Design Earthquake for Nuclear Power Plants Considering Variability of Soil Parameters

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Summary

For Nuclear Power Plants at soil sites, effects of local soils on design earthquake should be considered. Because most NPPs are built at soil sites, design earthquake should consider effects of local soils. Probabilistic Seismic Hazard Analysis based on Ground Motion Prediction Equations (GMPEs) is used to construct design earthquakes. However, GMPEs for soil sites cannot give satisfactory results, because generic soils are used. Thus, GMPEs need to be modified to make them suitable for soil sites. Based on the modified GMPEs, design earthquakes on the soil surface can be constructed accurately.

1. 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 at Nuclear Power Plant (NPP) sites are generally less than the shear wave velocity threshold (750 m/sec), the effects of local soil conditions on PSHA need to be considered.

In the design of NPPs, Safe Shutdown Earthquakes (SSEs) are used in the design and represented by Design Response Spectra (DRS), such as Uniform Hazard Spectra (UHS), derived from PSHA. Some empirical GMPEs [2] for soil sites could 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 these equations to probabilistically estimate ground motions at the soil surface above a similar soil deposit [1]. This requirement actually greatly restricts the usage of empirical GMPEs to construct the soil UHS.

To overcome this problem, McGuire et al. [9] 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 [11] proposed a method to calculate Peak Ground Acceleration (PGA) at the soil surface. Cramer [6] also 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 [3] obtained site amplification distribution by regression analysis, and proposed equations to perform PHSA for two different 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 [6] considered the variability of soil parameters, but did not use vector-valued site response analysis method. Tsai [11] and Bazzurro [3] 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. The frameworks for PSHA for soil sites are presented, and a method to construct UHS on the soil surface is proposed. Using the proposed methods in this paper, PSHA for an example soil site is performed and the acceptable soil UHS of the soil site are also constructed.

2. Local Site Condition

During many earthquakes, local geology and soil conditions profoundly influenced the important characteristics−amplitude, frequency content, and duration−of strong ground motions. Extent of their influence depends on geometries and properties of the subsurface materials, topographies of the sites, and characteristics of the incident bedrock motions.

Uncertainties in geotechnical properties of soils are very common. Past research [8] showed that variability of soil parameters is suitable to be modelled 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.

3. Seismic Site Response Analysis

Due to uncertainties in incident bedrock motions, this paper proposes multiple incident bedrock motion intensity measures to evaluate seismic responses of soil sites. Since multiple incident bedrock motion intensity measures are used, this analysis method is called vector-valued site response analysis.

At a specific soil site, if $\mathrm{G_k}$ 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.

4. 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 bedrock underneath the soil surface. Reference [10] 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.

GMPEs are invalid to describe the attenuation relation of ground motions propagating from seismic sources to soil surface. Site amplification distribution is used to modify bedrock GMPEs in order to provide new attenuation relations valid for soil sites with modified uncertainties.

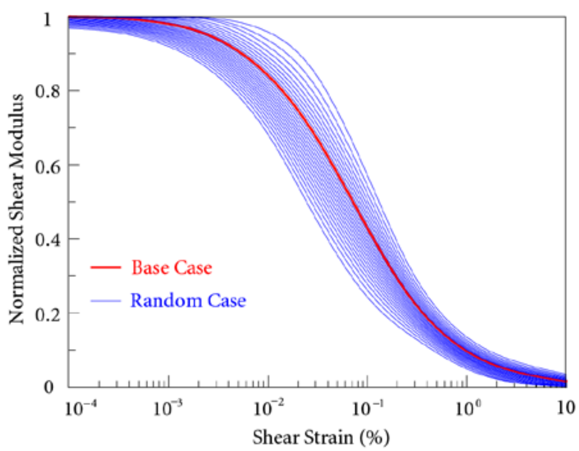

Figure 1. Randomized normalized shear modulus of the first soil layer

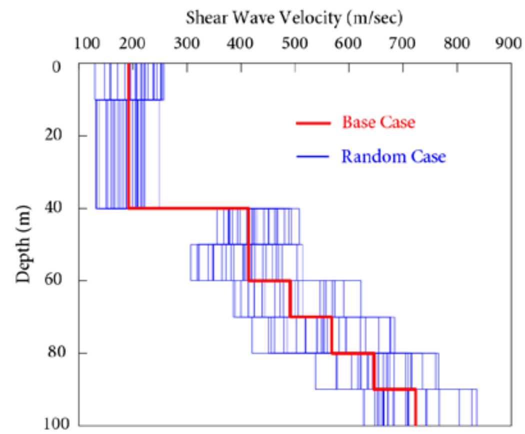

Figure 2. Randomized shear wave velocity of the soil site

5. UHS at Soil Site

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 expressed as

$$\lambda_{s_k} = p\{S_a(T_k) \geq s_k\} = \int_0^\infty \int_0^\infty \int_0^\infty p\{A_k \geq s_k/x_k | x_k, \text{pga}, z_2\} \{\sum_{i=1}^{N_S} \nu_i \int_0^\infty \int_0^\infty f_{X_k,\text{PGA},Z_2}(x_k, \text{pga}, z_2 | m, r) f_{M,R}(m, r) \text{d}m\text{d}r\}_i \text{d}x_k \text{d}(\text{pga}) \text{d}z_2 \quad (2)$$

where PGA is the peak ground acceleration of incident bedrock motions, Z_2 is another incident bedrock motion intensity measure (such as, spectral acceleration of incident bedrock motions 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 $f_{X_k,\text{PGA},Z_2}(x_k, \text{pga}, z_2 | m, r)$ 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 [7].

6. Soil UHS of Example Soil Site

For an example soil site at Charleston, South Carolina, seismic site responses is simulated by DEEPSOIL. Based on the simulation results, site amplification is calculated. Then site amplification regression analysis is performed. Based on the functional form proposed by Abrahamson et al. [2] and Bazzurro [4], a more accurate regression model is proposed

$$\ln A = c_0 + c_1 \ln X + c_2 \ln \mathrm{PGA} + c_3 \ln Z_2 + c_4 (\ln X)^2 + c_5 (\ln \mathrm{PGA})^2 + c_6 (\ln Z_2)^2 + \sigma_{\ln A} \quad (3)$$

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

The bedrock GMPEs proposed by Boore and Atkinson [6] are modified by the site amplification regression model. Using the modified GMPEs, PSHA for the soil site are performed accurately. Two different characterizations of the site are used: *base case*, with deterministic soil parameters whose values are equal to their best engineering estimates, and *random case*, with 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
0.05	−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
0.5	−0.2238	−0.6386	−0.2160	0.0	−0.1006	−0.0432	0.0	0.3054
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

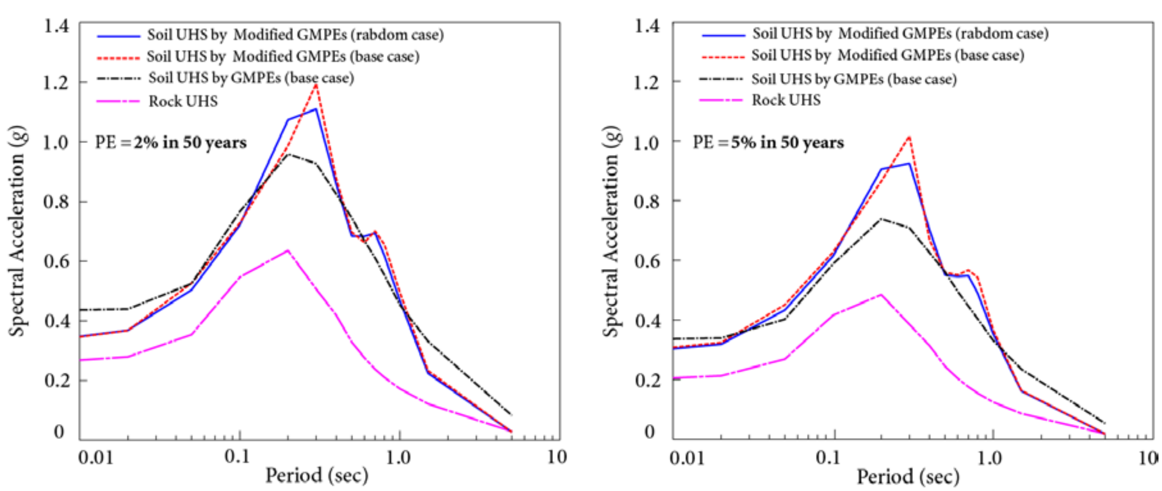

Figure 3. Uniform Hazard Spectra

Using equation (2), seismic hazard curves on the soil surface are calculated. Using the seismic hazard curves at controlling periods, the soil UHS are constructed, as shown in Figure 3. Comparing the soil UHS and the rock UHS, it can be seen that their spectral shapes and spectral amplitudes are different. In addition, from Figure 3, it can be seen that the soil UHS by the modified GMPEs (base case) are different from the soil UHS by GMPEs (base case). Comparing the soil UHS by the modified GMPEs under random case and those by the modified GMPEs under base case, we further conclude that the variability of soil parameters affects both spectral shapes and spectral amplitudes of the soil UHS.

7. Conclusion

From the work in this paper, we conclude that (1) the spectral shapes and spectral amplitudes of the rock UHS are greatly different from those of the soil UHS; (2) the variability of soil parameters affects both spectral shapes and spectral amplitudes of the soil UHS; and (3) the soil UHS by the modified GMPEs is highly suitable for practical application.

8. References

[1] ANS. (2008). *American National Standard Probabilistic Seismic Hazards Analysis, ANSI/ANS-2.29-2008*. American Nuclear Society, Illinois, USA

[2] Abrahamson, N. A., and Silva, W. J. (1997). Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismological Research Letters*, 68(1), 94-127.

[3] Bazzurro, P., and Cornell, C. A. (2004). Nonlinear soil-site effects in probabilistic seismic hazard analysis. *Bulletin of the Seismological Society of America*, 94(6), 2110-2123.

[4] Bazzurro, P., and Cornell, C. A. (2004). Ground-motion amplification in nonlinear soil sites with uncertain properties. *Bulletin of the Seismological Society of America*, 94(6), 2090-2109.

[5] Boore, D. M., and Atkinson, G. M. (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. *Earthquake Spectra*, 24(1), 99-138.

[6] Cramer, C. H. (2003). Site-specific seismic-hazard analysis that is completely probabilistic. *Bulletin of the Seismological Society of America*, 93(4), 1841-1846.

[7] Jayaram, N., and Baker, J. W. (2008). Statistical tests of the joint distribution of spectral acceleration values. *Bulletin of the Seismological Society of America*, 98(5), 2231-2243.

[8] Lumb, P. (1966). The variability of natural soils. *Canadian Geotechnical Journal*, 3(2), 74-97.

[9] McGuire, R. K. W., Silva, J. and Constantino, C. (2001). *Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines*. Office of Nuclear Regulatory Research, Division of Engineering Technology

[10] Regnier, J., Bonilla, L. F., Bertrand, E., Duval, A. M., Beauval, C., Scotti, O., and Gehl, P. (2008, October). Variability of one-dimensional soil amplification estimates at four sites of the French permanent accelerometer network (RAP). *In Proceed. 14th World Conference on Earthquake Engineering*, Beijing, China.

[11] Tsai, C. C. P. (2000). Probabilistic seismic hazard analysis considering nonlinear site effect. *Bulletin of the Seismological Society of America*, 90(1), 66-72.