A GEOTECHNICAL SEISMIC SITE RESPONSE EVALUATION PROCEDURE

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SUMMARY

A simplified empirically-based seismic site response evaluation procedure that includes a measure of the dynamic stiffness of the surficial materials and a measure of the depth to bedrock as primary parameters is introduced. This geotechnical site classification scheme provides an alternative to geologic-based and shear wave velocity-based site classification schemes. The proposed scheme is used to analyze the ground motion data from the Northridge and Loma Prieta earthquakes. Period-dependent and intensity-dependent spectral acceleration amplification factors for different site conditions are presented. The proposed scheme results in a significant reduction in standard deviation when compared with a simpler "rock vs. soil" classification system. The standard deviations resulting from the proposed classification scheme are comparable with the standard deviations obtained using the more elaborate (and costly) code-based average shear wave velocity classification scheme.

INTRODUCTION

Significant damage and loss of life has been directly related to the effect of local site conditions in recent earthquakes, such as the 1985 Mexico City, 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe earthquakes (e.g. Seed et al 1987, Chang et al. 1996). While there are potentially other factors contributing to damage (such as topographic and basin effects, liquefaction, ground failure, or structural deficiencies), the amplification of ground motion due to local site conditions plays an important part in increasing seismic damage. The correlation between site effects and building damage is dramatically illustrated in Figure 1 for the 1967 Caracas, Venezuela, Earthquake. Larger amounts of damage occurred when the natural period of the buildings and the site were closely matched. These observations suggest that a correct quantification of site effects is necessary for a complete assessment of seismic hazard. Moreover, the quantification of site effects must include a measure of uncertainty for its incorporation into a probabilistic seismic hazard assessment analysis.

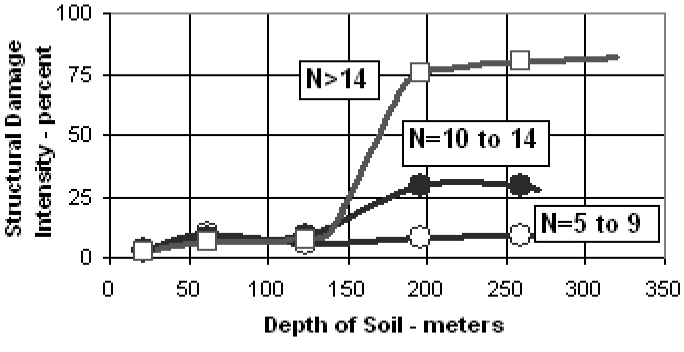

Figure 1. Relationship between structural damage intensity and soil depth in the Caracas Earthquake of 1967; N = # of stories (from Seed and Alonso 1974).

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The importance of site effects in characterizing seismic ground motions has long been recognized. Recently, Borcherdt (1994) developed intensity-dependent, short and long period amplification factors based on the average shear wave velocity measured over the upper 30 m of a site. This work, along with work by Seed [Seed et al.,1991] and Dobry [Dobry et al., 1994] has been incorporated into the 1997 Uniform Building Code (UBC). Using the average shear wave velocity to classify a soil profile has the advantage of simplicity and uniformity. As shown in Figure 1, site response is also a function of profile depth, thus ignoring profile depth may have a detrimental effect in ground motion prediction. Moreover, the Borcherdt [1994] site amplification factors are based primarily on observations from the 1989 Loma Prieta Earthquake, which shows significant nonlinear site response effects; whereas, observations from the 1994 Northridge Earthquake indicate that site amplification factors should not decrease as significantly with increasing ground motion intensity. Hence, the current code site factors may be unconservative, and this should be re-evaluated using the extensive Northridge ground motion database.

Site effects have also been introduced into most current attenuation relationships [e.g. Abrahamson and Silva, 1997]. However, most attenuation relationships account for site effects only through a broad site classification system that divides sites into "rock and shallow stiff soil", "deep stiff soil", and "soft soil" [e.g. Abrahamson and Silva, 1997]. Data from recent earthquakes show that a further refinement in this classification system is warranted and results in better predictions of seismic ground motions.

This paper introduces a new classification system that includes both a measure of soil stiffness and profile depth. The site classification system is applied to ground motion sites from two recent earthquakes, the 1989 Loma Prieta Earthquake and the 1994 Northridge Earthquake. Results are used to evaluate the validity of the proposed classification system and to compare its performance to a simplified "soil vs. rock" and to a shear wave velocity-based classification systems. Emphasis is placed on evaluating the importance of profile depth on site effects. Finally, spectral amplification factors with respect to a baseline site condition are presented. These factors can be incorporated into an attenuation relationship for a complete estimate of ground motion consistent with local soil conditions.

SITE CLASSIFICATION

The amplification of ground motions at a nearly level site is significantly affected by the natural period of the site ($T_n = 4H/V_s$; where T_n = natural period, H = soil depth, and V_s = shear wave velocity). Both dynamic stiffness and depth are important. Other important seismic site response factors include the impedance ratio between the soil deposit and underlying bedrock, the material damping of the soil deposits, and the nonlinear response of soft an potentially liquefiable soil deposits. The effect of nonlinearity is largely a function of soil type (e.g. plasticity index in Vucetic and Dobry, 1991). Factors such as cementation and geologic age may also affect the nonlinear behavior of soils. To account partially for these factors, a site classification scheme should include a measure of the dynamic stiffness of the site and a measure of the depth of the deposit.

The site classification scheme proposed herein is an attempt to account for the factors affecting seismic site response while minimizing the amount of data required for site characterization. The site classification scheme is based on two main parameters and two secondary ones. The primary parameters are:

- Type of deposit, i.e. hard rock, rock, weathered rock, stiff soil, soft soil, and potentially liquefiable sand. These general divisions introduce a measure of dynamic stiffness to the classification scheme. However, a generic description of a site is sufficient for classification, without the need for measuring shear wave velocity over the upper 30 m.

- Depth to bedrock or to a significant impedance contrast.

The secondary parameters are depositional age and soil type. The former divides soil sites into Holocene or Pleistocene groups, the latter into primarily cohesive or cohesionless soils. These subdivisions are introduced to capture the anticipated different nonlinear responses of these soils. Table 1 summarizes the geotechnical site classification scheme developed by Bray and Rodriguez-Marek [1997].

GROUND MOTION DATA

Ground motion data from two recent events, the 1989 Loma Prieta Earthquake and the 1994 Northridge Earthquake, were used in this study. The ground motion recordings were obtained from a database provided by Dr. Walter Silva from Pacific Engineering and Analysis [Silva, personal comm.]. The database consists of computed elastic spectral acceleration values at 5% damping. The ground motion sites included in the database were classified according to the site classification scheme presented in Table 1. A detailed list of sites and their corresponding classification is presented in Rodriguez-Marek et al. [1999].

Table 1. Geotechnical Site Categories [Bray and Rodriguez-Marek, 1997]

Site	Description	Site Period	Comments
A	Hard Rock	≤ 0.1 s	Hard, strong, intact rock (Vs ≥ 1500 m/s).
B	Rock	≤ 0.2 s	Most "unweathered" California rock cases (Vs ≥ 760 m/s or < 6 m of soil).
C-1	Weathered/Soft Rock	≤ 0.4 s	Weathered zone > 6 m and < 30 m (Vs ≥ 360 m/s increasing to ≥ 700 m/s).
-2	Shallow Stiff Soil	≤ 0.5 s	Soil depth > 6 m and < 30 m
-3	Intermediate Depth Stiff Soil	≤ 0.8 s	Soil depth > 30 m and < 60 m
D-1	Deep Stiff Holocene Soil, either S (Sand) or C (Clay)	≤ 1.4 s	Soil depth > 60 m and < 210 m. Sand has low fines content (< 15%) or non-plastic fines (PI < 5). Clay has high fines content (> 15%) and plastic fines (PI > 5).
-2	Deep Stiff Pleistocene Soil, S (Sand) or C (Clay)	≤ 1.4 s	Soil depth > 60 m and < 210 m. See D1 for S or C sub-categorization.
-3	Very Deep Stiff Soil	≤ 2 s	Soil depth > 210 m.
E-1	Medium Depth Soft Clay	≤ 0.7 s	Thickness of soft clay layer 3 m to 12 m.
-2	Deep Soft Clay Layer	≤ 1.4 s	Thickness of soft clay layer > 12 m.
F	Special, e.g., Potentially Liquefiable Sand or Peat	≈ 1 s	Holocene loose sand with high water table ($z_w \leq 6$ m) or organic peats.

STATISTICAL ANALYSIS

The ground motion sites were divided into the major categories indicated in the site classification scheme (Table 1). The Northridge Earthquake lacks measurements at soft soil sites (Site E), and ground motion stations at soft soil sites in the Loma Prieta Earthquake are poorly distributed with regards to distance. For these reasons, soft soils (Site E) were excluded from the analysis. Similarly, potentially liquefiable soils (Site F) were excluded from the statistical analysis, because their response is a result of a number of factors that cannot be easily categorized for these earthquakes. A further subdivision of site categories C and D into the sub-categories listed in Table 1 was also studied, and is presented elsewhere [Rodriguez-Marek et al., 1999]. In summary, although Pleistocene clay deposits produced more amplification than the other sub-categories, the limited database precluded adding these sub-categorizations at this time.

A regression analysis was performed to obtain event and site specific attenuation relationships for acceleration response spectral values at selected periods. Details on the regression analysis are presented elsewhere [Rodriguez-Marek et al., 1999]. Results for each earthquake are shown in Figure 2. In general, the major site categories presented in Table 1 show distinct behavior. In the following section, the earthquake-specific attenuation relationships obtained using the classification system introduced in this work are compared with results from a simplified “Rock vs. Soil” classification scheme. The results from the regression analyses are also used to evaluate the effect of profile depth in site response.

EVALUATION OF RESULTS

Comparison with a simplified Rock vs. Soil classification scheme

Most current attenuation relationships use a broad and general site classification, dividing sites in either rock/shallow soil or deep stiff soil, in addition to deep soft clay sites [e.g. Abrahamson and Silva, 1997]. This simplified site classification scheme is also often applied in design practice, especially in probabilistic seismic hazard assessment where uncertainties require quantification. Results from this study, however, show that this classification is an oversimplification, and a further subdivision of the generic "rock" site into two distinct categories is warranted [Rodriguez-Marek et al., 1999]. As a basis for comparison, the earthquake-specific attenuation model for the Northridge Earthquake developed by Somerville and Abrahamson [Somerville, personal comm.] is compared with the model developed in this study (see Figure 3). The Somerville and Abrahamson (S&A) model divides sites into rock/shallow soil (rock) and deep stiff soils (soil), as is done in most current attenuation relationships. Deep soft soil sites are excluded in this comparison.

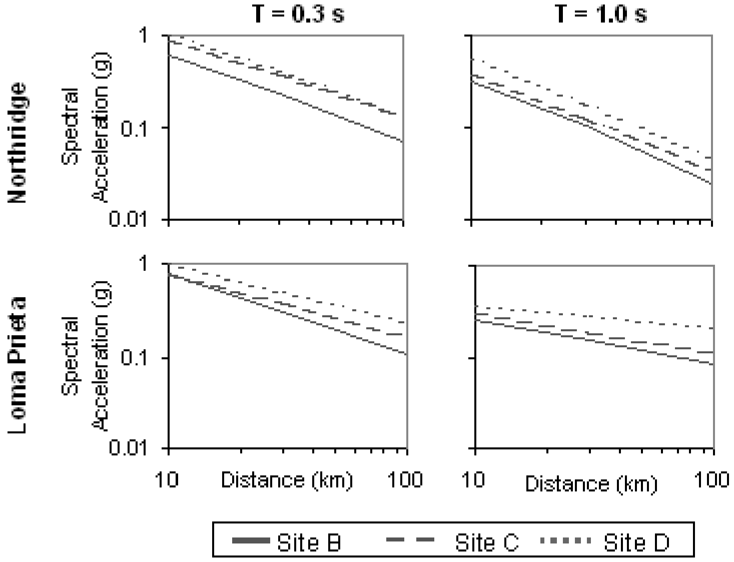

Figure 2. Event-specific attenuation relationships for selected periods. Median spectral acceleration values (5% damping) vs. distance.

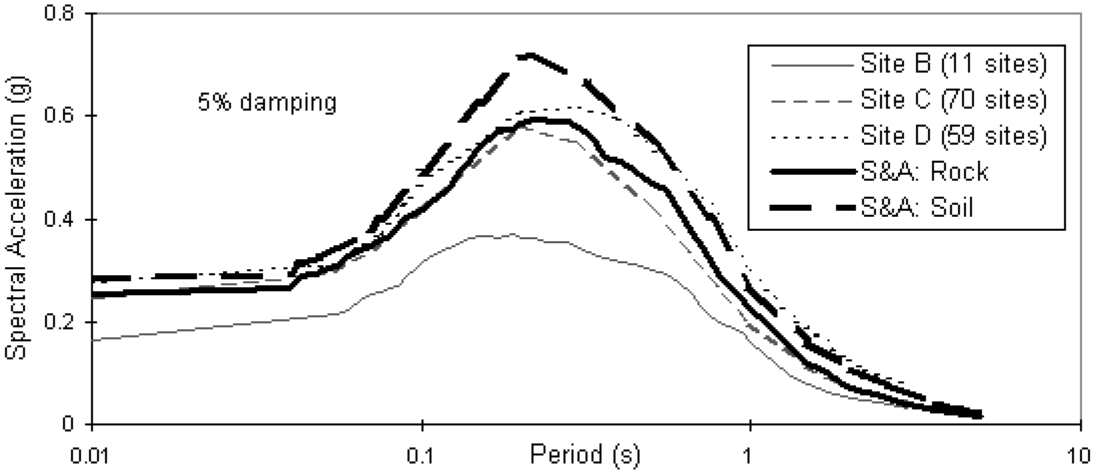

Figure 3. Response spectra for the Northridge Earthquake at a distance of 20 km. Comparison of a simplified "Rock vs. Soil" classification system with the classification system presented in this work.

In general, the spectra for soil sites in S&A generally match the spectra for Site D (deep stiff soils). However, the spectra for rock sites in S&A generally match the spectra for Site C (shallow and intermediate depth soils and weathered/soft rock). The latter finding reflects the fact that for the joint database of rock and shallow soil sites, 83% of the sites are shallow soil or weathered rock sites, and only 17% of these sites actually belong to the Site B classification (competent rock sites). This ratio may reflect the ratio prevalent in most attenuation relationships. This result is significant because the generic "rock" category of attenuation relationships is generally used as a baseline site condition for site-specific site response studies. The prevalence of weathered/soft rock and shallow depth soils in the generic "rock" category indicates that an unaccounted factor of safety is implicit in an analysis in which the generic "rock" category is used as competent bedrock in a traditional site response analysis. As more ground motion data becomes available, a review of the current ground motion database is necessary to identify a baseline condition based on a more discriminating site classification scheme. Of equal significance is the reduction of uncertainty that results from subdividing the generic "rock" category into the indicated subdivisions (See Table 2).

Table 2. Standard deviations for the earthquake specific attenuation relationship for the Northridge Earthquake (B&R-M) compared with standard deviations from an earthquake specific attenuation relationship by Somerville and Abrahamson (S&A; Somerville, personal comm.). Values of the standard deviation of the sample standard deviation are given in parenthesis.

Period	B&R-M Site B	B&R-M Site C	B&R-M Site D	S & A Rock	S&A Soil
PGA	.32 (.07)	.47 (.04)	.36 (.03)	.53	.48
0.3	.40 (.08)	.54 (.05)	.41 (.04)	.60	.51
1	.45 (.11)	.60 (.05)	.36 (.03)	.62	.48
2	.48 (.12)	.57 (.05)	.41 (.04)	.57	.60

Evaluation of profile depth as a factor in site response

Earlier versions of the United States Uniform Building Code (UBC) addressed site effects through a classification scheme based on site period, i.e., including both stiffness and profile depth as classification parameters. Recent codes, however, disregard the depth of the soil deposit and use mean shear wave velocity over the upper 30 m as the primary parameter for site classification. The choice of a single parameter for site classification has many practical advantages [Borcherdt, 1994], however, overlooking the importance of profile depth can lead to significant shortcomings.

For a comparison of the classification system presented herein with a shear wave velocity based classification system, the data set for both earthquakes was also divided according to the 1997 UBC (i.e. using the average shear wave velocity measured over the upper 30 m of the site). Table 3 compares the standard deviations at selected periods resulting from the regression analysis using both classification systems. The standard deviations obtained using both classification systems are comparable. Some reduction in the standard deviation is observed for soil sites at a period of one second. This is a result of the inclusion of depth as a classification criterion.

Table 3. Standard deviations at selected periods for the proposed and 1997 UBC classification schemes. Values of the standard deviation of the sample standard deviation are given in parenthesis.

	Northridge				**Loma Prieta**			
	T = 0.3 s		**T = 1.0 s**		**T = 0.3 s**		**T = 1.0 s**	
Site	B&R-M	UBC	B&R-M	UBC	B&R-M	UBC	B&R-M	UBC
B	.40(.07)	.46(.07)	.45(.11)	.52(.09)	.51(.08)	.52(.10)	.58(.10)	.61(.11)
C	.54(.05)	.54(.06)	.60(.05)	.54(.06)	.38(.05)	.36(.05)	.53(.08)	.52(.07)
D	.41(.04)	.42(.03)	.36(.03)	.41(.03)	.39(.06)	.39(.06)	.59(.09)	.64(.10)

The influence of profile depth, however, is best illustrated by observing the behavior of sites belonging to a common shear wave velocity classification category. Figure 4 shows the residuals for a period of 1 second for sites in the Northridge Earthquake that correspond to UBC category C (360 m/s < Vs ≤ 720 m/s). Observe that sites with larger profile depth have consistently higher residuals. This is a direct result of the increased site period due to a larger profile depth. Conversely, for sites with profile depths ranging from 6 m to 60 m. (i.e. sites belonging to category C for the classification system presented in this study) the residuals show a bias that is a function of the average shear wave velocity. That is, sites with a larger average shear wave velocity have lower mean residuals, while softer sites (i.e. with a lower average shear wave velocity) have higher mean residuals (Table 4). Interestingly, this bias was not observed for sites deeper than 60 m [Rodriguez-Marek et al., 1999]. These results clearly indicate that a classification system that includes both stiffness and profile depth is more complete and leads to better prediction of ground motions. From the viewpoint of the practitioner, these results indicate that the classification system presented herein performs at least as well as a classification system based on a more exhaustive measure of shear wave velocity. Moreover, the benefit of using a full measurement of the average shear wave velocity is more important for stiff soil sites with shallow to intermediate depths than it is for deep stiff soil sites.

Table 4. Mean residuals for Site C (soft/weathered rock and stiff soils shallower than 60 m).

Shear wave velocity	T = 0.3 s	T = 1.0 s
360 < Vs ≤ 720 m/s	-0.14	-0.34
180 < Vs ≤ 360 m/s	0.19	0.19

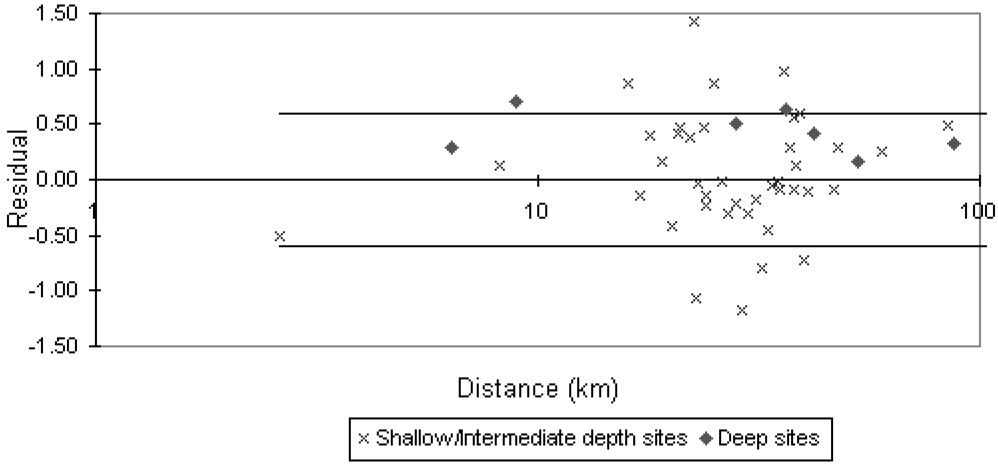

Figure 4. Residuals for a spectral period of 1 s for the Northridge Earthquake. All sites shown have a common shear wave velocity classification (360 m/s < Vs ≤ 720 m/s).

AMPLIFICATION FACTORS

To extend the applicability of the results presented in this work, spectral amplification factors with respect to a baseline site condition were developed. Following standard practice, rock (Site B) is used as the baseline site condition. However, as indicated before, current attenuation relationships use a baseline site condition that reflects mostly site condition C. Hence, care must be exercised if the amplification factors are used to adjust spectral values predicted using standard “rock” attenuation relations [see Rodriguez-Marek et al. 1999].

Spectral amplification factors are shown in Figure 5 for each earthquake. For the Loma Prieta Earthquake, a reduction in spectral amplification factors for increasing levels of base rock motion is observed for periods shorter than one second. This trend is consistent with nonlinear soil behavior. At periods greater than one second, spectral amplification values do not necessarily decrease with increasing levels of base rock motion, as soil response nonlinearity would also tend to increase the response at larger periods as the site softened. Other issues may have affected the data in this period range, such as basin effects and surface waves. In addition, rather than a reflection of soil response, these observations may be a result of the significant scatter of the data at long periods. Moreover, for high values of PGA, the attenuation relationships are not well constrained due to the lack of near-fault data for the Loma Prieta Earthquake. Amplification factors from the Northridge Earthquake do not show the same degree of nonlinearity, as do the results from Loma Prieta. Because the current UBC is based mainly on observational data from the Loma Prieta Earthquake [e.g. Borcherdt, 1994], amplification factors presented in the UBC may be misleadingly unconservative.

The spectral amplification factors from each earthquake were combined to develop a set of recommended amplification factors. The factors were combined at equal PGA values using a weighting scheme inversely proportional to the variance of the sample mean. The standard deviations for each site condition were averaged using the same weighting schemes. The resulting amplification factors are given in Table 5.

Table 5. Comparison of spectral amplification factors between this work (B&R-M) and the 1997 Uniform Building Code.

a) Average over the short period range, F_a (0.1 s – 0.5 s).

Z	.075		.15		.2		.3		.4	
Site	B& R-M	UBC	B& R-M	UBC	B& R-M	UBC	B& R-M	UBC	B& R-M	UBC
B	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C	1.5	1.2	1.3	1.2	1.3	1.2	1.2	1.1	1.2	1.0
D	1.8	1.6	1.6	1.5	1.6	1.4	1.5	1.2	1.4	1.1

b) Average over the mid-period range, F_v (0.4 s – 2.0 s).

Z	.075		.15		.2		.3		.4	
Site	B& R-M	UBC	B& R-M	UBC	B& R-M	UBC	B& R-M	UBC	B& R-M	UBC
B	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
C	1.4	1.7	1.3	1.7	1.3	1.6	1.3	1.5	1.2	1.4
D	2.1	2.4	2.0	2.1	1.9	2.0	1.8	1.8	1.8	1.6

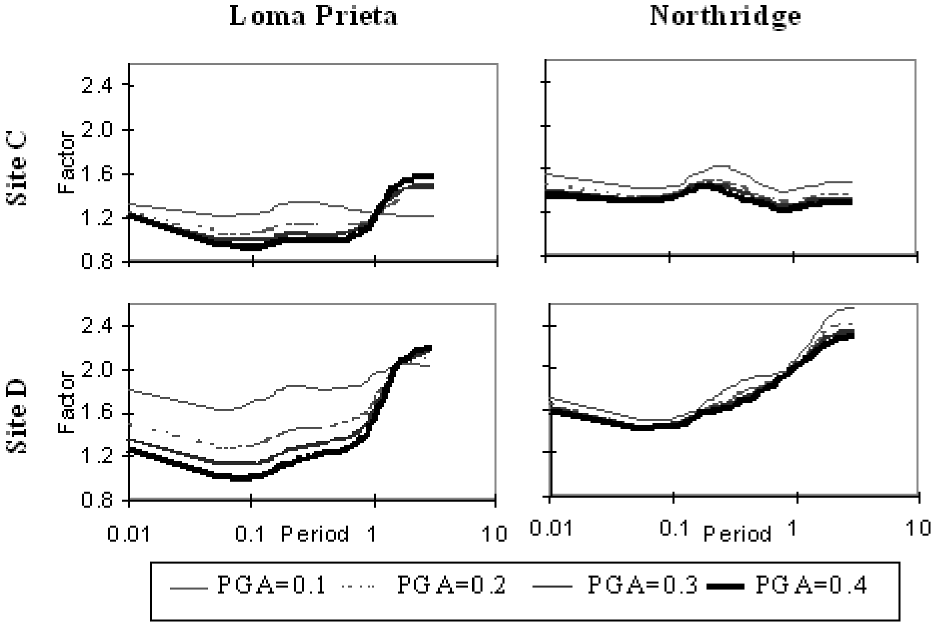

Figure 5. Spectral amplification factors with respect to Site B (Rock) for the Northridge and Loma Prieta Earthquakes.

CONCLUSIONS

A site classification scheme based on a general geotechnical characterization of the site that includes depth to bedrock as a key parameter is introduced. Two important conclusions were reached:

- Current attenuation relationships use as the baseline site condition a generic “rock” class that groups soft rock/shallow stiff soil and competent rock sites. The results shown in this paper indicate a significant difference in responses of these two site classes. This, in turn, highlights the need to review the database to redefine the baseline site condition for "rock" attenuation relationships.

- The standard deviations resulting from the proposed classification system are comparable with the standard deviations obtained using a more burdensome average shear wave velocity classification system. This illustrates that depth of the soil deposit is an important parameter for the estimation of seismic site response. A site classification scheme should account both for site stiffness and profile depth.

The spectral amplification factors presented in this work can be used in general probabilistic seismic hazard assessment. However, caution should be exercised when using these factors, because they are obtained from a data set containing only two earthquakes. Hence, intra-event scatter could be assessed for these two earthquakes, but inter-event scatter could not be evaluated conclusively.

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