Title
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Publication Date
2023-12-11

Peer reviewed

Panel Review of Ground Motion Characterization Model in 2023 NSHM

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The 2023 National Seismic Hazard Model (NSHM; Petersen et al., 2023) has two major components – a seismic source characterization (SSC) model and a ground motion characterization (GMC) model. The US Geological Survey (USGS) established separate panels to review and provide input on these two models. Both panels are advisory, meaning that they provide input on technical issues for consideration by the USGS NSHM team, but they do not have decision making authority. Here, we report on the activities and recommendations of the Ground Motion Characterization Panel, made up of the authors of this review. Final modeling decisions are presented in separate USGS documents, including Petersen et al., (2023) and Moschetti et al., (2023). Where modeling decisions depart from our recommendations, the rationale is explained in those publications.

The panel was formed in mid-January 2023 and was active until mid-April 2023. Our activities commenced with online workshops organized by USGS on January 18 and 20, 2023. In these workshops and a subsequent workshop on March 21, 2023, we viewed presentations by USGS staff on key issues affecting the GMC model development and had opportunities to ask questions. We were provided with questions after each workshop, to which we responded in two question-answer style communications. The main purpose of this short report is to summarize our responses to those questions. The report is organized by subject area, and in each area we synthesize the questions asked and our responses. Following the close of the panel activities, a tiger team was formed to provide input to the USGS on issues related to the NGA Subductions models as applied to Alaska and to review a bias correct factor discussed below for application in

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central and eastern North America (CENA). The Alaska recommendations are not discussed here, as they were outside of the panel scope. Since the bias issue was within our scope, we briefly describe the tiger team recommendations below.

During the course of our deliberations on various technical issues, there were questions about the degree to which models published after 2020 could be considered in GMC model development. These questions arose because there had been discussion in the previous (2018) NSHM Steering Committee about setting a deadline for technical contributions that would be considered in the 2023 NSHM. This deadline was set as 2020. Some of the models considered for use in the 2023 NSHM were published after 2020. In late April USGS personnel, in collaboration with the panel, provided clarity on the policy:

> *For the 2023 NSHM update, SSC and GMC data and models published before 2021 are given full consideration by the NSHM team.*
>
> *Information that becomes available after the 2020 deadline may or may not be considered during model development. USGS NSHM staff, in consultation with the steering committee, exercise their discretion and judgment regarding utilization of recent results, and do so when justified in terms of the result's scientific credibility and significance to hazard.*

Responses in the text below reflect the application of this policy.

The GMC panel supports suggestions that have been made at the Steering Committee level to encourage incorporation of epistemic uncertainty into the communication of NSHM results to the public.

1.0 Subduction-Zone GMMs for 2023 NSHM

1.1 GMM Selection

1.1.1 Application of NGA-Subduction Models

The panel was asked whether we agreed with the use of NGA-Sub ground motion models (GMMs), specifically the Cascadia components of those GMMs. The GMM logic tree for Cascadia also includes two older GMMs – a model for Japan (Zhao et al., 2006) and a simulation-based model (Atkinson and Macias 2009). We understand these models are included to increase epistemic uncertainty at long periods.

We are generally supportive of applying the NGA-Sub GMMs in Cascadia. We suggested that USGS check that the range in ground motion space produced by epistemic uncertainty on the global model is captured by the epistemic uncertainty in the Cascadia model.

1.1.2 Application of Earlier Models

In addition to NGA-Sub models, earlier models by Zhao et al. (2006) and Atkinson and Macias (2009) (hereafter AM09) were also recommended by USGS for implementation within the subduction logic tree. We provided input encouraging consideration of alternatives to Zhao et al. (2006) and AM09. Regarding the former, we suggested that this model be dropped given that it is out of date and is based on Japanese data, which we now understand (from the NGA-Sub project) to have different features (attenuation rates, etc.) than the Cascadia versions of NGA-Sub models. We encouraged USGS to consider replacing AM09 with an alternative model for interface events derived from the M9 simulations for Cascadia presented by Wirth et al. (2018).

An alternative model for replacing AM09 is to scale one of the NGA-Sub GMMs so that it is consistent with the average amplitude of the M9 simulations. The M9 simulations have been available since 2018, so these are not brand-new results (while a formal review was not performed by the panel, the results are familiar to several panelists). To demonstrate the potential application of this approach, panelist Abrahamson looked at the difference between the M9 simulations and the Abrahamson and Gulerce (2022) (AG22) GMM for sites in the Seattle region and for a wider region shown in Figure 1 and also the differences between the AM09 GMM for M9 and the AG22 GMM. For each oscillator period, the mean difference between the natural logs (simulations minus GMM) is termed C_{SIM}.

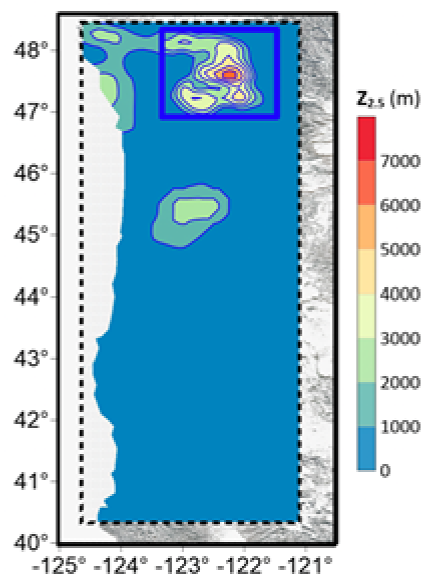

Figure 1. The "Seattle region" is shown by the blue box. The region bounded by the dashed black line but excluding the Seattle region is called the "outside Seattle region". Colors represent the depth to the 2.5 km/s velocity isosurface, $Z_{2.5}$ from (Stephenson et al., 2017).

The C_{SIM} term in Figure 2 is computed using the 30-m time-averaged shear wave velocity (V_{S30}) of 350 m/s in the GMM, which is an approximate average value for Seattle. The M9 simulations have a minimum V_S of 600 m/s, but they include the effects of deeper V_S profiles. Due to the correlation of V_{S30} and depth parameter $Z_{2.5}$ (depth to 2.5 km/s shear wave velocity isosurface) in the Cascadia data, some of the $Z_{2.5}$ scaling is mapped into the V_{S30} scaling. To address this, normalized basin depths are used in the GMMs. The normalized depth is dependent on V_{S30}. By using a fixed V_{S30} of 350 m/s across the region, which also implied a particular depth, we allow differences in site response across the basin as provided by the simulations to be represented in the plots (Figure 1) while also providing a reasonable basis for estimating a regional average bias (Figure 2).

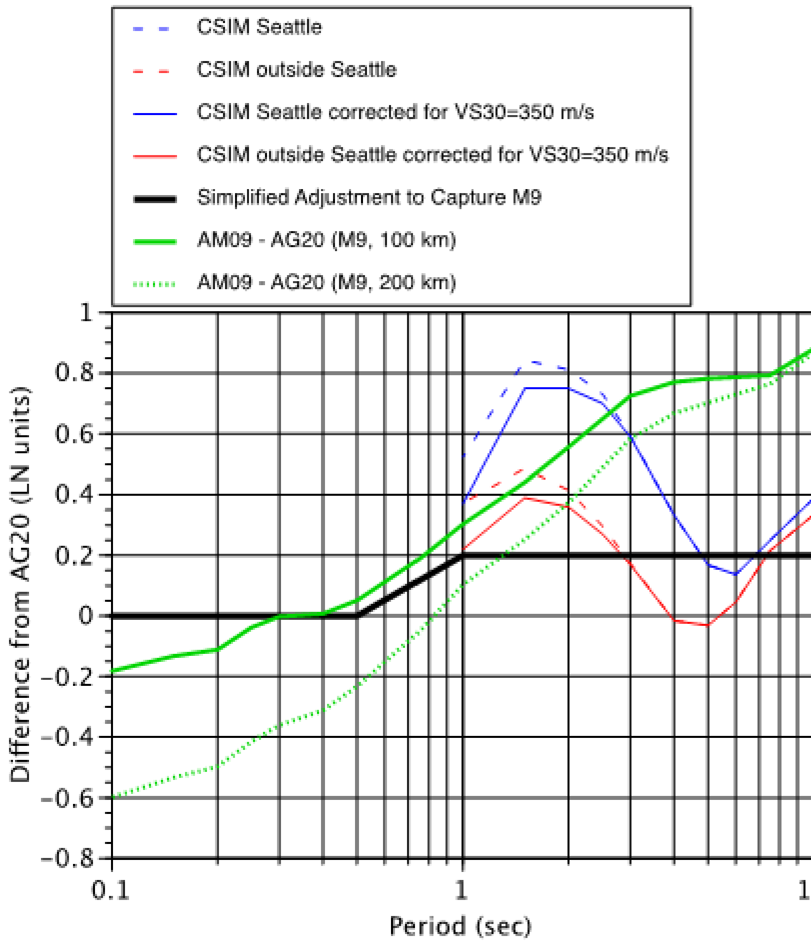

Figure 2. Comparison of average differences between the M9 simulations and the AG22 GMM (labeled as Abrahamson and Gulerce 2020; AG20) and between the AM09 simulation-based GMM and the AG22 GMM for M9 at 100 and 200 km.

The results show that the difference between the M9 simulations and the AG22 model are much smaller for the entire Cascadia region than for the Seattle region. The difference for the entire region may represent a better average difference for adjusting the GMM than the difference for the Seattle region.

For the entire region, a constant adjustment term of 0.2 ln units for T>1 sec for the AG22 GMM is a simple way to bring the M9 simulations into the GMM. The simplest approach for doing this is to apply this factor to all interface earthquakes, not just the M9. The factor would not be applicable to slab events. This process to estimate C_{SIM} values could be repeated for the other GMMs if desired.

Another option is to use the AM09 GMM to represent the larger amplitudes from the simulations. The difference between AM09 and AG22 is plotted in Figure 2. The AM09-AG22 difference is similar to the M9_SIM-AG22 difference in the period range of 1-2 sec, but the AM09-AG22 difference becomes much greater than the M9_SIM-AG22 difference at T>2 sec. There is a large reduction at the shorter periods. An alternative approach would be to adjust one or more of the NGA-Sub GMMs to be similar on average to the M9 simulations for the full region to replace AM09. Absent this alternative approach, it would be beneficial to keep AM09 in the set of models to increase epistemic uncertainty.

1.2 Magnitude Break Point

The panel was asked if the use of one single magnitude break point (M_b) with NGA-Sub GMMs (taken from Campbell 2020) is acceptable or if variable M_b values reflecting epistemic uncertainties are needed for implementation.

In our response, we indicated that predicted ground motions for events with magnitudes above the breakpoint are strongly impacted by the breakpoint magnitude. Uncertainties in breakpoint magnitudes can be gleaned from Campbell (2020). In the future, USGS staff may wish to evaluate the information in that paper and decide if further work could appreciably reduce uncertainties. The panel had mixed opinions regarding the inclusion of epistemic uncertainty in the break magnitude for the policy model at this stage. Understanding the range of break points used in the alternative NGA-Sub GMMs and considering the applicability of the selected values as part of the evaluation of the weights for the GMMs could result in an improved model.

1.3 Independent Logic Trees for Aleatory Variability Models

The USGS received recommendations during a public workshop to develop independent logic trees for aleatory variability relative to those for median models (refer to the list of past USGS NSHM workshops online here: https://www.usgs.gov/programs/earthquake-hazards/nshmp-workshops). The NSHM has been developed using the standard deviation from each GMM, together with its median model. We were asked to comment on whether this recommendation should be a priority for 2023 or could it be considered in the next update.

We do not consider separate aleatory variability logic trees for the policy model to be necessary at this time, but they could be considered for the research model. The applicability of the aleatory variability in the GMMs to the Cascadia site conditions and controlling distances for hazard in

Cascadia could be considered as part of the evaluation for the weights for the NGA-Sub GMMs (combined median and aleatory variability logic tree node).

1.4 Logic Tree Weights When Epistemic Uncertainty is Represented by a Sigma Term

Within-model epistemic uncertainty for two of the NGA-Sub GMMs is represented as a three-point distribution with weights 0.185/0.63/0.185 and are applied as μ-1σ/μ/μ+1σ, using the epistemic uncertainty σ values as-published with the GMMs. Because these branches do not represent any commonly used percentiles of a normal distribution, USGS proposed updating to μ-1.645σ/μ/μ+1.645σ such that the three branches are representative of the 5th, 50th, and 95th percentiles. We were asked if this is defensible.

The panel agrees that the revised multipliers on sigma will provide better hazard percentiles than were available previously (as an aside, other solutions in literature provide different multipliers, such as discussed in Keefer and Bodily, 1983). Extreme values are not accurately captured but +/- 1.645 sigma should be sufficient to establish a stable distribution from the 5th to 95th percentiles. If it was desired to capture the shape of the percentile CDF and extremes better, a 5-point distribution could be used.

When weights of 0.185/0.63/0.185 are implemented with a lognormal σ in other parts of the model (e.g., uncertainty in site amplification of NGA-East) the factor of 1.645σ can be used.

These weights are also used with NGA-West2 models, (Powers et al., 2021; Moschetti et al., 2023) but the underlying value of epistemic uncertainty that the USGS uses for these GMMs does not represent the standard deviation of lognormal ground motion. The panel was asked about potential changes to this model. We suggested that the current approach be retained. This model could be improved for future use, but this would be a large effort. It is not clear to the panel if Al Atik and Youngs (2014) is being used as a minimum epistemic uncertainty, which would be our preferred approach.

2.0 WUS-CEUS Boundary

USGS has proposed an updated CEUS-WUS boundary model, which is based on tomography and ground-motion data and is a refinement to the previous model (Petersen et al., 2023). We were asked if full weight should be given to the revised boundary. The panel agrees with the proposed boundary change and giving it full weight in the logic tree.

3.0 Site Response in WUS Basins

3.1 Application of Empirical Models

The NGA-West2 project established site response models in which sediment depth was considered as a second site parameter to supplement V_{S30} (Bozorgnia et al., 2014). Most of the GMMs centered the models so that differences of the depth parameter relative to a V_{S30}-based average depth are used as the model independent variable.

For the 2023 NSHM, USGS evaluated the depths for different sedimentary basins and identified the published site amplification models that are consistent with the data (Ahdi et al., 2023). A number of questions related to this line of investigation were presented to the panel, as described in the following paragraphs, for the Portland/Tualatin, Reno, California Central Valley, Los Angeles region, and San Francisco Bay region basins. For any basin, regardless of location, the key questions that we considered were (1) is it better to apply depth scaling from a poorly defined depth structure or to use V_{S30}-scaling alone and (2) are the basin depth scaling relations in the GMMs applicable to the target basin? When contemplating these questions, we recognized that the NGA-West2 site terms are strongly influenced by southern California data, so the site response models largely reflect conditions present in deep basin structures that are typical of that region.

The following subsections summarize the input that was provided by the panel for specific basins.

3.1.1 Portland/Tualatin

USGS presented analyses of this basin using NGA-West2 GMMs because the events that they considered were shallow crustal. However, NGA-West2 models were not calibrated for this region. NGA-Sub models were developed for this region, but only used ground motions from subduction earthquakes. If one accepts the premise that site response does not appreciably depend on event type, then NGA-Sub models would be better suited to this region than NGA-West2 models. There are ground motion data in the Portland and Tualatin basins that were considered in NGA-Sub models during the development of GMM site terms. The Portland/Tualatin data were not found to be biased with respect to the overall regional site response for Cascadia, but the ability of those data to distinguish depth-dependent site effects was limited due to limited recordings. At the present time, using only the Cascadia V_{S30} scaling, with the depth effects reserved for the research model, may be most appropriate implementation.

3.1.2 Reno

USGS examinations of this basin indicated large uncertainties in site metadata, disagreements between region-specific V_{S30}-Z_1 relationships, and misfits of NGA-West2 basin-amplification models. The panel was asked if we agree with not using depth models for this region. In response, the panel indicated that by not modeling depth effects in the Reno basin, in effect the mean depths conditioned on V_{S30} are being used, which are likely much deeper than those in the Reno basin. For this reason, use of the recently published Valley province site response model (Nweke et al., 2022a), which captures these effects for similarly shallow features in southern California may be better. However, we recognize that the width definition of Valleys does not apply to Reno and that this could create inconsistency. Moving forward, the use of the seismic response of other shallow basins (e.g., graben-type basins in southern California, for example Chino and San Bernardino basins), could be considered as a proxy for basins of this type.

3.1.3 California Central Valley

Based on the results of Ahdi et al. (2023), it was proposed to give full weight on the Great Valley Z_1 and $Z_{2.5}$ depth models as used with NGA-West2 models. The panel was asked to comment and generally agreed with this approach, but encouraged consideration of epistemic uncertainties in depth parameters in future NSHM updates. Although somewhat dated, Stewart et al., (2005) analyzed depth uncertainties in southern CA, which provides a basis for estimating these uncertainties. Similar considerations would apply to other western US basins.

3.1.4 Los Angeles and San Francisco regions

USGS proposed a logic tree with 50-50 weight on (1) the treatment of the as-modeled NGA-West2 depth-based (Z_1, $Z_{2.5}$) amplification models and (2) the 2018 NSHM basin implementation in basins, outside of basins, and at the basin edge. A key distinction between (1) and (2) is that option (1) allows ground motion reduction for shallow basins relative to the V_{S30}-scaling model and option (2) does not. Asked to comment, the panel agreed with the use of ground motion reductions relative to what is provided by the V_{S30}-scaling model for these conditions. However applying such reductions for negative-differential depths sites in the Los Angeles basin and San Fernando Valley, per the Nweke et al., (2020, 2022a) studies, may not be accurate. In other words, the panel felt that implementation (2) could receive full weight in the Los Angeles Basin and San Fernando Valley.

3.2 CyberShake Basin-Amplification Model

Researchers within the NSHM project and outside entities (Nweke et al., 2022b) investigated the use of 3D simulations provided by the Southern California Earthquake Center (SCEC) Cybershake program (Graves et al., 2011) to develop site response estimates in southern California basins.

The panel agrees with using the CyberShake-based depth-scaling as part of the policy model. However, the validation of the SCEC BBP and CS simulation methods has shown that the long-periods (T>3 sec) are overestimated both for one dimensional (1D) and three dimensional (3D) crustal structures (Dreger et al., 2015, Nweke et al., 2022b) so the direct amplitudes are problematic for application.

USGS proposed giving the CyberShake basin amplifications 0.25 weight due to good availability of data in southern California. The panel felt that higher weights could be considered because basin factors may depend on the source locations. Since the CyberShake simulations sample the distribution of earthquakes in the source model, they better represent the basin terms for future earthquake locations than the basin terms based on empirical data from recent earthquakes. A higher weight for the CyberShake simulations could be appropriate given that the scaling seems to be reasonably close to data in prior research (Nweke et al. 20222b) and CyberShake samples additional paths that are likely hazard-controlling.

USGS asked if there are issues to consider with respect to using the CyberShake-derived basin-depth scaling models. The panel's response was that the use of differential depths in the application of the scaling, rather than the depths themselves, would avoid double counting of basin effects that were mapped into the V_{S30} scaling of the GMMs.

The panel was asked if we have specific input on the value of the CyberShake-derived basin-depth scaling models at δZ_1 = 0 and $Z_{2.5}$ = 1-3 km, at which depths the empirical NGA-West-2 basin-amplification models have values of zero. The panel responded that the use of a 0.1 factor at the reference depth, as recommended by Nweke et al., (2022a) for the Boore et al., (2014) model, is correct. The applicability of this factor for other GMMs is unknown.

4.0 M9 Basin-Amplification Models

Wirth et al. (2018) presented a set of 3D simulations for M9 interface events in the Pacific Northwest. Those simulation results have been suggested for use in site response modeling.

USGS has proposed applying the M9 basin amplification results through the factor-of-two adjustment factor presented in the Petersen et al., (2023) overview paper and in Smith et al. (2023). Asked to comment, the panel concurred with using basin depth scaling derived from M9 simulations (0.5 weight) in addition to that available from NGA-Subduction models (0.5 weight), as proposed.

5.0 Atlantic and Gulf Coastal Plains Amplification Models

5.1 Application of Depth-Based Model for Coastal Plain Sites

In the 2018 NSHM, a region-specific site response model for central and eastern North America (CENA) was used in the NSHM for the first time. This model was presented in Stewart et al., (2020) and depends on V_{S30}. The model did not differentiate by sediment thickness across CENA. Since that time, USGS has developed sediment thickness maps for the Atlantic and Gulf coastal plain regions of CENA (Boyd et al. 2023). Chapman and Guo (2021) developed a site amplification model that accounts for sediment thicknesses, but it relies on a reference site condition that is unconstrained; furthermore, the model is dependent on period, magnitude, and distance.

USGS proposed explicit incorporation of the effects of deep sediments through the Chapman and Guo (2021) model with a weight of 0.25. Because the model is based on a reference site approach, USGS independently estimated the reference site condition, which was recommended as about 1000-2000 m/s. While this is a large range, USGS noted that the sensitivity to the reference site condition was very small, so a more precise estimate of the reference velocity is not needed. The panel was asked to comment on the use of the Chapman and Guo model, adjusted for the reference site condition, with a weight of 0.25.

The panel commends USGS for producing the depth models presented in Boyd et al. (2023). Several studies, including Chapman and Guo (2021), Pratt and Schleicher (2021), and Schleicher and Pratt (2021) have found site amplification in these regions that is related to sediment depth in ways that is consistent with our physical understanding of site response behavior (as depth increases, amplification increases at long periods and decreases at short periods). Moreover, the topic appears to be of practical significance, given the levels of amplification observed in that research.

The panel expressed concern about applying Chapman and Guo (2021) because it was derived using a reference site approach. As such, the amplification is referenced to the average site condition across the reference sites, which is unknown. The most direct way to evaluate the reference site condition would be to evaluate V_{S30} (through measurements or the use of a proxy model) at the reference sites, which has not been done for this case.

The panel is concerned that the lack of sensitivity to V_{S30} that was found in calibrating the Chapman and Guo (2021) model to a reference velocity is an artifact of the Stewart et al. (2020) model, in which the V_{S30} scaling is generally small between about 700 m/s and 2000 m/s due to a modeling decision made during the development of that model. If Stewart et al. (2020) had made different assumptions to extrapolate beyond the V_{S30} data range considered to the 3000 m/s reference condition, stronger scaling over this range could have been identified. As a consequence, the sensitivity to the reference site condition across the range investigated in the USGS study is uncertain and potentially stronger than what was proposed for the 2023 update.

In consideration of these factors, the panel considered two potential options:

1. Recognizing that there is likely a depth effect in the site amplification, even though the reference condition is uncertain, accept the application of the current USGS model at 0.25 weight.
2. Recognizing the difficulty in identifying a reference site condition applicable to the Chapman and Guo (2021) model noted above, reject the inclusion of the model as it is not sufficiently developed for application in the NSHM.

Individual panelists have different views on the relative merits of arguments (1) and (2). A consensus was not reached.

5.2 Other Considerations

The panel was asked if USGS should account for uncertainty in sediment thickness or in the Chapman and Guo (2021) reference condition. Our understanding is that both of these uncertainties are largely unknown. While consideration of uncertainties is advisable, it would have to be solely based on judgment at the present stage.

The panel was asked about the use of other amplification/deamplification models for the coastal plains (i.e., Harmon et al., 2019) and the NGA-East Gulf Coast path model (Goulet et al. 2018). The panel's response was that the Harmon et al., (2019) simulations did not consider sufficiently large sediment depths to be useful in the coastal plains. The NGA-East Gulf Coast path model is published and well-supported so integrating this model in the NSHM could be an improvement if its implementation is possible with the available time. Other recent work on this topic (e.g., Pezeschk et al., 2021) could also be considered in the research model.

6.0 Adjustment Factor for NGA-East GMMs

6.1 Should Bias Factors be Applied?

Studies have shown that the use of the NGA-East GMMs with the CENA site amplification models employed in the 2018 NSHM (Stewart et al., 2020) leads to biased ground motion predictions, with overprediction at short periods and under-prediction at long periods. This work has been presented by a collection of researchers including the NGA-East geotechnical working group (GWG) (e.g., Ramos-Sepúlveda et al., 2023) and independently verified by USGS researchers (Moschetti et al., 2023). The GWG study has recommended mean bias factors and their epistemic uncertainties.

The panel was asked if we support the use of empirical adjustments to CEUS GMMs through the use of a logic tree (0.5-weight on the use of an adjustment, 0.5-weight on unadjusted models). We agreed with the application of the adjustment factors and felt that a weight higher than 0.5 could be considered for the logic tree branch that applies the bias correction.

The use of the bias factors was subsequently considered by the tiger team, which supported their application with two modifications: (1) re-weighting regional data sets used in their derivation and (2) modifying the bias for sites with V_{S30} > 1000 m/s (no change occurs for sites with V_{S30} <

1000 m/s). Both changes have been implemented and are described in detail by Ramos-Sepúlveda et al. (2023).

6.2 Regional Considerations

If the adjustment factors are introduced, USGS asked if the factors should be used inside/outside the Coastal Plains regions. Based on the results of Ramos-Sepúlveda et al. (2023), we agree with the use of the adjustment factor across CENA, with the possible exception of the Texas-Oklahoma-Kansas region. This is because similar bias trends have been observed across CENA in different regions, although the absolute levels of bias, particularly at short periods, are spatially variable. Accounting for these spatial variations in the uncertainty model may improve the NSHM.

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