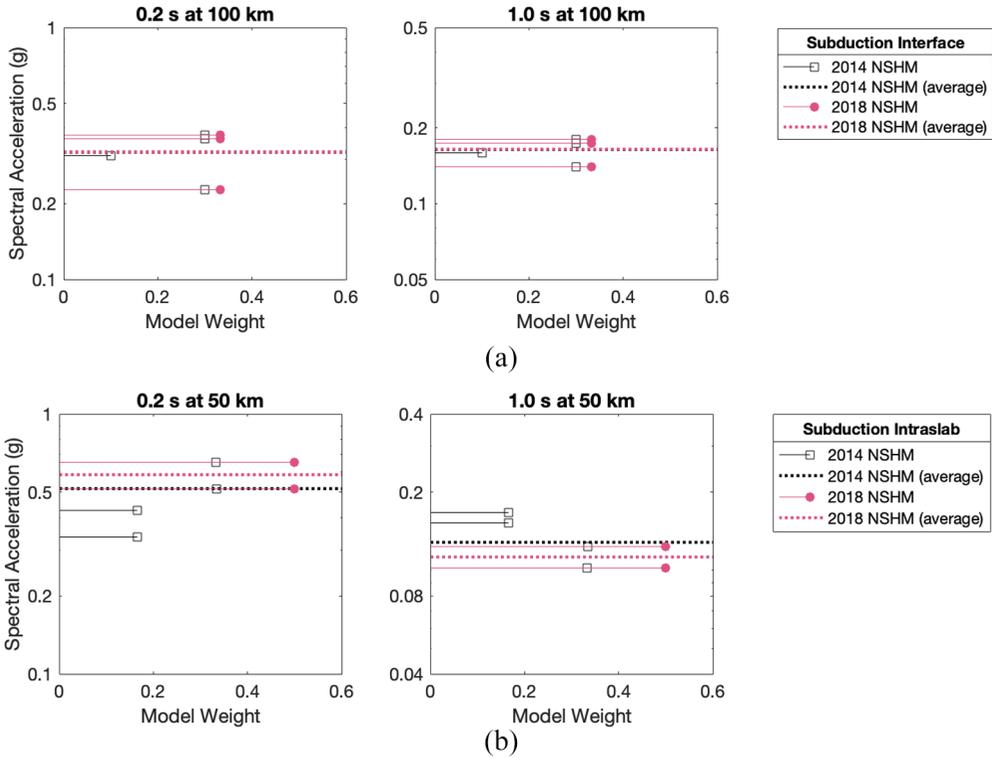


Figure 12. Epistemic uncertainty of WUS subduction GMMs represented by the range and distribution of ground motions at two example periods, 0.2 and 1 s, on a soft rock site ($V_{S30} = 760$ m/s) for (a) a magnitude 9 interface event at a distance of 100 km and (b) a magnitude 7 deep intraslab event at a distance of 50 km.

In deciding how to modify the subduction GMMs, we also considered replacing the entire site-effects model (i.e. including the V_{S30} term) of each GMM with that of CB14 and the Z_1 -based models. This approach proved difficult because the GMM site terms, both subduction and crustal, are developed for different rock reference conditions and intensity measures (PGA or SA), making them largely incompatible without extensive additional research. In the end, understanding that new subduction GMMs under development for use in future updates of the NSHM will include basin-effect terms (Abrahamson and Gülerce, 2020; Bozorgnia, 2020; Kuehn et al., 2020; Parker et al., 2020), we follow the discussions and guidance in Chang et al. (2014) and use only the CB14 basin scale factor to modify the 2018 WUS subduction GMMs.

Figures 13 and 14 show the effect of applying the CB14 basin-effect scale factor to the WUS subduction interface and intraslab GMMs, respectively. In these examples, we use a very deep basin-depth value representing a location in the vicinity of Seattle, $Z_{2.5} = 6.71$ km. For both interface and intraslab events on a soft rock site, inclusion of the CB14 basin-effect scale factor at periods greater than 0.5 s produces a shoulder in the ground motion spectrum at long periods, and long-period amplification is more pronounced at a DE site class. As noted previously, AM09 yields higher ground motions than the other interface GMMs at long periods (Figure 9a); this feature of AM09 leads to

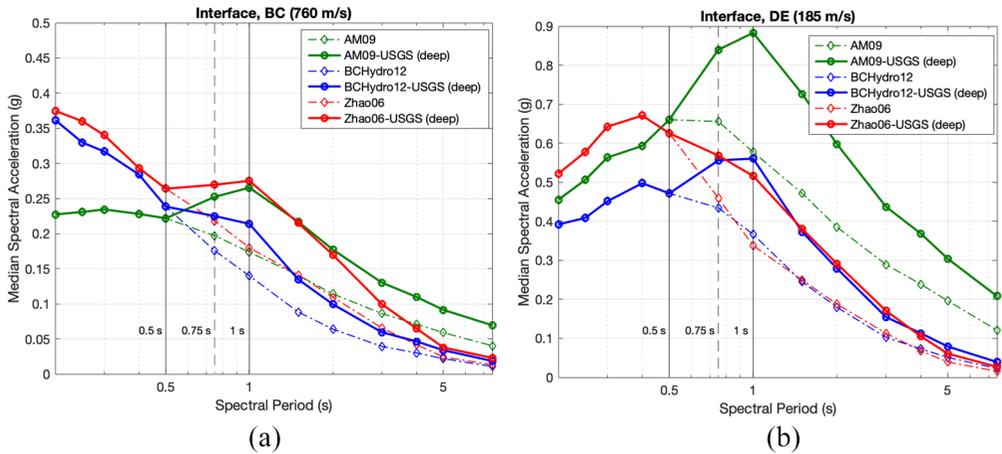


Figure 13. USGS implementation of WUS subduction GMMs for deep basins like Seattle, $Z_{2.5} = 6.71$ km, on site classes (a) BC and (b) DE for an interface event with magnitude 9 at a distance of 100 km.

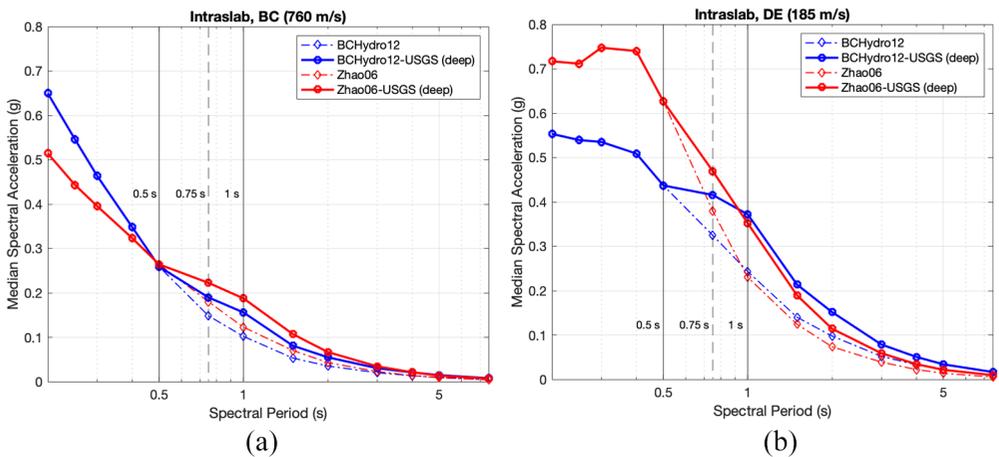


Figure 14. USGS implementation of WUS subduction GMMs for deep basins like Seattle, $Z_{2.5} = 6.71$ km, on site classes (a) BC and (b) DE for a deep intralab event with magnitude 7 at a distance of 50 km.

considerably higher ground motions at soft soil sites when considering deep basin effects (Figure 13b).

Implications of WUS GMM changes on hazard

This section shows the combined effects of changes in GMM medians, standard deviations, site-effect models, and epistemic uncertainty on hazard over multiple NSHM cycles. Difference and ratio maps of mean hazard with a 2% probability of exceedance in 50 years

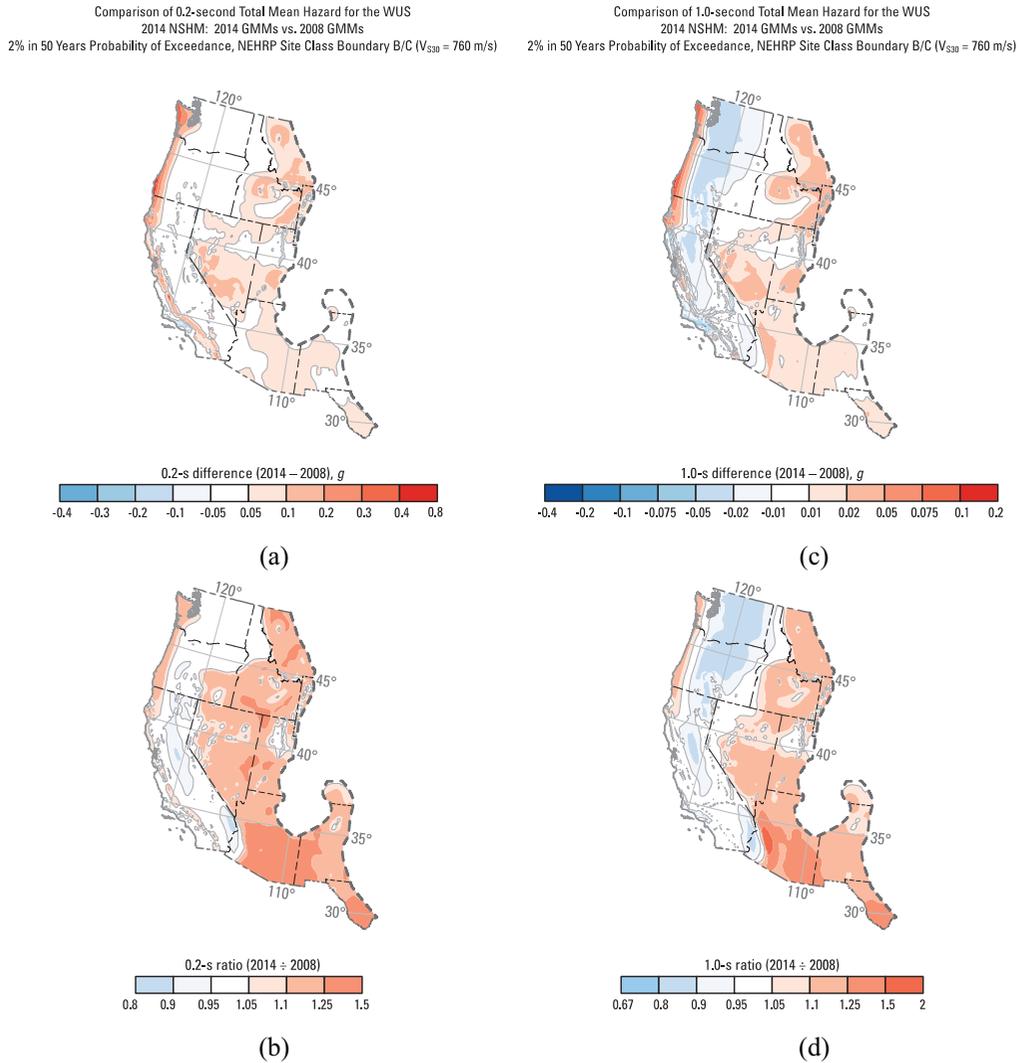


Figure 15. (a, c) Differences and (b, d) ratios in mean hazard, calculated using the 2008 and 2014 WUS GMMs (both using the 2014 source model) at 0.2- and 1-s spectral periods.

for the WUS using the 2014 NSHM source model, but with the 2008 and 2014 NSHM GMMs at 2 spectral periods, 0.2 and 1 s, are shown in Figure 15. Figure 16 shows the same comparison, using the 2014 NSHM source model, but paired with the 2014 and 2018 NSHM GMMs. Note that these maps are not representative of the total change in hazard given that they use the same source model; they only show the effects of GMM updates. Petersen et al. (2021) provide information on the total changes in hazard, including those due to source model updates.

In the 2014 NSHM update, the primary change to the 2008 crustal GMMs in the WUS was the adoption of the full suite of five NGA-West2 GMMs, replacing three NGA-West1 models. Features of the new models at 0.2 s included larger predicted ground motions near high slip rate strike-slip faults (e.g. along the San Andreas Fault in CA; Figure 15a) and

decreased near-field hanging-wall effects (e.g. in southern CA and along the Wasatch front in UT; Figure 15a). Broad increases in predicted ground motion across the WUS from 2008 to 2014 are attributed to increased far-field ground motion response to normal fault events in the NGA-West2 GMMs (Powers and Field, 2015; Rezaeian et al., 2014). Changes in the predicted Pacific Northwest ground motions arise from the updated composition and weighting of both interface and intraslab GMMs (Frankel et al., 2015). In the 2014 NSHM, the Youngs et al. (1997) intraslab GMM was replaced in favor of Zhao06 and BChydro12. In addition, the 2014 NSHM imposed a lower magnitude saturation in the AB03-CAS and AB03-GL intraslab GMM implementations. On the interface side, Youngs et al. (1997) was replaced with AM09 and BChydro12. Collectively, and consistent with Figure 10a, these GMM changes led to significant increases in calculated hazard along the California, Oregon, and Washington coastlines, where hazard is dominated by the earthquake potential of the Cascadia subduction zone; slight decreases in hazard occurred inland. Similar features are present in the 1 s difference and ratio maps (Figure 15c and d) with a more pronounced decrease in far-field subduction ground motions present across central and eastern Oregon and Washington. For more detail on the interplay of changes between the GMMs and extensive changes to the NSHM source model from 2008 to 2014, see Rezaeian et al. (2014, 2015); and Powers and Field (2015).

In the 2018 NSHM update, changes to GMMs and resultant calculated hazard were relatively minor as shown in Figure 16. Consistent with Figure 10a, both near- and far-field subduction ground motions changed, resulting in increased hazard along the Pacific Northwest coastline (Figure 16a) and decreased hazard slightly inland (Figure 16d) due to removal of the AB03 GMMs. Removal of the I14 model from the crustal GMM logic tree causes minor changes in hazard due to its relatively low weight (0.12) in the 2014 model. I14 predicts lower ground motions for $M > 7$ events at 1-s SA, resulting in increases in calculated hazard of 2%–5% along the fastest slipping faults in California (e.g. the San Andreas, Hayward, San Jacinto, and Garlock faults) that are capable of hosting the largest earthquakes (Figure 16c). Changes arising from removal of I14 are consistent with changes to the average median and standard deviation discussed earlier. The 1-s maps show the expected long period increases in hazard in the vicinity of Los Angeles, San Francisco, Salt Lake City, and Seattle due to the inclusion of spatially varying basin depth data (see Petersen et al., 2020, for higher resolution hazard ratio maps of the basins). Other changes present in the ratio maps for Montana, Wyoming, Utah, and Colorado are due to changes in CEUS GMMs, the influence of which extends as far west as -115° .

Future work

Improvements to the representation, quantification, and reduction of epistemic and aleatory uncertainty are currently a major focus of NSHM research and development. As demonstrated in this article, representation of epistemic uncertainty in the GMMs in the WUS is somewhat limited relative to 2018 updates to the CEUS GMMs (Rezaeian et al., 2021); this is especially true in the case of the subduction GMMs. Fortunately, the NGA-Subduction project is underway (Bozorgnia, 2020), and possible adoption of these models in the 2023 update to the CONUS NSHM would be a marked improvement in this area. In addition to multiple models available for consideration (Abrahamson and Gülerce, 2020; Kuehn et al., 2020; Parker et al., 2020), each NGA-Subduction GMM includes a model of epistemic uncertainty.

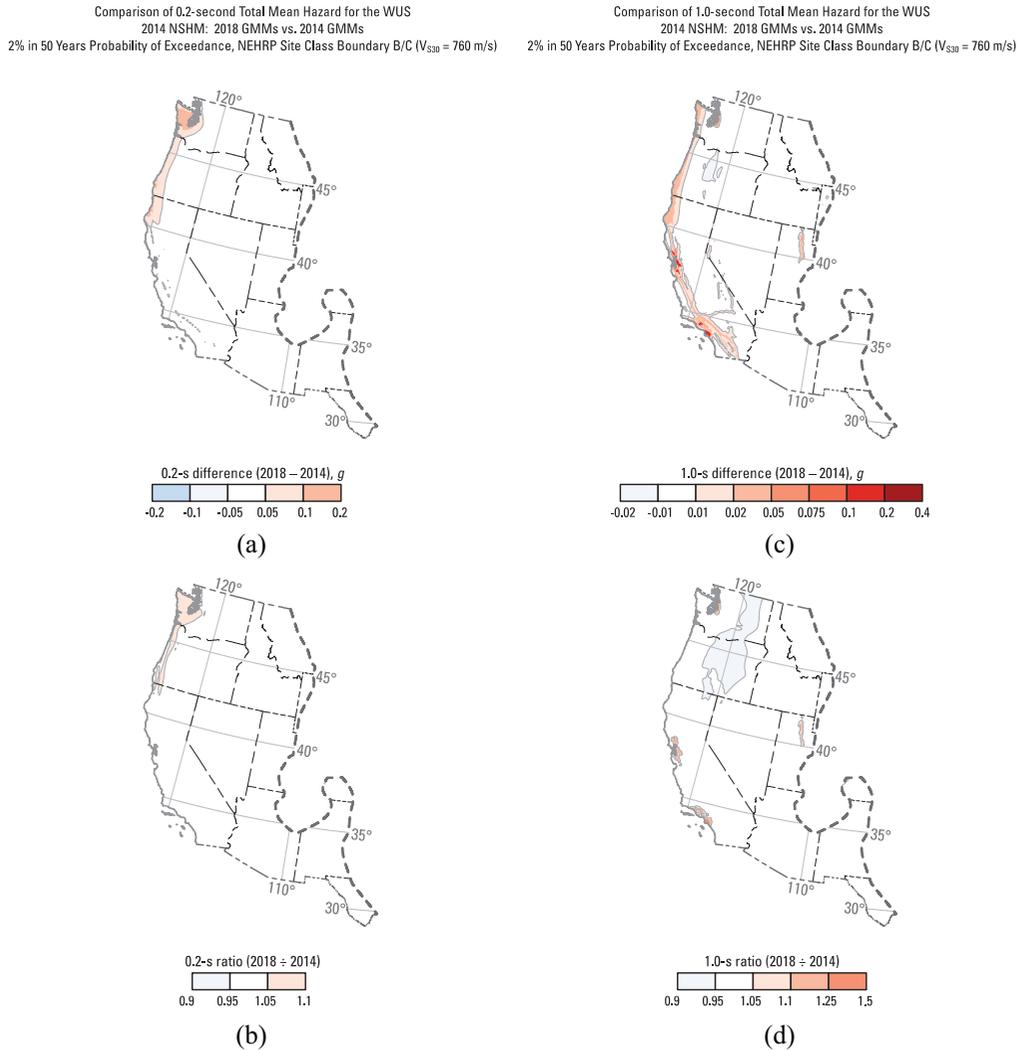


Figure 16. (a, c) Differences and (b, d) ratios in mean hazard, calculated using the 2014 and 2018 WUS GMMs (both using the 2014 source model) at 0.2- and 1-s spectral periods.

Site effects also continue to be an area of focus for future NSHM development. Specifically, site classes A and E, which are at the extremes supported by some NGA-West2 crustal GMMs, require additional study to validate median ground motion predictions. WUS subduction GMM site-effect models (e.g. Zhao06, AM09) could also be improved. As above, we expect the NGA-Subduction GMMs to include improved site-effect models with built-in basin-effect terms. There are also improvements to be made on the products and user-guidance side of the NSHM. While the new MPRS requirements and inclusion of basin effects have significantly improved and expanded the range of hazard maps and design ground motions available, users could obtain hazard values that are physically unlikely. For example, hazard computed for the hard rock maps (site class A) for the WUS will include deep basin effects, an unlikely combination, in some locations.

The 2018 update marks the first time spatially varying site data were included in a USGS NSHM. While including basin effects in localized areas for long periods is a significant advance, there is more to be done with respect to understanding and developing models for shallow basins and basin-edge effects, as well as developing more regionalized, partially non-ergodic, and non-ergodic GMMs. In addition to considering additional sedimentary basins in other regions of the WUS and improving site-effect models, work on which is ongoing, site data (i.e. basin depths, V_{S30}) can vary significantly over distances much smaller than the 0.05° (≈ 5 km) spacing of hazard values in the USGS maps. This warrants the USGS improving online tools for calculating hazard and supporting engineers conducting site-specific analyses because maps at higher resolutions are computationally expensive and impractical.

Summary

The USGS NSHMs are used in building design applications, which traditionally have been based on three spectral periods and one reference site class. The 2018 NSHM update supports the new MPRS recommendations of Project 17 for the future generation of building designs that call for hazard results at 22 spectral periods and 8 site classes. Resulting updates to the USGS GMM selection criteria necessitated the exclusion of some GMMs in the WUS and rebalancing the logic tree weights of those retained from previous editions of the CONUS NSHM. For WUS crustal GMMs, the Idriss (2014) model was excluded because it does not apply to ground motion estimation at soft soil sites. This change led to little impact on hazard at the three periods and one site class supported in the 2014 NSHM but, if included in the 2018 NSHM, would have produced very high ground motions under the expanded MPRS requirements. For WUS subduction interface GMMs, the Atkinson and Boore (2003) GMMs, both Cascadia and global models, were excluded due to lack of support for long periods and having weak attenuation at long distances. This change led to minor increases in computed hazard along the coast in the Pacific Northwest at short periods (e.g. 0.2 s) and minor decreases inland at long periods (e.g. 1 s; less than 10% in both cases). The most significant change in the 2018 NSHM in the WUS is the inclusion of deep basin effects to improve estimates of long period ($T \geq 1$ s) ground motions on soft site conditions. This change necessitated updates to WUS crustal GMMs and addition of basin-effect scale factors to WUS subduction GMMs to support the depth- and period-dependent USGS basin-effects model. The 2018 NSHM considers spatially varying basin depth data in the vicinity of Los Angeles, San Francisco, Salt Lake City, and Seattle. As a result, long period ground motions increased relative to 2014 in these regions. Epistemic uncertainty is fairly well represented in crustal GMMs, but that of subduction GMMs should be increased in the future.

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Additional resources

The code used to perform PSHA, including GMM calculations that are used to develop many of the figures in this paper, 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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