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SITE-SPECIFIC RESPONSE ANALYSIS AT NON-STANDARD SITES

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ABSTRACT

In current U.S. design practice, the effect of local soil conditions on seismic site response is sometimes accounted for based upon a seismic hazard analysis conducted for a reference site condition and National Earthquake Hazard Reduction Program (NEHRP) developed site factors based upon the shear wave velocity over the top 30 meters of the site. The appropriateness of the site factor approach and of using the Next Generation Attenuation (NGA) relationships to evaluate the seismic hazard at sites with soil profiles that do not conform to the profile used to develop the NEHRP site factors has been evaluated by performing site specific response analyses. Sites evaluated in these analyses include deep soil basins and sites with shallow impedance contrasts. One-dimensional equivalent linear analyses were conducted on columns of soil representative of deep soil basins and shallow impedance contrasts sites using a suite of ten time histories. Non-linear time domain one-dimensional site response analyses were also performed on the deep soil column using same suite of time histories. The suite of time histories was selected as representative of a magnitude 6.7 earthquake on a reverse fault at a distance of 19 km from the reference site. The spectra obtained from site response analyses were compared to spectra developed using NEHRP site factors and NGA models. Results of the comparison suggest that the use of NEHRP site factors or NGA relationships may not be appropriate for either sites with a sharp impedance contrast in the near surface or deep soil basin sites.

Keywords: Seismic site response; Deep soil basins; Sharp impedance contrast; NEHRP; NGA

INTRODUCTION

The influence of the deep soil basin and shallow impedance contrasts conditions on the seismic hazard at a site has been evaluated using four different methods. First, the peak and spectral accelerations required for design established using the results of a seismic hazard analysis for reference site conditions were adjusted for local site conditions using site factors based upon the average shear wave velocity over the top 30 meters of the site, $(V_s)_{30}$. Second, the seismic hazard analysis was conducted using attenuation relationships that incorporate the influence of local site conditions directly into the seismic hazard analysis. Next, one-dimensional equivalent linear site response analyses were conducted on 30, 60, and 500 meter soil columns using input time histories representative of the reference site ground motion. Finally, one-dimensional non-linear time domain site response analyses were performed on the 500m soil column using the same suite of time histories used in the equivalent linear analyses.

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The influence of local soil conditions on the seismic hazard at a site is often evaluated using the results of a seismic hazard analysis for a reference site condition and site factors developed under the National Earthquake Hazard Program (NEHRP) that depend upon $(V_s)_{30}$. These site factors, generally taken from recommendations developed under the NEHRP, are used to adjust the peak horizontal ground acceleration (PHGA), the spectral acceleration at 0.2 s (S_S), and spectral acceleration at 1.0 s (S_1) for the reference site conditions to account for local site conditions. These adjusted values are then used to develop a site dependent design spectrum. However, the site conditions employed in developing the NEHRP site factors assume a shear wave profile that is not representative of deep soil basin sites or shallow bedrock (shallow impedance contrast) sites. Therefore it is not clear if these site factors account for the spectral response characteristics of deep soil basin sites or shallow impedance contrast sites.

In lieu of using NEHRP site factors, a site specific seismic response analyses maybe used to evaluate the influence of local soil conditions on seismic response by propagating time histories characteristic of reference site ground motion upwards through a representative soil column. Site specific seismic response analyses are commonly performed in geotechnical engineering to characterize local site effects. There are two primary types of numerical methods used in seismic site response analysis; 1) the equivalent linear analysis method, and 2) the nonlinear analysis method. The equivalent linear approach employs a frequency domain solution to the wave propagation problem and approximates the non-linear cyclic response of soils using constant, strain-dependent values of modulus and damping. The non-linear approach, on the other hand, employs a time domain solution and models the actual hysteretic stress-strain response of the soil.

A recently developed alternative for considering the effect of local soil condition on the site response is the use in the seismic hazard analysis of Next Generation Attenuation (NGA) relationships that explicitly accounts for local soil conditions. There are four NGA relationships that can be used to incorporate the effect of local site conditions directly into seismic hazard analyses (Abrahamson and Atkinson 2008).

The objective of this work is to assess the applicability of NEHRP site factors and NGA relationships for characterizing the seismic hazard at shallow impedance contrast and deep soil basin sites.

SEISMIC HAZARD ANALYSIS USING NGA RELATIONSHIPS

The baseline seismic hazard for the analyses conducted herein was characterized using NGA relationships with parameters representative of the NEHRP reference site condition (refer to as NEHRP Site Class B). The seismic hazard was also characterized using NGA parameters representative of the two types of three non standard sites evaluated herein (the two shallow bedrock sites and one deep soil basin site). The NGA relationships used in this study were those developed by Campbell and Bozorgnia (2008), Abrahamson and Silva (2008), Boore and Atkinson (2008), and Chiou and Youngs (2008). These are the four NGA relationships that incorporate local site conditions directly into the seismic hazard analysis as a discriminating factor. The shear wave velocity in the upper 30m, used to establish the NEHRP site factors, is input directly into all four of these NGA equations. The four NGA models employed herein also distinguish between shallow and deep soil sites by incorporating either the depth to a shear wave velocity of 1000 m/s, $Z_{1.0}$, or depth to a shear wave velocity of 2500 m/s, $Z_{2.5}$, into the attenuation equations.

All four NGA relationships were employed to characterize the seismic hazard at the site and were equally weighted. For the NEHRP reference site conditions, the seismic hazard was characterized using NGA relationships with $(V_s)_{30}$ = 760 m/s, Z_1 = 100m, and $Z_{2.5}$ = 300m. These parameters are representative of the site profile used to develop NEHRP National Seismic Hazard Maps for the reference site condition (referred to as NEHRP Site Class B). The seismic hazard was characterized for the two shallow bedrock sites using NGA relationships with $(V_s)_{30}$ = 475m/s, Z_1 = 60m, and $Z_{2.5}$ = 150m and for the deep soil basin using $(V_s)_{30}$ = 475m/s, Z_1 = 500m, and $Z_{2.5}$ = 650m. Both the shallow bedrock and deep soil parameters is representative of NEHRP Site Class C.

NEHRP PROCEDURE

In the NEHRP procedure site factors that depend upon $(Vs)_{30}$ are used to adjust the values of PHGA, S_S, and S_1 for local site effects. The adjusted parameters are used to develop an acceleration response spectrum (ARS) that has a truncated shape for the use in structural analysis. The NEHRP design spectra developed using PHGA, S_S, and S_1 is shown in Figure 1.

For the purposes of this study, the design event was characterized as a magnitude 6.7 event on a reverse fault at a distance of 19 km from the site. The four NGA relationships yielded average values of 0.25g for the PHGA, 0.55g for S_S, and 0.19g for S_1. Figure 1 compares the mean, mean plus one standard deviation, and mean minus one standard deviation ARS from the four NGA relationships to the truncated NEHRP ARS for the reference site.

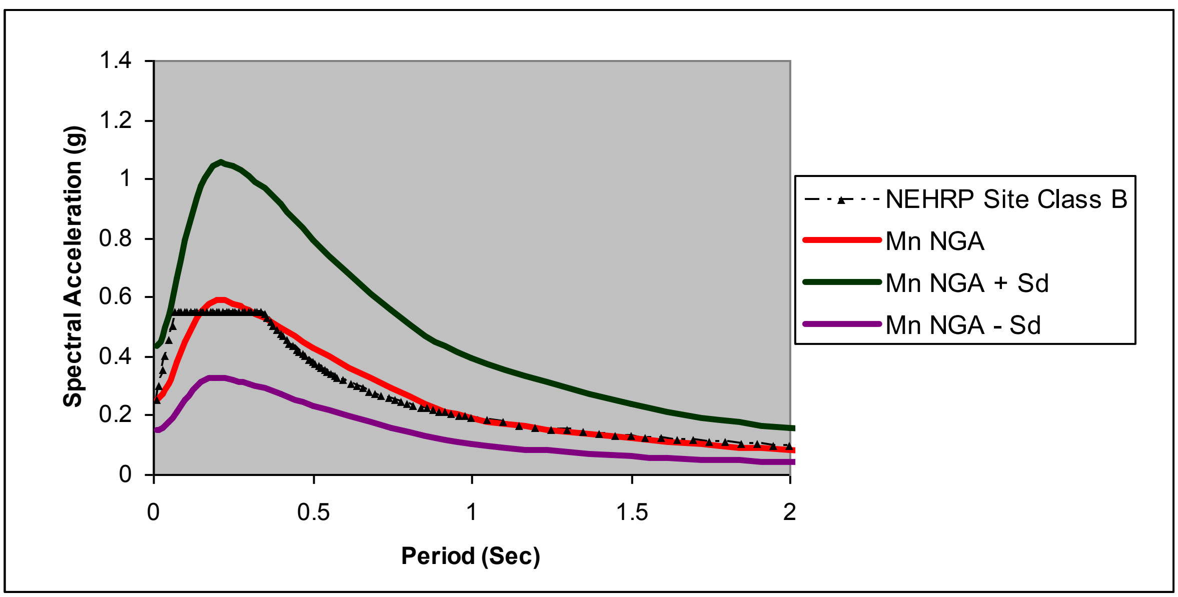

Figure 1. Truncated NEHRP spectrum along with NGA ARS for reference site

EQUIVALENT LINEAR ONE-DIMENSIONAL SEISMIC RESPONSE ANALYSES

Equivalent linear seismic response analyses were performed using the computer program SHAKE 2000 (Ordonez 2007), a commercial version of the widely used computer program SHAKE (Schnabel 1972). These seismic response analyses were performed on the three representative soil columns: the two shallow bedrock columns consisting of 30m and 60m of soil overlying bedrock and the deep soil basin site with 500 meters of soil top of bedrock. The equivalent linear seismic response analyses were conducted using ten-time histories selected to characterize the design event for reference site conditions.

Material Properties Used in the Equivalent Linear Analyses

Material properties required for the equivalent linear site response analysis included unit weight, shear wave velocity, and modulus reduction and damping curves for the soil column and unit weight and shear wave velocity for the underlying bedrock half space. These material properties were assigned based upon typical properties of NEHRP site Class C soil. A unit weight from 19.6 at the surface to 20.1 KN / m^3 at depth was assigned to the soil layer. The shear wave velocity was assumed to be equal to 450 m/s immediately below the surface increasing linearly to 495 m/s, just above of the bedrock half space for the 30m soil column, 570 m/s, just above bedrock for the 60m soil column, and 670 m/s just above bedrock for the 500m soil column. The bedrock "half space" was assigned a constant shear wave velocity of 1000 m/s and a unit weight of 21 KN/m^3. These soil and bedrock parameters are consistent with the parameters used in the NGA analyses. Overburden pressure-dependent modulus reduction and damping curves from EPRI (1993), with reduced damping and modulus degradation at higher overburden pressure were employed to compensate for the tendency of SHAKE to damp out higher frequency motions in deeper soil deposits.

Design Earthquake Ground Motions

To select representative time histories for the use in design, the significant duration of strong shaking for the moment magnitude 6.7 earthquake 19 km design earthquake was estimated based upon the Abrahamson and Silva (1996) relationship among significant duration, moment magnitude, and site-to-source distance. This relationship yielded a significant duration for the design event of nine seconds.

A suite of ten time histories from shallow crustal earthquakes worldwide were selected for the use in site response analysis. The earthquakes that generated these time histories were all between magnitudes of 6.2 to 7.6 with significant duration between 3.3 and 11 seconds and site-to-source distance between 10 and 19 km. These time histories were scaled to PHGA value of 0.25 g to "fill the band" between the mean and mean plus one standard deviation of the target spectra for the design earthquake. The ARS from these time histories and the average ARS for all ten time histories are shown in Figure 2, along with the median and plus and minus one standard deviation ARS from NGA equations for the reference site.

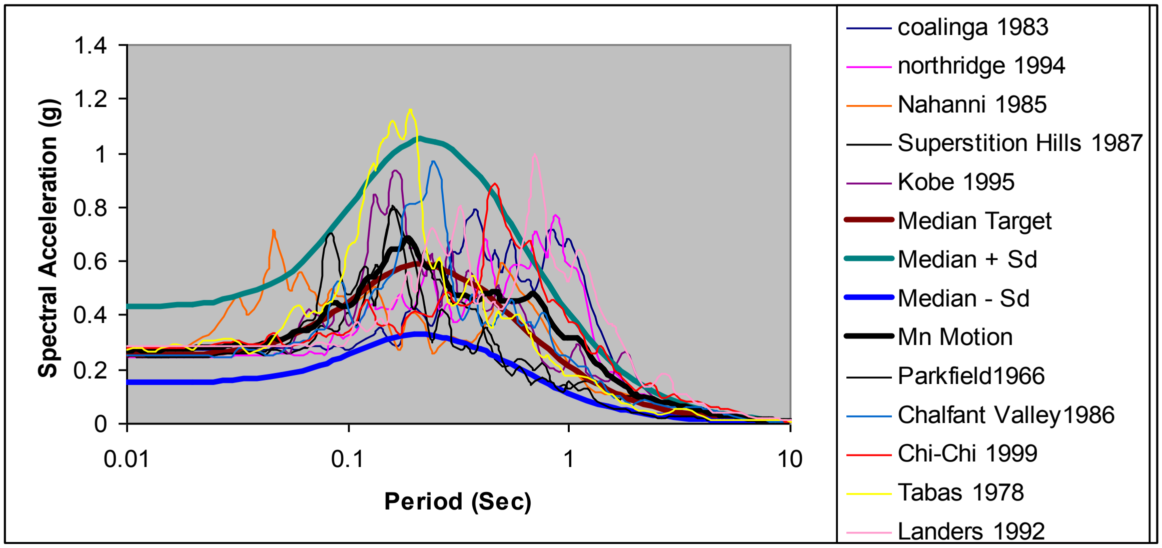

Figure 2. ARS of the suite of time histories compared with the reference site ARS

Each of the ten time histories was input as a bedrock outcrop motion to the SHAKE 2000 linear equivalent linear site response analysis. The ARS at the ground surface for 5% damping from the ten individual analyses are plotted with the ARS developed using the NGA relationships and truncated NEHRP design spectra for the site with bedrock at 30m below ground surface in Figure 3. Figure 4 shows the mean ARS from ten equivalent linear analyses along with the ARS developed using the NGA relationships and the truncated NEHRP design spectrum for the site with bedrock at 30 m below ground surface. The ARS from the ten individual equivalent linear analyses and the mean spectrum from the ten analyses are plotted in Figures 5 and 6, respectively, along with the ARS developed using the NGA relationships and with truncated NEHRP spectra for a site with bedrock at 60m below ground surface. Tables 1 and 2 summarize the results for the 30 and 60m soil columns. Figure 7 shows the ARS at ground surface for 5% damping from the ten individual equivalent linear analyses along with ARS developed using NGA relationships and the truncated NEHRP ARS for the deep soil basin site.

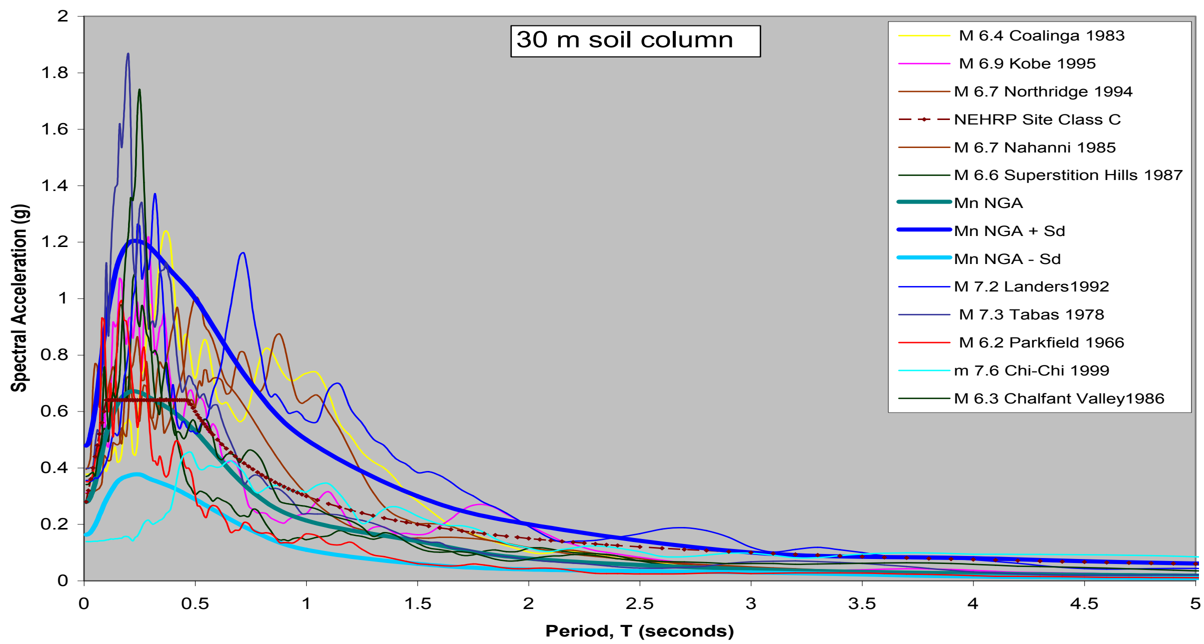

Figure 3. Equivalent Linear ARS for 30m shallow bedrock site

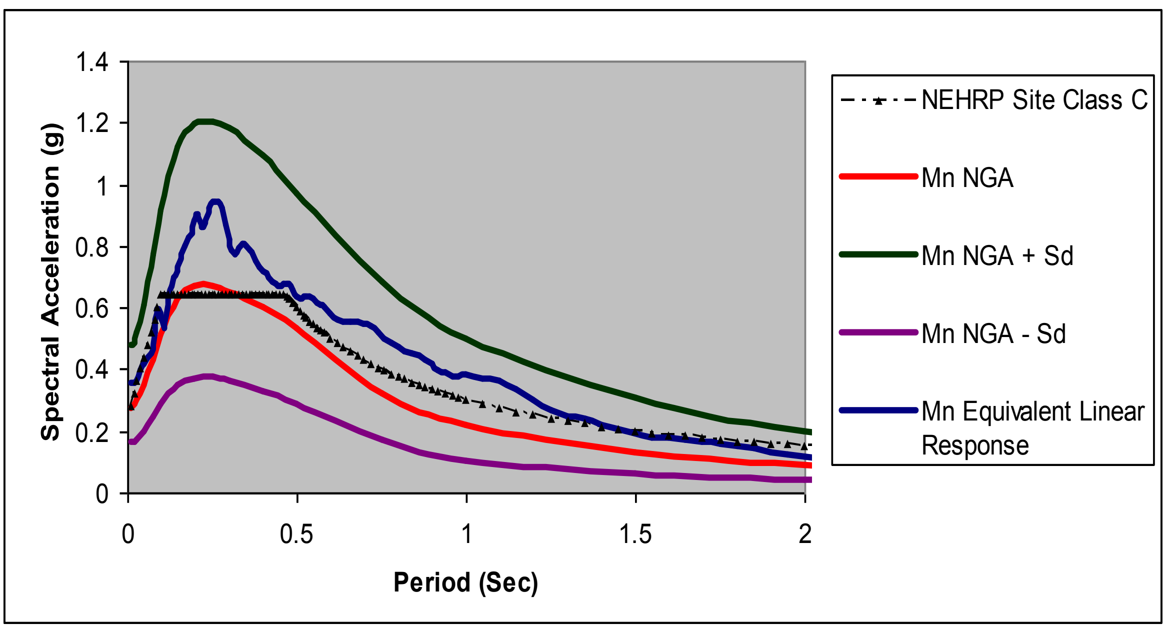

Figure 4. Equivalent Linear, NEHRP, and NGA spectrum for 30m shallow bedrock site

Table 1. Comparison of spectral accelerations values for 30m shallow bedrock site

Spectral Parameter	NEHRP	NGA	Equivalent Linear
PHGA	0.28g	0.27g	0.37g
S_s	0.64g	0.65g	0.90g
S_1	0.30g	0.23g	0.40g

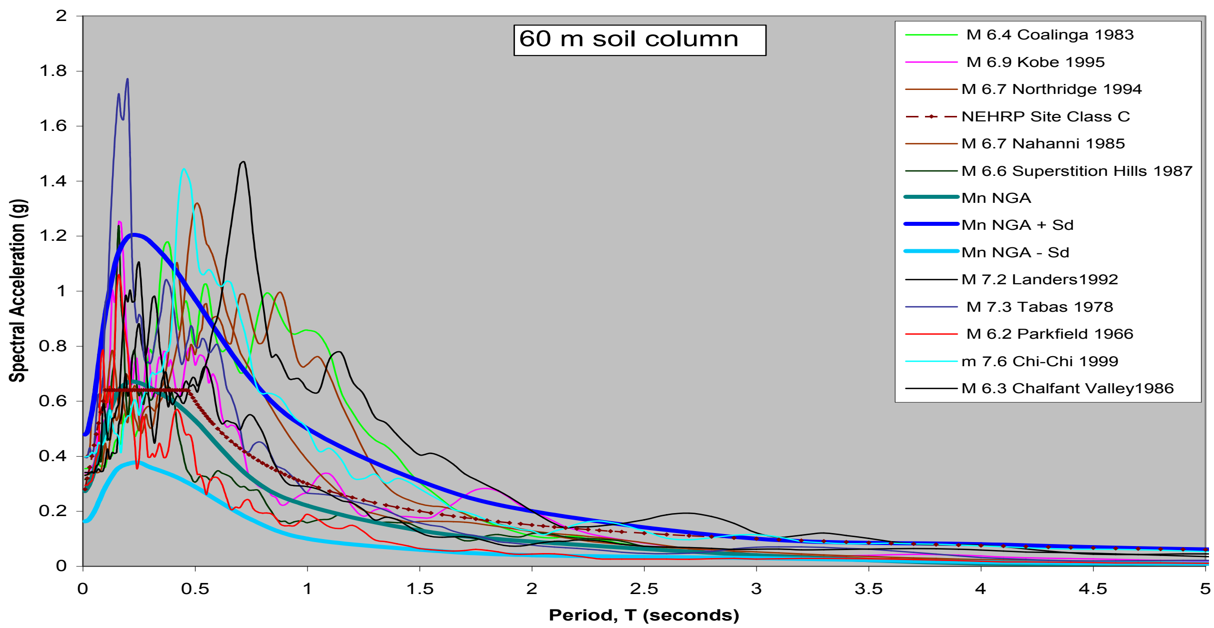

Figure 5. Equivalent Linear ARS for 60m shallow bedrock site

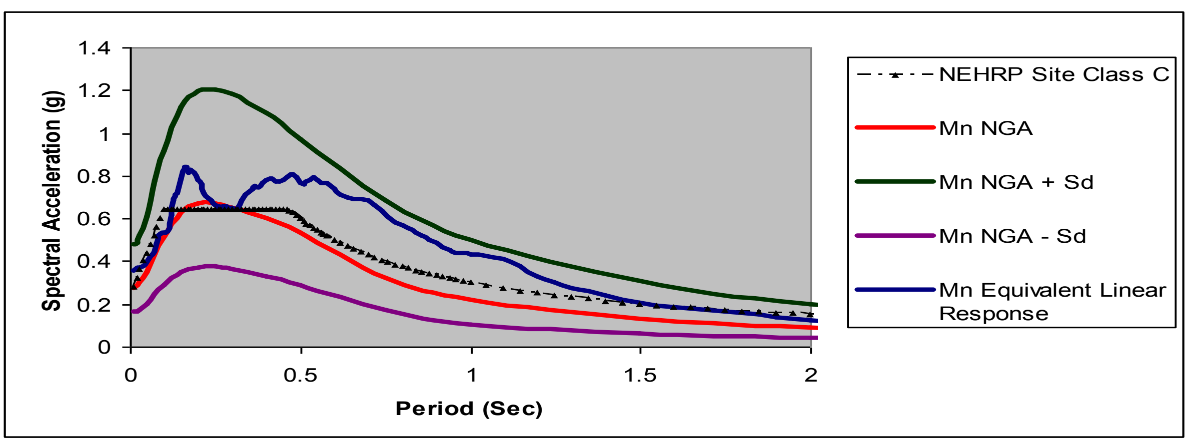

Figure 6. Equivalent Linear, NEHRP, and NGA spectra for 60m shallow bedrock site

Table 2. Comparison of spectral acceleration values for 60m shallow bedrock site

Spectral Parameter	NEHRP	NGA	Equivalent Linear
PHGA	0.28g	0.27g	0.37g
S_s	0.64g	0.65g	0.81g
S_1	0.30g	0.23g	0.46g

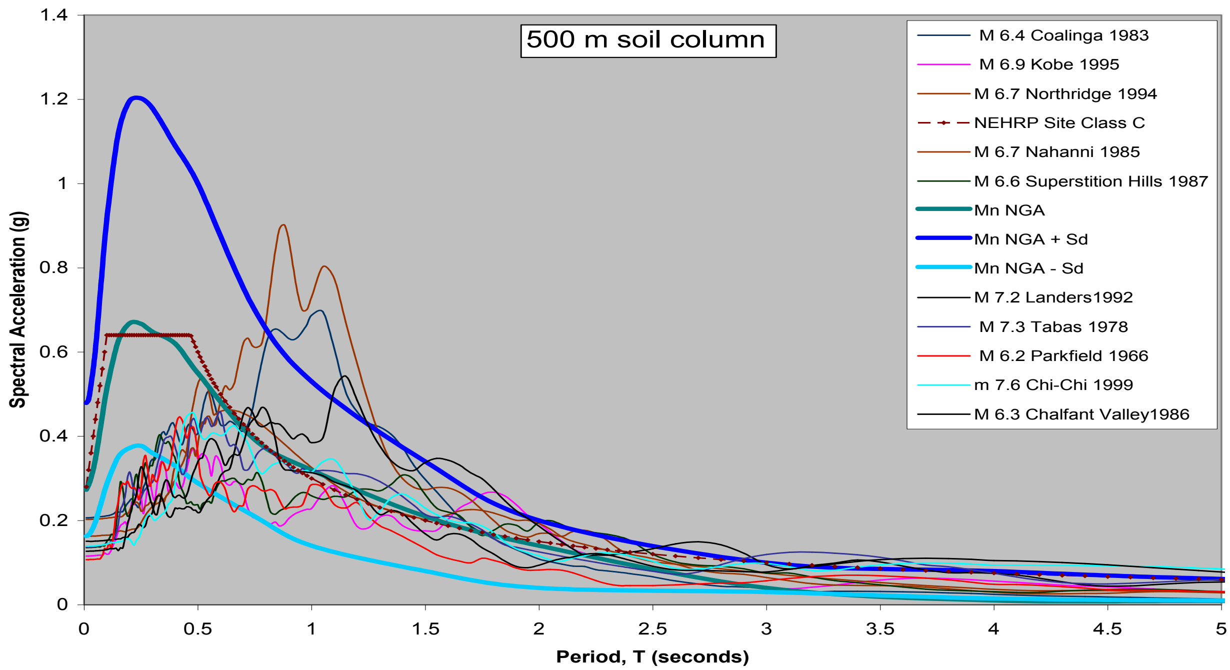

Figure 7. Equivalent Linear ARS for deep soil basin site

NON-LINEAR ONE-DIMENSIONAL SITE RESPONSE ANALYSES

The computer program DEEPSOIL (Hashash 2008) was used to perform non-linear one-dimensional time domain site response analyses on the 500m soil column. The DEEPSOIL analyses employed a backbone curve and unload/reload modulus based upon the modulus reduction and damping curves used in the equivalent linear analysis, modified as described by Hashash and Park (2001). However, DEEPSOIL uses Rayleigh damping and not hysteretic damping. Rayleigh damping parameters for DEEPSOIL analyses were determined by fitting the results of the linear visco-elastic analysis using conventional equivalent linear hysteretic damping to results of non-linear analysis with Rayleigh damping parameters at the fundamental period and at a second, higher period. The higher period at which the damping is fitted is varied until a good match is achieved between the results of linear elastic and non-linear analyses. For this case, fitting the damping at the first and seventeenth modes resulted in a good match between two types of analyses.

The 500m soil column used in the non-linear site response analysis was divided into 70 layers. As suggested by Hashash (2008), the thickness of each layer was calculated as the shear wave velocity divided by four times the maximum frequency used in the analysis. The maximum frequency used in the analysis was 25 Hz. The same ten time histories used in the equivalent linear analysis were employed in the non-linear analyses. ARS at the ground surface for 5% damping from the ten individual non-linear analyses and the mean spectrum from the ten analyses are compared to the ARS developed using the NGA relationships for deep soil basin site conditions in Figure 8. The mean ARS from the equivalent linear and non-linear analyses and mean and plus and minus one standard deviation ARS developed using the NGA relationships for deep soil basin site conditions are compared in Figure 9. Table 3 summarizes these results for the 500m soil column from linear equivalent, non-linear, NGA, and NEHRP analyses.

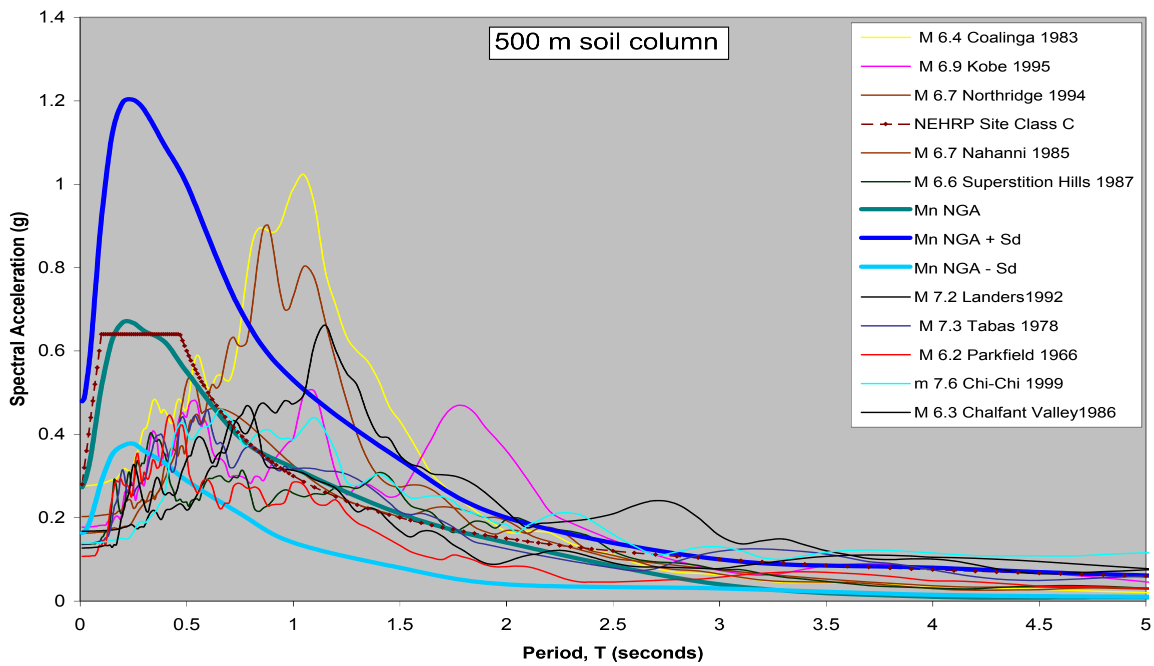

Figure 8. ARS from Non- Linear analyses for deep soil basin site

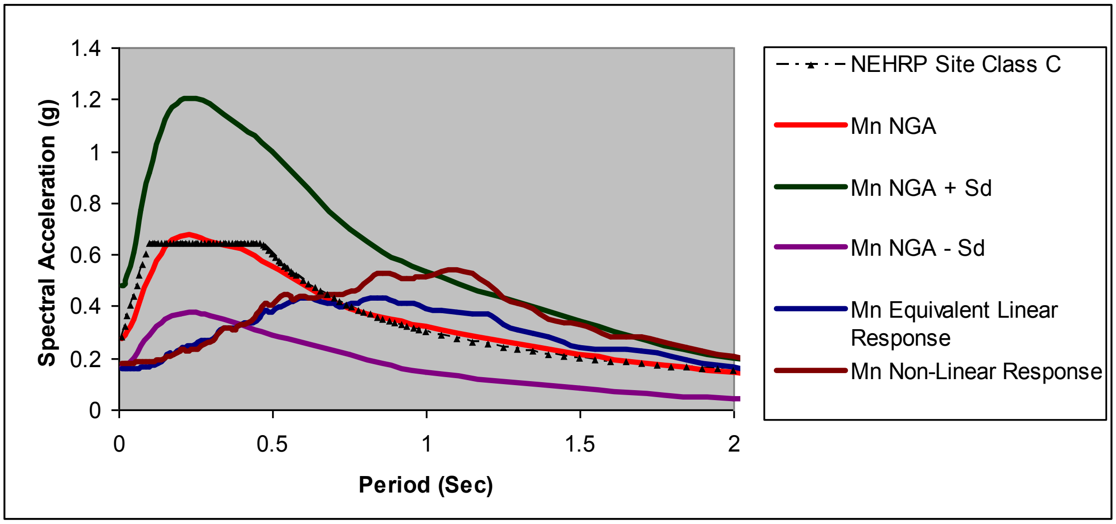

Figure 9. Equivalent Linear, Non-linear, NGA, and NEHRP spectra for deep soil site

Table 3. Comparison of spectral acceleration values for deep soil site

Spectral Parameter	NEHRP	NGA	Equivalent Linear	Non-Linear
PHGA	0.28g	0.27g	0 .18g	0.19g
S_s	0.64g	0.66g	0.20g	0.20g
S_1	0.30g	0.33g	0.39g	0.50g

The ARS derived using NGA and using the NEHRP Site factors are very conservative for short period structures as the deep sediment stack acts as a filter and deamplifies the short period motion (an effect not accounted for in the NGA and NEHRP spectra). However, at longer periods (periods greater than 0.8 second), the NGA and NEHRP acceleration response spectra are significantly below the ARS from the site response analyses.

SUMMARY AND CONCLUSION

The appropriateness of using the NEHRP site factors and soil profile dependent NGA relationships at sites with soil profiles that do not conform to the standard profile used to develop the NEHRP site factors (non-standard sites) has been evaluated by performing site specific seismic response analyses. Comparison of the results obtained using these different methods indicates that ARS for sites with sharp impedance contrast at a depth of 60m or less may fall between mean and mean plus sigma ARS from NGA relationships and that site-dependent NGA relationships may underestimate long period response of deep soil basin sites. Furthermore, the results of the equivalent linear analyses were systematically lower than the results of the non-linear analyses at the deep soil basin sites.

These results suggest that the use of NEHRP site factors may not be appropriate for either site with a sharp impedance contrast in the near surface or for the sites with bedrock at great depths. Results of the comparison suggest that the NGA relationships may not be capable of accounting for site-specific response effects for shallow bedrock sites or for deep soil sites with peak ground acceleration values greater than 0.2 g. Consideration should be given to classifying shallow bedrock and deep basin sites as special study (NEHRP Class F) sites, wherein a site-specific seismic response analysis is mandated.

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