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SITE-SPECIFIC RESPONSE ANALYSIS FOR DEEP SOIL BASINS

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ABSTRACT

The effect of deep soil deposits in Phoenix Basin on the seismic hazard for a 2500 years return period was evaluated using four different methods, including: 1) the results of a seismic hazard analysis for reference site conditions and National Earthquake Hazard Reduction Program (NEHRP) site factors; 2) the results of a seismic hazard analyses using Next Generation Attenuation (NGA) relationships; 3) one-dimensional equivalent linear site response analyses, and 4) one-dimensional non-linear site response analyses. Use of the NEHRP site factors yielded the lowest values of the four methods for the spectral accelerations required for design. Non-linear site response analyses, considered the most accurate method, yielded the highest values. Results of the equivalent linear analyses were systematically lower than the results of the non-linear analyses. Results of the seismic hazard analysis conducted using the NGA relationships fell in between the results of the equivalent linear and non-linear analyses at periods of 0.2 s or greater. The results suggest that, for the case of an area of relatively low seismicity that was considered herein, the NGA relationships are capable of accounting for deep soil basin site-specific response effects directly in a seismic hazard analysis. However, it must be recognized that the analysis conducted herein was for an area of relatively low seismicity and the differences among the various types of analyses may change significantly if higher levels of seismicity or softer ground conditions are considered.

Introduction

The influence of the deep soil basin conditions on the seismic hazard in the Phoenix Basin 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

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analyses were conducted on a soil column representative of Phoenix deep soil basin conditions using input time histories representative of the reference site ground motion. Finally, one-dimensional non-linear site response analyses were performed using the same soil column and time histories sued in the equivalent linear analyses.

In current design practice, the effect of local soil conditions on seismic site response is typically accounted for based upon a seismic hazard analysis conducted for a reference site condition and site factors that depend upon $(V_s)_{30.}$ These site factors, generally taken from recommendations developed under the National Earthquake Hazard Reduction Program (NEHRP), are then used to adjust the spectral acceleration at 0.2 s (S_S) and 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. Therefore it is not clear if these site factors account for the spectral response characteristics of deep soil basin sites.

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, where the equations of motion are solved in frequency domain (FD), and 2) the nonlinear analysis method, where the equations of motions are solved in the time domain (TD). The equivalent linear approach 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, attempts to model the actual hysteretic stress-strain response of the soil. While the equivalent linear approach is simpler and easier to implement, the non-linear approach is believed to more accurately simulate the cyclic stress-strain behavior, and therefore the seismic response, of soils (Hashash 2001).

In lieu of using NEHRP site factors, both equivalent linear and non-linear site response analyses maybe used to evaluate the influence of local deep soil basin conditions on seismic response by propagating time histories characteristic of reference site ground motion upwards through a representative soil column. Alternatively, the effect of local soil condition on the site response may be accounted for directly in the seismic hazard analysis by using one or more of the Next Generation Attenuation (NGA) relationships developed for the specific purpose of incorporating the effect of local site conditions directly into seismic hazard analyses (Abrahamson and Atkinson 2008). These four methods of analysis (NEHRP site factors, equivalent linear and non-linear site response analyses, and seismic hazard analysis using NGA relationships) have been employed to evaluate the impact of deep soil basin conditions on the seismic hazard in the Phoenix Basin, an area of low seismicity in the southwestern United States.

Phoenix Basin Local Soil Conditions

The Phoenix Basin is located between the tectonically more active regions of the North American Pacific plate boundary in California, Northern Arizona's Basin and Range Province, and the Rio Grand Rift in New Mexico. Phoenix lies within the Sonoran Desert section of the Basin and Range Physiographic province of the western United States. The Basin and Range province is characterized by northwest-southeast trending rugged mountain systems and broad and extensive alluvial valleys created when the North American continent was pulled apart starting about 30 million years ago. The continental lithosphere in the Basin and Range province has been stretched and thinned, resulting in a distinctive physiography of narrow mountain ranges separated by broad, sediment-filled basins (Henry and Gomez 1992).

Fig. 1 represents a map of the depth-to-bedrock in the Phoenix Basin derived from Arizona Geological Survey data (Zapata 2008). It can be noted from Fig.1 that the Phoenix Basin is dominated by a large area of deep soil (darker color on the map).

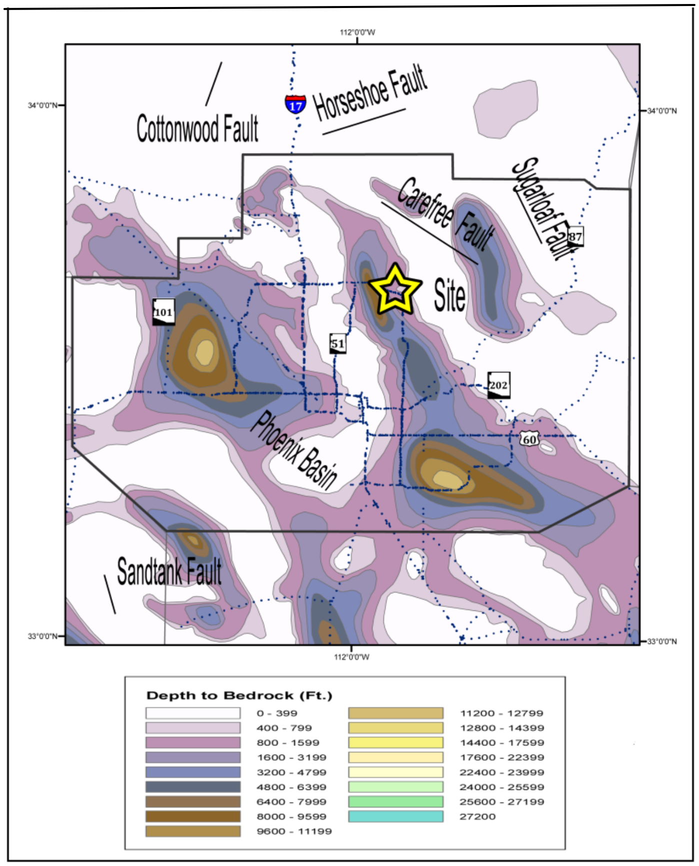

Figure 1. Map of depth-to-bedrock and seismic sources in Phoenix Basin.

Based upon the Standard Penetration Test blow counts at a number of sites within the Phoenix area, an average shear wave velocity in the top 30 m of 400 m/s was employed to characterize a representative site in the Phoenix Basin. No geotechnical data on deep soil conditions in the Phoenix Basin was available. Therefore, due to similarities in soil type and environment between the Phoenix and Las Vegas Basins, the shear wave velocity profile at depth for the Phoenix Basin was based upon typical values for the Las Vegas Basin from (Luke 2001). Fig. 2 compares the shear wave velocity profile used to characterize the Phoenix Basin to the shear wave velocity profiles for the deep soil basins of Charleston, South Carolina (Martin 2008) and the New Madrid seismic zone in the central United States (Hashash 2001) and the shear wave velocity profile for reference site conditions used to develop the NEHRP site factors.

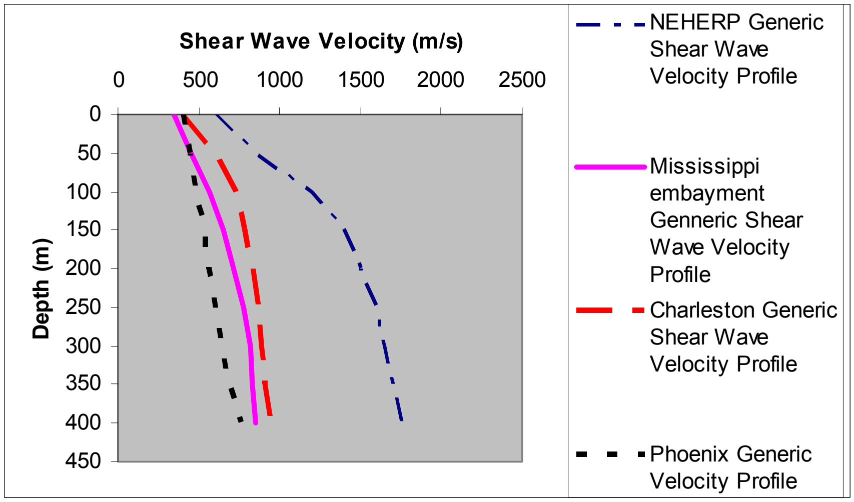

Figure 2. Shear wave velocity profiles for deep soil basins.

Probabilistic Seismic Hazard Analysis

Two different probabilistic seismic hazard analyses were conducted for the Phoenix Basin using the using the best available information on local seismic sources and state-of-the-art NGA relationships. One analysis was conducted using attenuation relationship parameters representative of the reference site condition (NEHRP Site Class B) and the second was conducted using parameters representative of the Phoenix deep soil basin. The NGA relationships used in the study were those developed by Campbell-Bozorgnia (2008) and Abrahamson and Silva (2008). These NGA relationships 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 classification, is input directly into the NGA equations. The two NGA models employed herein also distinguish between shallow and deep soil sites by incorporating the depth to a shear wave velocity of 1000 m/s, $Z_{1.0}$, into the attenuation equations.

Characteristics of seismic sources in the basin are described by Ghanat (2008). The known active fault seismic sources that may affect the Phoenix Basin are the Carefree, Horseshoe, Sugarloaf, Sand Tank, and Cottonwood Basin Fault. The location of these sources is shown on Fig. 1. The predominant style of faulting for all these sources is normal faulting. The closest active fault to the Phoenix Basin is the Carefree Fault, which is about 45 Km from downtown Phoenix and is believed to be capable of magnitude 6.3 event with an average recurrence interval of 5000 years.

Probabilistic seismic hazard analyses were conducted for the Phoenix Basin using NGA relationships with $(V_s)_{30}$ = 760 m/s and $Z_{1.0}$ = 75 m for NEHRP reference site conditions) and $(V_s)_{30}$ = 400m/s and $Z_{1.0}$ = 400 m for the Phoenix deep soil basin). The two NGA relationships employed in the analysis were equally weighted. Fig.3 shows the uniform hazard spectra (UHS) for a 2500 year return period from these two analyses for a site in north Phoenix designated by the star in Fig. 1.

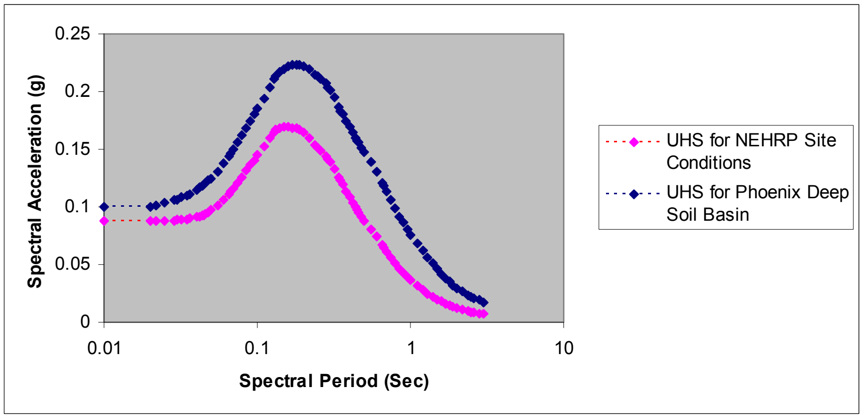

Figure 3. Uniform hazard spectra for the North Phoenix site for a 2500 yr return period.

NEHRP Procedure

The S_S and S_1 values of 0.16 g and 0.04 g, respectively, from the UHS corresponding to reference site conditions were adjusted for the local site conditions based upon the NEHRP procedure. The $(V_s)_{30}$ value of 400 m/s for the Phoenix Basin corresponds to NEHRP Site Class C. For Site Class C, the reference site value for S_S was adjusted to 0.20 g and the reference site value for S_1 was adjusted to a value of 0.06 g. Note that the UHS developed using the NGA relationships for site conditions representative of the Phoenix deep soil basin yielded spectral accelerations of 0.22 g and 0.08 g for S_S and S_1, respectively.

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). The seismic response analysis was performed for a representative column consisting of 400 meters of sandy soil on top of a bedrock half space. The bedrock "half space" at a depth of 400m was assigned a shear wave velocity of 1000 m/s, consistent with the model used in NGA analyses. Equivalent linear seismic response analyses were conducted for the representative column using five-time histories selected to characterize the design earthquake, a moment magnitude 6.0 earthquake 20 km from the site generating a PHGA of 0.10g 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 estimated based upon available boring logs and typical properties. The unit weight for the soil column was 17.25 KN/m^3 immediately below the ground surface and increased linearly to 19.6 KN/m^3 to just above bedrock, 400 m below ground surface. The bedrock was assigned a unit weight of 22 KN/m^3. The shear wave velocity was assumed to be equal to 400 m/s immediately below the surface increasing linearly to 750 m/s at 400 m, just above bedrock. The bedrock was assigned a shear wave velocity of 1030 m/s. Overburden pressure-dependent modulus reduction and damping curves (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. The material properties used in the equivalent linear site response analysis are summarized in Table 1.

Table 1. Material properties used in the equivalent linear analyses.

Material	**Unit Weight**	**Shear Wave Velocity**	**Modulus Reduction and Damping**
Sand	17.25-19.6 kN/m^3	400 – 750 m/s	EPRI [1993]
Bedrock	22 kN/m^3	1000 m/s	Linear Elastic

Design Earthquake Ground Motions

Based upon the deaggregated seismic hazard and the characterization of the local seismic sources as described by (Ghanat 2008), the design earthquake was established as a moment magnitude 6.0 earthquake 20 km from the site generating a PHGA of 0.10g for reference site conditions. To select representative time histories for the use in design, the significant duration of strong shaking of this design event 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 five seconds.

A suite of five time histories from shallow crustal earthquakes in the western United States were selected for the use in site response analysis. These earthquakes were all between magnitudes of 5.0 to 6.0 with significant duration between 3.3 and 11 seconds and site-to-source distance between 10 and 19 km. The characteristics of the five time histories used in the analysis are summarized in Table 2.

Table 2. Characteristics of the five time histories.

Seismic Record	**Fault Type**	**Moment Magnitude**	**Distance to Fault (km)**	**PHGA (g)**	**Scaled PHGA (g)**	**Significant Duration (s)**
Anza 1980	Strike Slip	5.0	13	0.11	0.10	7.6
Imperial Valley 1979	Strike Slip	5.2	15	0.097	0.10	11.0
Oroville 1975	Normal	6.0	10	0.092	0.10	6.0
Bishop 1984	Normal	5.8	19	0.106	0.10	3.3
Whittier 1987	Reverse	6.0	16	0.101	0.10	7.0

Each of the five time histories were input as bedrock outcrop motions to the analysis. Response spectra at the ground surface for 5% damping from the five individual analyses and the mean spectrum from the five analyses are plotted with the uniform hazard spectra developed using the NGA relationships for deep soil basin site conditions in Fig. 4. Based upon the mean of the five linear equivalent analyses, the value of S_S is 0.18g and the value of S_1 is 0.06g.

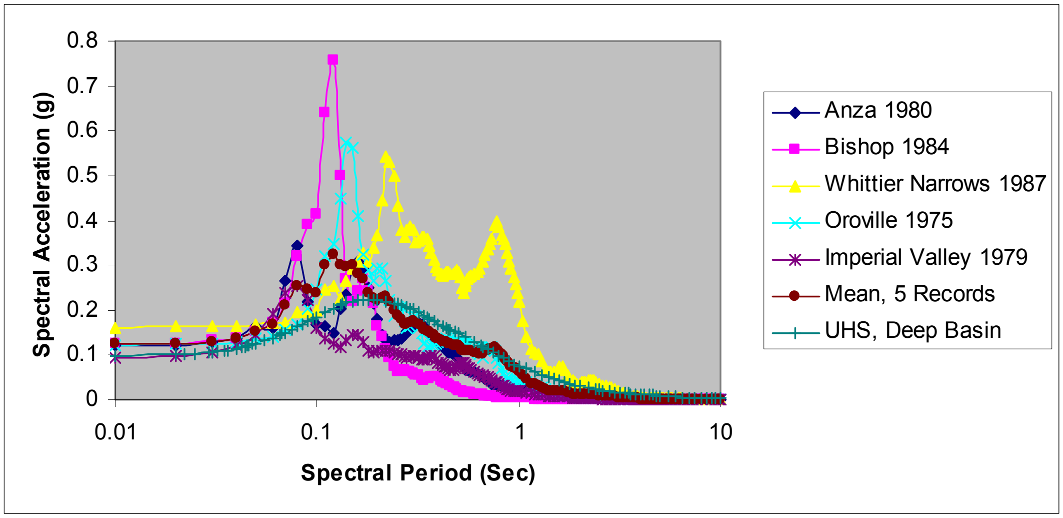

Figure 4. Acceleration response spectra from equivalent linear analyses.

The use equivalent linear analysis on soil profiles deeper than about 100 m has been questioned by several investigators (e.g. Luke at al. 2001, Hashash and Park 2002). These studies suggest that equivalent linear analysis may systematically underestimate higher frequency (1 Hz and greater) ground motions for deep soil profiles. The use of overburden dependent pressure-dependent soil properties is believed by the authors to compensate for this tendency to some extent, particularly for low intensity ground motions. However, this tendency remains a concern with respect to the use of equivalent linear analyses for deep soil profiles.

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. 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 are determined by fitting the results of a linear visco-elastic analysis using conventional equivalent linear hysteretic damping to results of non-linear analysis with Rayleigh damping parameters fitted 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 twenty-second modes resulted in a good match between two types of analyses. A detailed description of the DEEPSOIL model can be found in Hashash and Park (2001, 2002).

The 400m 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 five time histories used in the equivalent linear analysis were employed in the non-linear analyses. Acceleration response spectra at the ground surface for 5% damping from the five individual non-linear analyses and the mean spectrum from the five analyses are compared to the uniform hazard spectrum developed using the NGA relationships for deep soil basin site conditions in Fig. 5. The value of S_S is 0.29 g and the value of S_1 is 0.09 g for the mean spectrum from the non-linear analyses.

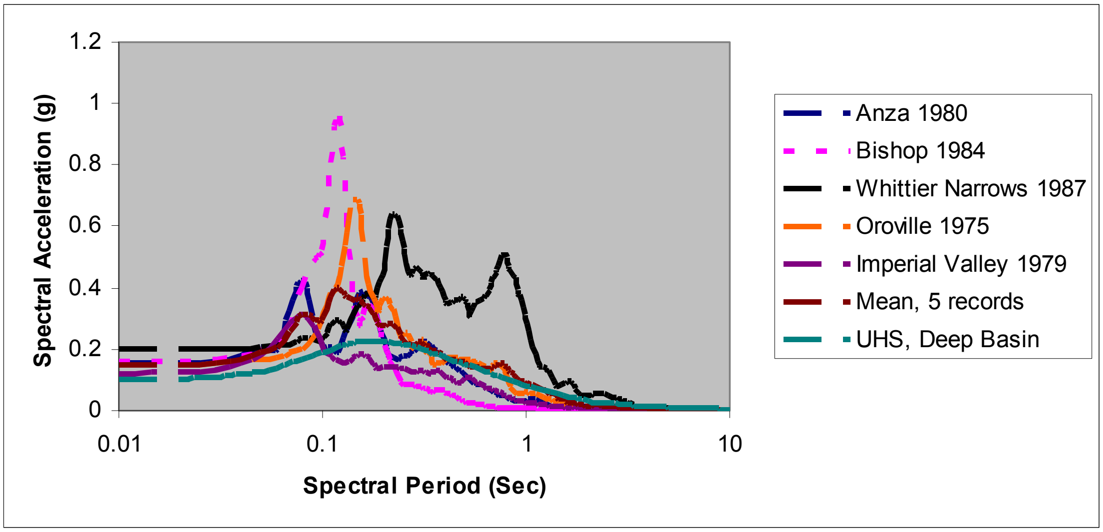

Figure 5. Acceleration response spectra from non-linear analyses.

The mean acceleration response spectra from the equivalent linear and non-linear analyses and the UHS developed using the NGA relationships for deep soil basin site conditions are shown in Fig. 6. While the UHS gives smaller spectral accelerations at periods of less than 0.2 s, there is relatively good agreement among all three methods at periods equal to or greater than 0.2 seconds. The equivalent-linear method gives systematically lower spectral acceleration than the non-linear method. However, this trend may be due to the low intensity of the design motions and may reverse if higher intensity motions (where non-linear effects become more significant) are considered. Table 3 compares the values for S_S and S_1 from the four methods of analysis. The values obtained using the reference site UHS and NEHRP site factors are essentially the lowest of the four methods for the considered spectral periods.

Table 3. Comparison of Deep Basin Spectral Values from Four Methods.

Period	Non-Linear	Linear Equivalent	UHS, Deep Basin	NEHRP
0.2 Sec	0.29 g	0.22 g	0.22 g	0.20 g
1 Sec	0.09 g	0.06 g	0.08 g	0.06 g

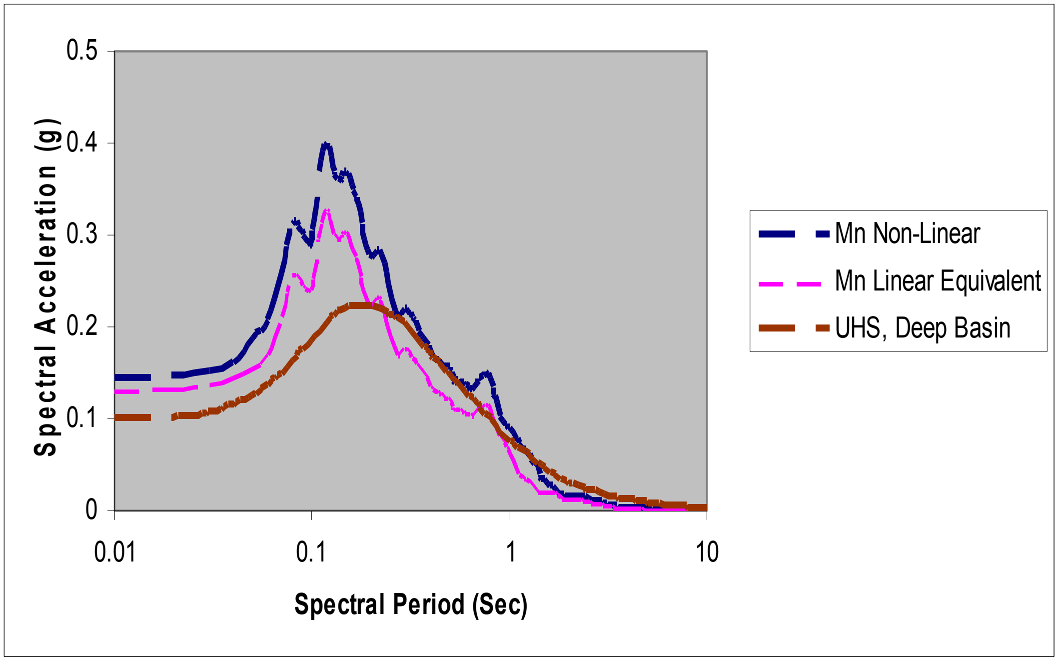

Figure 6. Comparison of acceleration response spectra.

Conclusion and Summary

The effect of deep soil deposits in the Phoenix Basin on the seismic hazard for a 2500 years return period was evaluated using four different methods. The effect of the local deep soil basin site conditions was evaluated directly using NGA relationships in the seismic hazard analyses and indirectly three different ways: using the results of the seismic hazard analysis for reference site conditions and NEHRP site factors, using one-dimensional equivalent linear site response analyses, and using one-dimensional non-linear site response analyses. Use of the NEHRP site factors yielded the lowest values for the spectral accelerations required for design of the four methods while the non-linear site response analyses, considered by the authors to be the most accurate means of assessing the impact of local site conditions, yielded the highest values. The results of the equivalent linear analyses were systematically lower than the results of the non-linear analyses. Results of the seismic hazard analysis conducted using the NGA relationships and input parameters representative of the deep soil basin conditions fell in between the results of the equivalent linear and non-linear analyses at spectral accelerations of periods of 0.2 s or greater, but were below both types of site response analysis at shorter periods. Importantly, comparison of the results suggest that, for the case of an area of relatively low seismicity that was considered herein, the NGA relationships are capable of accounting for the impact of deep soil basin site-specific response effects on the values of S_S and S_1 directly in a seismic hazard analysis. However, the NGA relationships do appear to under predict spectral accelerations at periods less than 0.2 s (e.g. at 0.1 s) and it must be recognized that the analysis conducted herein was for an area of relatively low seismicity. The differences among the various types of analyses may change significantly if higher levels of seismicity or softer ground conditions are considered.

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