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A STUDY ON SITE COEFFICIENTS FOR NEW SITE CATEGORIES SPECIFIED IN THE NEHRP PROVISIONS

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ABSTRACT

This paper presents a study to establish a probabilistic model and statistics for the site coefficients of the new site categories specified in the 1994 NEHRP Recommended Provisions. For the five site categories (SA, SB, SC, SD and SE) defined in the NEHRP Provisions, the synthetic acceleration time histories expected to occur in the eastern United States are generated for the rock sites with a seismologically based model, and the acceleration time histories for the soil sites are then determined using the SHAKE91 program. At the selected periods, the ratios of the spectral acceleration values of the soil sites to the corresponding value of the reference site are determined and these ratios are called the site coefficients. In the study, a total of 250 runs are carried out for each site category to take into account the uncertainties in modeling of seismic source, path attenuation, and site conditions. A regression analysis is performed to determine a probabilistic model for the site coefficient at each selected period. The site coefficients obtained from this study are compared to those specified in the NEHRP Provisions.

KEYWORDS

Earthquake motion, response spectrum, building code, site coefficients, soil profile.

INTRODUCTION

The effect of local site conditions on the characteristics of ground motion has long been recognized (Seed *et al.*, 1976). This effect is usually incorporated into building codes by specifying several site categories and assigning a site coefficient for each site category. Many concerns have been expressed regarding the appropriateness of existing definitions of site categories and the confusion in classifying sites using these definitions (Whitman, 1989). In the 1994 NEHRP Recommended Provisions for Seismic Regulations for New Buildings (FEMA, 1995), site categories and site coefficients were revised based on the results from the investigation of the 1989 Loma Prieta earthquake and other research studies (Rinne, 1994). The site coefficients (F_a and F_v) are specified in accordance with site categories and levels of ground shaking. According to Martin and Dobry (1994), the site coefficients F_a in the NEHRP Provisions are about the mean values and the site coefficients F_v are approximately the mean plus one standard deviation values, but the variations in these site coefficients are not completely specified. Furthermore, many researchers, for example, Nuttli (1981), have suggested that the characteristics of ground motions in the eastern United States are quite different from those in California. It is not clear that the site coefficients derived on the basis of the earthquake motion data in California are suitable for use in the eastern United States. In this paper, we present a study to establish a probabilistic model and statistics for the site coefficients of the new site categories specified in the 1994 NEHRP Provisions using the ground motions expected to occur in the eastern United States. The site coefficients obtained from this study are compared to those specified in the NEHRP Provisions.

where ρ_s and β_s are the effective density and shear wave velocity of the rock profile, while ρ_0 and β_0 are those at seismic source, and ξ is the equivalent damping ratio of the rock profile, which can be determined from the quality factors of the rock layers (Boore and Joyner, 1991).

The strong-motion segment of an acceleration time history is usually considered as a stationary random process. Under this condition, the one-sided power spectral density function $S_a(f)$ can be derived from the Fourier amplitude spectrum as follows:

$$S_a(f) = \frac{1}{\pi T_e} |A(f)|^2 \qquad (3)$$

where T_e is the strong-motion duration. In this study, the strong-motion duration is determined in accordance with the formula suggested by Huo and Hu (1994):

$$Ln(T_e) = -5.222 + 0.7511\,M + 0.5815\,Ln(R + 10) + \varepsilon \qquad (4)$$

in which ε is a normal random variable with a zero mean and the standard deviation of 0.37.

Given the power spectral density function, the stationary acceleration time histories can be generated using the method proposed by Shinozuka (1974) and the nonstationary acceleration time histories are then obtained by multiplying an envelope function to the stationary acceleration time histories.

Statistics of Site Coefficients for SA and SB Sites

For a given magnitude and epicentral distance, some seismic parameters such as the stress parameter, strong-motion duration, cut-off frequency, quality factor, etc. have significant effects on the resulting ground motion. The uncertainties in these parameters are quantified in generating accelerograms. The random seismic parameters identified by Hwang and Huo (1994) are used in this study and summarized in Table 3.

Table 3. Seismic parameters for generating synthetic earthquakes

Parameters	Distributions	Mean	Range
Stress parameter, $\Delta\sigma$	Uniform	150 bars	100 - 200 bars
High-cut frequency, f_m	Uniform	30 Hz	20 - 40 Hz
Radiation coefficient, $<R_{\theta\phi}>$	Uniform	0.56	0.48 - 0.64
Focal depth, H	Uniform	10 km	6 - 15 km
Phase angle, ϕ	Uniform	π	0 - 2π
Envelope function parameter, C_3	Uniform	0.5	0 - 1
γ_0 in quality factor $Q(f) = \frac{\pi}{\beta\gamma_0} f^{\eta}$	Uniform	0.0007	0.0006 - 0.0008
η in quality factor $Q(f) = \frac{\pi}{\beta\gamma_0} f^{\eta}$	Uniform	0.40	0.25 - 0.55
Strong motion duration, T_e	Lognormal	Eq. (4)	

Following the procedure used by Hwang and Huo (1994), five pairs of moment magnitude M and epicentral distance R (Table 4) are selected to establish earthquake ground motions with various levels of shaking intensity. For each pair of M and R, 50 samples for each random seismic parameter are generated according to the distribution and then the samples of all random parameters are combined using the Latin Hypercube sampling technique (Iman and Conover, 1980) to establish 50 sets of random seismic parameters. Using these 50 sets of samples, 50 acceleration time histories at the free surface are generated for three rock site categories using the ground motion model and the site conditions described above. The corresponding acceleration response spectra with 5% damping ratio are calculated thereafter (Lin *et al.*, 1996).

SITE COEFFICIENTS FOR ROCK SITES

Rock Sites

The six site categories specified in the 1994 NEHRP Provisions are shown in Table 1. The site category SF requires site-specific evaluations and thus it is excluded in this study. In addition to the remaining five site categories, we include an additional site category S0 for the bedrock site. Thus three types of rock sites, S0, SA and SB, are considered in this study. The bedrock site S0 consists of rock with a shear wave velocity β_0 of 3.5 km/s and a crustal density ρ_0 of 2.7 g/cm^3. Only one profile is constructed for the S0 site, since only one type of rock is considered for such a site. On the other hand, five profiles for the site categories SA and SB are constructed so that the ranges of shear wave velocity specified in Table 1 are taken into account. For illustration, the profiles and rock properties of the five SB sites are shown in Table 2.

Table 1. Site categories specified in 1994 NEHRP Provisions

Category	Description
SA	Hard rock with measured average shear wave velocity, $\bar{v}_s$ > 1,520 m/s ($\bar{v}_s$ > 5,000 ft/s)
SB	Rock with 760 m/s < $\bar{v}_s$ ≤ 1,520 m/s (2,500 ft/sec < $\bar{v}_s$ ≤ 5,000 ft/s)
SC	Very dense soil and soft rock with 365 m/s < $\bar{v}_s$ ≤ 760 m/s (1,200 ft/s < $\bar{v}_s$ ≤ 2,500 ft/s)
SD	Stiff soil with 183 m/s ≤ $\bar{v}_s$ ≤ 365 m/s (600 ft/s ≤ $\bar{v}_s$ ≤ 1,200 ft/s)
SE	Any profile with more than 3 m (10 ft) of soft clay defined as soil with PI > 20, w ≥ 4 percent, and s_u < 24 kPa (500 psf) or a soil profile with $\bar{v}_s$ < 183 m/s (600 ft/s)
SF	Soils requiring site-specific evaluations

Table 2. Five profiles of the SB site

Layer No.	Thickness (m)	SB-1		SB-2		SB-3		SB-4		SB-5	
		ρ	V_S	ρ	V_S	ρ	V_S	ρ	V_S	ρ	V_S
1	150	2.3	770	2.3	950	2.4	1130	2.4	1310	2.5	1500
2	150	2.4	1400	2.4	1550	2.5	1700	2.5	1800	2.5	1950
3	150	2.5	2100	2.5	2200	2.5	2300	2.5	2300	2.5	2400
4	150	2.6	2400	2.6	2500	2.6	2600	2.6	2600	2.6	2600
5	200	2.6	2700	2.6	2800	2.6	2900	2.6	2900	2.6	2900
6	200	2.7	3100	2.7	3100	2.7	3200	2.7	3200	2.7	3200
Bedrock	ρ_0 = 2.7 g/m^3, β_0 = 3500 m/s										

Ground Motion Model for Rock Sites

In the eastern United States, the recorded ground motions are sparse, thus the synthetic acceleration time histories are used. In this study, the synthetic time histories for the S0, SA and SB sites are generated using the method proposed by Hwang and Huo (1994). In their approach, the Fourier acceleration amplitude spectrum resulting from an earthquake with a moment magnitude M at an epicentral distance R from the site is formulated as proposed by Boore (1983):

$$A(f) = C \cdot S(f) \cdot D(f) \cdot AF(f) \tag{1}$$

where C is a scaling factor, $S(f)$ is the source spectral function, $D(f)$ is the diminution function, and $AF(f)$ is the amplification function of the rock profile. For the bedrock site S0, no amplification is expected and the amplification function $AF(f)$ is taken as 1. For the hardrock site SA and the softrock site SB, considering the decrease of shear wave velocity of the rock layers near the ground surface, the amplification function is taken as

$$AF(f) = \sqrt{\rho_0\, \beta_0 / \rho_s\, \beta_s}\; exp(-\pi\, \xi f) \tag{2}$$

Table 4. Pairs of moment magnitude and epicentral distance used in this study

M	6.5	7.1	7.4	7.7	7.9
R (km)	79	72	66	60	57

At each selected period, the ratios of the spectral values of the SA and SB sites to that of the S0 site are calculated. These ratios are called the site coefficients for the SA and SB sites and are denoted as $F_{A/0}(T)$ and $F_{B/0}(T)$, respectively. As an example, Figure 1 shows the $F_{B/0}(T)$ values at the period of 0.3 seconds versus various levels of PA_0, the peak acceleration of the S0 site. As shown in Figure 1, the site coefficients are scattered but they are independent of the PA_0 level, since $F_{A/0}(T)$ and $F_{B/0}(T)$ are only affected by the linear amplification of rock layers. The site coefficients $F_{A/0}(T)$ and $F_{B/0}(T)$ are taken to be lognormally distributed and the statistics (mean and coefficient of variation) at various periods are summarized in Table 5.

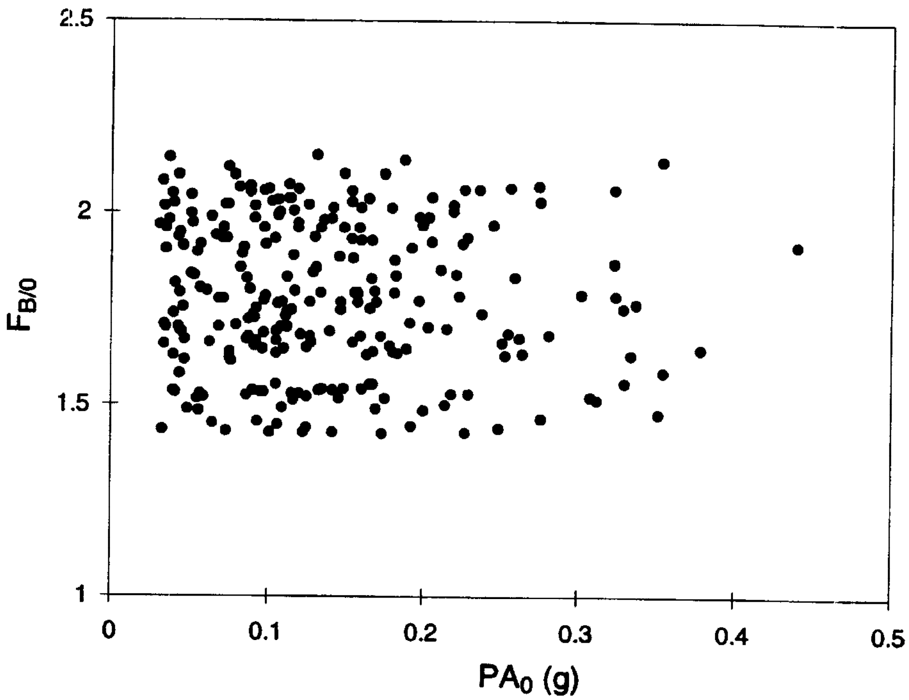

Fig. 1. Distribution of site coefficient $F_{B/0}$ at period of 0.3 second

Table 5. Statistics of site coefficients for SA and SB sites

Period (sec)	$F_{A/0}$		$F_{B/0}$	
	Mean	COV	Mean	COV
0.1	1.42	0.05	1.59	0.09
0.2	1.45	0.05	1.74	0.10
0.3	1.45	0.05	1.78	0.11
0.4	1.44	0.05	1.79	0.12
0.5	1.42	0.05	1.78	0.12
0.6	1.41	0.05	1.76	0.14
0.7	1.39	0.05	1.72	0.14
0.8	1.38	0.05	1.69	0.14
0.9	1.35	0.05	1.64	0.14
1.0	1.33	0.05	1.60	0.13
1.2	1.30	0.04	1.52	0.12
1.5	1.25	0.04	1.42	0.11
2.0	1.19	0.04	1.32	0.09
2.5	1.16	0.03	1.26	0.08
3.0	1.14	0.04	1.22	0.07
PA	1.40	0.05	1.59	0.08

SITE COEFFICIENTS FOR SOIL SITES

In this study, three soil site categories SC, SD and SE are considered. From an investigation of the subsurface conditions in the Memphis and Shelby County (Ng *et al.*, 1989), five soil profiles are constructed for each of three soil site categories. As an example, a sample of the SD soil profile is shown in Figure 2. Following Hwang and Huo (1994), the soil parameters considered as random variables are the relative density of sand D_r, undrained shear strength of clay S_u, shear modulus and damping ratio of the soils. The D_r and S_u are considered to be uniformly distributed and 50 samples for each of these two parameters are generated according to the uniform distribution. The shear modulus reduction curves and damping ratio curves for sands and clays used in this study are shown in Figure 3. Fifty uniformly distributed shear modulus reduction curves and damping ratio curves are generated within the range of mean plus and minus 2 standard deviations. The samples of all random soil parameters are combined using the Latin Hypercube sampling technique to establish 50 samples of the soil profile for each soil site category.

Depth 0.00 m	Description	Parameters
7.32 m	SILT (ML), MEDIUM DENSE	γ_s = 1.76 g/cm^3, D_r = 0.35 ~ 0.65
9.76 m	SAND (SP), MEDIUM DENSE	γ_s = 2.00 g/cm^3, D_r = 0.35 ~ 0.65
16.47 m	SAND (SP), VERY DENSE	γ_s = 2.16 g/cm^3, D_r = 0.85 ~ 1.00
22.88 m	SILTY CLAY (CL), VERY STIFF	γ_s = 2.08 g/cm^3, PI = 30 S_u = 95.80 ~ 191.60 kPa
31.42 m	CLAYEY SAND TO SAND (SC-SP), VERY DENSE	γ_s = 2.16 g/cm^3, D_r = 0.85 ~ 1.00
36.60 m	SILTY CLAY (CL), HARD	γ_s = 2.08 g/cm^3, PI = 30 S_u = 191.60 ~ 383.20 kPa
42.70 m	SAND (SP), VERY DENSE	γ_s = 2.16 g/cm^3, D_r = 0.85 ~ 1.00
48.80 m	CLAY (CL), VERY STIFF	γ_s = 2.08 g/cm^3, PI = 30 Su = 95.80 ~ 191.60 kPa
61.00 m	CLAY (CL), HARD	γ_s = 2.08 g/cm^3, PI = 30 S_u = 191.6 ~ 383.20 kPa
100.0 m	CLAY (CL), HARD	γ_s = 2.08 g/cm^3, PI = 50 S_u = 191.6 ~ 383.20 kPa
	SOFT ROCK	

Fig. 2. A sample of soil profile of the SD site category

For each site category and each pair of M and R, 50 samples of the acceleration time history at the outcrop of the SB (softrock) site are matched with the 50 samples of the soil profile to establish 50 samples of the earthquake-site system. For each earthquake-site sample, a nonlinear site response analysis is performed using the SHAKE91 program (Idriss and Sun, 1992) to generate the acceleration time history at the ground surface and the corresponding response spectrum with 5% damping ratio. At each selected period, the ratios of the spectral values of the three site categories SC, SD, and SE to that of the SB site are determined. These ratios are called site coefficients and are denoted as $F_{C/B}(T)$, $F_{D/B}(T)$, and $F_{E/B}(T)$, respectively. As an illustration, Figure 4 shows the $F_{D/B}(T)$ values at the period of 0.3 seconds versus various levels of PA_B, the peak acceleration value of the SB site. It is observed that the site coefficient values are scattered and correlated with the intensity of ground shaking. In this study, the site coefficient at a given period is modeled as a lognormal distribution and the relation of the logarithmic $F(T)$ with PA_B is expressed as

$$log[F(T)] = a(T)\ PA_B + b(T) + \varepsilon \qquad (5)$$

where $a(T)$ and $b(T)$ are the regression coefficients and ε is the zero-mean normal random variable representing the uncertainty of regression. Using the least square regression, the regression coefficients and the standard deviation of ε are determined for the site categories SC, SD and SE (Table 6).

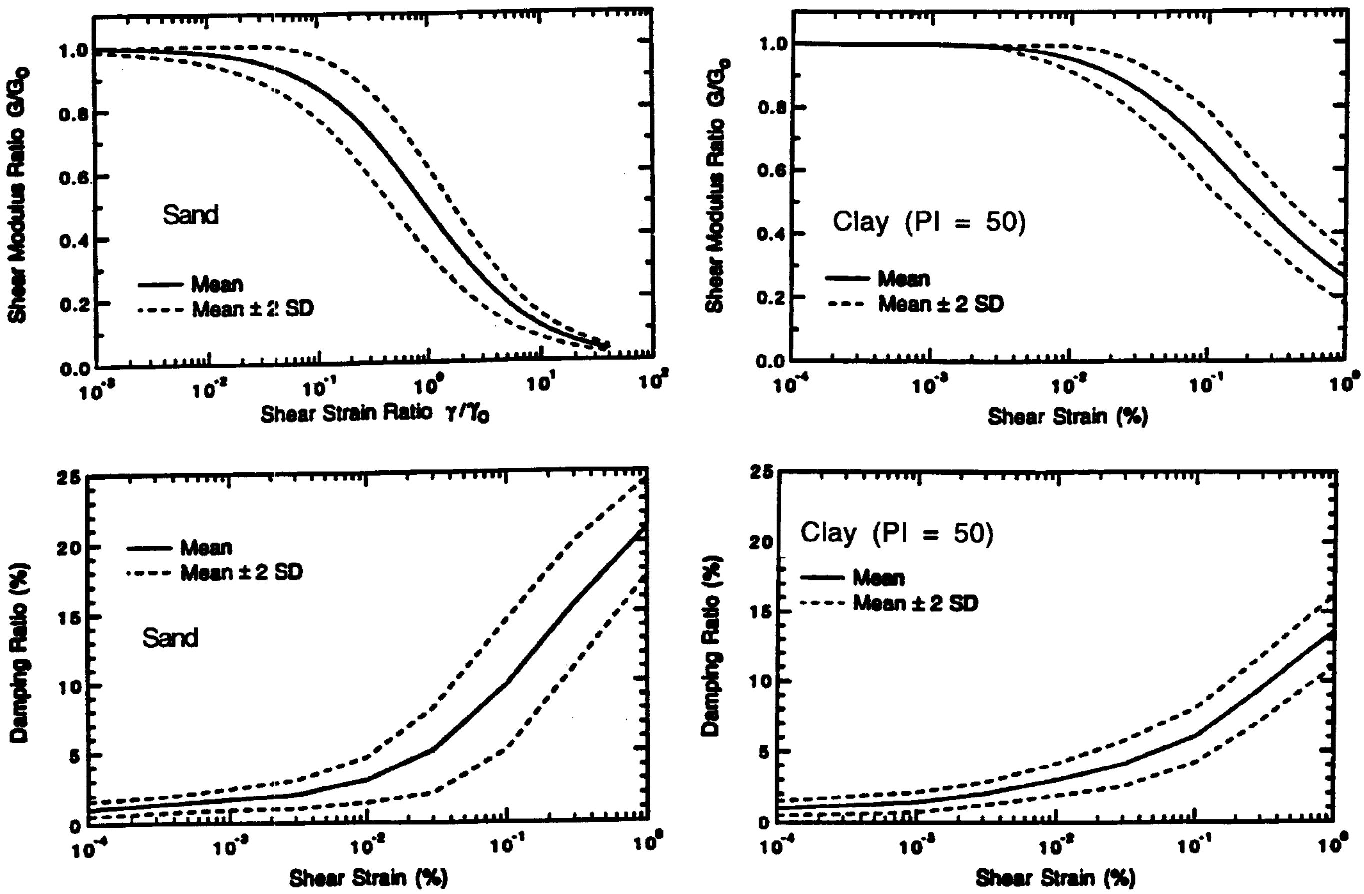

Fig. 3. Shear modulus of reduction curves and damping ratio curves for sands and clays

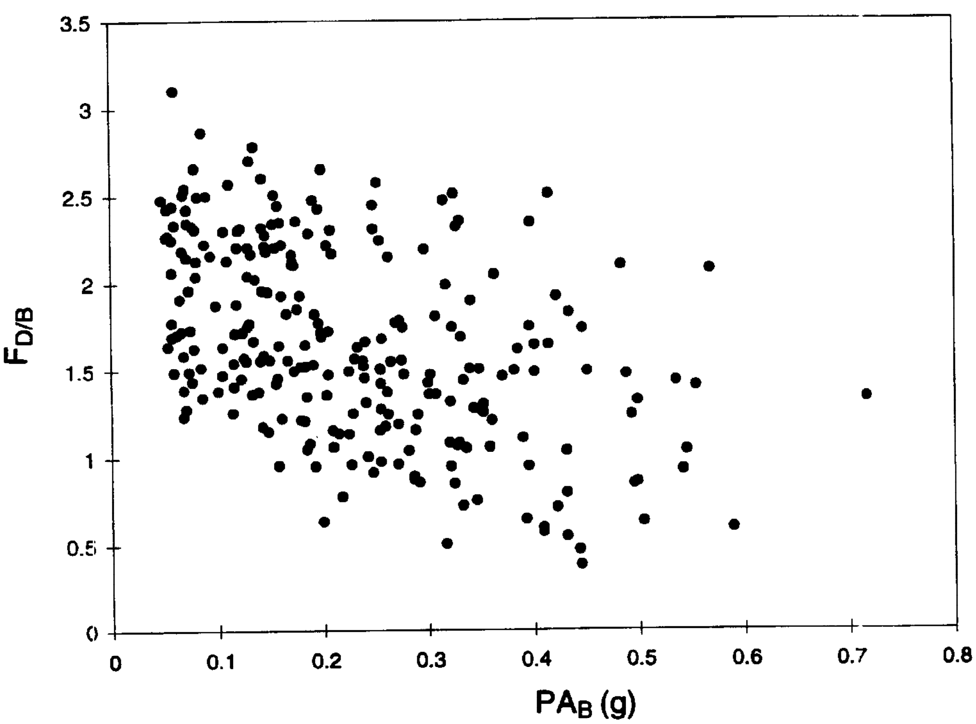

Fig. 4. Distribution of site coefficient $F_{D/B}$ at period of 0.3 second

COMPARISON WITH NEHRP PROVISIONS

In the 1994 NEHRP Provisions, F_a and F_v denote the site coefficients at the period of 0.3 and 1 seconds, respectively. The F_a and F_v values from this study and those specified in the 1994 NEHRP Provisions are shown in Table 7. It is noted that the F_a and F_v values from this study listed in the table are the mean values. For the rock sites SA and SB, the site coefficients from this study are the same as those specified in the NEHRP Provisions. For the SC site, the F_a and F_v values obtained from this study are close to the average values specified in the NEHRP Provisions. The site coefficients obtained from this study are independent of the intensity of ground shaking, implying the soils of the SC site behave in a linear manner. On the other hand, the site coefficients specified in the NEHRP Provisions decrease with the increase of ground shaking, implying a slightly nonlinear behavior of the soils. For the SD and SE sites, the F_v values specified in the NEHRP Provisions decrease when the intensity of ground shaking increases, but the values obtained from this study increase with the intensity of ground shaking. It is noted that the same trend is also reported by Toro *et al.* (1992) in their mapping of ground shaking in the Mississippi embayment. Furthermore, the F_a and F_v values from this study are in general larger than those specified in the NEHRP Provisions. This is particularly true for the SE site. In this study, all the soil profiles of the SE site consist of a soft clay layer with the plasticity index PI larger than 20. The soft clay layers are expected to amplify the input motion more significantly than the loose sand layers. Thus, including both soft clay layers and loose sand layers in the definition of the SE site category needs further investigation.

Table 6. Coefficients of regression equation $log[F(T)] = a(T)\ PA_B + b(T)$

Period (sec)	$F_{C/B}$			$F_{D/B}$			$F_{E/B}$		
	a	b	σ_{LnF}	a	b	σ_{LnF}	a	b	σ_{LnF}
0.1	-0.671	0.297	0.267	-2.684	0.616	0.546	-2.841	0.658	0.421
0.2	-0.464	0.493	0.200	-1.940	0.725	0.417	-2.104	0.927	0.359
0.3	0.052	0.280	0.166	-1.415	0.761	0.329	-1.439	1.036	0.328
0.4	-0.193	0.357	0.146	-1.168	0.913	0.289	-1.330	1.225	0.299
0.5	-0.179	0.468	0.189	-0.571	0.852	0.228	-0.863	1.217	0.259
0.6	-0.030	0.483	0.205	-0.332	0.846	0.197	-0.540	1.199	0.220
0.7	0.067	0.442	0.196	-0.387	0.942	0.202	-0.407	1.226	0.217
0.8	0.162	0.366	0.161	-0.222	0.992	0.217	-0.139	1.222	0.220
0.9	0.160	0.311	0.137	-0.020	0.969	0.232	0.185	1.135	0.226
1.0	0.152	0.269	0.122	0.199	0.905	0.230	0.445	1.023	0.233
1.2	0.126	0.202	0.095	0.592	0.689	0.226	0.791	0.760	0.236
1.5	0.059	0.153	0.073	0.649	0.490	0.216	0.786	0.532	0.213
2.0	0.039	0.089	0.053	0.480	0.318	0.173	0.503	0.349	0.160
2.5	-0.014	0.077	0.050	0.281	0.246	0.159	0.271	0.281	0.169
3.0	-0.033	0.063	0.037	0.163	0.185	0.139	0.156	0.212	0.140
PA	-0.662	0.324	0.244	-1.783	0.558	0.335	-1.883	0.721	0.267

Table 7. Comparison of F_a and F_v Values

Site category	Site coeff.	F_a					F_v				
	PA_B	0.1g	0.2g	0.3g	0.4g	0.5g	0.1g	0.2g	0.3g	0.4g	0.5g
SA	**This study**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**	**0.8**
	NEHRP	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
SB	**This study**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
	NEHRP	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
SC	**This study**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**
	NEHRP	1.2	1.2	1.1	1.0	1.0	1.7	1.6	1.5	1.4	1.3
SD	**This study**	**2.0**	**1.7**	**1.5**	**1.3**	**1.1**	**2.6**	**2.6**	**2.7**	**2.8**	**2.8**
	NEHRP	1.6	1.4	1.2	1.1	1.0	2.4	2.0	1.8	1.6	1.5
SE	**This study**	**2.6**	**2.2**	**1.9**	**1.7**	**1.5**	**3.0**	**3.1**	**3.3**	**3.4**	**3.6**
	NEHRP	2.5	1.7	1.2	0.9	n/a	3.5	3.2	2.8	2.4	n/a

CONCLUSIONS

In this paper, we present a study to establish a probabilistic model and statistics for the site coefficients of the new site categories specified in the 1994 NEHRP Provisions. The five site categories (SA, SB, SC, SD and SE) defined in the NEHRP Provisions and an additional site category S0 for the bedrock site are considered. For each site category, the synthetic acceleration time histories expected to occur in the eastern United States are generated for the rock sites (S0, SA and SB) with a seismologically based model, and the acceleration time histories for the soil sites (SC, SD and SE) are then determined using the SHAKE91 program. To take into account the uncertainties in modeling of seismic source, path attenuation, and site conditions, a total of 250 runs are carried out for each site category and then a regression analysis is performed to determine a probabilistic model for the site coefficient at each selected period.

In the NEHRP Provisions, F_a denotes the site coefficient at the period of 0.3 seconds, while F_v denotes the site coefficient at 1 second. The F_a and F_v values obtained from this study are compared to those specified in the NEHRP Provisions. It is observed that the site coefficients for the rock sites obtained from this study are the same as those specified in the NEHRP Provisions, while the site coefficients for the soil sites have significant differences. Thus, further investigations need to be carried out to establish the site coefficients for the soil sites.

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