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SEISMIC RESPONSE OF SHALLOW SITES IN EASTERN US: IMPLICATIONS TO THE STATE OF PRACTICE

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ABSTRACT

The response of shallow sites, with depth to bedrock less than 100 feet, in the geologic and tectonic setting of the Eastern United States (EUS) cannot generally be captured with code-based site factors. The need to address this issue on a regional basis became even more evident with the 2011 Mineral, Virginia earthquake. The difference in site response of EUS shallow soil profiles are mainly due to: (i) the sharp stiffness contrast between overburden soils and very hard underlying bedrock, and (ii) the bedrock ground motions that are typically of short duration, low intensity, and have high frequency content.

Soil amplification of shallow EUS sites is primarily controlled by the short-period portion (i.e., for periods less than 0.5 seconds) of the site response. Seismic guidelines represent the short-period soil amplification by the site coefficient F_a, as described in model code provisions based on NEHRP, ASCE7, or IBC. These codes estimate F_a values based on data from Western US (WUS) that reflect the regional geology and ground motions. Therefore application of code-based F_a can significantly underestimate the response of shallow EUS sites and may lead to unconservative designs. Moreover, application of code-based F_a values may result in unconservative liquefaction potential evaluations, typically performed using simplified methods that rely on the short period soil amplification.

This paper presents parametric studies that simulate site response of a range of typical EUS shear wave velocities and rock depths. The results and sensitivity of the site response to regional key parameters are evaluated and a modified approach in classifying shallow sites is proposed. The implications of such modifications in the regional seismic design practice and construction are presented.

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SEISMIC RESPONSE OF SHALLOW SITE IN EASTERN US: IMPLICATIONS TO THE STATE OF PRACTICE

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ABSTRACT

The response of shallow sites, with depth to bedrock less than 30 m (100 feet), in the geologic and tectonic setting of the Eastern United States (EUS) cannot generally be captured with code-based site factors. The need to address this issue on a regional basis became even more evident with the 2011 Mineral, Virginia earthquake. The difference in site response of EUS shallow soil profiles are mainly due to: (i) the sharp stiffness contrast between overburden soils and very hard underlying bedrock, and (ii) the bedrock ground motions that are typically of short duration, low intensity, and have high frequency content.

Soil amplification of shallow EUS sites is primarily controlled by the short-period portion (i.e., for periods less than 0.5 seconds) of the site response. Seismic guidelines represent the short-period soil amplification by the site coefficient Fa, as described in model code provisions based on NEHRP, ASCE7, or IBC. These codes estimate Fa values based on data from Western US (WUS) that reflect the regional geology and ground motions. Therefore application of code-based Fa can significantly underestimate the response of shallow EUS sites and may lead to unconservative designs. Moreover, application of code-based Fa values may result in unconsvervative liquefaction potential evaluations, typically performed using simplified methods that rely on the short period soil amplification.

This paper presents parametric studies that simulate site response of a range of typical EUS shear wave velocities and rock depths. The results and sensitivity of the site response to regional key parameters are evaluated and a modified approach in classifying shallow sites is proposed. The implications of such modifications in the regional seismic design practice and construction are presented.

Introduction

Application of "generic" procedures of contemporary seismic codes may not capture well the response of sites in the coastal areas of the EUS. This fact, mainly attributed to the significant stiffness contrast between the hard rock and soft overburden soils, is not surprising considering that the generic procedures were developed based on data from the WUS, with different geologic and seismotectonic setting. Recent studies and evidence from the 2011 Mineral, Virginia earthquake have emphasized the need to modify site factors for EUS. To this end, the authors are presenting parametric studies and offer discussions and recommendations.

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Design Response Spectrum Generation

Most state and local authorities in EUS follow recent versions of the International Building Code (IBC) model for their seismic provisions. This model is based on the seismic guidelines of ASCE7 that is intended for design of new vertical construction (building structures). Seismic loads are based on the Maximum Considered Earthquake (MCE), an event with a return period of approximately 2,500 years for sites far from well-defined faults, such as EUS. MCE ground motion parameters S_s (Spectral acceleration, Sa, for short periods) and S_1 (Sa at 1.0-sec period) for Site Class B rock having shear wave velocity V_s between 760 to 1500 m/s are provided in USGS hazard maps or can be derived through a Probabilistic Seismic Hazard Analysis (PSHA). S_s and S_1 parameters are multiplied by the corresponding site coefficients F_a and F_v (Fig. 1) to reflect soil amplification and develop a generic design response spectrum. Alternatively, the soil amplification can be developed through a site specific study that cannot be lower than 80% of the generic design response spectrum.

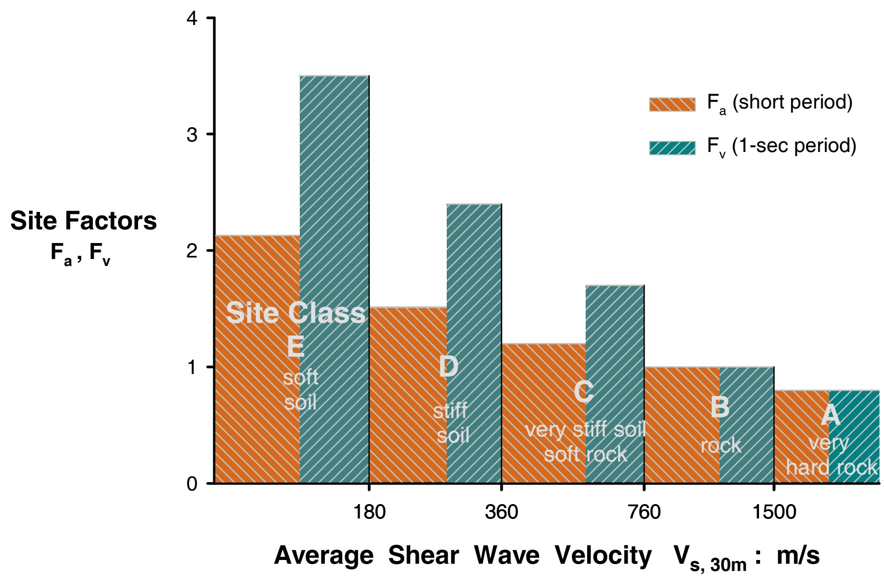


Figure 1. Site Classes A through E based on average V_s at the top 30 m, with short- and 1-sec site factors F_a, F_v values for typical EUS, seaboard sites (after Nikolaou et al., 2012).

Site Factors for EUS practice

The site coefficients F_a and F_v represent soil amplification from 0.1 to 0.5 s and from 0.4 to 2.0 s, respectively. They were developed using limited empirical data recorded in the San Francisco Bay Area during the 1989 Loma Prieta earthquake and supplemented by numerical simulations (Dobry and Iai, 2000). They are based on the average V_s of the top 30 m (100 ft) of the soil profile, $V_{s,30m.}$ This simplified site classification does not incorporate the depth to rock and the impedance contrast between soil and rock.

The applicability of WUS-developed site coefficients for the EUS has been studied by the authors in a series of publications (Nikolaou et. al. 2012, etc.). Our results have shown that in certain cases, actual site response cannot be represented by the generic simplified site factors approach. This is particularly true for the focus of this paper: shallow sites with relatively soft overburden soils over very stiff regional bedrock found at depths less than 30 m.

Following blindly the generic code procedure of ASCE7 for site classification can be misleading for EUS shallow sites. Specifically, Section 20.4 states: *"Profiles containing distinct soil and rock layers shall be subdivided into..... a total of n distinct layers in the upper 100 ft (30 m). Where refusal is met for a rock layer, N_i shall be taken as 100 blows/ft (328 blows/m).N_i and d_i... are for cohesionless soil, cohesive soil, and rock layers."* The inclusion of rock, which is particularly stiff in EUS (Hashash et al., 2013), in shallow site classification may lead to a "stiffer" site class than if the site was classified on soil properties alone (i.e., including only the overburden and excluding the rock). This can result in an unconservative design, reducing spectral response for long period structures by 20 to 30% and drastically underestimating response of short period structures. It also can lead to misleading building response, particularly when ductility is accounted for.

To avoid this pitfall in practice, the seismic committee for the upcoming New York City (NYC) Building Code proposed a clarification in the site classification language for shallow sites. Specifically, the NYC Code proposal requires that only materials encountered above rock (defined as the regional Class 1a, 1b, or 1c hard rock types) are considered. However, when refusal is met for a soft/decomposed rock layer of Class 1d, the NYC Code allows the ASCE7 equivalency of blow counts of N = 100 blows/ft.

Some recent research development propose alternative ways to better capture site response, incorporating key factors of depth to rock and impedance contrast, and the intensity of the ground motion itself. For example, Huang et al. (2010) proposed modified site factors based on averaging responses using NGA-West data across a range of periods and V_s values. Gazetas & Ziotopoulou (2010) proposed a site response approach that accounts for the site period, in the form of bi-normalized spectra, where Sa values are normalized by PGA and structural periods were normalized to the predominant soil period (T_p). Although the two studies did not use EUS sites, they both concluded that incorporating the natural vibration characteristics of a site in a systematic way, can produce site factors that can better capture the soil amplification effects.

Currently, the issue of EUS site factors is one of the research topics being studied by NGA-East, with the goal to modify site factors for use in this region. This research program is a concerted effort among the Nuclear Regulatory Commission, US Department of Energy, Electric Power Research Institute, US Geological Survey, and Pacific Earthquake Engineering Research (PEER) Center to develop the Next Generation Attenuation (NGA) equations for Eastern US.

Parametric Studies

Site and Ground Motion Characteristics

The site-specific ground motion parametric studies were performed using one-dimensional equivalent linear (Shake-type) analyses to produce ground surface motions as a result of regional, code-compatible, rock outcrop motions. Site response analyses were performed for a representative hypothetical site in the NYC metropolitan area with a generic cohesionless soil profile and shallow depth to bedrock ($D_{Bedrock}$) ranging from 15 to 60 ft (4.5 to 18.3 m). The V_s

profile was assumed to increase parabolically with depth (Fig. 2a) and the V_s bedrock ($V_{s,Bedrock}$) was assumed to range from 5,000 to 8,000 ft/s (1.5 to 2.4 km/s) to represent EUS regional bedrock. Darendeli (2001) shear modulus reduction and damping curves were applied to represent equivalent soil non-linearity.

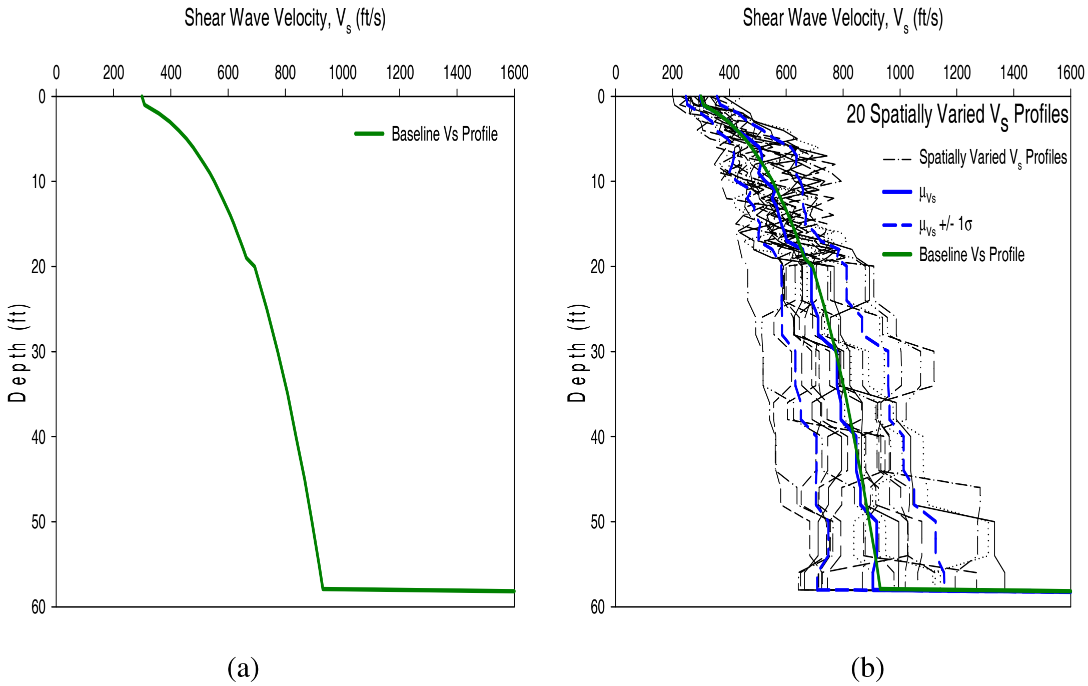
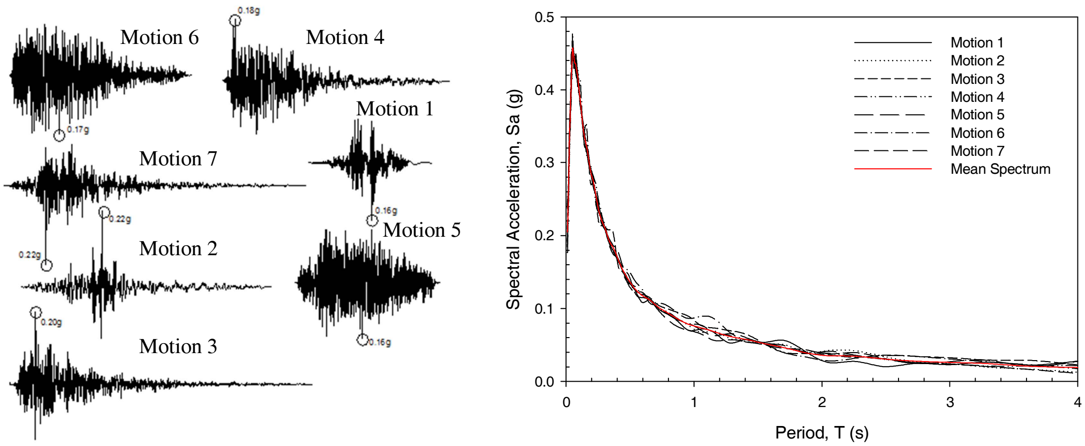


Figure 2. Shear wave velocity V_s profiles used in site response analysis: (a) Baseline V_s ; (b) 20 spatially varied V_s profiles.

The spatial variability and uncertainty in V_s that exist in nature was taken into account by varying the baseline V_s profile using Monte Carlo simulations as implemented in the program Strata (Kottke and Rathje, 2008). For the generic V_s profile in Fig. 2a, twenty (20) realizations of V_s profiles were generated. Spatially varied V_s profiles were generated using the random field models of (Toro, 1995), assuming a log-normal V_s distribution at any given depth and correlated between adjacent layers. The standard deviation of the natural log of V_s, σ_{lnVs}, was taken as 0.2 (a coefficient of variation of about 20%) and the interlayer correlation ρ_{IL} was assumed to be 0.8. Generated V_s profile realizations are shown in Fig. 2b together with the mean V_s (μV_s) profile, 84^{th} percentile V_s bounds, and the baseline V_s profile. The mean profile of generated V_s profiles closely matches the generic baseline V_s profile of Fig. 2a.

Due to a paucity of actual strong motion EUS records, we developed input rock outcrop motions by spectrally modifying records from other areas with similar hazard characteristics as the site. Seven seed rock motions were selected based on 2,500-year hazard deaggregation (see Nikolaou et al., 2012, for details.) Selected seed motions were modified using RSPMatch (Abrahamson, 1993) to match the rich high frequency content of EUS motions. Figure 3 presents the developed rock outcrop motions, with their mean response spectrum, matching the USGS Site Class A equivalent for this area, with approximate PGA of 0.2g, S_{MS} = 0.29g, and S_{M1} = 0.073g.



(a) (b)

Figure 3. Rock ground motions: (a) seed ground motions, (b) input rock outcrop motions used in site response analysis.

Site Response Analyses and Results

One-dimensional equivalent-linear site response analyses were performed using Strata (Kottke and Rathje, 2008) for generated V_s profiles with different combinations of $D_{Bedrock}$ and $V_{s,Bedrock}$. All seven input rock motions were propagated through each generated V_s profile. A total of 140 site response analyses (7 motions propagated through generated 20 V_s profiles) were performed for each $D_{Bedrock}$ of 15, 30, 45 and 60 ft and $V_{s,Bedrock}$ = 5000, 6500, and 8000 ft/s. In total, 1,680 site response analyses were performed.

The site response analyses were analyzed in terms of Sa/A, where Sa is the Spectral acceleration and A is the PGA, both at the ground surface. Figure 4 presents the results in two forms: (i) Sa/A versus structural period T (Figs 4 a, c, e, g); and (ii) bi-normalized spectra (Figs 4, b, d, f, h), where T is normalized to the predominant period (T_p) of the soil profile post-shaking (Ziotopoulou & Gazetas, 2001). Figure 4 also plots the mean spectra on both plot types. The bi-normalized spectra (shown on the right side) enable a more direct comparison of Sa/A across different site conditions, as the influence of different site periods is normalized out. In the bi-normalized spectra, the peak Sa/A for each profile corresponds to $T/T_p \sim 1$; therefore the mean of the bi-normalized spectra predicts higher Sa/A. This is opposed to the mean of the Sa/A *vs.* T spectra, where the mean spectrum is predicted over Sa/A values and peaks at different predominant periods (Fig. 4), averaging out the actual peaks.

In addition, we evaluated a range of three different $V_{s,Bedrock}$ values. Our evaluation found that the difference in ground surface response between $V_{s,Bedrock}$ = 5000, 6500, and 8000 ft/s was not significant. For the range of values evaluated, the bedrock stiffness does not have great influence on the predicted mean bi-normalized spectra. Therefore, for brevity, we have limited the data presented to only $V_{s,Bedrock}$ = 6,500 ft/s.

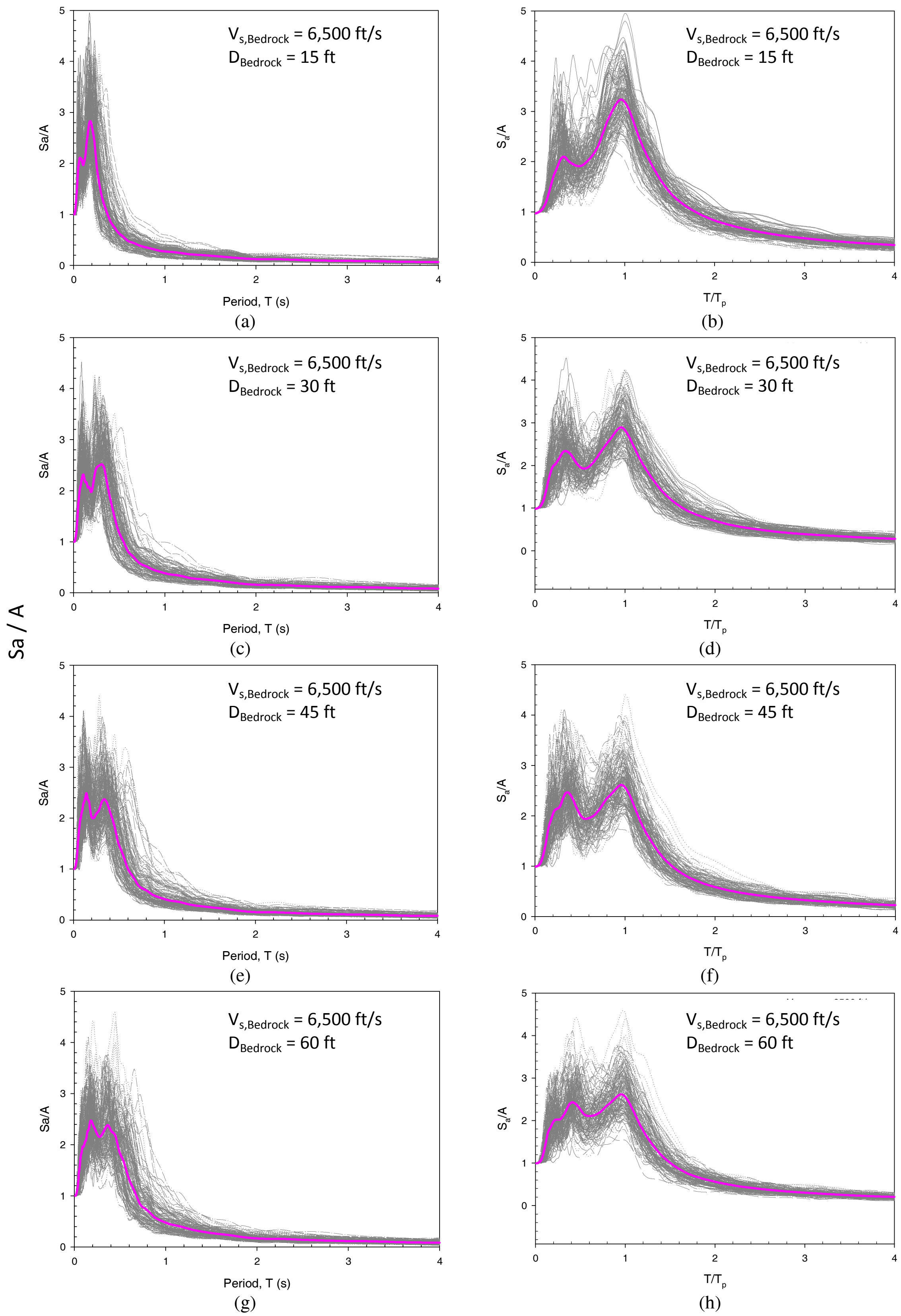


Figure 4. Ground response spectra: (a, c, e, g) Sa/A vs. T, (b, d, f, h) bi-normalized spectra.

Figure 5 presents mean bi-normalized spectra obtained from the site response analyses of spatially varied V_s profile with a range of depth to bedrock $D_{Bedrock}$. The peak of the mean Sa/A at T/Tp ~1 increases with decreasing $D_{Bedrock}$, the influence is pronounced for $D_{Bedrock}$ of 30 ft and 15ft (i.e. $D_{Bedrock} < 45$ ft). The results shown in Figure 4 (b, d, f, h) were normalized by the predominant period T_p of the site; therefore the peak Sa/A representing the site's first mode (i.e., the major peak) does not reflect the influence of soil nonlinearity on mean bi-normalized spectra. However, the second (lower) peak of the mean bi-normalized spectra reflects the influence of soil nonlinearity such that as the $D_{Bedrock}$ increases the second peak becomes more pronounced due to increasing nonlinearity of the soil column and shift to the right due to period elongation.

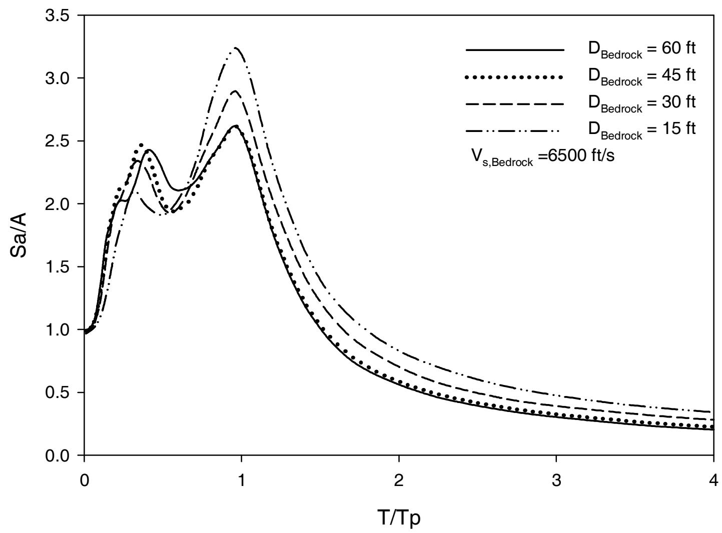


Figure 5. Influence of $D_{Bedrock}$ on mean bi-normalized spectra for $V_{s,Bedrock}$ of 6500 ft/s.

Conclusions

Design response spectra and site factors derived using "generic" Code procedures may result in unrepresentative design accelerations. This is particularly true for EUS shallow sites with significant stiffness contrast between the very hard regional rock underlying generally soft soils. The presented study conducted for typical EUS sites indicates that the V_{s30}-based F_a parameter (short-period site factor) alone may underpredict the actual site response. The study focused on understanding the influence of the depth to bedrock on the ground surface response in shallow deposits with high impedance contrast between soil and rock. The predicted surface response and normalized Sa/A increase as the $D_{Bedrock}$ decreases; Sa/A can increase as much as 20% as the depth to bedrock decreases from 60 ft to 15 ft depth.

Additional research is needed to investigate the influence of the bedrock depth of shallow soil sites with high impedance contrast on soil amplification and on site factors that are applied to design codes. The NGA-East project is currently studying these issues in an effort to develop a more robust method for site classification and for creating regional site factors representative of the particular geologic and ground motion characteristics of the EUS.

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