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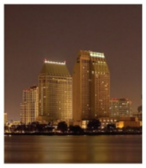
Site-Specific Response Analysis in the New Madrid Seismic Zone

Wei Zheng
Black & Veatch Corporation, Overland Park, KS

Youssef Hashash
University of Illinois at Urbana-Champaign, Urbana, IL

Mark M. Petersen
Black & Veatch Corporation, Overland Park, KS

Andrew S. Whittaker
University at Buffalo/ The State University of New York, Buffalo, NY



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Wei Zheng
Black & Veatch Corporation
Overland Park, Kansas, USA

Youssef Hashash
University of Illinois at Urbana-Champaign
Urbana, Illinois, USA

Mark M. Petersen
Black & Veatch Corporation
Overland Park, Kansas, USA

Andrew S. Whittaker
University at Buffalo, The State University of New York
Buffalo, New York, USA

ABSTRACT

A coal-fired power plant, Plum Point Energy Station, is being built in the city of Osceola, Arkansas, which is located in the New Madrid Seismic Zone (NMSZ). The project site is characterized as Site Class F, according to ASCE-7-05, because the soils at the site are prone to liquefaction. The depth of soil to rock is approximately 1 kilometer (km). A site-specific response study was required by the building code to determine the uniform hazard spectrum at the ground surface. The site-specific study included a probabilistic seismic hazard assessment to determine the Maximum Considered Earthquake (MCE) spectrum at an equivalent rock outcrop and a one-dimensional site response analysis to determine the ground surface response, given the rock outcrop motions. Spectral matching was used to generate the MCE ground motions at the rock outcrop. The equivalent linear site response code, SHAKE, and two nonlinear site response codes, SUMDES and DEEPSOIL, were used to generate the ground surface acceleration histories. The mechanical properties of the soils in the column were varied to assess the impact of changes in soil properties on free-field response. The function of the equivalent linear and nonlinear site response codes was identified. The amplification of the rock motion to the free field is discussed herein in terms of the site class factors presented in ASCE-7-05.

INTRODUCTION

A coal-fired power plant, Plum Point Energy Station, is being built in the city of Osceola in Mississippi County, Arkansas. The site is located on the west bank of the Mississippi River, between Brown Bayou and the Corps of Engineers levee. The site location is shown on Fig. 1. The Plum Point Energy Station is a pulverized coal-fired electric generating facility with a nominal electrical output of 650 megawatts (MW). The facility will be configured initially with one steam generator and one steam turbine generator.

The project site is located in the New Madrid Seismic Zone (NMSZ), as shown on Fig. 1. Site investigations indicated that the subsurface condition consists of very soft to soft clayey silt and clay layers underlain by a medium dense sand layer and a dense sand layer. A medium dense sand layer is present from a depth of approximately 10 to 15 meters below ground surface and is prone to liquefaction, based on the simplified method of Youd et al. (2001). The project site is characterized as Site Class F, according to ASCE-7-05. The governing building code for the project is the 2000 International Building Code (IBC), which requires a site-specific study to determine the uniform hazard spectrum at the ground surface.

The site-specific study included a probabilistic seismic hazard assessment to determine the Maximum Considered Earthquake (MCE) spectrum at an equivalent rock outcrop and a one-dimensional site response analysis to determine the ground surface response, given the rock outcrop motions. The MCE is defined by a uniform hazard spectrum with ordinates that have a 2 percent probability of exceedance in 50 years. Recorded and synthetic ground motions were appropriately selected and spectrally matched to generate the MCE ground motions at the rock outcrop. The thickness of unconsolidated sediments above the bedrock was estimated to be 880 meters. The dynamic soil and rock properties were developed by combining the shallow shear wave velocity profiles from geophysical tests and the typical shear wave velocity for deeper sediments (Romero and Rix, 2001). To determine the impact of changes in the near-surface soil properties on the free-field response, lower bound, average and upper bound soil properties were used for analysis. The equivalent linear

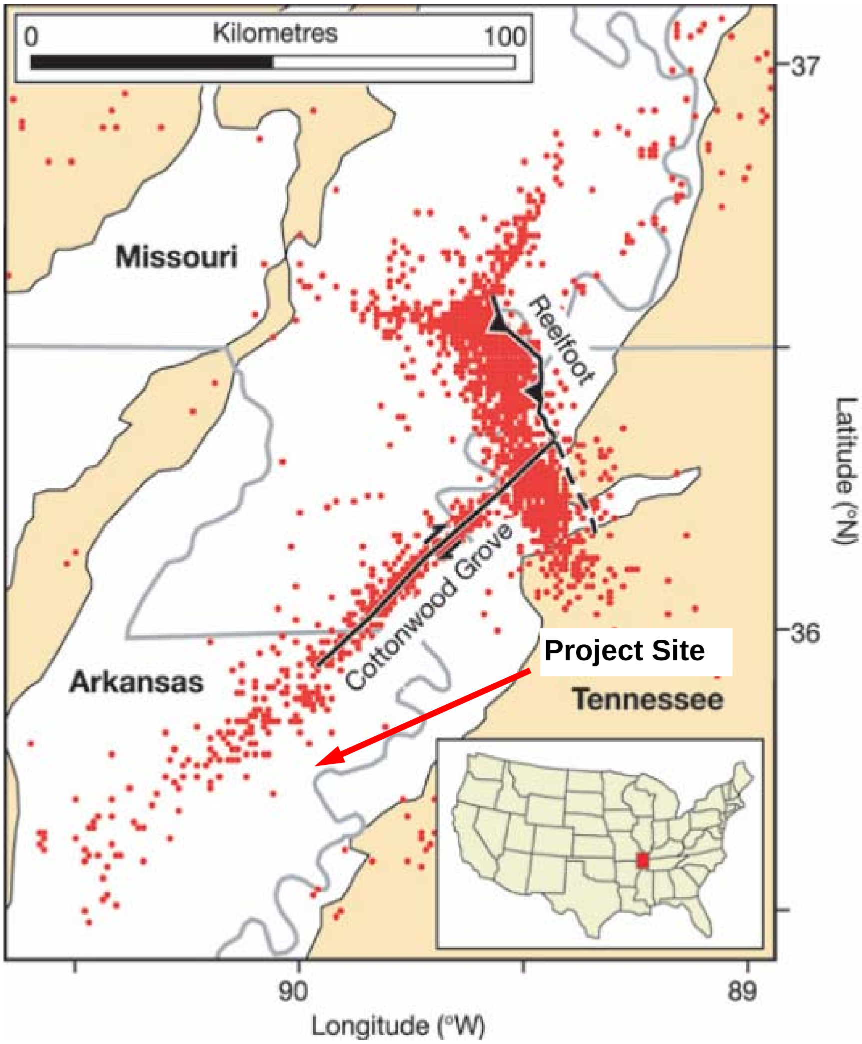


Fig. 1. Location of Project Site and the New Madrid Seismic Zone

site response code SHAKE (Schnabel et al., 1972) and two nonlinear site response codes, SUMDES (Li et al., 1992) and DEEPSOIL (Hashash and Park, 2001), were used to generate the ground surface acceleration histories and spectrum.

ASCE-7-05 requires that the ordinates of the design spectrum from the results of the site response analysis for Site Class F be no less than 80 percent of the ordinates of the code-based design spectrum for Site Class E. The project design spectrum was developed by enveloping the site-specific response spectrum and a spectrum with ordinates equal to 80 percent of the code spectrum for Site Class E. The site amplification coefficients were determined from the site response analysis and compared with the coefficients of ASCE-7-05.

NMSZ AND MISSISSIPPI EMBAYMENT

The NMSZ is an important seismic region in the United States. In 1811 and 1812, three earthquakes, estimated at magnitude 7.5 or greater, occurred near New Madrid, Missouri; numerous smaller earthquakes have been recorded since that time. The NMSZ occupies the central and northern portion of the Reelfoot rift from Marked Tree, Arkansas, to Caruthersville, Missouri. The seismic zone is defined by earthquake epicenters up to 10 km deep (McKeown et al., 1990). Hypocenters occur near the top of the granite-gneiss basement rock or in the Paleozoic sedimentary rock, particularly in weakened and deformed rock above the Blytheville and Pascola arches (McKeown et al., 1990). A system of faults within the central portion of the rift was the likely source of the 1811-1812 sequence of earthquakes (Johnston and Schweig, 1996). Although Newman et al. (1999) believe that the risk of a major quake in the NMSZ is overestimated, surface deformation associated with the Reelfoot fault, radiocarbon dates of disturbed organic layers, and studies of sand volcanoes and other paleoliquefaction features indicate that the NMSZ periodically produces strong earthquakes (Russ, 1979; Kelson et al., 1996; Tuttle et al., 2002).

The Mississippi Embayment (ME), which overlies the NMSZ, is a broad lowland in the east-central United States that opens southward through Missouri, Kentucky, Tennessee, Arkansas, Mississippi, and Louisiana (Fig. 2). The ME is bounded by

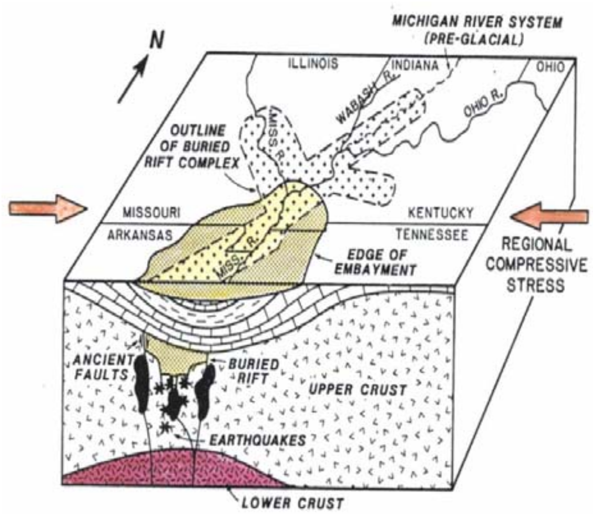


Fig. 2. Regional Tectonic Setting Showing a Cross Section of the Mississippi Embayment (Braile, 2004)

the Illinois basin to the north, the Nashville dome to the east, the Ouachita and Ozark uplifts to the west, and the Gulf of Mexico to the south. To the northeast, the ME merges with the east-trending Rough Creek graben in western Kentucky. The Mississippi River flows through the heart of the ME, south from its junction with the Missouri River. The ME is a south-southwest plunging trough filled with Cretaceous and younger fluviomarine and Quaternary eolian sediments (Cox et al., 2001). With the exception of rare beds of sandstone and limestone, the sediments are unconsolidated and fill the basin to a depth of more than 1,000 meters (McKeown et al., 1990). The sediments consist of interbedded clay, silt, sand, gravel and chalk that dip gently south toward the Gulf of Mexico; clastic fluvial facies dominate toward the north, whereas near-shelf and deeper-water facies dominate to the south (Ng et al., 1989). Underlying the sediments are approximately 3 km of Paleozoic sedimentary rock (Kane et al., 1981). The Dow Chemical No. 1 Wilson drill hole, approximately 7 km from the Plum Point site, was drilled into crystalline basement rock to a depth of about 3,700 meters (Collins et al., 1992). The boring logs indicate approximately 880 meters of unconsolidated sediments at that site, which is assumed to be the depth of unconsolidated sediments at the Plum Point site.

SEISMIC HAZARD ANALYSIS

The coordinates of the Plum Point site are latitude 35.6625 and longitude -89.9456. The interpolated probabilistic ground motion for the Plum Point site was generated using the US Geological Survey 1996 National Seismic Hazard Maps (USGS, 1996). The 1996 USGS data were chosen, instead of the 2002 USGS data, because the 1996 USGS data form the basis for the IBC 2000. Column 2 in Table 1 presents the spectral ordinates as a function of period. It should be noted that the reference site condition for the USGS maps is specified to be the boundary between National Earthquake Hazards Reduction Program (NEHRP) Site Classes B and C, corresponding to a shear wave velocity of 760 meters/second (m/s). Reference works (Ou and Herrmann, 1990; Nicholson et al., 1984) indicate that the shear wave velocity of the bedrock at the NMSZ is approximately 3,000 m/s, which should be categorized as NEHRP Site Class A (shear wave velocity in excess of 1,500 m/s). Factors for converting the spectral ordinates for the B/C boundary to Site Class A conditions were obtained from the Commentary to the 1996 USGS Hazard Maps (USGS, 1996) and from personal communications with Art Frankel of the USGS via Maury Power of Geomatrix (Geomatrix, 2006). The factors are reproduced in Table 1 as a function of period.

Table 1. Computation of Hard Rock Spectral Ordinates

Period (seconds)	B/C Boundary Spectral Acceleration (g)	Factor per Hazard Map Commentary	Site Class A Spectral Acceleration (g)
0	1.33	1.52	0.87
0.1	3.17	1.76	1.80
0.2	2.71	1.76	1.54
0.3	2.30	1.72	1.34
0.5	1.62	1.58	1.03
1.0	0.90	1.34	0.67
2.0	0.48	1.20	0.40

The MCE spectral ordinates for Site Class A were computed by dividing the USGS B/C boundary ordinates (Column 2 in Table 1) by the factors of Column 3 in Table 1. The resultant Site Class A spectral ordinates are presented in Column 4 of Table 1. The spectral accelerations for intermediate periods were interpolated linearly. For periods greater than 2 seconds, the NEHRP Site Class A horizontal spectral accelerations were computed as:

$$SA = SA_{A2}\left(\frac{2.0}{T}\right) \qquad (1)$$

where SA_{A2} is the Site Class A spectral acceleration at 2.0 seconds and T is the period (seconds). Figure 3 presents the MCE hard rock spectrum for horizontal motion.

MCE MOTIONS AT A ROCK OUTCROP

The MCE motions at a rock outcrop were developed from existing and synthetic earthquake histories via spectral matching. The selection of the appropriate seed earthquake histories focused first on similar tectonic conditions (intraplate events) and second on similar magnitudes to the controlling earthquake (moment magnitude of about 7.5). The Saguenay, Nahanni and Gazli events were all intraplate events. The Saguenay, Nahanni and Gazli events are the largest recorded intraplate earthquakes; however, they were significantly smaller in magnitude than the MCE for the NMSZ. The Kobe and Chi Chi earthquakes were interplate events but with

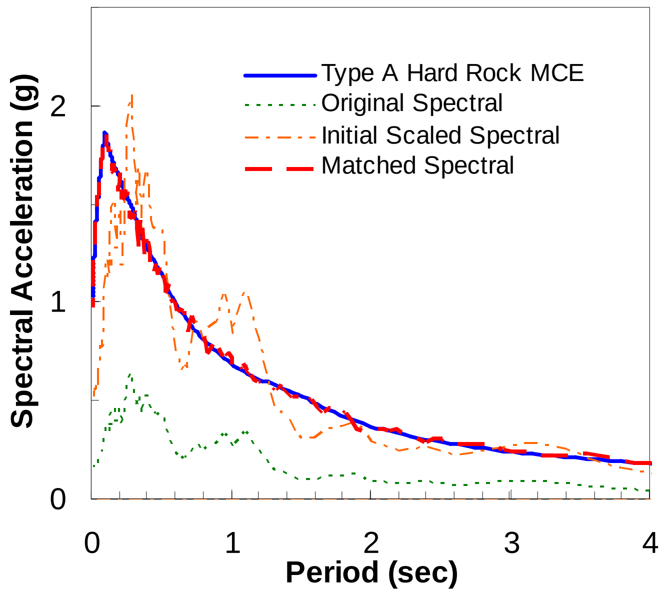


Fig. 3. MCE Hard Rock Spectrum (Spectral Matching for Component 2 of Chi Chi Earthquake ALS Station)

magnitudes of the order of the NMSZ MCE. Table 2 lists the earthquake histories used in the Plum Point Project site response analysis.

The earthquake histories used for the site response analysis were spectrally matched to the MCE hard rock spectrum of Fig. 3. The matching was performed using a module in EZ-FRISK 7.14 (Risk Engineering, 2005): RSPMATCH (Abrahamson, 1992 and 1998). An initial scaling factor was used to scale the ground motion to the approximate level of the design response spectrum. The same amplitude scale factor was used for both horizontal components of the ground motion. The spectral content of the earthquake histories was then modified to match the design spectrum. Figure 3 is an example of spectral matching using the Component 2 motion recorded at the ALS Station for the Chi Chi earthquake. An independent verification of the spectral matching process was performed using the geometric mean approach developed at the University at Buffalo (Huang et al., 2008). The geometric-mean scaling method scales each component in a pair of seed motions by a single factor to minimize the sum of the squared error between the target spectral values of Fig. 3 and the geometric mean of the spectral ordinates for the pair at periods of 0.2, 0.5, 1.5 and 4 seconds. The weighting factor for each period was 0.25. This scaling procedure preserves the record-to-record dispersion of spectral demand and the spectral shape of the seed ground motions.

SOIL AND ROCK CHARACTERISTICS

The project site is located adjacent to the Mississippi River and near the center of the NMSZ. Deep, unconsolidated sediments lie above the Paleozoic bedrock (Ng et al., 1989). The entire depth of the unconsolidated sediment should be considered in the site response analysis (Hashash and Park, 2001), i.e., 880 meters, based on the Dow Chemical No. 1 Wilson drill hole (refer to Fig. 4).

Six seismic cone penetration tests (CPTs) and one ReMi survey were performed at the project site. The ReMi survey is based on spectral analysis of surface waves (SASW) and multi-channel analysis of surface waves (MASW), as described by Nazarian and Stokoe (1984). The shear wave velocity profiles from those tests are shown on Fig. 5. The upper 36.5 meters of the site were parsed into a lower bound, an average and an upper bound velocity profile to determine the sensitivity of the site response to near-surface soil properties. The dynamic properties of soil deeper than 36.5 meters were created from the typical shear wave velocity profiles (Romero and Rix, 2001), which were based on a combination of surface information and a few deep wells of the ME. The entire shear wave velocity profile for this project is shown on Fig. 6. The unit weight of the complete soil profile and the properties of the bedrock were developed on the basis of the work of Romero and Rix (2001). The velocities in the upper bound profile are considerably greater than the average and lower bound velocities at depths between 15 and 30 meters.

Table 2. Earthquake Histories Used in Response Analysis

Earthquake	Date	Station	Moment Magnitude	Site Conditions	Peak Ground Acceleration (g)		
					H_1	H_2	V
Chi Chi	9/20/1999	TCU 079	7.6	C (USGS)	0.393	0.742	0.388
Gazli	5/17/1976	9201 Karakyr	6.8	A (Geomatrix)	0.608	0.718	1.264
Kobe	1/16/1995	Port Island	6.9	D (USGS)	0.696	0.324	--
L472 Bridge	Synthetic	--	7.5	--	1.505	1.512	0.954
Nahanni	12/23/1985	6097 Site 1	6.8	A (Geomatrix)	0.978	1.096	2.086
Chi Chi	9/20/1999	TCU 046	7.6	A (USGS)	0.116	0.133	0.104
Kocaeli	8/17/1999	Gebze	7.4	A (USGS)	0.244	0.137	0.203
Chi Chi	9/20/1999	ALS	7.6	B (USGS)	0.183	0.163	0.073
Chi Chi	9/20/1999	CHY 046	7.6	C (USGS)	0.182	0.142	0.079

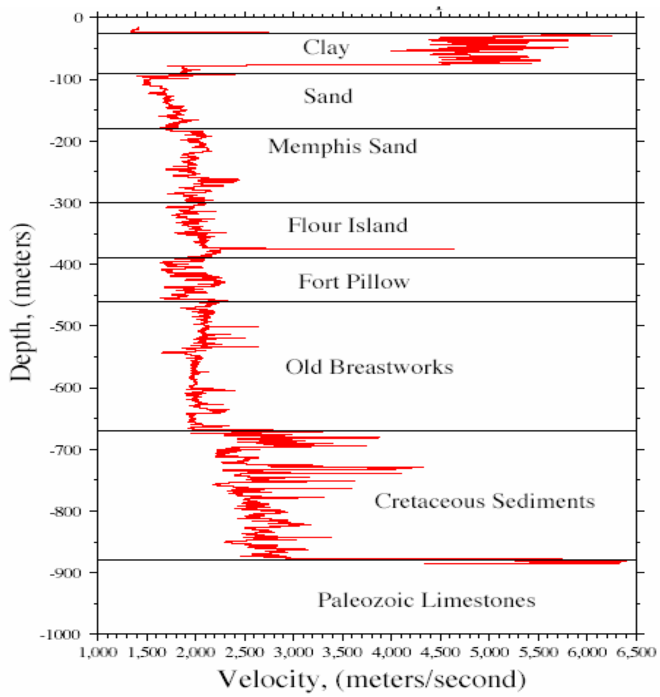


Fig. 4. P-Wave Velocity Profile of the Dow Chemical No. 1 Wilson Drill Hole (Cramer, 2004)

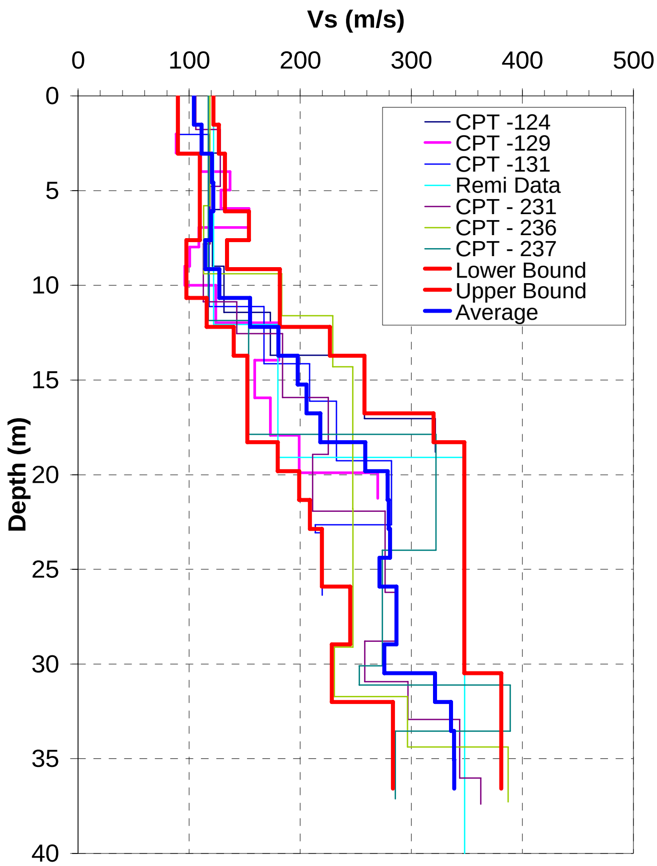


Fig. 5. Shear Wave Velocity Profile from Seismic CPTs and ReMi Surveying

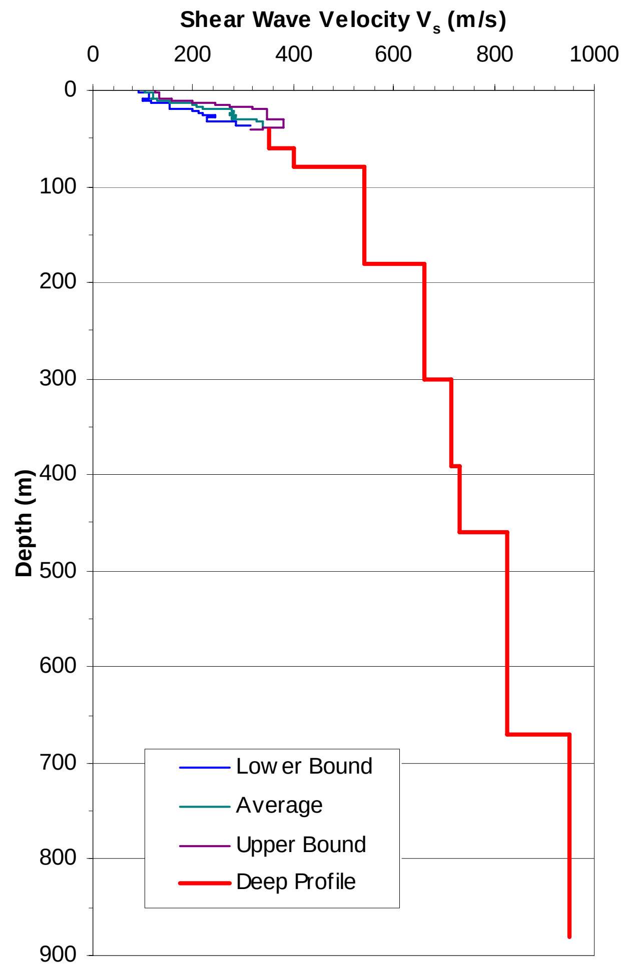


Fig. 6. Shear Wave Velocity Profile Used at Project Site

MATERIAL PROPERTY CURVES

According to data from the Wilson drill hole, the project site overlies Ordovician-aged Powell Dolomite. The measured P-wave velocity of the Powell Dolomite exceeds 5,000 m/s, which is characterized as NEHRP Site Class A. The crystalline rock of the continental basement was logged at roughly 4,300 meters. The estimated shear wave velocity of the hard bedrock underlying the sediments at a depth of 880 meters is approximately 3,000 m/s.

The relationships of shear modulus and damping versus shear strain must be established for site response analysis. In this section, stiffness and damping relationships are established for the soils in the upper 880 meters of the soil column.

Soils generally exhibit reduced shear stiffness and increased damping with increasing shear strain. Material property curves that present shear stiffness and damping relationships are used to characterize such behavior. The behavior of the entire soil column reflects modulus reduction effects, even at small strain ranges during earthquake loading. The important effect of confining pressure on material property curves is well recognized (Ishibashi and Zhang, 1993; Hardin et al., 1994): an increase in confining stress results in a smaller reduction of shear modulus and smaller damping at a given shear strain. Although the influence of confining pressure on soil behavior must be considered for the site response analysis, there is a lack of laboratory test data for ME soils at high confining pressures.

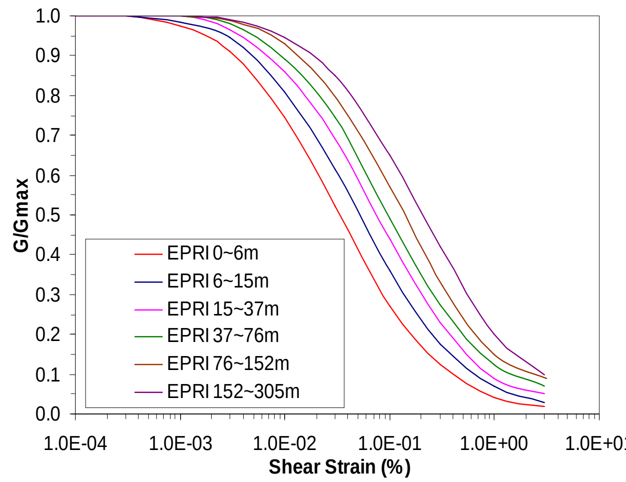
The Electric Power Research Institute (EPRI, 1993) developed a set of material property curves for sand to a depth of 305 meters. These curves are divided into six different depth ranges, as shown on Fig. 7. These curves were used for all surface and deep cohensionless materials for the response analysis. For sediments with depths greater than 305 meters, the curves with a range of depths between 152 and 305 meters were used. Two clay-like deposits, the Flour Island and the Old Breastworks, exist at depths from 303 to 394 meters and from 465 to 677 meters, respectively, based on the profile of the Dow Chemical No. 1 Wilson drill hole. The soil response of these two layers was considered to be similar to adjacent sands due to the high confining pressure, so the EPRI curves for depths between 152 and 305 meters were used for modeling. For the two surface clay layers, the material property curves were based on the value of the Plasticity Index (PI). The curves with PI values that were equal to 15 and 50 of Vucetic and Dobry (1991) were applied to the first and second layers, respectively.

ONE-DIMENSIONAL SITE RESPONSE ANALYSIS

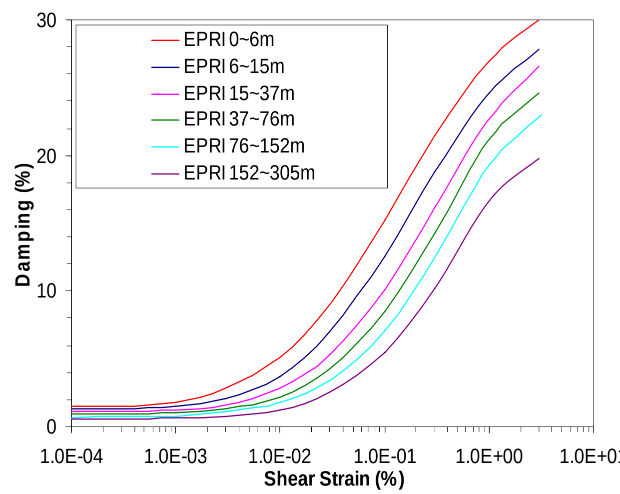
A site response analysis is a study that accounts for site-specific conditions, including site stratigraphy and soil/rock characteristics. The response at the ground surface is determined by the vertical propagation of seismic waves through the soil column.

Three computer codes capable of considering the effects of high confining pressures were used for the site response analysis: DEEPSOIL (Hashash and Park, 2001), SUMDES (Li et al., 1992) and SHAKE91+. SHAKE 91+, a modified version of the original SHAKE program, is an equivalent linear analysis code. DEEPSOIL can perform equivalent linear and nonlinear analyses; SUMDES is a nonlinear analysis code. The equivalent linear approach is considered less reliable than nonlinear analysis at ground shaking in excess of 0.4 g (Ishihara, 1986) or if the peak shear strains exceed approximately 2 percent (FHWA, 1997). DEEPSOIL and SUMDES were used to characterize free-field and in-column earthquake motions for structural analysis at the Plum Point Project. SHAKE 91+ was used to benchmark the results of the nonlinear analyses.

The soil column was discretized into 176 soil layers such that ground motion frequencies below 25 hertz (Hz) were not filtered numerically. Several sets of analyses were performed to validate the models. The average soil profile was used for



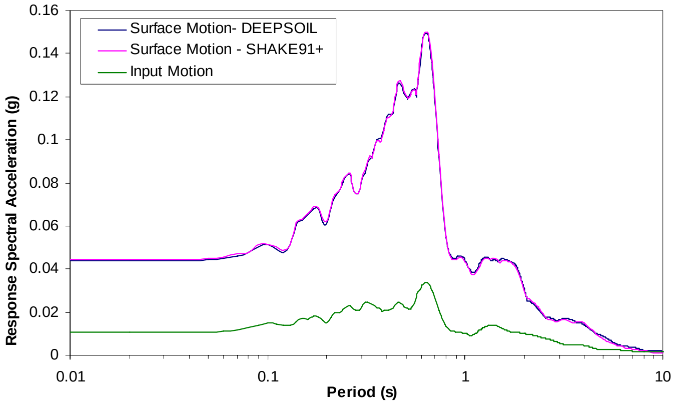
(a)



(b)

Fig. 7. EPRI Material Property Curves
(a) Shear Modulus Reduction Curve (b) Damping Curves

the comparisons. The first comparison was for the identical equivalent linear analysis in SHAKE 91+ and equivalent linear analysis in DEEPSOIL. One weak motion and one strong motion were used to evaluate the response at small and large strains, respectively. The weak motion was the east-west record from the 1989 Loma Prieta earthquake, recorded at Yerba Buena Island Station, California. The Yerba Buena earthquake history has a peak ground acceleration (PGA) of 0.067 g. To retain the soil's elastic response (for the purpose of comparing results), the amplitude of the motion was scaled down to 0.01 g. The strong motion record was obtained by spectrally matching one of the records from the 1976 Gazli earthquake recorded at the Karakyr station. The matched strong motion had a PGA of 0.87 g. Both motions were used as the outcrop input motions for the equivalent linear site response analyses using SHAKE 91+ and DEEPSOIL. The SHAKE 91+ and DEEPSOIL free-field acceleration response spectra are presented on Fig. 8. The results indicate that the two analyses yield effectively identical results.



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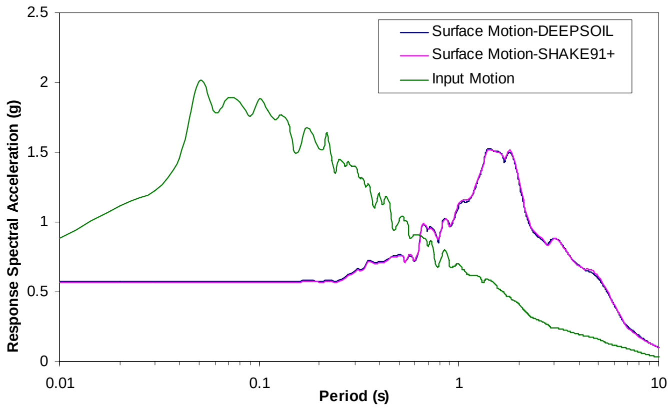
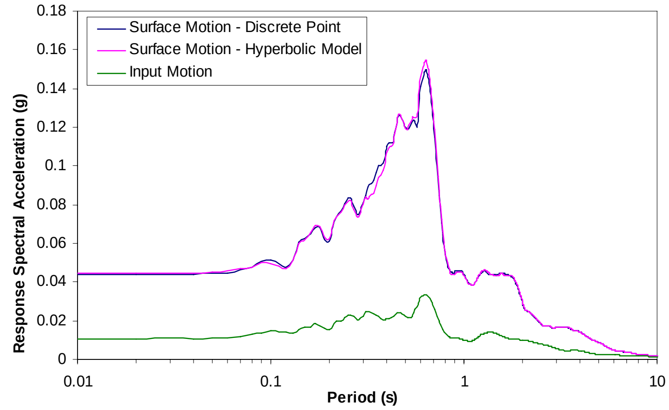


(b)

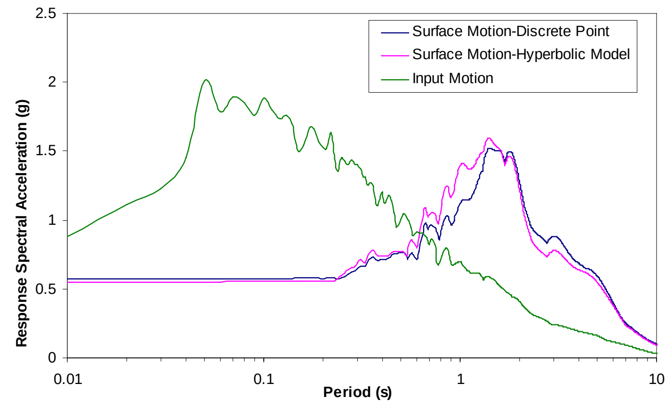
Fig. 8. Comparison of Response Spectra at Ground Surface (a) Weak Motion (b) Strong Motion

The second comparison was between two equivalent linear analyses performed in DEEPSOIL that used two different approaches for defining the modulus reduction and damping curves. One model used discrete data for the material property curves. The other used an extended hyperbolic model in DEEPSOIL (Hashash and Park, 2001) to match the material property curves. The purpose of this comparison was to establish appropriate parameters for the extended hyperbolic model for nonlinear analysis. The input motions were those used in the first comparison. The results shown on Fig. 9 indicate acceptable agreement between the two methods.

The third comparison made use of nonlinear analyses by DEEPSOIL and SUMDES. The input parameters determined for the extended hyperbolic model in the previous comparison were used in the DEEPSOIL analysis. The input parameters in the SUMDES analysis were determined by a similar curve matching process. The input motions were the same as those used in previous comparisons. The results are shown on Fig. 10. The comparison indicates that the two computer codes have comparable results for the weak motion and the long period range of the strong motion, but different results for the short period range of the strong motion where the DEEPSOIL analysis had a higher response.



(a)



(b)

Fig. 9. Comparison of Two Equivalent Linear Analyses in DEEPSOIL (a) Weak Motion (b) Strong Motion

DISCUSSION

Site response analyses were performed using the earthquake histories obtained from the sites listed in Table 2. The calculated surface motions are presented as 5 percent damped response spectra, as illustrated on Fig. 11. Three different soil profiles were used to consider variability in the soil properties. Figure 11 is an example of the DEEPSOIL nonlinear analyses using the average soil profile. The mean spectrum is the MCE spectrum at the ground surface. The design spectrum is taken as two thirds of the maximum earthquake spectrum, in accordance with ASCE-7-05. Fig. 11 also presents the IBC 2000 Site Class E spectrum, and a spectrum with ordinates that are 80 percent of the Site Class E spectrum. The relationship between maximum strain and depth are presented on Fig. 12 for different soil profiles in the top 200 meters. The results show significant nonlinearity (strain greater than 1 percent) in the upper 60 meters of soil.

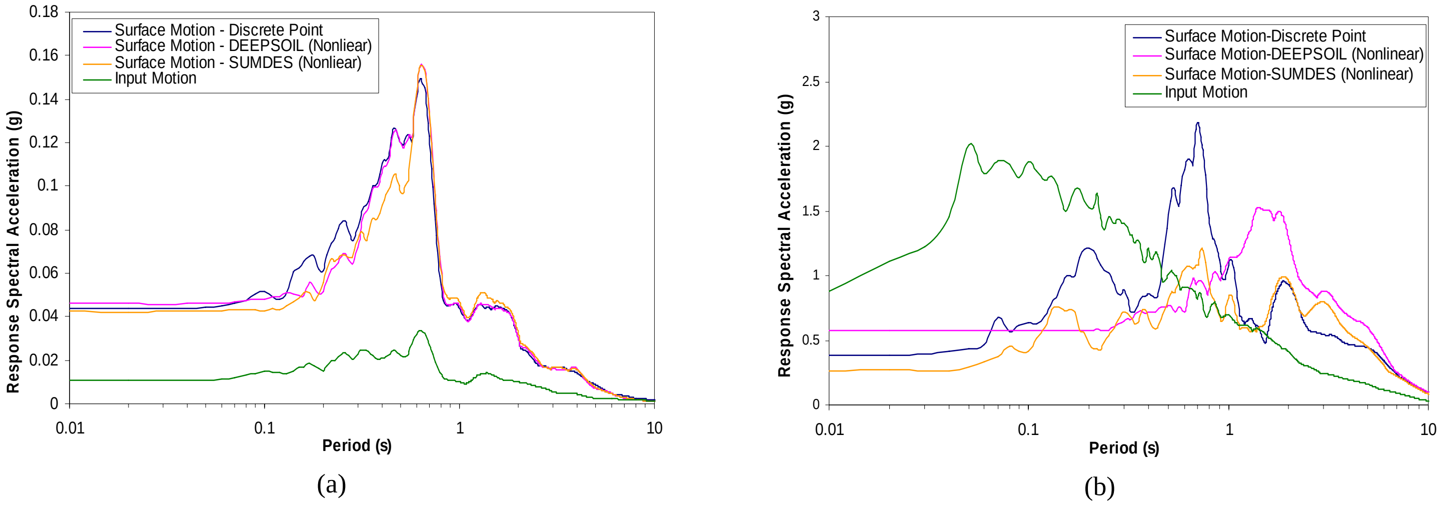


Fig. 10. Comparison of Nonlinear Analysis
(a) Weak Motion (b) Strong Motion

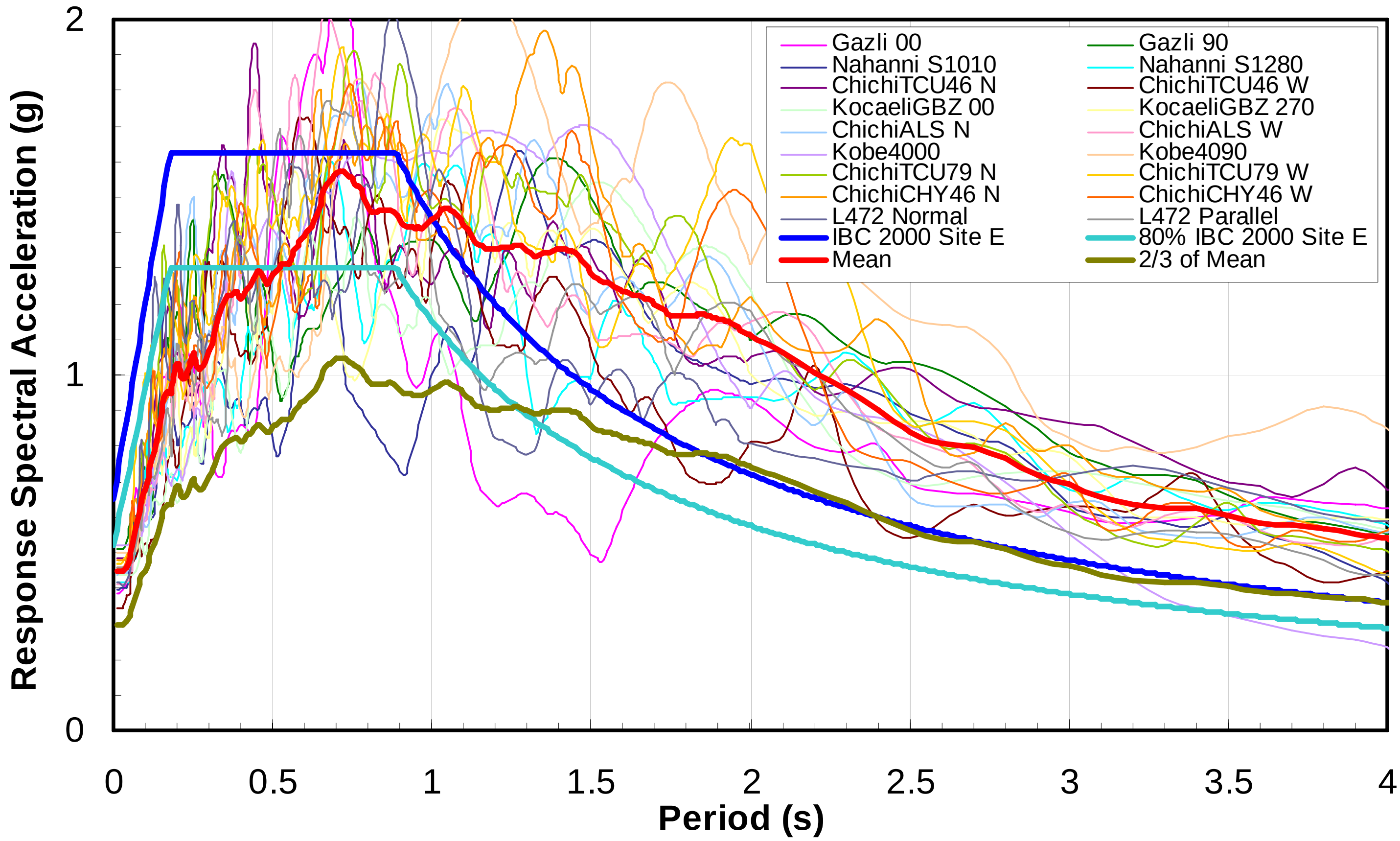


Fig. 11. Nonlinear Analyses Using Average Soil Profile in DEEPSOIL

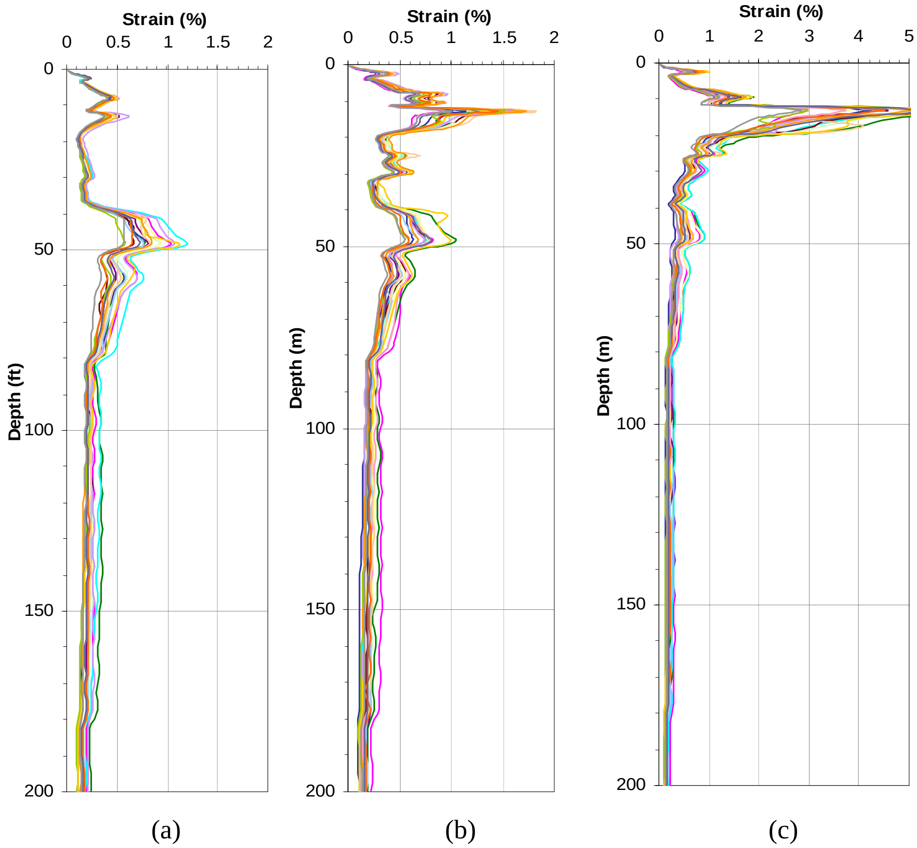


Fig. 12. Maximum Shear Strain Versus Depth in DEEPSOIL Analysis (a) Upper Bound (b) Average (c) Lower Bound

All of the response analysis results are plotted on Fig. 13. The results from DEEPSOIL generally agree with those from SUMDES in the long period range, but have higher values in the low period range. The difference in the low period range is caused by the different viscous damping schemes used in SUMDES and DEEPSOIL. SUMDES uses the simplified Rayleigh damping scheme with one input frequency. The simplified Rayleigh damping scheme has significant bias at high frequencies (Kwok et al., 2007) and could underestimate the response in the high frequency range. DEEPSOIL uses the full Rayleigh damping scheme with two input frequencies. The frequencies were selected through an iterative process where frequency and time-domain elastic solutions were matched over a frequency range of interest (Park and Hashash, 2004). As shown on Fig. 13, the SUMDES results appear to be insensitive to different soil profiles; however, the DEEPSOIL results show different responses for different soil profiles, particularly in the low period range. The equivalent linear analysis uses constant stiffness and damping to approximate the nonlinear soil behavior, which filters out low period components, as indicated on Fig. 13.

A spectrum with proposed site coefficients is plotted on Fig. 13 to envelop the nonlinear analysis results. The proposed site coefficients are F_a equal to 0.6 at a period of 0.2 s and F_v equal to 2.8 at a period of 1 s. Since liquefaction is not considered in the site response analysis, the proposed site coefficients can be compared with the ASCE-7-05 Site Class E coefficients F_a equal to 0.9 and F_v equal to 2.4. The comparison indicates that the proposed site coefficients are lower at the shorter period and higher at the longer period than the ASCE-7-05 site coefficients, which is consistent with the site-specific response analysis of Park and Hashash (2005) for Site Class D with deep ME soil profiles.

The design spectrum was developed by weighting the results from the different computer codes: 50 percent for the DEEPSOIL nonlinear analysis, 17 percent for the SUMDES analysis and 33 percent for the equivalent linear analysis. The weighted spectrum is provided on Fig. 14. The final design spectrum is provided on Fig. 14, which was developed by enveloping the results of the site-specific analysis (as described above) and a code-based spectrum with ordinates that are 80 percent of those for Site Class E.

CONCLUSION

The site of the Plum Point Energy Station is characterized as Site Class F by the 2000 IBC. The 2000 IBC does not provide spectral acceleration relationships for Site Class F and requires a site-specific response analysis. The site-specific response analysis was performed in accordance with ASCE-7-05, with both nonlinear and equivalent linear methods. The results

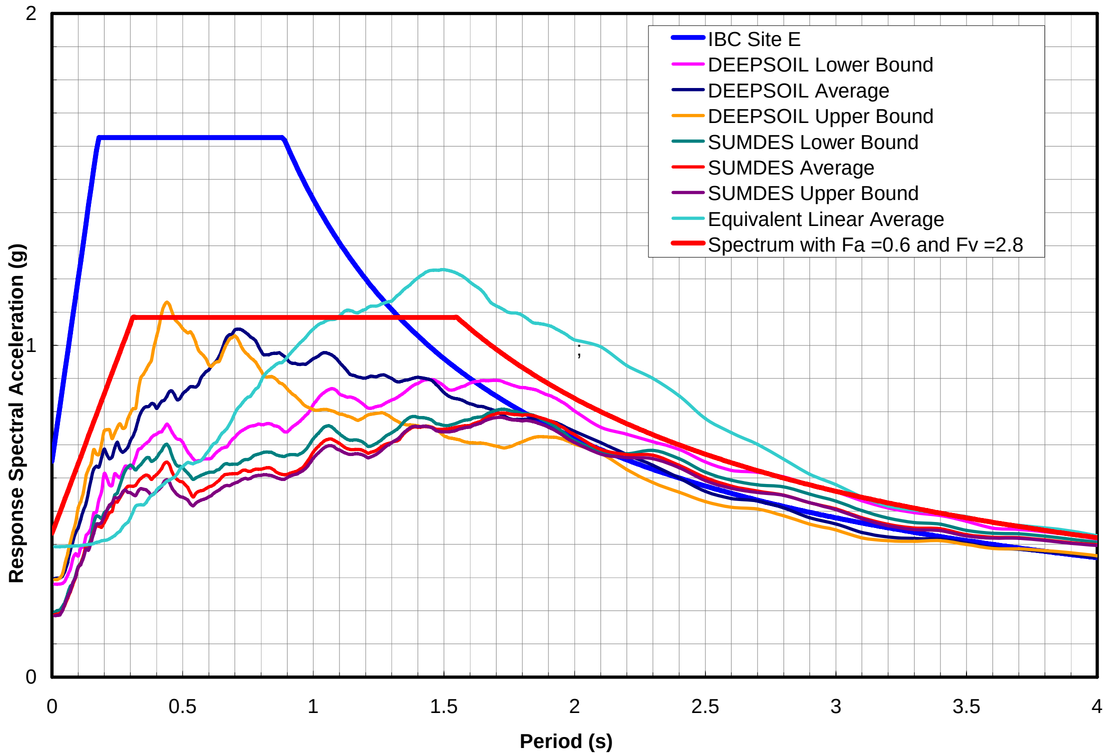


Fig. 13. Summary of Response Analyses

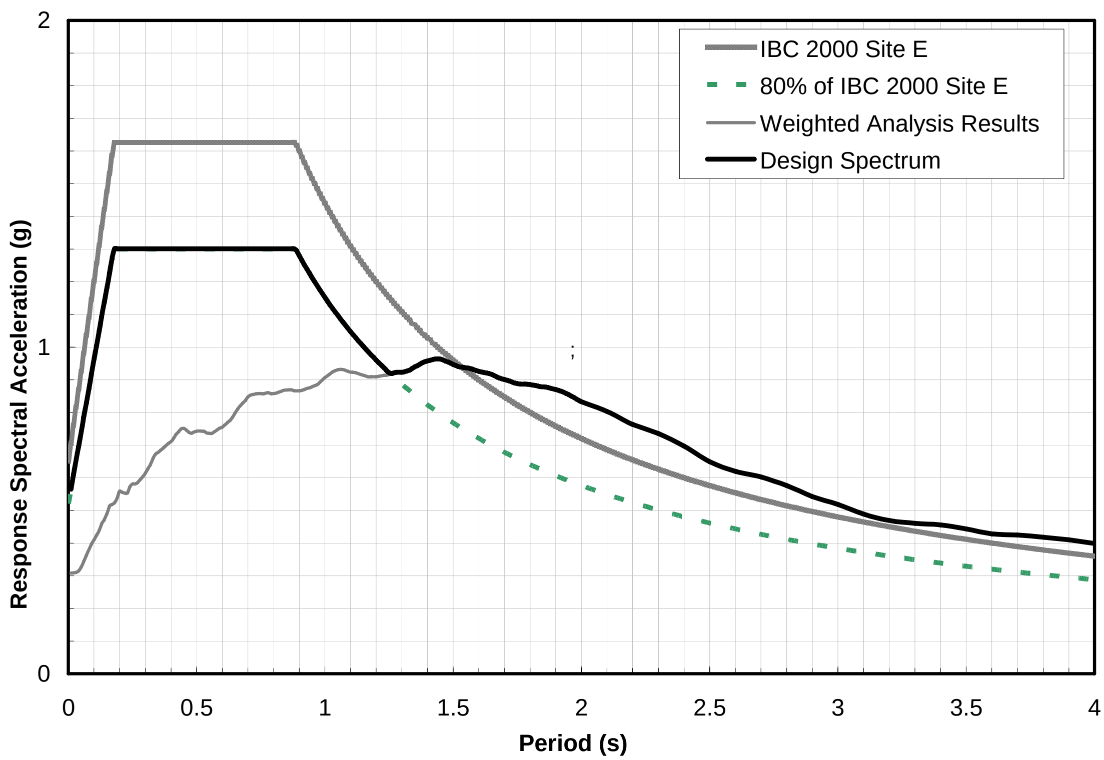


Fig. 14. Horizontal Design Spectrum at Ground Surface

from the nonlinear analysis appear to be more comparable in the long period range, since the response spectra generally follow the spectrum of Site Class E in this range. The upper 60 meters of soil show significant nonlinearity, with a maximum soil strain of up to 5 percent. The equivalent linear method may not capture the soil behavior under such a strain level. In addition, the constant stiffness and damping used in the equivalent linear analysis damped out the low period (less than 0.6 s) components, which could underestimate the response for structures in this period range. A comparison of the analysis between DEEPSOIL and SUMDES indicates that DEEPSOIL is more appropriate for the ME because of the more accurate response analysis at the shorter period.

The project's design spectrum was developed in accordance with ASCE-7-05 by enveloping the results of the site-specific analysis and a spectrum with ordinates of 80 percent of the spectrum for Site Class E. As indicated on Fig. 14, the ordinates of the site-specific spectrum are less than those of 0.8 times the Site Class E spectrum for periods of less than 1.3 seconds. Most structures on the project site have fundamental periods of less than 1.3 seconds, so significant benefits should be realized in terms of smaller structural components as a result of undertaking the site-specific study.

The site-specific site coefficients F_a and F_v were determined from the response analysis by enveloping the nonlinear analysis results. The proposed site coefficients are lower at the short period and higher at the long period than the ASCE-7-05 site coefficients. The deep soil sediments of the ME tend to filter out short-period components and amplify more long-period components when seismic waves propagate from rock to ground surface. The ASCE-7-05 site coefficients may not be appropriate for the ME because of the deep soil sediment.

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