

PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Update of the Chiou and Youngs NGA Ground Motion Model for Average Horizontal Component of Peak Ground Motion and Response Spectra

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The opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the study sponsor(s) or the Pacific Earthquake Engineering Research Center.

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ABSTRACT

This report presents an update to the Chiou and Youngs [2008a] NGA model for the prediction of horizontal peak ground acceleration and 5%-damped pseudo spectral acceleration for earthquakes in active tectonic regions such as California. The update is based on analysis of the greatly expanded NGA-West2 strong motion database. The updated model contains minor adjustments to the functional form developed by Chiou and Youngs [2008a] related to style of faulting effect, hanging wall scaling, scaling with the depth to the top of rupture, the effect of sediment depth, and the inclusion of two additional terms for the effects of fault dip and rupture directivity.

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1. Pages 36 and 37:

The revised GMPE formulation for median ground motions is given by Equation (3.11)

$$\begin{aligned} \ln(y_{refij}) &= c_{1} \\ &+ \left\{ c_{1a} + \frac{c_{1c}}{\cosh(2 \cdot \max(\mathbf{M}_{i} - 4.5, 0))} \right\} F_{RVI} \\ &+ \left\{ c_{1b} + \frac{c_{1d}}{\cosh(2 \cdot \max(\mathbf{M}_{i} - 4.5, 0))} \right\} F_{NMi} \\ &+ \left\{ c_{7} + \frac{c_{7b}}{\cosh(2 \cdot \max(\mathbf{M}_{i} - 4.5, 0))} \right\} \Delta Z_{TORi} \\ &+ \left\{ c_{7} + \frac{c_{7b}}{\cosh(2 \cdot \max(\mathbf{M}_{i} - 4.5, 0))} \right\} \left(\cos \delta_{i} \right)^{2} \\ &+ c_{2} \left(\mathbf{M}_{i} - 6 \right) + \frac{c_{2} - c_{3}}{c_{n}} \ln \left(1 + e^{C_{n}(C_{M} - \mathbf{M}_{i})} \right) \\ &+ c_{4} \ln \left(R_{RUPij} + c_{5} \cosh(c_{6} \cdot \max(\mathbf{M}_{i} - c_{HM}, 0)) \right) \\ &+ \left(c_{4a} - c_{4} \right) \ln \left(\sqrt{R_{RUPij}^{2} + c_{RB}^{2}} \right) \\ &+ \left\{ c_{r1} + \frac{c_{r2} - c_{3}}{\cosh(\max(\mathbf{M}_{i} - c_{r3}, 0))} \right\} R_{RUPij} \\ &+ c_{8} \max \left(1 - \frac{\max(R_{RUPij} - 40, 0)}{30} , 0 \right) \min \left(\frac{\max(\mathbf{M}_{i} - 5.5, 0)}{0.8} , 1 \right) e^{-c_{8a}} \left(\mathbf{M}_{i} - c_{8b} \right)^{2} \Delta DPP_{ij} \quad (3.11) \\ &+ c_{9} F_{HWij} \cos \delta_{i} \left\{ c_{9a} + (1 - c_{9a}) \tanh \left(\frac{R_{Nj}}{c_{9b}} \right) \right\} \left\{ 1 - \frac{\sqrt{R_{ABij}^{2} + Z_{TORi}^{2}}}{R_{RUPij} + 1} \right\} \end{aligned}$$

, and by Equation (3.12)

$$\ln(y_{ij}) = \ln(y_{ref_{ij}}) + \phi_1 \cdot \min\left(\ln(\frac{V_{S30j}}{1130}), 0\right) + \phi_2\left(e^{\phi_3(\min(V_{S30}, 1130) - 360)} - e^{\phi_3(1130 - 360)}\right) \ln(\frac{y_{ref_{ij}}e^{\eta_i} + \phi_4}{\phi_4}) + \phi_5\left(1 - e^{-\Delta Z_{1.0j}/\phi_6}\right) + \eta_i$$
(3.12)

- 2. Page 75: Replace line 4 by
 - γ_{Jp-It} : multiplicative adjustment factor for Japanese and Italian data. γ for Japan and Italy = $\gamma(\mathbf{M})$ for California multiplied by γ_{Jp-It} .
- 3. Page 76, Table A.1: Last row of column $3(\gamma_{Wn} \text{ for } T=10 \text{sec})$ should be 0.000.

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1 Introduction

This report presents an update to the Next Generation Attenuation (NGA) ground motion prediction equation (GMPE) developed by Chiou and Youngs [2008a]. The updated GMPE is based on analysis of the greatly expanded strong motion database developed by the Pacific Earthquake Engineering Research Center's (PEER) NGA-West2 Project, augmented by extensive numerical ground motion simulations conducted as part of the NGA-West2 Project. As was the case for Chiou and Youngs [2008a], the update model is for estimating horizontal ground motions caused by shallow crustal earthquakes occurring in active tectonic environments. Our model provides predictive equations for the orientation-independent average horizontal component of ground motions (RotD50) [Boore 2010]. Equations are provided for peak acceleration and 5%-damped pseudo-spectral acceleration for spectral periods of 0.01 to 10 seconds. The focus of this report is on developing GMPE for California, which is the main deliverable most useful to the sponsors (CEA, Caltrans, and PG&E), using exclusively California data from Class 1 earthquakes (mainshocks). In the final step of model development, the California data were supplemented with recordings from large earthquakes in other active tectonic regions to verify and refine the magnitude scaling and to provide more robust estimates of aleatory variability. Regional difference in ground-motion scaling between active tectonic regions in terms of site effects and distance attenuation were addressed as part of inclusion of the additional data. The updated Chiou and Youngs model developed for this report contains some modifications to the functional form developed by Chiou and Youngs [2008a] and the introduction of two terms to model dependence of ground-motion amplitude on fault dip and rupture directivity.

2 Ground Motion Data Used to Develop the Updated Model

The empirical data set used in this update was selected from the PEER NGA-West2 database [Ancheta et al. 2013]. We supplemented the NGA-West2 flat file with imputed values of missing metadata. These supplemental data, as well as record selection criteria, are discussed in this chapter.

2.1 SELECTION OF EMPIRICAL DATA

The data selection criteria used in this study is the same as that used previously as described in Chiou and Youngs [2008a, 2008b]. The dataset was restricted to free-field motions from shallow crustal earthquakes in active tectonic regions, principally California. Recordings made in large buildings and at depth were removed. We kept records from sites that have been characterized as having topographic effects (e.g., Tarzana Cedar Hill Nursery, Pacoima Dam left abutment). Our rationale for including these records is that the effect of topography has not been systematically studied for all of the records in the database and many other recording stations may have topographic enhancement or suppression of ground motions. Topographic effects are considered to be part of the variability introduced into ground motions by travel path and site effects. The ground motion model developed in this study explicitly accounts for site conditions. Therefore, recordings from sites for which there is no available information of the local soil conditions were excluded.

In Chiou and Youngs [2008a, 2008b] we used a combined empirical dataset from a number of active tectonic regions (principally from California, Taiwan, and Turkey, with limited data from Iran, Italy, and Japan). We did not find notable differences in the data from these regions. The expanded PEER NGA-West2 database included additional data from earthquakes in Italy and Japan, as well as data from earthquakes in New Zealand and China (Wenchuan). Preliminary evaluations of these data by Chiou and Youngs [2012] suggested that there may be regional differences in anelastic attenuation and V_{S30} scaling of ground motion amplitudes among the various active tectonic regions. Such differences were further examined and quantified in Section 3.1.3 and 3.2.2 as part of the development of the updated GMPE.

In the early stage of model development, we decided to focus on a California model and used only California data, therefore avoided the needs for addressing regional difference in ground motion scaling. After completing the California-specific GMPE, we decided to bring back relatively well-recorded large non-California earthquakes because the number of California earthquakes with magnitude greater than 7 is smaller than desired. Selection criteria of the non-California earthquakes were: (1) magnitude is M6 or greater; (2) number of recording is five or greater. These earthquakes were brought back to help verify and refine the magnitude scaling, style of faulting effects, and hanging wall effects. They also help provide more robust estimates of aleatory variability.

Data from earthquakes that occurred in oceanic crust offshore of California and Taiwan in oceanic crust were excluded because ground motions from these types of events have been found to be more consistent with ground motions from Wadati-Benioff zone (subduction intraslab) earthquakes than shallow crustal earthquakes [Geomatrix Consultants 1995]. Data from the 1992 Cape Mendocino earthquakes were included because the source depth places the event above the likely interface location [Oppenheimer et al. 1993].

Previously, we developed the GMPE using only data for distance of 70 km or less. This data cutoff was aimed to limit the impacts of bias in the data sample introduced by data truncation at large distances. In the updated model, instead of applying the same cutoff distance to all earthquakes, we developed an assessment of the maximum usable distance for each earthquake so that we could utilize as much data as possible for well-recorded earthquakes. This assessment also resulted in a shorter maximum distance (less than 70 km) for some of the older events, thus actually reduced the number of older data used in regression. More details are discussed later in Section 3.2.2.

In Chiou and Youngs [2008a] we included data from aftershocks (the Class 2 earthquakes as defined in Wooddell and Abrahamson [2012]) to help constrain the coefficients of the site response model. With the NGA-West2 database, it is no longer necessary to do so. Therefore, we removed data from Class 2 earthquakes located in the vicinity (within 20 km) of a Class 1 earthquake rupture. One notable Class 2 earthquake removed is the 1999 Duzce earthquake.

After applying the selections described above, a total of 12,444 records obtained from 300 earthquakes were selected for the final update of our GMPE. Among them, a total of 2587 records were selected from 18 non-California earthquakes. Figure 2.1 includes a scatter plot of distance-magnitude-region distribution of the final dataset. Finally, in the regression of response spectra at a spectral period T, we included only records having a minimum usable spectral frequency that is lower than 1/T. This selection practice led to a decreased data size as T increased (Figure 2.2).



Figure 2.1 Magnitude-distance-region distribution of selected records.



Figure 2.2 Number of usable records as a function of spectral period.

2.2 USE OF GROUND MOTION SIMULATIONS

Our 2008 GMPE included terms that model an increase in ground motion amplitudes at sites on the hanging wall of dipping fault ruptures. There were very limited empirical data available from hanging wall sites and the function form of the hanging wall model was largely based on conceptual considerations. The expanded NGA-West2 database includes some additional data from hanging wall sites, but the increase is not large. To augment these data, the NGA-West2 sponsored a set of ground motion simulations focused on investigating the variation of ground motion amplitudes near and on the hanging wall of dipping fault ruptures. Donahue and Abrahamson [2013] presented a summary of the simulation data and developed a model to represent the hanging wall effect.

2.3 SUPPLEMENT OF GROUND MOTION METADATA

2.3.1 Sediment Thickness (Z_{1.0})

The thickness of the near-surface sediments is represented in our NGA GMPE by the depth to the shear wave velocity horizon of 1.0 km/sec, $Z_{1.0}$. The completeness of this variable was greatly improved during the development of NGA-West2 database. The database provided $Z_{1.0}$ for sites within the Southern California Earthquake Center three-dimensional (3D) basin model, for sites in the USGS velocity model for the San Francisco Bay area, for sites in Japan, and for sites where measured shear-wave velocity profiles reached the 1.0 km/sec horizon.

For a site without $Z_{1.0}$, we estimated its $Z_{1.0}$ using an empirical correlation with V_{S30} . A correlation was previously developed from the available (V_{S30} , $Z_{1.0}$) data in the NGA-West1 database [Chiou and Youngs 2008a, 2008b]. Additional data in the NGA-West2 database and careful checking (which led to correction of obvious data errors and removal of data with default $Z_{1.0}$ value) has resulted in a revised correlation between V_{S30} and $Z_{1.0}$.

The majority of data used in the revised relation were from sites in California (Figure 2.1) and Japan (Figure 2.2). There is a clear difference in V_{S30} - $Z_{1.0}$ relation between these two regions; $Z_{1.0}$ is smaller in Japan than in California for soft soil sites. Also, for $V_{S30} > 500$ m/sec, the rate of decrease with V_{S30} is slower in Japan than in California. For these two reasons, we developed two V_{S30} - $Z_{1.0}$ relations, one for each region, as follows.

For California:

$$\ln(Z_{1.0}) = \frac{-7.15}{4} \ln(\frac{V_{S30}^4 + 571^4}{1360^4 + 571^4})$$
(2.1)

For Japan:

$$\ln(Z_{1.0}) = \frac{-5.23}{2} \ln(\frac{V_{s30}^2 + 412^2}{1360^2 + 412^2})$$
(2.2)

Based on Figure 2.3, one could argue that there is also a difference between southern California sites (red circles in the figure) and central California sites (blue circles). However, the difference is less than the difference between California and Japan. Because we focused on developing a California wide model, this difference was not included. Future refinements of our model will explore the need for regionalization within California.



Figure 2.3 Relationships between V_{S30} and $Z_{1.0}$ for California.





Figure 2.4 Relationship between V_{S30} and $Z_{1.0}$ for Japan.

2.3.2 Depth to Top of Rupture (Z_{TOR})

Source depth is represented in our GMPE by the depth to the top of rupture, Z_{TOR} . In the NGA-West2 database, Z_{TOR} was determined either from the available finite fault model or from hypocentral depth and **M** using the simulation method described in Appendix B of Chiou and Youngs [2008b]. As such, Z_{TOR} had been estimated for every earthquake in the database, except for a few poorly determined (small) earthquakes whose hypocenter location or magnitude is unknown.

Using California data in the NGA-West2 database, we developed a model relating Z_{TOR} to **M** and style of faulting. The developed relationship was used later to center Z_{TOR} (Section 3.1.2). In the forward application of our updated GMPE, this relationship could also be used as a tool to estimate the Z_{TOR} of a future California earthquake, given its magnitude and style of faulting.

Following Kaklamanos and others [2011], we applied the square root transformation to Z_{TOR} to increase the normality of residuals. The scatter plot of Figure 2.5 indicates that, while being a constant at $\mathbf{M} < 5$, $\sqrt{Z_{TOR}}$ is approximately a linear function of \mathbf{M} where $\mathbf{M} > 6$. This observation, together with the non-negative value of $\sqrt{Z_{TOR}}$, prompted us to model $\sqrt{Z_{TOR}}$ as a linear ramp function of \mathbf{M} using the relationship:

$$\sqrt{Z_{TOR}} = \max[a + b\max(\mathbf{M} - c, 0), 0]$$
(2.3)

In Equation (2.3), parameter *c* is the threshold magnitude below which $\sqrt{Z_{TOR}}$ is constant *a*, and parameter *b* is the slope for $\mathbf{M} > c$. As noted by Kaklamano et al. [2011], the $\sqrt{Z_{TOR}}$ - \mathbf{M} relationship for reverse and reverse oblique faulting is different from that for the other styles of faulting. We thus developed two models. One for the reverse and reverse oblique faulting,

$$Z_{TOR} = \max[2.704 - 1.226 \max(\mathbf{M} - 5.849, 0), 0]^2$$
(2.4)

and the other for the combined strike-slip and normal faulting,

$$Z_{TOR} = \max[2.673 - 1.136 \max(\mathbf{M} - 4.970, 0), 0]^2$$
(2.5)

 Z_{TOR} values predicted by these two models are shown as solid lines in Figure 2.5. The dot-dashed lines in the figure are predictions by the models of Kaklamano et al. [2011] developed using worldwide earthquakes in the NGA-West1 database. It should be noted that these models are similar at M > 5.5, where the datasets used in both models overlap considerably.



California Events

Figure 2.5 A scatter plot showing $\sqrt{Z_{TOR}}$ and M of California earthquakes in the NGA-West2 database. Solid lines are the regression models developed in this study for reverse faulting (blue line) and combined strike-slip/normal (red line) faulting. Dot-dashed lines are the models of Kaklamano et al. [2011].

3 Updated GMPE

As evidenced by the analysis presented in Choiu et al. [2010], the inclusion of a large data set of ground motions from small to moderate magnitude earthquakes (SMM) has a significant effect on ground motion scaling relationships. For this study, we defined SMM events as earthquakes in the range of 3 < M < 5.5. A large percentage of SMM ground motion records were obtained from the broad band networks of southern California and central California. Incorporation of these data as well as data from the additional well recorded large $M \ge 5.5$ magnitude (LM) earthquakes has led to modifications of model formulation and refinements of model coefficients. These changes and their basis are discussed in the first two sections of this chapter. The updated models for median motion and aleatory variability are presented in Sections 3.3 and 3.4, respectively.

In several exploratory analyses of the NGA-West2 database, we noted that groundmotion scaling may be different between SMM and LM earthquakes. After examining several source scaling in exploratory analysis, we selected the following function to model the observed differences,

$$f(\mathbf{M}_i) = \left\{ \alpha + \frac{\beta}{\cosh\left[2 \cdot \max\left(\mathbf{M}_i - 4.5, 0\right)\right]} \right\}$$
(3.1)

Equation (3.1) has a gradual transition from the asymptote $(\alpha + \beta)$ at $\mathbf{M} < 4.5$ to the other asymptote α at M6.5, straddling the magnitude boundary between SMM and LM. With this property, Equation (3.1) decoupled the scaling for LM and SMM and prevented undue influence on LM scaling by SMM earthquakes. The latter was particularly useful when the metadata in question (such as magnitude and focal mechanism) was of lesser quality for SMM earthquakes.

3.1 MODIFICATION OF MODEL FORMULATION

In response to the outcomes of several exploratory analyses, we modified the parts of our previous formulation related to the effects of style of faulting, depth to the top of rupture, hanging wall, and $Z_{1,0}$. These modifications and their basis are described in the first four subsections. We also added two terms to model the effects of rupture dip angle and rupture directivity; they are presented in the last two subsections.

Given that Class 2 (aftershock) data were no longer needed for constraining site response model, we decided not to include them in this update in order to simplify our analysis.

Consequently, we removed terms related to the effects of Class 2 earthquakes. We plan to explore and quantify the aftershock effects in a follow-up study.

3.1.1 Style of Faulting Effect for Reverse and Normal Faulting

As stated previously, we noted difference in style-of-faulting effect between SMM and LM earthquakes. As an example demonstrating such difference, Figure 3.1 shows event terms computed for an interim GMPE without style-of-faulting effects for 4 spectral periods. As indicated in the figure, reverse faulting effect (difference in smoothed curve between RV and SS) is stronger at LM than at SMM. Conclusions about normal faulting effect are less definite because there are only 8 normal faulting events in our dataset.





T3.000S



Figure 3.1 Event terms computed from an interim GMPE demonstrating the difference in style of faulting effect between small-to-moderate and large magnitude earthquakes.

Equation (3.1) tracked the magnitude trend of reverse faulting effect quite well. As a result, we modified our term for reverse faulting effect

from
$$c_{1a} F_{RVi}$$
 to $\left\{ c_{1a} + \frac{c_{1c}}{\cosh(2 \cdot \max(\mathbf{M}_i - 4.5, 0)))} \right\} F_{RV}$

and our term for normal faulting effect

from
$$c_{1b}F_{NMi}$$
 to $\left\{c_{1b} + \frac{c_{1d}}{\cosh(2 \cdot \max(\mathbf{M}_i - 4.5, 0))}\right\} F_{NMi}$

 F_{RVi} and F_{NMi} are reverse faulting and normal faulting flags defined in Chiou and Youngs [2008a, 2008b]. See also Section 3.3.1.

3.1.2 Depth to the Top of Rupture

We implemented two changes to the formulation of source depth effect. First, we centered Z_{TOR} on the Z_{TOR} -**M** relationships of Equations (2.4) and (2.5), rather than on a constant value of 4 km as in our 2008 GMPE. By centering on a **M**-dependent average, the **M** scaling of average Z_{TOR} was transferred to the general magnitude scaling, resulting in a sharp corner in the magnitude scaling curve, as evidenced by the much increased c_n at high frequencies (Table 3.2) compared to our 2008 model. This change in modeling concept has a small impact on median predictions. Instead of carrying Equations (2.4) and (2.5) in the equation for median, we created the new variable $\Delta Z_{TOR} = Z_{TOR} - E[Z_{TOR}]$, where $E[Z_{TOR}]$ is the mean Z_{TOR} given by Equations (2.4) and (2.5).

Secondly, we introduced **M** dependence into the Z_{TOR} scaling coefficient c_7 . Similar to style of faulting effects, we noted a difference in Z_{TOR} scaling between SMM and LM earthquakes. As an example demonstrating such difference, we computed event terms of California earthquakes for an interim GMPE without Z_{TOR} effects for 4 spectral periods. We grouped the event terms into nine non-overlapping magnitude bins. For each bin, we fitted event terms to a linear function of Z_{TOR} . The slopes of the fitted line (coefficient of Z_{TOR} scaling), along with their 95% confidence intervals, are shown in Figure 3.2 against magnitude. From the figure, we concluded that Equation (3.1) adequately model the magnitude dependence of Z_{TOR} scaling.

Based on the above discussions, we modified the Z_{TOR} formulation from

$$c_7 (Z_{TORi} - 4)$$

to

$$\left\{c_{7} + \frac{c_{7b}}{\cosh(2 \cdot \max(\mathbf{M}_{i} - 4.5, 0))}\right\} \Delta Z_{TORi}$$



Figure 3.2 Plots showing the variation of estimated coefficients of Z_{TOR} scaling with earthquake magnitude. The estimated scaling coefficients for earthquakes in nine 0.5-unit magnitude bins are shown as solid circles, and their 95% confidence intervals as vertical bars. The solid blue curve is the nonlinear least-squares fit to the bin coefficients by Equation (3.1).

3.1.3 Z_{1.0} Scaling

Sediment depth, represented by the depth to shear-wave velocity of 1.0 km/sec ($Z_{1.0}$), was used along with V_{S30} to model the amplification of surface motion by local site condition. Our previous study revealed ground motion amplification on deep sediment sites, i.e., sites whose $Z_{1.0}$ is larger than coefficient ϕ_7 in 2008 Chiou and Youngs GMPE. However, we did not observe clear evidence of the de-amplification of ground motion on shallow soil sites ($Z_{1,0}$ smaller than ϕ_7) as predicted by site response analysis. Guided by site response analysis, Abrahamson and Silva [2008] implemented a large de-amplification of long-period motions when a site's $Z_{1,0}$ is far below the average $Z_{1,0}$ for the site V_{S30} . Encouraged by their work and the benefits of predictor centering seen earlier, we centered $Z_{1,0}$ on the average $Z_{1,0}$ given by Equations (2.1) and (2.2) and used the centered variable $\Delta Z_{1,0}$ as predictor of sediment depth effects.

With $\Delta Z_{1.0}$, de-amplification on shallow soils was clearly illuminated. This modeling improvement is shown in Figure 3.5 by the negative average of station terms for negative $\Delta Z_{1.0}$. The station term in the figure was computed as the average residual of records available at a specific site and the residuals were from interim analyses that included both linear and nonlinear soil effects. The figure also suggests a stronger amplification for positive $\Delta Z_{1.0}$ in Japan than in California, suggesting a need for regionalization of sediment depth effects.

Guided by plots similar to Figure 3.5, we selected the following functional form for $\Delta Z_{1.0}$ scaling in our updated model,

$$\phi_5 \left(1 - e^{-\Delta Z_{1.0j}/\phi_6} \right) \tag{3.4}$$



Figure 3.3 Plots showing site terms versus $\Delta Z_{1.0}$. Solid curves are the smooth of site terms over $\Delta Z_{1.0}$ by local linear regression. The two dashed curves are the fitted models of Equation (3.4) to the site terms of Japan (green) and California (red).
3.1.4 Hanging Wall Scaling

The hanging wall (HW) scaling model developed in Chiou and Youngs [2008a] involved an amplification of ground motions for sites on the hanging wall that increased with increasing absolute value of R_X . The amplification function peaked at a value of R_X that was independent of the location of the down dip edge of the rupture. Once the value of R_X increased to the point where the site location moved beyond the surface projection of the bottom of the rupture, then a distance taper function rapidly decreased the hanging wall amplification. The analyses of ground motion simulation results presented in Donahue and Abrahamson [2013] show a somewhat more gradual rate of increase in the hanging wall amplification for sites above the rupture such that the peak amplification occurs nearer to the down dip edge of the rupture. Because there is very limited empirical data that can be used to define the R_X trends of HW amplification on top of the rupture, we used the simulation data to develop a revised hanging wall model.

The process used was similar to that employed by Donahue and Abrahamson [2013]. The footwall and neutral site data for individual simulations were fit using a simple distance attenuation functional form. Then the residuals with respect to this model were computed for the data from the simulated earthquake for sites located above the rupture ($R_{JB} = 0$). The process was repeated for each simulation, and the resulting sets of residuals combined. Figure 3.4 shows the resulting sets of residuals. Each plot shows the results for one dip angle. With the exception of the results from the M6 simulations, the residuals exhibit a similar trend for all of the larger magnitudes. This trend can be modeled by the function $tanh(R_X / c_{9b})$, where c_{9b} is a constant independent of magnitude. The residuals for the M6 simulations exhibit a different behavior, in that they peak at very small values of R_X , rather than at values of R_X near the down dip extent of the ruptures, which is the case for the simulation process for smaller magnitudes. Because of this different behavior, the residuals for the M6 simulations were not used to develop the hanging wall model.

The residuals shown on Figure 3.4 show a decrease in amplitude with increasing dip angle, δ , that can be modeled as a function of $\cos(\delta)$. The use of $\cos(\delta)$ rather than δ is motivated by considering the hanging wall effect to be a geometrical effect representing the location of a site relative to the projection of the entire rupture plane to the surface, and the this projection is directly related to $\cos(\delta)$. The simulation residuals also show a small step at $R_X = 0$. The simulations were fit with the model form given by Equation (3.5).

$$f_{HW} = c_9 \cos(\delta) \left\{ c_{9a} + (1 - c_{9a}) \tanh\left(\frac{R_X}{c_{9b}}\right) \right\} \left\{ 1 - \frac{\sqrt{R_{JB}^2 + Z_{TOR}^2}}{R_{RUP} + 1} \right\}$$
(3.5)

The fitted values of this function is compared to the residuals for $R_{JB} = 0$ sites on Figure 3.4. Figure 3.5 compares the hanging wall scaling factor (without the absolute scaling coefficient c_9) from Equation (3.5) to that for the Chiou and Youngs [2008a] model. The revised model shows stronger magnitude scaling than the previous model, consistent with the results of the simulations as modeled by Donahue and Abrahamson [2013]. The magnitude scaling is introduced by the term tanh (R_X / c_{9b}) . This term increases with increasing R_x , and this can only occur with wider ruptures (and corresponding larger magnitudes). Also consistent with Donahue

and Abrahamson [2013], we have implemented a step in ground motions at the fault trace for surface rupturing earthquakes. In our formulation, this step in ground motions disappears as the depth to top of rupture increases from zero. The constant in the denominator of the term

$$\left\{1 - \frac{\sqrt{R_{JB}^2 + Z_{TOR}^2}}{R_{RUP} + 1}\right\}$$
 was increased from 0.001 used in Chiou and Youngs [2008a] to 1 to provide

a smoother transition in amplitude with increasing Z_{TOR} .

The Donahue and Abrahamson [2013] hanging wall model shows less rapid attenuation of the hanging wall amplification with increasing R_X for sites located beyond the down dip edge of the rupture than the formulation developed by Chiou and Youngs [2008a]. For these types of site locations there is more empirical data available. These data indicate a faster decay of the hanging wall amplification with increasing R_X than is defined by the Donahue and Abrahamson [2013] hanging wall model. Figure 3.6 compares the residuals computed using Equation (3.5) for sites on the hanging wall side (positive R_x) for reverse faulting earthquakes against the distance

scaling term $\left\{1 - \frac{\sqrt{R_{JB}^2 + Z_{TOR}^2}}{R_{RUP} + 1}\right\}$. The solid and dashed red curves indicate the loess fit to the

residuals and the 90% confidence interval on the fit, respectively. As was found in Chiou and

Youngs [2008a, 2008b], the data are consistent with a linear trend in the term $\left\{1 - \frac{\sqrt{R_{JB}^2 + Z_{TOR}^2}}{R_{RUP} + 1}\right\}$.

Therefore, this distance decay formulation of Chiou and Youngs [2008a] was retained in the updated GMPE formulation with the small modification described above.



Figure 3.4 Residuals for simulated ground motion data at sites on top of the hanging wall (R_{JB} =0) for reverse faulting earthquakes with surface rupture (Z_{TOR} = 0). Solid curves indicate locally weighted least squares (Loess) fits to the data for each magnitude and the dashed line indicates the overall fitted model.



Figure 3.5 Comparison of revised hanging wall scaling formulation with that in Chiou and Youngs [2008]. New model based on Equation (3.3) is shown in red and 2008 formulation in black.



Figure 3.6 Distance attenuation of hanging wall effect. Red solid curve is a loess fit to the residuals and the red dashed curves indicate the 90% confidence interval of the fit.

3.1.5 Effect of Rupture Dip Angle

In exploratory analysis, we found that the event terms of SMM earthquakes decreased systematically with decreasing dip angle. We did not observe similar dependency in LM events. As a result, we added a term for dip angle and used Equation (3.1) to model the absence of this effect in LM earthquakes. Functional form of the added term is

$$\left\{c_{11} + \frac{c_{11a}}{\cosh(2 \cdot \max(\mathbf{M}_i - 4.5, 0))}\right\} \cos(\delta_i)^2$$

Coefficient c_{11} (dip-angle scaling for LM earthquakes) was fixed to 0 for all periods (see Table 3.2).

3.1.6 Directivity Effect

The 2008 NGA-West1 GMPEs did not include directivity. Instead, directivity was implemented as a *post facto* factor. Implementation of directivity effect in the updated GMPE was one of the focuses of our model update. Among the five directivity parameterizations discussed in the Directivity Working Group report [Spudich et al. 2013], we choose the direct point parameter (*DPP*) as our predictor for directivity effect. The rationales for choosing *DPP* over *IDP* (the

ioschrone directivity parameter used in Spudich and Chiou [2008]) were given in Chiou and Spudich [2013].

As with $Z_{1.0}$ and Z_{TOR} , we centered *DPP* on the average *DPP* of the earthquake in question. The average *DPP* is the mean over a suite of sites located at the same distance to that earthquake. It is a function of distance and is specific to the earthquake rupture being investigated. Using ΔDPP (centered *DPP*) forces a GMPE to explicitly scale ground-motion amplitude relative to the median representing the average directivity at a given distance to fault. Centering also allows the GMPE users to predict the average directivity effect (by simply setting ΔDPP to 0) if site- and rupture-specific directivity is not to be explicitly included in the ground motion prediction.

We adopted the narrow-band formulation proposed by Spudich and Chiou [2013] for its improved handling of M- and period-dependence. Their form was rearranged so that it could be incorporated into our regression model one period at a time. The rearranged form is

$$f_D = c_8 f_R f_M e^{-c_{8a}(\mathbf{M} - c_{8b})^2} \Delta DPP$$
(3.6)

Relating to the original narrow-band formulation, coefficient c_{8a} is related to the bandwidth parameter (g), coefficient c_{8b} is the magnitude for which the analyzed period is the period of peak effect (T_{max}), and coefficient c_8 is the peak effect (b_{max}). Note that in the original formulation c_8 is a linear function of **M** in the **M** > 5.7 range. In our analysis we found that this linear dependence was unstable across periods and was statistically insignificant for many periods; therefore we did not include the linear magnitude dependence in our updated model. Also in the original formulation, c_8 is period independent. This property cannot be implemented in our one-period-at-a-time regression setting. As a workaround, we estimated c_8 for each of the analyzed periods between 0.75 sec and 10 sec, and took the weighted average of the individual estimates as our final c_8 estimate.

Function f_R in Equation (3.6) is the same distance taper used in Spudich and Chiou [2008].

$$f_{R} = \max\left[0, \ \left(1 - \frac{\max(R_{RUP} - 40, \ 0)}{30}\right)\right]$$
(3.7)

Function f_M is a magnitude taper similar to the one used by Spudich and Chiou [2008],

$$f_M = \min\left[1, \frac{\max(\mathbf{M} - 5.5, 0)}{0.8}\right]$$
 (3.8)

Due to the absence of finite-fault information, directivity effect for $\mathbf{M} < 5.7$ earthquakes cannot be investigated in this update. We assumed directivity effect at $\mathbf{M} < 5.5$ is negligible, though some recent studies (for example, Boatwright [2007]) suggested otherwise. This assumption was implemented via the magnitude taper f_M , which reduced c_8 from a non-zero value to zero from \mathbf{M} 6.3 to \mathbf{M} 5.5.

3.2 REFINEMENT OF MODEL COEFFICIENTS

The formulation for magnitude and distance scaling of ground motion amplitudes was examined as part of the update efforts. Our conclusion was that the formulation continues to provide a good fit to the trends in the NGA-West2 database, although model coefficients needed to be adjusted.

3.2.1 Magnitude Scaling

Development of the magnitude scaling formulation in our 2008 GMPE was guided by the results of simulations using seismological models for earthquake source spectra and evaluation of ground motion data of small to moderate California earthquakes. The functional form is given in Equation (3.9).

$$\ln(y) \propto c_2 \mathbf{M} + \frac{1}{c_n} (c_2 - c_3) \times \ln[1 - \exp\{c_n (c_{\mathbf{M}} - \mathbf{M})\}]$$
(3.9)

Coefficient c_2 is the slope of the magnitude scaling relationship for earthquakes whose theoretical corner frequency is well above the spectral frequency of interest and c_3 is the slope for earthquakes whose corner frequency is well below the spectral frequency. Coefficient c_n controls the width of the magnitude range over which the transition from c_2 scaling to c_3 scaling occurs. Coefficient c_M is the magnitude at the midpoint of this transition and its value varies with the spectral period of the ground motion parameter y. Subsequent analyses by Chiou et al. [2010] showed that this functional form is able to model magnitude scaling of strong ground motion over the magnitude range of M3 to M8, requiring only modification of the model coefficients from those presented in Chiou and Youngs [2008] to extend the GMPE below magnitude M5.5. The analyses of the extensive data from M3.5 to M5 earthquakes included in the NGA-West2 database confirms that the functional form for magnitude scaling developed in Chiou and Youngs [2008a] appropriately models ground motion amplitudes over a wide magnitude range.

As discussed above, coefficient c_3 and c_M were revised to reflect the magnitude scaling of SMM earthquakes in NGA-West2 database. Due to the centering of Z_{TOR} , coefficient c_n was also revised to accommodate the M-scaling in the average Z_{TOR} , as discussed in Section 3.12.

3.2.2 Distance Scaling

Analyses presented in Chiou and Youngs [2008b] demonstrated that a range of formulations for distance scaling could be used to satisfactorily model the magnitude-dependent effects of extended ruptures on the distance scaling of ground motion amplitudes in the distance range of 0 to approximately 100 km. The formulation developed in Chiou and Youngs [2008] is shown by Equation (3.10) The formulation utilizes a magnitude (and period) independent near source geometric attenuation coefficient, c_4 , coupled with a magnitude dependent additive distance constant (some called it fictitious depth), defined by the expression $c_5 \cosh \{c_6 \max(\mathbf{M}-c_{HM},0)\}$, to capture the effects of extended ruptures. This near source distance scaling then transitions into a far source distance scaling proportional to $R^{-1/2}$ (coefficient c_{4a} was set to -0.5) in order to model the transition from body wave geometric spreading near the source to surface/Lg wave geometric spreading at larger distances. The far source distance scaling was coupled with a magnitude dependent attenuation term $\gamma(\mathbf{M})R_{RUP}$ to model the effects of anelastic attenuation and scattering

(i.e., Q). This function form was shown to model the variation in ground motion amplitudes over the distance range of 0 to several hundred kilometers for data from well recorded earthquakes. The formulation has the advantage of providing a convenient mechanism to accommodate differences in Q among different tectonic regions.

$$\ln(\gamma) \propto c_4 \ln \left[R_{RUP} + c_5 \cosh \left\{ c_6 \max(\mathbf{M} - c_{HM}, 0) \right\} \right] + (c_{4a} - c_4) \ln \sqrt{R_{RUP}^2 + c_{RB}^2} + \gamma(\mathbf{M}) R_{RUP} \quad (3.10)$$

The magnitude dependent additive distance constant term in Chiou and Youngs [2008a] is period dependent as was derived from fitting the general distance scaling functional form to the ground motion data for individual earthquakes. Figure 3.7 compares the Chiou and Youngs [2008a] relationships for $c_5 \cosh{c_6 \max(\mathbf{M}-c_{HM},0)}$ with values of the additive constant obtained from initial fitting the general distance attenuation function to data for individual large magnitude earthquakes that were added as part of the update of the ground motion database from NGA-West1 to NGA-West2. As indicated, the values of the additive distance constant for the new earthquakes are consistent with the relationships developed in Chiou and Youngs [2008a].



Figure 3.7 Comparison of additive distance coefficient obtained from fits to individual earthquakes added to the NGA West2 database to relationships developed in Chiou and Youngs [2008a] (shown by the solid curves).

The Q term, $\gamma(\mathbf{M}) R_{RUP}$, was assessed in Chiou and Youngs [2008a] by fitting data for individual California earthquakes using truncated regression (e.g., Toro [1981]; Bragato [2004]) to account for data truncation at low amplitudes and large distances. Fits to limited data for earthquakes in other regions were shown to produce similar values for $\gamma(\mathbf{M})$. More recently, Chiou and Youngs [2012] found from preliminary analysis of the NGA-West2 database that there are significant regional differences in $\gamma(\mathbf{M})$. Accordingly, as part of the updated model, the functional form of Equation (3.10) was fit to the data of individual earthquakes in the NGA West2 database. In initial fitting these data, all coefficients of the Chiou and Youngs [2008a] model were fixed at their published values except for the constant term and the value of γ for each magnitude and spectral period. The fixed coefficients included the additive distance coefficient $c_5 \cosh\{c_6 \max(\mathbf{M} - c_{HM}, 0)\}$, the V_{S30} scaling coefficients, and sediment depth $(Z_{1,0})$ scaling coefficients. The analysis of $\gamma(\mathbf{M})$ in Chiou and Youngs [2008a] was restricted to PGA and used the data from three well recorded small California earthquakes to define the variation of $\gamma(\mathbf{M})$ with spectral period. The updated NGA West2 database provides sufficient data to extend this analysis over the full period range for many earthquakes.

Figure 3.8 shows an example of the fit to the data for a single earthquake, the October 31, 2007 M5.45 earthquake 11 km east of Milpitas in northern California. Each panel shows the fit for a single ground motion parameter. The black circles indicate the data used in the fitting and the black X symbols indicate the data excluded because it is outside of the usable frequency range for the specific recording. Truncated regression analyses were performed using the truncation levels indicated by the horizontal colored dashed lines. The resulting median models are indicated by the solid colored curves plotted for the average value of V_{S30} and $Z_{1.0}$ of the data. The vertical dashed line indicates a cut off distance set at the point where the truncation level represents minus 2.5 standard deviations below the fitted median model. These cut off distances were used to set the distance limits used in the fitting of the entire dataset in the mixed effects regressions used to develop the updated model coefficients, as will be discussed below. As indicated on the figure, the function form of Equation (3.10) provides a good representation of the trends in the data over a wide distance and spectral period range.

Figure 3.9 shows the fit to the data for the January 17, 1994 M6.69 Northridge earthquake in southern California. For this earthquake, the effects of data truncation are much more apparent. At high frequencies, the data are sufficient to provide an estimate of γ , although with greater uncertainty than the estimates for the earthquake data shown in Figure 3.8. There is also a greater loss of usable data at longer periods due to a narrow range of usable frequencies.



Figure 3.8 Fit of the distance scaling function form Equation (3.10) to the data for the 2007/10/31 M 5.45 earthquake in Northern California. Solid colored curves indicate the fitted model plotted for the average V_{S30} and $Z_{1.0}$ of the data and the corresponding dashed horizontal colored lines indicate the truncation level used in the fit.



Figure 3.9 Fit of the distance scaling function form Equation (3.10) to the data for the 1994/01/17 M 6.69 Northridge earthquake in Southern California. Solid colored curves indicate the fitted model plotted for the average V_{s30} and $Z_{1.0}$ of the data and the corresponding dashed horizontal colored lines indicate the truncation level used in the fit.

The process shown on Figures 3.8 and 3.9 was repeated for all earthquakes in the NGA-West2 database with sufficient data to define γ . It was found that five or more recordings at distances less that 100 km and five or more recordings at distances greater 100 km, with the recordings space over a wide distance range were needed in order to get a stable estimate of γ . The resulting values of γ obtained from the fits of individual California earthquakes are shown on Figure 3.10 for PGA and PSA at periods of 0.05, 0.1, 0.2, 0.3, 0.5, 1, and 2 sec. The values for individual earthquakes are color coded to indicate Southern California and Northern (Central) California. Tests of the values did not show a statistical difference between the populations of values for Northern and Southern California earthquakes and the data for all of California were used to develop a combined model.



Figure 3.10 Values of γ obtained from fits of the distance scaling function form Equation (3.10) to the data for individual California earthquakes. The vertical lines indicate 90% confidence intervals for the individual earthquake γ values.

The fitted values of γ for individual earthquakes were then used to examine the variation of γ with magnitude and period. Figure 3.11 shows the variation of γ with period for three magnitude intervals. For each period and magnitude, a variance weighted average value of the fitted values of γ for individual earthquakes was computed. The results show that the variation in γ with period is magnitude dependent. This somewhat complex behavior is likely due to differences in the frequency content of motions contributing to peak response spectral amplitude at a given period as the magnitude of the earthquake changes.



Figure 3.11 Average values of γ for California earthquakes in three magnitude intervals obtained from fits of the distance scaling function form Equation (3.10) to the data for individual California earthquakes. The data points represent variance weighted averages of the fits for individual earthquakes and the vertical lines indicate 90% confidence intervals for the individual earthquake γ values.

Smooth curves were fit to the values for each magnitude interval, as shown on Figure 3.11. These curves were used to define the starting model for $\gamma(\mathbf{M})$ for California shown on Figure 3.12. The $\gamma(\mathbf{M})$ model parameters were then refined in the final stages of model building using the combined data set.

The analysis of data from individual earthquakes was extended to data from other tectonic regions. Figure 3.13 shows the results of fitting the function form of Equation (3.10) to data for individual earthquakes from Italy, Japan, New Zealand, Taiwan, Turkey, and Wenchuan, China. The values for New Zealand, Taiwan, and Turkey are similar to those obtain for California earthquakes. The values for Italy and Japan indicate greater attenuation with distance (lower Q). The data for the Wenchuan, China, earthquake and its aftershocks shows less distance attenuation than California (higher Q). These results indicate the need to account for differences in γ when combining data from multiple regions. These differences were not readily apparent in our previous analysis due to the limited extent of data from other regions contained in the

previous NGA database and the fact that those earthquakes came from regions with similar attenuation characteristics (e.g., Taiwan and Turkey).

Using the initial $\gamma(\mathbf{M})$ model, the next step was to examine the parameters that control the near source distance scaling to verify the conclusions reached by the comparison shown on Figure 3.7. The fit to data for individual earthquakes was repeated using the initial $\gamma(\mathbf{M})$ model shown on Figure 3.12 to compute the additive distance term $c_5 \cosh\{c_6 \max(\mathbf{M} - c_{HM}, 0)\}$, in Equation (3.10), which for an individual earthquake is a constant C_i . Figure 3.14 shows the resulting values compared to the relationship developed in Chiou and Youngs [2008a]. The results indicate that the values of C_i at larger magnitudes are consistent with our previous relationship, but the results for smaller magnitudes deviate from the previous model. Accordingly, parameters c_5 and c_{HM} were adjusted as part of this update.



Figure 3.12 Initial model for γ (M) as a function of spectral period for California.



ure 3.13 Values of γ obtained from fits of the distance scaling function form Equation (3.2) to the data for individual earthquakes in other regions. The vertical lines indicate 90% confidence intervals for the individual earthquake γ values. The black dashed line indicates the California model for γ shown on Figure 3.12.

As discussed above, as part of the fits to the data for individual earthquakes, a cutoff distance was defined that represents an estimate of the largest distance for which the data are unaffected by truncation. This distance is termed $R_{max}(T)_i$ and varies with period and from earthquake to earthquake. The value of $R_{max}(T)_i$ for each earthquake and period was set at the point where the truncation level used it fitting the data represents minus 2.5 standard deviations below the fitted median model. For a number of earthquakes, the values of $R_{max}(T)_i$ are relatively large. For example, the results shown on Figure 3.8 indicate values in excess of 200 km for many periods. However, for other earthquakes, the values of $R_{max}(T)_i$ are less than the 70 km cutoff distance we used in developing our previous model. An example of this is the data for the Northridge earthquake, shown on Figure 3.9. Figure 2.1 shows the resulting magnitude and distances ranges for the selected data.



Figure 3.14 Values of C_i ($c_5 \cosh\{c_6 \max(M-c_{HM},0)\}$ for an individual earthquake) obtained from fits of the distance scaling function form Equation (3.10) to the data for individual earthquakes. The vertical lines indicate 90% confidence intervals for the individual earthquake C_i values. The black dashed line indicates relationship developed in Chiou and Youngs [2008a].

3.2.3 V_{S30} Scaling

Our formulation of V_{S30} scaling was found to adequately model the behavior of the ground motions in the NGA-West2 database. We felt, however, it was necessary to re-estimate the linear

scaling (coefficient ϕ_1) because there were much more weak motion data and data at large distances in the NGA-West2 database than in the previous database. The much larger NGA-West2 data set would provide a better constrain on ϕ_1 . Furthermore, the new $\Delta Z_{1.0}$ scaling (described in Section 3.1.3) would modify the old median amplitude for soft (low- V_{S30}) sites and thus alter ϕ_1 . A comparison of the revised ϕ_1 against the 2008 values is given in Figure 3.15. The new estimates indicate a stronger V_{S30} linear scaling than what we previously estimated, possibly due to the two factors stated above.



Figure 3.15 Comparison of linear V_{S30} -scaling coefficient obtained from fits to the dataset of this study to relationships developed in Chiou and Youngs [2008a] (shown by the dashed curves).

3.3 UPDATED GMPE

3.3.1 Median Ground Motion

The revised model formulation for median ground motions is given by Equation (3.11) for ground motion on the reference site condition ($V_{S30} = 1130$ m/sec),

$$\ln(y_{refy}) = c_{1} + \left\{ c_{1a} + \frac{c_{1c}}{\cosh(2 \cdot \max(\mathbf{M}_{i} - 4.5, 0))} \right\} F_{RV_{i}} + \left\{ c_{1b} + \frac{c_{1d}}{\cosh(2 \cdot \max(\mathbf{M}_{i} - 4.5, 0))} \right\} F_{NM_{i}} + \left\{ c_{7} + \frac{c_{1d}}{\cosh(2 \cdot \max(\mathbf{M}_{i} - 4.5, 0))} \right\} \Delta Z_{TOR_{i}} + \left\{ c_{7} + \frac{c_{7b}}{\cosh(2 \cdot \max(\mathbf{M}_{i} - 4.5, 0))} \right\} \Delta Z_{TOR_{i}} + \left\{ c_{11} + \frac{c_{11b}}{\cosh(2 \cdot \max(\mathbf{M}_{i} - 4.5, 0))} \right\} (\cos \delta_{i})^{2} + c_{2} \left(\mathbf{M}_{i} - 6 \right) + \frac{c_{2} - c_{3}}{c_{n}} \ln \left(1 + e^{C_{n}(C_{M} - \mathbf{M}_{i})} \right) + c_{4} \ln \left(R_{RUPy} + c_{5} \cosh(c_{6} \cdot \max(\mathbf{M}_{i} - c_{iHA}, 0)) \right) + \left(c_{4a} - c_{4} \right) \ln \left(\sqrt{R_{RUPy}^{2} + c_{RB}^{2}} \right) + \left\{ c_{71} + \frac{c_{72}}{\cosh(\max(\mathbf{M}_{i} - c_{73}, 0))} \right\} R_{RUPy} + c_{8} \max \left(1 - \frac{\max(R_{RUPy} - 40, 0)}{30}, 0 \right) \min \left(\frac{\max(\mathbf{M}_{i} - 5.5, 0)}{0.8}, 1 \right) e^{-c_{8a}(\mathbf{M}_{i} - c_{8b})^{2}} \Delta_{DPPy}$$
(3.11)
$$+ c_{9} F_{IBWy} \cos \delta_{i} \left\{ c_{9a} + (1 - c_{9a}) \tanh \left(\frac{R_{Xy}}{c_{9b}} \right) \right\} \left\{ 1 - \frac{\sqrt{R_{IBY}^{2} + Z_{TORi}^{2}}}{R_{RUPy} + 1} \right\}$$

and by Equation (3.8) for ground motion on the surface of soil condition,

$$\ln(y_{ij}) = \ln(y_{ref_{ij}}) + \phi_1 \cdot \min\left(\ln(\frac{V_{S30j}}{1130}), 0\right) + \phi_2\left(e^{\phi_3\left(\min(V_{S30}, 1130) - 360\right)} - e^{\phi_3\left(1130 - 360\right)}\right) \ln(\frac{y_{ref_{ij}} + \phi_4}{\phi_4}) + \phi_5\left(1 - e^{-\Delta Z_{1.0j}/\phi_6}\right) + \eta_i + \varepsilon_{ij}$$
(3.12)

The predictor variables are:

Μ	=	Moment magnitude.
<i>R_{RUP}</i>	=	Closest distance (km) to the rupture plane.
R_{JB}	=	Joyner-Boore distance (km) to the rupture plane.
R_X	=	Site coordinate (km) measured perpendicular to the fault strike from the fault line, with the down-dip direction being positive (See Figure 3.12 of Chiou and Youngs [2008b]).
F_{HW}	=	Hanging-wall flag: 1 for $R_X \ge 0$ and 0 for $R_X < 0$.
δ	=	Fault dip angle.
Z _{TOR}	=	Depth (km) to top of rupture.
F_{RV}	=	Reverse-faulting flag: 1 for $30^{\circ} \le \lambda \le 150^{\circ}$ (combined reverse and reverse-oblique), 0 otherwise; λ is the rake angle.
F_{NM}	=	Normal faulting flag: 1 for $-120^\circ \le \lambda \le -60^\circ$ (excludes normal-oblique), 0 otherwise.
V _{S30}	=	Travel-time averaged shear wave velocity (m/sec) of the top 30 m of soil.
$Z_{1.0}$	=	Depth (m) to shear wave velocity of 1.0 km/sec.
$\Delta Z_{1.0}$	=	$Z_{1.0}$ (m) centered on the California-specific average $Z_{1.0}$ model [Equation (2.1)].
DPP	=	Direct point parameter for directivity effect [Chiou and Spudich 2013].
ΔDPP	=	DPP centered on the earthquake-specific average DPP.

Model coefficients (variable names starting with the letter *c* or ϕ) are listed in Tables 3.1 to 3-3. In the tables, we underlined the coefficients that were unmodified in this update and used the bold face on those that were added or given a different meaning (such as ϕ_5 and ϕ_6). Because we excluded data from Class 2 earthquakes (aftershocks), we did not include Class 2 earthquake terms in Equation (3.11) and Table 3.2.

To simplify, Equations (3.11) and (3.12) were written for application in California, although our regression analysis included region-dependent terms to account for the known regional difference in anelastic attenuation and site effects. To apply our GMPE to regions where regional differences were accounted for, one should use the region-specific coefficients given in Appendix A. Also, in application to Japanese data, the Japan-specific average $Z_{1.0}$ model [Equation (2.2)] should be used to center $Z_{1.0}$.

3.3.2 Aleatory Variability

The current terminology used to express the components of aleatory variability use the symbol τ for the inter-event component and the symbol ϕ for intra-event variability, with the symbol σ used for total aleatory variability, such that $\sigma^2 = \tau^2 + \phi^2$. However, to avoid confusion with our use of the symbol ϕ for the parameters of the site amplification model, we retain the symbols used in Chiou and Youngs [2008]: τ for the inter-event component, σ for intra-event variability, with the symbol σ_T used for total aleatory variability.

The first stage of the variance analysis was to examine the magnitude dependence of τ and σ . Figures 3.16–3.19 show the values of τ and σ computed from the residuals for overlapping magnitude bins with width 0.5 magnitude units. Values are shown based on residuals for all distances and for distances of 100 km or less. At this stage, the values were computed without consideration of nonlinear soil effects. The figure shows values of τ and σ for PSA residuals at periods of 0.01, 0.02, 1.0, and 3.0 sec. Slightly lower values of aleatory variability were obtained using the residuals for distances of 100 km and less than were obtained using residuals from all distances. Given the small differences, the residuals for all distances were used to develop the aleatory variability model. The results indicated lower values of τ for larger magnitudes at all periods. Values of σ were lower for larger magnitude at short periods, but become larger at large magnitudes at long periods.

The fitted values of τ and σ indicate magnitude dependence at most periods. Therefore, the tri-linear form used in our previous model was applied. Some experimentation indicated that the appropriate magnitude break points for τ_1 , τ_2 , σ_1 , and σ_2 were at M5 and M7.25. Figure 3.20 shows the resulting values of τ_1 , τ_2 , σ_1 , and σ_2 . It was found that the magnitude dependence of τ was influenced by the large event term for the M6.61 Tottori, Japan earthquake. Given that the event term for this earthquake is well above those for all other earthquakes, the aleatory model was developed without the residuals for this earthquake.

The final functional form for the total standard deviation, σ_T , is given by Equation (3.13):

$$\sigma_{T}^{2} = (1 + NL_{0})^{2} \tau^{2} + \sigma_{NL_{0}}^{2}$$

$$\tau = \tau_{1} + \frac{\tau_{2} - \tau_{1}}{2.25} (\min(\max(\mathbf{M}, 5), 7.25) - 5)$$

$$\sigma_{NL_{0}} = \left(\sigma_{1} + \frac{\sigma_{2} - \sigma_{1}}{2.25} (\min(\max(\mathbf{M}, 5), 7.25) - 5)\right) \times \sqrt{\sigma_{3}F_{\text{inf erred}}} + 0.7F_{Measured} + (1 + NL_{0})^{2}$$

$$NL_{0} = \phi_{2} \left(e^{\phi_{3}(\min(V_{S30}, 1130) - 360)} - e^{\phi_{3}(1130 - 360)}\right) \left(\frac{y_{ref}}{y_{ref} + \phi_{4}}\right)$$
(3.13)

Equation (3.13) implemented the approximate method of Chiou and Youngs [2008b]. The coefficients ϕ_2 and ϕ_3 are those in Equation (3.12) and their values are listed in Table 3.3. Because we excluded data from Class 2 earthquakes (aftershocks), we did not include σ_4 (increase in σ for Class 2 earthquakes). Unlike the median model, we did not account for regional differences in τ and σ . The values of σ_1 and σ_2 listed in Table 3.3 are reduced from those shown on Figure 3.20 to account for the non-linear soil effects.



Figure 3.16 Values of τ (top) and σ computed for PGA residuals in magnitude bins 0.5 magnitude units wide.



Figure 3.17 Values of τ (top) and σ computed for 0.17-sec PSA residuals in magnitude bins 0.5 magnitude units wide.



Figure 3.18 Values of τ (top) and σ computed for 1-sec PSA residuals in magnitude bins 0.5 magnitude units wide.



Figure 3.19 Values of r (top) and σ computed for 3-sec PSA residuals in magnitude bins 0.5 magnitude units wide.



Figure 3.20 Values of τ_1 , τ_2 , σ_1 , and σ_2 computed from the residuals excluding non-linear soil effects.

Table 3.1Period-independent coefficients of model for ln(y) – Equation (3.11).

<u>C</u> 2	<u>C</u> 4	<u>C_{4a}</u>	<u>C_{RB}</u>	C ₈	C _{8a}
1.06	-2.1	-0.5	50	0.2153	0.2695

Table 3.2(a)Period-dependent coefficients of model for $ln(y_{ref})$ – Equation (3.11).

Period (sec)	C ₁	C _{1a}	C _{1b}	C _{1c}	C _{1d}	Cn	C _M	C ₃	C 5	C _{HM}	<u>C</u> 6
0.01	-1.5070	0.1650	-0.3729	-0.1650	0.1977	16.0875	4.9993	1.9636	6.4551	3.0956	0.4893
0.02	-1.4788	0.1650	-0.3772	-0.1650	0.2180	15.7118	4.9993	1.9636	6.4551	3.0963	0.4892
0.03	-1.3116	0.1650	-0.4429	-0.1650	0.3484	15.8819	4.9993	1.9636	6.4551	3.0974	0.4890
0.04	-1.1159	0.1650	-0.5122	-0.1650	0.4733	16.4556	4.9993	1.9636	6.4551	3.0988	0.4888
0.05	-0.9464	0.1650	-0.5544	-0.1650	0.5433	17.6453	4.9993	1.9636	6.4551	3.1011	0.4884
0.075	-0.6749	0.1650	-0.5929	-0.1650	0.5621	20.1772	5.0031	1.9636	6.4551	3.1094	0.4872
0.1	-0.5735	0.1650	-0.5760	-0.1650	0.4633	19.9992	5.0172	1.9636	6.8305	3.2381	0.4854
0.12	-0.5439	0.1650	-0.5583	-0.1650	0.4000	18.7106	5.0315	1.9795	7.1333	3.3407	0.4837
0.15	-0.5543	0.1650	-0.5345	-0.1650	0.3337	16.6246	5.0547	2.0362	7.3621	3.4300	0.4808
0.17	-0.5933	0.1650	-0.5188	-0.1650	0.2961	15.3709	5.0704	2.0823	7.4365	3.4688	0.4787
0.2	-0.6865	0.1650	-0.4944	-0.1650	0.2438	13.7012	5.0939	2.1521	7.4972	3.5146	0.4755
0.25	-0.8720	0.1650	-0.4517	-0.1650	0.1620	11.2667	5.1315	2.2574	7.5416	3.5746	0.4706
0.3	-1.0558	0.1650	-0.4122	-0.1650	0.0881	9.1908	5.1670	2.3440	7.5600	3.6232	0.4665
0.4	-1.3800	0.1650	-0.3532	-0.1650	-0.0287	6.5459	5.2317	2.4709	7.5735	3.6945	0.4607
0.5	-1.6472	0.1650	-0.3101	-0.1650	-0.1158	5.2305	5.2893	2.5567	7.5778	3.7401	0.4571
0.75	-2.1421	0.1650	-0.2219	-0.1650	-0.2708	3.7896	5.4109	2.6812	7.5808	3.7941	0.4531
1	-2.5266	0.1650	-0.1694	-0.1650	-0.3527	3.3024	5.5106	2.7474	7.5814	3.8144	0.4517
1.5	-3.0655	0.1650	-0.1376	-0.1650	-0.3454	2.8498	5.6705	2.8161	7.5817	3.8284	0.4507
2	-3.4114	0.1645	-0.1218	-0.1645	-0.2605	2.5417	5.7981	2.8514	7.5818	3.8330	0.4504
3	-3.8330	0.1168	-0.1053	-0.1168	-0.0914	2.1488	5.9983	2.8875	7.5818	3.8361	0.4501
4	-4.1207	0.0732	-0.1008	-0.0732	-0.0306	1.8957	6.1552	2.9058	7.5818	3.8369	0.4501
5	-4.3438	0.0484	-0.0996	-0.0484	-0.0129	1.7228	6.2856	2.9169	7.5818	3.8376	0.4500
7.5	-4.7493	0.0220	-0.0994	-0.0220	-0.0014	1.5737	6.5428	2.9320	7.5818	3.8380	0.4500
10	-5.0370	0.0124	-0.1000	-0.0124	0.0001	1.5265	6.7415	2.9396	7.5818	3.8380	0.4500

Period (sec)	C ₇	C _{7b}	C _{8b}	C9	C _{9a}	C _{9b}	C ₁₁	C _{11b}	$c_{\gamma 1}$	$c_{\gamma 2}$	$c_{\gamma 3}$
0.01	0.0352	0.0462	0.4833	0.9228	0.1202	6.8607	0.0	-0.4536	-0.007141	-0.006768	4.1293
0.02	0.0352	0.0472	1.2144	0.9296	0.1217	6.8697	0.0	-0.4536	-0.007226	-0.006929	4.0715
0.03	0.0352	0.0533	1.6421	0.9396	0.1194	6.9113	0.0	-0.4536	-0.007520	-0.007160	4.0009
0.04	0.0352	0.0596	1.9456	0.9661	0.1166	7.0271	0.0	-0.4536	-0.007881	-0.007477	3.9647
0.05	0.0352	0.0639	2.1810	0.9794	0.1176	7.0959	0.0	-0.4536	-0.008295	-0.007460	3.9832
0.075	0.0352	0.0630	2.6087	1.0260	0.1171	7.3298	0.0	-0.4536	-0.009266	-0.006565	4.1949
0.1	0.0352	0.0532	2.9122	1.0177	0.1146	7.2588	0.0	-0.4536	-0.009710	-0.005490	4.4844
0.12	0.0352	0.0452	3.1045	1.0008	0.1128	7.2372	0.0	-0.4536	-0.009806	-0.004840	4.6730
0.15	0.0352	0.0345	3.3399	0.9801	0.1106	7.2109	0.0	-0.4536	-0.009805	-0.003897	4.8266
0.17	0.0352	0.0283	3.4719	0.9652	0.1150	7.2491	0.0	-0.4536	-0.009733	-0.003334	4.8670
0.2	0.0352	0.0202	3.6434	0.9459	0.1208	7.2988	0.0	-0.4440	-0.009505	-0.002690	4.8796
0.25	0.0352	0.0090	3.8787	0.9196	0.1208	7.3691	0.0	-0.3539	-0.008918	-0.002127	4.8371
0.3	0.0352	-0.0004	4.0711	0.8829	0.1175	6.8789	0.0	-0.2688	-0.008251	-0.001812	4.7579
0.4	0.0352	-0.0155	4.3745	0.8302	0.1060	6.5334	0.0	-0.1793	-0.007267	-0.001274	4.5523
0.5	0.0352	-0.0278	4.6099	0.7884	0.1061	6.5260	0.0	-0.1428	-0.006492	-0.001074	4.4049
0.75	0.0352	-0.0477	5.0376	0.6754	0.1000	6.5000	0.0	-0.1138	-0.005147	-0.001115	4.2079
1	0.0352	-0.0559	5.3411	0.6196	0.1000	6.5000	0.0	-0.1062	-0.004277	-0.001197	4.0126
1.5	0.0352	-0.0630	5.7688	0.5101	0.1000	6.5000	0.0	-0.1020	-0.002979	-0.001671	3.6733
2	0.0352	-0.0665	6.0723	0.3917	0.1000	6.5000	0.0	-0.1009	-0.002301	-0.002237	3.5073
3	0.0160	-0.0516	6.5000	0.1244	0.1000	6.5000	0.0	-0.1003	-0.001344	-0.003108	3.4748
4	0.0062	-0.0448	6.8035	0.0086	0.1000	6.5000	0.0	-0.1001	-0.001084	-0.003670	3.5179
5	0.0029	-0.0424	7.0389	0.0000	0.1000	6.5000	0.0	-0.1001	-0.000994	-0.003767	3.5479
7.5	0.0007	-0.0348	7.4666	0.0000	0.1000	6.5000	0.0	-0.1000	-0.000964	-0.003784	3.5954
10	0.0003	-0.0253	7.7700	0.0000	0.1000	6.5000	0.0	-0.1000	-0.000950	-0.003747	3.6253

Table 3.2(b)(Continued) Period-dependent coefficients of model for $ln(y_{ref})$ – Equation (3.11).

Period (sec)	φı	<u>Φ</u> 2	<u>φ</u> ₃	<u>\$4</u>	ф 5	ф6
0.01	-0.5210	-0.1417	-0.007010	0.102151	0.0000	300
0.02	-0.5055	-0.1364	-0.007279	0.108360	0.0000	300
0.03	-0.4368	-0.1403	-0.007354	0.119888	0.0000	300
0.04	-0.3752	-0.1591	-0.006977	0.133641	0.0000	300
0.05	-0.3469	-0.1862	-0.006467	0.148927	0.0000	300
0.075	-0.3747	-0.2538	-0.005734	0.190596	0.0000	300
0.1	-0.4440	-0.2943	-0.005604	0.230662	0.0000	300
0.12	-0.4895	-0.3077	-0.005696	0.253169	0.0000	300
0.15	-0.5477	-0.3113	-0.005845	0.266468	0.0000	300
0.17	-0.5922	-0.3062	-0.005959	0.265060	0.0000	300
0.2	-0.6693	-0.2927	-0.006141	0.255253	0.0000	300
0.25	-0.7766	-0.2662	-0.006439	0.231541	0.0000	300
0.3	-0.8501	-0.2405	-0.006704	0.207277	0.0010	300
0.4	-0.9431	-0.1975	-0.007125	0.165464	0.0040	300
0.5	-1.0044	-0.1633	-0.007435	0.133828	0.0100	300
0.75	-1.0602	-0.1028	-0.008120	0.085153	0.0340	300
1	-1.0941	-0.0699	-0.008444	0.058595	0.0670	300
1.5	-1.1142	-0.0425	-0.007707	0.031787	0.1430	300
2	-1.1154	-0.0302	-0.004792	0.019716	0.2030	300
3	-1.1081	-0.0129	-0.001828	0.009643	0.2770	300
4	-1.0603	-0.0016	-0.001523	0.005379	0.3090	300
5	-0.9872	0.0000	-0.001440	0.003223	0.3210	300
7.5	-0.8274	0.0000	-0.001369	0.001134	0.3290	300
10	-0.7053	0.0000	-0.001361	0.000515	0.3300	300

Table 3.3Coefficients of site response model for ln(y) - Equation (3.12).

Period (sec)	τ_1	τ_2	σ_1	σ ₂	<u> </u>
0.01	0.4010	0.2470	0.5530	0.4106	0.8000
0.02	0.4080	0.2420	0.5567	0.4107	0.8000
0.03	0.4320	0.2320	0.5676	0.4136	0.8000
0.04	0.4460	0.2460	0.5816	0.4197	0.8000
0.05	0.4670	0.2750	0.5933	0.4265	0.8000
0.075	0.4860	0.4190	0.5976	0.4544	0.8000
0.1	0.4680	0.4270	0.5868	0.4761	0.8000
0.12	0.4530	0.3840	0.5892	0.4795	0.8000
0.15	0.4170	0.2970	0.5892	0.4798	0.8000
0.17	0.4030	0.2560	0.5877	0.4839	0.8000
0.2	0.3860	0.2310	0.5799	0.4848	0.8000
0.25	0.3690	0.2070	0.5643	0.4796	0.7999
0.3	0.3680	0.1980	0.5525	0.4813	0.7997
0.4	0.3760	0.1700	0.5338	0.4824	0.7988
0.5	0.3750	0.1710	0.5228	0.4837	0.7966
0.75	0.3880	0.1780	0.4870	0.5089	0.7792
1	0.4340	0.2330	0.4699	0.5158	0.7504
1.5	0.4960	0.2180	0.4452	0.5326	0.7136
2	0.5110	0.2310	0.4221	0.5335	0.7035
3	0.4770	0.2750	0.4135	0.4866	0.7006
4	0.5160	0.3300	0.3982	0.4769	0.7001
5	0.5080	0.3370	0.3857	0.4552	0.7000
7.5	0.4340	0.3290	0.3641	0.4467	0.7000
10	0.3320	0.4040	0.3495	0.3973	0.7000

Table 3.4Coefficients of variance model – Equation (3.13).

4 Evaluation of Updated Model

4.1 BETWEEN-EVENT RESIDUALS

Figure 4.1 shows the between-event residuals (event term η), for 4 spectral periods of T = 0.01 (PGA), 0.2, 1, and 3 sec. In the range $3.5 \le M \le 8$, they do not exhibit a significant trend with M or a large offset from 0. Our updated model has the tendency to under predict T = 3 sec data in the range of M < 3.5, as evidenced by the positive event terms. There are outliers at large magnitude exhibiting large (> 2 τ) absolute event terms at different periods. They are the 1999 M7.6 ChiChi earthquake (for PGA and T=0.2 sec), the 2000 M6.6 Tottori earthquake (for PGA, T = 0.2 and 3 sec), and the 2008 M7.9 Wenchuan, China, earthquake (for T = 1 and 3 sec). All three earthquakes occurred outside California.



Figure 4.1 Between-event residuals (event terms) for spectral periods of 0.01 (PGA), 0.2, 1, and 3 sec.

4.2 WITHIN-EVENT RESIDUALS

Figures 4.2–4.5 show the within-event residuals plotted versus **M**, R_{RUP} , V_{S30} , and $\Delta Z_{1.0}$ for spectral periods of 0.01 (PGA), 0.2, 1 and 3 sec, respectively. In general, these residuals do not exhibit significant trends within the body of a predictor, but several trends are noted near the ends of predictor domain. We assumed no site response relative to y_{ref} for V_{S30} greater than 1130 m/sec. Although a limited number of such data are in the PEER-NGA database, their residuals, if anything, show a slight downward trend for 0.01 and 0.2 sec, and a upward trend for T = 3 sec. Non-California data are responsible for the downward trend for 0.2 sec at $V_{S30} < 180$ m/sec. It suggests there may be a regional difference in V_{S30} scaling, possibly in the nonlinear part of the soil response.



Figure 4.2 Within-event residuals for spectral period of 0.01 sec (PGA) plotted against M, R_{RUP} , V_{S30} , and $\Delta Z_{1.0}$.



Figure 4.3 Within-event residuals for spectral period of 0.2 sec plotted against M, R_{RUP} , V_{S30} , and $\Delta Z_{1.0}$.



Figure 4.4 Within-event residuals for spectral period of 1 sec plotted against M, R_{RUP} , V_{S30} , and $\Delta Z_{1.0}$.



Figure 4.5 Within-event residuals for spectral period of 3 sec plotted against M, R_{RUP} , V_{S30} , and $\Delta Z_{1.0}$.

4.3 SOIL NONLINEARITY

As discussed in Section 3.2.3, we retained both the formulation and model coefficients (ϕ_2 , ϕ_3 , and ϕ_4) for nonlinear soil response. To provide a visual validation of this decision, we present Figure 4.6. Residuals in the figure are within-event residuals for T = 0.2 sec computed for our updated model without the effects of V_{S30} (i.e., for a V_{S30} of 1130 m/sec). Residuals computed this way can be regarded as soil amplification relative to the event-specific median motion on reference rock condition. The residuals are grouped by the level of reference motion ($y_{ref} exp(\eta)$) and plotted against V_{S30} in Figure 4.6 to show how V_{S30} trend varies with the input reference motion. The soil amplification predicted by our updated model is also shown in the figure as the thick solid (dark red) curve. The predicted curve tracks closely the V_{S30} trend of the residuals (shown as the solid orange curve) for $V_{S30} > 200$ m/sec, our model over estimates the empirical amplification; in other words, the nonlinearity in the data on very soft soil is stronger than what is predicted by our model.


Figure 4.6(a) Intra-event residuals plotted as a function of V_{S30} . These residuals are computed for the updated model for the V_{S30} = 1130 m/sec condition. Data from M > 6 earthquake are shown in black; data from M < 6 are in blue. The smoothed V_{S30} trend of these residuals is shown as the thick orange curve. The thick solid red curve is the predicted nonlinear soil amplification by our updated model and the thin read solid line is the predicted linear amplification. The range of event-specific median motion on reference condition is shown in the lower left corner of each plot.



Figure 4.6(b) (continued).

4.4 COMPARISON WITH THE 2008 CHOIU AND YOUNGS GMPE

In 2008, we used Sadigh et al. [1997] as the baseline for comparison. In this update, our 2008 model (CY2008) becomes the new baseline to which we now compare the updated model (CY2013).

4.4.1 Comparison of Median Motion

Comparisons of median prediction between CY2008 and CY2013 are shown in Figures 4.7 and 4.8. For comparison plots, we use $V_{S30} = 760$ m/sec and $\Delta DPP = 0$, for average directivity. We set ΔZ_{TOR} and $\Delta Z_{1.0}$ to 0 for predictions by CY2013. Equivalently, for predictions by CY2008 we use average Z_{TOR} for the given **M** (Equation (2.4) if reverse earthquake, Equation (2.5) if strike-slip earthquake) and average $Z_{1.0}$ for the given V_{S30} [Equation (2.1)].

As discussed in Chapter 3, we made modifications/additions to the 2008 formulation and revised a large number of model coefficients. The unmodified coefficients were found to be still valid, as discussed previously. Many of these model changes affect only ground motion prediction for SMM earthquakes (M < 5.5). As a result, large discrepancy in predictions between CY2008 and CY2013 occurs mostly at M < 5.5 (Figure 4.7 and Figure 4.8). At M > 6.0, the typical discrepancy is smaller than 20%.

Figure 4.9 shows comparisons of predicted HW motions for a reverse earthquake of 45° dip. For this example, we set Z_{TOR} to zero for both models to show the HW effect of a surface rupture event. Predicted HW amplification by CY2013 is smaller and shows stronger **M** scaling than what were predicted by CY2008, as discussed in Section 3.1.4.

Figure 4.10 and Figure 4.11 show comparisons of predicted median response spectra for $V_{S30} = 760 \text{ m/sec}$ and $V_{S30} = 310 \text{ m/sec}$, respectively.



Figure 4.7(a) Predicted median amplitude vs. magnitude for vertical strike slip earthquake ($\Delta Z_{TOR}=0$, $\Delta Z_{1.0}=0$, and $\Delta DPP=0$).



Period = 1 (sec); V_{S30} = 760 (m/s)

Period = 3 (sec); V_{S30} = 760 (m/s)

Figure 4.7(b) (continued).



Period = 0.01 (sec); V_{S30} = 760 (m/s)

Period = 0.2 (sec); V_{S30} = 760 (m/s)

Figure 4.8(a) Predicted median amplitude vs. distance for vertical strike slip earthquake ($\Delta Z_{TOR}=0$, $\Delta Z_{1.0}=0$, and $\Delta DPP=0$).



Period = 1 (sec); V_{S30} = 760 (m/s)

Period = 3 (sec); V_{S30} = 760 (m/s)

Figure 4.8(b) (continued).



Period = 0.01 (sec); V_{S30} = 760 (m/s)

Period = 0.2 (sec); V_{S30} = 760 (m/s)

Figure 4.9(a) Predicted median amplitude vs. distance for reverse slip earthquake of 45° dip. Note that this comparison is for surface rupture event, Z_{TOR} =0. $\Delta Z_{1.0}$ and ΔDPP are equal to 0.



Period = 1 (sec); V_{S30} = 760 (m/s)

Period = 3 (sec); V_{S30} = 760 (m/s)





Figure 4.10 Median response spectra predicted by the 2008 Chiou and Youngs NGA model (thin lines) and the updated model (thick lines). Predictions are made for vertical strike-slip earthquakes and NEHRP B-C boundary (V_{S30} =760 m/sec).



Figure 4.11 Median response spectra predicted by the 2008 Chiou and Youngs NGA model thin lines) and the updated model (thick lines). Predictions are made for vertical strike-slip earthquakes and firm soil condition (V_{s30} = 310 m/sec).

4.4.2 Comparison of Aleatory Variability

Figure 4.12 compares the total standard deviations for the updated model under linear soil response with those for CY2008 model. Figure 4.13 shows the effect of soil nonlinearity on the total standard deviations of PGA.



Figure 4.12 Total standard deviations for the updated model with effects for linear soil response.



Figure 4.13 Total standard deviations for the updated model with effects of nonlinear soil response.

5 Example Calculations

The updated GMPE is implemented in the FORTRAN routine CY13.FOR. This program is included in the companion package. Also in the package are the inputs and outputs for four example scenarios: M5 and M7 strike-slip earthquakes and M5 and M7 reverse-faulting earthquakes. The required input variables are indicated by the header record in the example input files. The routine accepts its main input and writes the output to the console. After invoking at the command prompt, the routine loops over prompts for the input and output files.

6 Model Applicability

The GMPE update developed in this study is considered to be applicable for estimating pseudospectral accelerations (5% of critical damping) and peak motions for earthquakes in active tectonic regions in which the following conditions apply:

- $3.5 \le M \le 8.5$ for strike-slip earthquakes
- $3.5 \le M \le 8.0$ for reverse and normal faulting earthquakes
- $Z_{TOR} \leq 20 km$
- $0 \le R_{RUP} \le 300 \text{ km}$
- $180 \text{ m/sec} \le V_{S30} \le 1500 \text{ m/sec}$

Compared to Chiou and Youngs [2008a], the lower bound of the applicable magnitude range was decreased to 3.5 because of the large number of SMM earthquakes in our regression dataset. However, because all SMM data were from California, our GMPE may not be applicable to SMM earthquakes in other active tectonic regions.

The upper bound of the applicable distance was increased to 300 km because of the use of extensive data at distances from 200 to 300 km (Figure 2.1). For application in other active tectonic regions where earthquakes at distances greater than about 50 km are a major contributor to the hazard, adjustments to the γ (**M**) coefficients $c_{\gamma I}$ and $c_{\gamma 2}$ may be warranted. These adjustments can be made using the hybrid approach developed by Campbell [2003]. In making such adjustments, we stress the need for the user to obtain estimates of Q for the two regions that are based on geometric spreading models at large distances that are consistent with the one used in this study.

The site response portion of the ground motion model was constrained such that all ground motion amplification factors are 1 for V_{S30} greater than 1130 m/sec. As the rock velocity increases we expect shallow crustal damping (i.e., "kappa") to decrease, resulting in increases in high-frequency motion. Data for such sites are not sampled in the NGA-West2 database in sufficient quantity to estimate this effect, and it is not captured in our model. Such effects should be considered if the model is to be applied to sites with V_{S30} greater than 1500 m/sec.

We increased the lower bound of the V_{S30} applicable range because of the residual trend observed on Figure 4.3.

The updated model was developed using recordings from earthquakes with a maximum Z_{TOR} of 20 km. Furthermore, the $Z_{TOR} - \mathbf{M}$ data shown in Figure 2.5 suggest that the applicable

range of ΔZ_{TOR} should be decreasing with **M**. We do not recommend using large ΔZ_{TOR} for **M** > 7 as such events are not well presented in the NGA-West2 database.

The ground motion model presented here is sensitive to the value of $\Delta Z_{1,0}$. Majority of data used in our updated model were from the southern California, the San Francisco Bay area, and Japan. When applying our model to these regions, the same 3D velocity models should be used to obtain site $Z_{1,0}$. For application to a site not covered by these velocity models and there are no other information to determine the site $Z_{1,0}$, it is suggested that the user use $\Delta Z_{1,0} = 0$ to predict the median amplitude for sites of the same V_{S30} . When applying our GMPE to a site whose $Z_{1,0}$ is much smaller than the average $Z_{1,0}$ (a large negative $\Delta Z_{1,0}$), the prediction should be checked to ensure that the predicted motion (particularly for long periods) is not lower than the predicted median for reference rock condition (V_{S30} =1130).

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Appendix A: Model Coefficients for Non-California Regions

In this appendix we provide the estimated model coefficients obtained as part of the model update to account for known regional difference in anelastic attenuation and site effects. These coefficients are:

 γ_{Jp-It} : γ adjustment factor for Japanese and Italian data.

Note that, since the Japanese and Italian events used in our update are of 6.0 < M < 6.9, this factor is applicable only for that M range.

 γ_{Wn} : γ adjustment factor for the **M** 7.9, 2008 Wenchuan earthquake data.

 ϕ_{1Jp} : ϕ_1 for Japanese data.

 ϕ_{5Jp} : ϕ_5 for Japanese data.

 ϕ_{6Jp} : ϕ_6 for Japanese data.

Period (sec)	γJp-It	γ_{Wn}	$\phi_{ t lJp}$	ϕ_{5JP}	$\phi_{ m 6JP}$
0.01	1.5817	0.7594	-0.6846	0.4590	800
0.02	1.5740	0.7606	-0.6681	0.4580	800
0.03	1.5544	0.7642	-0.6314	0.4620	800
0.04	1.5502	0.7676	-0.5855	0.4530	800
0.05	1.5391	0.7739	-0.5457	0.4360	800
0.075	1.4804	0.7956	-0.4685	0.3830	800
0.1	1.4094	0.7932	-0.4985	0.3750	800
0.12	1.3682	0.7768	-0.5603	0.3770	800
0.15	1.3241	0.7437	-0.6451	0.3790	800
0.17	1.3071	0.7219	-0.6981	0.3800	800
0.2	1.2931	0.6922	-0.7653	0.3840	800
0.25	1.3150	0.6579	-0.8469	0.3930	800
0.3	1.3514	0.6362	-0.8999	0.4080	800
0.4	1.4051	0.6049	-0.9618	0.4620	800
0.5	1.4402	0.5507	-0.9945	0.5240	800
0.75	1.5280	0.3582	-1.0225	0.6580	800
1	1.6523	0.2003	-1.0002	0.7800	800
1.5	1.8872	0.0356	-0.9245	0.9600	800
2	2.1348	0.0000	-0.8626	1.1100	800
3	3.5752	0.0000	-0.7882	1.2910	800
4	3.8646	0.0000	-0.7195	1.3870	800
5	3.7292	0.0000	-0.6560	1.4330	800
7.5	2.3763	0.0000	-0.5202	1.4600	800
10	1.7679	0.0031	-0.4068	1.4640	800

 Table A.1
 Model coefficients for non-California regions.

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