Final Technical Report

USGS Award Number G11AP20033

Incorporating Site Effects in Ground Motion Prediction Equations

Authors:
Laurie G. Baise and Eric M. Thompson

Affiliation:
Department of Civil and Environmental Engineering
Tufts University
113 Anderson Hall, Medford, MA 02255

617-627-2211, 617-627-3994 (fax)

Laurie.baise@tufts.edu, Eric.thompson@tufts.edu

Start Date: 1 January, 2011
End Date: 31 December, 2011

Abstract

Ground motion prediction equations (GMPEs) are developed for specific tectonic environments using multivariate regression on ground motion databases, and the relationships are updated as more earthquake data are obtained (Kramer, 1996; Abrahamson and Shedlock, 1997). Early ground motion prediction equations generally included only magnitude and distance as explanatory variables (Douglas, 2003, 2004, 2006, 2008). Over the past 20 years, however, many GMPEs have become increasingly complex in terms of the number of explanatory variables and in the complexity of the functional forms. Site effects were first accounted for as categorical variables for “rock” vs. “soil” (Abrahamson and Silva, 1997; Campbell, 1997) or by different equations for rock and soil sites (Sadigh *et al.*, 1997). Boore *et al.* (1997) included the 30 m S-wave velocity (V_{S30}) as a continuous site response explanatory variable in their GMPE. Four of the five recently-developed Next Generation Attenuation (NGA) models include V_{S30} as the primary site parameter (Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008). Additionally, three of the five NGA GMPEs include a depth parameter (such as $Z_{1.0}$, the depth to the 1.0 km/sec V_S horizon) to improve the ability of the GMPEs to model site effects. Recent discussions in the literature have highlighted the need to seek a site response parameter that can outperform V_{S30} (Douglas *et al*., 2009; Castellaro *et al.*, 2008). In this project, we evaluate alternative site effect terms (as compared to V_{S30}) within existing GMPEs.

Introduction

Over the past 20 years, ground motion prediction equations (GMPEs) have become increasingly complex in terms of the number of explanatory variables and in the complexity of the functional forms. Site effects were first accounted for as categorical variables for “rock” vs. “soil” (Abrahamson and Silva, 1997; Campbell, 1997) or by different equations for rock and soil sites (Sadigh *et al.*, 1997). Boore *et al.* (1997) included the 30 m S-wave velocity (V_{S30}) as a continuous site response explanatory variable in their GMPE. Recent discussions in the literature have highlighted the need to seek a site response parameter that can outperform V_{S30} (Douglas *et al.*, 2009; Castellaro *et al.*, 2008).

Abrahamson and Silva (2008) explained that the site effects term is responsible for the largest amount of epistemic uncertainty in GMPEs. One of the major obstacles to incorporating site response in GMPEs is the paucity of strong motion stations that have measured V_S. Thus, it is essential to expand the number of V_S profiles at strong motion stations. Only about 30% of the stations in the NGA database have measured values of V_{S30} (Power *et al.*, 2008); the remaining V_{S30} values are inferred using correlations of V_{S30} with surficial geology, such as those published by Wills and Clahan (2006).

The depth parameters ($Z_{1.0}$ and $Z_{2.5}$) that were added in the NGA project to further constrain site effects are even more difficult to estimate than V_{S30}. These values have been measured at far fewer sites than V_{S30}: only 54 sites in the NGA flatfile have profiles that reach 1.0 km/sec (Chiou and Youngs, 2008). The methods of estimating the depth parameters from other site characteristics (e.g., V_{S30}; Abrahamson and Silva, 2008; Chiou and Youngs, 2008) are unable to infer the depth parameters accurately. Our recent study on the prediction accuracy of the recent NGA GMPEs (Kaklamanos and Baise, 2011) indicates that adding complex site terms ($Z_{1.0}$ and $Z_{2.5}$) without a supporting dataset does not improve the accuracy of the GMPEs.

Site response is known to be effected by the sediment velocity and the depth to significant impedance contrasts. One criticism of V_{S30} is that 30 m is an arbitrary depth that may or may not include significant impedance contrasts. The selection of 30 m as the primary averaging depth for site response classification was a decision based in part on the fact that typical site investigations did not exceed 30 m depth. There has been an expansion of velocity measurements in recent years, which also includes many velocity profiles that extend to larger depths. Thus, the focus of this project is to investigate the use of larger averaging depths as an improved site term in GMPEs.

The general approach that we follow is to analyze the residuals from an existing GMPE for which the site term is removed by assuming a constant rock V_{S30}. For this purpose, we use the Boore and Atkinson (2008) GMPE (BA08). A key step in this analysis is to compile records from strong motion stations with deep velocity profiles. By limiting the database to those sites with deep velocity profiles, we can test the strength of the site term without including uncertainty from additional empirical correlations (i.e., geology to Vs30 correlations). We use a regression analysis to determine if different site terms, in particular, different averaging depths, can provide significant improvements over V_{S30}. We also include the effect of soil nonlinearity following a similar approach as Choi and Stewart (2005).

Data

We compiled a dataset of V_S profiles at strong motion stations that have deep velocity profiles. The profiles are mainly from KiK-net (410) and these all have profiles extending to approximately 100 m or more. In order to include as much California data as possible, we have relaxed the profile depth criteria by allowing profiles that only extend to 75 m, which results in an additional 99 profiles; 44 of these are from the Boore (2003) compendium, 54 are from surface wave measurements in Parkfield (Thompson *et al.*, 2011), and 1 station (the Meloland Geotechincal Array) is from ROSRINE. The resulting "flatfile" has 513 records from 21 earthquakes, summarized in Table 1.

Table 1: Summary of the number of records from each earthquake.

Earthquake	**#**		**Earthquake**	**#**		**Earthquake**	**#**
Chuetsu-oki	207		Iwate	127		Tottori, Japan	41
Niigata, Japan	39*		Parkfield	32		Coalinga-01	24
Northridge-01	8		Loma Prieta	6		Sierra El Mayor	6
Imperial Valley-06	4		Anza-02	3		Gulf of California	3
Morgan Hill	3		CA/Baja Border Area	2		Hector Mine	2
Whittier Narrows-01	2		Whittier Narrows-02	2		Coyote Lake	1
Landers	1		N. Palm Springs	1		Yountville	1

In order to compute the BA08 predictions, we need to compute the Joyner-Boore distance (R_{JB}), which is a function of the finite fault dimensions. We use the tabulated values in the NGA West database (Chiou *et al.*, 2008) where available. For those events that are not included in this database, we used published finite fault models to compute R_{JB} (Honda and Aoi, 2009; Suzuki *et al.*, 2010; Fukuyama *et al.*, 2003; Pulido and Dalguer, 2009; Asano and Iwata, 2009). Also, for the Sierra El Mayor earthquake, we used the finite fault model reported in the metadata page of ShakeMap.

Figure 1 gives the V_{S30} vs PGA distribution of this database. This shows that there are many large amplitude ground motions that span a wide range of site conditions. Similarly, Figure 2 gives the histogram of the V_{S30} values, where the bins have been set to match the NEHRP site class boundaries. Most of the records fall into site class D or C, however there are about 10 records in site class E.

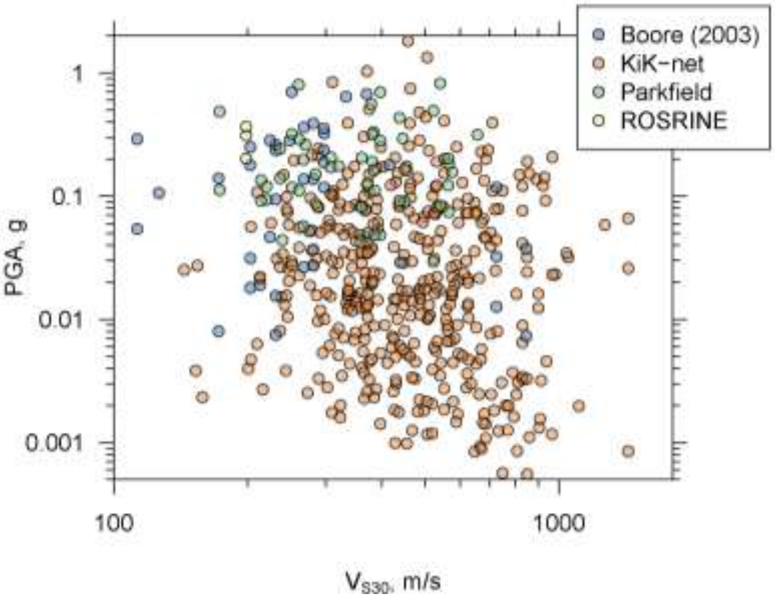

Figure 1: PGA vs V_{S30} for the records in the deep-profile database.

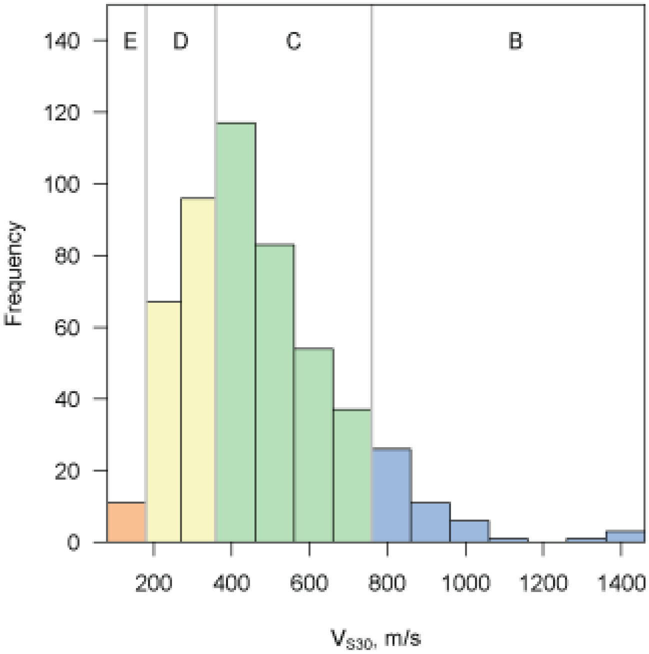

Figure 2: Histogram of VS30 for the records in the deep-profile database.

Definition of Site Amplification and Reference Motion

We use the “non-reference site” approach (Field and Jacob, 1995) to estimate the site response amplification based on GMPEs. For each of the stations, we compute the BA08 response spectra for the reference site condition (V_{S30} = 760 m/s): $Sa^{BA08}(T)$. We then compute the amplification as the residual:

$$\ln[a'(T)] = \ln[Sa^{OBS}] - \ln[Sa^{BA08}(T)] \ ,$$

where $Sa^{OBS}(T)$ is the recorded response spectra at period T. We compute the event terms (i.e., the mean $\ln(a')$ for each event), using all the records in the NGA flatfile, not just those records that are summarized in Table 1. We then compute $\ln(a)$ by subtracting the event terms from $\ln(a')$.

Assessing different Averaging Depths

Following Boore *et al.* (1997), we account for the velocity dependence of the amplification with a linear site amplification term:

$$\ln(a) = b_0 + b_{lin} \ln(V_{SZ} / V_{ref})$$

where $V_{ref} = 760$ m/s, and b_0 and b_{lin} are coefficients estimated by regression, and V_{SZ} is the average shear wave velocity to depth z. Note that since we have already corrected the $\ln(a)$ values for the event term, there is no need for the mixed-effects regression here. For the baseline model, we compute the regression for the coefficients in the above equation without the b_{lin} term. Figure 3 shows $\sigma_{\ln}$ and b_{lin} as a function of period for the regression without b_{lin} and for regressions with b_{lin} for V_{SZ} where z = 10, 30, 50, and 100 m.

Given that the appropriate averaging depth should be proportional to wavelength (Joyner *et al.*, 1981), we would expect this figure would show that each V_{SZ} performed best for a different period range, with V_{S10} being best for the smallest periods, then V_{S30} for intermediate, etc. But surprisingly, V_{S10} never performs better (in the sense of giving a smaller $\sigma_{\ln}$) than V_{S30}. But we do see that V_{S50} and V_{S100} give somewhat smaller $\sigma_{\ln}$ at periods of 0.5 s and larger. Another surprising observation is that none of the site terms decrease $\sigma_{\ln}$ over the “no site term” case at periods around 0.06-0.1 s. At shorter periods (T < 0.06 s), the site terms do help, but they all seem to perform equally well in terms of sigma. Thus, we can conclude that V_{S100} performs better than V_{S30}, but that the improvements are generally seen at periods of 0.5 s and greater.

This can easily be criticized for all the usual reasons, chief among them is that V_{S100} is not available at nearly as many stations as V_{S30} and is more difficult/expensive to measure. However, given that it is measured at so many KiK-net stations and an increasing number of California stations, we think that it may be a worthwhile exercise to investigate the ability of deeper averaging depths to decrease $\sigma_{\ln}$ for when it is available (see also discussion in Boore *et al.*, 2011).

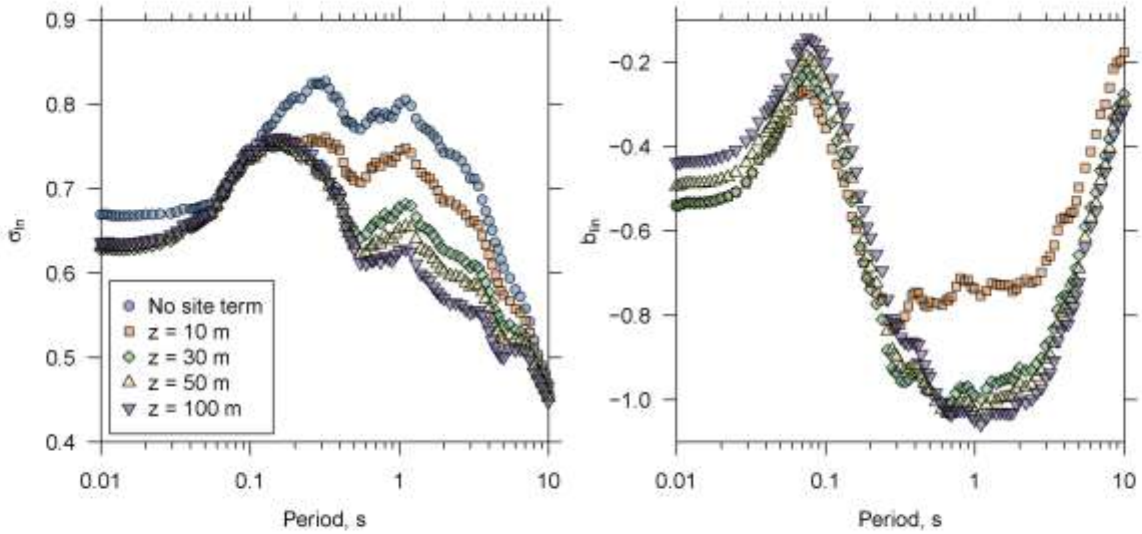

Figure 3: $\sigma_{\ln}$ and b_{lin} as a function of period for the regression without b_{lin} and for regressions with b_{lin} for V_{SZ} where z = 10, 30, 50, and 100 m.

Nonlinearity

Following Choi and Stewart (2005), but substituting V_{S100} for V_{S30}, we add a nonlinear site term as follows:

$$\ln(a) = b_0 + b_{lin} \ln(V_{S100} / V_{ref}) + b_{nl} \ln(PGA_r / 0.1) \ .$$

Choi and Stewart (2005) additionally derive a relationship for b_{nl} as a function of V_{S30}. Here, we take a somewhat simpler approach: to allow b_{nl} to vary with velocity, we add an interaction term to the regression:

$$\ln(a) = b_0 + b_{lin}\ln(V_{S100}/V_{ref}) + b_{nl}\ln(PGA_r/0.1) + b_{\text{int}}\ln(V_{SZ})\ln(PGA_r/0.1).$$

Given that most nonlinearity will occur in the very near-surface layers, we expect that a shallower averaging depth will be more effective as the V_{SZ} within the b_{int} term. Figure 4 compares the $\sigma_{\ln}$ of the regression and the b_{int} terms as V_{SZ} varies (note that we also include the $\sigma_{\ln}$ for the regression with only b_{lin} with V_{S100} as a reference).

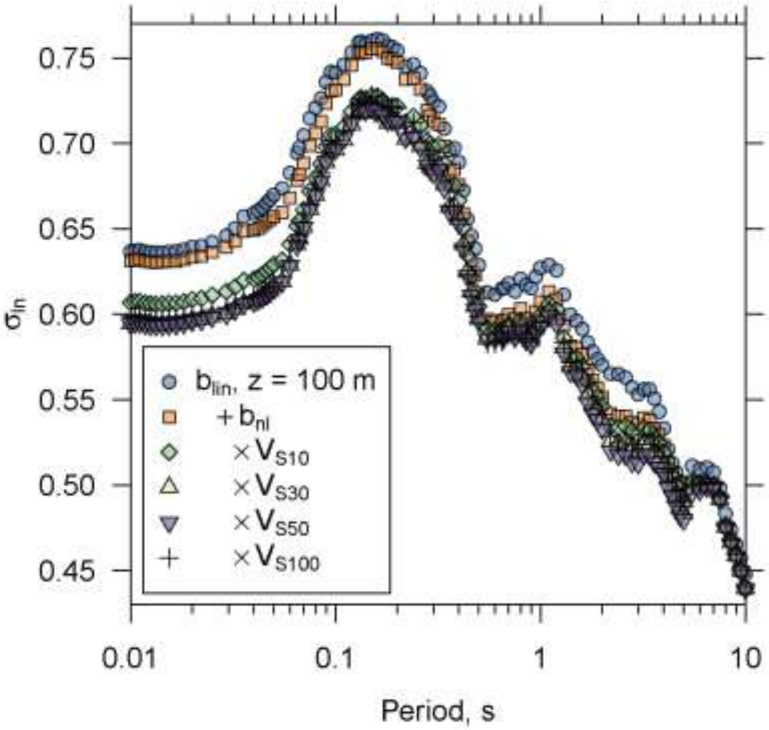

Figure 4: $\sigma_{\ln}$ for the nonlinear regressions with varying averaging depths for the b_{int} term.

The orange squares are for the regression with the b_{lin} term but without the b_{int} term. The fact that the $\sigma_{\ln}$ does not decrease relative to the b_{lin}-only regression indicates the need for the interaction term (and we would expect that the nonlinear effect will be larger for smaller velocities and smaller periods). The b_{nl} term is substantially improved with the addition of the interaction term, but the $\sigma_{\ln}$ is not very sensitive to the averaging depth (surprisingly, V_{S10} performs significantly worse than the others at short periods). Although it makes little difference, the V_{S50} term performs slightly better than the others on average.

Summary

We created a dataset of 513 recorded ground motions from 21 earthquakes that was limited to sites with deep velocity profiles (>75 m). The majority of records come from the KiK-Net array in Japan (414) with the remaining (99) records from California. The resulting dataset includes records from a range of site classes and ground motion level and therefore broadly samples the site response explanatory variables. We tested a series of depth-averaged *Vs* parameters (V_{SZ} where z = 10, 30, 50, and 100 m) as alternative site terms with an existing GMPE. Using the Boore and Atkinson (2008) GMPE, we evaluated the performance of the site parameter by comparing $\sigma_{\ln.}$ In summary, V_{S100} performs better (in the sense of giving a smaller $\sigma_{\ln}$) than V_{S30} at periods of 0.5 s and greater. At short periods (less than 0.1 s), none of the site parameters decrease $\sigma_{\ln}$.

References

Abrahamson, N. A., and K. M. Shedlock (1997). Overview, *Seismol. Res. Lett.* 68**,** 9–23.

Abrahamson, N. A., and W. J. Silva (1997). Empirical response spectral attenuation relations for shallow crustal earthquakes, *Seismol. Res. Lett.* 68**,** 94–127.

Abrahamson, N. A., and W. J. Silva (2008). Summary of the Abrahamson & Silva NGA ground-motion relations, *Earthquake Spectra* 24, 67–97.

Asano K. and T.. Iwata (2009). Source Rupture Process of the 2004 Chuetsu, Mid-Niigata Prefecture, Japan, Earthquake Inferred from Waveform Inversion with Dense Strong-Motion Data, , *Bull. Seism. Soc. Am.* 99, 123-140.

Boore, D. M. (2003). A compendium of *P*- and *S*-wave velocities from surface-to-borehole logging: Summary and reanalysis of previously published data and analysis of unpublished data, *U. S. Geological Survey Open-File Report 03-191*, 13 pp.

Boore, D. M., and G. M. Atkinson (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s, *Earthquake Spectra* 24**,** 99–138.

Boore, D. M., W. B. Joyner, and T. E. Fumal (1997). Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work, *Seism. Res. Letters* 68, 128-153.

Boore, D. M., E. M. Thompson, and H. Cadet (2011). Regional correlations of VS30 and velocities averaged over depths less than and greater than 30 m, *Bull. Seism. Soc. Am.* 101, 3046-3059.

Campbell, K. W. (1997). Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra, *Seismol. Res. Lett.* 68**,** 154–179.

Campbell, K. W., and Y. Bozorgnia (2008). NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s, *Earthquake Spectra* 24, 139–171.

Castellaro, S., F. Mulargia, and P. L. Rossi (2008). Vs30: proxy for seismic amplification? *Seismol. Res. Lett.* 79, 540–543.

Choi, Y. and J. P. Stewart (2005). Nonlinear site amplification as function of 30 m shear wave velocity, *Earthquake Spectra* 21, 1-30.

Chiou, B. S.-J., and R. R. Youngs (2008). An NGA model for the average horizontal component of peak ground motion and response spectra, *Earthquake Spectra* 24, 173–215.

Chiou, B., Darragh, R., Gregor, N., and Silva, W. (2008). NGA Project Strong-Motion Database, *Earthquake Spectra* 24, 23-44.

Douglas, J. (2003). Earthquake ground motion estimation using strong-motion records: a review of equations for the estimation of peak ground acceleration and response spectral ordinates, *Earth Sci. Rev.* 61**,** 43–104.

Douglas, J. (2004). Ground motion estimation equations 1964–2003: Reissue of ESEE Report 01-1: ‘A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)’ with corrections and additions, *Tech. rept. 04-001-SM.* Department of Civil and Environmental Engineering; Imperial College of Science, Technology, and Medicine; London.

Douglas, J. (2006). Errata of and additions to ‘Ground motion estimation equations 1964–2003,’ *Intermediary report RP-54063-FR.* BRGM, Orleans, France.

Douglas, J. (2008). Further errata of and additions to ‘Ground motion estimation equations 1964–2003,’ *Final report BRGM/RP-56187-FR.* BRGM, Orleans, France.

Douglas, J., P. Gehl, L. F. Bonilla, O. Scotti, J. Régnier, A.-M. Duval, and E. Bertrand (2009). Making the most of available site information for empirical ground-motion prediction, *Bull. Seismol. Soc. Am.* 99, 1502–1520.

Field, E.H., and Jacob, K.H. (1995). A comparison and test of various site-response estimation techniques, including 3 that are not reference-site dependent, *Bull. Seismol. Soc. Am.* 85, 1127-1143.

Fukuyama, E., W. L. Ellsworth, F. Waldhauser, and A. Kubo (2003). Detailed Fault Structure of the 2000 Western Tottori, Japan, Earthquake Sequence, *Bull. Seism. Soc. Am.* 93, 1468–1478.

Honda, R. and S. Aoi (2009). Array Back-Projection Imaging of the 2007 Niigataken Chuetsu-oki Earthquake Striking the World’s Largest Nuclear Power Plant, *Bull. Seism. Soc. Am.* 99, 141-147.

Kaklamanos, K., and L. G. Baise (2011). Model Validations and Comparisons of the Next Generation Attenuation of Ground Motions (NGA-West) Project, *Bull. Seism. Soc. Am.* 101, 160-175.

Joyner, W. B., R. E. Warrick, and T. E. Fumal (1981). The effect of Quaternary alluvium on strong ground motion in the Coyote Lake, California, earthquake of 1979, *Bull. Seism. Soc. Am.* 71, 1333-1349.

Kramer, S. L. (1996). *Geotechnical earthquake engineering*, Prentice Hall, Upper Saddle River, N.J.

Pulido, N. and L. A. Dalguer (2009). Estimation of the High-Frequency Radiation of the 2000 Tottori (Japan) Earthquake Based on a Dynamic Model of Fault Rupture: Application to the Strong Ground Motion Simulation, *Bull. Seism. Soc. Am.* 99, 2305-2322.

Sadigh, K., C. Y. Chang, J. A. Egan, F. Makdisi, and R. R. Youngs (1997). Attenuation relationships for shallow crustal earthquakes based on California strong motion data, *Seismol. Res. Lett.* 68**,** 180–189.

Suzuki, W, S. Aoi, and H. Sekiguchi (2010). Rupture Process of the 2008 Iwate-Miyagi Nairiku, Japan, Earthquake Derived from Near-Source Strong-Motion Records, *Bull. Seism. Soc. Am.* 100, 256-266.

Thompson, E. M., Baise, L. G., Kayen, R. E., Morgan, E. C., and Kaklamanos, J. (2011). Multiscale site-response mapping: a case study of Parkfield, California, *Bull. Seism. Soc. Am.* 101, 1081-1100.