30 Mar 2001, 1:30 pm - 3:30 pm

Uncertainties and Residuals in Ground Motion Estimates at Soil Sites

Jonathan P. Stewart
University of California, Los Angeles, CA

Mehmet B. Baturay
University of California, Los Angeles, CA

UNCERTAINTIES AND RESIDUALS IN GROUND MOTION ESTIMATES AT SOIL SITES

Jonathan P. Stewart
University of California, Los Angeles
Los Angeles, CA-USA-90095

Mehmet B. Baturay
University of California, Los Angeles
Los Angeles, CA-USA-90095

ABSTRACT

For a given seismic source, ground motions at soil sites can be estimated using either soil attenuation relationships, or ground response analyses with input motions scaled to match spectral ordinates from rock attenuation relationships. Ground response analyses are performed with the expectation that accounting for nonlinear sediment response improves the accuracy and reduces the uncertainty in estimated motions. Discussed here are the benefits of ground response analyses as a function of site condition. This is accomplished by preparing statistical predictions of ground motions at 36 strong motion recording sites on soil. Two predictions are made, one using a modified soil attenuation relationship, the other using ground response analyses with a large suite of carefully selected and scaled input motions. Predictions from both methods are compiled as 5% damped spectral ordinates, and are expressed as medians and standard errors. These quantities can then be compared to the spectra of the recorded motion to evaluate the residuals of the estimates. For periods, $T <$ 1 s, ground response analyses are found to improve the accuracy of ground motion predictions relative to soil attenuation. However, a positive bias in median ground response estimates is found that indicates a systematic underprediction of ground motion.

INTRODUCTION

For a given seismic source, ground motions at soil sites are generally estimated using either soil attenuation relationships, or ground response analyses with input motions scaled to match specified spectral ordinates from rock attenuation relationships. In either case the attenuation relationships are relied upon to capture source and path effects on ground motion. Site response analyses are performed to account for the nonlinear response of shallow sediments, and hopefully reduce the uncertainty in the estimated ground motions on soil.

The relative influence of source/path and site response effects on residuals between recorded and estimated soil site ground motions has been previously investigated. Lee (1996) examined the southern California strong motion inventory for soil and rock sites compiled by SCEC. He found that residuals from the Abrahamson and Silva (1997) attenuation relationship at short and intermediate periods are not systematically high or low for soil sites with multiple ground motion recordings, implying that "random" source/path variability is more pronounced than the site response effect (which should produce a consistent residual across multiple events). Others have found consistent site response effects through comparisons of strong motions from a particular event recorded at similar site-source distances and azimuths, but different site conditions (e.g. Seed et al., 1987; Idriss, 1990). Site effects during specific events have also been identified from statistical studies of the regional variations in spectral ordinates across different geologic conditions (Borcherdt and Gibbs, 1976; Borcherdt, 1994; Rodriguez-Marek et al., 1999).

The disconnect between the findings from Lee's interpretation of southern California data and the significant site effects found from other empirical and analytical studies indicates a need to identify the geologic conditions where site effects cause ground motions on soil to significantly and consistently differ from the predictions of soil attenuation relations. Accordingly, this paper evaluates the "benefit" gained from ground response studies as compared to the simple use of soil attenuation relations as a function of the general geologic conditions at a site. Specifically, we compare the ability of soil attenuation relations and carefully performed ground response analyses to capture the 5%-damped spectral accelerations for 36 sites with widely varying geologic conditions that have recorded strong ground motion. The intent is to provide a rational basis for deciding when costly site exploration work and ground response analyses are justified from the standpoint of their ability to reduce the residuals and the uncertainty in ground motion estimates on soil.

SITE SELECTION

Criteria for site selection were: (1) at least one strong motion recording must be available at the site, (2) soil conditions must be well characterized, including shear wave velocity measurements, and (3) sites should include roughly equal numbers of shallow stiff soil sites, moderately deep stiff soil sites, deep stiff soil sites, and soft soil sites.

Available strong motion and geologic data was reviewed, and 7-11 sites were selected in each of the following categories:

I. Shallow stiff soil over rock (soil depth < 30 m)
II. Moderate depth stiff soil (soil depth = 45-90 m)
III. Deep stiff soil (soil depth > 120 m)
IV. Soft soil (Vs ≤ 150 m/s; soft soil depth > 3 m)

Details on the sites selected in each category can be found in Stewart and Baturay (2000).

DEVELOPMENT OF INPUT MOTIONS

This section reviews the means by which input motions were developed for use in ground response analyses for each site. The objective of these time history selection and scaling procedures is to develop a suite of specific time histories representing possible realizations of the motion that would have been expected at the site had the geologic condition been rock.

Time History Selection

A strong motion database for shallow crustal earthquakes in active tectonic regions was used for the selection of time histories. As described in Stewart and Baturay (2000), the database was supplemented to provide for each time history a simple representation of likely near fault rupture directivity effects on the recorded motions. This was accomplished using a Rupture Directivity Index (RDI), defined as the change of the geometric mean $T = 3$ s spectral acceleration due to rupture directivity effects as computed by the model of Somerville et al. (1997) with minor modifications (Abrahamson, *pers. communication*). A site experiencing no rupture directivity effect has RDI=1.0. For strike-slip faults, RDI varies from 1.48 (forward directivity), to 0.55 (backward directivity). The range for dip slip faults is 1.16 to 0.72.

The seismological criteria by which rock time histories were selected are listed below, where the term "target" refers to a characteristic of the causative earthquake for the subject site.

Magnitude: Selected recordings must have been triggered by an event with a magnitude within ± 0.5 of the target.

Amplitude: Time histories were sought that had an maximum horizontal acceleration (MHA) within a factor of two to four of the target MHA on rock (evaluation of target described below).

Site Condition: For relatively deep soil sites, (Types II to IV), time histories were selected from rock sites or sites with < 20 m of soil. For Type I sites, time histories were selected from only rock sites.

Rupture Directivity: Time histories should have RDI's that are similar to the target RDI. Target RDI is based on site location relative to the fault plane, not deviations of the recorded motion from an attenuation model.

Since near fault motions show a strong orientation effect, care was taken to properly orient input motions for ground response analyses intended to predict fault parallel or fault normal motions on soil (Stewart and Baturay, 2000).

Scaling of Input

The intent of scaling was to provide an ensemble of time histories with median spectral ordinates matching the "best estimate" soft rock spectrum for the subject event and site, while retaining the inherent variability in the estimated rock motion.

The best estimate spectrum is taken as median 5% damped spectral ordinates from the Abrahamson and Silva (1997) rock site attenuation relation, with the following modifications:

- Period dependent event terms provided by Abrahamson (1999, *personal communication*) which quantify event-specific deviations from the general attenuation model.
- Median rupture directivity effects and motion orientation effects as computed by the models in Somerville et al. (1997) and modified by Abrahamson (*pers. communication*).
- Removal of near-surface amplification effects at weathered California rock sites. This is accomplished using period-dependent reductions of outcropping rock motion by Idriss (1999) to more adequately represent the motions anticipated on less weathered rock profiles such as occur at depth (i.e. underlying a soil profile).

The best estimate spectrum obtained by these procedures represents the median ground motion expected at the site had the geologic condition been soft rock. At a particular period, T, this median spectral acceleration is denoted $\mu_{be}(T)$. The objective of the time history scaling is for the median of the ensemble of time histories, $\mu_{th}(T)$, to match $\mu_{be}(T)$.

The scaling of the time histories is performed in two stages. First, individual time history k is scaled up or down by factor $(F_1)_k$ so that its response spectrum, $S_k(T)$, matches $\mu_{be}(T)$ in an average sense over the range T=0-1 s. Denoting the median spectra of the scaled time histories as $\mu_{sth}(T)$ [i.e., $\mu_{sth}(T)$ is the median of $S_k(T) \times (F_1)_k$ across all k], a set of period-dependent scaling factors are defined as:

$$F_2(T) = \frac{\mu_{be}(T)}{\mu_{sth}(T)} \quad (1)$$

The second scaling consists of time domain response spectral matching of each individual time history k to a target spectrum that is $S_k(T) \times (F_1)_k \times F_2(T)$. The time domain response spectral matching is performed using RSPMATCH (Abrahamson, 1998). An example outcome of the scaling procedure is shown in the top frame of Figure 1. The heavy solid line indicates the target spectrum, $\mu_{be}(T)$, which is the adjusted median from rock attenuation. Uncertainty in the estimate is represented with the heavy dashed lines. The median and median ± 1σ spectral accelerations from the twice-scaled input motions are shown on the same figure using light lines. The median of the ensemble matches the target nearly exactly, while maintaining the inherent variability across the time histories associated with source/path.

GROUND RESPONSE MODELING

Ground response modeling was performed using an equivalent-linear characterization of dynamic soil properties as implemented in the program SHAKE91 (Idriss and Sun, 1992). The program computes the response of a horizontally layered soil deposit over a uniform half-space subjected to vertically propagating shear waves. The following sections review important details of the SHAKE91 analyses.

Because SHAKE uses an equivalent-linear soil model, soil conditions are described by small strain shear wave velocity (V_S) and relationships for normalized shear modulus (G/G_{max}) and hysteretic soil damping (β) with shear strain. For each of the sites selected for this study, V_S profiles were obtained from in situ measurements by either downhole or suspension logging techniques. Modulus reduction and damping curves were specified on the basis of soil type, soil plasticity, and depth. Details on the V_S data and modulus reduction/damping curves selected for each site are given in Stewart and Baturay (2000). No variability in soil properties was considered in this study.

STATISTICAL ANALYSIS OF RESULTS

Analysis

In this section, we compare 5% damped spectral accelerations of recorded time histories on soil to estimated spectra from a modified soil attenuation relationship and ground response analyses. Estimated spectra by both methods are represented by their median value and their standard error in natural log units.

The first estimate of soil spectra is taken using the Abrahamson and Silva (1997) soil attenuation relation, with modifications for event terms and near-fault effects as described previously for rock sites. For soil site *j* in site category *i*, the natural logs of the median spectral ordinates obtained by the modified attenuation relation are denoted $A_{ij}(T)$, and the standard error term is denoted $[\sigma_a(T)])_{ij}$. Since all the median and standard error terms considered here have a functional dependence on period, this will be dropped in subsequent nomenclature.

The second estimate of soil spectra is from ground response analysis. Again considering soil site *j* in site category *i*, the natural log of the calculated spectra using input motion *k* is denoted $(G_{ij})_k$. Taking N_j as the number of input time histories used in ground response analyses for site *j*, the median and standard error of $(G_{ij})_k$ for k=1..N_j are denoted G_{ij} and $(\sigma_g)_{ij}$, respectively. Hence, for soil site *j* in site category *i*, the two statistical estimates of computed soil spectra are denoted:

	Attenuation	Ground Response Analysis
Median	A_{ij}	G_{ij}
Standard Error	$(\sigma_a)_{ij}$	$(\sigma_g)_{ij}$

An example comparison of the exponent of A_{ij} & $A_{ij}\pm(\sigma_a)_{ij}$ and G_{ij} & $G_{ij}\pm(\sigma_g)_{ij}$ to the spectrum of the recorded motion is shown in the bottom two frames of Figure 1 (Apeel #2 site).

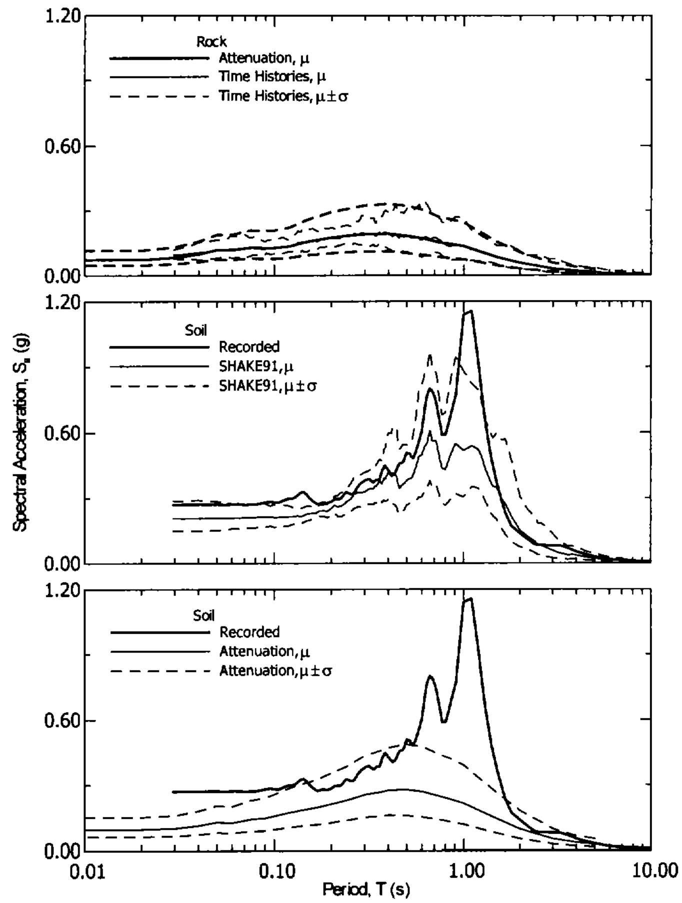

Fig. 1. Spectral accelerations @ 5% damping. Input motions (top frame), ground response results (middle frame), and soil attenuation results (bottom frame). Site is Apeel #2 Redwood Shores, fault normal direction, 1989 Loma Prieta earthquake.

Denoting the natural log of the recorded, or "observed," ground motion as O_{ij}, residuals between the estimated median spectra (i.e., "μ" spectra) and observed spectra for soil site *j* in site category *i* are taken as:

$$(r_{g1})_{ij} = O_{ij} - G_{ij}: \quad \text{residual, } \mu \text{ estimate, ground response}$$

$$(r_{a1})_{ij} = O_{ij} - A_{ij}: \quad \text{residual, } \mu \text{ estimate, soil attenuation} \quad (2)$$

We also consider a separate, median plus one standard error estimate of ground motion (i.e. the "$\mu+\sigma$" spectra). Residuals of these ground motion estimates are taken as:

$$(r_{g2})_{ij} = O_{ij} - \left(G_{ij} + (\sigma_g)_{ij}\right): \text{ residual, } \mu+\sigma \text{ est., ground resp.}$$

$$(r_{a2})_{ij} = O_{ij} - \left(A_{ij} + (\sigma_a)_{ij}\right): \text{ residual, } \mu+\sigma \text{ est., soil atten.} \quad (3)$$

Median minus one standard error ground motion estimates were found to be poor predictors of observed ground motion at all periods, and hence are not carried forward. Plots of $(r_{a1})_{ij}$ & $(r_{a2})_{ij}$ and $(r_{g1})_{ij}$ & $(r_{g2})_{ij}$ are shown in Figure 2 for the Apeel #2 site.

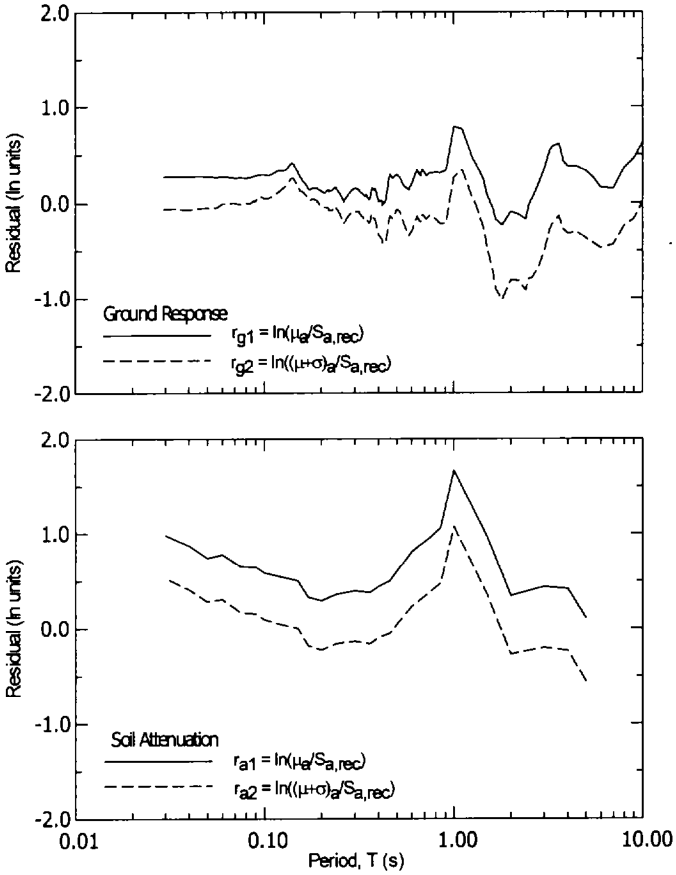

Fig. 2. Residuals of median (μ) and median + one standard error ($\mu+\sigma$) ground motion estimates, Apeel #2 Redwood Shores, fault normal direction, 1989 Loma Prieta earthquake

The medians and standard errors of residuals within category i are taken across the j=1..M_i sites (assuming category i to have M_i sites). These statistical quantities are denoted as follows:

$$(R_{g1})_i,\ (\sigma_{g1})_i = \text{median, standard error of } (r_{g1})_{ij}$$
$$(R_{a1})_i,\ (\sigma_{a1})_i = \text{median, standard error of } (r_{a1})_{ij} \qquad (4)$$

Similar definitions apply for the median plus one standard error ground motion estimates, with "2" replacing "1" in the subscripts in Eq. 4. Since the number of sites in each category (M_i) is fairly small (7-11), the uncertainty in the estimates of median quantities $(R_{g1})_i$ & $(R_{g2})_i$ and $(R_{a1})_i$ & $(R_{a1})_i$ should be considered. This uncertainty in these medians can be estimated as,

$$\left(\overline{\sigma}_{g1}\right)_i^2 = \left(\sigma_{g1}\right)_i^2 / M_i \qquad (4)$$

where $\left(\overline{\sigma}_{g1}\right)_i$ denotes the standard error of the estimate of $(R_{g1})_i$. Similar definitions apply for the other median quantities considered.

Figures 3-4 present the variation of category median residuals ($R_{g1\text{-}2} \pm \overline{\sigma}_{g1}$ and $R_{a1\text{-}2} \pm \overline{\sigma}_{a1}$) and category standard errors ($\sigma_{g1\text{-}2}$ and $\sigma_{a1\text{-}2}$) with T for soil Types III and IV. Table 1 summarizes average residuals of μ and $\mu+\sigma$ ground motion estimates across period ranges $T \leq 1.0$ s and $T > 1.0$ s for all soil categories.

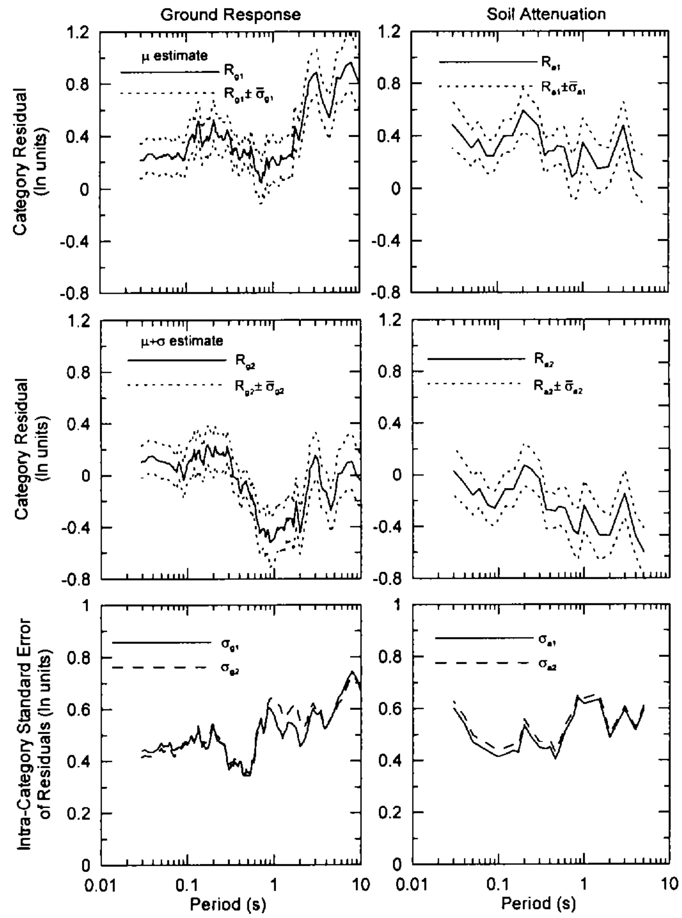

Fig. 3. Category median residuals and standard error terms, Type III sites (deep stiff soil, z > 120 m)

<u>Interpretation</u>

We begin our interpretation of the results by focusing on soft clay sites (Type IV), for which the trends are most clearly defined. Referring to Fig. 4 and Table 1, two principal findings emerge from the category statistics, as summarized below.

<u>Benefit of ground response analysis</u>. The benefit of performing ground response analysis is measured by comparing category residuals and standard errors for the μ ground response and soil attenuation ground motion estimates. Both category residuals and standard errors are smaller for the ground response estimates for $T <\sim$ 1-2 s. The smaller residual means that ground response analyses more accurately predict ground motions, and the smaller standard error means that the residuals are more consistent across sites in the category. Of the two benefits, the reduction in standard error is most pronounced.

<u>Bias in ground response results</u>. The category residuals for the μ ground response estimates are non-zero with a high level of confidence for $T <\sim 1$ s. Across this period range, the $\mu+\sigma$ estimate has much smaller residuals (average of 0.07 as compared to 0.39 for μ). At longer periods, the results are less consistent, although the μ estimate preliminarily appears to be reasonable.

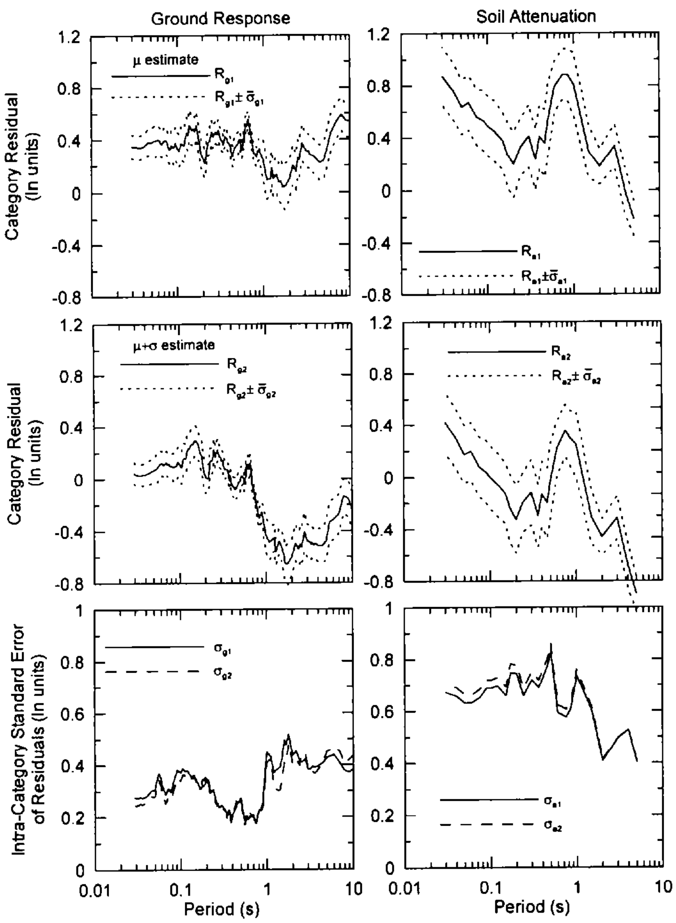

Fig. 4. Category median residuals and standard error terms, Type IV sites (soft clay)

With respect to the first comment above (benefit of ground response), site categories other than Type IV exhibit mixed trends. For $T \leq 1$ s, μ ground response estimates have smaller residuals than μ soil attenuation estimates in all site categories. The residual reduction for μ ground response estimates at $T \leq 1$ s is modest for Type II and III (moderate to deep soil), but is relatively pronounced for Type I sites (shallow soil). The significant uncertainty reduction observed in ground response results for Type IV sites is not observed for other site categories. Comparing averaged σ_{gl} and σ_{al} values in Table 1, ground response is seen to provide lower uncertainty for Type III sites, but σ_{gl} is actually larger than σ_{al} for Type I and II sites. These results indicate that while ground response analyses generally provide more accurate spectra for these site classes (i.e., $R_{gl} < R_{al}$), there is a relatively high level of uncertainty in the amount of bias in computed spectra. This means that the ground response procedures are modeling ground motion variations between sites relatively poorly, implying that other factors are significantly affecting these variations (e.g., source and path effects).

The bias observed at Type IV sites in μ ground motion estimates for $T < \sim 1$ s is also present at Type II and III sites. No significant bias is observed for $T \leq 1$ s at Type I sites. Median attenuation estimates are also biased for $T \leq 1$ s in all site categories, indicating that motions in each category exceed the median values for soil sites. This suggests that the data set used in the study is biased towards unusually strong ground motions (such sites are often considered desireable candidates for drilling). Nonetheless, based on the results presently available, the following usage of ground response analysis results appears to provide the smallest residuals for $T \leq 1$ s at the sites considered:

Type I (shallow soil): μ estimate
Type II (med. Depth soil): μ+0.5σ estimate
Type III (deep soils): μ+σ estimate
Type IV (soft clay): μ+σ estimate

Table 1a: Average category residuals and standard errors of median (μ) ground motion estimates

Site	Residual[1] ($T \leq 1.0$ s)		Residual[1] ($T > 1.0$ s)		Standard Error ($T \leq 1.0$ s)		Standard Error ($T > 1.0$ s)	
	R_{gl}	R_{al}	R_{gl}	R_{al}	σ_{gl}	σ_{al}	σ_{gl}	σ_{al}
I *	0.03	0.22	0.30	-0.08	0.47	0.44	0.71	0.55
II	0.15	0.28	0.75	0.38	0.49	0.32	0.44	0.46
III	0.29	0.34	0.58	0.19	0.45	0.48	0.57	0.57
IV	0.39	0.54	0.25	0.11	0.28	0.68	0.41	0.49

Table 1b: Average category residuals and standard errors of μ+σ ground motion estimates

Site	Residual[1] ($T \leq 1.0$ s)		Residual[1] ($T > 1.0$ s)		Standard Error ($T \leq 1.0$ s)		Standard Error ($T > 1.0$ s)	
	R_{g2}	R_{a2}	R_{g2}	R_{a2}	σ_{g2}	σ_{a2}	σ_{g2}	σ_{a2}
I	-0.30	-0.26	-0.37	-0.69	0.48	0.44	0.75	0.56
II	-0.16	-0.22	0.15	-0.24	0.53	0.32	0.53	0.47
III	0.00	-0.17	-0.16	-0.43	0.45	0.51	0.60	0.58
IV	0.07	0.03	-0.46	-0.53	0.27	0.72	0.40	0.49

*omitting Potrero Canyon site

The cause of the residuals for the last three site categories is not well understood. However, as noted above, it may be paritially associated with a bias in the data set. The residuals may also be partially attributable to errors associated with the use of the equivalent linear method of ground response computation, or errors in the selection of dynamic soil properties. It is noted that ground motion estimates at small periods (where the bias is most consistently observed) are especially sensitive to soil hysteretic damping ratio, β. Overestimation of β would cause an underestimation of ground response that would increase with soil thickness (because for a given frequency more wavelengths subject to soil damping will be present in thicker soil deposits). This trend is observed in the data, i.e. R_g increases with increasing depth of soil.

For $T > 1$ s, the μ ground response estimate provides large residuals for the Type II and III sites, implying that the ground response models are not capturing the long-period components of the ground motions. This is not surprising, as many of the sites in these categories are near basin edges where basin edge effects can be significant at large periods. The bias in this period range for μ soil attenuation is smaller, implying that basin effects are to some degree represented in the empirical database for soil sites. Further, no significant long period bias is observed in μ ground response estimates at Type I sites, where basin edge effects would generally not be expected.

The observed significance of site response effects for Type IV sites, and to some extent Type III sites, is consistent with previous studies (e.g., Idriss, 1990; Chang, 1996). In addition, the large σ_g values for the Type II and III sites appear to be consistent with Lee's (1996) finding that ground response effects are generally small relative to source/path effects at soil sites in southern California.

Finally, it should be noted that the results summarized in Figs. 3-4 and Table 1 are for a limited number of sites within each category. Many more sites should be added within each category to enable more stable and robust estimates of the category residuals and standard errors terms. Such work is underway and may change the findings reported above.

CONCLUSIONS

In this paper we have estimated ground motions for accelerograph sites on soil using ground response analyses and a modified soil attenuation relationship. Residuals between recorded and estimated motion were calculated to elucidate trends in the results of each ground motion estimation procedure across geotechnical site categories. For $T < 1$ s, we find that ground response analyses improve the accuracy of ground motion predictions relative to attenuation in all site categories. However, the uncertainty in the residual of the estimated ground motions is large for shallow soil sites and stiff soil sites, indicating that factors other than site response are "randomly" varying the motions from site-to-site. We interpret this as a strong source/path effect on these soil site motions. Conversely, for soft clay sites, the standard error of ground response estimates is small, indicating a strong and systematic influence of ground response that is well captured by the analysis.

For $T > 1$ s, substantial positive bias is observed in median ground response results for moderate to deep stiff soil sites, which may be a basin effect. Ground motion estimates from soil attenuation relations are more accurate within this period range. A somewhat surprising result from this study is a consistent bias for $T < 1$ s in ground response results for site categories other than shallow stiff soil. Given this bias, our preliminary recommendation for the interpretation of ground response results is that median plus one standard error ground motions be used for soft soil and deep stiff soil sites if the input is scaled to the median rock motion. For moderate depth and shallow soil sites, further study is needed before recommendations can be made.

ACKNOWLEDGEMENTS

This research was supported by the Pacific Earthquake Engineering Research Center through the PEARL sponsor organizations including the Pacific Gas & Electric Company, the California Energy Commission, and the California Department of Transportation under Award Number 09566.

REFERENCES

Abrahamson, N.A. [1998]. Non-stationary spectral matching program RSPMATCH, PG&E Internal Report, February.

Abrahamson, N.A. and Silva, W.J. [1997]. Empirical response spectral attenuation relations for shallow crustal earthquakes, *Seism. Research Letters*, 68(1), 94-127.

Borcherdt, R. D. and Gibbs, J. F. [1976]. Effects of local geological conditions in the San Francisco Bay region on ground motions and the intensities of the 1906 earthquake, *Bull. Seism. Soc. Am.*, 66 (2), 467-500.

Borcherdt, R.D. [1994]. Estimates of site dependent response spectra for design (methodology and justification), *Earthquake Spectra*, EERI, 10(4), 617-653.

Chang, S.W. [1996]. Seismic response of deep stiff soil deposits, *Ph.D. Dissertation*, Univ. of California, Berkeley.

Idriss, I.M. [1990]. Response of soft soil sites during earthquakes, *Proc. H. Bolton Seed Memorial Symposium*, J.M. Duncan (ed.), Vol. 2, 273-290.

Idriss, I.M. [1999]. Quantitative geotechnical site characterization, PG&E/PEER Task 3.E Internal Report.

Idriss, I.M. and Sun, J.I. [1992]. SHAKE91: A computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits, Center for Geotech. Modeling, Univ. of California, Davis.

Lee, Y. [1996]. Evaluation of attenuation relations in the Southern California region, *M.S. Dissertation*, Geophysics Department, Univ. of Nevada, Reno.

Rodriguez-Marek, A., Bray, J.D., and Abrahamson, N.A. [1999]. Task 3: Characterization of site response, general site categories, *Rpt. No. PEER 1999/03*, Pacific Earthquake Engineering Research Center, Richmond, CA.

Seed, H.B., Romo, M.P., Sun, J.I., Jaime, A., and Lysmer, J. [1987]. Relationships between soil conditions and earthquake ground motions in Mexico City in the earthquake of September 19, 1985, *Rpt. No. UCB/EERC-87/15*, Earthquake Engineering Research Center, Univ. of California, Berkeley.

Stewart, J.P. and Baturay, M.B. [2000]. "Evaluation of uncertainties in ground motion estimates at soil sites," *Rpt. No. UCLA/CEE-2000/01*, Univ. of California, Los Angeles.

Somerville, P.G., Smith, N.F., Graves, R.W., and Abrahamson, N.A. [1997]. Modification of empirical strong motion attenuation relations to include the amplitude and duration effects of rupture directivity, *Seism. Research Letters*, 68(1), 94-127.