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COMPARATIVE PROBABILISTIC-DETERMINISTIC INVESTIGATIONS FOR EVALUATION OF SEISMIC SOIL-STRUCTURE RESPONSE

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ABSTRACT

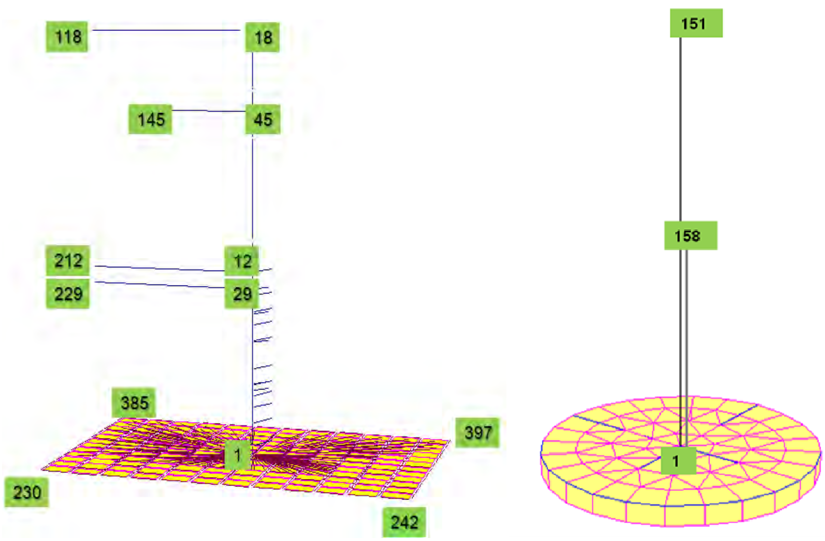
Probabilistic seismic soil-structure interaction (SSI) analysis is theoretically the most thorough analysis to include the effects of inherent uncertainties related to the seismic input motion and soil and structural material behavior. The paper discusses the application of probabilistic SSI analysis to nuclear structures based on the new ASCE 04-2013 standard (2013) recommendations for the deterministic and probabilistic SSI analyses. Probabilistic and deterministic SSI analyses are comparatively performed for two case studies: i) EPRI AP1000 RB stick model and ii) PWR RB stick model. Both soft soil and rock sites are considered. The probabilistic SSI analyses assume that the spectral shape of the site-specific GRS seismic input and the soil profile stiffness and damping profiles are idealized as random fields. The structural stiffness and damping random variations are modeled for each structural element group as a pair of random variables that depend in an opposite way on the structural stress level. To perform the deterministic and probabilistic SSI analyses the ACS SASSI software including Option Pro was used. The comparative SSI results include in-structure response spectra (ISRS) at different locations with the two investigated RB complexes. A comparison of probabilistic ISRS computed using different the new ASCE 04-2013 recommended methods is included.

SCOPE OF THE PROBABILISTIC-DETERMINISTIC INVESTIGATIONS

The general purpose of the analytical methods employed in structural design standards is to provide reasonable levels of conservatism to account for load uncertainties. In particular, the goal of the new ASCE 04-2013 a standard is that based on a set of recommendations to develop seismic deterministic SSI responses that correspond approximately to a 80% non-exceedance probability level. For probabilistic seismic SSI analyses, probabilistic responses defined with the 80% non-exceedance probability level are considered adequate. In this paper we performed comparative probabilistic-deterministic investigations for two RB complexes with the intention to confirm the safety goal to achieve a 80% non-exceedance probability level for deterministic SSI responses, and also to evaluate in more detail the differences between the computed ISRS with these RB complexes based on the recommended deterministic and probabilistic SSI approaches.

CASE STUDIES

Two RB complex models were considered as shown in Figure 1: i) EPRI AP1000 stick model (Short et al., 2007) and ii) PWR RB stick model. For these two RB models, uncracked structural models (with a full concrete elastic modulus and a reduced damping ratio of 4%) were considered for deterministic SSI analyses. For probabilistic analysis structural material stiffness and damping were considered as two functionally related random variables as indicated in Figure 2. The two dependent random variables were assumed to be lognormal variables with the mean elastic modulus reduction factor of 0.9 and mean damping of 6%.



Stiff	Damp
0.01	0.20
0.10	0.17
0.20	0.15
0.30	0.13
0.40	0.11
0.50	0.10
0.60	0.09
0.70	0.08
0.80	0.07
0.90	0.06
1.00	0.05

Figure 1 EPRI AP1000 Stick (left) and PWR RB Stick (Right)

Figure 2 Damping as Function of Stiffness Reduction

The probabilistic seismic input ground response spectra (GRS) were considered to be lognormally distributed random fields in frequency. The coefficient of variation was 25% for the soft soil site and 30% for rock site. The correlation structure in frequency that is related to the soil layering filtering effects on incident vertically propagation waves was considered to correspond to a correlation length of 0.7 Hz for the soft soil site and 10 Hz for the rock site. Using the GRS random field model in frequency (Method 2 in ASCE 04-2013), 100 LHS realizations were simulated for the soil and rock sites as shown in Figure 2. The ensemble of simulations matches closely the assumed statistics as shown in Figure 2 for mean GRS.

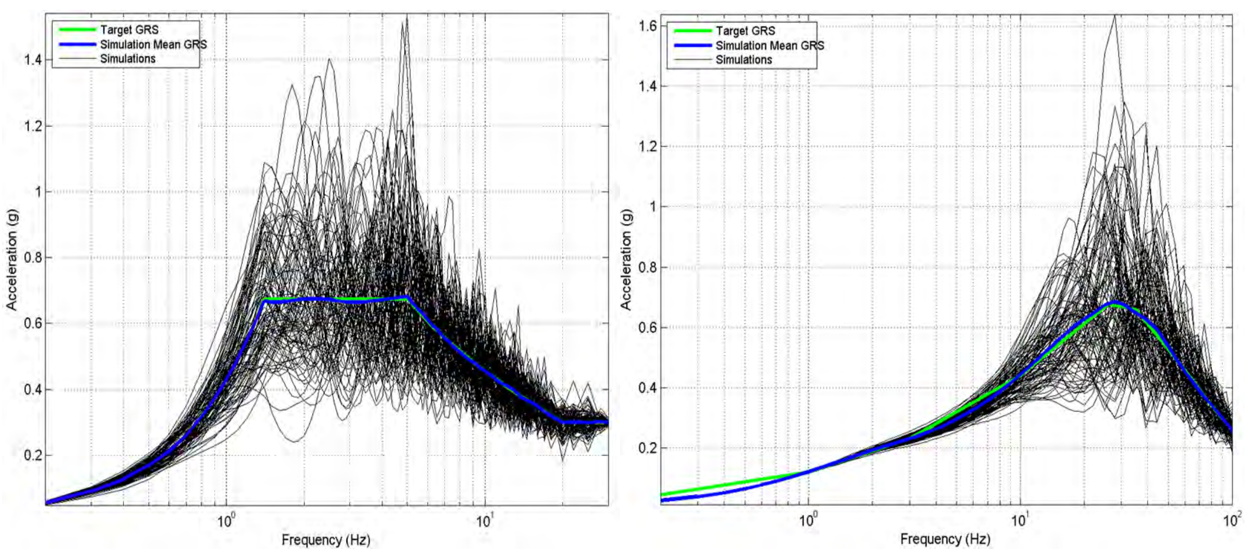
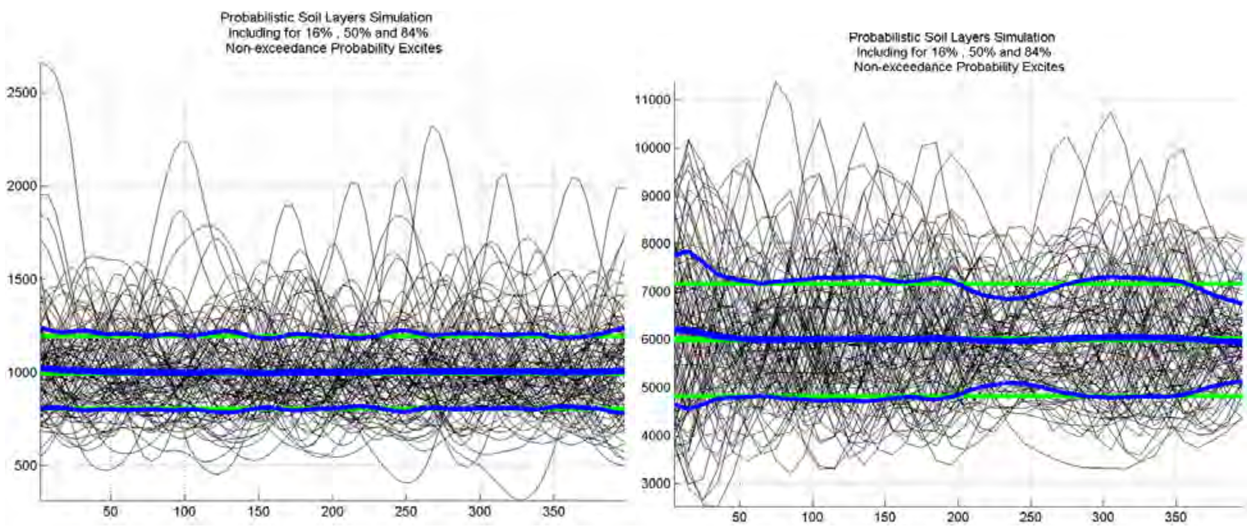
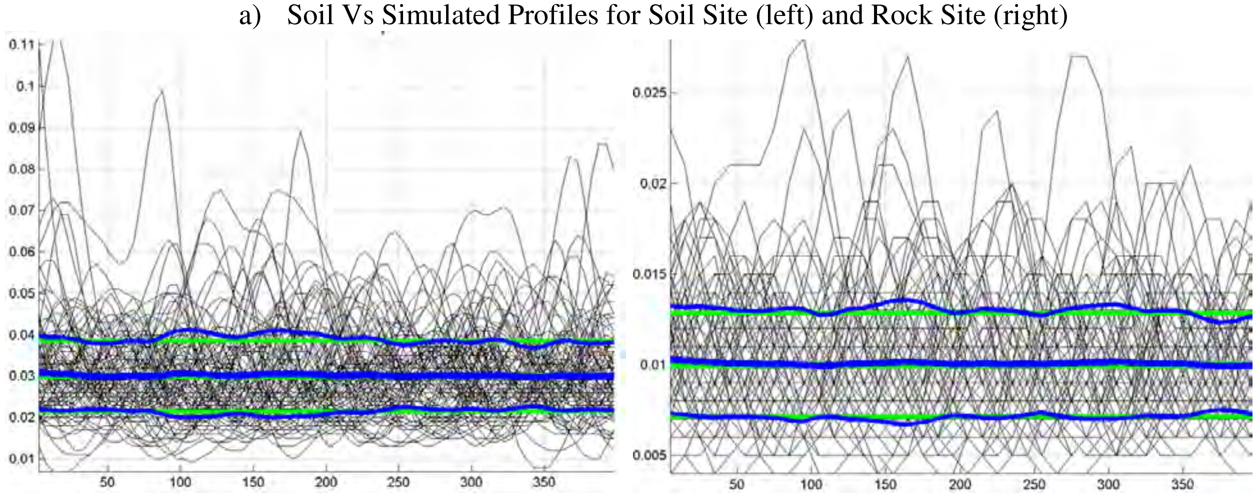


Figure 2 Probabilistic Simulations of the GRS Spectral Variations for Soil Site (left) and Rock Site (right)

For deterministic SSI analysis, the mean GRS was assumed as input. For probabilistic soil profiles, the Vs and the hysteretic damping were considered as two correlated lognormal random fields as function of depth. The coefficient of variation was 20% for Vs and 30% for hysteretic damping. A negative correlation coefficient of -0.60 was assumed between the Vs and hysteretic damping. The spatial correlation length in vertical direction was assumed to be about 20 ft. Figure 3 show the 100 LHS simulated soil Vs and damping profiles for the soil site (left) and rock site (right). For deterministic SSI analysis three soil profiles were considered, namely the best-estimate value for the soil shear modulus (BE), half of the best-estimate as lower bound (LB) and twice of the best estimate as upper bound (UB).



a) Soil Vs Simulated Profiles for Soil Site (left) and Rock Site (right)



b) Soil Damping Simulated Profiles for Soil Site (left) and Rock Site (right)

Figure 3 Probabilistic Simulations of Soil Vs and Damping Profiles for Soil (left) and Rock Site (right)

The deterministic and probabilistic SSI analysis were performed using the ACS SASSI software including the Option Pro capability (Ghiocel, 1998, 2002, 2013) that incorporates probabilistic SSI approaches in line with the recommendations of the new ASCE 04-2013 standard.

RESULTS

The comparative horizontal and vertical ISRS computed using deterministic and probabilistic SSI analyses are shown in Figures 4 through 7. For the EPRI AP1000 model three locations were selected: 1) basemat center, 2) top of ASB (Auxiliary Shield Building), and 3) top of SCV (Steel Containtment Vessel). For the PWR RB model also three locations were selected: 1) basemat center, 2) top of CS (Containtment Shell), 3) top of IS (Internal Structure).

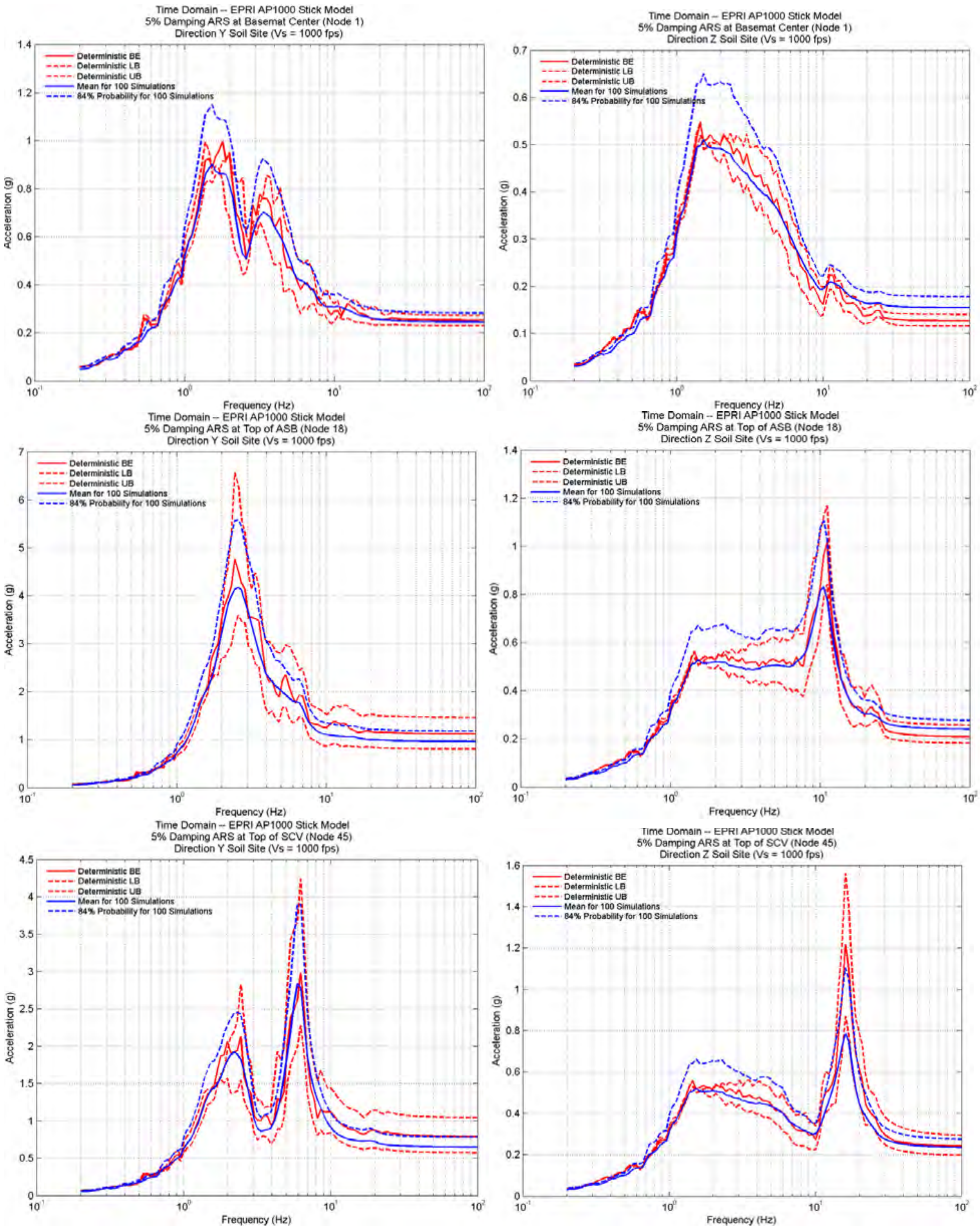


Figure 4 Deterministic and Probabilistic (for Mean and 84% Non-Exceedance Probability) 5% Damping ISRS in X and Z Directions for the EPRI AP1000 Stick Model and the Soil Site: Basemat Center (top), Top of ASB (middle) and Top of SCV (bottom)

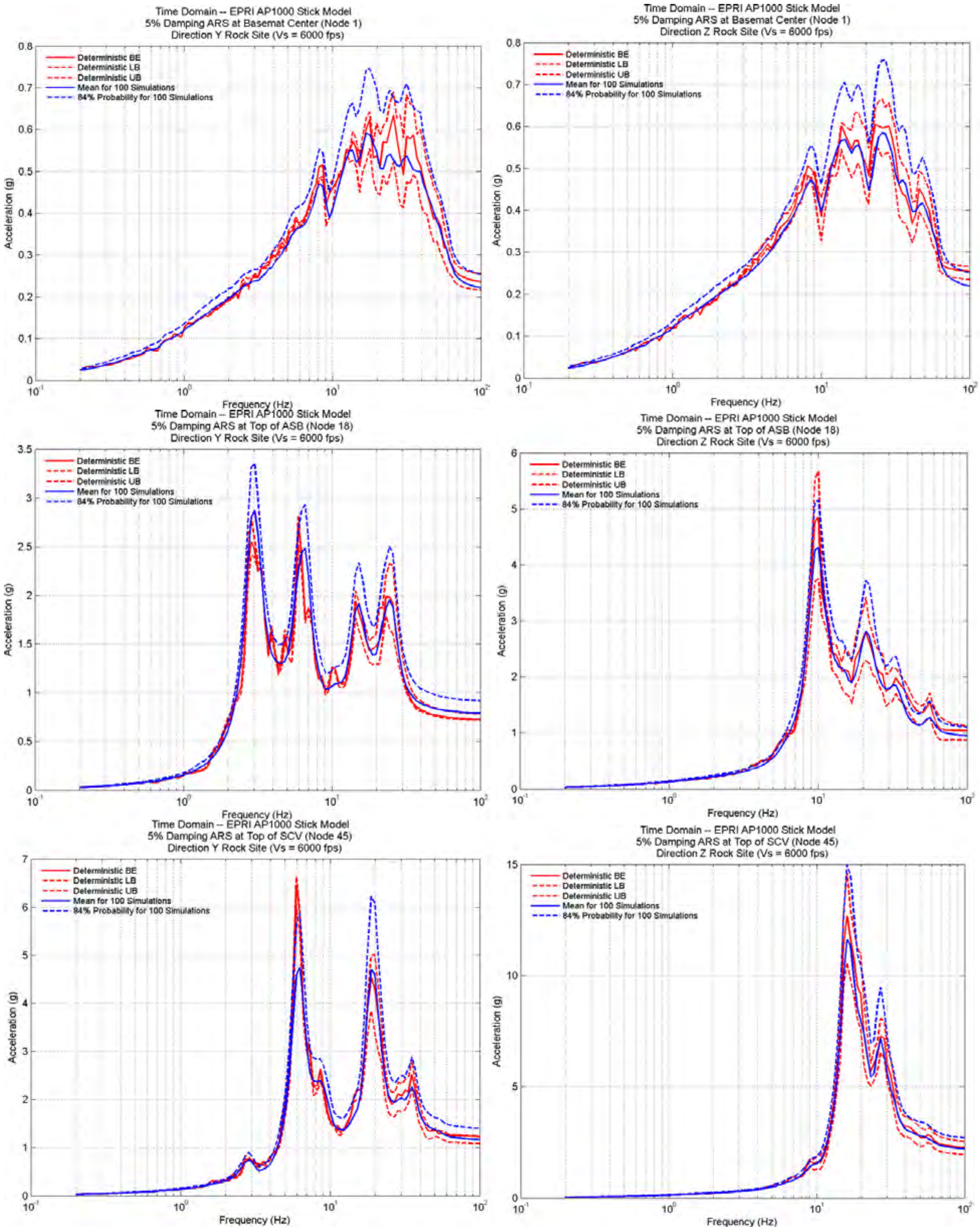


Figure 5 Deterministic and Probabilistic (for Mean and 84% Non-Exceedance Probability) 5% Damping ISRS in X and Z Directions for the EPRI AP1000 Stick Model and the Rock Site:
Basemat Center (top), Top of ASB (middle) and Top of SCV (bottom)

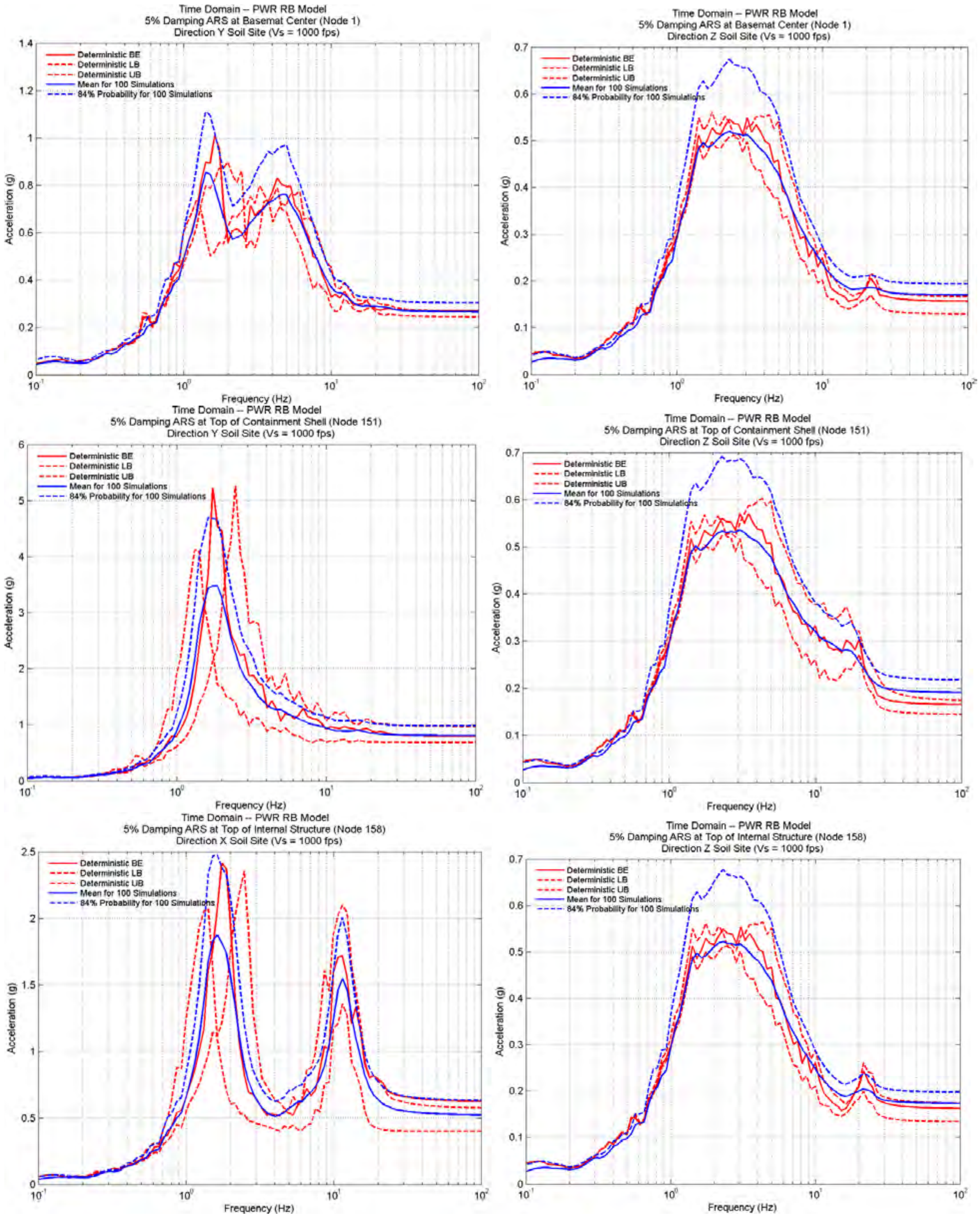


Figure 6 Deterministic and Probabilistic (for Mean and 84% Non-Exceedance Probability) 5% Damping ISRS in X and Z Directions for the PWR RB Stick Model and the Soil Site: Basemat Center (top), Top of CS (middle) and Top of IS (bottom)

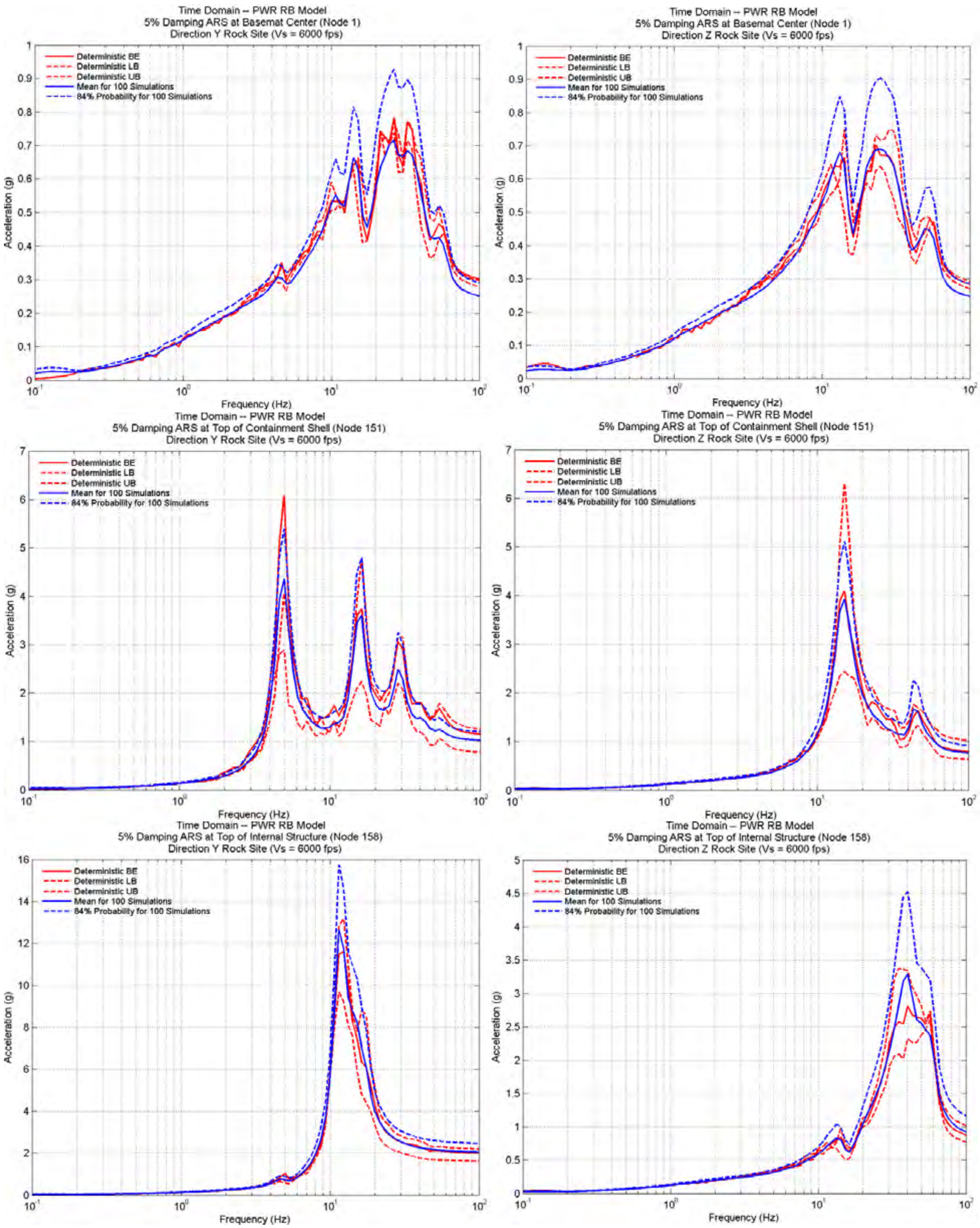


Figure 7 Deterministic and Probabilistic (for Mean and 84% Non-Exceedance Probability) 5% Damping ISRS in X and Z Directions for the PWR RB Stick Model and the Rock Site: Basemat Center (top), Top of CS (middle) and Top of IS (bottom)

The comparisons between the deterministic and probabilistic ISRS computed for EPRI AP1000 and PWR RB sticks indicate that in an overall, average sense, the goal for achieving a deterministic SSI response that corresponds approximately to the 80% non-exceedance probability response is accomplished. Typically, the deterministic ISRS, computed as the envelope ISRS for the three deterministic soil profiles, LB, BE and UB soils, is always above mean probabilistic response, most of the cases between the mean and 84% probability responses, sometimes much larger than 84% probability response. However, there are some systematic trends and some exceptions to be pointed out.

At the basemat level, the deterministic ISRS are closer to the mean response rather than 84% probability response, most likely corresponding to around 65% to 70% probability responses. For locations at higher elevations within AP1000 and PWR RB models, not at the basemat elevation, and for soil sites, the computed deterministic envelope ISRS correspond to 80% to 95% probability responses. However, for rock sites, the ISRS comparisons shows some exceptions in both horizontal and vertical directions for which the deterministic ISRS is close to 60% probability responses, or very close to the mean probability responses.

PROBABILISTIC SSI RESPONSES USING DIFFERENT ASCE 04-2013 METHODS

The recent ASCE 04-2013 standard draft includes different probabilistic SSI modeling approaches for seismic GRS input spectra and soil Vs and damping profile variations, from simple independent or fully correlated random variable models to more refined random field models. Thus, in addition to the probabilistic SSI simulation models used in the previous sections for the comparative deterministic-probabilistic ISRS results, for the EPRI AP1000 stick on the soil site, we also consider two other, simpler probabilistic simulation models as recommended by the new ASCE 04-2013. . We used 30 and 60 LHS simulations for these models. These probabilistic simulation models are shown in Figures 8 and 9. The GRS model assumed no spectral shape variation (Method 1 in ASCE 04-2013). The GRS input spectra, and soil Vs and damping were assumed as lognormal random variables. For the 30 LHS simulations, the soil profiles were assumed to be fully correlated in depth. For the 60 LHS simulations, soil profiles were assumed to be statistically independent. The simulated soil Vs profiles are plotted in Figure 9.

Figure 10 compares the 84% probability ISRS computed using the three ASCE 04 approaches for probabilistic seismic input and soil profile simulations, and using different number of LHS simulations.

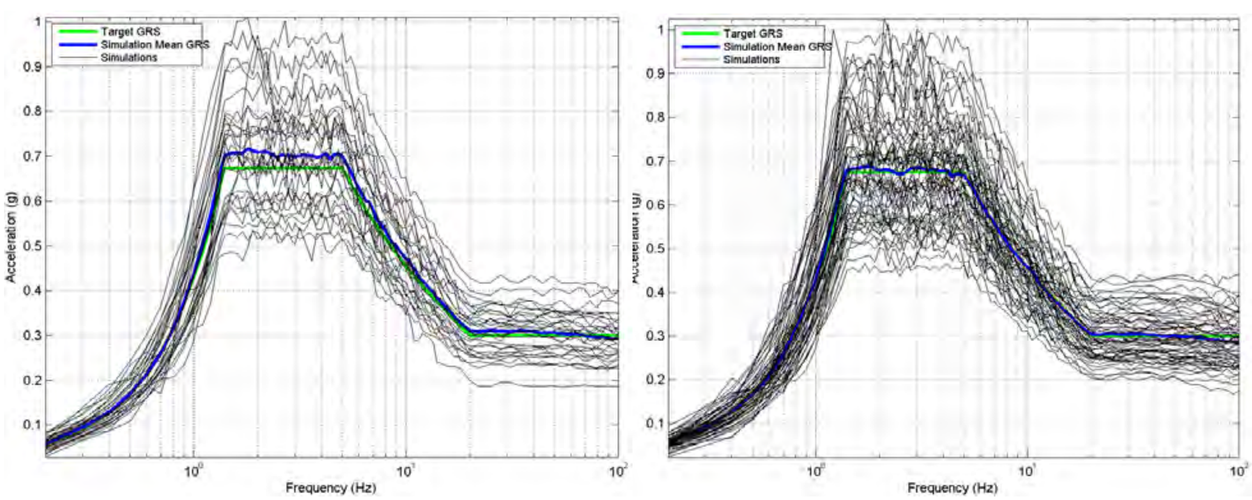


Figure 8 Probabilistic GRS Input Spectra using 30 LHS (left) and 60 LHS (right) Simulations

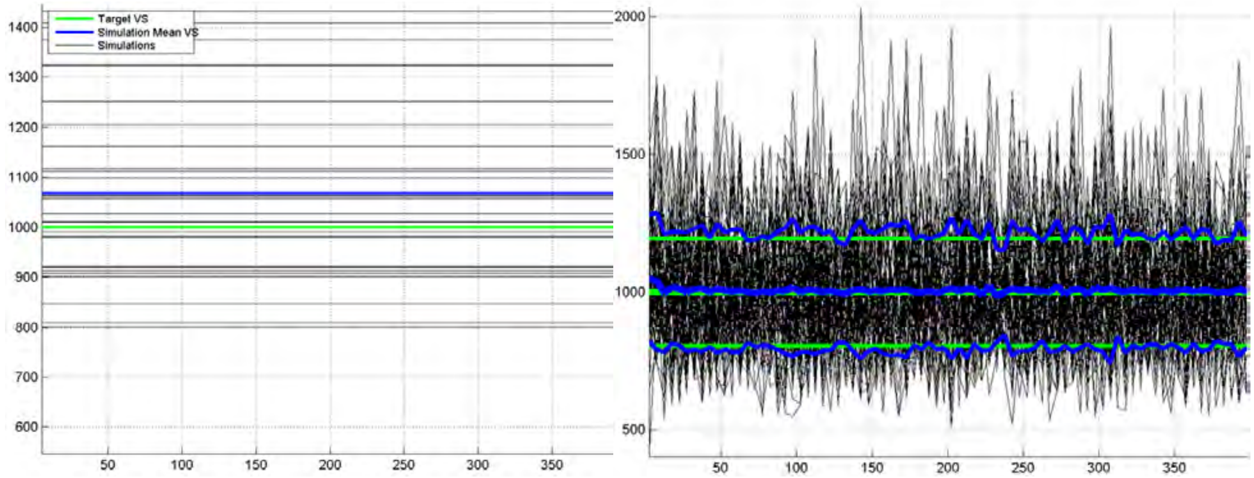


Figure 9 Probabilistic Soil Vs Soil Profiles using 30 LHS (left) and 60 LHS (right) Simulations

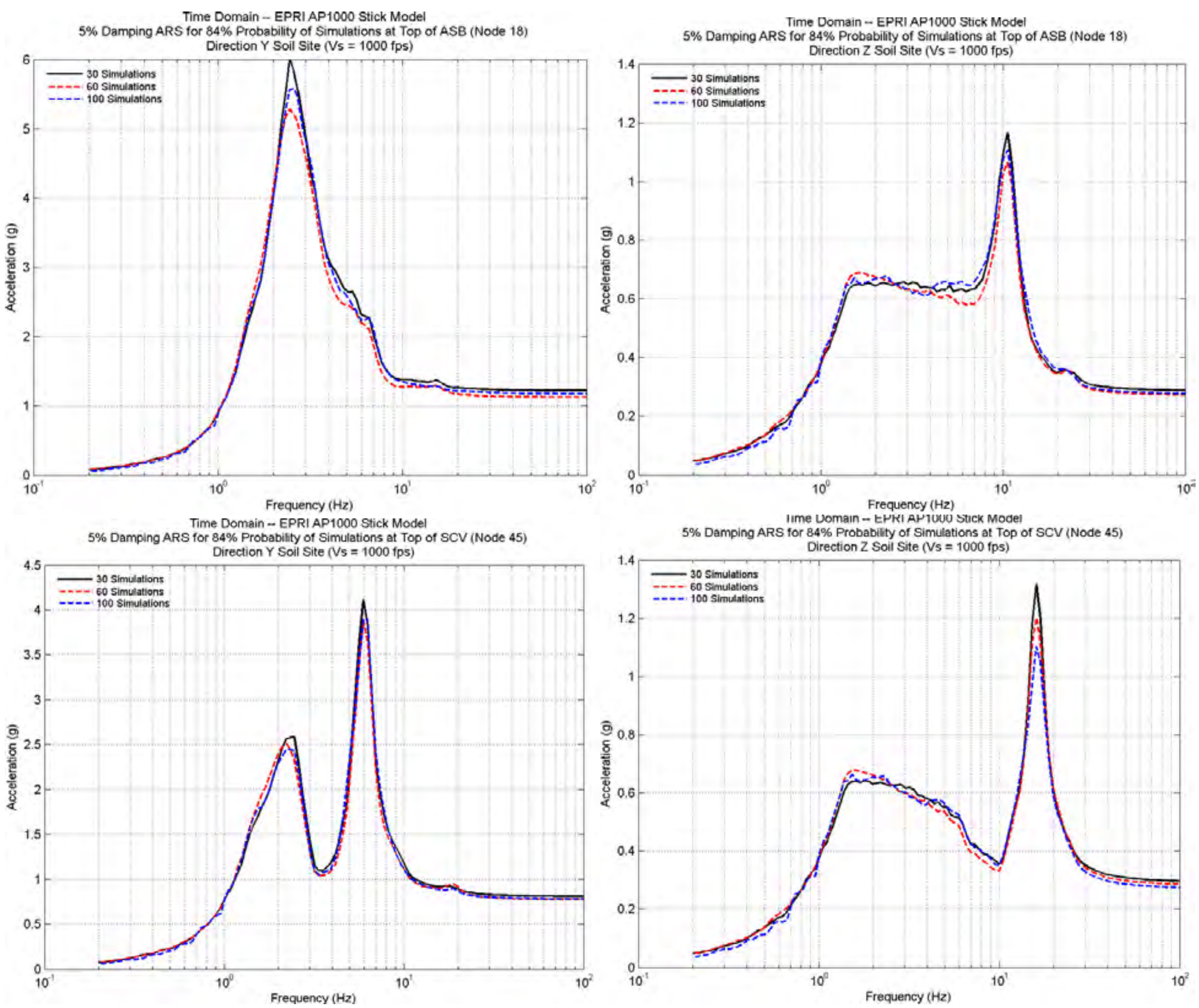


Figure 11 84% Non-Exceedance Probability ISRS for 30, 60 and 100 LHS Simulations

Figure 11 results indicate that for the investigated EPRI AP100 stick model on the soil site, the differences between the 84% probability ISRS computed using 30, 60 and 100 LHS simulations and different probabilistic modeling options are up to 20%, but most likely much smaller. Thus, for the investigated case study, different probabilistic SSI approaches as recommended by the new ASCE 04-2013 provide closely matching ISRS responses.

CONCLUSIONS

The deterministic-probabilistic SSI analysis investigation results confirm in an overall, average sense the safety goal of ensuring that the recommended deterministic SSI approaches produce a SSI response that corresponds to a 80% non-exceedance probability response.

The presented ISRS results show that there are a number of exceptions when the deterministic SSI results correspond to either lower or higher non-exceedance probability responses, in the 60% to 95% percent range. Based on the limited investigations, it appears that deterministic SSI results are slightly less conservative for rock sites than for soft soil sites. Additional investigations are needed to clarify this aspect in more detail.

The comparisons of the 84% probability ISRS computed using different probabilistic SSI simulation models as recommended by the new ASCE standard indicated consistent, closely matching results.

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