DEVELOPMENT OF A DATABASE OF NONLINEAR GROUND MOTION AMPLIFICATION FUNCTIONS FOR SOIL DEPOSITS OF VARIOUS NEHRP SOIL CATEGORIES

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1. Motivation and scope of the study

Incorporating information about site soil conditions into probabilistic seismic hazard analysis (PSHA) and risk analysis (PSRA) studies is crucial for obtaining an accurate seismic hazard and risk representation. In most cases the local site effects are accounted for by using ground motion prediction equations for generic soil categories, such as the NEHRP soil categories A to E. Ground motion attenuation relationships developed for generic soil, however, do not permit the full inclusion of detailed site-specific geotechnical information. The impact on the hazard and risk estimates of neglecting specific site information is left unquantified. For important structures the hazard at the surface is often quantified by modifying the site bedrock hazard estimates using soil-specific amplification functions. The surface hazard is obtained by multiplying the rock hazard by the mean amplification function without consideration of its uncertainty, a practice that leads to questionable results.

Probabilistically robust methods have been recently developed (e.g., Bazzurro and Cornell, 2004a, 2004b; Baturay and Stewart, 2003) that allow incorporating frequency-dependent amplification functions into PSHA and PSRA studies. The frequency-dependent amplification functions, *AF(f)*, is defined here as

$$AF(f) = \frac{S_a^s(f)}{S_a^r(f)} \tag{1}$$

where the numerator is the spectral acceleration at the oscillator frequency *f* of a ground surface motion and the denominator is the spectral acceleration at the bedrock. These methods can be applied both to specific soil deposits, as originally intended, and to generic ones belonging to a given soil class, such as the NEHRP soil category. To implement such methods, however, the median (or mean) of *AF(f)* and a measure of its dispersion—both quantities preferably conditioned on a measure of the intensity of rock motion, such as PGA or spectral acceleration at the oscillator frequency *f*—are needed. To facilitate a practical implementation of such methods, which have been included into the OpenSHA software (Goulet *et al*., 2007), we have assembled a database of *AF(f)*'s for 143 soil columns belonging to various NEHRP soil categories computed using an enhanced version of the nonlinear computer program SUMDES (Li *et al*., 1992). Most of these columns are representative of those commonly found in Southern California. Using this database or modifications of it, one could envision OpenSHA users to a) select the soil profile and characteristics that most closely resemble the soil conditions at the site of interest; b) have the OpenSHA software extract the appropriate *AF(f)*s and c) compute the soil-specific ground motion hazard estimates at the surface and the frequency range over which such estimates are considered valid. The *AF(f)* would be obtained without performing costly soil amplification analyses, which may be beyond the budget of some projects. However, if the user has little knowledge about the site soil conditions beyond the NEHRP category and the "soil type" (i.e., sand or clay), and still desires to include this limited information into the PSHA or PSRA study, then OpenSHA could extract the *AF(f)* statistics for that generic soil category.

2. Database of soil columns

The characteristics of the 143 soil columns selected for this study are listed in Table 1 for NEHRP Soil Category C (35 columns), in Table 2 for NEHRP Soil Category D (72 columns), and in Table 3 for NEHRP Soil Category E (36 columns). Note that Vs_{30} refers to the shear wave velocity in the top 30 meters, "NC" stands for normal consolidated clay/silt, "OCR" for Over Consolidation Ratio, "Cu" for undrained shear strength, "const" means that the quantity (OCR or Cu) is constant over depth, while "var" means that the OCR decreases over depth, and p_{tot} is the pressure initially applied at the ground surface and subsequently removed to pre-consolidate the soil deposit. The water table in the loose and dense saturated sandy and gravelly columns was set at 2m below the ground surface. The shear wave velocity in the bedrock, Vs_{rock}, was set equal to 800m/s. Note that, according to customary practice, if the soil column is shorter than 30m the value of Vs_{30} is computed as the weighted average of the shear wave velocity in the soil and in the bedrock.

Soil Column No.	Depth to Bedrock (m)	Soil Description	Vs_{30} [m/s]	NEHRP Category
1	5	OCR cost=8 high plasticity	364	C
2	5	OCR cost=8 low plasticity	364	C
3	15	Dense saturated sand	369	C
4	7.5	Loose saturated sand	383.4	C
5	5	OCR var ptot=300 high plasticity	386.2	C
6	5	OCR var ptot=300 low plasticity	386.2	C
7	5	Cu cost=50 low plasticity	389.6	C
8	5	Cu cost=50 high plasticity	389.6	C
9	10	Cu cost=350 high plasticity	400.7	C
10	10	Cu cost=350 low plasticity	400.7	C
11	5	OCR cost=20 low plasticity	421.3	C
12	5	OCR cost=20 high plasticity	421.3	C
13	10	Dense saturated sand	428.3	C
14	30	Dense saturated gravel	437.8	C
15	40	Dense saturated gravel	437.8	C
16	60	Dense saturated gravel	437.8	C
17	100	Dense saturated gravel	437.8	C
18	150	Dense saturated gravel	437.8	C
19	5	OCR var ptot=900 high plasticity	439.1	C
20	5	OCR var ptot=900 low plasticity	439.1	C
21	5	Loose saturated sand with cyclic mobility	446.9	C
22	5	Loose saturated sand	446.9	C
23	5	OCR var ptot=1500 high plasticity	466.3	C
24	5	OCR var ptot=1500 low plasticity	466.3	C
25	7.5	Dense saturated sand	470.4	C
26	5	Cu cost=200 high plasticity	481.5	C
27	5	Cu cost=200 low plasticity	481.5	C
28	20	Dense saturated gravel	481.9	C
29	15	Dense saturated gravel	514.4	C
30	5	Cu cost=350 low plasticity	521.1	C
31	5	Cu cost=350 high plasticity	521.1	C
32	5	Dense saturated sand	527.7	C
33	10	Dense saturated gravel	559.8	C
34	7.5	Dense saturated gravel	590.6	C
35	5	Dense saturated gravel	630.65	C

Table 1. Characteristics of the 35 NEHRP Category C soil columns considered in this study.

Soil Column No.	Depth to Bedrock (m)	Soil Description	Vs_{30} [m/s]
1	40	Cu cost=200 low plasticity	191
2	40	Cu cost=200 high plasticity	191
3	60	Cu cost=200 high plasticity	191
4	60	Cu cost=200 low plasticity	191
5	80	Cu cost=200 low plasticity	191
6	80	Cu cost=200 high plasticity	191
7	30	Loose saturated sand	193.8
8	40	Loose saturated sand	193.8
9	40	Loose saturated sand with cyclic mobility	193.8
10	60	Loose saturated sand	193.8
11	60	Loose saturated sand with cyclic mobility	193.8
12	100	Loose saturated sand	193.8
13	100	Loose saturated sand with cyclic mobility	193.8
14	150	Loose saturated sand	193.8
15	150	Loose saturated sand with cyclic mobility	193.8
16	20	OCR cost=8 low plasticity	205.1
17	20	OCR cost=8 high plasticity	205.1
18	10	NC clay low plasticity	214.8
19	10	NC clay high plasticity	214.8
20	40	OCR cost=20 low plasticity	218.7
21	40	OCR cost=20 high plasticity	218.7
22	60	OCR cost=20 low plasticity	218.7
23	60	OCR cost=20 high plasticity	218.7
24	80	OCR cost=20 high plasticity	218.7
25	80	OCR cost=20 low plasticity	218.7
26	100	OCR cost=20 low plasticity	218.7
27	100	OCR cost=20 high plasticity	218.7
28	150	OCR cost=20 high plasticity	218.7
29	150	OCR cost=20 low plasticity	218.7
30	10	OCR cost=2 low plasticity	224
31	10	OCR cost=2 high plasticity	224
32	40	Cu cost=350 low plasticity	225.25
33	40	Cu cost=350 high plasticity	225.25
34	60	Cu cost=350 high plasticity	225.25
35	60	Cu cost=350 low plasticity	225.25
36	80	Cu cost=350 high plasticity	225.25
37	80	Cu cost=350 low plasticity	225.25
38	100	Cu cost=350 high plasticity	225.25
39	100	Cu cost=350 low plasticity	225.25
40	150	Cu cost=350 high plasticity	225.25
41	150	Cu cost=350 low plasticity	225.25
42	20	Loose saturated sand	241.4
43	20	Loose saturated sand with cyclic mobility	241.4
44	20	Cu cost=200 high plasticity	245.8
45	20	Cu cost=200 low plasticity	245.8
46	20	OCR cost=20 high plasticity	256.4
47	20	OCR cost=20 low plasticity	256.4
48	10	Cu cost=50 low plasticity	272.7
49	10	Cu cost=50 high plasticity	272.7
50	30	Dense saturated sand	275.9
51	40	Dense saturated sand	275.9
52	60	Dense saturated sand	275.9
53	100	Dense saturated sand	275.9
54	150	Dense saturated sand	275.9
55	10	OCR cost=8 low plasticity	277.5
56	10	OCR cost=8 high plasticity	277.5
57	15	Loose saturated sand	279.7
58	20	Cu cost=350 high plasticity	282.3
59	20	Cu cost=350 low plasticity	282.3
60	5	NC clay low plasticity	303.1
61	5	NC clay high plasticity	303.1
62	5	OCR cost=2 high plasticity	305.2
63	5	OCR cost=2 low plasticity	305.2
64	20	Dense saturated sand	328.7
65	10	OCR cost=20 low plasticity	333.6
66	10	OCR cost=20 high plasticity	333.6
67	5	Cu cost=20 high plasticity	337.3
68	5	Cu cost=20 low plasticity	337.3
69	10	Loose saturated sand with cyclic mobility	338.9
70	10	Loose saturated sand	338.9
71	10	Cu cost=200 high plasticity	358.9
72	10	Cu cost=200 low plasticity	358.9

Table 2. Characteristics of the 72 NEHRP Category D soil columns considered in this study.

Soil Column No.	Depth to Bedrock (m)	Soil Description	Vs30 [m/s]	NEHRP Category
1	40	NC clay high plasticity	118.6	E
2	40	NC clay low plasticity	118.6	E
3	60	NC clay high plasticity	118.6	E
4	60	NC clay low plasticity	118.6	E
5	80	NC clay low plasticity	118.6	E
6	80	NC clay high plasticity	118.6	E
7	100	NC clay low plasticity	118.6	E
8	100	NC clay high plasticity	118.6	E
9	150	NC clay low plasticity	118.6	E
10	150	NC clay high plasticity	118.6	E
11	40	OCR cost=2 low plasticity	130.3	E
12	40	OCR cost=2 high plasticity	130.3	E
13	60	OCR cost=2 high plasticity	130.3	E
14	60	OCR cost=2 low plasticity	130.3	E
15	80	OCR cost=2 low plasticity	130.3	E
16	80	OCR cost=2 high plasticity	130.3	E
17	100	OCR cost=2 low plasticity	130.3	E
18	100	OCR cost=2 high plasticity	130.3	E
19	150	OCR cost=2 high plasticity	130.3	E
20	150	OCR cost=2 low plasticity	130.3	E
21	20	NC clay high plasticity	148	E
22	20	NC clay low plasticity	148	E
23	20	OCR cost=2 high plasticity	159.7	E
24	20	OCR cost=2 low plasticity	159.7	E
25	40	Cu cost=100 high plasticity	160	E
26	40	Cu cost=100 low plasticity	160	E
27	40	OCR cost=8 low plasticity	170.8	E
28	40	OCR cost=8 high plasticity	170.8	E
29	60	OCR cost=8 low plasticity	170.8	E
30	60	OCR cost=8 high plasticity	170.8	E
31	80	OCR cost=8 high plasticity	170.8	E
32	80	OCR cost=8 low plasticity	170.8	E
33	100	OCR cost=8 low plasticity	170.8	E
34	100	OCR cost=8 high plasticity	170.8	E
35	150	OCR cost=8 low plasticity	170.8	E
36	150	OCR cost=8 high plasticity	170.8	E

Table 3. Characteristics of the 36 NEHRP Category E soil columns considered in this study

The soil columns collected for this study were selected according to the following criteria:

- A sufficient wide range of Vs_{30} within the boundaries of each NEHRP soil category.
- Various soil types with different amplification characteristics, including both non-plastic and plastic soils, and sufficiently wide ranges of relative density (in non-plastic soils) and overconsolidation ratios (in plastic soils).
- Inclusion of non-plastic soils both sensitive and non-sensitive to cyclic mobility effects.
- A sufficiently wide range of bedrock depths and columns elastic fundamental frequencies, as these quantities are known to significantly impact site amplification.

Fourteen different homogeneous *soil conditions* are represented:

1. Loose *saturated* sand with *no cyclic mobility*,
2. Dense *saturated* sand with *no cyclic mobility*,
3. *Saturated* gravel with *no cyclic mobility*,
4. Loose *saturated* sand with *cyclic mobility*,
5. Dense *saturated* sand with *cyclic mobility*,
6. *Saturated* gravel with *cyclic mobility*,
7. Normally consolidated – *low plasticity* clay/silt;
8. Normally consolidated – *high plasticity* clay/silt;
9. Overconsolidated with constant OCR ($2 \leq OCR \leq 20$ *constant* with depth) – *low plasticity* clay/silt;
10. Overconsolidated with constant OCR ($2 \leq OCR \leq 20$ *constant* with depth) – *high plasticity* clay/silt;
11. Overconsolidated with constant Cu ($50 \leq Cu \leq 350$ *constant* with depth) – *low plasticity* clay/silt;
12. Overconsolidated with constant Cu ($50 \leq Cu \leq 350$ *constant* with depth) – *low plasticity* clay/silt;
13. Overconsolidated with variable OCR (OCR *variable* with depth – $300kPa \leq p_{top} \leq 1500kPa$) – *low plasticity* clay/silt;
14. Overconsolidated with variable OCR (OCR *variable* with depth – $300kPa \leq p_{top} \leq 1500kPa$) – *high plasticity* clay/silt.

All saturated sand and gravel sites were analyzed with and without susceptibility to cyclic mobility effects. In the latter case the two model parameters that in SUMDES control pore pressure build up, namely *d* and *k*, were deactivated (i.e., d=k=100), whereas in the former case d=5 and k=0.5 were assumed. These values imply a moderate level of cyclic mobility not representative of complete liquefaction in very loose soils. Clays and silts were represented at various overconsolidation levels that were obtained by assuming mechanical consolidation under the action of a surface load ($300kPa \leq p_{top} \leq 1500kPa$) subsequently removed. The result is an overconsolidation ratio (OCR) that decreases with depth and that tends to one (i.e., normal consolidation conditions) at large depths. In cohesionless non-plastic soils, grain size characteristics are associated with different shapes of the stress-strain relationship (e.g., Seed *et al*., 1970; 1986; Stokoe *et al*., 2005) that is usually represented by the G/G_{max} vs. γ curve, where G is the current secant shear modulus, G_{max} is the shear modulus at very small strain levels, and γ is the single amplitude shear strain. In this study the $G/Gmax$ vs. γ curves for sands and gravels were established based on Stokoe *et al*. (2004). Similarly, in cohesive-plastic soils the shape of the G/G_{max} vs. γ curve is affected by the plasticity level and age (e.g., Vucetic and Dobry, 1991; Zhang *et al*., 2005), and the behavior of high plasticity/younger soils tends to display less nonlinearity than low plasticity/older materials in the low to medium strain range. In this study the G/G_{max} vs. γ curves for low plasticity and high plasticity soils are consistent with a plasticity index of about 15 (Vucetic and Dobry, 1991) and with a nearly non-plastic Quaternary soil as reported by Zhang *et al*. (2005). For high plasticity soil the G/G_{max} vs. γ curves are consistent with a plasticity index of about 50 (Vucetic and Dobry, 1991) and with a Quaternary soil with plasticity index of about 100 (Zhang *et al*., 2005).

3. Database of ground motion records

Each one of the 143 soil columns has been subject to the suite of 51 rock accelerograms shown in Table 4. Note that the records were chosen, when possible, for sites with $Vs_{30} \geq 800$m/s.

#	Earthquake	Date	Station	Mw	R (km)	PGA [g]
1	SouthernCalif	11/22/52	San-Luis Obispo	6	76.3	0.04
2	SanFrancisco	03/22/57	Golden-Gate	5.3	11.1	0.10
3	SanFernando	06/28/66	Cedar	6.6	86.6	0.02
4	Parkfield	06/28/66	San-Luis Obispo	6.2	76	0.01
5	Litle	12/09/70	Creek-Cedar	5.3	18.9	0.01
6	San Fernando	09/02/71	Lake-Hughes#4	6.6	24.2	0.14
7	San Fernando	09/02/71	Pacoima-Dam	6.6	11.9	1.23
8	Tabas	09/16/78	Tabas	7.4	56.9	0.84
9	Coyote-Lake	06/08/79	Gilroy-Array	5.7	13.7	0.10
10	Norcia	09/19/79	Bevagna	5.9	36	0.02
11	Anza	02/25/80	Pinyon-Flat	5.2	12.7	0.11
12	Irpinia	11/23/80	Arienzo	6.9	77.2	0.03
13	Irpinia	11/23/80	Auletta	6.9	33.1	0.06
14	Irpinia	11/23/80	Bagnoli	6.9	22.6	0.14
15	Irpinia	11/23/80	Bisaccia	6.9	23.3	0.10
16	Irpinia	11/23/80	Sturno	6.9	30.3	0.25
17	Irpinia	11/23/80	Auletta-2	6.9	37.1	0.02
18	Irpinia	11/23/80	Bagnoli-2	6.9	22.3	0.05
19	Irpinia	11/23/80	Bisaccia-2	6.9	18.9	0.08
20	Irpinia	11/23/80	Sturno-2	6.9	26.6	0.07
21	MorganHill	04/24/84	GilroyArray1	6.2	16.2	0.07
22	MorganhHill	04/24/84	USCS-LickObs	6.9	16.3	0.04
23	Whittier	01/10/87	Mt-Wilson-1	6	19.6	0.12
24	Whittier	01/10/87	Mt-Wilson-2	5.3	18.7	0.16
25	Whittier	01/10/87	Vasquez	6	54.2	0.06
26	Whittier	01/10/87	LA	6	19.6	0.04
27	Hollister	01/10/87	Gilroy-Array	5.1	11.1	0.11
28	LomaPrieta	10/18/89	SFCliff	6.9	84.4	0.07
29	LomaPrieta	10/18/89	SFTelegraph	6.9	82	0.08
30	LomaPrieta	10/18/89	UCSC	6.9	17.9	0.31
31	LomaPrieta	10/18/89	SFRincon	6.9	79.7	0.08
32	LomaPrieta	10/18/89	Piedmont	6.9	78.3	0.08
33	LomaPrieta	10/18/89	Gilroy	6.9	11.2	0.41
34	LomaPrieta	10/18/89	SFPacific	6.9	81.6	0.06
35	LomaPrieta	10/18/89	Point	6.9	88.6	0.07
36	Cape-Medoncino	04/25/92	Petrolia	7	4.9	0.59
37	BigBear	06/28/92	Rancho	6.5	69.1	0.09
38	Northridge	01/17/94	Burbank	6.7	20	0.12
39	Northridge	01/17/94	LittleRock	6.7	46.9	0.07
40	Northridge	01/17/94	Wilson	6.7	36.1	0.23
41	Northridge	01/17/94	Vasquez	6.7	24.2	0.15
42	Northridge	01/17/94	Wonderland	6.7	22.7	0.11
43	Northridge	01/17/94	San-Susana	6.7	14.6	0.28
44	Northridge	01/17/94	Antelope	6.7	63.9	0.05
45	Northridge	01/17/94	Lake-Hughes#4	6.7	49.9	0.06
46	Northridge	01/17/94	Sandberg	6.7	61.8	0.09
47	Northridge	01/17/94	Wrightwood	6.7	77.6	0.06
48	Northridge	01/17/94	Pacoima-Dam	6.6	11.9	0.42
49	Northridge	01/17/94	Pacoima-Dam	6.7	20.4	0.43
50	SanFernando	01/17/94	Pasadena-Seismo	6.6	39.1	0.09
51	Kobe	01/16/95	University	6.9	0.2	0.31

Table 4. List of accelerograms used in this study. Legend: Mw=moment magnitude; R=rupture-to-site distance.

4. Amplification functions

To summarize, in the following we compare plots of the median amplification functions, $AF(f)$, as a function of the oscillator frequency, f, for different NEHRP soil categories (Figure 1a) and subcategories (Figure 1b and Figure 2). These amplification functions were obtained running all the records in Table 4 through all the soil columns specified in the caption of each figure. Figure 1a shows, for example, that moving from NEHRP category C to categories D and E the frequencies of maximum amplification decreases considerably from about 8Hz for NEHRP C to about 0.8Hz for NEHRP E, while the median values of the maximum amplification factors increase from about 1.7 to more than 2.5. From Figure 1b and Figure 2 it can be observed that when the soil plasticity increases, both the frequency of maximum amplification and the maximum amplification values tend to increase for categories C and D. This is not the case for NEHRP E soils. In all cases high plastic soils display higher amplification values at high frequencies and lower amplification values at low frequency. This trend is more pronounced for category D.

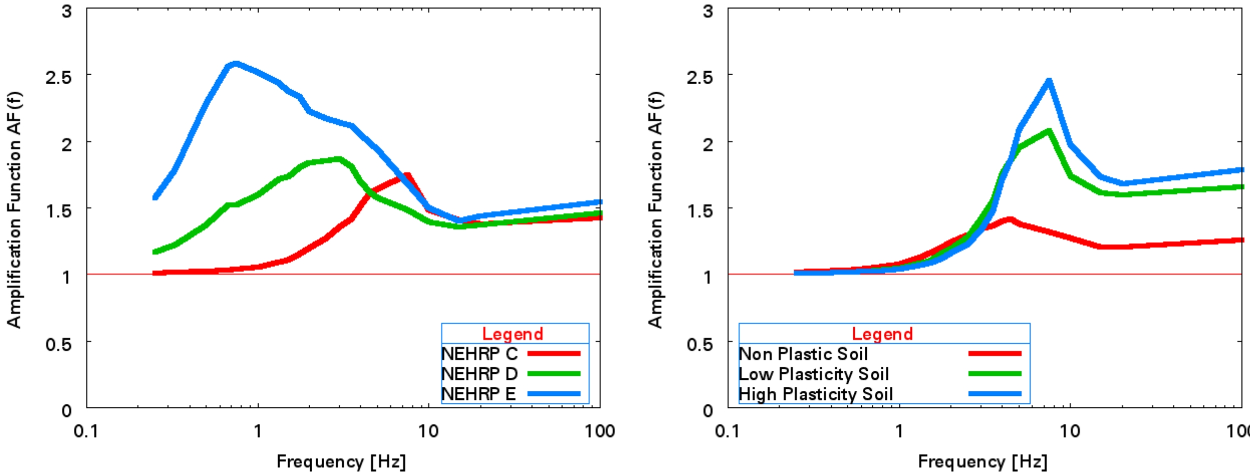
Note that the *AF(f)* curves in Figure 1 and Figure 2 do not show the effect of the nonlinearity of the soil response on *AF(f)*. The effect of the strength of the input motion and, therefore, of the nonlinearity of the soil response is shown in Figure 3 for NEHRP C and D soil columns and in Figure 4 for NEHRP E soil columns. These plots show that when the input bedrock motion increases the amplification at medium to high frequency tends to decrease due to soil nonlinearity. The opposite trend, although not as strong, is observed at low frequencies as non-linearity induces a reduction in the frequency of maximum amplification. The latter phenomenon appears to be more pronounced in categories C and D, where it is hardly observed in category E.

A more formal analysis of the effect of the input motion on the amplification curve of NEHRP D soil columns is shown in Figure 5 for f=1Hz and f=5Hz and in Figure 6 for PGA. Note that in these last two figures the strength of the input motion is measured by the 5%-damped spectral acceleration, $S_a^r(f)$, at the same oscillator frequency at which the *AF* is sought. The regression model fit is quadratic in log space, namely:

$$\ln AF(f) \approx a + b \ln S_a^r(f) + c\left(\ln S_a^r(f)\right)^2 + \varepsilon_{\ln AF(f)} \sigma_{\ln AF(f)} \qquad (2)$$

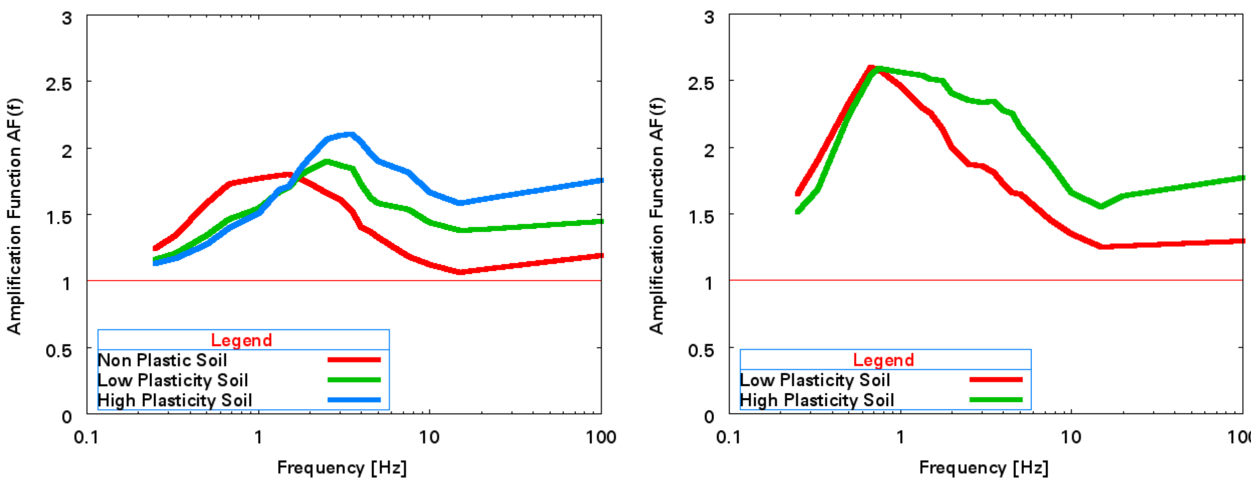
where a, b, and c are regression coefficients; $\sigma_{\ln Af(f)}$ is the standard deviation of *AF(f)* conditional on $S_a^r(f)$ (i.e., the standard error of estimation from the statistical regression); and $\varepsilon_{\ln Af(f)}$ is a standard normal variable. Each of the green data points is the result of a nonlinear soil response analysis of one of the columns in this category subject to one of the accelerograms in Table 4. The regression parameters a, b, and c and the value of $\sigma_{\ln Af(f)}$ for 21 values of f between 0.25Hz and 100Hz (i.e., PGA) for NEHRP soil category C, D, and E are listed in Table 5, Table 6, and Table 7, respectively. The rock spectral acceleration range of applicability of each model is also provided. The values of the parameters of Equation 2 that generated the curves in Figure 5 and Figure 6 are highlighted in Table 6. The shape of the regression curve varies considerably with frequency. At very low frequencies (not shown) no significant soil nonlinearity develops and therefore the amplification function is nearly horizontal with no or little amplification. At higher frequencies amplification at low to medium ground motion levels increases and the effects of soil nonlinearity is found to dominate the site response.

Finally, Figure 7 and Figure 8 show the variability of the median *AF(f)* for NEHRP D soil columns of different plasticity levels. Note that this total variability is due to both the record-to-record variability in *AF(f)* for the same soil column and to the column-to-column variability in *AF(f)*. The variability in the median *AF(f)*for NEHRP D soil columns does not seem to be significantly affected by the level of plasticity of the soil.



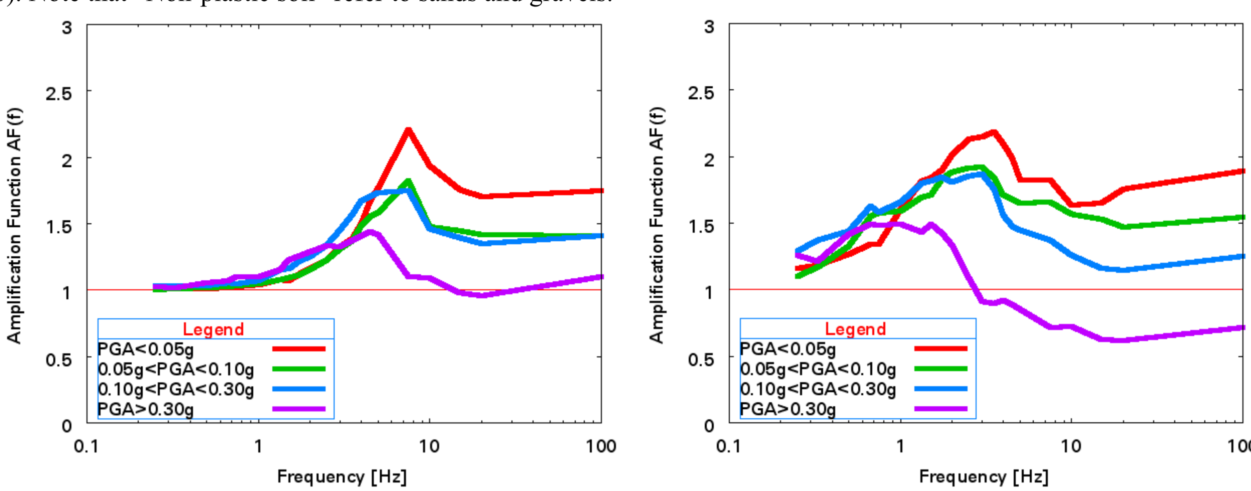
(a) (b)

Figure 1: (a) Median *AF(f)* for the NEHRP soil categories C, D, and E. (b) Effects of soil plasticity on the median *AF(f)* curves of NEHRP C soil columns. Note that "Non-plastic soil" refer to sands and gravels.



(a) (b)

Figure 2: Effects of soil plasticity on the median *AF(f)* curves of NEHRP D soil columns (a) and NEHRP E soil columns (b). Note that "Non-plastic soil" refer to sands and gravels.



(a) (b)

Figure 3: Effects of the severity of the input motion, here measured in terms of the PGA of the input record, on the median *AF(f)* curves of NEHRP C soil columns (a) and NEHRP D soil columns (b). The change in shape of the AF(f) curve is due to the nonlinearity in the soil response.

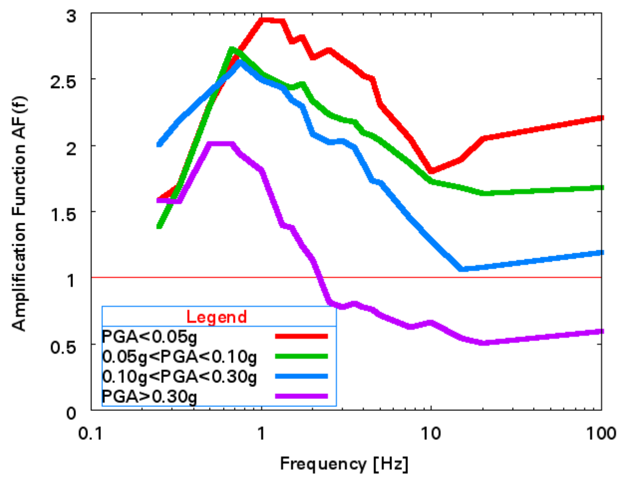


Figure 4: Effects of the severity of the input motion, here measured in terms of the PGA of the input record, on the median *AF(f)* curves of NEHRP E soil columns.

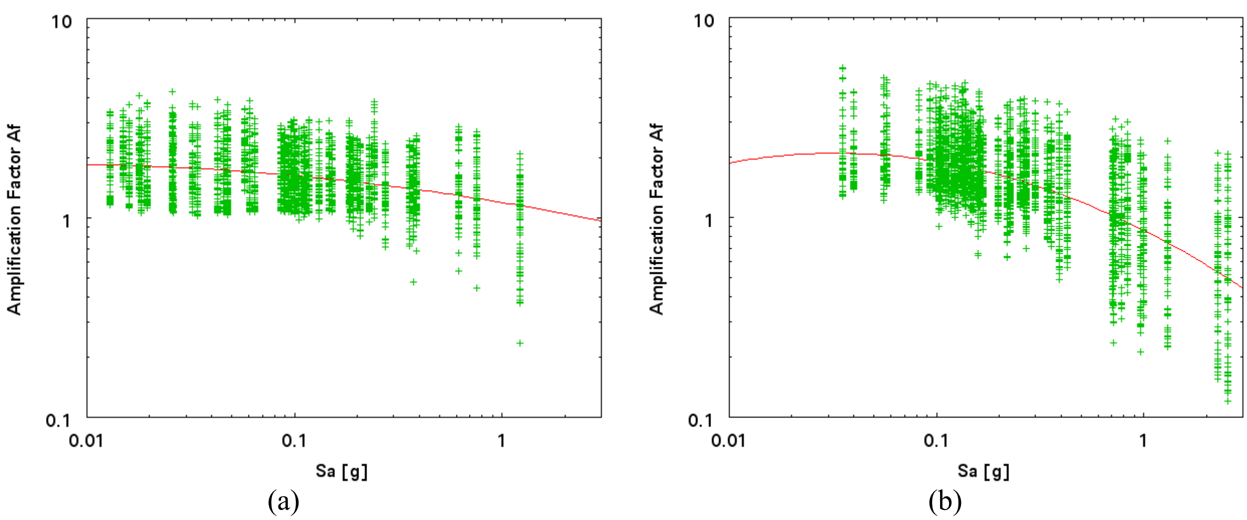


Figure 5: Median *AF(1Hz)* curve (a) and *AF(5Hz)* curve (b) for NEHRP D soil columns. The data points in green are the results of all the nonlinear dynamic analyses performed on the soil columns using the records in Table 4

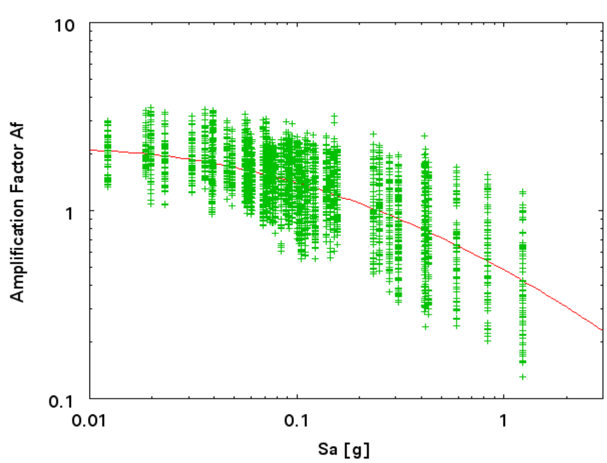


Figure 6: Median *AF(100Hz)* curve for NEHRP D soil columns. Note that 100Hz is associated with PGA. The data points in green are the results of all the nonlinear dynamic analyses performed on the soil columns using the records in Table 4.

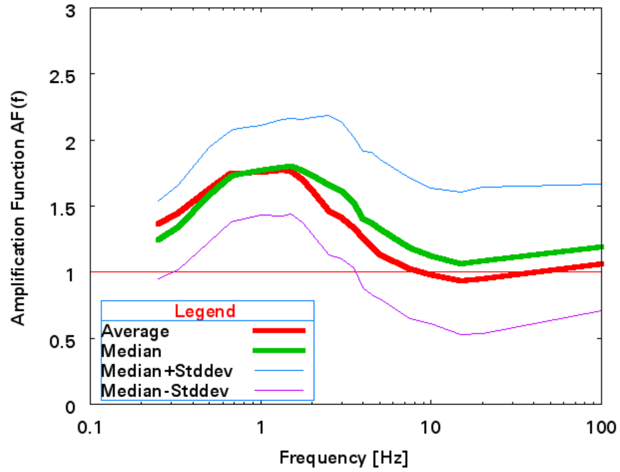
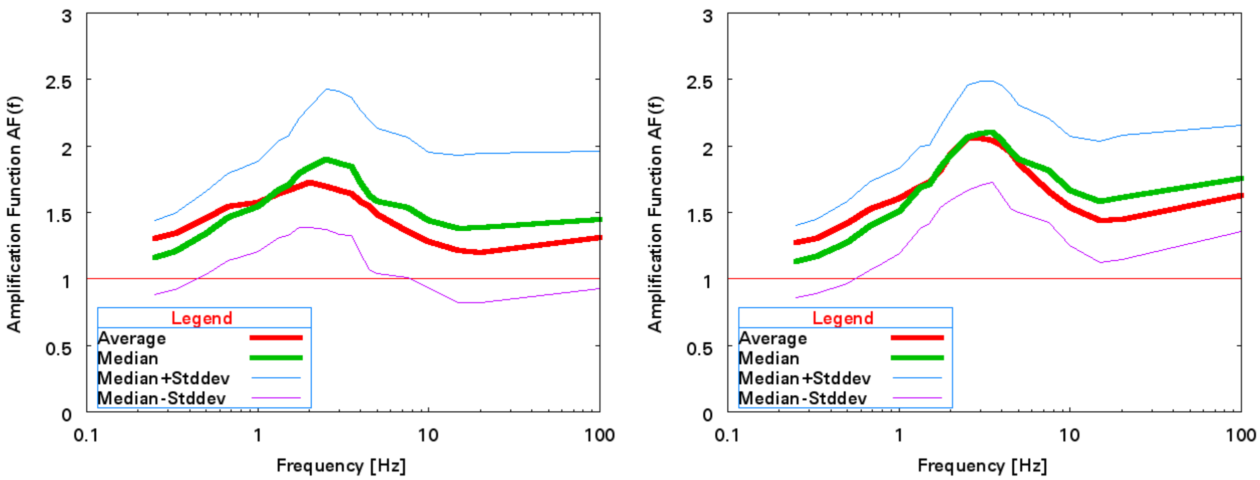


Figure 7. Average, median, and median ± one standard deviation *AF(f)* curves for non-plastic (i.e., sand and gravel) NEHRP D soil columns.



(a) (b)

Figure 8: Average, median, and median ± one standard deviation *AF(f)* curves for low-plasticity (a) and high-plasticity (b) NEHRP D soil columns

Freq. [Hz]	a	b	c	σ	*Sa* min [g]	*Sa* max [g]
0.25	0.080	0.000	0.000	0.113	0.00	0.17
0.33	0.070	0.000	0.000	0.109	0.00	0.29
0.5	0.071	0.000	0.000	0.108	0.00	0.53
0.67	0.077	0.000	0.000	0.102	0.00	0.83
0.75	0.080	0.000	0.000	0.100	0.00	1.00
1	0.092	0.000	0.000	0.114	0.01	1.22
1.33	0.130	0.000	0.000	0.129	0.01	1.58
1.5	0.144	0.000	0.000	0.137	0.01	1.45
1.75	0.177	0.000	0.000	0.150	0.02	1.31
2	0.203	0.000	0.000	0.159	0.02	1.65
2.5	0.262	-0.006	-0.004	0.185	0.02	2.89
3	0.261	-0.060	-0.014	0.212	0.03	1.83
3.5	0.316	-0.075	-0.018	0.261	0.02	2.01
4	0.358	-0.131	-0.034	0.297	0.03	3.33
4.5	0.363	-0.162	-0.032	0.337	0.02	2.64
5	0.369	-0.177	-0.034	0.360	0.04	2.55
7.5	0.208	-0.333	-0.054	0.384	0.03	2.42
10	0.127	-0.275	-0.042	0.336	0.02	1.88
15	-0.036	-0.261	-0.027	0.296	0.02	1.89
20	-0.150	-0.329	-0.041	0.290	0.01	1.82
100	-0.070	-0.265	-0.028	0.270	0.01	1.23

Table 5 Regression parameters of Equation 2 for NEHRP Soil Category C

Freq. [Hz]	a	b	c	σ	*Sa* min [g]	*Sa* max [g]
0.25	0.269	0.000	0.000	0.222	0.00	0.17
0.33	0.305	0.000	0.000	0.255	0.00	0.29
0.5	0.396	0.000	0.000	0.317	0.00	0.53
0.67	0.464	0.000	0.000	0.332	0.00	0.83
0.75	0.471	0.000	0.000	0.332	0.00	1.00
1	0.178	-0.175	-0.017	0.319	0.01	1.22
1.33	0.186	-0.207	-0.020	0.317	0.01	1.58
1.5	0.186	-0.240	-0.029	0.314	0.01	1.45
1.75	0.102	-0.376	-0.060	0.326	0.02	1.31
2	0.090	-0.387	-0.056	0.357	0.02	1.65
2.5	0.039	-0.435	-0.056	0.400	0.02	2.89
3	-0.084	-0.559	-0.082	0.383	0.03	1.83
3.5	-0.092	-0.530	-0.073	0.381	0.02	2.01
4	-0.117	-0.553	-0.083	0.407	0.03	3.33
4.5	-0.137	-0.525	-0.071	0.423	0.02	2.64
5	-0.151	-0.522	-0.077	0.412	0.04	2.55
7.5	-0.324	-0.577	-0.088	0.382	0.03	2.42
10	-0.421	-0.574	-0.085	0.401	0.02	1.88
15	-0.631	-0.586	-0.069	0.407	0.02	1.89
20	-0.774	-0.632	-0.068	0.393	0.01	1.82
100	-0.729	-0.609	-0.063	0.361	0.01	1.23

Table 6 Regression parameters of Equation 2 for NEHRP Soil Category D.

Freq. [Hz]	a	b	c	σ	*Sa* min [g]	*Sa* max [g]
0.25	0.511	0.000	0.000	0.281	0.00	0.17
0.33	0.610	0.000	0.000	0.315	0.00	0.29
0.5	0.396	-0.157	-0.011	0.340	0.00	0.53
0.67	0.329	-0.319	-0.036	0.302	0.00	0.83
0.75	0.183	-0.426	-0.051	0.290	0.00	1.00
1	-0.070	-0.622	-0.081	0.279	0.01	1.22
1.33	-0.015	-0.545	-0.064	0.286	0.01	1.58
1.5	-0.051	-0.595	-0.076	0.303	0.01	1.45
1.75	-0.129	-0.678	-0.097	0.315	0.02	1.31
2	-0.150	-0.653	-0.091	0.329	0.02	1.65
2.5	-0.168	-0.653	-0.086	0.349	0.02	2.89
3	-0.260	-0.749	-0.110	0.336	0.03	1.83
3.5	-0.227	-0.701	-0.100	0.339	0.02	2.01
4	-0.266	-0.745	-0.114	0.343	0.03	3.33
4.5	-0.275	-0.710	-0.100	0.351	0.02	2.64
5	-0.274	-0.710	-0.109	0.347	0.04	2.55
7.5	-0.411	-0.698	-0.101	0.318	0.03	2.42
10	-0.533	-0.701	-0.101	0.327	0.02	1.88
15	-0.812	-0.728	-0.083	0.328	0.02	1.89
20	-0.993	-0.775	-0.079	0.316	0.01	1.82
100	-1.069	-0.808	-0.082	0.304	0.01	1.23

Table 7 Regression parameters of Equation 2 for NEHRP Soil Category E.

5. Conclusions

This report includes the median and dispersion values for the amplification functions computed for different soil categories (e.g., NEHRP Type C, D, and E) and subcategories (e.g., sands and gravels). The database of *AF(f)*'s is based on nonlinear dynamic analyses performed using the computer program SUMDES of 143 soil columns each subjected to 51 rock ground motions. Note that, due to space limitations, similar tables and figures for each column could not be provided. The interest reader is advised to contact the authors for further information.

Before these *AF(f)*'s can be confidently adopted in real-life applications, they should be validated against both empirical soil amplification data and results from other nonlinear soil response analysis software. In addition, to obtain stronger ground motion records to be used as input to the soil response analyses, the rock records could be scaled to higher levels of severity. However, whether these scaled records may produce biased *AF(f)*'s is currently unknown. We intend to investigate these two issues within the SCEC3 program.

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7. SCEC2 Publications

No peer-reviewed publications from this study yet.