International Workshop on Earthquakes in North Iceland
Húsavík, North Iceland, 31 May - 3 June 2016

Treatment of Epistemic Uncertainty in Site Effects in Probabilistic Seismic Hazard Analyses

Russell A. Green[1], Emily Gibson[2], and Adrian Rodriguez-Marek[3]

[1]*Virginia Tech, Blacksburg, VA, USA (rugreen@vt.edu)*
[2]*US Defense Nuclear Facilities Safety Board, Washington, DC, USA (emilyg@dnfsb.gov)*
[3]*Virginia Tech, Blacksburg, VA, USA (adrianrm@vt.edu)*

Introduction

Probabilistic Seismic Hazard Analyses (PSHA) form the basis for developing regional seismic hazard maps, such as those that accompany building codes, as well as for estimating the site-specific seismic hazard for important projects (e.g., large dams, chemical processing plants, nuclear power plants). While the fundamental mechanics of PSHA remain the same as originally proposed by Cornell (1968), the accounting for uncertainty in estimating seismic hazard continually evolves. In this vein, uncertainty is currently classified as "aleatory variability" and "epistemic uncertainty." While these terms are somewhat unique to the vernacular of seismic hazard analysts, the concepts that they represent are widely known. Aleatory variability refers to the natural randomness of a process. Accordingly, as additional information about a process is obtained, an assessment of the associated aleatory variability can be refined, but it can only be reduced to a value dictated by the natural randomness of the factors governing the process. In contrast, epistemic uncertainty refers to the scientific uncertainty in modelling the process, due to limited data and knowledge. As a result, epistemic uncertainty can theoretically be reduced to zero.

The focus of the present study is on the treatment of epistemic uncertainty associated with site effects in PSHA, where site effects refers to the influence of a site's geologic profile on ground motions as they propagate up from a reference horizon at depth to the ground surface. One guiding principle in estimating epistemic uncertainty is that the less you know, the larger the estimated uncertainty should be. Implied in this principle is that higher uncertainty will result in a higher computed seismic hazard, providing the impetus for geologists, seismologist, and earthquake engineers to collect and analyse data related to the seismic hazard of a site/region. However, contrary to the spirit of this guiding principal, the treatment of epistemic uncertainty for site effects in the current high-end state-of-practice can result in a reduction in computed ground motions in a PSHA as epistemic uncertainty increases.

In the following, current approaches for treating the epistemic uncertainty associated with site effects in PSHA are briefly outlined. Next, the shortcoming of the EPRI (2012) approach is discussed, specifically that a reduction in computed ground motions can result as epistemic uncertainty increases. Finally, an alternative procedure for treating epistemic uncertainty associated with site effects that overcomes the identified shortcomings of the EPRI (2012) approach is conceptually presented.

Current Approaches for Treating Epistemic Uncertainty of Site Effects

Traditionally, PSHA have been performed for a reference site condition (usually "rock") or reference horizon at depth (usually a rock horizon that satisfies the elastic half-space assumption) and deterministic factors are applied to the computed seismic hazard to account for site effects. This approach is still used in many building codes in the US and worldwide (e.g., ASCE 7-10: ASCE, 2013), where the accompanying seismic hazard maps are for "rock" site conditions. However, the use of deterministic site amplification factors does not account for the uncertainty in site effects, which can be significant, and as a result, various approaches have been proposed to more formally incorporate site effects into PSHA (e.g., Bazzurro and Cornell, 2004). Following the 2011, M_w9.0 Tohoku earthquake in Japan and the ensuing accident at the Fukushima Daiichi nuclear power plant, the US Nuclear Regulatory Commission (NRC) established a task force to review and access the NRC's seismic regulations, among other objectives. In response to the recommendations resulting from the task force's review, the Electric Power Research Institute published a report (EPRI, 2012) that includes among other things a detailed approach for formally incorporating site effects in a PSHA, to include the treatment of aleatory variability and epistemic uncertainty. This report represents the high-end state-of-practice for incorporating site effects in PSHA.

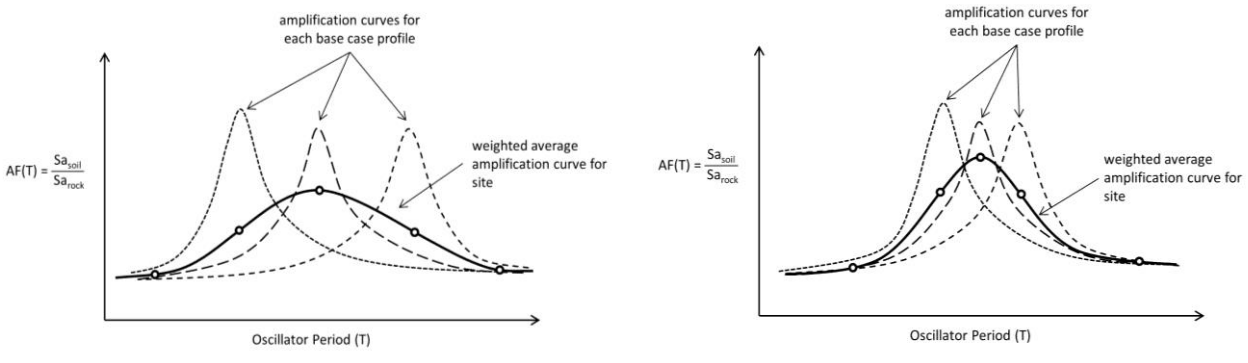
Although the distinction between aleatory variability and epistemic uncertainty for site effects is somewhat ambiguous, per EPRI (2012) aleatory variability encompasses the spatial variability of the dynamic soil properties at a site. Aleatory variability is accounted for by applying correlated random perturbations to small strain shear wave velocities (Vs), layer thicknesses, and stress-strain response characteristics for each layer in each of the three base case profiles (discussed below) used to develop the amplification curve for the site. A minimum of 30 realizations for each of the base case profiles is assumed sufficient to develop stable statistical estimates of the site effects.

In contrast to aleatory variability, epistemic uncertainty per EPRI (2012) encompasses uncertainty in the geologic profile and dynamic properties of the strata (i.e., things that could be determined with certainty given an unlimited amount of time, effort, and budget to perform a detailed field site characterization study and companion laboratory testing). Epistemic uncertainty in the profile stratigraphy is accounted for by developing best estimate (or mean), lower range, and upper range base case Vs profiles for a site. The lower and upper range base case Vs profiles are developed from the mean base case profile, which can be determined from either geotechnical/geophysical site investigations or inferenced from available geotechnical/geologic information. EPRI (2012) specifies $\sigma_{\mu}\ln = 0.35$ for base case Vs profiles determined from geotechnical/geophysical site investigations and $\sigma_{\mu}\ln = 0.50$ for base case Vs profiles inferenced from available geotechnical/geologic information (i.e., a larger epistemic uncertainty is assumed for base case profiles that are developed from less site-specific information). The lower and upper range base case Vs profiles correspond to the 10^{th} and 90^{th} fractiles of the assumed distribution around the mean base case Vs profile. To account for the epistemic uncertainty in the nonlinear dynamic soil properties, two different sets of nonlinear stress-strain response relationships are assumed for each stratum in each of the base case profiles.

The three base case Vs profiles are used in numerical site response analyses to develop a site amplification curve. Amplification curves for each of the base case profiles are combined using a logic tree approach. For a given base case profile, equal weights are used for the two branches of the logic tree for the two different sets of nonlinear stress-strain response relationships used in the site response analyses. A weighted average of the amplification curves for each of the three base case profiles is computed using weights of 0.4 for the amplification curve for the mean base case profile and 0.3 for the amplification curves for the upper and lower range profiles.

Shortcoming in the EPRI (2012) Approach for Treating Epistemic Uncertainty of Site Effects

As stated in the Introduction, one guiding principle in estimating epistemic uncertainty is that the less you know, the larger the estimated uncertainty should be. EPRI (2012) implements this principle by specifying a larger $\sigma_{\mu}\ln$ value for base case profiles inferenced from geotechnical/geologic information relative to profiles developed from geotechnical/geophysical site investigations (i.e., 0.50 vs. 0.35). These two values of uncertainty are equivalent to factors of 1.90 and 1.57, respectively, applied to mean base case Vs profile (i.e., the mean base case Vs profile is divided by the factor to compute the lower range base case Vs profile and multiplied by the factor to compute the upper range base case Vs profile). Figure 1 show conceptual plots of the amplification curves for each base case profiles and the weighted average amplification curves for the two assumed values of epistemic uncertainties. In this figure, an amplification curve (AF) is the ratio of the response spectral accelerations of the soil to rock motions (Sa_{soil}/Sa_{rock}) expressed as a function of oscillator period (T). As shown in this figure, the weighted average amplification curve corresponding to the larger epistemic uncertainty has a greater bandwidth than the curve corresponding to the smaller epistemic uncertainty, with the bandwidths of both the weighted average curves being much greater than those for the base case profiles. Also, the amplification curve corresponding to the smaller epistemic uncertainty is higher in amplitude than the curve corresponding to the larger epistemic uncertainty over a range of oscillator periods. If the fundamental period of the actual soil profile falls within the range of oscillator periods where the smaller epistemic uncertainty curve exceeds that of the larger epistemic curve, then the computed surface ground motions will be underestimated. This scenario contradicts the spirit of the guiding principle that less knowledge implies higher uncertainty and higher uncertainty results in higher computed seismic hazard.



(a) (b)

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.

Alternative Approach for Treating Epistemic Uncertainty of Site Effects

Borrowing from the bi-normalization concept proposed by Ziotopoulou and Gazetas (2010) for computing the statistical average of response spectra, an alternative approach to computing the weighted average of the amplification curves for the base case profiles is proposed. Specifically, it is proposed that amplification curves for the base case profiles be expressed as a function of the ratio of oscillator period to the degraded (or large strain) fundamental period of the profile (Tp) before the weighted average amplification curve is computed. This is conceptually shown in Figure

2 and is based on the premise that the peak in the amplification curve for a given base case profile corresponds to the degraded fundamental period of that base case profile. As shown in this figure, the weighted average amplification curve computed this way has both a bandwidth and amplitude that are statistically representative of the curves for all three of the base case profiles.

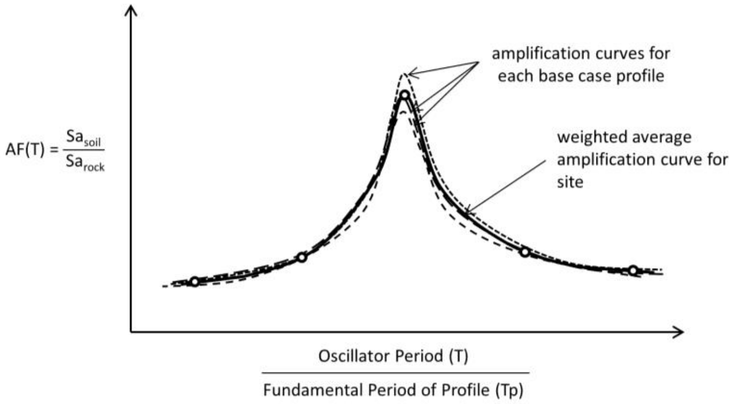


Figure 2. Amplification curves for each base case profiles expressed as function of the ratio of oscillator period to fundamental period of the soil profiles. The resulting weighted average amplification curve has both a bandwidth and amplitude that are statistically representative of curves for the base case profiles.

Using the weighted average amplification curve and PSHA data for the reference horizon, the seismic hazard curve at the ground surface, $G_Z(z)$, can be computed for a given oscillator period per the proposed approach using Eq (1).

$$G_Z(z) = \int_0^\infty \int_0^\infty P\left(Y \geq \frac{z}{x}\middle| x, T_p\right) f_{x,T_p}(x, T_p) dx\, dT_p \quad (1)$$

where: Y = AF(T), Z = Sa_{soil}, X = Sa_{rock}, $P(Y \geq x/z|x,Tp)$ is the conditional probability that AF(T) will exceed "z/x" given that the Sa_{rock} is equal to x and the fundamental period of the soil profile is equal to Tp, and $f_{x,Tp}(x,Tp)$ is the joint probability density function of Sa_{rock} and Tp. Although the computation of the seismic hazard at the ground surface for the proposed approach is slightly more involved than that for the EPRI (2012) approach, the treatment of epistemic uncertainty is in accord with the mechanics of the site effects phenomenon and overcomes the "statistical smoothing" of the base case amplification curves inherent to the EPRI (2012) approach.

Acknowledgements

Partial funding for this study was provided by the U.S. Defense Nuclear Facilities Safety Board (DNFSB). The authors gratefully acknowledge this support. However, any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the DNFSB.

References

ASCE, *Minimum Design Loads for Buildings and Other Structures*, ASCE Standard, ASCE/SEI 7-10, ASCE Press, American Society of Civil Engineers, Reston, VA, 2013.

Buzzurro, P., and C.A. Cornell, Nonlinear soil-site effects in probabilistic seismic-hazard analysis, *Bulletin of the Seismological Society of America* **94**, 2110-2123, 2004.

Cornell, C.A., Engineering seismic risk analysis, *Bulletin of the Seismological Society of America* **58**, 1583-1606, 1968.

EPRI, *Seismic Evaluation Guidance: Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic*, Report 1025287, Electric Power Research Institute, Palo Alto, CA, pp. 206, 2012.

Ziotopoulou, A., and G. Gazetas, Are current design spectra sufficient for soil-structure systems on soft soils, Chapter 8, *Advances in Performance-Based Earthquake Engineering* (M.N. Fardis, ed.), Springer Science, 79-87, 2010.