ACCOUNTING FOR SITE EFFECTS IN PROBABILISTIC SEISMIC HAZARD ANALYSIS: OVERVIEW OF THE SCEC PHASE III REPORT

Edward H FIELD[1] And SCEC PHASE III WORKING GROUP[2]

SUMMARY

Probabilistic seismic hazard analysis (psha) depends on empirical attenuation relations that quantify the amplitude of ground motion as a function of distance, magnitude, and sometimes other parameters. Given the variety of factors complicating earthquake shaking, attenuation relationships have a large degree of uncertainty (i.e., Observations are highly scattered about predicted values). An important question is the degree to which this scatter can be reduced by accounting for site effects. In this context we define a site effect as the tendency for mean ground motion, given all potentially damaging earthquakes throughout the region, to be significantly different from the predicted value.

The so-called "phase iii" effort of the southern california earthquake center has concentrated on identifying and accounting for such site effects in psha. In approximately 10 papers that will be published together in the near future, we have carried out both empirical and theoretical investigations of how attenuation relations can be evaluated and modified to account for site effects. Our findings show that certain site attributes, such as detailed geological classification and/or depth to basement at sediment sites, are correlated with ground motion amplitudes. We are presently quantifying how accounting for these systematic differences influences seismic hazard analysis.

Perhaps an equally important finding is that these site-effect corrections do not appreciably reduce the prediction uncertainty of attenuation relations. This can be understood by the fact that basin-edge induced surface waves, focusing and defocussing, and scattering in general, will be highly sensitive to the source location. These effects produce a high degree of variability from event to event at any given site, making the systematic site effects seem relatively small. However, even small corrections can have a significant impact on hazard analysis.

INTRODUCTION

Earthquake ground motion typically exhibits a high degree of variability due to site resonances, basin-edge induced surface waves, focusing and defocusing (constructive and destructive interference), directivity, and non-linear sediment amplification. A fundamental question, in both probabilistic and deterministic seismic hazard analysis, is the degree to which uncertainties in predicted ground motion due to these effects can be reduced by further research. The so-called "Phase III" report of the Southern California Earthquake Center (SCEC) addresses this question with respect to probabilistic seismic hazard analysis (PSHA).

PSHA depends on empirical attenuation relations that quantify the amplitude of ground motion as a function of distance, magnitude, and sometimes other parameters. Given the variety of factors complicating earthquake shaking, attenuation relationships have a large degree of uncertainty (i.e., observations are highly scattered about predicted values). An important question is the degree to which this scatter can be reduced by accounting for

[1] *Southern California Earthquake Center University of Southern California Email: field@usc.edu*
[2] *Southern California Earthquake Center University of Southern California Web Site: www.scec.org/research/phase3*

site effects. In this context, we define a site effect as the tendency for ground motion to be significantly different at a site for all potentially damaging earthquakes throughout the region.

The SCEC Phase III effort has concentrated on identifying and accounting for such site effects in PSHA. In a series of papers that will soon be published a special issue of the Bulletin of the Seismological Society of America (see www.scec.org/research/phase3), we have carried out both empirical and theoretical investigations of how attenuation relations can be evaluated and modified to account for site effects. Our findings (summarized below), show that certain site attributes, such as near-surface geology and/or depth to basement at sediment sites, are correlated with ground motion amplitudes. Models to account for these effects have been developed and tested with respect to their impact on PSHA.

SITE AMPLIFICATION FROM 3D MODELING OF GROUND MOTION

It is well established that sedimentary basins can significantly amplify earthquake ground motion. However, the amplification at any given site can vary with earthquake location. Therefore, to account for basin response in probabilistic seismic hazard analysis, we need to know the average amplification and intrinsic variability (standard deviation) at each site, given all earthquakes of concern in the region. Due to a dearth of empirical ground motion observations, theoretical simulations constitute our best hope of addressing this issue.

Olsen [2000] has used 0-0.4 Hz finite-difference, finite-fault simulations to estimate the three-dimensional (3D) response of the Los Angeles basin to nine different earthquake scenarios. Amplification is quantified as the peak velocity obtained from the 3D simulation divided by that predicted using a regional one-dimensional (1D) crustal model. Average amplification factors are up to a factor of 4, with the values from individual scenarios typically differing by as much as a factor of 2.5. Average amplification correlates with basin depth (Figure 1), with values near unity at sites above sediments with thickness less than 2 km, and up to factors near 4 above the deepest part of the basin (~9 km). There is also some indication that amplification factors are greater for events located farther from the basin edge. If the 3D amplification factors are divided by the vertical S-wave 1D response below each site, they are lowered by up to a factor of 1.7. Due to uncertainties concerning accuracy of the basin model, the rupture representation, the influence of anelastic attenuation, model resolution, and the fact that only nine scenarios have been considered, the amplification factors reported here are not recommended for application until they can be further tested against observations. However, the results do serve as a guide to what should be expected, particularly with respect to increased amplification factors at sites located above the deeper parts of the basin.

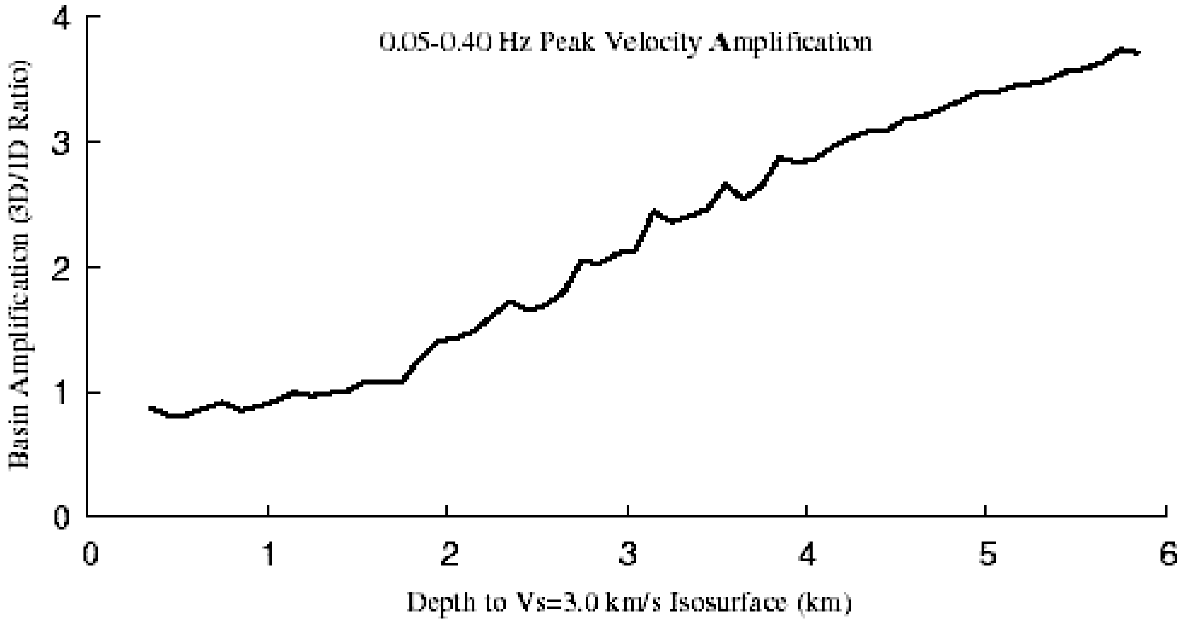

Figure 1. Los Angeles basin amplification (averaged over 9 different scenario earthquakes) versus basin depth (see Olsen, (2000) for details).

SITE RESPONSE FOR PROBABILISTIC SEISMIC HAZARD ANALYSIS

Site response factors can be applied as corrections to a rock attenuation relationship for use in probabilistic seismic hazard analysis. Steidl [2000] has determined amplification factors by averaging ratios between observed and predicted response spectral acceleration at 0.1, 0.3, 1.0, and 3.0 second periods. The observations come from the SCEC strong-motion database, and the predictions are based on the Sadigh [1997] rock attenuation relation. When separated and averaged according to surface geology, the ratios imply significantly different amplification factors for Quaternary, Tertiary, and Mesozoic units, and a Quaternary sub-classification may be warranted under certain conditions. An observed trend of decreasing Quaternary site amplification with higher input motion is consistent with nonlinear soil behavior, although a limited number of rock-site observations make this trend difficult to substantiate statistically. The low input-motion amplification factors are consistent with those obtained from independent aftershock studies. A trend is also seen with respect to sediment basin depth, where deeper sites have higher average amplification factors. These results are used to construct various alternative relations for southern California.

EVALUATION OF EMPIRICAL ATTENUATION RELATIONS

Several different empirical attenuation relations have been developed by various practitioners (see the January/February, 1997 issue of *Seismological Research Letters*). Each is based on different data and/or assumptions regarding, for example, sediment non-linearity. Six regressions that were judged likely to be appropriate for southern California were investigated by Lee et al. [2000] to determine which are most successful in predicting earthquake ground motion. The regressions have been tested against strong motion data accumulated in the region between 1933 and 1994, for earthquakes with magnitudes between 5.1 and 7.5, and for distances up to 150 km. The ground motion parameters examined included peak acceleration and response spectral acceleration at 0.3, 1.0, and 3.0 second periods. Some of the attenuation relations are found to be less consistent with southern California data and can be rejected for use in this particular region. Among those found to be most consistent, significant differences remain with respect to predicting ground motion under conditions not yet sampled in the data (e.g., near-source shaking for large earthquakes). Theoretical simulations can help resolve these ambiguities.

EXPECTED SHAPE OF REGRESSIONS FOR GROUND MOTION PARAMETERS ON ROCK

Among the various attenuation relations that have been presented, there exists an ambiguity with respect to whether or not the amplitudes of strong motion on rock show a magnitude-dependent distance decay. Given a high degree of scatter from a limited number of observations, current empirical data cannot resolve this issue. Therefore, Anderson [2000] has conducted a series of synthetic ground motion simulations to elucidate the magnitude dependence of the distance decay for rock sites.

Three different simulation techniques were used: one based on empirical Green functions; one based on theoretical Green functions with a simple source representation; and one based on theoretical Green functions with a composite source representation. All three techniques suggest that ground motion decays less rapidly with distance for larger magnitude earthquakes, evidence of a magnitude-dependent distance decay. Intuitively this can be explained as follows: at larger distances the Green functions are more complex due to various arrivals spread out over a longer duration of time. A larger earthquake, with more sub-events spread over a greater time period, will have constructive interference among the various arrivals from each sub-event, and the longer durations of the sub-event signals at larger distances will cause a proportionately greater increase in the amplitude than typically occurs at shorter distances. Six different attenuation relations were evaluated in terms of their consistency with this prediction.

EXPECTED SIGNATURE OF NON-LINEARITY ON REGRESSIONS

Nonlinear soil behavior may play an important role in modifying the degree of sediment amplification during strong ground motion. Currently available attenuation relations are divided on this issue, as some assume linearity and some allow for non-linearity. Because existing data are too limited and scattered to resolve this issue, we turn to theoretical simulations for guidance. Ni et al. [2000] investigated the response of two hypothetical soil profiles to several hundred synthetic seismograms. The non-linear constitutive properties of the soil are based on a standard geotechnical model (derived from laboratory studies), and the non-linear response is computed using an explicit formulation (as opposed to the equivalent linear formulation).

The model predicts that ratios of peak ground acceleration (PGA) between the soil surface and bedrock below are a decreasing function of input PGA values. A transition from amplification to de-amplification occurs for input PGA between 0.2 and 0.4 g. Ni et al. [2000] also examined spectral acceleration (SA) ratios, defined as the ratios of SA between the surface of the soil profile and the input. These SA ratios vary with the natural periods considered. At short periods (less than 0.3s) the SA ratios behave similarly to PGA ratios -- they show amplification for lower input SA and de-amplification for higher input SA levels. At longer periods, the influence of input SA level on the SA ratio decreases, and very few examples of de-amplification are observed. Six sets of empirical attenuation curves have been evaluated on the basis of this prediction, and some are found to be more consistent with the predictions than others. Although this does not resolve the issue of non-linearity, as their results are based on a particular geotechnical model, it does provide guidance in terms of the expected shape of attenuation curves.

RESIDUALS FROM A REGRESSION ON STRONG GROUND MOTION

Lee and Anderson [2000] have evaluated the possibility of tailoring an existing generic attenuation relationship to the task of predicting earthquake ground motion specifically in southern California. They focused on four ground-motion parameters (PGA and 0.3, 1.0, and 3.0 sec SA) and used the regression of Abrahamson and Silva [1997] (which was found to perform well for southern California). Differences between observed and predicted values (residuals) were examined, as a function of several site attributes, in order to determine whether corrections could be made to improve the predictions. Results indicate that residuals are correlated with basin depth, 3D model predictions, and detailed Quaternary surface geology (Figure 2). They propose several models (corrections to the attenuation relationship) based on these results. Although some of these corrections constitute significant amplification/deamplification factors, none provide a dramatic reduction of the prediction uncertainty (sigma).

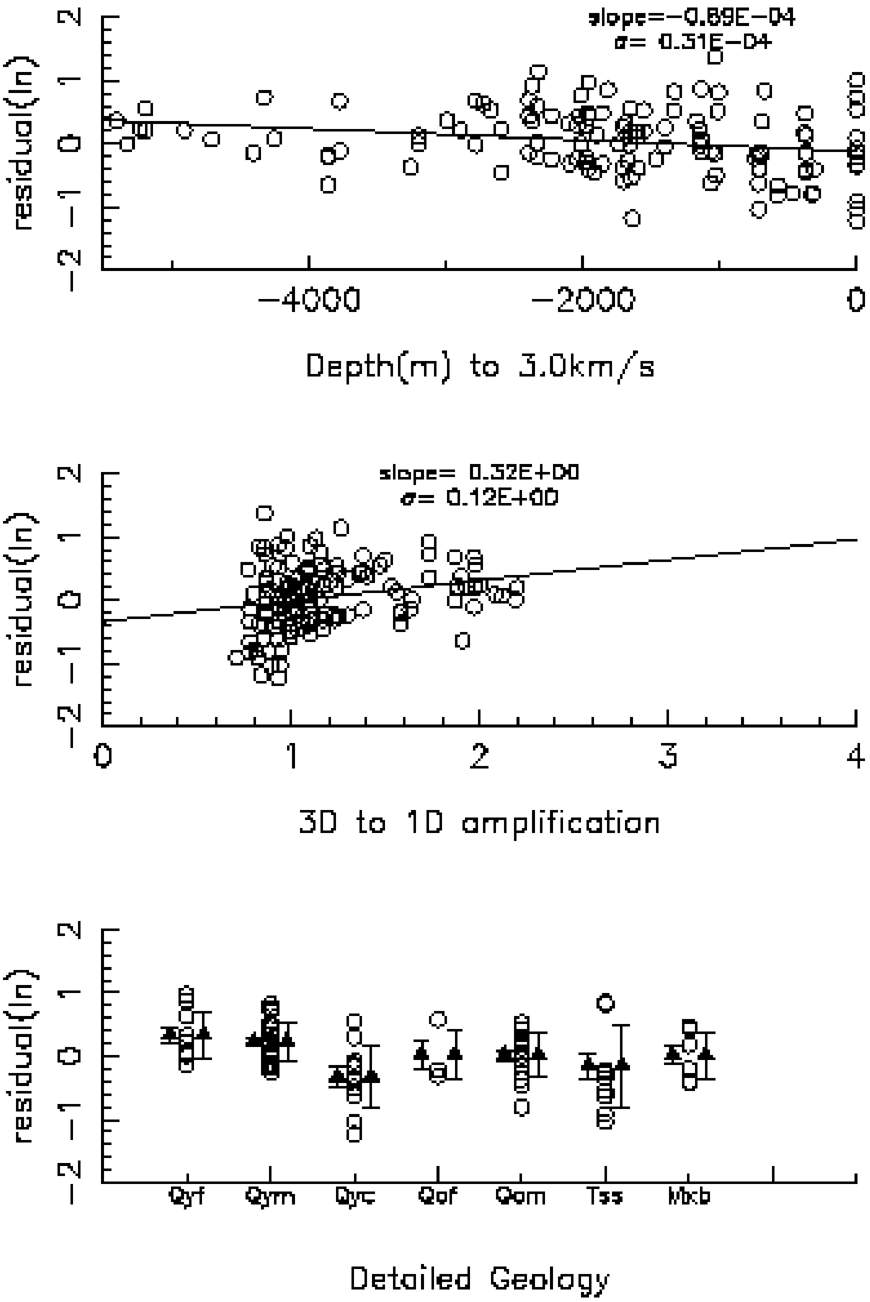

Figure 2. Correlation of attunuation-relationship residuals with basin depth (top), predicted 3D basin amplification (middle), and detailed geology (bottom) for 3-second response spectra. The predicted values account for rock versus soil differences. All three cases exhibit significant correlation (or differences in the case of detailed geology). These results are from Yajie and Anderson (2000).

PSHA TEST CALCULATIONS

The various papers in the Phase III report have identified several ways in which probabilistic seismic hazard analysis might be improved by accounting for site effects. Field et al. [2000] have investigated the degree to which the suggested modifications impact PSHA (in terms of 10% and 2% in 50 years hazard curves). The question being addressed is whether the differences are large enough to warrant the effort. First, six previously established attenuation relations, that differ significantly in terms of predicted ground motion under conditions not yet sampled by empirical observations, have been applied independently in hazard calculations. This indicates how differing assumptions regarding nonlinear sediment amplification, for example, influence the predicted hazard. Second, the models presented by Steidl [2000] and Lee and Anderson [2000], which have been customized for southern California to account for various site attributes (such as detailed surface geology and basin depth) have be evaluated with respect to PSHA. The results of these and other tests will be summarized in the oral presentation.

CONCLUSIONS

From the SCEC Phase III effort, several alternative models for accounting for site effects in southern California have been developed and tested. Significant site attributes include depth to basement rock and detailed surface geology. Perhaps an equally important finding is that accounting for these site effects does not appreciably reduce the prediction uncertainty of attenuation relations. This can be understood by the fact that basin-edge induced surface waves, focusing and defocusing effects, and scattering in general, are highly sensitive to the source location. These effects produce a high degree of variability between earthquakes at any given site, making the systematic site effects seem relatively small. However, even small corrections can have a significant impact on hazard analysis.

Issues that remain to be resolved include the specific effects of non-linear sediment behavior (change in amplification as a function of ground motion level), and ground motion behavior during large (M>7) earthquakes, particularly in the near field. Existing data are limited in terms of addressing these conditions. As we await additional observations, theoretical investigations can provide valuable insights.

REFERENCES

Abrahamson, N, and W. Silva, "Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes", *Seism. Res. Lett.*, v. 68, n. 1, pp. 94-127.

Anderson , JG, "Expected Shape of Regressions for Ground Motion Parameters on Rock" , *special SCEC Phase III issue of Bull. Seism. Soc. Am.*, In preparation.

Field, E.H, M.D. Petersen, and C.H. Cramer, N. Abrahamson, "Probabilistic Seismic Hazard Calculations: Test of Various Possible Site Response Parameterizations" , *special SCEC Phase III issue of Bull. Seism. Soc. Am.*, In preparation.

Lee, Y, J.G. Anderson, "Study of Residuals from a Regression on Strong Ground Motion" , *special SCEC Phase III issue of Bull. Seism. Soc. Am.*, In preparation.

Lee, Y, J.G. Anderson, and Y. Zeng , "Evaluation of Empirical Attenuation Relations" , *special SCEC Phase III issue of Bull. Seism. Soc. Am.*, In preparation.

Ni, S.-D., J.G. Anderson, Y. Zeng, and R.V Siddharthan , "Expected Signature of Nonlinearity on Regression for Strong Ground Motion Parameters" , *special SCEC Phase III issue of Bull. Seism. Soc. Am.*, In preparation.

Olsen, K.B., "Site Amplification in the Los Angeles Basin from 3D Modeling of Ground Motion", *special SCEC Phase III issue of Bull. Seism. Soc. Am.*, In preparation.

Sadigh, K, C.Y. Chang, J.A. Egan, F. Makdisi, and R.R. Youngs, "Attenuation relationships for shallow crustal earthquakes based on California strong motion data", *Seism. Res. Lett.*, v. 68, n. 1, pp. 180-189.

Steidl , J.H., "Site Response in Southern California for Probabilistic Seismic Hazard Analysis" , *special SCEC Phase III issue of Bull. Seism. Soc. Am.*, In preparation.