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ACCOUNT FOR UNCERTAINTY IN THE CONTEXT OF SEISMIC SITE RESPONSE ANALYSIS

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ABSTRACT

Sources of uncertainty in subsurface site conditions are included, as standard practice, in seismic site amplification analysis. Considering that current U.S. NRC regulations define the design level motion based on the mean response, this paper examines the effects of increasing the amplitude of modeled uncertainty on the seismic site amplification response. Two sites representing two different Eastern U.S. site conditions are analyzed, with one deep soil site and one shallow rock site. The uncertainty incorporated in generating the set of simulated profiles is the main parameter under scrutiny, in particular, the effect of the amplitude of the variation of shear-wave velocity on the resulting response.

The analysis finds that a larger variation does not necessarily contribute to a more conservative site response estimate when only the mean response is used for the purpose of design. Furthermore, excessively large variations result in the masking of the real characteristics of the site, and an often un-conservative response, especially when small inter-layer correlation coefficients for shear-wave velocity are considered (as opposed to perfect inter-layer correlation). Several recommendations are made with the aim of capturing the most realistic site response. In particular, the implementation of these recommendations should result in a reasonably conservative design motion in the case of poorly investigated sites, and an accurate and not overly conservative design motion in the case of well investigated sites, as is the case of most of the new generation of nuclear power plants.

INTRODUCTION

Sources of uncertainty in subsurface site conditions are included, as standard practice, in seismic site amplification analysis. A typical procedure for site-specific amplification analysis comprises of developing a best estimate soil/rock profile for the site including its dynamic properties and associated uncertainties. A set of simulated profiles with a minimum sample size of 60, as indicated in RG 1.208 (USNRC, 2007), is generated to represent these properties and their range of variation. The mean site amplification response, resulting from the set of profiles, is computed and used for deterministic design purposes.

There is a common supposition in the industry that including a larger variation in the subsurface profile properties (e.g. shear modulus) leads to a conservative response estimate. The concept is widely applied in the soil profile simulation preceding seismic site amplification analysis, by including a larger variation to cover the both the measured aleatory uncertainty, as well as the un-measured but estimated epistemic uncertainty. Many applications of this concept can be observed in the current standard design certification efforts, and in numerous permit applications, for new nuclear power plant sites.

Considering that the design level motion is based on the mean response as is the case in U.S. NRC current regulations (USNRC, 2007), as opposed to a larger fractile (84th percentile for example), the aforementioned concept is examined in this paper. The variation incorporated in generating the set of simulated profiles is the main parameter under scrutiny, in particular, the effect of the amplitude of the variation of the shear-wave velocity of the soil/rock layers on the resulting response.

SITE CONDITIONS AND VARIATIONS

Two example sites representing two different but common Eastern U.S. site conditions are analyzed, with one deep soil site and one shallow rock site. The deep soil site is characterized by successive layers of mostly sandy and silty soils in the top 500 ft, followed by successive weathered and competent rock strata to a total depth of around 4000 ft, where bedrock is found defined by a minimum shear-wave velocity of 9200 ft/sec. The geotechnical investigation of the site defined the main dynamic properties and their associated uncertainties. These parameters include shear-wave velocity, unit weights, soil layer thicknesses, as well as strain-dependent property curves which specify shear-modulus reduction and damping ratios as a function of shear strain. The shear-wave velocity profile and the aleatory uncertainty associated with it, expressed in terms of the natural logarithmic standard deviation (log-SD), assuming logarithmic normal distribution, are presented in Figure 1. Note the gradual increase of shear-wave velocity with depth and the relatively moderate log-SD on the order of 0.15. Strain-dependent property curves were assigned for the different soil layers as well as for the weathered rock, and their uncertainty was defined following Costantino (1996). For deeper rock layers where the strain levels are expected to be small and which are expected to behave linearly, damping ratio is strain-independent and the material is assumed to behave linearly, in other words, shear modulus does not present any degradation with strain.

In the case of the rock site, a shallow soil layer of around 15 ft thick is found at the surface followed by a 50 ft thick layer of mildly weathered rock which lies over competent rock to a total depth of 160 ft, where bedrock is found. As in the case of the deep soil site, an extensive geotechnical investigation provided estimates for all dynamic parameters and their variations. Only the top layers of weathered rock is assigned strain-dependent properties while the rock layers starting at a depth of around 65 ft behave linearly. Figure 2 provides the best estimate shear-wave velocity profile and its uncertainty, which is defined by log-SD on the order of 0.1 to 0.15.

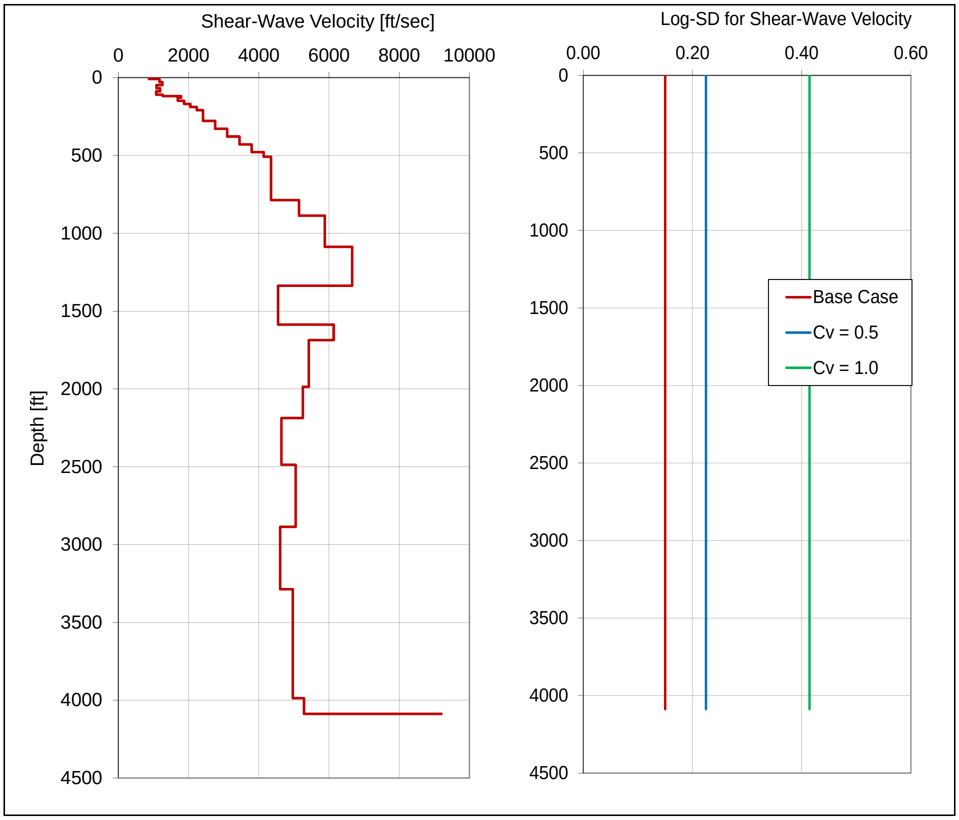

Figure 1. Best Estimate shear-wave velocity profile and log-SD for soil site.

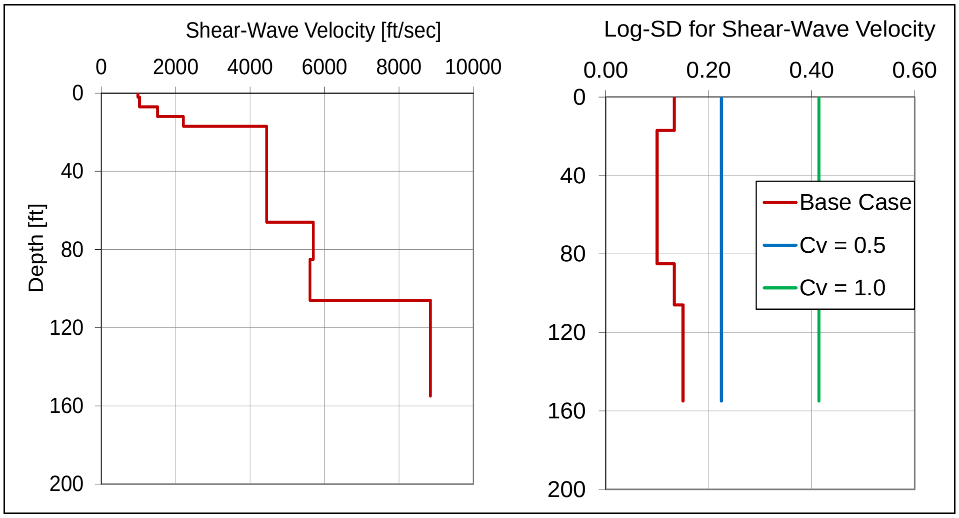

Figure 2. Best Estimate shear-wave velocity profile and log-SD for soil site.

SOIL PROFILE SIMULATION

Soil profile simulation refers to the process of generating a number of (randomized) soil profiles, where each profile has a unique combination of dynamic properties all within the range of expected variation at the site. According to RG 1.208 (USNRC, 2007), a minimum sample size of 60 simulated profiles are needed to adequately represent the variation and reduce the standard error of the mean for the various simulated properties. In the present study, the Bechtel computer program SPS (Bechtel, 2011) is used to generate the simulated profiles and a sample size of 100 is selected. The program allows for the consideration of uncertainty in shear-wave velocity, layer thicknesses, and strain-dependent property curves. In addition, inter-layer correlation of shear-wave velocity is considered as well as correlations between different parameters.

For the purpose of this study, for each of the two considered sites, six sets of 100 simulated profiles are generated. All sets share the same set of input best estimate parameters and variations, except for the variation of shear-wave velocities, defined by the log-SD, and the inter-layer correlation of shear-wave velocity (ρ_V). As summarized in Table 1, three sets have perfect inter-layer correlation (ρ_V=1), while the other three sets are assigned ρ_V based on the inter-layer correlation model in Toro (1996). Within each group of the three sets sharing the same ρ_V, different log-SD for V_s are used, where the first set uses the base case log-SD, as presented in Figure 1 and Figure 2, and as measured at the site, and the second and third sets use log-SD of 0.225 and 0.414, respectively. These log-SD correspond to a C_v of 0.5 and 1.0 on shear modulus, respectively, as defined in ASCE 4-98 (ASCE, 2000), and may be considered as typical values of medium and high amplitudes of V_s variation, as opposed to the relatively lower variation amplitude represented by the base case. Note that the random seed is kept constant for all six sets of the particular site, such that all six sets will have the exact set of properties except for the parameters that are modified in between (shear wave velocity due to different log-SD and ρ_V).

Table 1: Soil profile simulation (randomization) sets.

	Soil Site		Rock Site	
	ρ_V (Toro, 1995)	$\rho_V = 1$	ρ_V (Toro, 1995)	$\rho_V = 1$
Base case – V_s Log-SD = 0.1 to 0.15	SoilBC	SoilBC_Ro1	RockBC	RockBC_Ro1
V_s Log-SD = 0.225	SoilCv0.5	SoilCv0.5_Ro1	RockCv0.5	RockCv0.5_Ro1
V_s Log-SD = 0.414	SoilCv1.0	SoilCv1.0_Ro1	RockCv1.0	RockCv1.0_Ro1

SITE AMPLIFCATION ANALYSIS

Seismic site amplification analysis is implemented using the Bechtel Computer program P-SHAKE (Bechtel, 2009). The program is based on the same equivalent-linear theory used in SHAKE (Schnabel et al., 1972) combined with random vibration theory (RVT), see Deng and Ostadan (2008), which allows for the use of input motions in the form of acceleration response spectra (ARS), instead of acceleration time histories in the case of SHAKE. ARS amplification functions are calculated as the ratio of the response ARS at the considered horizon to the input ARS which is applied at the bedrock level. For each set of simulated profiles, natural logarithmic mean (median) amplification functions and corresponding log-SD are calculated as a function of frequency, at the considered horizon. In this paper, the focus will be on the response at the foundation elevation, which is taken at a 40 ft depth horizon from finished ground surface, a typical embedment depth for nuclear reactors, calculated as a full-column outcrop motion.

Site amplification analysis is performed for all 12 sets of simulated profiles (see Table 1) for the de-aggregated input rock motions, following Approach 2A in NUREG/CR 6728 (McGuire et al., 2001). The input rock motions are the low frequency (LF) and high frequency (HF) motions at the 1E-4 and 1E-5 mean annual probabilities of exceedance (MAPE). Figure 3 presents the median amplification functions for the soil site base case set, with perfect inter-layer correlation ("SoilBC_Ro1" in Table 1). Note that amplification occurs in the low frequency range and particularly at 0.3 Hz, which is the fundamental frequency for the 4000 ft deep soil column, and at around 1.3 Hz, while de-amplification is observed at the higher frequency range, between 15 Hz and 70 Hz, as is typical of deep soil sites. Some non-linearity is observed as illustrated by the lower amplification functions in the high frequency range for the higher intensity motions (HF 1E-5 and LF 1E-5).

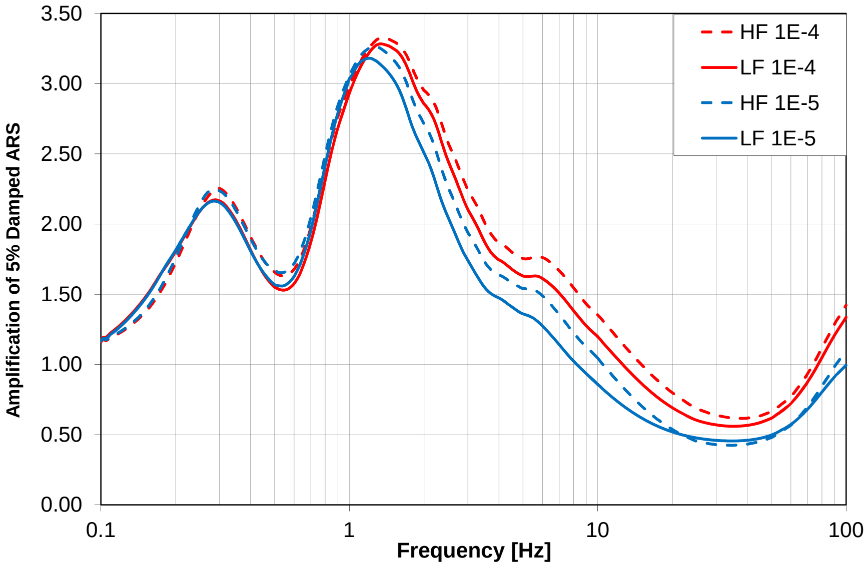

Figure 3. Median Amplification functions for soil site at foundation horizon (40 ft depth).

Figure 4 presents the median amplification functions for the rock site base case set, with perfect inter-layer correlation (“RockBC_Ro1” in Table 1). In contrast to the deep soil site, amplification at the rock site is observed in the high frequency range with a peak at around 10 Hz, and the response due to the four applied motions is almost identical indicating very limited non-linearity.

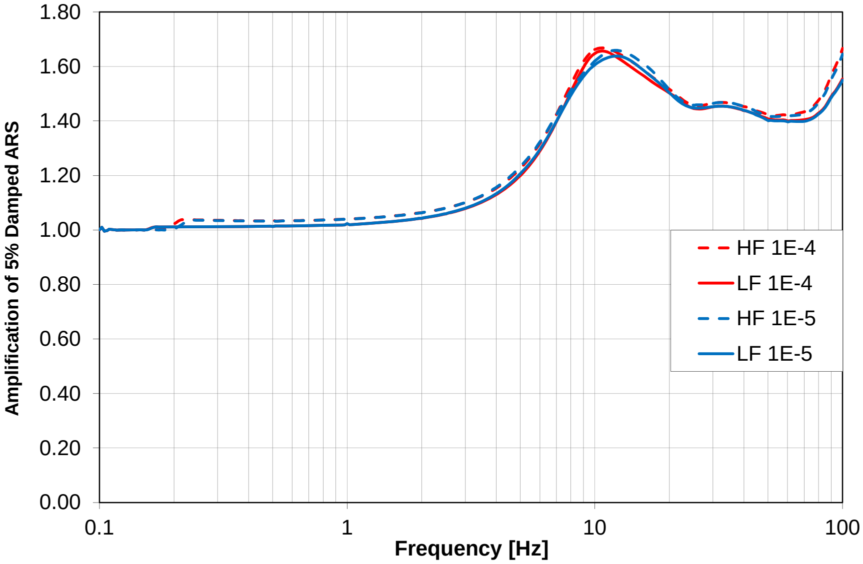

Figure 4. Median Amplification functions for rock site at foundation horizon (40 ft depth).

COMPARISON AND PERCENTILES

The effect of variation amplitude, represented by log-SD of shear-wave velocity, on site response estimates is examined next. While for the brevity, the comparison is presented for the HF 1E-4 motion only, the results and conclusions can be shown to be applicable at all levels of motion. Figure 5 compares the median ARS for the HF 1E-4 motion at the soil site, for the three soil profile simulation sets, with perfect inter layer correlation (ρ_V =1), see Table 1. A reduction of response at the peaks is observed, associated with the larger log-SD (or larger C_v) cases, as well as an increase in response at the troughs. This can be attributed to the larger spread of the seismic response between the simulated profiles, which when averaged produces a diluted response that masks the characteristics of the site and results in a mis-estimation that is not necessarily conservative. This is demonstrated further by comparing the 84th percentile responses in Figure 5, calculated as one log-SD away from the median response, where the response associated with the larger variation is larger almost in the entire frequency range. However, noting that the performance-based design response spectrum for nuclear power plants is based on the mean response (USNRC, 2007), rather than a higher percentile, the larger log-SD for V_s results in unconservative estimates.

Figure 6 makes the same comparison for the three sets of simulated profiles using inter-layer correlation for V_s less than unity (ρ_V <1) based on the inter-layer correlation model in Toro (1995). The comparison shows a similar trend as observed earlier, with the exception that the median response for the case with C_v=1.0 results in reduced ARS amplification in almost the entire frequency range. This is attributed to the increased impedance difference between layers, which is introduced into the model and exaggerated by the large log-SD for V_s. In addition to the unconservative response estimate, the result is further dilution of the response characteristics of the site.

In the case of the rock site, the same trends recorded for the soil site are observed although in a milder way. This is shown in Figure 7 and Figure 8 for the two case of inter-layer correlation for V_s (ρ_V =1 and ρ_V <1), respectively.

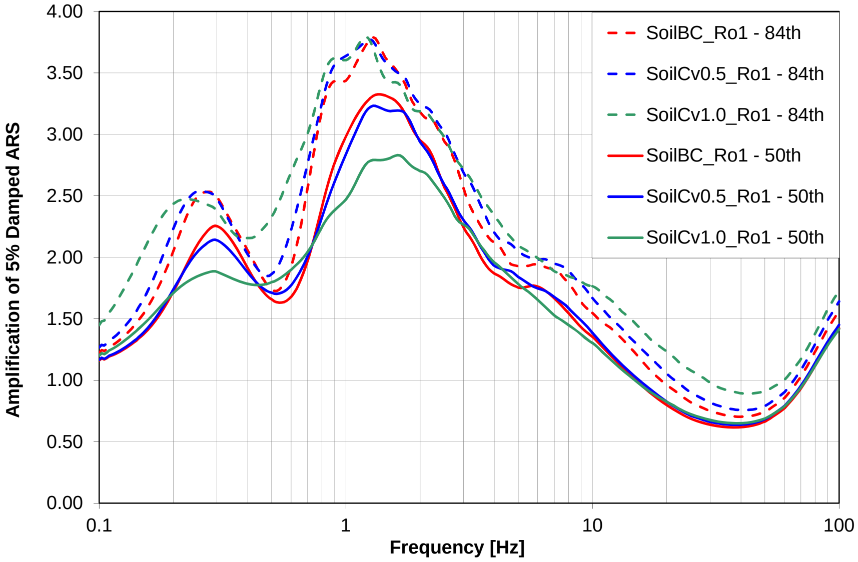

Figure 5. Median and 84th percentile amplification functions for soil site (ρ_V =1) at foundation horizon.

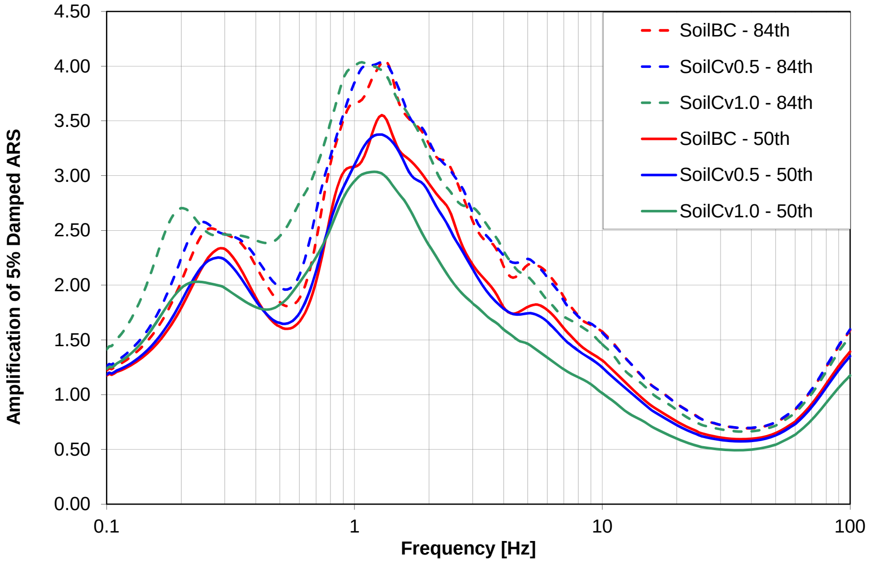

Figure 6. Median and 84th percentile amplification functions for soil site (ρ_V <1) at foundation horizon.

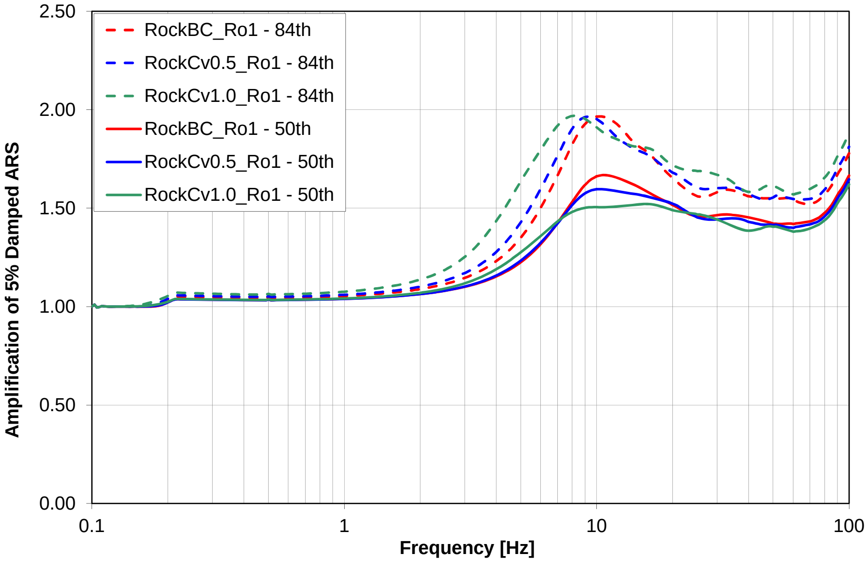

Figure 7. Median and 84th percentile amplification functions for rock site (ρ_V =1) at foundation horizon.

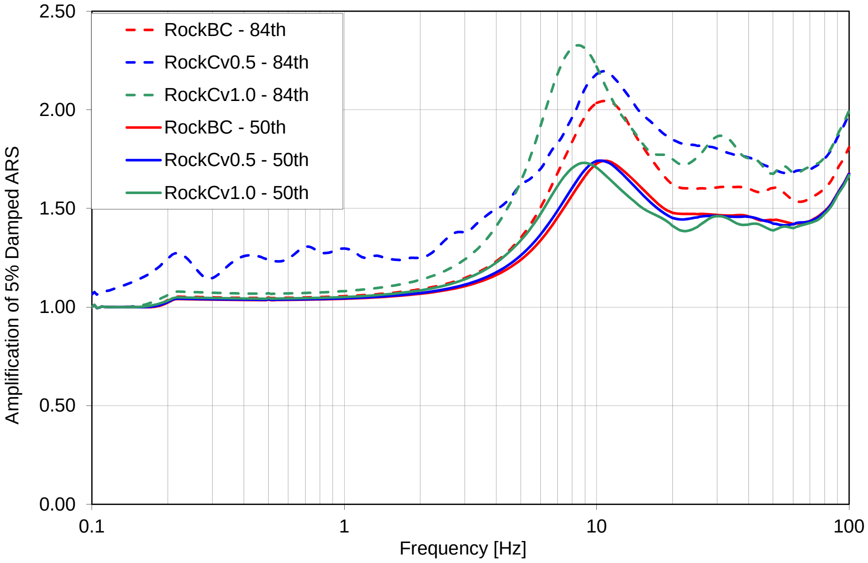

Figure 8. Median and 84th percentile amplification functions for rock site (ρ_V <1) at foundation horizon.

CONCLUSIONS

The analysis conducted in this paper examines the effect of the amplitude of variation considered for soil/rock dynamic properties, and particularly shear-wave velocity on the seismic amplification response. A summary of the main observations and findings are summarized below:

- Increasing the amplitude of variation (log-SD for *Vs*) does not increase the mean response, but rather results - in some cases - in the masking of the real characteristics of the site, and an often un-conservative response.

- Excessively large variations of V_s associated with low inter-layer correlation (ρ_V <1) results in a decrease in ARS amplification due to the introduced impedance difference between layers. This is especially true in the case of deep soil sites
- Higher percentiles of ARS amplification functions (e.g. 84th percentile) adequately represent the site amplification response including the recorded scatter in response due to large uncertainties of simulated soil/rock dynamic properties
- This paper uses Approach 2A in NUREG/CR-6728 (McGuire, 2001). However, the above observations apply when using other approaches to calculate the mean soil uniform hazard response spectra.

Recommendations

Based on the above observations, several recommendations are made with the aim of capturing the most realistic site response estimate, without compromising the amount of conservatism. In particular, the implementation of these recommendations should result in a reasonably conservative design motion in the case of poorly investigated sites, and an accurate and not overly conservative design motion in the case of well investigated sites, as is the case of most of the new generation of nuclear power plants.

- The use of excessive variation to express epistemic uncertainty can lead to un-conservative response estimates and should be avoided, especially if it introduces large impedance differences between soil/rock layers
- In the case of truly uniformly highly variable site, an averaging effect exists and might result in a decrease of response. However, in this case, the effect of inter-layer correlation of V_s plays an important role in determining the response and must be handled carefully
- The use of mean response in design does not account for the amplitude of modeled uncertainty in the site dynamic properties. This can be bettered if a higher percentile is used for the purpose of design
- Given current regulations (USNRC, 2007), in the case of poorly investigated sites and/or highly non-uniform and variable data, alternative best estimate soil columns need to be considered, each with limited modeled uncertainty, and the final response computed as the envelop of the mean responses calculated for each soil column set

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