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MODELS FOR INCORPORATING SITE EFFECTS INTO PROBABILISTIC SEISMIC HAZARD ANALYSES

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SUMMARY

Probabilistic seismic hazard analyses (PSHA) use empirical attenuation relations to define probability density functions (PDFs) for response spectral acceleration conditioned on magnitude and distance. These PDFs are typically lognormal, and thus are described by a median and standard deviation. Within the context of PSHA, site effects are important to the extent that they may (1) bias the median relative to what would be obtained from attenuation relations and (2) affect the standard deviation. In this paper we summarize recent work that enables the median and standard deviation from attenuation models to be adjusted to account for local site conditions. The discussion will focus on two levels of detail regarding site data. The first level is the common case in which only general descriptors of site characteristics are available such as surface geology or $V_{s\text{-}30}$ (average shear wave velocity in upper 30 m). We identify the most effective of those descriptors, and for the corresponding site categories present empirical amplification models for median spectral acceleration and site-dependent standard deviations. The second level of data quality occurs when boring logs and in situ velocity measurements are available, which enables geotechnical ground response analyses to be performed. We compare the bias and standard deviation of spectral accelerations estimated from ground response analyses and site amplification factors. We find that ground response analyses are most beneficial for soft soil site conditions, and present guidelines for integrating the analysis results into PSHA.

1.0 INTRODUCTION

Earthquake ground motions at soil sites are affected by source, path, and local site response effects. Those effects are typically combined for implementation using probabilistic seismic hazard analyses (PSHA). Hazard analyses use empirical attenuation relations that define a probability density function for a ground motion intensity measure (such as response spectral acceleration, S_a) conditioned on the occurrence of an earthquake with a particular magnitude at a particular distance from the site. Attenuation relations include site effects through a site term, which is derived using data from all sites within broadly defined categories

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(e.g., rock and soil). It is possible that for a particular site condition the predictions from attenuation relations are inaccurate. There are two meanings associated with this use of the word “inaccurate.” First, the predictions could have bias, which is the difference between the medians of observed and calculated motions for the site condition. Second, the predictions could have an incorrect dispersion relative to observation. Two ways of accounting for site effects to improve the accuracy of ground motion predictions relative to attenuation are: (1) adjustment of attenuation predictions with amplification factors, and (2) site-specific geotechnical analysis of local ground response effects. Note that our terminology distinguishes “site” effects from “ground response” effects. Site effects refer to the cumulative effects of ground response, basin response, and surface topography. Ground response refers to the influence of relatively shallow geologic materials on (nearly) vertically propagating body waves (i.e., the 1-D wave propagation problem).

In engineering practice, site effects are most commonly accounted for using either site terms in attenuation relationships or NEHRP site factors, which utilize the $V_{s\text{-}30}$-based categorization scheme in Table 1 [1]. In this paper, we present an alternative methodology for evaluating site effects that was developed with the objective of minimizing bias and dispersion in ground motions estimates. In particular, the quality of a method of ground motion estimation is taken as its ability to provide unbiased ground motion estimates for the respective site categories and to have the smallest possible standard deviation. The minimization of standard deviation can be thought of as improving our ability to account for site-to-site variations in ground motion intensity measures.

Table 1. NEHRP site categories, after Dobry [1]

NEHRP Category	Description	Mean Shear Wave Velocity to 30 m ($V_{s\text{-}30}$)
A	Hard Rock	> 1500 m/s
B	Firm to hard rock	760-1500 m/s
C	Dense soil, soft rock	360-760 m/s
D	Stiff soil	180-360 m/s
E	Soft clays	< 180 m/s
F	Special study soils, e.g., liquefiable soils, sensitive clays, organic soils, soft clays > 36 m thick	

Detailed supporting documentation for the recommendations provided here is presented by Stewart [2], Baturay [3], and Choi [4]. In this paper, we distill a coherent set of recommendations from previous work, briefly describe the process by which the key aspects of the recommendations were arrived at, and then identify shortcomings (bias) in the NEHRP site factors that form the basis of most current U.S. practice.

2.0 RECOMMENDED GUIDELINES

An analysis of the probability density function for ground motion intensity measures at soil sites begins with the use of appropriate rock attenuation relationships. These relationships provide motions for representative average rock site conditions. For active tectonic regions such as most of California and portions of Turkey and Japan, this representative average rock site condition corresponds to relatively soft, weathered rock that would typically fall near the middle of NEHRP category C. Appropriate rock attenuation relations for such conditions include those of Abrahamson [5], Campbell [6], and Sadigh [7]. Application of such relationships yields a median and standard deviation of the intensity measure given a set of seismological variables (e.g., magnitude, distance, focal mechanism). The intensity measure considered here is 5% damped response spectral acceleration.

In the following, the standard deviation of an intensity measure is assumed to have two sources: station-to-station variability for a given earthquake (referred to as intra-event dispersion) and event-to-event variability (referred to as inter-event dispersion). This separation of dispersion sources is characteristic of random effects regression procedures (see Abrahamson [8] for details).

2.1 Methods for Evaluating Site Effects

In general, soil site effects will modify the median and standard deviation of ground motion estimates. The manner by which such modifications should be made depends on the site condition. If the site profile contains a significant impedance contrast (i.e., a jump in shear wave velocity across a layer interface of approximately a factor of two or more), that contrast is likely to significantly affect the nature of ground motions at the ground surface, and therefore should be directly considered in the analysis of site effects. The presence of such impedance contrasts is most common in profiles that include soft soils, such as lacustrine or marine clay sediments. Evaluations of site effects for such site conditions should utilize site-specific 1D ground response analyses with either equivalent-linear or non-linear analysis procedures.

Many soil profiles do not contain significant impedance contrasts. In California, this is often the case for alluvial soil sites or stiff soil sites deposited by other means. For this common site condition, site effects can be adequately captured using site amplification factors, which are defined relative to generalized descriptors of site condition. The most effective site descriptors are a site-specific V_{s-30} value or a detailed description of surface geology that takes into consideration sediment age + depositional environment or age + sediment texture.

2.2 Guidelines for Ground Response Analyses

The objective of ground response analysis is to estimate a ratio of response spectra (RRS), which is calculated from the ratio of outcropping ground surface motions to outcropping motions representative of reference rock. The RRS is used to modify the median rock spectrum to estimate the median soil spectrum. The analyses can be performed using equivalent-linear or non-linear analysis codes; however, the verification work discussed subsequently is based on equivalent-linear analysis.

A suite of input motions should be selected for magnitudes and distances similar to those controlling the site hazard and for rock site conditions. The number of time histories in the suite should be sufficiently large that a statistically stable estimate of RRS can be obtained. The motions should be scaled (single scale factor applied across all periods) to match the ordinates of the target rock spectrum in an average sense so that the effects of site nonlinearity are appropriately accounted for. The analyses should consider appropriate sources of variability, including: (1) variability in soil properties, as represented by shear wave velocity and modulus reduction/damping curves; and (2) variability in the frequency content and phasing of the scaled input motions. The dispersion in RRS, denoted σ_{RRS}, results from the variable levels of nonlinear response associated with the input motions and soil property variability as well as from the variable phasing of the input motions.

For periods $T < 1$ s, the median soil motion obtained by the above process is unbiased. At longer periods, ground response analyses may under-predict spectral accelerations, which instead should be estimated using amplification factors or attenuation relationships.

The standard deviation that should be used in conjunction with the median can be separated into two components – (1) σ_{RRS} and (2) uncertainties related to the imperfect nature of the target spectrum and imperfect modeling physics. The second uncertainty parameter, denoted as $\sigma_{g\text{-}net}$, has been estimated as follows:

> T < 1 s: $\sigma_{g\text{-}net}$ = 0.38 for soft clays, 0.56 for NEHRP Categories C-D
> T > 1 s: $\sigma_{g\text{-}net}$ evaluated from amplification factor or attenuation.

The total dispersion for use in PSHA (σ) can be calculated from the above values and σ_{RRS} as follows:

$$\sigma^2 = (\sigma_{g-net})^2 + (\sigma_{RRS})^2 + (0.23)^2 \tag{1}$$

The 0.23 factor in Eq. 1 represents inter-event dispersion as derived by Abrahamson [5]. The sum of the first two terms represents the intra-event dispersion.

2.3 Guidelines for Application of Amplification Factors

The use of site amplification factors involves three basic steps: (1) classify the site according to an appropriate categorization scheme, (2) calculate the median period-dependent amplification value [denoted $F(T)$] for the site category, (3) evaluate the appropriate dispersion level associated with the category and period.

Site descriptors found to be effective at minimizing intra-event standard deviation are a site-specific $V_{s\text{-}30}$ value or a detailed description of surface geology that takes into consideration sediment age + depositional environment or age + sediment texture. The quantity $V_{s\text{-}30}$ is calculated as the ratio of 30 m to the time for shear waves to travel from 30 m depth to the ground surface. With regard to surface geology schemes, recommended categories for materials of Quaternary age are delineated as follows:

<u>Depositional Environment</u>	<u>Material Texture</u>
Quaternary alluvium	Holocene coarse-grained
Holocene lacustrine/marine	Holocene fine/mixed texture
	Pleistocene

For rock sites (i.e., pre-Quaternary materials), geologic classifications are based principally on age [i.e., Tertiary (T) or a combined category of Mesozoic or igneous rock (M+I)].

With the use of the $V_{s\text{-}30}$-based site descriptor, median amplification factor F is evaluated as follows:

$$\ln(F) = c \ln\left(\frac{V_{s-30}}{V_{ref}}\right) + b \ln\left(\frac{PHA_r}{0.1g}\right) \tag{2}$$

where c and V_{ref} are regression coefficients. Velocity terms V_{ref} and $V_{s\text{-}30}$ have units of m/s, and PHA_r is in units of gravity. Parameter b represents the $V_{s\text{-}30}$-based site non-linearity term defined as follows

$$b = b_1 \qquad \text{Category E} \tag{3a}$$

$$b = b_2 + (V_{s-30} - b_V)^2 \frac{b_1 - b_2}{(180 - b_V)^2} \qquad 180 < V_{s\text{-}30} < b_V \text{ (m/s)} \tag{3b}$$

$$b = b_2 \qquad V_{s\text{-}30} > b_V \tag{3c}$$

where b_1, b_2, and b_V are model parameters. In the application of Eq. 3, sites are considered as Category E if the profile contains more than 3 m of soft clay (i.e., material with low shear strength and moderate to high plasticity; see BSSC [9] for details), regardless of V_{s-30}. The variation of b with V_{s-30} is shown in Figure 1 for spectral acceleration at T = 1 s. A complete set of regression parameters is presented by Choi [4]. Independent sets of regression parameters for use with Eqs. 2-3 were compiled for use with the rock attenuation relationships of Abrahamson [5], Campbell [6], and Sadigh [7].

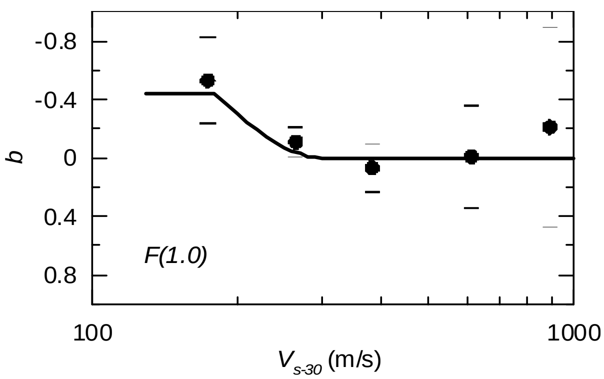

Fig. 1. Variation of site non-linearity factor *b* with V_{s-30} for 1.0 s period. Symbols indicate regression results for data within velocity categories, line represents model fit. Source: Choi [4]

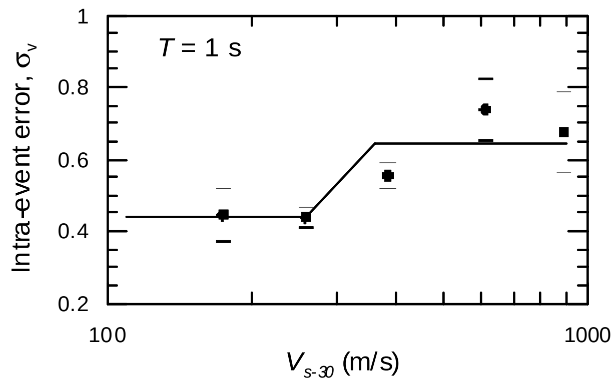

Fig. 2. Variation of inter-event error term σ_v with V_{s-30} for 1.0 s period. Symbols indicate regression results for data within velocity categories, line represents model fit. Source: Choi [4]

With the use of surface geology based classification schemes, median amplification factor F is evaluated as follows:

$$\ln(F) = a + b\ln(PHA_r) \tag{4}$$

where a and b are category- and period-dependent model parameters. Those parameters and intra-event error terms are compiled by Stewart [2] across the period range of 0.01 to 5 s and are intended for use with the rock attenuation relationship of Abrahamson [5].

The standard deviation term for use in PSHA (σ) can be taken as

$$\sigma = \sqrt{\sigma_v^2 + \sigma_e{}^2} \tag{5}$$

where σ_v denotes intra-event standard deviation from the amplification factor models and σ_e represents the inter-event error. Dispersion σ_e should be taken as 0.23 regardless of T if the geology-based amplification factor models are used (Eq. 4) [2, 5]. Period-dependent σ_e terms were compiled by Choi [4] for use with the V_{s-30}-based amplification model in Eqs. 2-3. Dispersion σ_v is tabulated as a function of period in the respective amplification factor models [2, 4].

3.0 JUSTIFICATION FOR RECOMMENDATIONS

The recommendations in Section 2 are supported by statistical analyses of earthquake ground motion data from shallow crustal earthquakes in active tectonic regions by Stewart [2], Baturay [3], and Choi [4]. Several specific recommendations are especially important and are elaborated upon in this section. Those recommendations are:

1. The guidelines regarding site conditions where geotechnical ground response analyses are worthwhile (presented in Section 2.1).
2. The recommendations related to the intra-event standard deviation associated with the results of geotechnical ground response analyses (presented in Section 2.2).
3. The recommended site categorization schemes (presented in Section 2.3).

3.1 Site Conditions where Geotechnical Ground Response Analyses are Worthwhile

The guidelines presented in Section 2.1 state that ground response analyses are recommended only for sites containing a significant impedance contrast. The corollary to those guidelines is that such analyses are not worthwhile for soil sites lacking significant impedance contrasts, which is often the case for California alluvial soil sites and many other stiff soil sites.

Those guidelines are based on work by Baturay [3] in which spectral accelerations from recordings were compared to predictions derived using ground response analysis procedures. Results were compiled for 134 motions from 68 sites, and prediction residuals were interpreted to assess model bias and dispersion.

The ground response analyses by Baturay [3] were performed using equivalent-linear procedures for sites with ground motion recordings and well characterized ground conditions, including in situ measurements of shear wave velocity and detailed descriptions of soil type. Input motions were generated through a process by which:

1. A target response spectrum for rock site conditions was estimated from rock attenuation relations [5] with appropriate corrections for rupture directivity effects [10, 11], weathered rock effects [12], and event-specific bias in the attenuation models (i.e., so-called event terms), and
2. Suites of time histories with appropriate magnitude, distance, and rupture directivity characteristics were scaled to match the target spectrum in average sense over the period range 0 – 1.0 s and then re-scaled such that the median of the suite matched the target spectrum while retaining natural record-to-record variability.

Because suites of input motions were used in the ground response analyses, suites of output motions were also obtained, the median of which was compared to the recordings. Also compared to the recordings were predictions from rock attenuation relations coupled with site factors [5, 2]. The results in Figure 3 were obtained by compiling those median predictions across many sites within various site categories.

Shown in the three rows of Figure 3 are category statistics for NEHRP Categories C-D and geology category Hlm = Holocene lacustrine and marine sediments. Hlm is shown here in lieu of NEHRP E because of a paucity of data in the NEHRP E category. The symbols in the figure are defined as follows:

Symbol μ denotes median
Symbol σ denotes standard deviation
Symbol se_{μ} denotes standard error of the median (i.e. uncertainty in the location of median)
Symbol se_{σ} denotes standard error of the standard deviation
Subscript *rg* denotes **r**esidual for **g**round response analysis results
Subscript *ras* denotes **r**esidual for **a**ttenuation with **s**ite factors

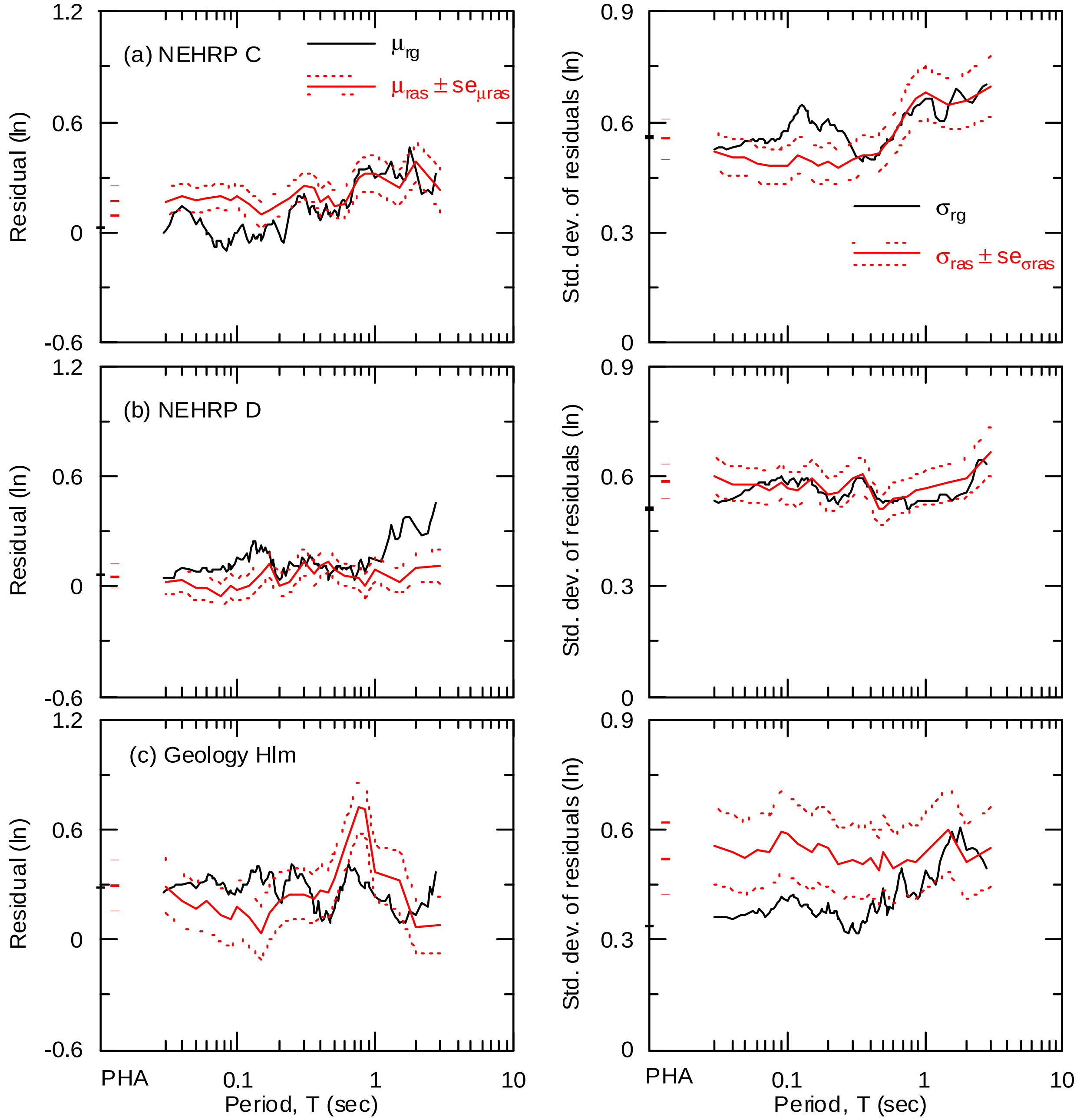

Fig. 3. Category residuals for NEHRP C-D sites and Hlm sites

The left frames of each row in Figure 3 show the median residuals (e.g., μ_{rg}) from ground response, attenuation, and attenuation with amplification factors, along with the error bounds on the median for the amplification factors model (i.e., $\mu_{ras} \pm se_{\mu ras}$). The right frames similarly show the standard deviation of the residuals (e.g., σ_{rg}) for all models along with the error bounds for the amplification factors model (i.e., $\sigma_{ras} \pm se_{\sigma ras}$).

The amplification factors model provides a convenient baseline set of results against which to compare the results of other models. This is because the amplification factors represent empirical customizations of the Abrahamson [5] attenuation relation for specific site categories, and are based on a large world-wide ground motion inventory. Hence, ground motion predictions obtained through use of the amplification models are the expected median for each category. Nonetheless, median residuals from the amplification model may be non-zero if the site data used in the ground response study are biased with respect to the available data for the category as a whole. From a qualitative standpoint, statistically significant bias is considered to occur when zero is not within the range of $\mu_{ras} \pm se_{\mu ras}$. As shown in Figure 3, this bias is generally not observed for NEHRP Category D, but is observed at all periods for Category C and near PHA and 1.0 s for Hlm. This bias results from the process by which sites are selected for detailed geotechnical ground characterization work – i.e., sites with unusually large ground motions are disproportionately selected. It is important to consider this bias, which is inherent to the database, when interpreting the bias reported for a particular prediction method such as ground response.

The first important issue that is discussed is the potential bias of ground response analysis results. For all site categories, initial inspection of Figure 3 suggests significant positive bias in ground response results (i.e., $\mu_{rg} > 0$) for many periods. However, the amount of this bias is generally not statistically distinct from the bias associated with the amplification factors, suggesting that the ground response analysis results themselves are *not* biased.

The second issue discussed is the reduction of dispersion of ground response results relative to alternative prediction methods. As shown in Figure 3, the standard deviation of residuals for Categories C-D from the ground response model and the amplification model are generally qualitatively similar (i.e., $\sigma_{rg} \approx \sigma_{ras}$) across the period range considered, whereas $\sigma_{rg} < \sigma_{ras}$ for Hlm at small periods (T < 1.0 s). Statistical testing confirmed these qualitative results, namely that for NEHRP C-D σ_{rg} and σ_{ras} are not significantly distinct, whereas for Hlm σ_{rg} is significantly smaller than σ_{ras} for T < 0.5-1.0 s. Those error terms are similar at longer periods for Hlm.

Based on the above discussion, ground response analyses are beneficial for soft soil sites such as those typically associated with lacustrine and marine sediments. The benefit of ground response results for those sites is that they better capture site-to-site variations in spectral acceleration at small periods (T < 1.0 s), leading to a smaller dispersion of prediction residuals. This dispersion has significance with respect to the intra-event dispersion that should be used in PSHA, as discussed further in the following section.

3.2 Standard Deviation of Ground Response Analysis Results

Guidelines for the calculation of standard deviation (σ) associated with ground response analysis results were provided above in Section 2.2, and are summarized by Eq. 1. Those guidelines are based on discretization of the full intra-event dispersion into contributions associated with:

1. Aleatory factors, including variability in the estimated target rock spectrum relative to the true rock spectral ordinates (this in analogous to the dispersion represented by the standard deviation in attenuation models) and variability in the true site response physics relative to those modeled by 1D ground response analyses. This uncertainty was referred to as $\sigma_{g\text{-}net}$.

2. Known sources of uncertainty, such as the variability in RRS due to random soil properties and input motions (e.g., σ_{RRS}).

Baturay [3] derived $\sigma_{g\text{-}net}$ from the data set described above in Section 3.1. This was accomplished by reducing the variance associated with the σ_{rg} values shown in Figure 3 by the variance associated with known sources of uncertainty, which in the case of Baturay's analyses included σ_{RRS} and the standard error of the input (rock) spectrum. The latter source of known uncertainty was included because the ground response predictions were taken directly from the calculated surface waveforms, and not as the product of RRS and the input (rock) spectrum, which would ordinarily be done in a design context.

The results of Baturay's $\sigma_{g\text{-}net}$ calculations are shown in Figure 4. The results suggest similar levels of dispersion for Categories C and D, but a much lower level of dispersion for Hlm at low periods ($T < 1$ s). For $T > 1$ s, net dispersion levels for the three categories are approximately equal. The guidelines given in Section 2.2 for $\sigma_{g\text{-}net}$ are average values across the appropriate period ranges from Figure 4.

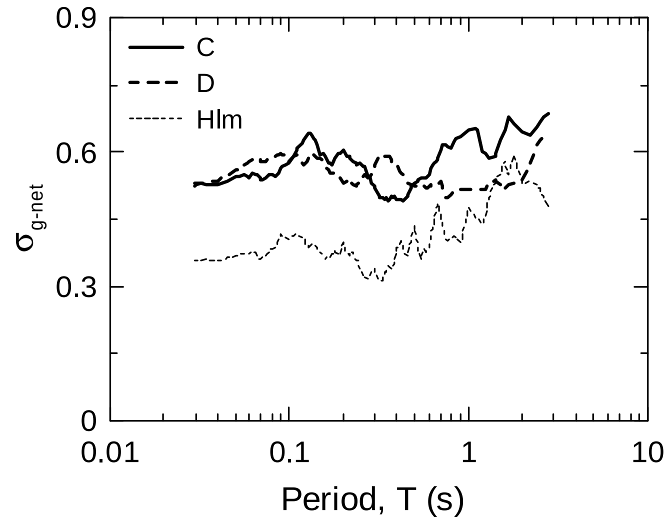

Fig. 4. Variation with period and site category of ground response prediction dispersion associated with aleatory uncertainty in input spectra and imperfect modeling physics

3.3 Recommended Site Categorization Schemes

As described in the introduction (Section 1.0), the quality of a method of ground motion estimation can be assessed by its ability to provide unbiased ground motion estimates and the smallest possible standard deviation. Low standard deviation implies that the method accurately captures site-to-site variations in ground motion intensity measures, which are produced in part by local variations in site condition. In Section 3.1, it was shown that ground response analyses can reduce dispersion relative to site amplification factors for relatively young lacustrine or marine soils. However, for the more common case of alluvial soils, ground response analyses were not found to reduce dispersion levels. Hence, for such conditions our emphasis shifts to identifying the method of site classification that produces the lowest standard deviation of prediction residuals.

Stewart [2] and Choi [4] developed site amplification factors for most of the common methods of classifying site condition. Those methods included:

1. Surface geology-based classifications based only on sediment age, or based on age supplemented with information on sediment texture or depositional environment
2. NEHRP site categories defined on the basis of $V_{s\text{-}30}$.
3. Geotechnical categories defined on the basis of soil stiffness and approximate thickness (Rodriguez-Marek [13])
4. Direct use of $V_{s\text{-}30}$ as the site descriptor.

Site classification techniques (1)-(3) utilize discrete site categories. Stewart [2] classified a large number of strong motion sites according to those categories, and calculated site factors as the residuals from the rock attenuation relationship of Abrahamson [5]. For a given classification scheme with M categories and N_i strong motion records within category i, an inter-category standard deviation term (σ_R) was calculated as follows:

$$\sigma_R = \sqrt{\frac{\sum_{i=1}^{M} \sum_{j=1}^{N_i} \left(\varepsilon_{ij} - \varepsilon_i\right)^2}{\left(\sum_{i=1}^{M} N_i\right) - 2M}} \tag{6}$$

where ε_{ij} = prediction residual of ground motion j within category i, and ε_i = median residual across N_i motions in category i. Inter-category standard deviation σ_R represents the average dispersion of data within all categories belonging to a given scheme. This was calculated for three geology-based classification schemes along with the geotechnical and NEHRP scheme, with the results shown in Figure 5 for soil categories.

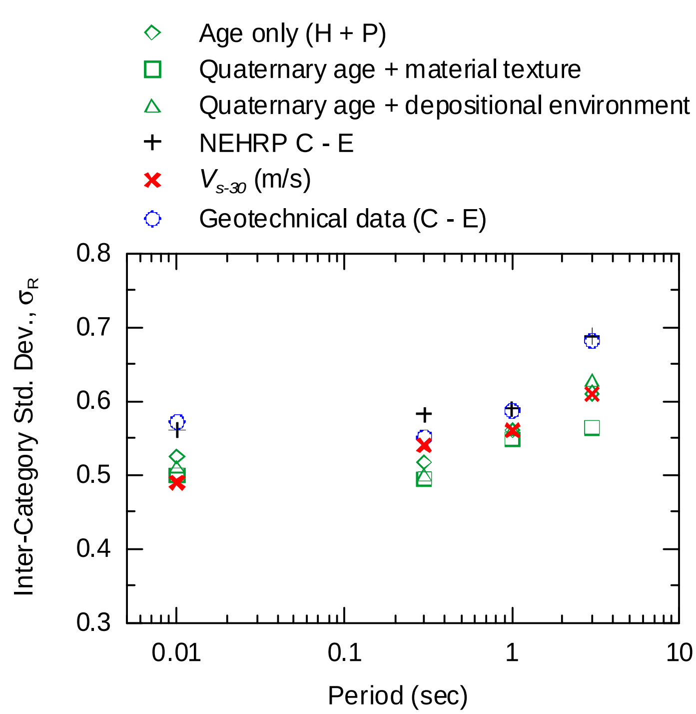

Fig. 5. Inter-category standard deviation terms for spectral acceleration, soil categories.

Site classification technique (4) above (direct use of V_{s-30} as the site descriptor) was utilized by Choi [4] in the development of amplification factors and standard deviation terms that are direct functions of V_{s-30}. The average prediction residual across all values of V_{s-30} from that site amplification model is analogous to σ_R as calculated by Eq. 5 for a discrete-category classification scheme. Accordingly, those prediction residuals are also plotted in Figure 5.

The largest error terms at all periods are obtained from the NEHRP and geotechnical classification schemes. The smallest error terms are generally obtained with the direct use of V_{s-30} as a site parameter and from detailed geology schemes such as age + depositional environment or age + material texture. Maximum differences in the category dispersion values are as large as 0.1 in natural logarithmic units. These variations in dispersion are large enough to have an important effect on seismic hazard calculations (e.g., Field [14]).

4.0 BIAS IN NEHRP SITE FACTORS

As described previously, Choi [4] developed empirical amplification factors as a function of V_{s-30}. Those factors provide the amplification of response spectral acceleration relative to the reference rock condition in three widely used attenuation relationships (Abrahamson [5], Campbell [6], and Sadigh [7]). Those same attenuation models are used by the USGS to develop national seismic hazard maps for rock. Accordingly, since the reference motions for the Choi [4] study are similar to those used in the NEHRP provisions (BSSC [9]), Choi's amplification factors provide a means by which to validate the NEHRP factors. A check of this nature is important because the NEHRP site factors were developed in large part from direct comparisons of rock and soil recordings (e.g., Borcherdt [15, 16]), which could lead to biased site factors if the rock recordings used in formulating the comparisons are not representative of the reference rock conditions in attenuation relations.

A comparison of this type is shown in Figure 6. A range of V_{s-30}-based site factors is given based on the velocities that define the limits of the NEHRP categories. Note that there are variable levels of nonlinearity in Category D. Significant bias of the NEHRP site factors can be seen in all categories, which results in over-prediction of spectral acceleration. As explained by Choi [4], this bias occurs for several reasons: (1) while the NEHRP site factors are intended to be referenced to V_{s-30} = 760 m/s, they are in fact effectively referenced to a higher velocity of approximately 850-1000 m/s, and (2) the intended reference velocity of 760 m/s is higher than the actual effective velocity of the rock sites to which the Choi [4] amplification factors are referenced (and for which the national seismic hazard maps were developed). Accordingly, the bias shown in Figure 6 is largely associated with the offset between the true reference rock velocity (approximately 500-700 m/s, depending on period) and the reference velocity for which the NEHRP factors apply (approximately 850-1000 m/s).

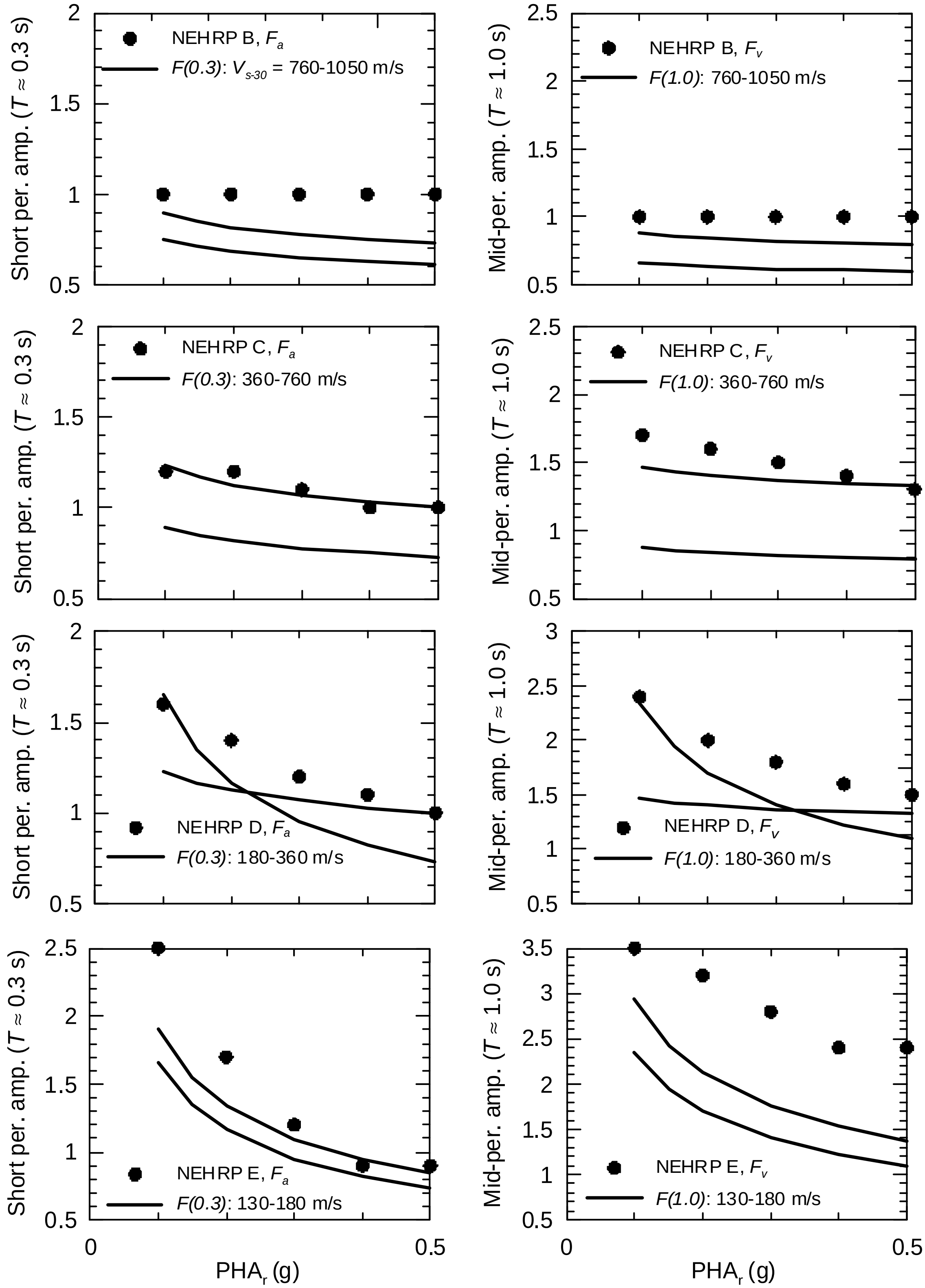

Fig. 6. Comparison of average amplification factors from Choi [4] (solid lines) to NEHRP recommended amplification factors (dots). The two solid lines represent amplification factors at the velocity limits of the respective site categories.

5.0 SUMMARY AND CONCLUSIONS

In this paper, we have presented a coherent set of recommendations for incorporating the effects of site condition into the median and standard deviation of response spectral acceleration conditional on magnitude, site-source distance, and other seismological variables. The work presented here is a synthesis of previous work by Stewart [2], Baturay [3], and Choi [4]. The recommendations can be synthesized as follows:

Step 1 (median motion for reference condition): Use an appropriate rock attenuation relationship to evaluate the median ground motion for the site condition as a function of magnitude, distance, and other relevant seismological variables.

Step 2 (assess site condition): Using available borehole, geophysical, and/or geologic data, evaluate whether the site contains a significant impedance contrast that would warrant performing ground response analyses (i.e., a jump in shear wave velocity across a layer interface of approximately a factor of two or more). Otherwise, classify the site using $V_{s\text{-}30}$ or according to detailed surface geology.

Step 3 (median for actual site condition): If *ground response analyses* are used, median is taken for $T <$ 1 s as the product of the ratio of response spectra calculated from the ground response analyses and the reference motion spectrum. For longer periods, the median should be taken from a soil attenuation relationship or a rock attenuation relationship coupled with empirical site factors. If *amplification factors* are used, the median is taken as the product of the amplification factor (evaluated using Eq. 2 or 3-4) and the reference motion spectrum.

Step 4 (standard deviation for actual site condition): If *ground response analyses* are performed, for T $<$ 1 s standard deviation is calculated using Eq. 1, with $\sigma_{g\text{-}net}$ taken using the guidelines presented in Section 2.2 and σ_{RRS} evaluated directly from the ensemble of ground response analysis results. For longer periods, the standard deviation should be taken from an empirical model (attenuation or site factors). If *amplification factors* are used, standard deviation is calculated using Eq. 5, with individual standard deviations terms (σ_v and σ_e) selected according to the guidelines in Section 2.3.

Step 5 (subsequent use of results): The median and standard deviation for the actual site condition evaluated in Steps 3-4 are used in standard probabilistic seismic hazard analysis routines. The results could also be used in deterministic analyses for selected magnitude/site-source distance combinations.

The advantages of the above recommendations relative to current practice are that they enable site effects to be rationally accounted for within a fully probabilistic context; they provide a clear, rational basis for deciding when costly ground response analyses are worthwhile for a project site; and they remove the bias that is inherent to the use of NEHRP site factors (e.g., see Figure 6), or that would be present with the use of site factors for broadly defined site categories as are used in attenuation relationships.

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