International Workshop on Uncertainties in Nonlinear Soil Properties and their Impact on Modeling Dynamic Soil Response

PEER Headquarters, UC Berkeley
March 18-19, 2004

A COMPARISON OF SITE-SPECIFIC AND EMPIRICAL METHODS FOR SITE RESPONSE EVALUATION

Jonathan P. Stewart[1] and Mehmet B. Baturay[2]

ABSTRACT

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 a NEHRP site category. 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 discuss the bias and standard deviation of spectral accelerations estimated from ground response analyses relative to those obtained with 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.

INTRODUCTION

Earthquake ground motions at soil sites are affected by source, path, and local site response effects. Those effects are typically combined for implementation in engineering design practice 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

---

[1] Associate Professor, UCLA Civil & Environmental Engineering Dept., USA, jstewart@seas.ucla.edu
[2] Senior Staff Engineer, Geosyntec Consultants, Oakland, CA, USA

categories (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. Site-specific ground response analyses are sometimes performed, but engineers have historically lacked clear guidelines regarding when such analyses are worthwhile and how the results of such analyses should be integrated into probabilistic seismic hazard analyses (PSHA). In this paper, we present guidelines on the use of site-specific ground response analyses and their use in PSHA. These findings are condensed from an earlier, more complete paper (Baturay and Stewart, 2003).

Table 1. NEHRP site categories, after Dobry et al. (2000)

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	

SITE CONDITIONS WHERE GROUND RESPONSE ANALYSES ARE WORTHWHILE

Baturay and Stewart (2003) compared spectral accelerations from strong motion recordings to predictions derived using ground response analysis procedures. Results were compiled for 134 motions from 68 sites, and prediction residuals were interpreted to assess the models' relative bias and dispersion.

The ground response analyses 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 (Abrahamson and Silva, 1997) with appropriate corrections for rupture directivity effects (Somerville et al., 1997; Abrahamson, 2000), weathered rock effects (Idriss, 2003), 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 (Abrahamson and Silva, 1997) coupled with site factors (Stewart et al., 2003). The results in Figure 1 were obtained by compiling those median predictions across many sites within various site categories.

Shown in the three rows of Figure 1 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

The left frames of each row in Figure 1 show the median residuals (e.g., μ_{rg}) from ground response 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 both 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 ground response analyses. This is because the amplification factors represent empirical customizations of the Abrahamson and Silva (1997) attenuation relation for specific site categories, and are based on a large world-wide ground motion inventory. Hence, the intensity measure 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, significant bias is considered to occur when zero is not within the range of $\mu_{ras} \pm se_{\mu ras}$. As shown in Figure 1(b), 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.

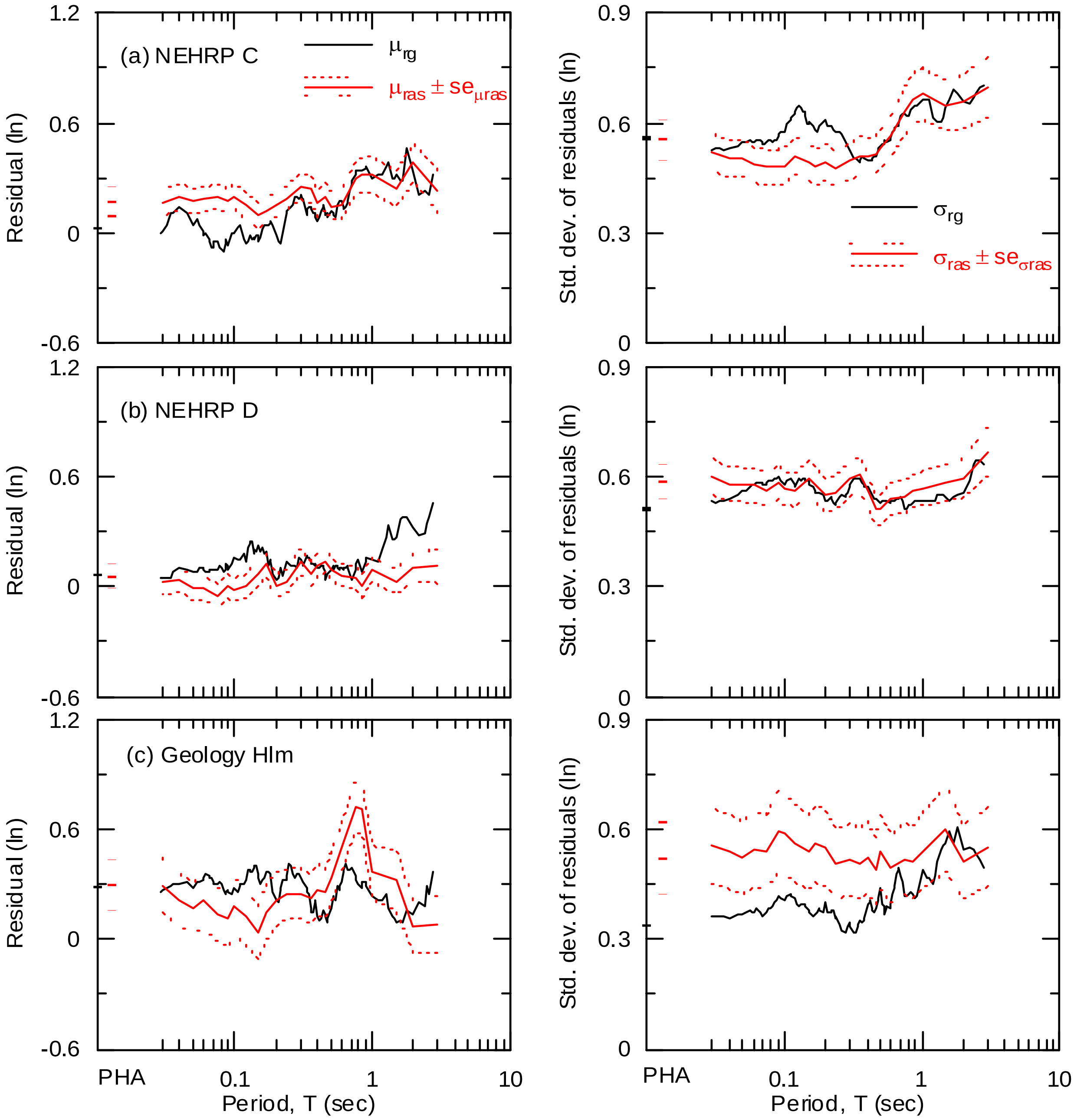

Fig. 1. Category residuals for NEHRP C-D sites and Hlm sites

The first important issue that is discussed is the potential bias of ground response results. For all site categories, initial inspection of Figure 1 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 (i.e., the bias observed in Figure 1 is associated with the data set and not the analysis procedure).

The second issue discussed is the reduction of dispersion of ground response results relative to alternative prediction methods. As shown in Figure 1, 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 qualitiative 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. Moreover, since the median of ground response analyses appears to be unbiased for $T < 1.0$ s, it would appear that the median ground motion for use in PSHA can be taken as the product of the input spectrum (i.e., from rock attenuation) and the median RRS from ground response analyses. An alternative means by which to calculate the median ground surface motion is to use the median of the calculated time histories. This is reasonable provided that the input motion suite is not biased with respect to the target input spectrum. For $T > 1$ s, median motions should be calculated using soil attenuation relations or rock attenuation relations coupled with amplification factors.

STANDARD DEVIATION OF GROUND RESPONSE ANALYSIS RESULTS

The calculation of standard deviation (σ) associated with ground response analysis results can be evaluated by partitioning the full intra-event dispersion into contributions associated with:

1. Unknown, aleatory factors, including variability in the estimated target rock spectrum relative to the true rock spectral ordinates (this in analogous to the ordinary aleatory uncertainty 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 is referred to as $\sigma_{g\text{-}net}$.
2. Known sources of uncertainty, which are (a) the variability in the outcropping soil/input ratio of response spectra (RRS) due to random soil properties and input motions, which leads to different levels of nonlinearity (denoted σ_{RRS}), and (b) the standard error of input motion spectra (denoted $se_{g\text{-}in}$).

Baturay and Stewart (2003) derived $\sigma_{g\text{-}net}$ from the data set described in the previous section. This was accomplished by reducing the variance associated with the σ_{rg} values shown in Figure 1 by the variance associated with the above known sources of uncertainty,

$$(\sigma_{g-net})_i^2 = (\sigma_{rg})_i^2 - (\overline{se}_{g-out})_i^2 \tag{1}$$

where $(\overline{se}_{g-out})_i$ indicates the average for all sites within site category i of $(se_{g\text{-}out})_{ij}$, which in turn is the standard error of the median intensity measure from the ground response analysis output time history suite for site j in category i.

The results of the $\sigma_{g\text{-}net}$ calculations are shown in Figure 2. 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. Based on the results in Figure 2, it appears that for forward (design) calculations, $\sigma_{g\text{-}net}$ can be estimated as follows:

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

Assuming median ground surface motions are taken as the product of the input spectrum and median RRS, the corresponding dispersion for use in PSHA (σ) can be calculated as follows:

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

The 0.23 factor in Eq. 2 represents inter-event dispersion as derived by Abrahamson and Silva (1997).

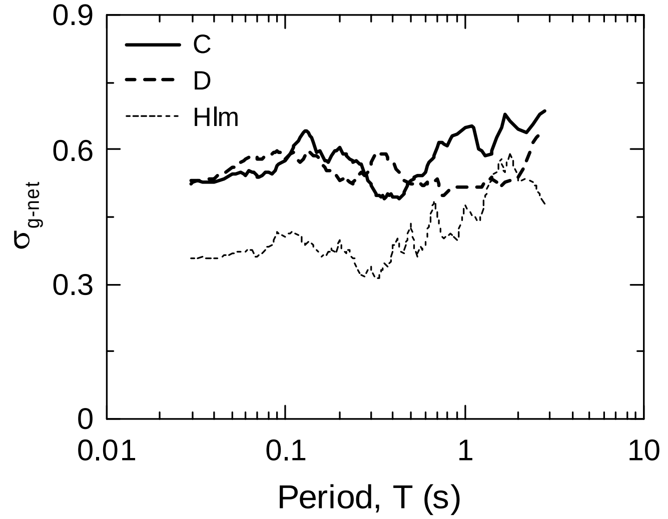

Fig. 2. Variation with period and site category of ground response prediction dispersion associated with aleatory uncertainty in input spectra and imperfect modeling physics

SUMMARY AND CONCLUSIONS

In this paper, we have summarized recommendations for incorporating the results of ground response analyses into PSHA. Specifically, we have presented guidelines on the conditions for which such analyses are worthwhile and recommendations on the interpretation of the median and standard deviation of response spectral acceleration from ground response results. The work presented here is a synthesis of previous work by Baturay and Stewart (2003). 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 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 according to an appropriate site categorization scheme and use site factors to evaluate the median and standard deviation of ground motion at all periods, which would negate the need for Steps 3-5 below.

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

Step 4 (standard deviation for actual site condition): If ground response analyses are performed, for $T < 1$ s standard deviation is calculated using Eq. 2, with $\sigma_{g\text{-}net}$ taken using the guidelines presented previously 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).

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

ACKNOWLEDGEMENTS

Support for this work was provided by the Pacific Earthquake Engineering Research Center's Program of Applied Earthquake Engineering Research of Lifeline Systems supported by the State Energy Resources Conservation and Development Commission and the Pacific Gas and Electric Company. In addition, the support of the California Department of Transportation's PEARL program is acknowledged.

REFERENCES

Abrahamson NA. (2000). “Effects of rupture directivity on probabilistic seismic hazard analysis,” *Proc. 6th International Conference on Seismic Zonation*, Earthquake Engineering Research Institute, Oakland, CA.

Abrahamson NA and Silva WJ. (1997). “Empirical response spectral attenuation relations for shallow crustal earthquakes,” *Seism. Research Letters*, 68 (1), 94-127.

Baturay MB and Stewart JP. (2003). “Uncertainty and bias in ground motion estimates from ground response analyses,” *Bull. Seism. Soc. Am.*, 93 (5), 2025-2042.

Dobry R, Borcherdt RD, Crouse CB, Idriss IM, Joyner WB, Martin GR, Power MS, Rinne EE, and Seed RB. (2000). “New site coefficients and site classification system used in recent building seismic code provisions,” *Earthquake Spectra*, 16 (1), 41-67.

Idriss IM. (2003). Personal communication

Stewart JP, Liu AH, and Choi Y. (2003). “Amplification factors for spectral acceleration in tectonically active regions,” *Bull. Seism. Soc. Am.*, 93 (1), 332-352.

Somerville PG, Smith NF, Graves RW, and Abrahamson NA. (1997). “Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity,” *Seism. Research Letters*, 68 (1), 199-222.