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Impact of Site Response Epistemic Uncertainty within a Probabilistic Seismic Hazard Analysis Framework

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ABSTRACT

Uncertainty can be separated into “aleatory” and “epistemic” components. Within the framework of a probabilistic seismic hazard analysis (PSHA) both of these components of uncertainty can and should be accounted for. Aleatory variability refers to the natural randomness of a process. Its assessment can be improved but it can only be reduced as much dictated by the natural process. Epistemic uncertainty, however, refers to the engineering uncertainty in modelling the process, due to lack of sufficient data and knowledge. In theory, the epistemic uncertainty can be reduced to zero. The goal of this study is to investigate the impact of epistemic uncertainty in site response analysis when computing Ground Motion Response Spectra (GMRS).

One general principle that is perceived in engineering practice is that the less information engineers have, the larger is the uncertainty and the higher is the estimated seismic hazard. As a result, the effort spent on collecting more data and reducing uncertainty is rewarded by reducing the seismic hazard. This very basic principal is not only violated in the current practice of seismic hazard analysis but it works contrary to the very basic principle so that the larger uncertainty yields lower seismic hazard. The current state-of-practice [1] can result in a reduction in computed seismic hazard as epistemic uncertainty increases. This could result in the folly of avoiding site specific investigations because more precise knowledge of the site conditions (i.e., a decrease in epistemic uncertainty) may lead to an increase in the estimated seismic hazard. Following this current state of practice approach [1], the use of a large epistemic uncertainty for cases in which limited information is known about the characterization of the site response analysis can lead to a lower mean amplification with a broad bandwidth. However, with improved data and thus lower epistemic uncertainty the mean amplification factors may increase with a more narrow bandwidth. This observation contradicts the general principle described earlier that less information implies higher uncertainty and results in higher computed seismic ground motions [2].

For this study, a test case was generated to include two cases with five base case profiles and the more standard use of three base case profiles. Weights for each base case are estimated following current [1] approach implemented for the case of five and three base case profiles. The weighted average amplifications of the case of the five base case profiles do not show significant difference from those based on the three base case profiles. As part of this test case it is shown that the variation in the mean based ground motions is indeed less sensitive to the assigned variations in the site response analysis (e.g., three profiles vs. five profiles). However, a key conclusion is that when evaluating the ground motions at a higher fractile level, for example, the 84th percentile, it is observed that the analysis based on additional site specific data can lead to lower ground motions. This observation is consistent with the premise that the collection and use of additional site specific data can lead to lower uncertainties and ultimately lower and more refined ground motions. To capture this benefit, however, the seismic provisions controlling the development of ground motions would need to consider higher fractile levels than the mean which is currently defined in the guidelines. The seismic input motion calculated at the higher fractile level (e.g. 84th percentile) can be scaled down (using appropriate scale factor for a well investigated site) to the mean level, such that no additional conservatism is implied for the well investigated sites, but the lack of information for sparsely investigated sites is penalized.

NOMENCLATURE

PSHA = Probabilistic Seismic Hazard Analysis
GMRS = Ground Motion Response Spectra
UHRS = Uniform Hazard Response Spectra
HF = High Frequency
LF = Low Frequency
MAFE = Mean Annual Frequency of Exceedance

INTRODUCTION

In a Probabilistic Seismic Hazard Analysis (PSHA) for important projects such as large dams, nuclear power plants and facilities, etc., the concepts of “uncertainty” are presented as “aleatory” and “epistemic”. Aleatory variability refers to the natural randomness of a process. Its assessment can be improved but it can only be reduced as much dictated by the natural process. Epistemic uncertainty, however, refers to the engineering uncertainty in modelling the process, due to lack of sufficient data and knowledge. In theory, the epistemic uncertainty can be reduced to zero. The goal of this study is to explore an issue raised by [2] to consider epistemic uncertainty in site effects when computing Ground Motion Response Spectra (GMRS). This paper represents a summary of the full study conducted as part of the 2017 Bechtel Technical Grant [3].

One general principle that is perceived in engineering practice is that the less information engineers have, the larger is the uncertainty and the higher is the estimated seismic hazard. As a result, the effort spent on collecting more data and reducing uncertainty is rewarded by reducing the seismic hazard. This very basic principal is not only violated in the current practice of seismic hazard analysis but it works contrary to the very basic principle so that the larger uncertainty yields lower seismic hazard. The current state-of-practice approach [1] can result in a reduction in computed seismic hazard as epistemic uncertainty increases. This could result in the folly of avoiding site specific investigations because more precise knowledge of the site conditions (i.e., a decrease in epistemic uncertainty) may lead to an increase in the estimated seismic hazard. The current approach [1] implements epistemic uncertainty by specifying a larger standard deviation for base case VS profiles developed from geotechnical site investigation (for example, 0.50 for (a) vs 0.35 for (b) shown in Figure 1 taken from [2]). Figure 1 shows conceptual plots of site amplification for each of three base case profiles as a function of oscillator period (T). The weighted average amplification with larger epistemic uncertainty in Figure 1(a) has a greater bandwidth and lower amplitude than that with smaller epistemic uncertainty in Figure1(b).

The contradiction of the general principle, less information implies higher uncertainty and results in higher computed seismic ground motion, observed above by [2] was explored using the test case results for this study. Hatch Units 1 and 2 nuclear power plant site was selected for this study. A test case was generated in this technical grant study to include five base case profiles, instead of three, by adding two additional base case profiles, one between the lower-range (left) and the best-estimate (middle); and the other between the best-estimate and the upper-range (right) base case profiles. The attempt is to “fill” the gaps between the three amplification curves. Weights for the case of five base case profiles are estimated following current [1] approach implemented for five base case profiles.

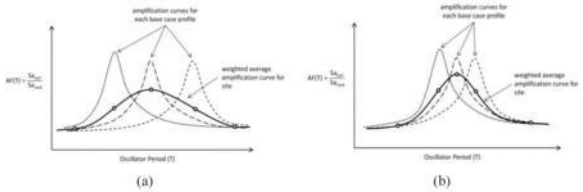


Figure 1. Amplification curves for each base case profiles and weighted average amplification curve for: (a) large assumed epistemic uncertainty, and (b) small epistemic uncertainty. The bandwidths of both weighted average amplification curves are greater than those for the base case profiles, and the amplitude of the weighted average curve for small epistemic uncertainty exceeds that for larger epistemic uncertainty over a range of oscillator periods. (from [2]).

INPUT SOIL PROFILE PROPERTIES

The dynamic properties of the subsurface material for the Hatch nuclear power plant site are provided in [4]. The finished grade for the site is defined at Elevation 129 ft for the main plant area based on Mean Sea Level (MSL) datum. As presented in [4], the adjusted depth to rock, based on the site grade of El. 129 feet is 4087 feet. To model the epistemic uncertainty of soil properties, five shear-wave velocity base case profiles (5th, 16th, 50th, 84th, and 95th percentiles) were generated. It is noted that 5th- and 95th- percentile base case profiles were used in this study, instead of 10th- (lower-range) and 90th-percentile (upper-range) recommended by [1], because the added 16th- and 84th-percentile base case profiles will be somewhat too close to the [1] recommended base case profiles. In addition, two alternative sets of strain-dependent property curves were recommended for the top 279 ft of soil in [4] for the Hatch site. However, for this study, only one set of the property curves were used, labelled as “Set G1”. Lastly, the epistemic uncertainty in deep soil damping below 509 ft depth, calculated through kappa estimates [1] is also represented by five alternative kappa values (5th, 16th, 50th, 84th, and 95th percentiles). Therefore, a total of 25 (5 x 1 x 5) base case soil profiles are generated to be considered for the study of the epistemic uncertainty of soil properties at the Hatch site. Various combinations of these base case profiles generate different cases in this technical grant study.

BASE CASE PROFILES

The median base case profile for Hatch Units 1 and 2 was based on existing subsurface information contained in the FSAR for Units 1 and 2 [4], additional and more recent information obtained for the investigations carried out for independent spent fuel storage installation (ISFSI) foundations ([5], [6], [7], and [8]), and nearby oil well data. Uncertainty in the soil/rock column, particularly VS data, is accounted for using a logarithmic standard deviation of 0.35 [1] to develop 5th, 16th, 84th and 95th percentile profiles per the [1] guidance by subtracting 0.58 (5th) and 0.35 (16th); and adding 0.35 (84th) and 0.58 (95th) in natural log units to the median VS. 1. Figure 2a and Figure 2b depict the best estimate velocities for the in situ materials for full depth of the column and ground surface down to 600 feet, respectively.

Based on the descriptions of the materials provided in the FSAR Section 2.5.1.2.2 [4], a total unit weight value of 125 pcf is assigned to the underlying materials considering a distribution of sand, clay, limestone, siltstone, and sandstone. A total unit weight value of 165 pcf is assigned to the bedrock – the Triassic materials at the base of the soil column.

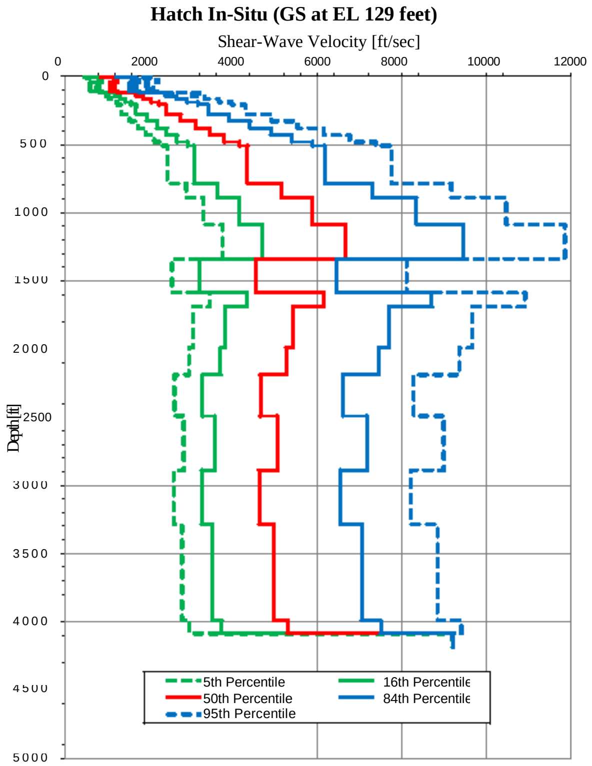


Figure 2a. In situ Soil Column Shear Wave Velocity.

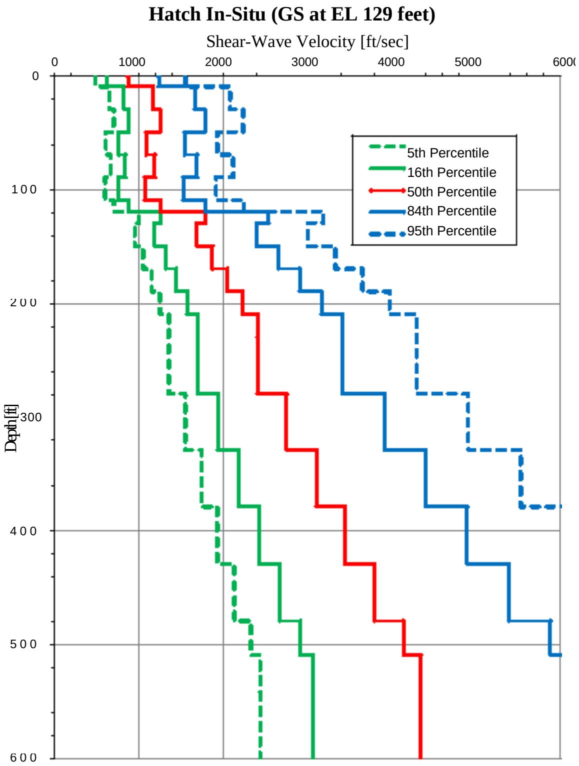


Figure 2b In situ Soil Column Shear Wave Velocity to Depth of 600 feet .

SHEAR MODULUS AND DAMPING CURVES

No site specific data regarding shear modulus degradation and damping versus cyclic shear strain were available for either the backfill materials or the in situ soils and rock at the Hatch site. It is noted that two alternative sets of strain-dependent property curves were recommended [9] for the top 279 ft of soil, both equally weighted, to account for epistemic uncertainty. The aleatory variability of the curves, represented by the coefficient of variation as a function of strain, is also provided. However, for this study, only one set of the property curves were used, labelled as “Set G1”, and described. Between the ground surface (Elevation 129 feet) and Elevation 0 (Depth of 129 feet) feet the [10] depth range curves of 50-120 feet are used illustrated in Figure 3a (G/Gmax) and Figure 3b (damping). Between Elevation 0 feet and Elevation -150 feet (Depth of 279 feet) the EPRI depth range curves of 120-250 feet are used and plotted in the same figures. Between Elevation -150 feet and Elevation -380 feet (Depth of 509 feet, Tampa and Oligocene Formations) VS ranges from about 2,700 to 4,100 fps (2,756 to 4,140 fps), increasing with depth. This material is assumed to be a more weathered rock than the materials encountered deeper in the profile. Thus, the [11] curves for weathered rock are used and illustrated in Figure 3a and Figure 3b.

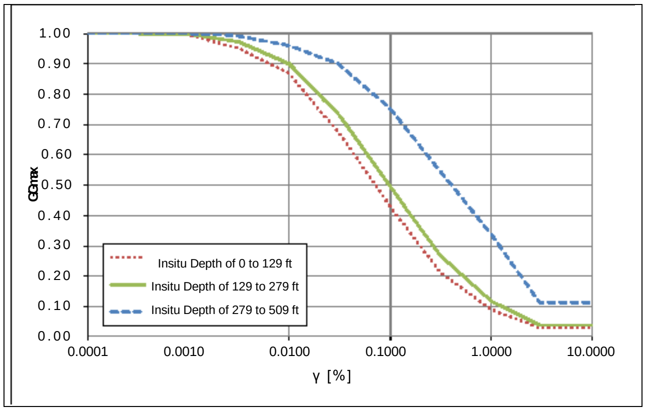
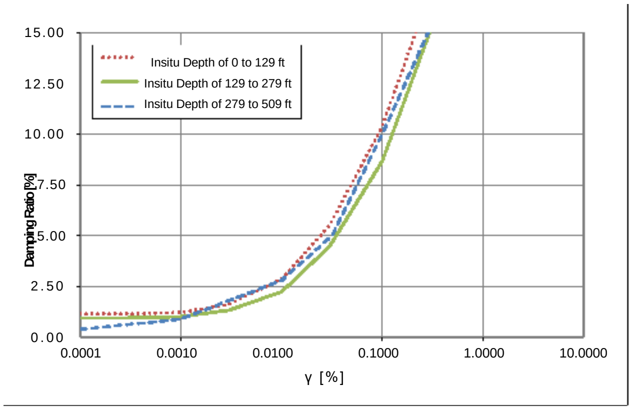


Figure 3a. Strain-Dependent Shear Modulus



Curves - Extended to 10% Shear Strain for (Set G1).

Figure 3b. Strain-Dependent Damping Ratio Curves - Extended to 10% Shear Strain for (Set G1).

Note that the strain-dependent property curves for the in-situ soil are extended to a maximum shear strain of 10% instead of 1%, as specified [9]. The shear modulus reduction coefficients are extended, as illustrated in Figure 3a, based on a constant residual strength up to 3% shear strain, and then kept constant up to 10% shear strain. This assumption is made because of the lack of data at high strain levels to improve numerical stability in the subsequent site response analysis. While this assumption limits the magnitude of soil stiffness reduction resulting in higher estimates of site response under high strain levels, it is expected to have a negligible impact on the overall results because very few runs are expected to exceed the specified 1% strain limit. Note that in the case of damping curves, damping ratios are truncated at 15%, as a conservative measure with respect to their subsequent use in site response analysis.

From the Ocala (Elevation -380 feet) to the top of the Triassic, the VS profile generally exceeds 4,300 fps and increases with increasing depth. These materials are taken to be medium/competent rock and the shear modulus is assumed to remain constant with strain (no degradation). To determine damping ratios, kappa should be computed according to the procedure outlined in Appendix B of the [1]. For the half space below the Triassic, where the Vs exceeds 9,200 fps a damping value of 1% is used.

KAPPA

Based on the guidance [1], the Hatch site is considered a deep soil site thus a median kappa value of 0.040 sec is considered for the site column. As specified in [1], a natural log standard deviation of 0.4 was used to estimate the 5th, 16th, 84th and 95th percentile values of kappa. This range of kappa values encompasses the values (e.g., 0.060, 0.054, and 0.052 sec) listed in [1] for deep soil sites.

In the site response analyses, the material above the depth of 509 feet is modeled as nonlinear with strain dependent shear-modulus reduction and material damping curves. Below the depth of 509 feet, the material is considered to be linear for all analyses with damping ratio calibrated to provide the proscribed total site kappa at the surface of the site.

INPUT ROCK SPECTRA

Site-specific horizontal 5% damped rock acceleration response spectra (ARS) calculated at hard rock with a minimum shear wave velocity of 9,200 ft/sec were provided in [12] and [13]. One set of low frequency (LF) and high frequency (HF) motions at each of five mean annual frequencies of exceedance (MAFE) 1E-3, 1E-4, 1E-5, 1E-6, and 1E-7 are presented in **Error! Reference source not found.**, for a total of 10 spectra (2 x 5). The rock ARS are used as input outcrop motions at the bedrock horizon for site response analysis and are plotted in Figure 4.

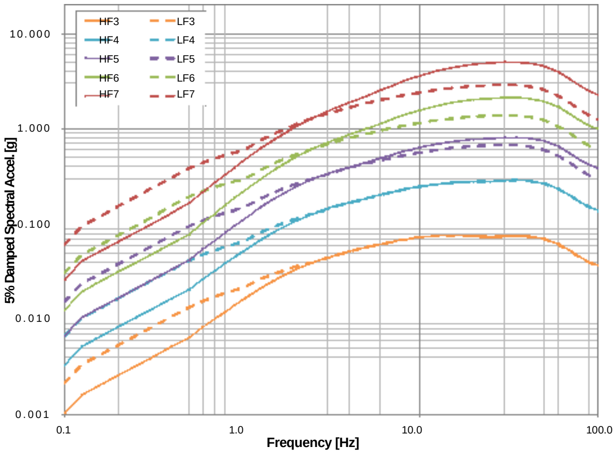


Figure 4. High Frequency (HF) and Low Frequency (LF) Input Rock Spectra.

SOIL PROFILE SIMULATION

To account for the aleatory variability in material properties that is expected to occur across a site at the scale of a typical nuclear facility, variability in the assumed VS profiles has been incorporated in the site response calculations. For the Hatch site, simulated VS profiles were developed from the median base case profile. The 5th, 16th, 50th, 84th and 95th percentile profiles. The Bechtel Soil Profile Simulation (SPS) program was used to generate a set of 60 site-specific simulated (randomized) soil columns for each base case soil profile (5th, 16th, 50th, 84th, and 95th) to represent the dynamic properties of the site while considering the uncertainty associated with each of these properties and correlations between different parameters.

Given the limited geotechnical information available, the following alternatives were considered: five VS base case VS models, one set of curves are used to model the strain-dependent behavior of the soil layers, and five different total kappa values. The generation of simulated soil profiles requires the input Best Estimate (BE) properties and their associated uncertainty. The uncertainty is expressed in terms of statistical distribution, standard deviation (SD) and correlation between different engineering parameters. In order to model the variation of soil properties, for each of the 25 base soil columns, a set of 60 simulated soil profiles is generated. For the randomization process the soil layer thickness, shear wave velocity, strain depending properties and deep soil and rock damping are randomized based on empirically based correlation models [14].

SITE RESPONSE EVALUATIONS

To perform the site response analyses for the Hatch site, a random vibration theory (RVT) approach was employed, using the Bechtel PSHAKE program. This process utilizes a simple, efficient approach for computing site-specific amplification functions and is consistent with existing NRC guidance and the [1]. The guidance in [1] on incorporating epistemic uncertainty in shear-wave velocities, kappa, non-linear dynamic properties and source spectra for plants with limited at-site information was followed for the Hatch site.

For each combination of the base profiles and its corresponding 60 randomized profiles and input motions, the site amplification is computed as the ratio between 5% damped geologic outcrop pseudo acceleration response spectrum at the control point and bedrock. The analysis is carried out at 301 frequency points ranging from 0.1 to 100 Hz and equally spaced in logarithmic space. The median (computed as the logarithmic mean) and the logarithmic standard deviation (log-SD) of the site amplification at each frequency are then computed. An example of the computed log mean amplification function and standard deviation is shown in Figure 5 for the suite of HF and LF input motions.

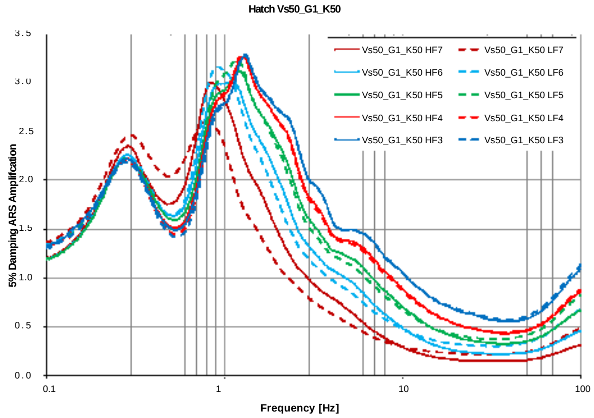


Figure 5a. Log mean amplification factors.

Impact of Site Response Epistemic Uncertainty within a Probabilistic Seismic Hazard Analysis Framework

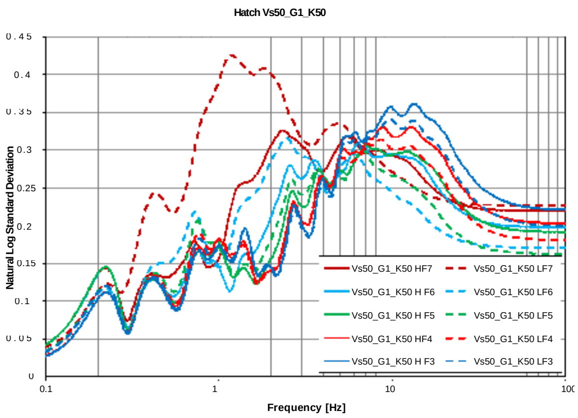


Figure 5b. Log standard deviation.

APPROACH 3 GROUND MOTIONS

Given the site response analysis, resulting surface ground motions were computed following an approach 3 methodology [15]. This approach accounts for the mean site amplification but also the uncertainty associated with these amplification factors and the input hazard curve. Following this methodology UHRS are computed for the MAFE level of 10^{-4} and 10^{-5}.

The results for Case 1 and Case 3developed in [3] are plotted in Figure 6a for the 10^{-4} hazard level and Figure 6b for the 10^{-5} hazard level. Case 1 represents the case in which additional information is obtained for the site characterization representing a reduction in the epistemic uncertainty. Case 3 is for the case with more limited information and hence a larger epistemic uncertainty. As is observed in Figure 6, the impact on reducing the epistemic uncertainty (i.e. Case 1) does not significantly impact the mean results, however, it does have a larger impact on the 84th fractile level with an observed reduction on average by about 10%. This observation provides a technical justification for the collection of additional data at a given site, especially if higher fractile levels than the mean are considered.

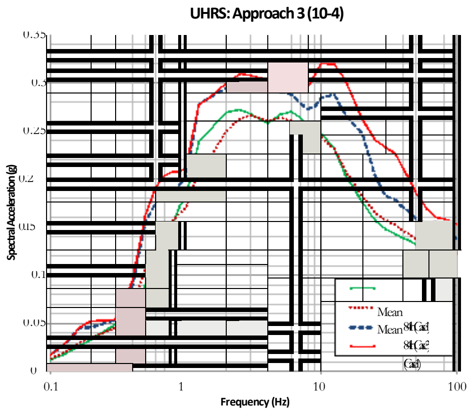


Figure 6a. Comparison of mean and 84th-Percentile 10^{-4} UHRS and GMRS of Case 1 and Case 3.

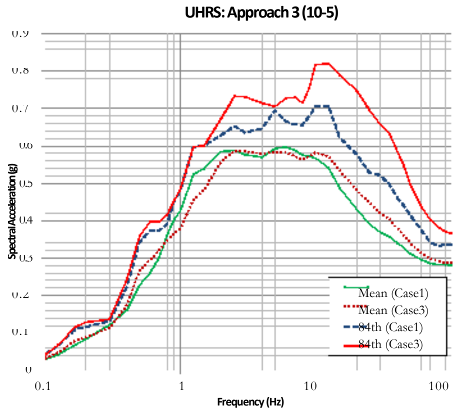


Figure 6a. Comparison of mean and 84th-Percentile 10^{-5} UHRS and GMRS of Case 1 and Case 3.

CONCLUSIONS AND RECOMMENDATIONS

A summary of few cases of epistemic uncertainties in site effects of the PSHA are presented in this paper. The full study is contained in [3]. Based on the results of this study [3], it is recommended that introduction of epistemic uncertainties, including VS, kappa, dynamic property curves, etc., needs careful and thorough considerations. Each branch of the epistemic uncertainties and its associated weight needs to be evaluated based on knowledge of the site. Simply following the current EPRI approach [1] implementing epistemic uncertainty of the site effects could result in a lower ground motion than anticipated at the site.

As shown in Figures 6a and 6b, this study showed that the mean 10^{-4}, 10^{-5} UHRS (GMRS can be similarly inferred) for base case profiles with baseline epistemic uncertainties (Case 1) are very close to those with significantly larger epistemic uncertainties (Case 3) using

Approach 3 with alternative hazard curves that were combined in the site response logic tree. However, the 84th percentiles of the 10^{-4}, 10^{-5} UHRS (GMRS can be similarly inferred) corresponding to the case with larger than baseline epistemic uncertainties (Case 3) are significantly higher. This observation leads to a key finding from this study that in cases in which additional site specific data can be incorporated into the site response analysis and seismic hazard analysis, a reduction of the epistemic uncertainty can lead to a reduction in the resulting ground motions. However, for the mean hazard level which the current regulations are primarily associated with does not have as significant correlation to the ground motion results as the higher fractile levels (e.g., 84th percentile).

Given the above observation it is a recommendation of this study to provide ground motion estimates for more than just the mean hazard level for critical projects to assist in the engineering judgement and ultimately engineering design decisions. We further recommend using a higher fractile of the input motion (e.g. 84th percentile) as the basis for determining the design basis motion. Note this recommendation does not imply a more conservative input for a well investigated site as the seismic input motion calculated at the higher fractile level would be scaled down (using appropriate scale factor for a well investigated site) to the mean level, however, the lack of information for sparsely investigated sites is penalized. Such an approach would resolve the folly of avoiding more site specific information.

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