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PROBABILISTIC SEISMIC HAZARD ANALYSIS WITH NONLINEAR SITE EFFECTS IN THE MISSISSIPPI EMBAYMENT

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SUMMARY

An integrated probabilistic seismic hazard analysis procedure that accounts for non-linear site effects, PSHA-NL, is developed. PSHA-NL procedure follows the methodology used in developing the 2002 USGS hazard maps and in addition generates a compatible set of ground motion records. The motions are propagated using site response analysis. Surface uniform hazard response spectra are computed from the propagated ground motions.
The test bed of this study is the Mississippi Embayment, which is a deep deposit located in the Central United States and extends as deep as 1 km. The developed procedure is applied to compute the surface uniform hazard response spectra and derive embayment specific site coefficients. The site coefficients are summarized in a format similar to NEHRP site coefficients, with an added dimension of the Mississippi Embayment deposits thickness to the Paleozoic rock. The proposed site coefficients compare well with the commonly used NEHRP site coefficients for 30 m profiles, the reference profile in NEHRP Provisions. However, for thicker soil profiles, the developed site coefficients are lower at short periods and higher at long periods than NEHRP site coefficients.

INTRODUCTION

Probabilistic seismic hazard analysis (PSHA), first developed by Cornell [1], accounts for the uncertainties in the size, location, rate of recurrence of earthquakes, and the variation of resulting ground motion characteristics in estimation of the seismic hazard. PSHA computes the mean annual rate of exceedance of a ground motion parameter at a particular site from the aggregate risk of potential earthquakes of many different magnitudes occurring at a range of source-site distances. The output of a PSHA is amplitudes of ground motion parameters at selected annual probabilities of exceedance, e.g. United States Geological Survey (USGS) hazard maps. USGS hazard maps depict geographic distribution of amplitudes of four ground motion parameters, which are peak ground acceleration (PGA) and spectral accelerations at 0.2, 0.3 and 1.0 sec periods at three probabilities of exceedance (2%, 5%, and 10% in 50 years) for the United States [2]. The ground motion amplitude is that which would be expected at a weak

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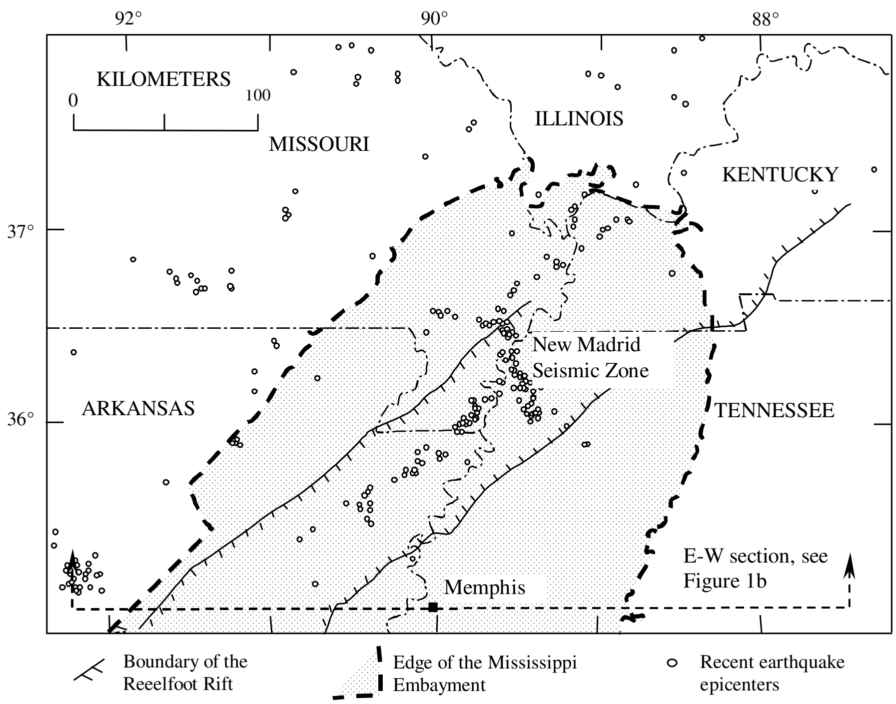
rock site, with near surface shear velocity of 760 m/sec (B/C boundary according to National Earthquake Hazard Reduction Program (NEHRP) Provisions).

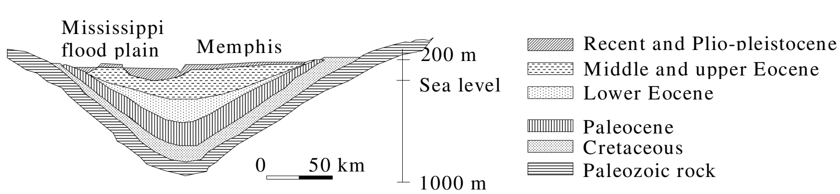
USGS ground motion parameters are used with the site coefficients proposed in 1997 edition of the NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures [3] to develop surface ground motion parameters. The site coefficients are multiplied to the mapped spectral acceleration at 0.2 sec, S_s, and at 1 second, S_1. The NEHRP site coefficients are related to site classes defined using the weighted average shear wave velocity of the top 30 m of the profile. The coefficients do not account for site effects of deeper profiles such as those encountered in the Mississippi Embayment (ME) which extend as deep as 1 km.

THE MISSISSIPPI EMBAYMENT AND NEW MADRID SEISMCI ZONE

The ME, which overlies the New Madrid Seismic Zone (NMSZ), Figure 1a, is a syncline or a trough-like depression is filled with sediments of clay, silt, sand, gravel, chalk and lignite ranging in age from Cretaceous to recent Holocene. There is no well-consolidated rock above the Paleozoic rock, except for



a. Plan view of the Mississippi Embayment and major structures within it. Circles denote the clustered pattern of earthquake epicenters that define the New Madrid Seismic Zone within the Reelfoot Rift margins.



b. E-W section through Memphis (after [4]). Note: Vertical dimension is highly exaggerated, and the embayment trough has a shallow slope of less than 1/150.

Figure 1 The Mississippi Embayment.

some local beds of ferruginous and calcareous sandstone and limestone [5]. The New Madrid Seismic Zone (NMSZ), shown in Figure 1a, is a clustered pattern of earthquake epicenters between 5 and 15 km deep and lies mostly within the Reelfoot rift. The NMSZ is regarded as the most seismically active zone in the eastern United States. The deep embayment deposits present unique challenges for estimating local site effects on propagated ground motion.

The ME profiles exhibit a high impedance contrast between the Palezoic bedrock (Vs = 3000 m/sec) and overlying unconsolidated deposit (Vs < 1000 m/sec) that are not considered in development of the NEHRP site coefficients. The B/C boundary (Vs=760 m/sec) occurs arbitrarily within the embayment deposits and does not reflect a geology boundary in the embayment.

PROPOSED PROCEDURE TO DEVELOP SITE COEFFICIENTS FOR THE MISSISSIPPI EMBAYMENT

This paper develops nonlinear site coefficients for the ME using an integrated probabilistic seismic hazard analysis procedure which accounts for non-linear site effects (PSHA-NL). The procedure for developing the site coefficients comprises the following three elements:

- *<u>I: Site selection</u>*: Several representative locations are selected within the ME to cover the range of spectral accelerations in the ME and NEHRP Provisions.
- *<u>II: Probabilistic seismic hazard analysis with non-linear site effects PSHA-NL:</u>* A new procedure that combines the probabilistic seismic hazard analysis with site response analysis is developed. The developed procedure provides a framework in which any geologic site effects can be directly accounted. The procedure is applied to the ME.
- *<u>III: Determination of site coefficients:</u>* Site coefficients consistent with the probabilistic approach are developed using the calculated UHRS.

Each of the components of the procedure is described in detail in the following sections, with additional details provided in Park and Hashash [21, 22].

SITE SELECTION

The upper ME is a deep basin ranging in thickness from very shallow (less than 30m) up to 1 km in depth. Seismic hazard varies, from less than 0.65g up to higher than 1.5g for 0.2 sec spectral accelerations for 2% in 50 years probability of exceedance. Ideally, analyses should be performed throughout the ME to cover the range of embayment depths and seismic hazards. The computational cost of the required series of analyses is presently prohibitive. Therefore, locations are selected to represent the range of spectral acceleration levels expected within the ME and covered in NEHRP Provisions [3].

Table 1 Selected locations for PSHA in the ME.

Site No	S_s (g)[1]	S_l (g)[1]	PGA (g)	Lat. (°)	Long. (°)	F_a[2]	F_v[2]
1	0.656	0.20	0.31	37.0	-87.5	1.28	2
2	0.75	0.22	0.34	35.5	-88.6	1.2	1.96
3	1.00	0.30	0.57	35.5	-89.2	1.1	1.8
4	1.25	0.34	0.66	36.0	-90.9	1.0	1.72
5	1.50	0.40	0.80	37.5	-89.5	1.0	1.6
6	1.84	0.50	1.0	36.8	-88.8	1.0	1.5

[1] From 2% in 50 years 2002 USGS hazard maps

[2] From 1997 NEHRP Provisions

Six locations are selected in the ME as summarized in and shown in Figure 2. The high seismic hazard levels of the ME do not allow representation of the full range of spectral accelerations of the NEHRP Provisions using 2% in 50 years hazard levels.

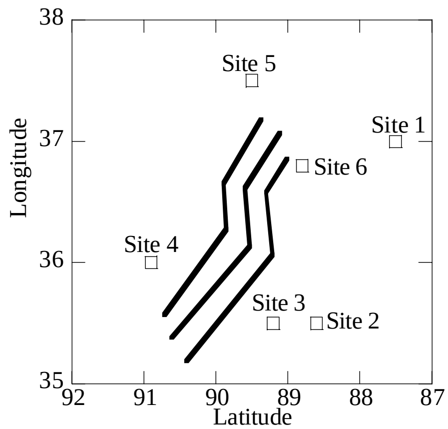


Figure 2 Selected locations in the Mississippi embayment for PSHA.

The selected locations are not intended to represent geologically specific sites and the sediment thickness at the selected sites is hypothetically varied from 30 m to 1000 m to represent the sediment thickness range encountered in the ME.

PROBABILISTIC SEISMIC HAZARD ANALYSIS WITH NONLINEAR SITE EFFECTS (PSHA–NL) AT THE MISSISSIPPI EMBAYMENT

A new PSHA procedure that integrates the site effects, PSHA-NL, is developed. The procedure is composed of three main steps, which are 1) source characterization, 2) ground motion time history generation, and 3) site response. Step 1 and 2, an extension of the work of Wen and Wu [6], approximates the USGS hazard maps. The main difference between USGS hazard maps is that actual seismic motion time histories are developed. Step 3 is performed to characterize the effect of the embayment deposits on ground motion propagation. The output of the procedure is a suite of surface ground motions and UHRS that are later used to develop the ME site coefficients. The procedure is described in detail in the following sections.

Step 1 Source characterization

First step of the proposed PSHA procedure is characterizing the seismic sources for future earthquakes. The USGS hazard maps define two types of sources, which are a) characteristic and b) gridded seismic sources. The characteristic sources represent sources at which the recurrence interval and magnitude can be estimated based on geologic evidence. The gridded seismic sources are intended to cover the historical seismicity and large background source zones. The background source zones are used to assign hazard in areas with little historical seismicity but with the potential to generate damaging earthquakes. The gridded seismic sources do not have fixed recurrence interval and magnitude. The seismicity of the gridded sources is described by the recurrence rate, which is a continuous function that relates annual rate of exceedance and magnitude. The seismicity is defined for every $0.1° \times 0.1°$ grid in the central and eastern U.S [2]. The characteristic and gridded sources are treated separately and added to the final seismic hazard.

The proposed procedure utilizes the seismicity information, for both characteristic and gridded seismic sources, from USGS hazard maps, but develops actual sources that occur within a finite number of simulation years (N). Wen and Wu [6] suggest that 90,000 simulation years are required to result in occurrence rates compatible with USGS hazard maps. Same number of simulation years is used in this study.

Characteristic earthquakes

The characteristic source that has the highest contribution to the seismic hazard in the ME is the NMSZ. USGS uses three fictitious NMSZ faults, as shown in Figure 2. The S-shaped faults do not represent actual faults, but rather intended to encompass the area of highest historic seismicity. A logic tree is used to assign characteristic earthquake moment magnitudes (M) ranging from 7.3 to 8.0, but the calculated hazard is equivalent to using a single M = 7.7 event.

In development of the USGS hazard maps, it is assumed that future characteristic earthquakes at NMSZ faults occur at closest distances from the site to each of the three faults. The main reason why the distance probability density function is not used, which results in equal probability of occurrence of epicenters along the faults, is because for every 500 years on average, the earthquake that occurs in NMSZ faults is not a single event but a sequence of events along the entire length of the fault [7]. The recurrence rate of the NMSZ faults is fixed at 1/500 years. The contributions of the faults are weighted such that the middle fault is assigned 0.5 weight (wt), whereas the upper and lower faults are assigned 0.25 wt.

The proposed procedure follows the USGS assumption whereby the characteristic earthquakes occur at points in the NMSZ fictitious faults that are at closest distances from the site. The number of characteristic earthquake event is equal to N (number of simulation years) × 1/500 years (recurrence rate) distributed between the middle and outer faults. The number of the characteristic earthquakes for the middle fault is N (simulation years) × 1/500 years × 0.5 (weight factor), whereas the number is N (simulation years) × 1/500 years × 0.25 (weight factor) for the adjacent faults.

Gridded seismic sources

The recurrence rate used to characterize the seismicity of the gridded seismic sources in the USGS hazard maps are used in the proposed simulations [6]. The occurrence in time during a ten-year period is calculated according to a Poisson process, using the USGS defined recurrence rate. The magnitude, given the occurrence of an earthquake, is then assigned according to the magnitude distribution for gridded seismic events proposed by USGS. The simulation is repeated for a total of 9000 10-year simulations to result in 90,000 simulation years. The numbers of generated sources during the 90,000 simulation years range from 9000 to 10,000.

Step 2 Ground motion time history generation

USGS hazard maps use attenuation relationships to estimate ground motion parameters from the characterized sources. The main difference between the proposed PSHA procedure and USGS hazard maps is that instead of using the attenuation relationships, actual ground motion time histories are developed from the sets of magnitude and source-to-site distance information from the source characterization process. The generation of actual ground motion time histories eliminates the need to use attenuation relationships, provided that the characteristics of the ground motion approximate the attenuation relationships. The 2002 USGS maps incorporate five attenuation relationships in estimation of the ground motion parameters which include single-corner and double-corner point source models, broadband model, and hybrid model using both empirical data and stochastic model [2]. Only the point source stochastic model is used in this study, due to the lower contributions and difficulties in incorporating the broadband and hybrid models in the simulation. Both single corner and double corner point source models are used, whereby single corner and double corner models are assigned the same weight, for both gridded seismic sources and characteristic sources. The stochastic model SMSIM (version 2.2) [8], which has been used in development of the point source model based attenuation relationships, are used to develop ground motion time histories using the USGS defined input parameters [2].

Comparison with USGS hazard maps

The attenuation relationships incorporated in the USGS hazard maps use the Fourier amplification function, to represent amplification at B/C boundary [9]. The ground motions generated (hard rock motions at Palezoic bedrock) are converted to B/C boundary motions to compare with USGS hazard maps. A maximum cap is imposed on the converted ground motions, as in the 2002 USGS hazard maps. Whereas USGS hazard maps impose different caps for PGA and 0.2 sec spectral acceleration, only the PGA is capped in the proposed simulation since the proposed simulation procedure uses ground motion time history. The ground motion can only be scaled to a single selected ground motion parameter.

The response spectra of the converted ground motions are compiled to develop the seismicity curves of the spectral accelerations. The uniform hazard response spectrum (UHRS) is developed from the seismicity curves [10] at a selected design probability of exceedance. 2% in 50 years UHRS are developed at the selected six sites. Additional UHRS are developed at site 1 to cover the range of spectral accelerations specified in NEHRP Provisions (S_s = 0.25g, S_s = 0.5g, and S_1 = 0.1g) that are lower than the 2% in 50 years UHRS of the selected sites. The 3.6%, 4.9%, and 7.7% in 50 years UHRS are developed that results in S_s = 0.25g/ S_1=0.057g, S_s = 0.40g/ S_1=0.10g , *and* S_s = 0.50g/ S_1=0.145g, respectively.

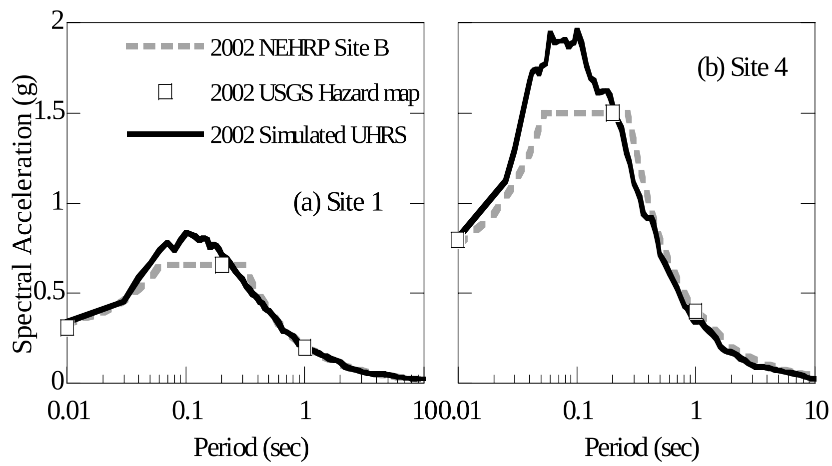


Figure 3 Comparison of 2% probability of exceedance in 50 years simulated UHRS at B/C boundary with 2002 USGS hazard maps at selected sties: a) Site 1 and b) Site 4.

Step 3 Site response analysis

The generated ground motions at hard rock are propagated to the ground surface to account for the effects of embayment deposits. Given the nearly horizontal layering of the deposits in the ME, one dimensional (1-D) nonlinear and equivalent site response analysis is used to estimate local site effects. The characteristic ground motions are propagated using nonlinear analysis as the PGA of the resulting ground motions at the selected sites range between 0.06g to 1.0g. The ground motions from gridded seismic sources are propagated using equivalent linear analysis as 99.6% to 98.6% of the ground motions have a PGA lower than 0.1 g. Both the nonlinear and equivalent linear analyses are performed using DEEPSOIL. The response spectra of the propagated surface motions are used to develop the UHRS.

1-D Site response analysis

The seismic wave propagation is simulated using 1-D site response analysis code DEEPSOIL. DEEPSOIL, which features both the nonlinear and equivalent linear analysis, has been developed to simulate ground motion propagation through very deep deposits [10, 11, 12, 13].

The nonlinear analysis features a) confining pressure dependent constitutive model, b) increased numerical accuracy, c) full Rayleigh and extended Rayleigh damping formulations to reduce the artificial damping introduced due to uncontrolled frequency dependence of viscous damping formulation. The constitutive model is based on modified hyperbolic model developed by Matasovic [14], with additional parameters to allow coupling between the confining pressure and shear stress. The equivalent linear approach implemented is similar to that in SHAKE [15] but a) the limitations on number of material properties and layers are removed and b) allows choosing both the frequency dependent and independent complex shear modulus, whereas SHAKE only allows frequency dependent complex shear modulus [10]. The frequency independent complex shear modulus is used in performing the equivalent linear analysis.

Shear wave velocity profiles

Generic profiles developed for the two geologic categories [16], Uplands and Lowlands, of the ME are shown in Figure 4 . The results of various in situ tests conducted to measure shear velocity profiles in the embayment were first compiled and synthesized to develop regional generic profiles for the embayment up to 70 m. The two profiles differ only up to 70 m, whereby Lowlands profile shows lower shear velocity compared to the Uplands profile due to loose Holocene-age deposits found in the alluvial plains. The profiles are extended to the maximum depth of the embayment, which is approximately 1000 m. Several profiles were developed for the deep Mississippi embayment profiles based on travel time, Mini-Sosie test, and boring logs [16]. They were compiled and a composite profile was obtained by calculating the arithmetic mean of the profiles. Both profiles are used in the simulation. The bedrock is assumed to have a shear wave velocity of 3000 m/sec [17, 18].

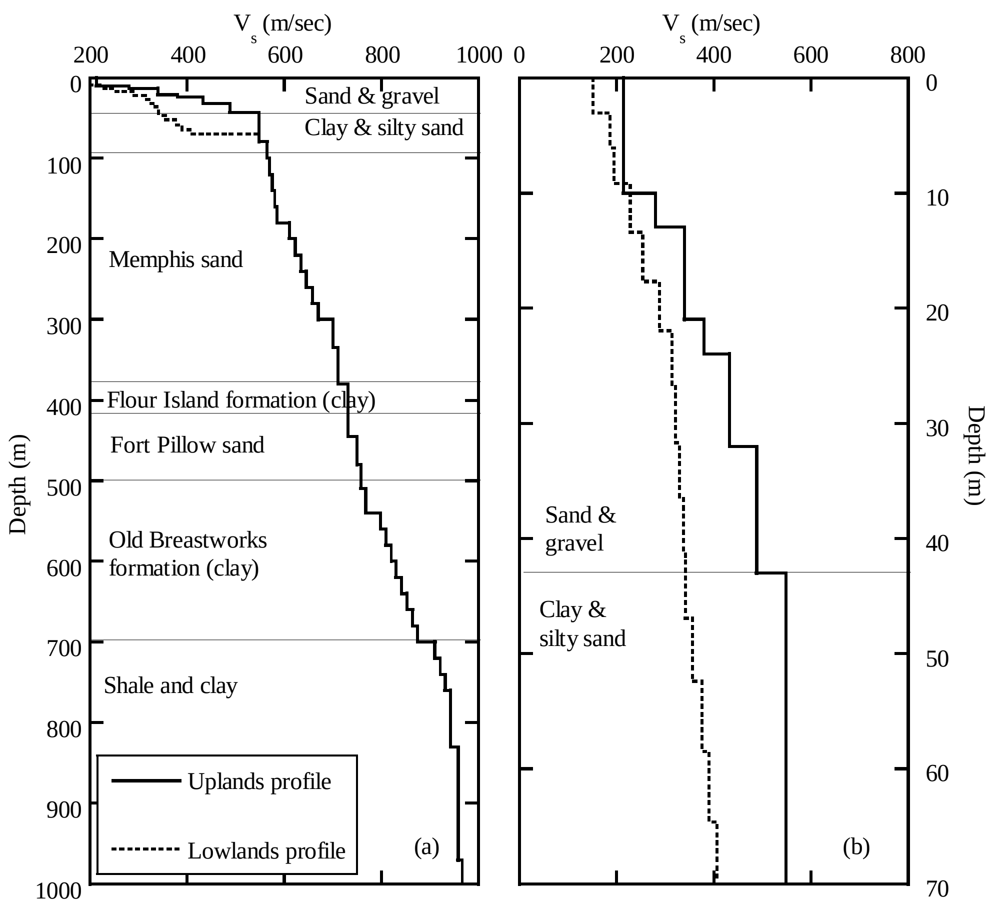


Figure 4 Simplified Mississippi embayment stratigraphy and generic shear wave velocity profiles (Uplands and Lowlands) a) up to 1000 m and b) up to 70m. The profiles are the same below the depth of 70m [19].

Dynamic properties of the ME

Two sets of dynamic soil properties are used in the study to account for the uncertainty in the material properties; a) the generic dynamic soil properties developed by EPRI [20] and b) the ME specific dynamic soil properties [21]. Both properties are shown in Figure 5. The ME specific dynamic properties are constrained through weak motions recorded during the Enola Earthquake, 2001 and laboratory test data of ME soils at low confining pressures [21]. The Enola Earthquake recordings are used to back-calculate the small strain damping properties. The back-calculated small strain damping is much higher than the generic damping profile by EPRI. Overall, the confining pressure dependency of the ME specific properties is higher than EPRI curves, the ME curves becoming stiffer than the EPRI curves with increase in confining pressure.

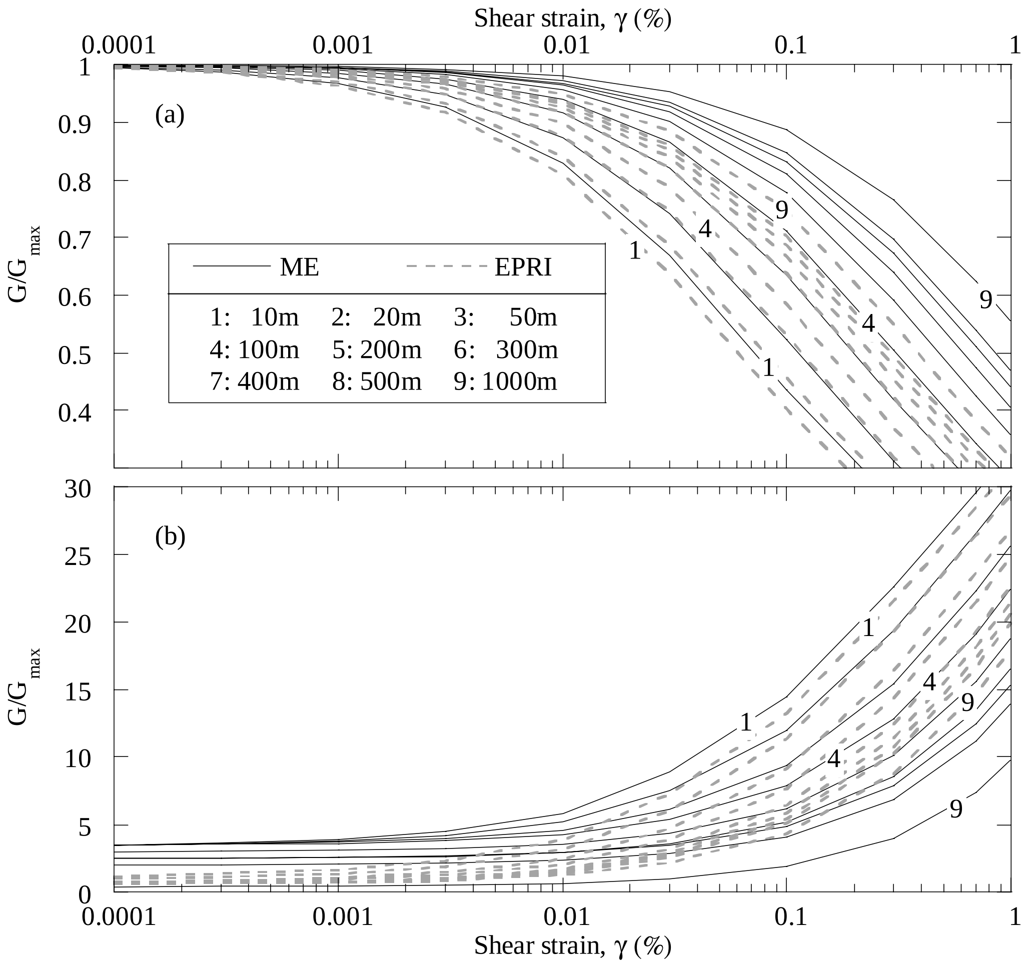


Figure 5 Comparison of the proposed Mississippi Embayment properties (solid lines and termed ME) with the modified hyperbolic curves to fit [20] curves (dashed lines and termed EPRI).

EVALUATION OF UHRS FOR SELECTED ANALYSIS

The response spectra of the propagated surface ground motions are compiled to develop the UHRS. Figure 6a shows UHRS for site 1 (S_s = 0.66g, S_1 = 0.2g), for depths from 30 m to 1000 m. The Uplands profile and ME properties are used to develop the UHRS. The 30 m UHRS compares well with the NEHRP design response spectrum (F_a =1.28, and F_v = 2). However, the UHRS continuously decreases with increasing deposit thickness at short periods (approximately up to 0.5 sec). The rate of reduction is quite pronounced up to a thickness of 300 m, but very subtle at higher thickness. This is due to low strain levels and viscous damping at higher thickness. The amplification at long periods, on the other hand, increases significantly. The amplification shifts to longer periods due to a shift to higher resonant periods with increase in column thickness. The UHRS plots demonstrate the need to incorporate soil profile thickness dependent design site coefficients. The short period site coefficient decreases, whereas the long period site coefficient increases with soil column thickness.

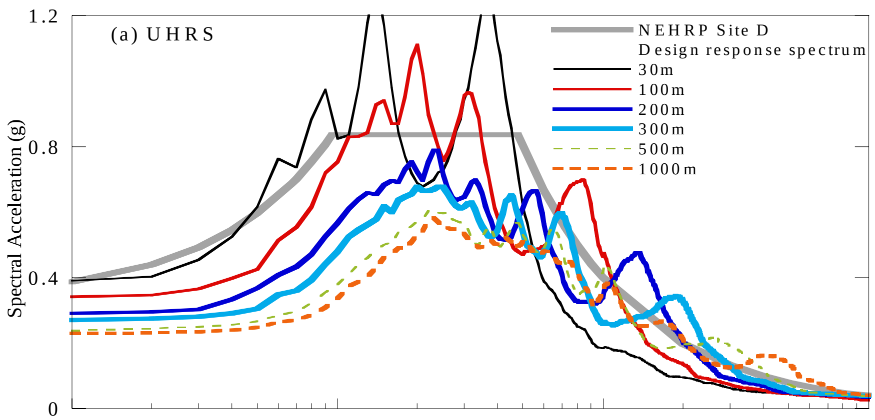


Figure 6 UHRS at Site 1 using Uplands profile / ME properties and six profiles ranging in thickness from 30 m to 1000 m. NEHRP Site D Design response spectrum is shown in thick gray line in plot.

Influence of material properties and soil profile

Figure 7 compare UHRS of site 1 using all combinations of shear wave velocity profiles (Uplands and Lowlands profiles) and material properties (ME and EPRI properties). Lowlands profile results in lower short period amplification than Uplands and slight shifting to higher periods due to the lower shear wave velocity at the upper 70 m of the profile.

The effect of the material properties is much more pronounced compared to the effect of the shear wave velocity profile. EPRI properties have much lower small strain damping compared to the ME properties. Therefore, the UHRS and corresponding F_a is larger at short period when using EPRI properties than when using ME properties. The thickness dependency is also less due to overall lower small strain damping ratio when using the EPRI properties. The long period amplification is very similar when using EPRI or ME properties except for 1000 m profile, where the lower confining pressure dependency of EPRI properties results in softer behavior of the soil column and the long period amplification is much larger than when using ME properties.

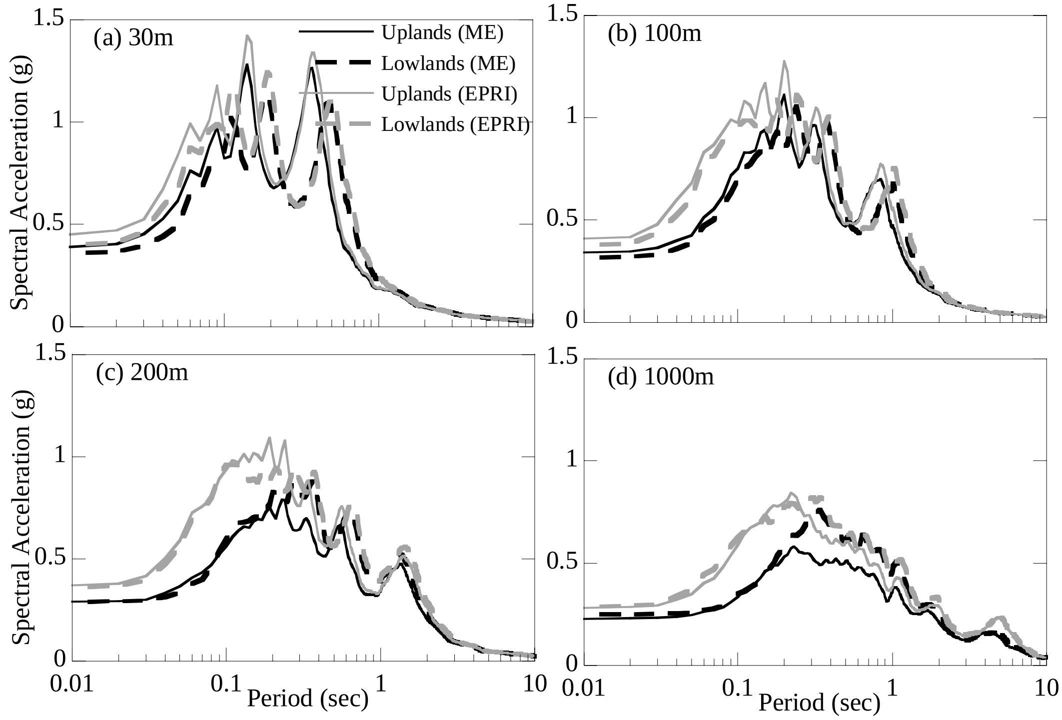


Figure 7 Comparison of UHRS (2% in 50 years) for Site 1 using various combinations of Uplands and Lowlands profiles and ME and EPRI soil properties.

COMPUTED UHRS BASED SITE COEFFICIENTS

Soil profile thickness dependent site coefficients for the ME are developed based on the UHRS. The site coefficients are chosen such that a reasonable envelope of the UHRS is obtained. Design spectra using the proposed site coefficients and the computed UHRS for site 1 are shown in Figure 8.

This procedure is used to develop the site coefficients for all analyses, using Uplands/Lowlands profiles, and using both the ME/EPRI properties. Proposed site coefficients using Uplands and ME properties are shown in Figure 9. The proposed coefficients are summarized in a similar format to NEHRP Provisions, with the addition of dependency on the embayment thickness. Decrease in F_a for 1000 m profile is approximately 30%, but F_v increases by approximately 20%. The probabilistically derived site coefficients clearly demonstrate the importance of sediment thickness dependency on site coefficients. More details on the proposed site coefficients are discussed in Park and Hashash [22], in which the upper and lower bound are developed for both Uplands and Lowlands of the ME.

The proposed site coefficients are for the Mississippi Embayment and Site D only. However, the PSHA-NL methodology is general and can be applied to any sites in the US, provided that the site dynamic properties are available. It should be recognized that the proposed design spectra do not envelope the peaks of the UHRS. Therefore, site-specific analysis is recommended in design of critical structures to avoid the resonant periods at which the hazard is the highest. Site-specific analysis is also warranted in design of long period longitudinal structures in deep embayment deposits, since the design spectrum will underestimate very long period amplification.

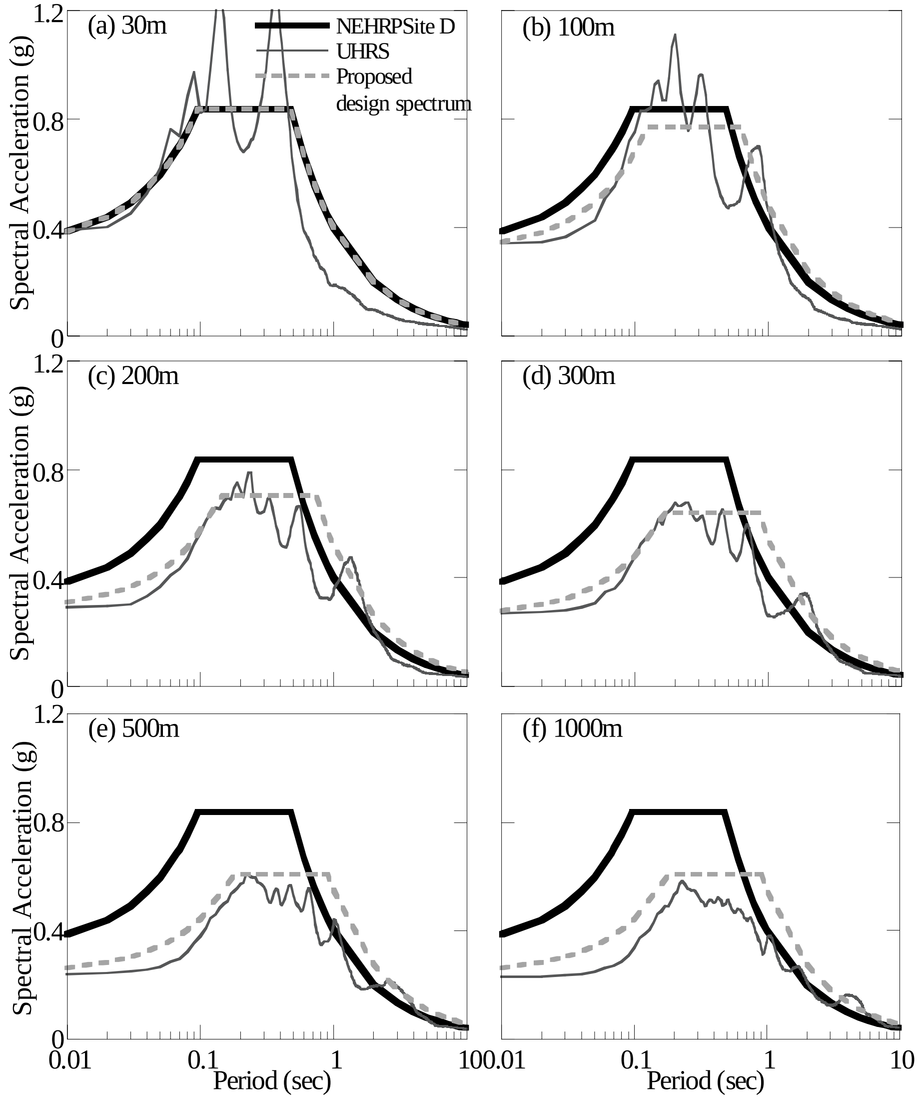


Figure 8 UHRS (2% in 50 years) and design spectra with soil profile thickness dependent site coefficients for Site 1 using Uplands profile and ME dynamic properties.

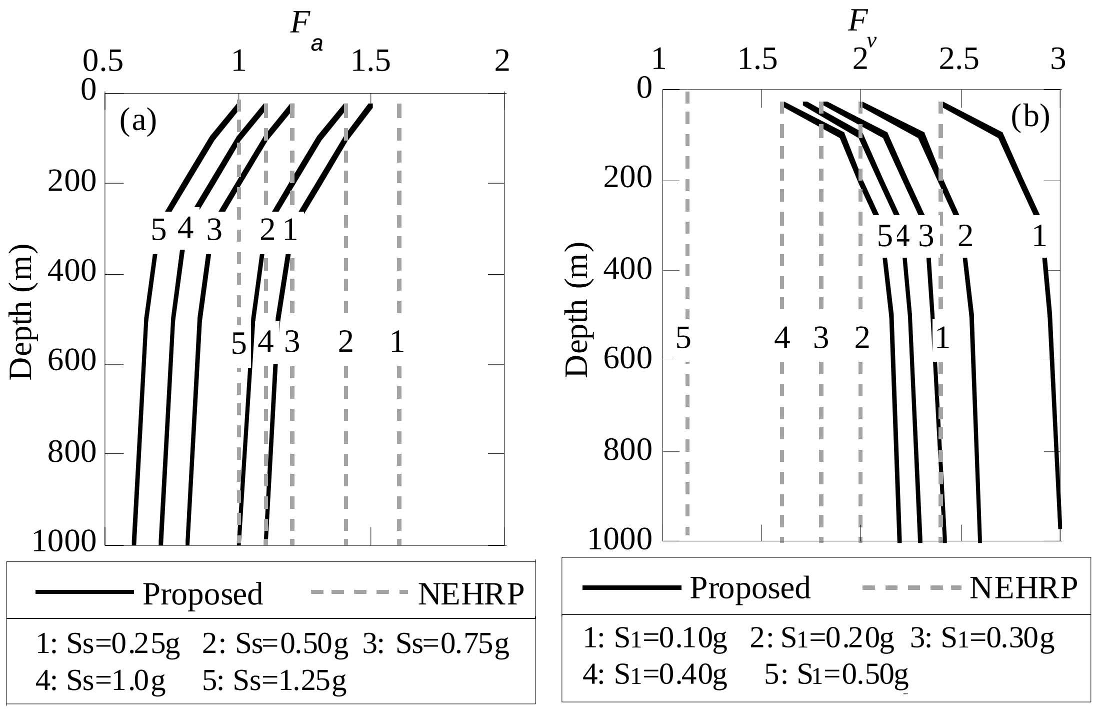


Figure 9 Recommended site coefficients for Uplands using ME properties: (a) F_a and (b) F_v.

SUMMARY AND CONCLUSIONS

A new methodology for determining probabilistic site coefficients is developed and applied to the Mississippi Embayment. Initially, PSHA is performed to reproduce the USGS hazard maps, but at the same time generates a compatible set of ground motion time histories. The generated motions are propagated through generic profiles of the Mississippi Embayment, taking into account non-linear site effects of individual motions. Two generic shear velocity profiles (Uplands and Lowlands) and two sets of dynamic properties (ME specific properties and generic EPRI properties) are used to account for the uncertainty in the soil properties. Surface UHRS are computed and used to develop site coefficients. The coefficients show a strong dependence on Mississippi Embayment deposit thickness to the Paleozoic rock, a physically meaningful impedance boundary. The proposed site coefficients are presented in NEHRP style with the added dimension of embayment thickness. Results indicate that proposed coefficient for embayment thickness of 30m compare well with NEHRP site coefficients. However, for deep soil profiles of the ME, the proposed site coefficients are lower at short periods and higher at long periods than the 1997 NEHRP site coefficients.

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