Transactions, **SMiRT-22**
San Francisco, California, USA - August 18-23, 2013
Division IV (Characterization of Loads)

Probabilistic Seismic Hazard Analysis Considering Nonlinear Soil Effects and Variability of Soil Parameters

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ABSTRACT

This paper presents a probabilistic framework to accurately estimate ground motions at the soil surface. In this framework, the variability of soil parameters, the nonlinear property of soils, and the vector-valued seismic site responses analysis comprehensively integrate into Probabilistic Seismic Hazard Analysis (PSHA) for soil sites. Local soil conditions greatly affect ground motions propagating from bedrock to soil surface; the evaluation of ground motions at the soil surface needs to consider effects of the local soil conditions. Ground Motion Prediction Equations (GMPEs) using the generic soil to characterize local soil conditions are possible to estimate ground motions at the soil surface, but the estimation is not acceptable for critical structures because of lacking accuracy. Site amplification is used to modify the bedrock GMPEs to make them suitable for soil site. Based on the modified GMPEs, PSHA for soil sites are performed accurately and a method to construct acceptable soil UHS are proposed. Finally, this paper constructs the soil UHS for an example soil site by GMPEs and by the modified GMPEs, respectively, compares the soil UHS by the different methods, studies influences of variability of soil parameters and nonlinear property of soils on spectral shapes and spectral amplitudes of UHS.

INTRODUCTION

Hazard curves calculated from Probabilistic Seismic Hazard Analysis (PSHA) for general surficial rock condition–with shear wave velocity of the rock material greater than 750 m/sec according to U.S. Geological Survey classification criteria–should be consistent with the definition of rock for the Ground Motion Prediction Equations (GMPEs) used in the PSHA. Because the surficial shear wave velocities of Nuclear Power Plant (NPP) sites are generally less than the shear wave velocity threshold, the effects of local soil conditions on PSHA need to be considered.

In the design of NPPs, Safe Shutdown Earthquakes (SSEs) are used and represented by Design Response Spectra (DRS), such as Uniform Hazard Spectra (UHS), derived from PSHA. When incident bedrock motions propagate from bedrock to soil surface, the soil deposit changes characteristics of ground motions; the extent of this change largely depends on features of the incident bedrock motions and characteristics of the local soil deposit. Thus, differences between Uniform Hazard Spectra at soil sites (soil UHS) and Uniform Hazard Spectra at rock sites (rock UHS) are caused and governed by this change.

Some empirical GMPEs (Abrahamson 1997; Campbell 2003; Boore 2008) could to be used to construct the soil UHS in the same way as constructing the rock UHS. However, they use generic soils to characterize various practical soil sites. Thus, empirical GMPEs are constrained by the ground motion data that they used to develop their attenuation relationships, and it is only appropriate to use the attenuation relationships to probabilistically estimate ground motions at the soil surface above a similar soil deposit with consideration of the effects of differences between the practical site-specific profile and the generic profile used in the estimation (ANS 2008). This requirement actually greatly restricts the usage of empirical GMPEs to construct the soil UHS.

To overcome this problem, McGuire *et al.* (2001) have suggested that site amplification be used to modify the bedrock GMPEs into site-specific attenuation relations prior to perform PSHA for soil sites.

Based on this idea, several methods have been proposed to perform PSHA for soil sites. Tsai (2000) proposed a method to calculate Peak Ground Acceleration (PGA) at the soil surface. Cramer (2003) proposed an equation to calculate the soil-hazard curve following the suggestions of McGuire. Based on seismic site response analysis with the consideration of nonlinear site effects, Bazzurro (2004a, 2004b) obtained site amplification distribution by regression analysis, and proposed equations to perform PHSA for soil sites.

Three issues should be considered in PSHA for soil sites: the variability of soil parameters, the nonlinear property of soils, and the vector-valued site response analysis method. However, past research concerning PSHA for soil sites did not completely combine these three issues. The method proposed by Cramer (2003) considered the variability of soil parameters, but did not use vector-valued site response analysis method. Tsai (2000) and Bazzurro (2004b) focused on the nonlinear property of soils in PSHA for soil sites, not considering the variability of soil parameters and the vector-valued site response analysis method.

In this paper, the variability of soil parameters, the nonlinear properties of soils, and the vector-valued seismic site response analysis method are comprehensively considered in PSHA for soil sites. Using site amplification regression model, the bedrock GMPEs are modified. The frameworks for PSHA for soil sites are presented, and a method to construct the soil UHS is proposed. Using the proposed methods in this paper, PSHA for an example site is performed, and acceptable soil UHS for the example site are also constructed.

LACAL SITE CONDITIONS

In many earthquakes, local geology and soil conditions profoundly influenced the important characteristics−amplitude, frequency content, and duration−of strong ground motions (Beresnev 1996). Extent of their influence depends on geometries and properties of the subsurface materials, topographies of the sites, and characteristics of the incident bedrock motions. Shear wave velocity, normalized shear modulus, and damping ratio are three most important parameters of subsurface materials affecting seismic site responses.

Uncertainties in geotechnical properties of soils are very common. Past research (Lumb 1996) showed that variability of soil parameters can be modeled by either normal distribution or lognormal distribution. Examples of randomized normalized shear modulus with average coefficients of variation 0.12 and randomized shear wave velocity with average coefficients of variation 0.3 are shown in Figures 1 and 2.

SEISMIC SITE RESPONSE ANALYSIS

The computer program DEEPSOIL is used to perform seismic site response analysis, which uses *Modified Konder and Zelasko* (MKZ) model to characterize the nonlinear behavior of soils under dynamic loads. To perform site response analysis, 65 seismograms from 23 different earthquakes occurring between 1971 and 2002 are selected from Pacific Earthquake Engineering Research (PEER) Center strong ground motion database.

Due to uncertainties in incident bedrock motions, using only one incident bedrock motion intensity measure to predict seismic responses of soil sites cannot give satisfactory results. Therefore, this paper proposes multiple incident bedrock motion intensity measures to predict seismic responses of soil sites. Since multiple incident bedrock motion intensity measures are used, this analysis method is called vector-valued site response analysis.

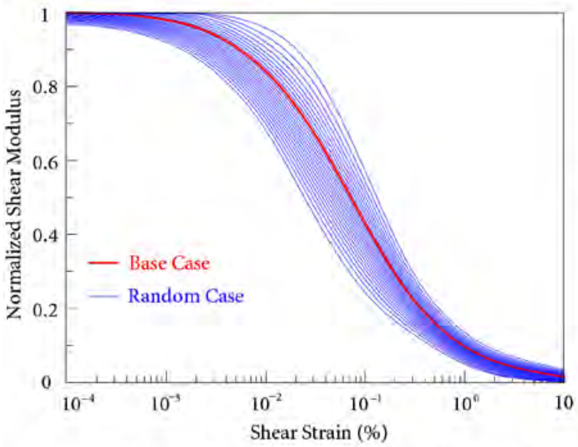


Figure 1. Randomized normalized shear modulus of one soil layer

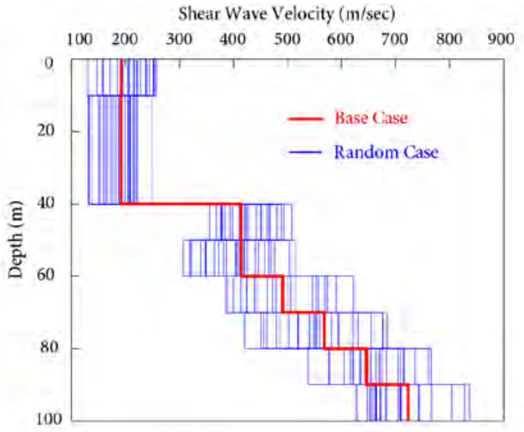


Figure 2. Randomized shear wave velocity of one soil site

At a specific soil site, if G_k is taken as a response measure of the soil site corresponding to a vibration period T_k, its probability is given by

$$p(g_k) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty} p(g_k|i_{m1}, i_{m2}, \dots, i_{mn}) f_{I_{m1}I_{m2}\dots I_{mn}}(i_{m1}, i_{m2}, \dots, i_{mn}) di_{m1} di_{m2} \dots di_{mn} \quad (1)$$

where $I_{m1}, I_{m2}, \dots, I_{mn}$ are incident bedrock motion intensity measures, and $f_{I_{m1}I_{m2}\dots I_{mn}}(i_{m1}, i_{m2}, \dots, i_{mn})$ is the joint probability density function.

SITE AMPLIFICATION

Site amplification is defined as the ratio of spectral acceleration of a ground motion at a soil surface to spectral acceleration of the ground motion at a bedrock underneath the soil surface. Site amplification plays a crucial role in the prediction of ground motions at the soil surface; local site effects on seismic site responses are evaluated by site amplification. Reference (Regnier *et al* 2008) showed that site amplification of a soil site is affected by many factors: the incident bedrock motion, the shear wave velocity, the soil normalized shear modulus, the damping ratio, and the thickness of soil layers. Reference (Rogers *et al* 2007) also showed that the greatest influence comes from the amplitudes and frequency contents of the incident bedrock motions.

GMPEs are valid to describe the attenuation relation of ground motions propagating from seismic sources to bedrock, but they are invalid to describe the attenuation relation of ground motions propagating from seismic sources to bedrock and then to soil surface, because the generic soil instead of site-specific soil is used in GMPEs to characterize the soil deposit sitting on bedrock. Using site amplification distribution to modify bedrock GMPEs, the modified GMPEs provide new attenuation relations valid for soil sites with modified uncertainties.

REGRESSION ANALYSIS

The construction of a regression model involves selection of predictor variables and selection of a functional form for the regression relation. In reality, numerous factors affect the response variable. A major consideration in selecting predictor variables is the extent to which a chosen variable contributes to reducing the remaining variation of the response variable after allowance is made for the contributions of other predictor variables that have tentatively been included in the regression model. The selection of a functional form for regression relation is tied to the selection of predictor variables. Linear or quadratic regression functions are often used as satisfactory first approximations to regression functions of unknown nature (Neter *et al* 1996).

Because site amplification is period-dependent, the regression analysis is done period-by-period to predict the mean site amplification and corresponding variance at individual periods. Past research (Abrahamson 1997; Bazzurro 2004a; Cramer 2003) showed that the period-dependent site amplification $A(T)$ depends on intensity measures of incident bedrock motions. Abrahamson *et al.* (1997) proposed an equation for median site amplification by regression analysis based on earthquake records,

$$\ln A(T) = a_{10} + a_{11}\ln(PGA_{\text{rock}} + c_5) \tag{2}$$

where PGA_{rock} is peak ground acceleration of incident bedrock motions at bedrock, a_{10}, a_{11} and c_5 are regression coefficients.

PSHA FOR SOIL SITES

Using the modified GMPEs, PSHA for soil sites yields accurate results. Consider a specific soil site in a region where there are N_S potential seismic sources, and take $S_a(T_k)$ as the intensity measure of ground motions at the soil surface. For a given spectral acceleration value x_k at bedrock corresponding to period T_k, if A_k represents its site amplification, the probability $p\{S_a(T_k) \geq s_k\}$ is equivalent to the probability $p\{A_k \geq \frac{s_k}{x_k}\}$. Thus, the annual probability of $S_a(T_k)$ exceeding a specified target value of s_k is

$$\lambda_{s_k} = p\{S_a(T_k) \geq s_k\} = \int_0^\infty \int_0^\infty \int_0^\infty p\{A_k \geq s_k/x_k | x_k,\text{pga},z_2\} \left\{\sum_{i=1}^{N_S} \nu_i \int_0^\infty \int_0^\infty f_{X_k,\text{PGA},Z_2}(x_k,\text{pga},z_2|m,r) f_{M,R}(m,r)\,\text{d}m\text{d}r\right\}_i \text{d}x_k\text{d}(\text{pga})\text{d}z_2 \tag{3}$$

where PGA is the peak ground acceleration of incident bedrock motions, Z_2 is another intensity measure of incident bedrock motion (such as spectral acceleration averaged over the second resonant vibration period range of the soil deposit), M is earthquake magnitude, R is source-to-site distance, ν_i is the mean annual rate of exceedance for seismic source i.

The function $f_{M,R}(m,r)$ represents the joint probability density function of M and R, $f_{X_k,\text{PGA},Z_2}(x_k,\text{pga},z_2|m,r)$ is the multivariate lognormal probability density function of x_k, pga and z_2 conditional on m and r. Given a pair of m and r, a vector of the natural logarithm of spectral accelerations at multiple periods have been empirically tested follow multivariate normal distribution (Jayaram and Baker 2008).

PSHA OF EXAMAPLE SOIL SITE

For a soil site at Charleston, South Carolina, 1950 random cases are generated by combining 30 random site profiles and 65 ground motions (65×30 = 1950). Computer program DEEPSOIL is used to simulate seismic site responses. Based on the simulation results, site amplification spectra are calculated, as shown in Figure 3. It can be seen that there are two resonant period ranges, 0.6 sec to 0.8 sec and 0.2 sec to 0.4 sec, corresponding to the first resonant vibration period range and the second resonant vibration period range of the soil columns, respectively.

Based on the site amplifications calculated from the simulation results, site amplification regression analysis is performed. Four potential predictor variables are determined for the regression analysis: peak ground acceleration of incident bedrock motions, denoted by PGA, spectral acceleration of incident bedrock motions at the target vibration period, denoted by X, spectral acceleration of incident bedrock motions averaged over the first resonant vibration period range (0.6-0.8 sec), denoted by Z_1, and spectral acceleration of incident bedrock motions averaged over the second resonant vibration period range (0.2-0.4 sec), denoted by Z_2. The *all-possible regression* (Neter *et al* 1996) method is used to select the appropriate set of predictor variables, and coefficient of determination R_p^2 of different sets of predictor variables are used as the selection criteria, as shown in Figure 4.

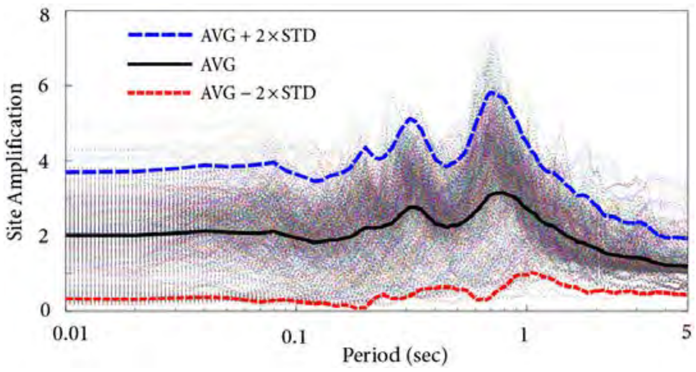
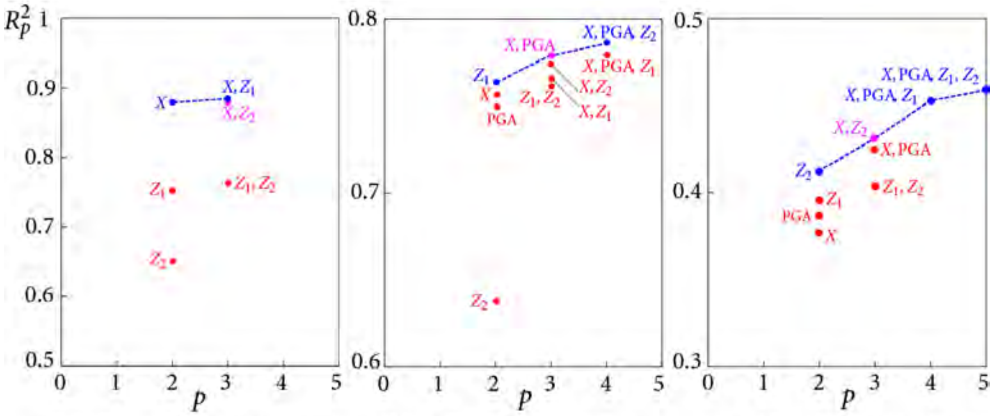


Figure 3. Site amplification for the soil site under 1950 random cases



(a) all-possible-regression for 0.01 sec

(b) all-possible-regression for 0.2 sec

(c) all-possible-regression for 1.0 sec

Figure 4. R_p^2 plots for all-possible-regression of site amplifications at selected periods

Considering the total number of predictor variables used and values of R_p^2 of different sets of predictor variables, the set of X and Z_2 is selected for periods 0.02 sec, 0.05 sec, 0.1 sec, 1.0 sec, 1.5 sec, and 5.0 sec, and the set of X and PGA is selected for periods 0.2 sec, 0.3 sec, 0.4 sec, 0.5 sec, 0.6 sec, 0.7 sec, and 0.8 sec. Based on the functional form proposed by Abrahamson *et al.* (1997) and Bazzurro (2004b), a more accurate regression model is proposed

$$\ln A = c_0 + c_1 \ln X + c_2 \ln \mathrm{PGA} + c_3 \ln Z_2 + c_4 (\ln X)^2 + c_5 (\ln \mathrm{PGA})^2 + c_6 (\ln Z_2)^2 + \sigma_{\ln A} \qquad (4)$$

where $c_0, c_1, \dots, c_6$ are regression coefficients, whose values are shown in Table 1, and $\sigma_{\ln A}$ is the natural logarithmic standard deviation of site amplification.

Using the proposed methods in this paper, PSHA for the example site is performed. First, bedrock GMPEs proposed by Boore and Atkinson (2008)–characterizing ground motions propagating from seismic sources to the bedrock underneath the soil deposit–are modified by the site amplification regression model. Then, using the modified GMPEs, PSHA for the example site are performed accurately. Two different numerical characterizations of the example site are used: *base case*, using deterministic values of soil parameters (best engineering estimates), and *random case*, using uncertain soil parameters.

Table 1: Regression coefficients and standard deviation

T (sec)	c_0	c_1	c_2	c_3	c_4	c_5	c_6	$\sigma_{\ln A}$
0.01	−1.0281	−1.1678	0.0	0.1844	−0.1199	0.0	0.0	0.2098
0.02	−0.8877	−1.0044	0.0	0.0794	−0.0874	0.0	−0.0330	0.2123
0.05	−0.4671	−0.6859	0.0	−0.1584	−0.0490	0.0	−0.0843	0.2230
0.1	−0.3097	−0.6519	0.0	−0.1789	−0.0524	0.0	−0.0851	0.2483
0.2	−0.5493	−0.4789	−0.4929	0.0	−0.0701	−0.0610	0.0	0.3232
0.3	−0.2650	−0.5950	−0.3880	0.0	−0.0916	−0.0581	0.0	0.3121
0.4	−0.2305	−0.5373	−0.3934	0.0	−0.0705	−0.0880	0.0	0.2972
0.5	−0.2238	−0.6386	−0.2160	0.0	−0.1006	−0.0432	0.0	0.3054
0.6	−0.3324	−0.6579	−0.2832	0.0	−0.0963	−0.0429	0.0	0.3469
0.7	−0.2455	−0.5928	−0.3416	0.0	−0.0814	−0.0496	0.0	0.3518
0.8	−0.2802	−0.7701	−0.2064	0.0	−0.1218	−0.0196	0.0	0.3232
1.0	0.1947	−0.3488	0.0	−0.3500	−0.0587	0.0	−0.0704	0.3073
1.5	0.3184	−0.1341	0.0	−0.0259	0.0	0.0	0.0	0.3366
5.0	0.5042	0.1974	0.0	0.2068	0.0390	0.0	0.0	0.2091

From these figures, we conclude that the soil-hazard curve is much higher than the rock hazard curve in medium ranges of spectral accelerations, but slightly higher or lower in high ranges of spectral accelerations. Under low to medium incident bedrock motion intensities, seismic responses of a soil deposit increase with increment of the incident bedrock motion intensities; ground motions at the soil surface are amplified, resulting in that the soil-hazard curve is much higher than the rock-hazard curve. However, under high incident bedrock motion intensities, soils exhibit nonlinear properties and yield large shear strains. The large shear strains increase soil damping ratio and reduces the intensity of ground vibrations, resulting in that the soil-hazard curve is slightly higher or lower than the rock-hazard curve.

Uniform Hazard Spectra on the Soil Surface

Using the seismic hazard curves at 14 controlling periods, i.e., 0.01 sec, 0.02 sec, 0.05 sec, 0.1 sec, 0.2 sec, 0.3 sec, 0.4 sec, 0.5 sec, 0.6 sec, 0.7 sec, 0.8 sec, 1.0 sec, 1.5 sec, and 5.0 sec, the soil UHS are constructed, as shown in Figure 7. Comparing the soil UHS and the rock UHS, it can be seen that their spectral shapes and spectral amplitudes are different.

From Figure 7, it can be seen that the soil UHS by the modified GMPEs (base case) are different from the soil UHS by GMPEs (base case). Because GMPEs for soil sites use the generic soil instead of the site-specific soils, the soil UHS by GMPEs are treated with less rigor. The modified GMPEs take account of the site-specific soils in detail; therefore, the soil UHS by the modified GMPEs are highly suitable for practical application, particularly for critical structures.

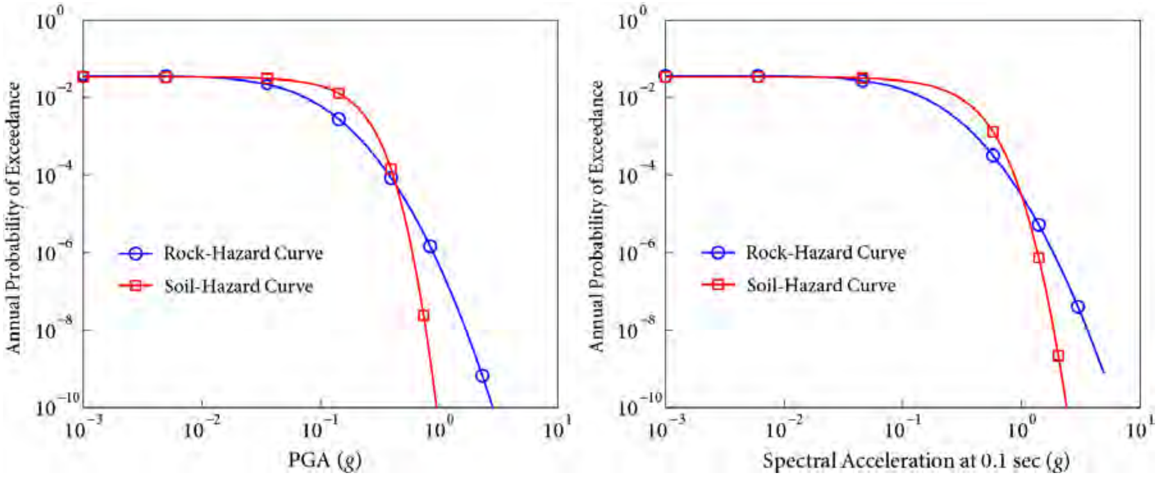


Figure 5. Seismic hazard curves for PGA and 0.1 sec

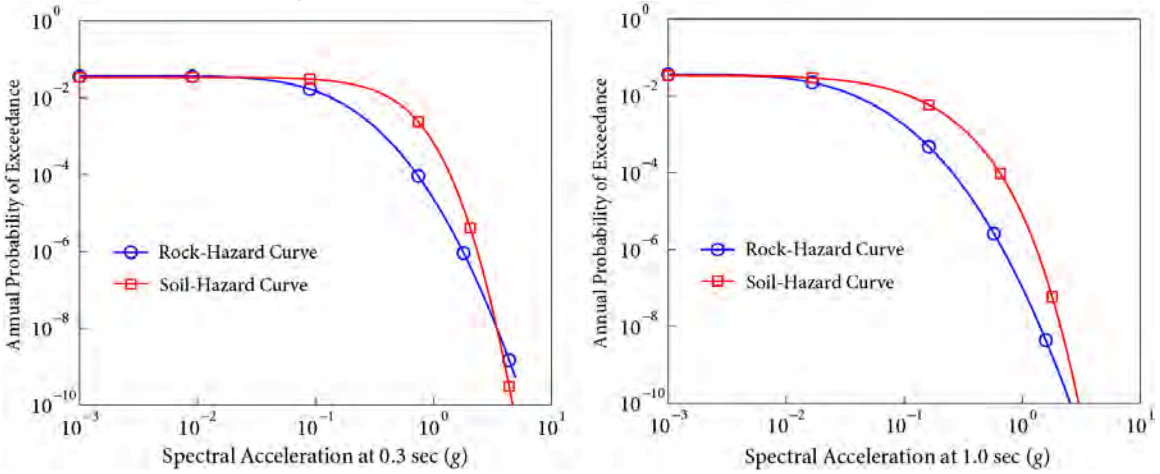


Figure 6. Seismic hazard curves for 0.3 sec and 1.0 sec

Comparing the soil UHS by the modified GMPEs under the random case and the base case, we further conclude that the variability of soil parameters affects both spectral shapes and spectral amplitudes of the soil UHS; this is because the variability of soil parameters remarkably affects resonant periods of soil deposits. Under low incident bedrock motion intensities, soils usually exhibit linear response and the uncertainty in resonant periods of a soil deposit is mainly caused by the uncertainty of shear wave velocity. Thus, the uncertainty of shear wave velocity dominates contributions of the uncertainty of soil parameters to the variability of site amplification under low incident bedrock motion intensities. Under medium to high incident bedrock motion intensities, soils usually exhibit nonlinear responses and stiffness degradation, represented by normalized shear modulus reduction curves, and resonant periods of a soil deposit shift. Thus, the uncertainty of normalized shear modulus dominates contributions of the uncertainty of soil parameters to the variability of site amplification under medium to high incident bedrock motion intensities. As site amplifications at different controlling periods determine the spectral shapes and spectral amplitudes of the soil UHS, the variability of soil parameters should be considered in the construction of the soil UHS.

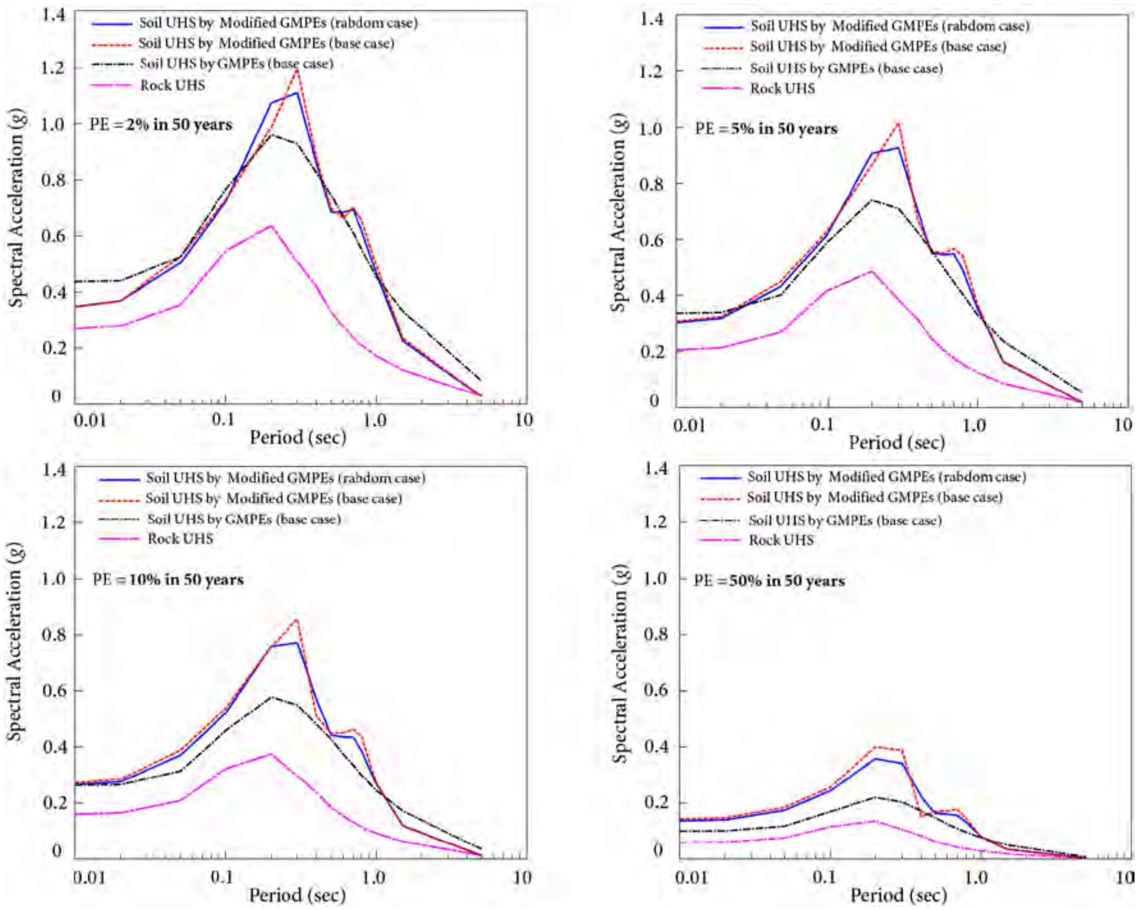


Figure 7. Uniform Hazard Spectra

In addition to the variability of soil parameters, the nonlinear property of soils also affects spectral amplitudes of the soil UHS. Under medium to high incident bedrock motion intensities, as soils exhibit stiffness degradation, large soil shear strain is caused. This large shear strain further increases soil damping ratio, which at last reduces the intensity of ground vibrations. Thus, the spectral amplitudes of the soil UHS are lower than those without considering the nonlinear property of soils.

CONCLUSION

This paper presents methods to perform PSHA for soil sites. Using the proposed methods, the soil UHS at the example site are constructed. Based on the research work, we conclude that the variability of soil parameters and the nonlinear property of soils affect results of PSHA for soil sites. The variability of soil parameters and the nonlinear property of soils affect spectral amplitudes and spectral shapes of the soil UHS; therefore, the variability of soil parameters and the nonlinear property of soils are necessary to be considered in the construction of the soil UHS.

We conclude that spectral shapes and spectral amplitudes of the rock UHS are greatly different from those of the soil UHS. The rock UHS reflect characteristics of the ground motions propagating from seismic sources to bedrock, while the soil UHS reflect characteristics of the ground motions propagating from seismic sources to bedrock and then to soil surface. Therefore, these differences are caused by the effects of local soil deposit.

The significant differences between the soil UHS by the modified GMPEs (base case) and the soil UHS by GMPEs (base case) show that constructing the soil UHS by GMPEs using the generic soil is not acceptable in practice. Because of the modified GMPEs' capacity to predict ground motions at the soil surface more accurately than GMPEs, the soil UHS by the modified GMPEs is highly suitable for practical application, in particular for those critical facilities (such as NPPs) that require more accurate design spectra.

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