PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

Ground-Motion Prediction Equations for Arias Intensity Consistent with the NGA-West2 Ground-Motion Models

Charlotte Abrahamson

Department of Chemical Engineering
University of California, Santa Barbara

Hao-Jun Michael Shi

Department of Mathematics
University of California, Los Angeles

Brian Yang

Department of Computer Science
Stanford University

PEER Report No. 2016/05
Pacific Earthquake Engineering Research Center
Headquarters at the University of California, Berkeley

July 2016

PEER 2016/05
July 2016

Ground-Motion Prediction Equations for Arias Intensity Consistent with the NGA-West2 Ground-Motion Models

Charlotte Abrahamson
Department of Chemical Engineering
University of California, Santa Barbara

Hao-Jun Michael Shi
Department of Mathematics
University of California, Los Angeles

Brian Yang
Department of Computer Science
Stanford University

PEER Report 2016/05
Pacific Earthquake Engineering Research Center
Headquarters at the University of California, Berkeley

July 2016

ABSTRACT

Following the approach outlined in the Watson-Lamprey and Abrahamson [2006] conditional model for Arias intensity, we use the NGA-West2 database to derive a new scaling model for Arias intensity given peak ground acceleration (PGA), T = 1 sec spectral acceleration (SA_{T1}), shear-wave velocity in the top 30 m (V_{S30}), and magnitude. By combining this conditional model with each of five NGA-West2 ground-motion models for PGA and SA_{T1}, we derived five new ground motion prediction equations (GMPEs) for the median and standard deviation of Arias intensity. These five GMPEs for Arias intensity capture the more complex ground-motion scaling effects found in some of the NGA-West2 GMPEs, such as hanging-wall effects, sediment-depth effects, soil nonlinearity effects, and regionalization effects. This allows for Arias intensity values to be estimated that are consistent with the NGA-West2 GMPEs.

ACKNOWLEDGMENTS

This study was supported by the Pacific Earthquake Engineering Research Center (PEER). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsoring agency.

We thank Dr. Norman Abrahamson for suggesting this problem to us, for providing guidance regarding data analysis methods, interpretation of the results, and insights into engineering applications, and for providing helpful suggestions on the manuscript. We also thank Dr. Yousef Bozorgnia for providing the dataset for CB12 and useful comments on the manuscript.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction

1.1 TRADITIONAL MODELS FOR ARIAS INTENSITY

Arias intensity (I_a) has been recognized as a useful indicator of damage potential for earth dams in seismic analysis [Travasarou et al. 2003]. There have been several empirical models developed for I_a in the past decade (e.g., Travasarou et al. [2003] (TBA03); Stafford et al. [2009] (SBP09); Foulser-Piggott and Stafford [2012] (FPS12); and Campbell and Bozorgnia [2012] (CB12). These I_a models have used a relatively simple parameterization to fit the Arias intensity with the exception of the CB12 model. This creates a potential inconsistency with the pseudo-spectral acceleration (PSA) values developed using ground-motion prediction equations (GMPEs) with more complex parameterization. For example, if the site is located over the hanging wall, then the PSA values at short periods may be increased by a factor of 2 to 3 compared to footwall sites at the same distance; but if the I_a model does not include hanging-wall effects, then the I_a computed for the site may be too small and may not be consistent with the I_a expected for the given PSA. Similarly, if there are strong nonlinear site effects, then the PSA values based on GMPEs that include nonlinearity will be inconsistent with the I_a values based on I_a models that do not include these effects.

1.2 CONDITIONAL GROUND-MOTION MODELS

Watson-Lamprey and Abrahamson [2006] developed a conditional model for I_a that included the observed peak ground acceleration (PGA) and 1-sec spectral acceleration (SA_{T1}) as predictive parameters in addition to the earthquake magnitude, distance, and time-averaged shear-wave velocity over the top 30 m (V_{S30}). The I_a model is called conditional because it estimates the I_a given the observed PGA and SA_{T1} values.

This report uses the conditional ground-motion model approach to develop an updated conditional model for I_a that is consistent with the NGA-West2 ground-motion models. The advantage of the conditional ground-motion model approach for predicting the I_a is that the more complicated scaling that are included in the NGA-West2 GMPEs—such as short-distance saturation, hanging-wall effects, soil-depth effects, soil nonlinearity effects, and regionalization effects—are accommodated by estimating the median and standard deviations of the PGA and SA_{T1} using the NGA-West2 GMPEs [Abrahamson et al. 2014 (ASK14); Boore et al. 2014 (BSSA14); Campbell and Bozorgnia 2014 (CB14); Chiou and Youngs 2014 (CY14); and Idriss, 2014 (I14)]. This allows for estimation of I_a values that are consistent with the estimated PSA values from more recent GMPEs to include more complex scaling, such as the NGA-West2 GMPEs.

2 Dataset

2.1 DATASET SELECTION

This study used the Pacific Earthquake Engineering Research Center (PEER) NGA-West2 database [Ancheta et al. 2014], which includes earthquakes that occurred through 2011 and contains over 21,000 three-component recordings from California and worldwide, with moment magnitudes, **M**, ranging from **M**3.0–**M**7.9. We use the same subset of this dataset as the ASK14 model, which consists of 15,730 recordings (distances between 0 and 400 km from 326 earthquakes with magnitudes between 3 and 7.9). There were five recordings with missing I_a values [Record Serial Number (RSN) 4236, 8164, 8165, 8166, 8169)]. The initial regression studies also found that there were ten recordings that were significant outliers in terms of only their I_a values (RSN 9048, 13483, 14046, 14727, 15374, 17041, 17206, 17305, 17800, and 20407). We did not correct these ten records and simply removed them from our dataset.

The resulting magnitude and distance distribution of the 15,715 recordings in the selected dataset is shown in Figure 2.1. Of this dataset, 506 recordings have a minimum useable frequency greater than 1 Hz, indicating that their SA_{T1} values are unusable. Removing these 506 recordings leads to our final dataset of 15,209 recordings.

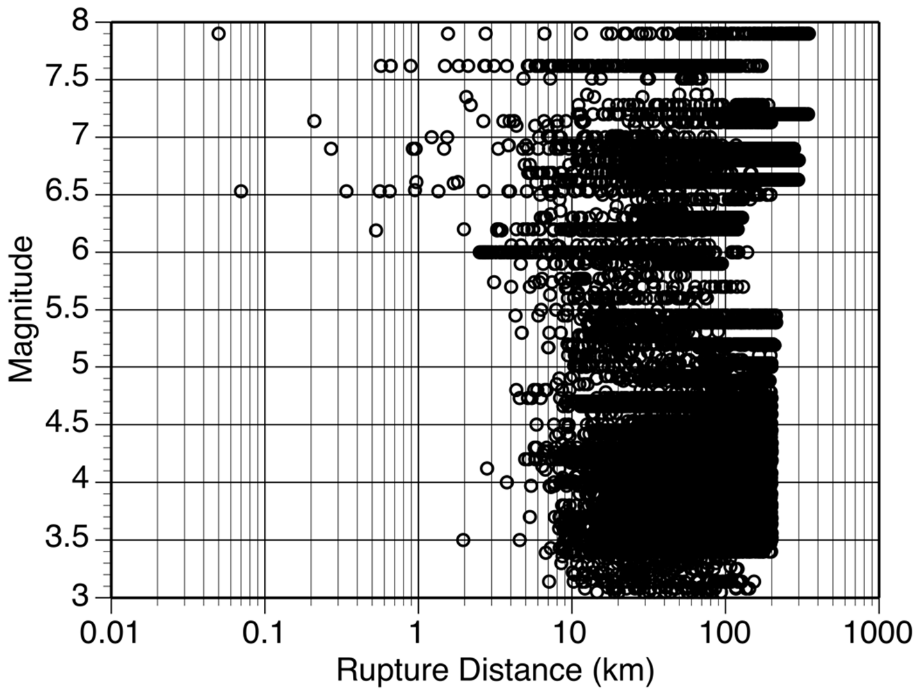


Figure 2.1 Magnitude and distance distribution of the selected I_a dataset.

3 Conditional Arias Intensity Model

3.1 FUNCTIONAL FORM

The Arias intensity is defined as

$$I_a = \frac{\pi}{2g} \int a^2(t)\, dt \tag{3.1}$$

where $a(t)$ is the acceleration in m/sec^2, g is the acceleration of gravity, and I_a is the Arias intensity in m/sec [Arias 1970]. Following Watson-Lamprey and Abrahamson [2006], we develop a conditional model for Arias intensity that includes the observed PGA and SA_{T1} as predictor variables. Watson-Lamprey and Abrahamson [2006] used the following functional form for their conditional I_a model:

$$\begin{aligned} \ln\left[I_a\left(\text{m/sec}\right)\right] = c_1 + c_2 \ln\left(V_{S30}\right) + c_3 M + c_4 \ln\left(\text{PGA}\right) + c_5 \ln\left(SA_{T1}\right) \\ + c_6 \ln\left(R_{\text{RUP}}\right) + c_7 \left[\ln\left(R_{\text{RUP}}\right)\right]^2 \end{aligned} \tag{3.2}$$

An initial exploratory analysis using the NGA-West2 database showed that the coefficients for the distance terms (c_6 and c_7) were not significantly different from zero. (c_6 and c_7 are highly correlated so both terms cannot be determined. The t-ratio for c_6 is -0.16.) Therefore, the distance terms were removed and the form listed in Equation (3.3) was used for developing the conditional I_a model.

$$\ln\left[I_a\left(\text{m/sec}\right)\right] = c_1 + c_2 \ln\left(V_{S30}\right) + c_3 M + c_4 \ln\left(\text{PGA}\right) + c_5 \ln\left(SA_{T1}\right) \tag{3.3}$$

where V_{S30} is in m/sec, and PGA and SA_{T1} are in g.

It is common to use a random-effects regression model for developing GMPEs to account for the correlation in the data through the event terms (e.g., Abrahamson and Youngs [1992]); however, because we developed a conditional model that includes the recorded PGA and SA_{T1} as input parameters, some of the correlation within an event is already captured through the observed PGA and SA_{T1} terms. We used the random-effects regression in the statistics program JMP (SAS Institute) to estimate the coefficients for the conditional I_a model. The resulting coefficients are listed in Table 3.1 along with the standard errors of the estimates. Table 3.1 shows that the I_a scales more strongly with PGA than SA_{T1} because the I_a is a high-frequency parameter; however, the SA_{T1} term is also statistically significant, shown by the large *t*-ratio of 44.

This conditional model for I_a has a total standard deviation of 0.38 natural log units (intra-event standard deviation $\phi = 0.35$, inter-event standard deviation $\tau = 0.15$). This standard deviation is much smaller than the standard deviations for traditional I_a models (not conditioned on observed PGA and SA_{T1}) that are about 1.0 natural log units, indicating that the I_a can be computed with much smaller aleatory variability if PGA and SA_{T1} are known, due to strong correlation of the I_a with the PGA and SA_{T1}.

Table 3.1 Parameter estimates, standard errors, and *t*-ratios for scaling model.

Term	Estimate	Standard Error	*t*-ratio
c_1	0.47	0.069	7
c_2	-0.28	0.0085	–33
c_3	0.50	0.011	45
c_4	1.52	0.0038	399
c_5	0.21	0.0047	44

3.2 EVALUATION OF RESIDUALS

The residuals for the conditional I_a model are shown in Figures 3.1 and 3.2 as a function of the four model input parameters: PGA, SA_{T1}, M, and V_{S30}. Figure 3.1 shows the inter-event residuals as a function of magnitude. Figure 3.2 shows the intra-event residuals as a function of PGA, SA_{T11}, and V_{S30}. The lack of trends in the residuals shows that the simple scaling in Equation (3.3) adequately captures the dependence of the I_a on these four parameters.

We also checked the residuals for other parameters that are used in GMPEs for PSA but were not used in our conditional I_a model. The lower frame of Figure 3.1 shows the inter-event residuals as a function of depth to top of rupture (Z_{TOR}). Figure 3.3 shows the intra-event results as a function of rupture distance (R_{RUP}), soil depth to V_S = 1 km/sec ($Z_{1.0}$), and rock PGA (PGA_{1100}) for soil sites with $V_{S30} < 270$ m/sec. There is no trend in the residuals as a function of these parameters, indicating that the I_a scaling with these parameters, including the effects of nonlinear site response on the I_a, is captured in the conditional model through the use of the observed PGA and SA_{T1} values. To check the magnitude dependence of the distance scaling, Figure 3.4 shows the intra-event residuals versus distance separated by magnitude. There are no systematic trends in the residuals, indicating that the magnitude dependence of the distance scaling for I_a is also captured through the use of the observed PGA and SA_{T1} values.

Finally, we checked the residuals for sites that are expected to show hanging-wall (HW) effects. The intra-event residuals for sites on the HW side of the rupture ($R_x > 0$) and located over or near the hanging-wall (Joyner-Boore distance, $R_{JB} < 5$ km) from earthquakes with $\mathbf{M} > 6$ and dip < 60° show a small under-prediction of the I_a. The trend in the residuals is nearly constant with R_{JB}, magnitude, and dip. The average amplitude of the offset in the HW residuals (0.11 ln units) is small compared to the size of the HW effects in the GMPEs (e.g., about 0.7 ln units in the ASK14 model for sites over the HW), indicating that the simple conditional model accounts for most of the HW effect. Because sites located over the HW are an important factor in building design, an additional term is added to the conditional I_a model to improve the model for HW sites. Although the residuals show a constant shift, this needs to be tapered for sites at larger distances, smaller magnitudes, and steeper dips. Therefore, we applied the form of the dip, magnitude, and distance tapers for the HW term from the ASK14 model [Equations (3.5), (3.6), and (3.7)]. The HW term is given by:

$$HW_{\text{resid}} = c_8 F_{HW} T_1(\text{dip}) T_2(M) T_5(R_{JB}) \tag{3.4}$$

where F_{HW} is a flag that is 1 for sites located on the hanging-wall side of the rupture and 0 for sites located on the footwall side of the rupture:

$$T_1(\text{dip}) = \begin{cases} (90-\text{dip})/45 & \text{for dip} > 30 \\ 60/45 & \text{for dip} < 30 \end{cases} \tag{3.5}$$

$$T_2(M) = \begin{cases} 1 & \text{for } M \geq 6.5 \\ 1 + 0.2(M-6.5) - 0.8(M-6.5)^2 & \text{for } 5.5 < M < 6.5 \\ 0 & \text{for } M \leq 5.5 \end{cases} \tag{3.6}$$

$$T_5(R_{jb}) = \begin{cases} 1 & \text{for } R_{jb} = 0 \\ 1 - \dfrac{R_{jb}}{15} & \text{for } R_{jb} < 15 \\ 0 & \text{for } R_{jb} \geq 15 \end{cases} \tag{3.7}$$

The estimate of c_8 is 0.09 with a standard error of 0.03.

3.3 EVALUATION OF ALEATORY VARIABILITY

The regression analysis assumes that the $\ln(I_a)$ residuals have a normal distribution. This assumption is evaluated using normal probability plots. Figure 3.8 shows the normal probability plots of the inter-event and intra-event residuals. The distribution of inter-event residuals is consistent with a normal distribution except for the lower tail, which is not important for engineering applications because we are concerned with large damaging ground motions. The distribution of the intra-event residuals is generally consistent with the normal distribution, with the exception of the upper and lower tails, starting at about the 1% and 99% levels (e.g., about ±2.3 standard deviations). Figure 3.8 shows that the I_a intra-event residuals have fat tails compared to the normal distribution. Similar fat tails have been observed for the intra-event response spectral values using the NGA-West2 dataset [Geopentech 2015 Chapter 11].

The fat tails for the intra-event residuals can be described using a mixture model, given by the weighted average of two normal distributions: one has a mean of 0, standard deviation of 0.40 and weight of 0.56; the other has a mean of 0, standard deviation of 0.27 and weight of 0.44. The normal probability plot using the mixture model is shown in Figure 3.9. The mixture model adequately captures the fat tails in the upper range.

The intra-event residual distribution deviates from a normal distribution at around 2.3 standard deviations, but it is consistent with the mixture model distribution up to 4 standard deviations. If the I_a model is used to compute probabilistic hazard at low probability levels, then the mixture model should be used to compute the conditional probability of exceedance as shown below, where $\Phi(x)$ is the cumulative standard normal distribution.

$$P\left(I_a > z \middle| \text{PGA}, SA_{T1}, M, V_{S30}\right) = 0.56\left\{1-\Phi\left[\frac{\ln(z)-\ln(I_a)}{\sqrt{\phi_1^2+\tau^2}}\right]\right\}+0.44\left\{1-\Phi\left[\frac{\ln(z)-\ln(I_a)}{\sqrt{\phi_2^2+\tau^2}}\right]\right\} \tag{3.8}$$

where ϕ_1 and ϕ_2 are the intra-event standard deviations from the mixture model ($\phi_1 = 0.40$ and $\phi_2 = 0.27$), and τ is inter-event standard deviation ($\tau = 0.15$).

The regression also assumes that the I_a residuals are homoscedastic. This assumption is evaluated by visual inspection of the scatter of residuals shown against the predictive parameters in Figures 3.1, 3.2, 3.3, and 3.4. The amplitude of the scatter of residuals does not appear to have any trends with the predicted parameters (magnitude, PGA, SA_{T1}, and V_{S30}). For PSA GMPEs, the standard deviation is often modeled with a dependence on the earthquake magnitude (e.g., ASK14, BSSA14, CB14, CY14, and I14). The magnitude dependence of the standard deviation for the conditional I_a model is evaluated by computing the intra-event and inter-event standard deviations for different magnitude ranges (Table 3.2). There is no systematic increase or decrease in the inter-event and intra-event standard deviations (τ and ϕ) with magnitude.

Table 3.2 Standard deviation of the conditional I_a residuals by magnitude bin.

Magnitude Range	Number of Earthquakes	Number of Recordings	ϕ (LN units)	τ (LN units)	σ (LN units)
2.5–3.5	25	821	0.38	0.11	0.40
3.5–4.5	169	7713	0.36	0.14	0.39
4.5–5.5	54	2235	0.33	0.17	0.37
5.5–6.5	49	1785	0.29	0.16	0.33
6.5–7.5	25	2622	0.37	0.14	0.40
7.5–8.5	4	539	0.35	too few eqk	

3.4 COMPARISON OF CONDITIONAL I_a MODELS

The conditional I_a model developed in this section is compared to the WLA06 conditional I_a model in Figures 3.10 and 3.11. The coefficients for the magnitude scaling and V_{S30} scaling in the current model are similar to the coefficients in the WLA06. This leads to similar magnitude and V_{S30} scaling between the two models; see Figure 3.10.

The coefficient for the ln(PGA) term is much larger in the current model (1.52) than in the WLA06 model (1.30), suggesting that the current model leads to stronger scaling with PGA than the WLA06 model; however, the ln(PGA) is correlated with the ln[PSA(T=1)], and the coefficient for the ln[PSA(T=1)] term is much smaller in the current model (0.21) than in the WLA06 model (0.33). This difference in the PSA(T=1) scaling offsets much of the difference in the PGA scaling between the two models.

Because the relative values of the PGA and PSA(T=1) depend on the spectral shape, Figure 3.11 shows the scaling with ln(PGA) for magnitudes of 5.0, 6.5, and 8.0. The largest differences in the ln(PGA) scaling is at the **M**5 range. This reflects the large increase in the number of recordings from moderate magnitude earthquakes in the NGA-West2 dataset used in this study compared to the NGA-West1 dataset used by WLA06. Similarly, the scaling with ln[PSA(T=1)] is shown in the right-hand frame of Figure 3.11 for magnitudes 5.0, 6.5, and 8.0. As with the ln(PGA) scaling, the correlation of the ln(PGA) and the ln[PSA(T=1)] values reduces the differences in the predicted I_a from the two models.

The predicted I_a values using the current conditional I_a model and using the WA06 conditional I_a model are very similar even though the current model uses a much larger database. In contrast, the predicted I_a values using the traditional (non-conditional) approach show a stronger dependence on the dataset used to develop the model (see Chapter 4). Therefore, using the conditional I_a model approach leads to more robust ground-motion models for I_a than using the traditional approach.

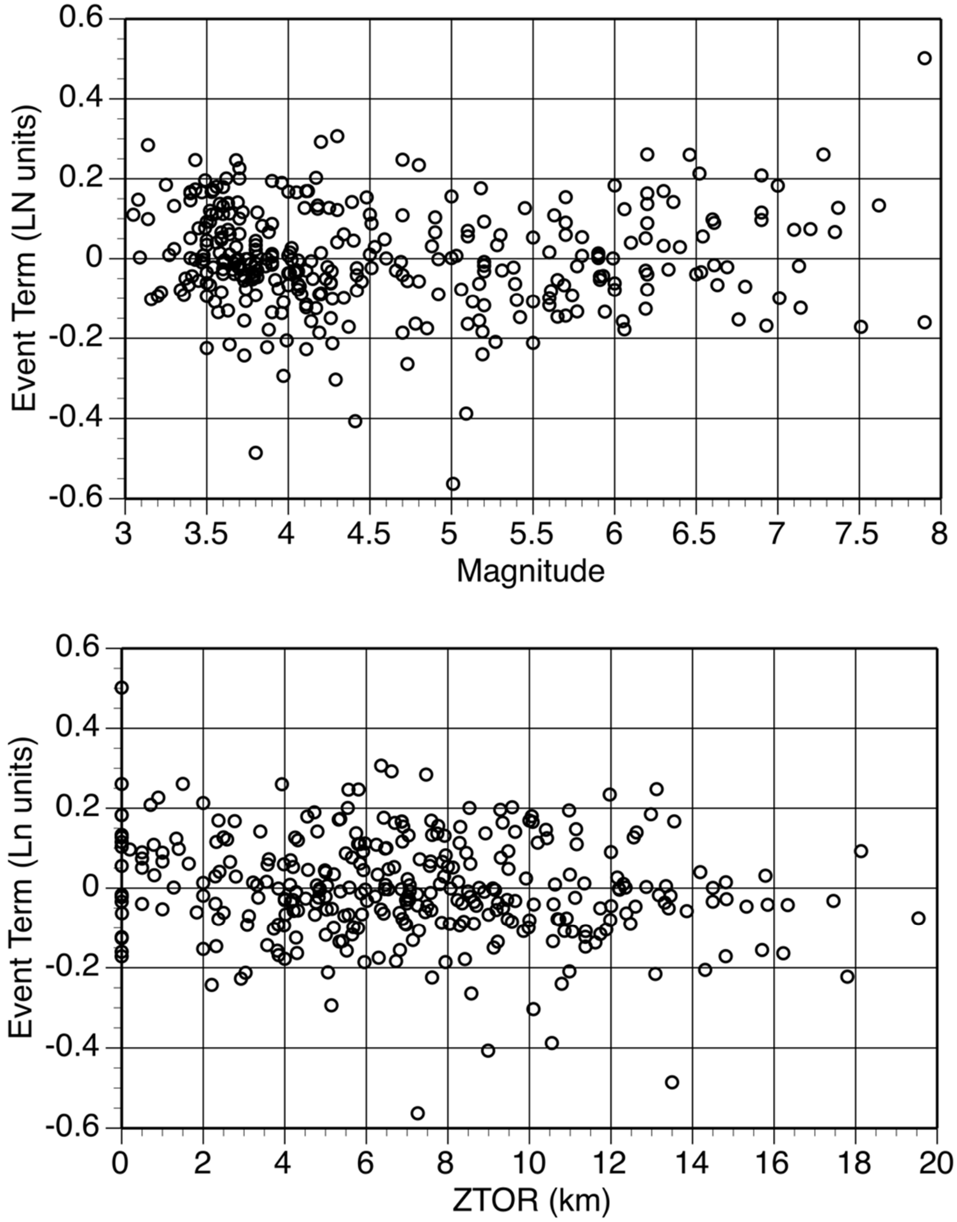
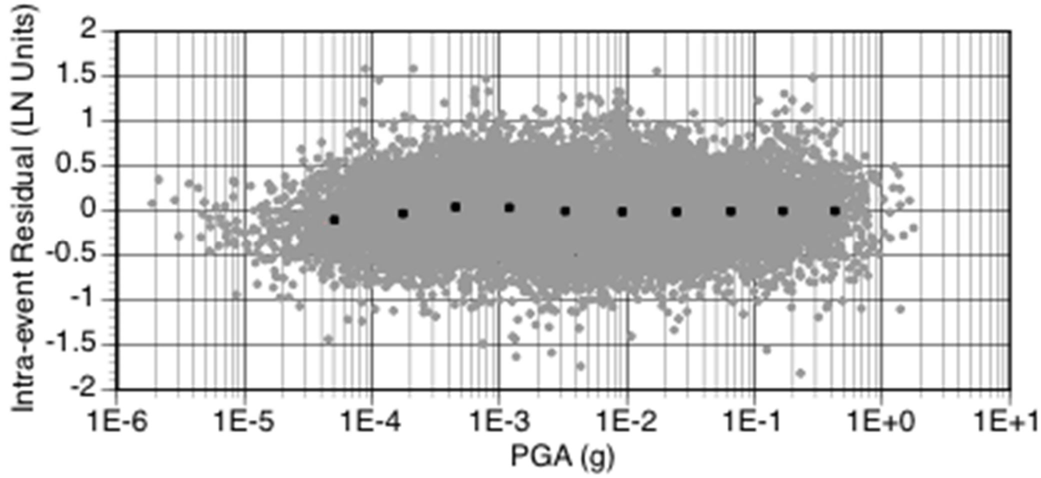
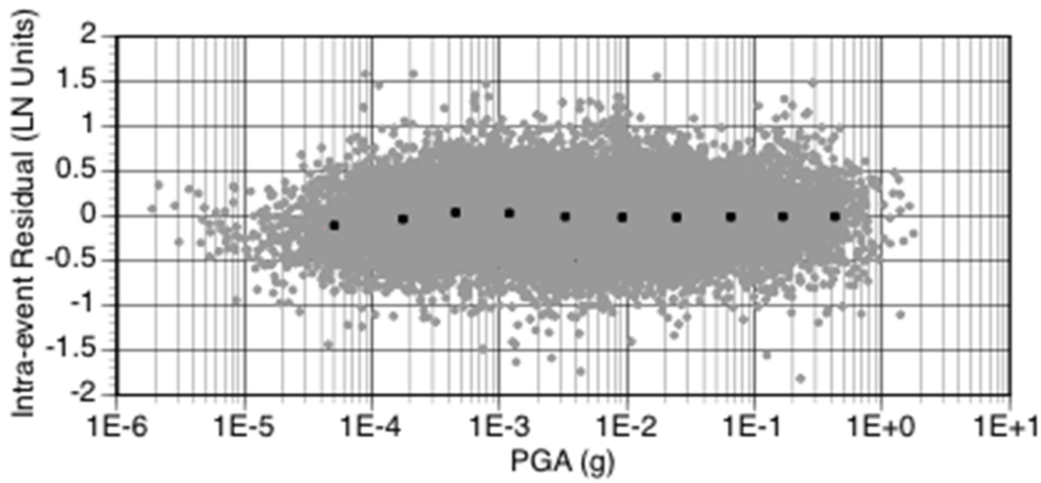


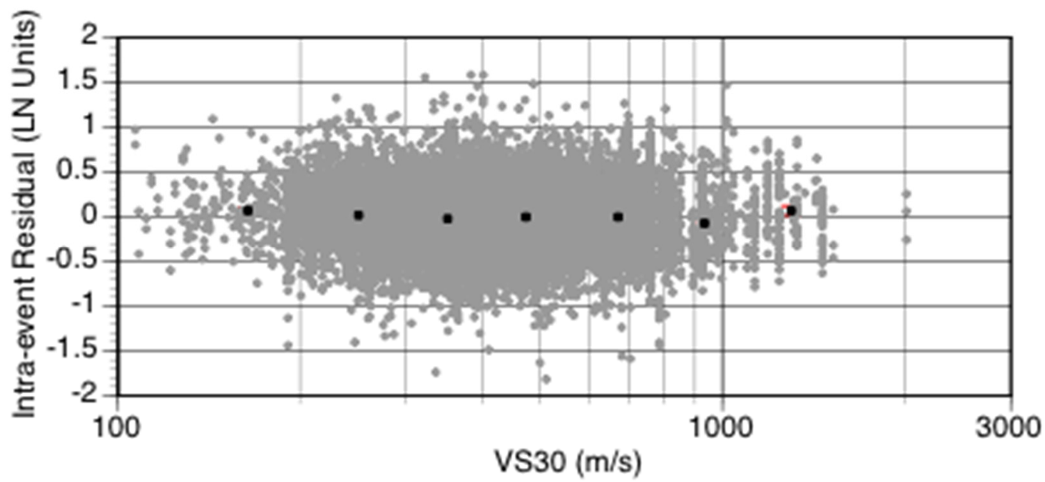
Figure 3.1 Inter-event residuals of the conditional I_a model as a function of magnitude (top) and Z_{TOR} (bottom).



(a)



(b)



(c)

Figure 3.2 Intra-event residuals of conditional I_a model as a function of (a) PGA, (b) SA_{T1}, and (c) V_{S30}.

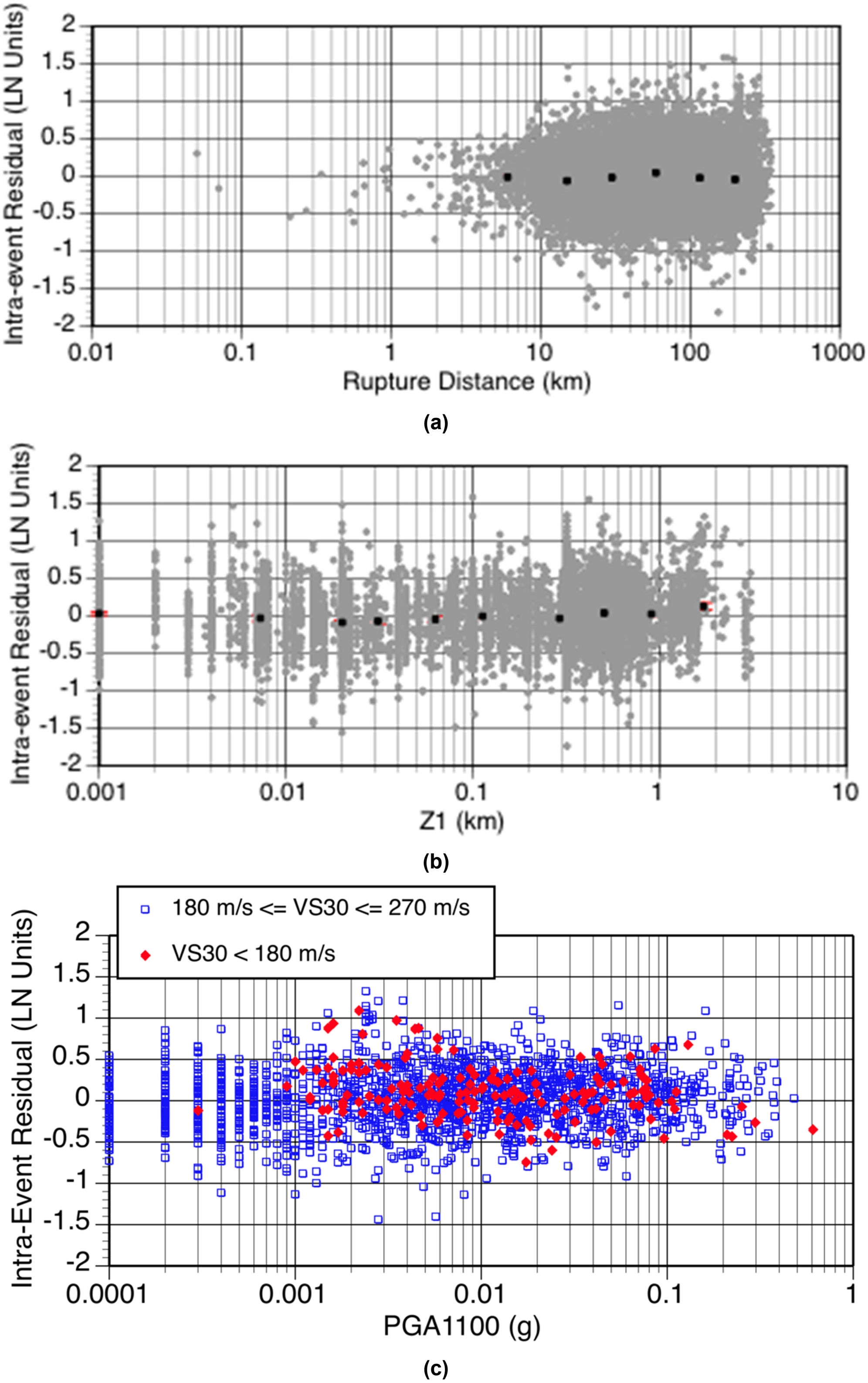


Figure 3.3 **Intra-event residuals of the conditional I_a model as a function of parameters not included in the conditional model.**

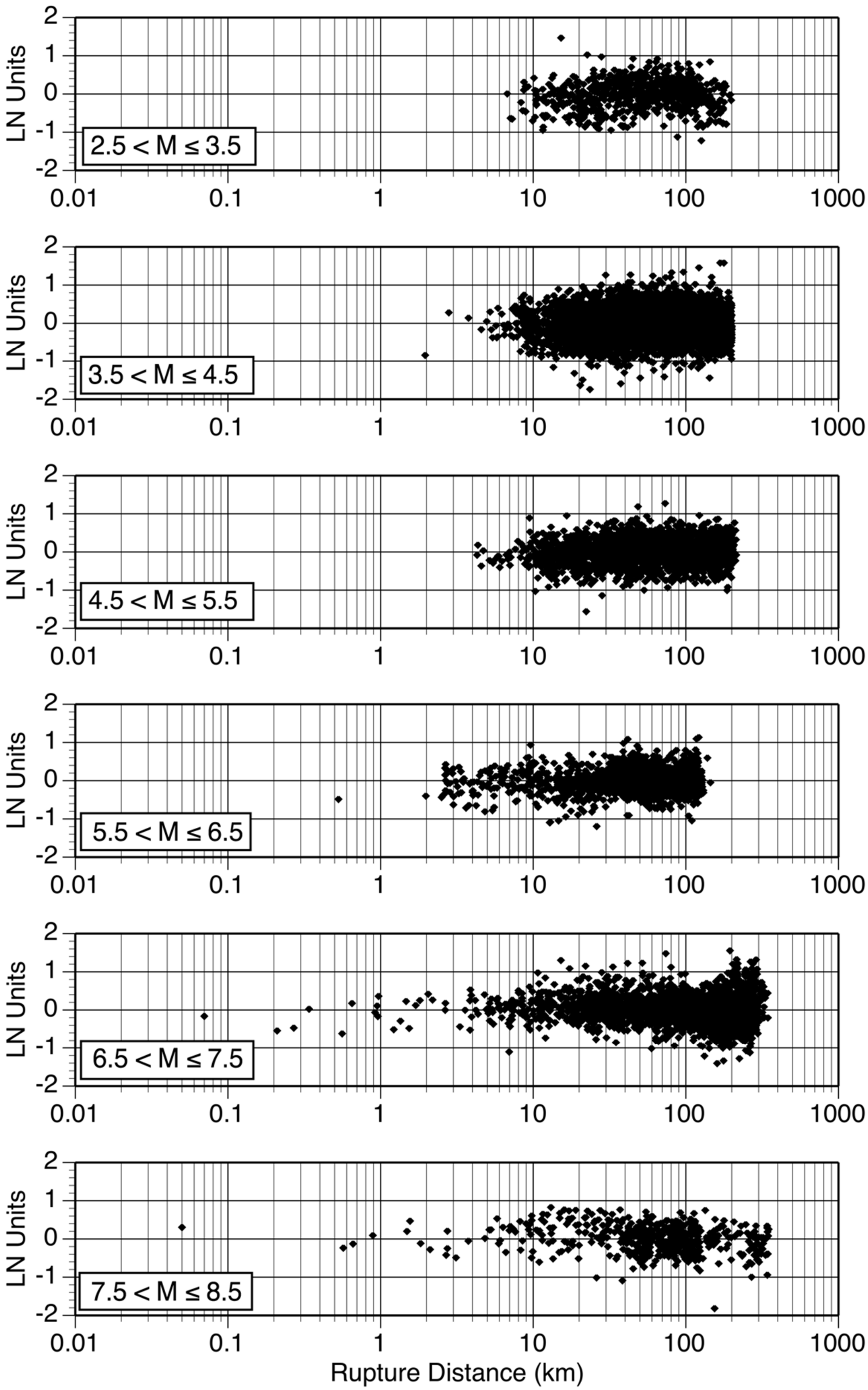


Figure 3.4 Intra-event residuals of the conditional I_a model as a function of rupture distance separated by magnitude bin.

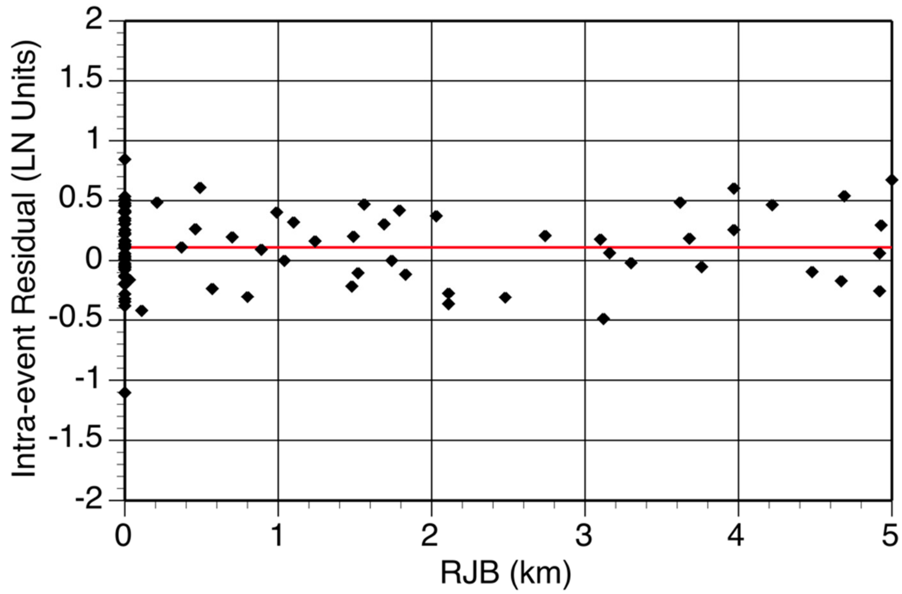


Figure 3.5 **Intra-event residuals of conditional I_a model for sites with expected hanging-wall effects (M ≥ 6, dip ≤ 60, R_{JB} ≤ 5 km, R_X > 0) as a function of R_{JB}. The red curve shows the mean residual.**

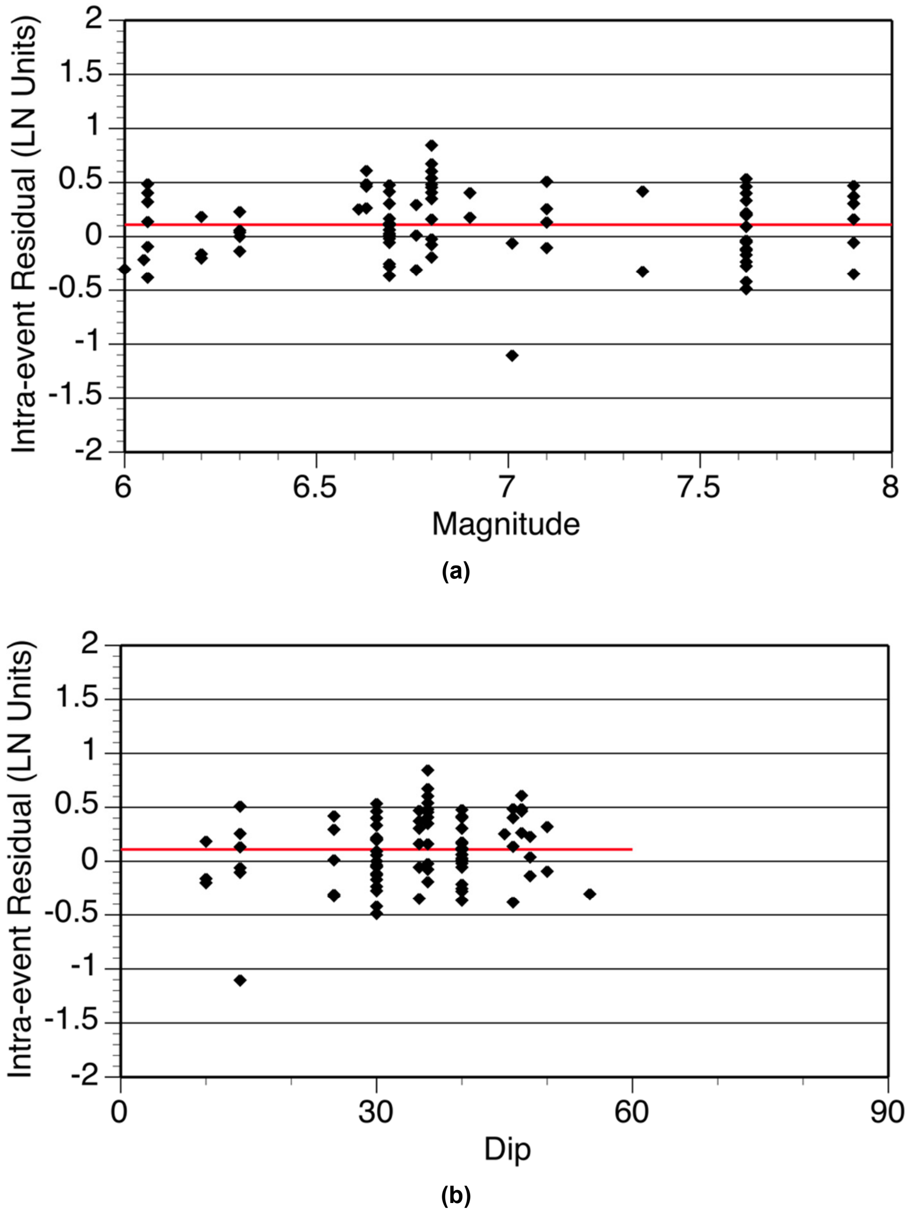


Figure 3.6 **Intra-event residuals of conditional I_a model for sites with expected hanging-wall effects (M ≥ 6, dip ≤ 60, R_{JB} ≤ 5 km, R_X > 0) as a function of (a) magnitude and (b) dip. The red curve shows the mean residual.**

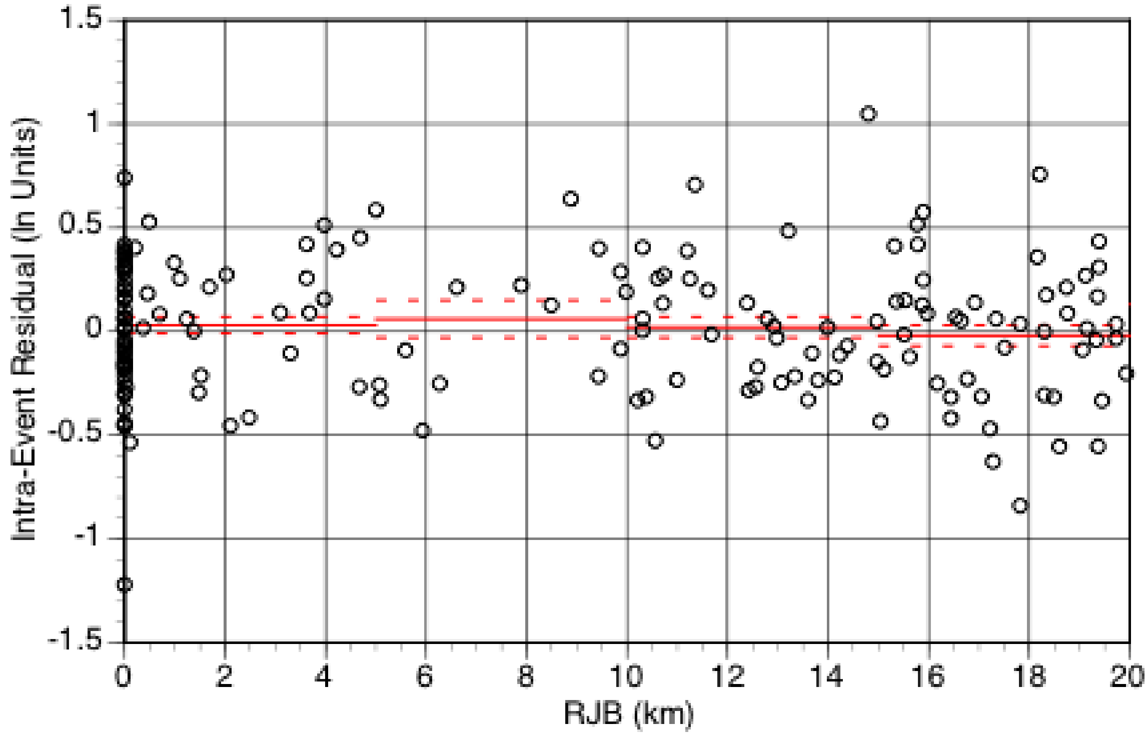
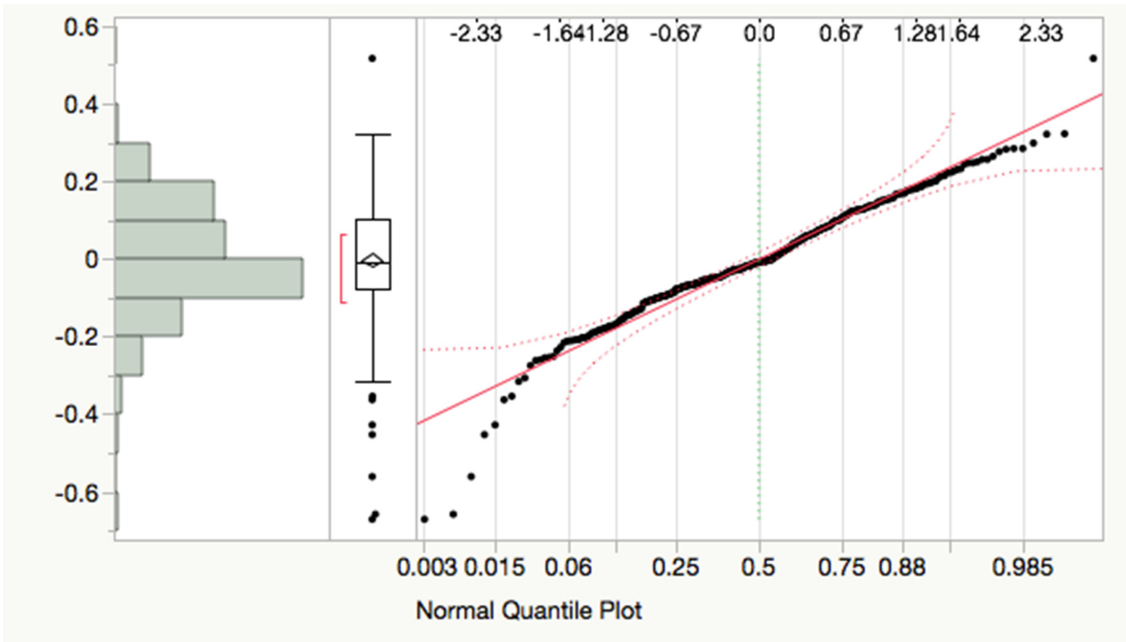
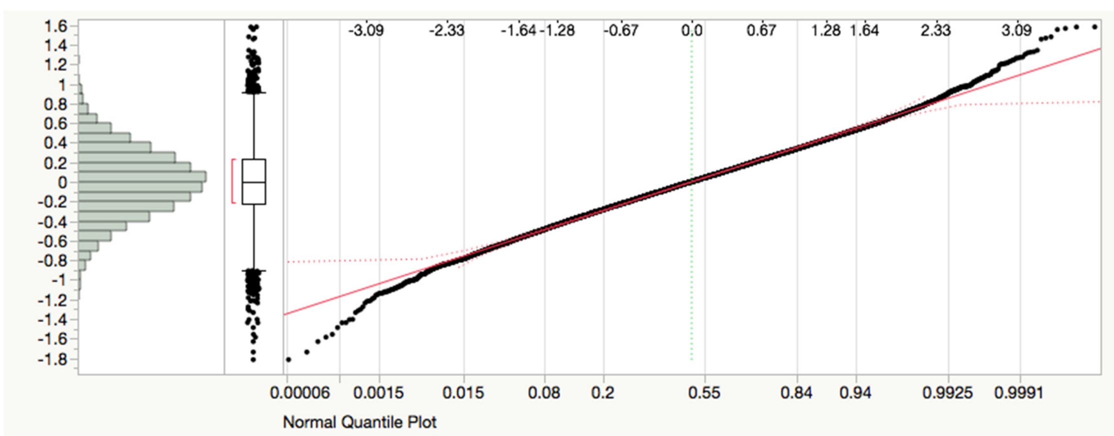


Figure 3.7 **Intra-event residuals of conditional I_a model for sites with expected hanging-wall effects (M ≥ 6, dip ≤ 60, $R_X > 0$) after including the HW term in Equation (3.4). The red curves shows the mean residual for distance bins and the red dashed curves show the plus and minus one standard error of the mean residual.**



(a)



(b)

Figure 3.8 **Normal probability plot for the (a) inter-event residuals and the (b) intra-event residuals for the conditional I_a model.**

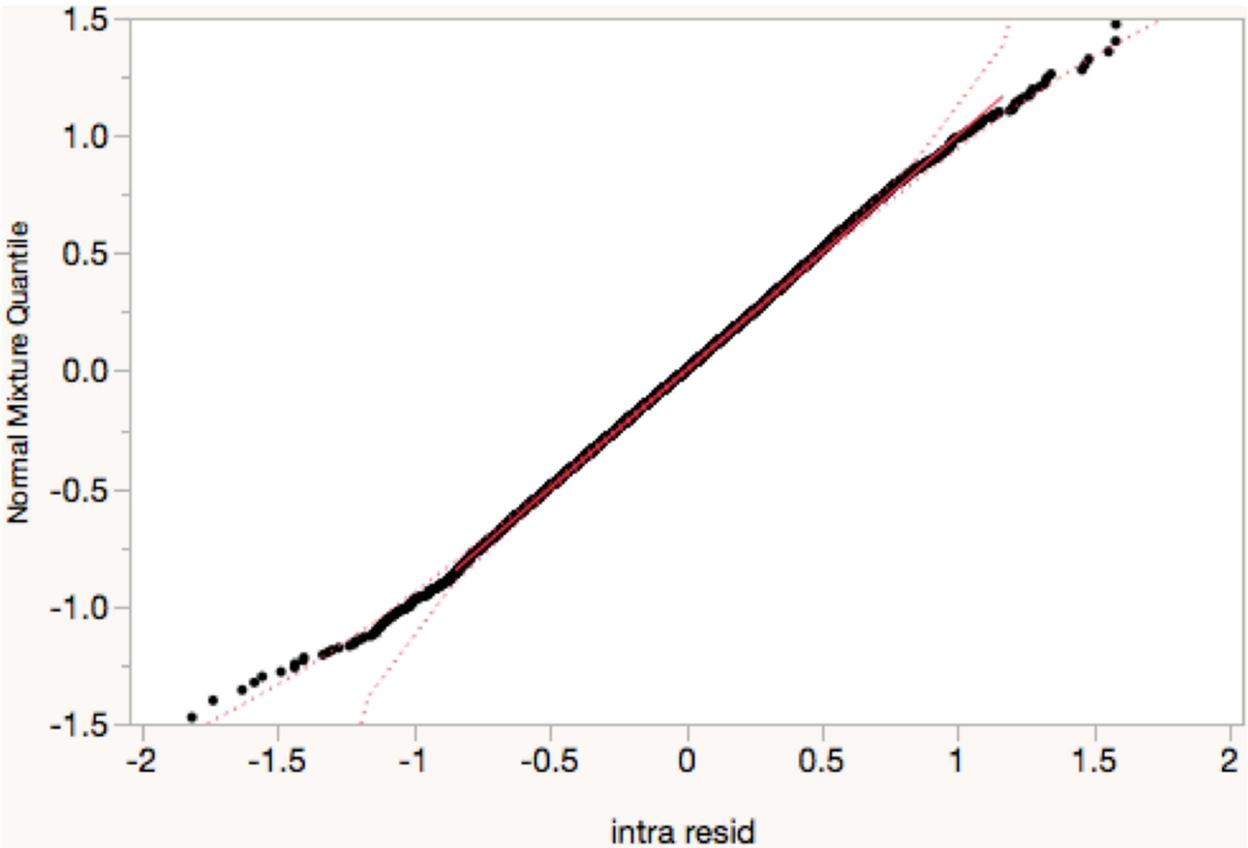


Figure 3.9 **Normal probability plot for the intra-event residuals (in ln units) using the mixture model for the conditional I_a model.**

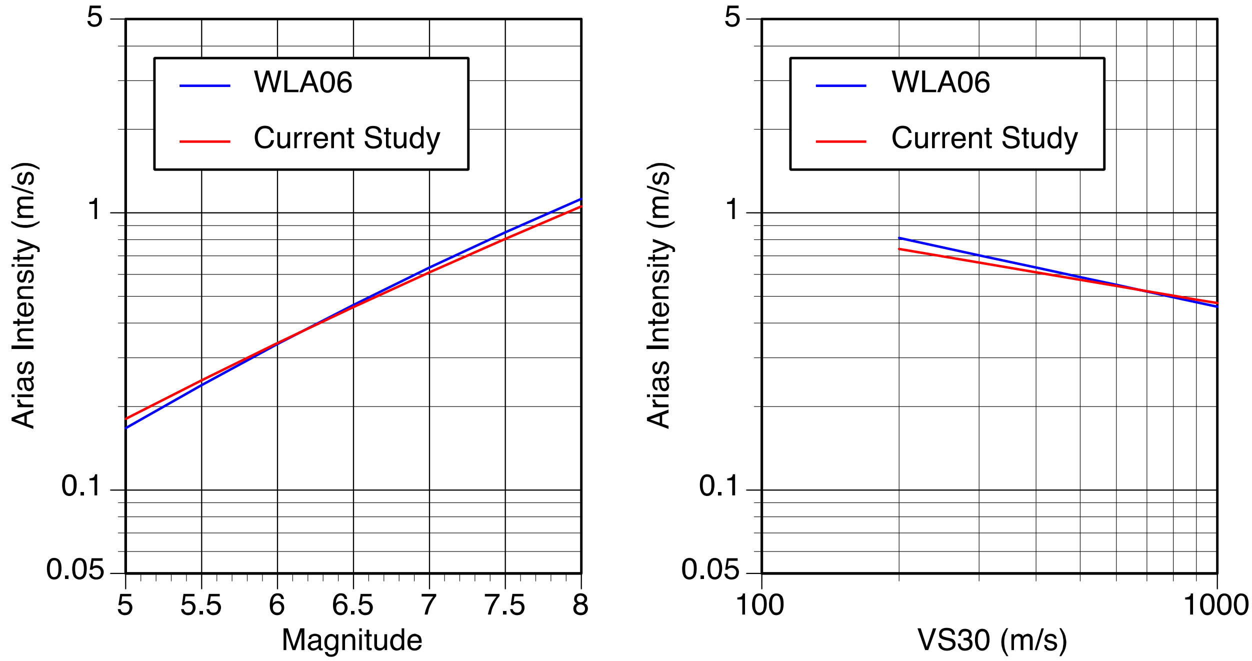


Figure 3.10 Comparison of the scaling for the WLA06 conditional I_a model with the results of this study.

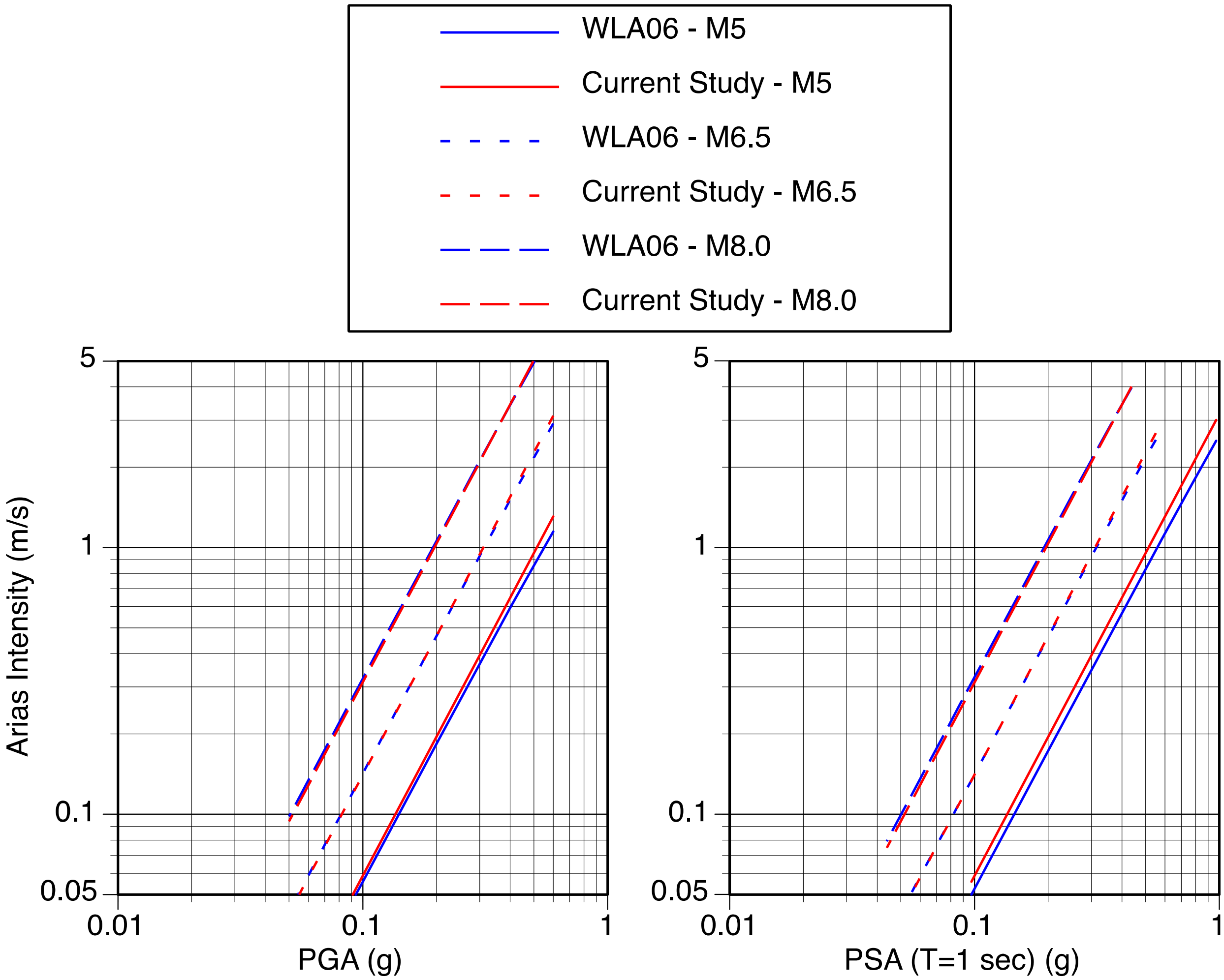


Figure 3.11 **Comparison of the scaling for the WLA06 conditional I_a model with the results of this study. Because the PSA (*T*=1) is correlated with PGA, the scaling with PGA or PSA is shown for fixed magnitudes (fixed spectral shape).**

4 Arias Intensity Ground Motion Prediction Equations

4.1 MOVING FROM CONDITIONAL MODELS TO TRADITIONAL MODELS

For a given earthquake scenario and site location, we use the median PGA and median SA_{T1} values from the individual NGA-West2 ground motion models combined with the conditional I_a model in Equations (3.3) and (3.4) to develop a median I_a for each NGA-West2 model, as shown in Equation (4.1).

$$\ln\left[I_a\left(\mathrm{m/sec}\right)\right] = c_1 + c_2\ln\left(V_{S30}\right) + c_3 M + c_4\ln\left(\mathrm{PGA}\right) + c_5\ln\left(SA_{T1\mathrm{med}}\right) + c_8 F_{HW}\begin{cases} 1 & \text{if } R_{JB} < 5 \text{ km} \\ 1 - \dfrac{R_{JB}-5}{5} & \text{if } 5 < R_{JB} < 10 \text{ km} \\ 0 & \text{if } R_{JB} > 10 \text{ km} \end{cases} \tag{4.1}$$

This median I_a depends on the median PGA and SA_{T1} from the NGA-West2 GMPEs and is no longer conditioned on the observed PGA and SA_{T1}.

The variance for the I_a GMPE can be calculated using propagation of errors [Bevington and Robinson 1969] as follows:

$$\sigma^2_{\ln(I_a)} = \sigma^2_{\ln(I_a)|\ln(\mathrm{PGA}),\ln(SA_{T1})} + \sigma^2_{\ln(\mathrm{PGA})}\left[\frac{\partial\ln(I_a)}{\partial\ln(\mathrm{PGA})}\right]^2 + \sigma^2_{\ln(SA_{T1})}\left[\frac{\partial\ln(I_a)}{\partial\ln(SA_{T1})}\right]^2 + 2\mathrm{COV}\left[\ln(\mathrm{PGA}),\ln(SA_{T1})\right]\left[\frac{\partial\ln(I_a)}{\partial\ln(\mathrm{PGA})}\right]\left[\frac{\partial\ln(I_a)}{\partial\ln(SA_{T1})}\right] \tag{4.2}$$

where

$$\mathrm{COV}\left[\ln(\mathrm{PGA}),\ln(SA_{T1})\right] = \rho\left[\varepsilon_{\ln(\mathrm{PGA})},\varepsilon_{\ln(SA_{T1})}\right]\left[\sigma_{\ln(\mathrm{PGA})},\sigma_{\ln(SA_{T1})}\right] \tag{4.3}$$

and ρ is the correlation coefficient, and ε is the normalized residual from the NGA-West2 GMPE. The partial derivatives were calculated from Equation (4.1). The $\sigma_{\ln(\mathrm{PGA})},\sigma_{\ln(SA_{T1})}$ term is the standard deviation for the conditional I_a in Equation (3.3). We used the correlation coefficient, $\rho[\varepsilon_{\ln(\text{PGA})}, \varepsilon_{\ln(SA_{T1})}]$, from the Baker and Jayaram [2008] model. Although this correlation model was derived from the NGA-West1 dataset, Carlton and Abrahamson [2014] showed that correlations are stable for different datasets. The values of the partial derivatives, correlation coefficient, and standard deviation of the conditional I_a model in Equations (4.2) and (4.3) are listed in Table 4.1.

Table 4.1 Parameter Values for Computing the Standard Deviation.

$\sigma_{\ln(I_a)\|\ln(\text{PGA}),\ln(SA_{T1})}$	$\rho\left[\varepsilon_{\ln(\text{PGA})}, \varepsilon_{\ln(SA_{T1})}\right]$	$\frac{\partial \ln(I_a)}{\partial \ln(\text{PGA})}$	$\frac{\partial \ln(I_a)}{\partial \ln(SA_{T1})}$
0.38	0.52	1.53	0.20

Using the values in Table 4.1, the total standard deviation (combined intra-event and inter-event) for the I_a GMPEs is given by Equation (4.4).

$$\sigma_{\ln(I_a)} = \sqrt{0.144 + 2.34\sigma^2_{\ln(PGA)} + 0.04\sigma^2_{\ln(Sa_{T1})} + 0.318\sigma_{\ln(PGA)}\sigma_{\ln(Sa_{T1})}} \tag{4.4}$$

where $\sigma_{\ln(PGA)}$ and $\sigma_{\ln(Sa_{T1})}$ are the standard deviations given by the NGA-West2 models. The intra-event and inter-event standard deviations can also be estimated. The correlation for the intra-event and inter-event residuals are very similar [Carlton and Abrahamson 2014]. Assuming the correlations from Baker and Jayaram [2008] are valid for both the intra-event and inter-event residuals, the intra-event and inter-event standard deviations for the I_a are shown in Equations (4.5) and (4.6).

$$\phi_{\ln(I_a)} = \sqrt{0.144 + 2.34\phi^2_{\ln(PGA)} + 0.04\phi^2_{\ln(Sa_{T1})} + 0.318\phi_{\ln(PGA)}\phi_{\ln(Sa_{T1})}} \tag{4.5}$$

$$\tau_{\ln(I_a)} = \sqrt{0.144 + 2.34\tau^2_{\ln(PGA)} + 0.04\tau^2_{\ln(Sa_{T1})} + 0.318\tau_{\ln(PGA)}\tau_{\ln(Sa_{T1})}} \tag{4.6}$$

As a check, the I_a values are computed using the median PGA and SA_{T1} from the ASK14 GMPE, i.e., it is no longer a conditional model. Using these estimated I_a values, the inter-event and intra-event residuals of the I_a are computed using a random-effects regression with only a constant term. The estimated constant term is small: 0.02 natural log units. The inter-event residuals and the intra-event residuals do not show a trend with magnitude or distance. The small constant term and the lack of trends in these residuals indicate that I_a based on the conditional I_a model combined with the ASK14 GMPE for the median PGA and SA_{T1} is consistent with the scaling of the observed I_a values.

4.2 MODEL RESULTS

The resulting I_a models using the five NGA-West2 GMPEs are compared to previously published I_a models. Figures 4.1(a-d) compare the distance scaling of the I_a models for vertically dipping strike–slip earthquakes for V_{S30} of 520 m/sec for magnitude 5, 6, 7, and 8, respectively. Default values are used for the focal depth and depth to top of rupture terms. The default values for $Z_{1.0}$ and $Z_{2.5}$ are 0.22 km and 0.94 km for V_{S30} = 520 m/sec, respectively, based on the scaling in ASK14 for $Z_{1.0}$ and the scaling in CB14 for $Z_{2.5}$. For V_{S30} = 270 m/sec, the $Z_{1.0}$ and $Z_{2.5}$ values are 0.47 km and 1.98 km, respectively. At large distances, the I_a models have a steeper slope than the previously published models because they scale with the NGA-West2 GMPE's, which are better constrained at large distances. The resulting models are also more tightly grouped than the other models are, comparatively. This shows that the resulting models are more robust than models based on the common approach of conducting an independent regression for the I_a model, which generally does not have the physical constraints built into how the model extrapolates as in the case of the PSA GMPEs.

Figures 4.2 and 4.3 compare the magnitude scaling for the I_a models for vertically dipping strike–slip earthquakes for a rupture distance of 10 km and two V_{S30} values: 270 m/sec and 520 m/sec. In the **M**6–**M**7 range, the NGA-West2 I_a models are similar to prior models, but they differ at **M**5 and **M**8 magnitudes where the previous models have fewer data and are extrapolated. Here, the CB14 model is similar to the CB12 model because of similar complex forms but mainly differ at **M**8 magnitudes with lower values in the CB12 model.

Figure 4.4 compares the short-distance scaling for the I_a models for dipping faults for **M**7. This shows a larger difference between the NGA-West2 I_a model and prior models that did not include hanging-wall effects (all except CB12) for sites located over the hanging wall due to the simple forms used in prior models.

Figure 4.5 compares the standard deviations for the I_a models developed herein with the standard deviations from previously published models. The standard deviations for the new models are generally consistent with the FPS12 empirical model but are significantly larger than the TBA03, SBP09 and CB12 empirical models. Both the FPS12 and CB12 use the NGA-West1 dataset and use a direct regression on the I_a data, but the selected subsets are different. As a result, the FPS12 standard deviation is much larger than the CB12 standard deviation.

To understand the cause of the difference in the standard deviations, Figure 4.5 includes a comparison with the standard deviation computed from the CB12 dataset from NGA-West1 and the ASK14 dataset from NGA-West2. The intra-event and inter-event standard deviations for ln(I_a) computed using these two subsets are listed in Table 4.2. Applying the results of the conditional I_a model to the CB08 equation for PGA and SA_{T1} and corresponding dataset for computing residuals leads to ϕ of 0.78 and τ of 0.36, which are similar to the standard deviation terms from CB12 (ϕ = 0.77, τ = 0.31). In contrast, applying the conditional I_a model to the ASK14 model for PGA and SA_{T1} and corresponding dataset leads to much larger ϕ and τ values (ϕ = 0.89, τ = 0.61 for **M** > 5.5), which are consistent with the standard deviations for the five new models based on the NGA-West2 equations. They are also consistent with the standard deviation of the FPS12 empirical model. This shows that the increase in the standard deviations for the new I_a models compared to several of the previous empirical models, shown in Figure 4.5, is not an artifact of the use of a conditional I_a model. Instead, it is related to the selected dataset.

Table 4.2 Inter-event, intra-event, and total standard deviations for two different datasets and reference GMPEs.

Dataset and reference GMPE	Magnitude range	ϕ (LN units)	τ (LN units)	σ (LN units)
ASK14 (R_{RUP} < 80 km)	3.0 < **M** < 4.0	1.23	0.72	1.43
	4.0 < **M** < 5.5	1.16	0.72	1.37
	M > 5.5	0.89	0.61	1.08
CB08	**M** > 4.3	0.78	0.36	0.86

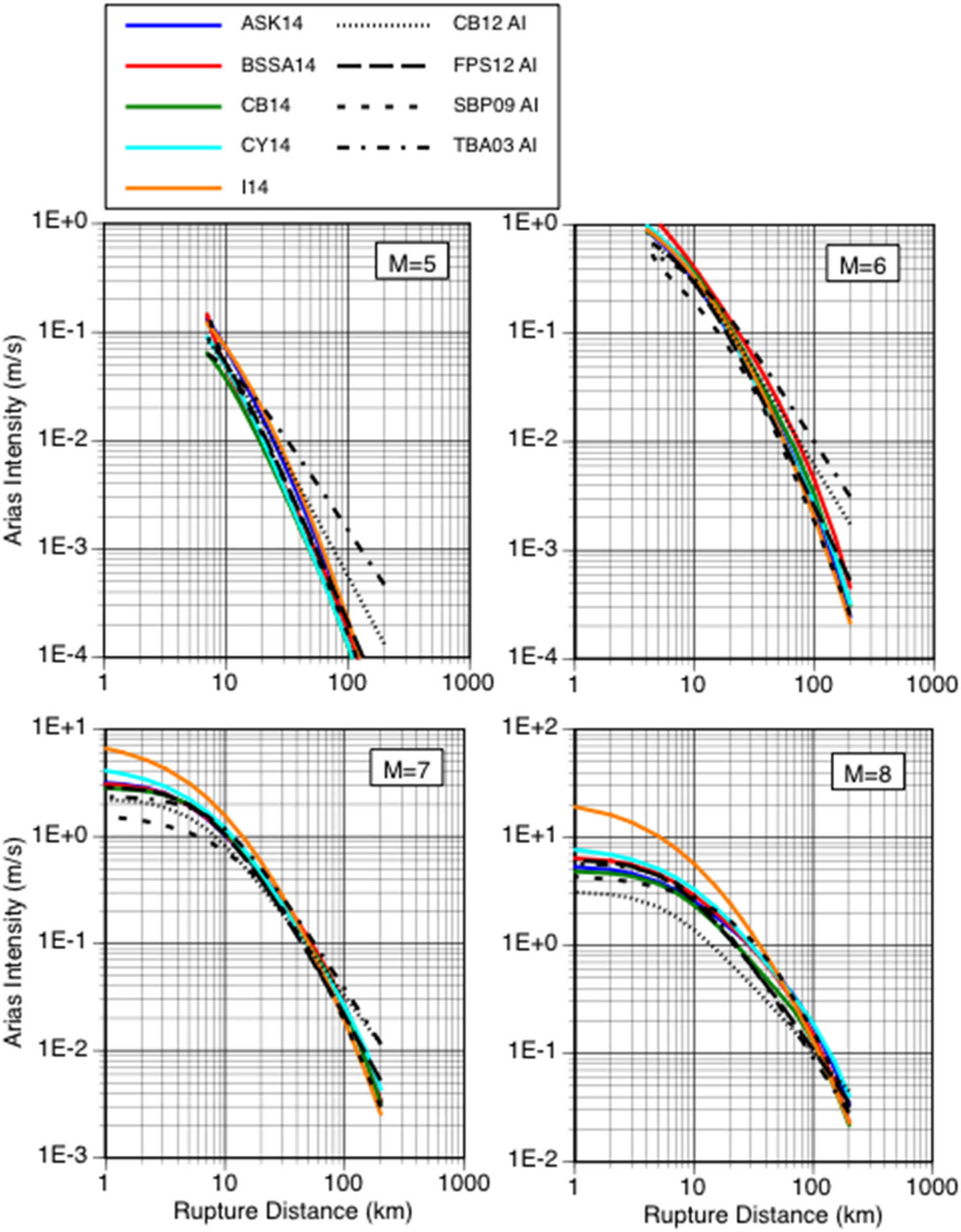


Figure 4.1 **Comparison of the distance scaling of the median I_a models for strike–slip faults for V_{S30} = 520 m/sec (TBA03 class C, SBP09 class B). (a) M = 5, (b) M = 6, (c) M = 7, and (d) M = 8.**

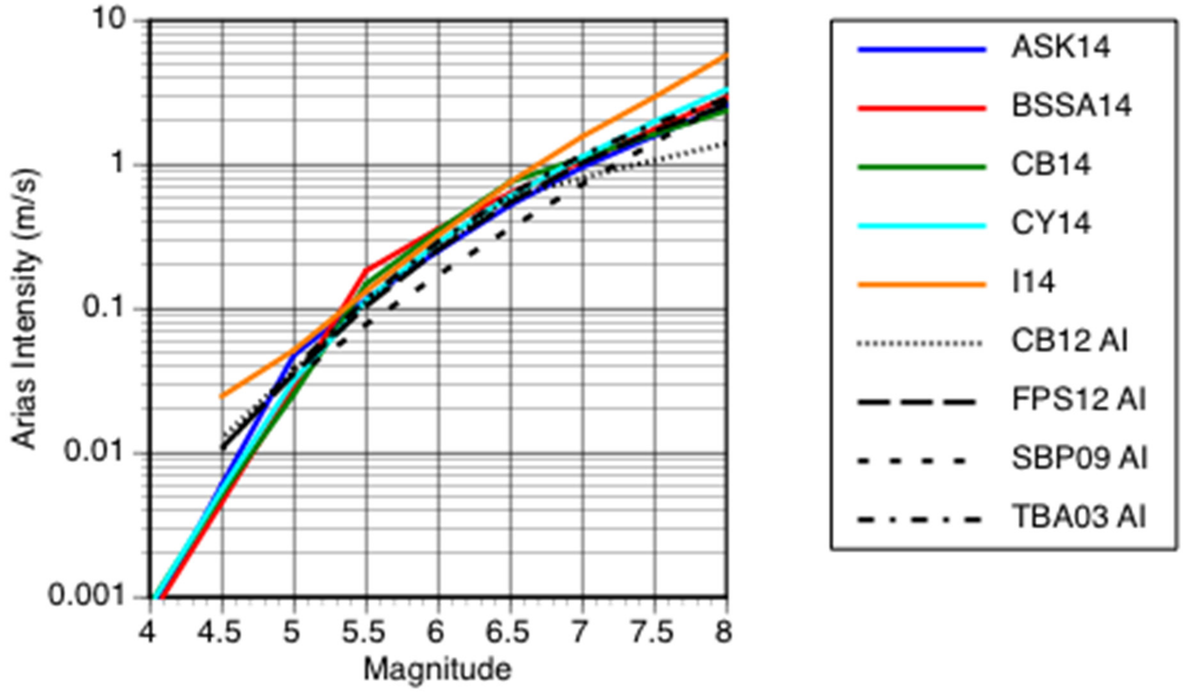


Figure 4.2 **Comparison of the magnitude scaling of the median I_a models for strike-slip faults for a rupture distance of 10 km and V_{S30} = 520 m/sec (TBA03 class C, SBP09 class B).**

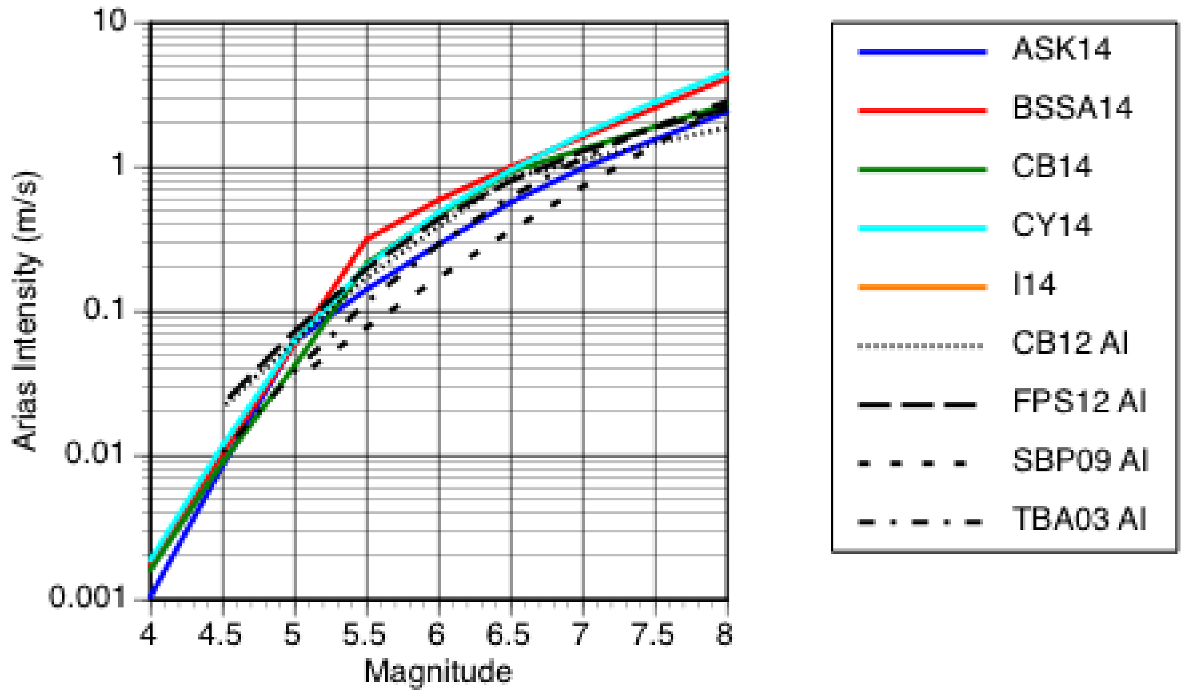


Figure 4.3 **Comparison of the magnitude scaling of the median I_a models for strike-slip faults for a rupture distance of 10 km and V_{S30}=270 m/sec (TBA03 class D, SBP09 class D).**

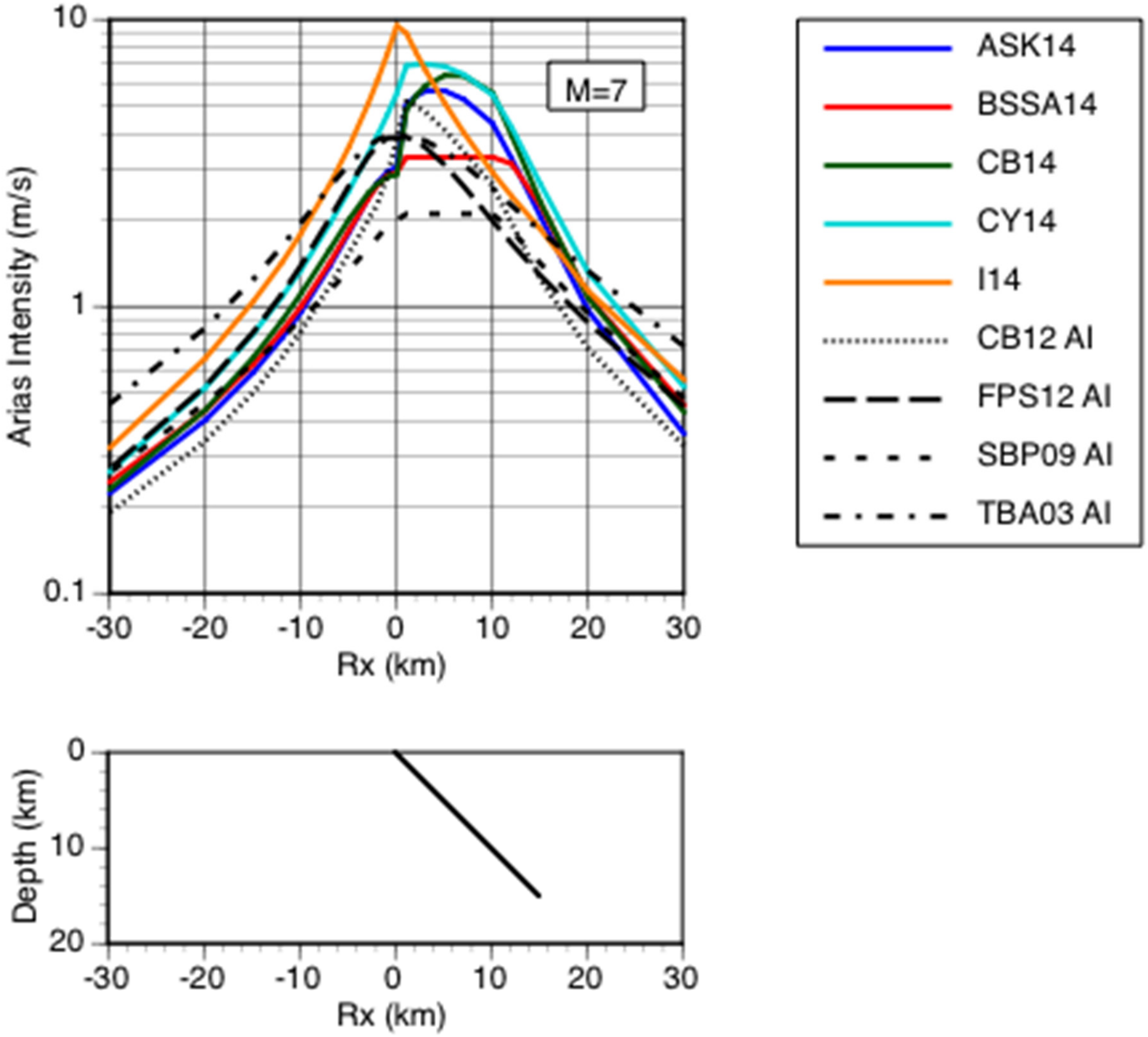


Figure 4.4 Comparison of the median I_a for dipping faults for M = 7 and V_{S30} = 520 m/sec (TBA03 class D, SBP09 class D).

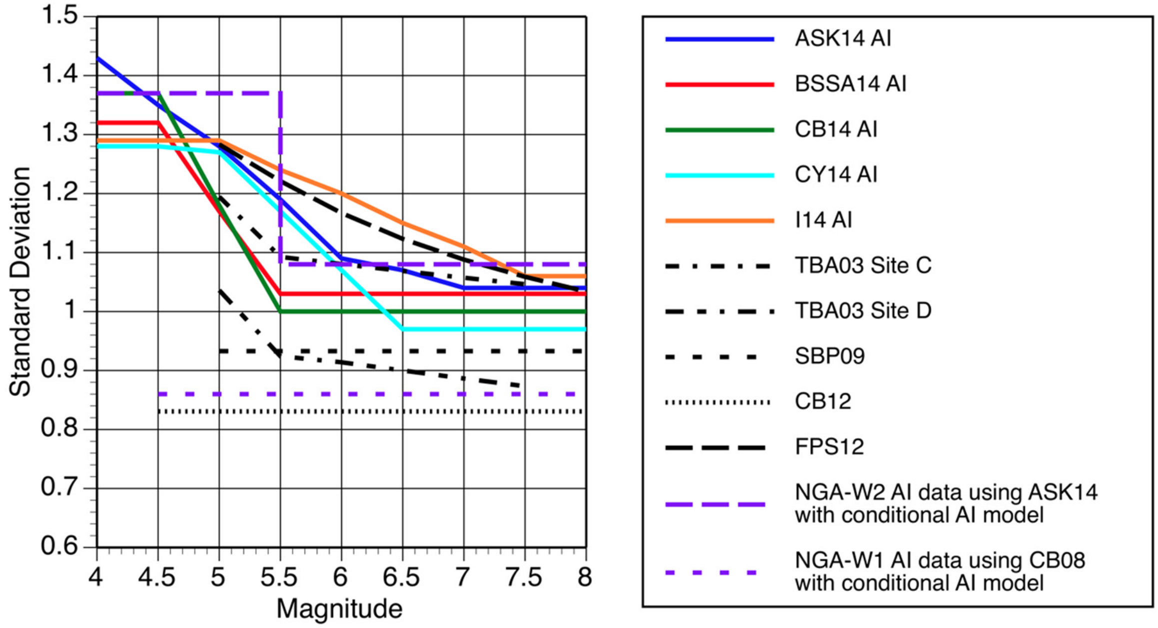


Figure 4.5 **Comparison of the standard deviations for the I_a models based on the NGA West2 GMPEs using Equation (4.4) with the standard deviations from previously published I_a models. Also shown are the standard deviation estimated from the NGA-West2 data within 80 km using the ASK14 I_a model and the standard deviation estimated from the NGA-West1 data used by CB12 with the Campbell and Bozorgnia [2008] GMPE (CB08).**

5 Conclusions

It is common to develop estimates of the I_a in addition to the PSA values for defining the design ground motion. If the I_a is estimated using an I_a GMPE based on a simple functional form but the PSA is estimated using GMPEs that considers more complex effects, such as hanging-wall effects and nonlinear site effects, then there may be inconsistencies between the estimated I_a value and the estimated PSA. This inconsistency can be avoided by using conditional I_a models combined with the GMPEs for PGA and SA_{T1}. A key advantage of the approach used in this paper is that the extrapolation and more complex scaling in the GMPEs can be captured in the I_a model. Also, because the conditional I_a model has a small standard deviation, it is more robust than traditional I_a models, leading to a suite of I_a models that have a much smaller range of median I_a than the traditional models. The derived models have a larger standard deviation than many of the previous models, which we attribute to dataset differences.

The conditional I_a model [Equation (3.3)] can be used directly (without the NGA-West2 GMPEs) to develop design I_a values that are consistent with the design spectrum by using the PGA and SA_{T1} of the design spectrum as inputs to the conditional I_a model. The full I_a model [Equations (4.1) and (4.4)] combines the conditional I_a with a PSA GMPE-producing I_a models that include complex features of the PSA GMPE, such as hanging-wall effects, nonlinear site effects, directivity effects, magnitude, and/or distance dependent standard deviations. This paper combined the conditional I_a model with the five NGA-West2 GMPEs, but the conditional I_a model, with its small variability and simple form, can be combined with other crustal GMPEs. In addition, as new PSA GMPEs are developed in the future, the conditional I_a model developed herein can be combined with new PSA GMPEs to rapidly develop new I_a GMPEs consistent with new PSA GMPEs because the standard deviation of the conditional I_a model is very small relative to the other aleatory terms in GMPEs.

6 References

Abrahamson N.A., Youngs R. (1992). A stable algorithm for regression analyses using the random effects model," *Bull. Seism. Soc. Am.*, 82: 505–510.

Abrahamson N.A., Silva W.J., Kamai R. (2014). Summary of the ASK14 ground-motion relation for active crustal regions, *Earthq. Spectra*, 30: 1025–1055.

Ancheta T.D., Darragh R.B., Stewart J.P., Seyhan E., Silva W. J., Chiou B.S.-J., Wooddell K.E., Graves R.W., Kottke A.R., Boore D.M., Kishida T., Donahue J.L. (2014). NGA-West2 database, *Earthq. Spectra*, 30: 989–1005.

Arias A. (1970). A measure of earthquake intensity. In: *Seismic Design for Nuclear Power Plants*, R.J. Hansen (ed.). MIT Press: Cambridge, MA; pp. 438–483.

Baker J.W., Jayaram N. (2008). Correlation of spectral acceleration values from NGA ground motion models, *Earthq. Spectra*, 24: 299–317.

Bevington P.R., Robinson D.K. (1969). *Data Reduction and Error Analysis for the Physical Sciences* (Vol. 336). New York: McGraw-Hill.

Boore D.M., Stewart J.P., Seyhan E., Atkinson G.M. (2014). NGA-West 2 equations for predicting PGA, PGV, and 5%-Damped PSA for shallow crustal earthquakes, *Earthq. Spectra*, 30: 1057–1085.

Campbell K.W., Bozorgnia Y. (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, *Earthq. Spectra,* 24: 139–171.

Campbell K.W., Bozorgnia Y. (2012). A comparison of ground motion prediction equations for Arias intensity and cumulative absolute velocity developed using a consistent database and functional form, *Earthq. Spectra*, 28: 931–941.

Campbell K.W., Bozorgnia Y. (2014). NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5%-damped linear acceleration response spectra, *Earthq. Spectra*, 30: 1087–1115

Carlton B., Abrahamson N.A. (2014). Issues and approaches for implementing conditional mean spectra in practice, *Bull. Seismol. Soc. Am*., 104: 503–512.

Chiou B.S.-J., Youngs R.R. (2014). Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra, *Earthq. Spectra*, 30: 1117–1153.

Foulser-Piggott R., Stafford P.J. (2012). A predictive model for Arias intensity at multiple sites and consideration of spatial correlations, *Earthq. Eng. Struct. Dyn.*, 41: 431–451.

Geopentech (2015). *Southwestern United States Ground Motion Characterization SSHAC Level 3 – Technical Report Rev 2.*

Idriss I. M. (2014). An NGA-West2 empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes, *Earthq. Spectra*, 30: 1155–1177.

Stafford P.J., Berrill J.B., Pettinga J.R. (2009). New predictive equations for Arias intensity from crustal earthquakes in New Zealand, *J. Seismol*., 13: 31–52.

Travasarou T., Bray J.D., Abrahamson, N.A. (2003). Empirical attenuation relationship for Arias intensity, *Earthq. Eng. Struct. Dyn.*, 32: 1133–1155.

Watson-Lamprey J.A., Abrahamson N.A. (2006). Selection of ground motion time series and limits on scaling, *Soil Dyn. Earthq. Eng.*, 26: 477–482.

PEER REPORTS

PEER reports are available as a free PDF download from http://peer.berkeley.edu/publications/peer_reports_complete.html. Printed hard copies of PEER reports can be ordered directly from our printer by following the instructions at http://peer.berkeley.edu/publications/peer_reports.html. For other related questions about the PEER Report Series, contact the Pacific Earthquake Engineering Research Center, 325 Davis Hall Mail Code 1792, Berkeley, CA 94720. Tel.: (510) 642-3437; Fax: (510) 642-1655; Email: clairejohnson@berkeley.edu.

PEER 2016/05 *Ground-Motion Prediction Equations for Arias Intensity Consistent with the NGA-West2 Ground-Motion Models.* Charlotte Abrahamson, Hao-Jun Michael Shi, and Brian Yang. July 2016.

PEER 2016/04 *The M_W 6.0 South Napa Earthquake of August 24, 2014: A Wake-Up Call for Renewed Investment in Seismic Resilience Across California.* Prepared for the California Seismic Safety Commission, Laurie A. Johnson and Stephen A. Mahin. June 2016.

PEER 2016/03 *Simulation Confidence in Tsunami-Driven Overland Flow.* Patrick Lynett. May 2016.

PEER 2016/02 *Semi-Automated Procedure for Windowing time Series and Computing Fourier Amplitude Spectra for the NGA-West2 Database.* Tadahiro Kishida, Olga-Joan Ktenidou, Robert B. Darragh, and Walter J. Silva. May 2016.

PEER 2016/01 *A Methodology for the Estimation of Kappa (κ) from Large Datasets: Example Application to Rock Sites in the NGA-East Database and Implications on Design Motions.* Olga-Joan Ktenidou, Norman A. Abrahamson, Robert B. Darragh, and Walter J. Silva. April 2016.

PEER 2015/13 *Self-Centering Precast Concrete Dual-Steel-Shell Columns for Accelerated Bridge Construction: Seismic Performance, Analysis, and Design*. Gabriele Guerrini, José I. Restrepo, Athanassios Vervelidis, and Milena Massari. December 2015.

PEER 2015/12 *Shear-Flexure Interaction Modeling for Reinforced Concrete Structural Walls and Columns under Reversed Cyclic Loading*. Kristijan Kolozvari, Kutay Orakcal, and John Wallace. December 2015.

PEER 2015/11 *Selection and Scaling of Ground Motions for Nonlinear Response History Analysis of Buildings in Performance-Based Earthquake Engineering*. N. Simon Kwong and Anil K. Chopra. December 2015.

PEER 2015/10 *Structural Behavior of Column-Bent Cap Beam-Box Girder Systems in Reinforced Concrete Bridges Subjected to Gravity and Seismic Loads. Part II: Hybrid Simulation and Post-Test Analysis*. Mohamed A. Moustafa and Khalid M. Mosalam. November 2015.

PEER 2015/09 *Structural Behavior of Column-Bent Cap Beam-Box Girder Systems in Reinforced Concrete Bridges Subjected to Gravity and Seismic Loads. Part I: Pre-Test Analysis and Quasi-Static Experiments*. Mohamed A. Moustafa and Khalid M. Mosalam. September 2015.

PEER 2015/08 *NGA-East: Adjustments to Median Ground-Motion Models for Center and Eastern North America*. August 2015.

PEER 2015/07 *NGA-East: Ground-Motion Standard-Deviation Models for Central and Eastern North America*. Linda Al Atik. June 2015.

PEER 2015/06 *Adjusting Ground-Motion Intensity Measures to a Reference Site for which V_{S30} = 3000 m/sec*. David M. Boore. May 2015.

PEER 2015/05 *Hybrid Simulation of Seismic Isolation Systems Applied to an APR-1400 Nuclear Power Plant.* Andreas H. Schellenberg, Alireza Sarebanha, Matthew J. Schoettler, Gilberto Mosqueda, Gianmario Benzoni, and Stephen A. Mahin. April 2015.

PEER 2015/04 *NGA-East: Median Ground-Motion Models for the Central and Eastern North America Region*. April 2015.

PEER 2015/03 *Single Series Solution for the Rectangular Fiber-Reinforced Elastomeric Isolator Compression Modulus*. James M. Kelly and Niel C. Van Engelen. March 2015.

PEER 2015/02 *A Full-Scale, Single-Column Bridge Bent Tested by Shake-Table Excitation.* Matthew J. Schoettler, José I. Restrepo, Gabriele Guerrini, David E. Duck, and Francesco Carrea. March 2015.

PEER 2015/01 *Concrete Column Blind Prediction Contest 2010: Outcomes and Observations.* Vesna Terzic, Matthew J. Schoettler, José I. Restrepo, and Stephen A Mahin. March 2015.

PEER 2014/20 *Stochastic Modeling and Simulation of Near-Fault Ground Motions for Performance-Based Earthquake Engineering*. Mayssa Dabaghi and Armen Der Kiureghian. December 2014.

PEER 2014/19 *Seismic Response of a Hybrid Fiber-Reinforced Concrete Bridge Column Detailed for Accelerated Bridge Construction*. Wilson Nguyen, William Trono, Marios Panagiotou, and Claudia P. Ostertag. December 2014.

PEER 2014/18 *Three-Dimensional Beam-Truss Model for Reinforced Concrete Walls and Slabs Subjected to Cyclic Static or Dynamic Loading*. Yuan Lu, Marios Panagiotou, and Ioannis Koutromanos. December 2014.

PEER 2014/17 *PEER NGA-East Database.* Christine A. Goulet, Tadahiro Kishida, Timothy D. Ancheta, Chris H. Cramer, Robert B. Darragh, Walter J. Silva, Youssef M.A. Hashash, Joseph Harmon, Jonathan P. Stewart, Katie E. Wooddell, and Robert R. Youngs. October 2014.

PEER 2014/16 *Guidelines for Performing Hazard-Consistent One-Dimensional Ground Response Analysis for Ground Motion Prediction*. Jonathan P. Stewart, Kioumars Afshari, and Youssef M.A. Hashash. October 2014.

PEER 2014/15 *NGA-East Regionalization Report: Comparison of Four Crustal Regions within Central and Eastern North America using Waveform Modeling and 5%-Damped Pseudo-Spectral Acceleration Response*. Jennifer Dreiling, Marius P. Isken, Walter D. Mooney, Martin C. Chapman, and Richard W. Godbee. October 2014.

PEER 2014/14 *Scaling Relations between Seismic Moment and Rupture Area of Earthquakes in Stable Continental Regions*. Paul Somerville. August 2014.

PEER 2014/13 *PEER Preliminary Notes and Observations on the August 24, 2014, South Napa Earthquake*. Grace S. Kang and Stephen A. Mahin, Editors. September 2014.

PEER 2014/12 *Reference-Rock Site Conditions for Central and Eastern North America: Part II – Attenuation (Kappa) Definition*. Kenneth W. Campbell, Youssef M.A. Hashash, Byungmin Kim, Albert R. Kottke, Ellen M. Rathje, Walter J. Silva, and Jonathan P. Stewart. August 2014.

PEER 2014/11 *Reference-Rock Site Conditions for Central and Eastern North America: Part I - Velocity Definition*. Youssef M.A. Hashash, Albert R. Kottke, Jonathan P. Stewart, Kenneth W. Campbell, Byungmin Kim, Ellen M. Rathje, Walter J. Silva, Sissy Nikolaou, and Cheryl Moss. August 2014.

PEER 2014/10 *Evaluation of Collapse and Non-Collapse of Parallel Bridges Affected by Liquefaction and Lateral Spreading*. Benjamin Turner, Scott J. Brandenberg, and Jonathan P. Stewart. August 2014.

PEER 2014/09 *PEER Arizona Strong-Motion Database and GMPEs Evaluation*. Tadahiro Kishida, Robert E. Kayen, Olga-Joan Ktenidou, Walter J. Silva, Robert B. Darragh, and Jennie Watson-Lamprey. June 2014.

PEER 2014/08 *Unbonded Pretensioned Bridge Columns with Rocking Detail*. Jeffrey A. Schaefer, Bryan Kennedy, Marc O. Eberhard, and John F. Stanton. June 2014.

PEER 2014/07 *Northridge 20 Symposium Summary Report: Impacts, Outcomes, and Next Steps*. May 2014.

PEER 2014/06 *Report of the Tenth Planning Meeting of NEES/E-Defense Collaborative Research on Earthquake Engineering*. December 2013.

PEER 2014/05 *Seismic Velocity Site Characterization of Thirty-One Chilean Seismometer Stations by Spectral Analysis of Surface Wave Dispersion*. Robert Kayen, Brad D. Carkin, Skye Corbet, Camilo Pinilla, Allan Ng, Edward Gorbis, and Christine Truong. April 2014.

PEER 2014/04 Effect of Vertical Acceleration on Shear Strength of Reinforced Concrete Columns. Hyerin Lee and Khalid M. Mosalam. April 2014.

PEER 2014/03 *Retest of Thirty-Year-Old Neoprene Isolation Bearings.* James M. Kelly and Niel C. Van Engelen. March 2014.

PEER 2014/02 *Theoretical Development of Hybrid Simulation Applied to Plate Structures.* Ahmed A. Bakhaty, Khalid M. Mosalam, and Sanjay Govindjee. January 2014.

PEER 2014/01 *Performance-Based Seismic Assessment of Skewed Bridges.* Peyman Kaviani, Farzin Zareian, and Ertugrul Taciroglu. January 2014.

PEER 2013/26 *Urban Earthquake Engineerin*g. Proceedings of the U.S.-Iran Seismic Workshop. December 2013.

PEER 2013/25 *Earthquake Engineering for Resilient Communities: 2013 PEER Internship Program Research Report Collection.* Heidi Tremayne (Editor), Stephen A. Mahin (Editor), Jorge Archbold Monterossa, Matt Brosman, Shelly Dean, Katherine deLaveaga, Curtis Fong, Donovan Holder, Rakeeb Khan, Elizabeth Jachens, David Lam, Daniela Martinez Lopez, Mara Minner, Geffen Oren, Julia Pavicic, Melissa Quinonez, Lorena Rodriguez, Sean Salazar, Kelli Slaven, Vivian Steyert, Jenny Taing, and Salvador Tena. December 2013.

PEER 2013/24 *NGA-West2 Ground Motion Prediction Equations for Vertical Ground Motions*. September 2013.

PEER 2013/23 *Coordinated Planning and Preparedness for Fire Following Major Earthquakes*. Charles Scawthorn. November 2013.

PEER 2013/22 *GEM-PEER Task 3 Project: Selection of a Global Set of Ground Motion Prediction Equations.* Jonathan P. Stewart, John Douglas, Mohammad B. Javanbarg, Carola Di Alessandro, Yousef Bozorgnia, Norman A. Abrahamson, David M. Boore, Kenneth W. Campbell, Elise Delavaud, Mustafa Erdik, and Peter J. Stafford. December 2013.

PEER 2013/21 *Seismic Design and Performance of Bridges with Columns on Rocking Foundations*. Grigorios Antonellis and Marios Panagiotou. September 2013.

PEER 2013/20 *Experimental and Analytical Studies on the Seismic Behavior of Conventional and Hybrid Braced Frames*. Jiun-Wei Lai and Stephen A. Mahin. September 2013.

PEER 2013/19 *Toward Resilient Communities: A Performance-Based Engineering Framework for Design and Evaluation of the Built Environment.* Michael William Mieler, Bozidar Stojadinovic, Robert J. Budnitz, Stephen A. Mahin, and Mary C. Comerio. September 2013.

PEER 2013/18 *Identification of Site Parameters that Improve Predictions of Site Amplification*. Ellen M. Rathje and Sara Navidi. July 2013.

PEER 2013/17 *Response Spectrum Analysis of Concrete Gravity Dams Including Dam-Water-Foundation Interaction*. Arnkjell Løkke and Anil K. Chopra. July 2013.

PEER 2013/16 *Effect of Hoop Reinforcement Spacing on the Cyclic Response of Large Reinforced Concrete Special Moment Frame Beams.* Marios Panagiotou, Tea Visnjic, Grigorios Antonellis, Panagiotis Galanis, and Jack P. Moehle. June 2013.

PEER 2013/15 *A Probabilistic Framework to Include the Effects of Near-Fault Directivity in Seismic Hazard Assessment*. Shrey Kumar Shahi, Jack W. Baker. October 2013.

PEER 2013/14 *Hanging-Wall Scaling using Finite-Fault Simulations.* Jennifer L. Donahue and Norman A. Abrahamson. September 2013.

PEER 2013/13 *Semi-Empirical Nonlinear Site Amplification and its Application in NEHRP Site Factors*. Jonathan P. Stewart and Emel Seyhan. November 2013.

PEER 2013/12 *Nonlinear Horizontal Site Response for the NGA-West2 Project.* Ronnie Kamai, Norman A. Abramson, Walter J. Silva. May 2013.

PEER 2013/11 *Epistemic Uncertainty for NGA-West2 Models.* Linda Al Atik and Robert R. Youngs. May 2013.

PEER 2013/10 *NGA-West 2 Models for Ground-Motion Directionality.* Shrey K. Shahi and Jack W. Baker. May 2013.

PEER 2013/09 *Final Report of the NGA-West2 Directivity Working Group.* Paul Spudich, Jeffrey R. Bayless, Jack W. Baker, Brian S.J. Chiou, Badie Rowshandel, Shrey Shahi, and Paul Somerville. May 2013.

PEER 2013/08 *NGA-West2 Model for Estimating Average Horizontal Values of Pseudo-Absolute Spectral Accelerations Generated by Crustal Earthquakes*. I. M. Idriss. May 2013.

PEER 2013/07 *Update of the Chiou and Youngs NGA Ground Motion Model for Average Horizontal Component of Peak Ground Motion and Response Spectra*. Brian Chiou and Robert Youngs. May 2013.

PEER 2013/06 *NGA-West2 Campbell-Bozorgnia Ground Motion Model for the Horizontal Components of PGA, PGV, and 5%-Damped Elastic Pseudo-Acceleration Response Spectra for Periods Ranging from 0.01 to 10 sec.* Kenneth W. Campbell and Yousef Bozorgnia. May 2013.

PEER 2013/05 *NGA-West 2 Equations for Predicting Response Spectral Accelerations for Shallow Crustal Earthquakes*. David M. Boore, Jonathan P. Stewart, Emel Seyhan, and Gail M. Atkinson. May 2013.

PEER 2013/04 *Update of the AS08 Ground-Motion Prediction Equations Based on the NGA-West2 Data Set*. Norman Abrahamson, Walter Silva, and Ronnie Kamai. May 2013.

PEER 2013/03 *PEER NGA-West2 Database.* Timothy D. Ancheta, Robert B. Darragh, Jonathan P. Stewart, Emel Seyhan, Walter J. Silva, Brian S.J. Chiou, Katie E. Wooddell, Robert W. Graves, Albert R. Kottke, David M. Boore, Tadahiro Kishida, and Jennifer L. Donahue. May 2013.

PEER 2013/02 *Hybrid Simulation of the Seismic Response of Squat Reinforced Concrete Shear Walls*. Catherine A. Whyte and Bozidar Stojadinovic. May 2013.

PEER 2013/01 *Housing Recovery in Chile: A Qualitative Mid-program Review*. Mary C. Comerio. February 2013.

PEER 2012/08 *Guidelines for Estimation of Shear Wave Velocity.* Bernard R. Wair, Jason T. DeJong, and Thomas Shantz. December 2012.

PEER 2012/07 *Earthquake Engineering for Resilient Communities: 2012 PEER Internship Program Research Report Collection.* Heidi Tremayne (Editor), Stephen A. Mahin (Editor), Collin Anderson, Dustin Cook, Michael Erceg, Carlos Esparza, Jose Jimenez, Dorian Krausz, Andrew Lo, Stephanie Lopez, Nicole McCurdy, Paul Shipman, Alexander Strum, Eduardo Vega. December 2012.

PEER 2012/06 *Fragilities for Precarious Rocks at Yucca Mountain.* Matthew D. Purvance, Rasool Anooshehpoor, and James N. Brune. December 2012.

PEER 2012/05 *Development of Simplified Analysis Procedure for Piles in Laterally Spreading Layered Soils.* Christopher R. McGann, Pedro Arduino, and Peter Mackenzie–Helnwein. December 2012.

PEER 2012/04 *Unbonded Pre-Tensioned Columns for Bridges in Seismic Regions.* Phillip M. Davis, Todd M. Janes, Marc O. Eberhard, and John F. Stanton. December 2012.

PEER 2012/03 *Experimental and Analytical Studies on Reinforced Concrete Buildings with Seismically Vulnerable Beam-Column Joints*. Sangjoon Park and Khalid M. Mosalam. October 2012.

PEER 2012/02 *Seismic Performance of Reinforced Concrete Bridges Allowed to Uplift during Multi-Directional Excitation*. Andres Oscar Espinoza and Stephen A. Mahin. July 2012.

PEER 2012/01 *Spectral Damping Scaling Factors for Shallow Crustal Earthquakes in Active Tectonic Regions.* Sanaz Rezaeian, Yousef Bozorgnia, I. M. Idriss, Kenneth Campbell, Norman Abrahamson, and Walter Silva. July 2012.

PEER 2011/10 *Earthquake Engineering for Resilient Communities: 2011 PEER Internship Program Research Report Collection*. Heidi Faison and Stephen A. Mahin, Editors. December 2011.

PEER 2011/09 *Calibration of Semi-Stochastic Procedure for Simulating High-Frequency Ground Motions*. Jonathan P. Stewart, Emel Seyhan, and Robert W. Graves. December 2011.

PEER 2011/08 *Water Supply in regard to Fire Following Earthquake*. Charles Scawthorn. November 2011.

PEER 2011/07 *Seismic Risk Management in Urban Areas*. Proceedings of a U.S.-Iran-Turkey Seismic Workshop. September 2011.

PEER 2011/06 *The Use of Base Isolation Systems to Achieve Complex Seismic Performance Objectives*. Troy A. Morgan and Stephen A. Mahin. July 2011.

PEER 2011/05 *Case Studies of the Seismic Performance of Tall Buildings Designed by Alternative Means.* Task 12 Report for the Tall Buildings Initiative. Jack Moehle, Yousef Bozorgnia, Nirmal Jayaram, Pierson Jones, Mohsen Rahnama, Nilesh Shome, Zeynep Tuna, John Wallace, Tony Yang, and Farzin Zareian. July 2011.

PEER 2011/04 *Recommended Design Practice for Pile Foundations in Laterally Spreading Ground.* Scott A. Ashford, Ross W. Boulanger, and Scott J. Brandenberg. June 2011.

PEER 2011/03 *New Ground Motion Selection Procedures and Selected Motions for the PEER Transportation Research Program*. Jack W. Baker, Ting Lin, Shrey K. Shahi, and Nirmal Jayaram. March 2011.

PEER 2011/02 *A Bayesian Network Methodology for Infrastructure Seismic Risk Assessment and Decision Support*. Michelle T. Bensi, Armen Der Kiureghian, and Daniel Straub. March 2011.

PEER 2011/01 *Demand Fragility Surfaces for Bridges in Liquefied and Laterally Spreading Ground.* Scott J. Brandenberg, Jian Zhang, Pirooz Kashighandi, Yili Huo, and Minxing Zhao. March 2011.

PEER 2010/05 *Guidelines for Performance-Based Seismic Design of Tall Buildings.* Developed by the Tall Buildings Initiative. November 2010.

PEER 2010/04 *Application Guide for the Design of Flexible and Rigid Bus Connections between Substation Equipment Subjected to Earthquakes.* Jean-Bernard Dastous and Armen Der Kiureghian. September 2010.

PEER 2010/03 *Shear Wave Velocity as a Statistical Function of Standard Penetration Test Resistance and Vertical Effective Stress at Caltrans Bridge Sites.* Scott J. Brandenberg, Naresh Bellana, and Thomas Shantz. June 2010.

PEER 2010/02 *Stochastic Modeling and Simulation of Ground Motions for Performance-Based Earthquake Engineering.* Sanaz Rezaeian and Armen Der Kiureghian. June 2010.

PEER 2010/01 *Structural Response and Cost Characterization of Bridge Construction Using Seismic Performance Enhancement Strategies.* Ady Aviram, Božidar Stojadinović, Gustavo J. Parra-Montesinos, and Kevin R. Mackie. March 2010.

PEER 2009/03 *The Integration of Experimental and Simulation Data in the Study of Reinforced Concrete Bridge Systems Including Soil-Foundation-Structure Interaction.* Matthew Dryden and Gregory L. Fenves. November 2009.

PEER 2009/02 *Improving Earthquake Mitigation through Innovations and Applications in Seismic Science, Engineering, Communication, and Response*. Proceedings of a U.S.-Iran Seismic Workshop. October 2009.

PEER 2009/01 *Evaluation of Ground Motion Selection and Modification Methods: Predicting Median Interstory Drift Response of Buildings*. Curt B. Haselton, Editor. June 2009.

PEER 2008/10 *Technical Manual for Strata.* Albert R. Kottke and Ellen M. Rathje. February 2009.

PEER 2008/09 *NGA Model for Average Horizontal Component of Peak Ground Motion and Response Spectra.* Brian S.-J. Chiou and Robert R. Youngs. November 2008.

PEER 2008/08 *Toward Earthquake-Resistant Design of Concentrically Braced Steel Structures*. Patxi Uriz and Stephen A. Mahin. November 2008.

PEER 2008/07 *Using OpenSees for Performance-Based Evaluation of Bridges on Liquefiable Soils*. Stephen L. Kramer, Pedro Arduino, and HyungSuk Shin. November 2008.

PEER 2008/06 *Shaking Table Tests and Numerical Investigation of Self-Centering Reinforced Concrete Bridge Columns*. Hyung IL Jeong, Junichi Sakai, and Stephen A. Mahin. September 2008.

PEER 2008/05 *Performance-Based Earthquake Engineering Design Evaluation Procedure for Bridge Foundations Undergoing Liquefaction-Induced Lateral Ground Displacement*. Christian A. Ledezma and Jonathan D. Bray. August 2008.

PEER 2008/04 *Benchmarking of Nonlinear Geotechnical Ground Response Analysis Procedures.* Jonathan P. Stewart, Annie On-Lei Kwok, Yousseff M. A. Hashash, Neven Matasovic, Robert Pyke, Zhiliang Wang, and Zhaohui Yang. August 2008.

PEER 2008/03 *Guidelines for Nonlinear Analysis of Bridge Structures in California.* Ady Aviram, Kevin R. Mackie, and Božidar Stojadinović. August 2008.

PEER 2008/02 *Treatment of Uncertainties in Seismic-Risk Analysis of Transportation Systems*. Evangelos Stergiou and Anne S. Kiremidjian. July 2008.

PEER 2008/01 *Seismic Performance Objectives for Tall Buildings.* William T. Holmes, Charles Kircher, William Petak, and Nabih Youssef. August 2008.

PEER 2007/12 *An Assessment to Benchmark the Seismic Performance of a Code-Conforming Reinforced Concrete Moment-Frame Building.* Curt Haselton, Christine A. Goulet, Judith Mitrani-Reiser, James L. Beck, Gregory G. Deierlein, Keith A. Porter, Jonathan P. Stewart, and Ertugrul Taciroglu. August 2008.

PEER 2007/11 *Bar Buckling in Reinforced Concrete Bridge Columns.* Wayne A. Brown, Dawn E. Lehman, and John F. Stanton. February 2008.

PEER 2007/10 *Computational Modeling of Progressive Collapse in Reinforced Concrete Frame Structures*. Mohamed M. Talaat and Khalid M. Mosalam. May 2008.

PEER 2007/09 *Integrated Probabilistic Performance-Based Evaluation of Benchmark Reinforced Concrete Bridges*. Kevin R. Mackie, John-Michael Wong, and Božidar Stojadinović. January 2008.

PEER 2007/08 *Assessing Seismic Collapse Safety of Modern Reinforced Concrete Moment-Frame Buildings*. Curt B. Haselton and Gregory G. Deierlein. February 2008.

PEER 2007/07 *Performance Modeling Strategies for Modern Reinforced Concrete Bridge Columns*. Michael P. Berry and Marc O. Eberhard. April 2008.

PEER 2007/06 *Development of Improved Procedures for Seismic Design of Buried and Partially Buried Structures*. Linda Al Atik and Nicholas Sitar. June 2007.

PEER 2007/05 *Uncertainty and Correlation in Seismic Risk Assessment of Transportation Systems*. Renee G. Lee and Anne S. Kiremidjian. July 2007.

PEER 2007/04 *Numerical Models for Analysis and Performance-Based Design of Shallow Foundations Subjected to Seismic Loading.* Sivapalan Gajan, Tara C. Hutchinson, Bruce L. Kutter, Prishati Raychowdhury, José A. Ugalde, and Jonathan P. Stewart. May 2008.

PEER 2007/03 *Beam-Column Element Model Calibrated for Predicting Flexural Response Leading to Global Collapse of RC Frame Buildings*. Curt B. Haselton, Abbie B. Liel, Sarah Taylor Lange, and Gregory G. Deierlein. May 2008.

PEER 2007/02 *Campbell-Bozorgnia NGA Ground Motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameters*. Kenneth W. Campbell and Yousef Bozorgnia. May 2007.

PEER 2007/01 *Boore-Atkinson NGA Ground Motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameters*. David M. Boore and Gail M. Atkinson. May 2007.

PEER 2006/12 Societal Implications of Performance-Based Earthquake Engineering. Peter J. May. May 2007.

PEER 2006/11 *Probabilistic Seismic Demand Analysis Using Advanced Ground Motion Intensity Measures, Attenuation Relationships, and Near-Fault Effects*. Polsak Tothong and C. Allin Cornell. March 2007.

PEER 2006/10 *Application of the PEER PBEE Methodology to the I-880 Viaduct*. Sashi Kunnath. February 2007.

PEER 2006/09 *Quantifying Economic Losses from Travel Forgone Following a Large Metropolitan Earthquake*. James Moore, Sungbin Cho, Yue Yue Fan, and Stuart Werner. November 2006.

PEER 2006/08 *Vector-Valued Ground Motion Intensity Measures for Probabilistic Seismic Demand Analysis*. Jack W. Baker and C. Allin Cornell. October 2006.

PEER 2006/07 *Analytical Modeling of Reinforced Concrete Walls for Predicting Flexural and Coupled–Shear-Flexural Responses*. Kutay Orakcal, Leonardo M. Massone, and John W. Wallace. October 2006.

PEER 2006/06 *Nonlinear Analysis of a Soil-Drilled Pier System under Static and Dynamic Axial Loading.* Gang Wang and Nicholas Sitar. November 2006.

PEER 2006/05 *Advanced Seismic Assessment Guidelines.* Paolo Bazzurro, C. Allin Cornell, Charles Menun, Maziar Motahari, and Nicolas Luco. September 2006.

PEER 2006/04 *Probabilistic Seismic Evaluation of Reinforced Concrete Structural Components and Systems*. Tae Hyung Lee and Khalid M. Mosalam. August 2006.

PEER 2006/03 *Performance of Lifelines Subjected to Lateral Spreading.* Scott A. Ashford and Teerawut Juirnarongrit. July 2006.

PEER 2006/02 *Pacific Earthquake Engineering Research Center Highway Demonstration Project.* Anne Kiremidjian, James Moore, Yue Yue Fan, Nesrin Basoz, Ozgur Yazali, and Meredith Williams. April 2006.

PEER 2006/01 *Bracing Berkeley. A Guide to Seismic Safety on the UC Berkeley Campus.* Mary C. Comerio, Stephen Tobriner, and Ariane Fehrenkamp. January 2006.

PEER 2005/16 *Seismic Response and Reliability of Electrical Substation Equipment and Systems.* Junho Song, Armen Der Kiureghian, and Jerome L. Sackman. April 2006.

PEER 2005/15 *CPT-Based Probabilistic Assessment of Seismic Soil Liquefaction Initiation.* R. E. S. Moss, R. B. Seed, R. E. Kayen, J. P. Stewart, and A. Der Kiureghian. April 2006.

PEER 2005/14 *Workshop on Modeling of Nonlinear Cyclic Load-Deformation Behavior of Shallow Foundations.* Bruce L. Kutter, Geoffrey Martin, Tara Hutchinson, Chad Harden, Sivapalan Gajan, and Justin Phalen. March 2006.

PEER 2005/13 *Stochastic Characterization and Decision Bases under Time-Dependent Aftershock Risk in Performance-Based Earthquake Engineering*. Gee Liek Yeo and C. Allin Cornell. July 2005.

PEER 2005/12 *PEER Testbed Study on a Laboratory Building: Exercising Seismic Performance Assessment.* Mary C. Comerio, Editor. November 2005.

PEER 2005/11 *Van Nuys Hotel Building Testbed Report: Exercising Seismic Performance Assessment.* Helmut Krawinkler, Editor. October 2005.

PEER 2005/10 *First NEES/E-Defense Workshop on Collapse Simulation of Reinforced Concrete Building Structures.* September 2005.

PEER 2005/09 *Test Applications of Advanced Seismic Assessment Guidelines.* Joe Maffei, Karl Telleen, Danya Mohr, William Holmes, and Yuki Nakayama. August 2006.

PEER 2005/08 *Damage Accumulation in Lightly Confined Reinforced Concrete Bridge Columns.* R. Tyler Ranf, Jared M. Nelson, Zach Price, Marc O. Eberhard, and John F. Stanton. April 2006.

PEER 2005/07 *Experimental and Analytical Studies on the Seismic Response of Freestanding and Anchored Laboratory Equipment.* Dimitrios Konstantinidis and Nicos Makris. January 2005.

PEER 2005/06 *Global Collapse of Frame Structures under Seismic Excitations*. Luis F. Ibarra and Helmut Krawinkler. September 2005.

PEER 2005//05 *Performance Characterization of Bench- and Shelf-Mounted Equipment.* Samit Ray Chaudhuri and Tara C. Hutchinson. May 2006.

PEER 2005/04 *Numerical Modeling of the Nonlinear Cyclic Response of Shallow Foundations.* Chad Harden, Tara Hutchinson, Geoffrey R. Martin, and Bruce L. Kutter. August 2005.

PEER 2005/03 *A Taxonomy of Building Components for Performance-Based Earthquake Engineering.* Keith A. Porter. September 2005.

PEER 2005/02 *Fragility Basis for California Highway Overpass Bridge Seismic Decision Making*. Kevin R. Mackie and Božidar Stojadinović. June 2005.

PEER 2005/01 *Empirical Characterization of Site Conditions on Strong Ground Motion.* Jonathan P. Stewart, Yoojoong Choi, and Robert W. Graves. June 2005.

PEER 2004/09 *Electrical Substation Equipment Interaction: Experimental Rigid Conductor Studies.* Christopher Stearns and André Filiatrault. February 2005.

PEER 2004/08 *Seismic Qualification and Fragility Testing of Line Break 550-kV Disconnect Switches.* Shakhzod M. Takhirov, Gregory L. Fenves, and Eric Fujisaki. January 2005.

PEER 2004/07 *Ground Motions for Earthquake Simulator Qualification of Electrical Substation Equipment.* Shakhzod M. Takhirov, Gregory L. Fenves, Eric Fujisaki, and Don Clyde. January 2005.

PEER 2004/06 *Performance-Based Regulation and Regulatory Regimes.* Peter J. May and Chris Koski. September 2004.

PEER 2004/05 *Performance-Based Seismic Design Concepts and Implementation: Proceedings of an International Workshop.* Peter Fajfar and Helmut Krawinkler, Editors. September 2004.

PEER 2004/04 *Seismic Performance of an Instrumented Tilt-up Wall Building.* James C. Anderson and Vitelmo V. Bertero. July 2004.

PEER 2004/03 *Evaluation and Application of Concrete Tilt-up Assessment Methodologies.* Timothy Graf and James O. Malley. October 2004.

PEER 2004/02 *Analytical Investigations of New Methods for Reducing Residual Displacements of Reinforced Concrete Bridge Columns.* Junichi Sakai and Stephen A. Mahin. August 2004.

PEER 2004/01 *Seismic Performance of Masonry Buildings and Design Implications.* Kerri Anne Taeko Tokoro, James C. Anderson, and Vitelmo V. Bertero. February 2004.

PEER 2003/18 *Performance Models for Flexural Damage in Reinforced Concrete Columns.* Michael Berry and Marc Eberhard. August 2003.

PEER 2003/17 *Predicting Earthquake Damage in Older Reinforced Concrete Beam-Column Joints.* Catherine Pagni and Laura Lowes. October 2004.

PEER 2003/16 *Seismic Demands for Performance-Based Design of Bridges.* Kevin Mackie and Božidar Stojadinović. August 2003.

PEER 2003/15 *Seismic Demands for Nondeteriorating Frame Structures and Their Dependence on Ground Motions.* Ricardo Antonio Medina and Helmut Krawinkler. May 2004.

PEER 2003/14 *Finite Element Reliability and Sensitivity Methods for Performance-Based Earthquake Engineering*. Terje Haukaas and Armen Der Kiureghian. April 2004.

PEER 2003/13 *Effects of Connection Hysteretic Degradation on the Seismic Behavior of Steel Moment-Resisting Frames.* Janise E. Rodgers and Stephen A. Mahin. March 2004.

PEER 2003/12 *Implementation Manual for the Seismic Protection of Laboratory Contents: Format and Case Studies*. William T. Holmes and Mary C. Comerio. October 2003.

PEER 2003/11 *Fifth U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*. February 2004.

PEER 2003/10 *A Beam-Column Joint Model for Simulating the Earthquake Response of Reinforced Concrete Frames.* Laura N. Lowes, Nilanjan Mitra, and Arash Altoontash. February 2004.

PEER 2003/09 *Sequencing Repairs after an Earthquake: An Economic Approach.* Marco Casari and Simon J. Wilkie. April 2004.

PEER 2003/08 *A Technical Framework for Probability-Based Demand and Capacity Factor Design (DCFD) Seismic Formats*. Fatemeh Jalayer and C. Allin Cornell. November 2003.

PEER 2003/07 *Uncertainty Specification and Propagation for Loss Estimation Using FOSM Methods.* Jack W. Baker and C. Allin Cornell. September 2003.

PEER 2003/06 *Performance of Circular Reinforced Concrete Bridge Columns under Bidirectional Earthquake Loading*. Mahmoud M. Hachem, Stephen A. Mahin, and Jack P. Moehle. February 2003.

PEER 2003/05 *Response Assessment for Building-Specific Loss Estimation.* Eduardo Miranda and Shahram Taghavi. September 2003.

PEER 2003/04 *Experimental Assessment of Columns with Short Lap Splices Subjected to Cyclic Loads*. Murat Melek, John W. Wallace, and Joel Conte. April 2003.

PEER 2003/03 *Probabilistic Response Assessment for Building-Specific Loss Estimation*. Eduardo Miranda and Hesameddin Aslani. September 2003.

PEER 2003/02 *Software Framework for Collaborative Development of Nonlinear Dynamic Analysis Program*. Jun Peng and Kincho H. Law. September 2003.

PEER 2003/01 *Shake Table Tests and Analytical Studies on the Gravity Load Collapse of Reinforced Concrete Frames.* Kenneth John Elwood and Jack P. Moehle. November 2003.

PEER 2002/24 *Performance of Beam to Column Bridge Joints Subjected to a Large Velocity Pulse.* Natalie Gibson, André Filiatrault, and Scott A. Ashford. April 2002.

PEER 2002/23 *Effects of Large Velocity Pulses on Reinforced Concrete Bridge Columns.* Greg L. Orozco and Scott A. Ashford. April 2002.

PEER 2002/22 *Characterization of Large Velocity Pulses for Laboratory Testing.* Kenneth E. Cox and Scott A. Ashford. April 2002.

PEER 2002/21 *Fourth U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*. December 2002.

PEER 2002/20 *Barriers to Adoption and Implementation of PBEE Innovations.* Peter J. May. August 2002.

PEER 2002/19 *Economic-Engineered Integrated Models for Earthquakes: Socioeconomic Impacts.* Peter Gordon, James E. Moore II, and Harry W. Richardson. July 2002.

PEER 2002/18 *Assessment of Reinforced Concrete Building Exterior Joints with Substandard Details.* Chris P. Pantelides, Jon Hansen, Justin Nadauld, and Lawrence D. Reaveley. May 2002.

PEER 2002/17 *Structural Characterization and Seismic Response Analysis of a Highway Overcrossing Equipped with Elastomeric Bearings and Fluid Dampers: A Case Study*. Nicos Makris and Jian Zhang. November 2002.

PEER 2002/16 *Estimation of Uncertainty in Geotechnical Properties for Performance-Based Earthquake Engineering*. Allen L. Jones, Steven L. Kramer, and Pedro Arduino. December 2002.

PEER 2002/15 *Seismic Behavior of Bridge Columns Subjected to Various Loading Patterns*. Asadollah Esmaeily-Gh. and Yan Xiao. December 2002.

PEER 2002/14 *Inelastic Seismic Response of Extended Pile Shaft Supported Bridge Structures.* T.C. Hutchinson, R.W. Boulanger, Y.H. Chai, and I.M. Idriss. December 2002.

PEER 2002/13 *Probabilistic Models and Fragility Estimates for Bridge Components and Systems.* Paolo Gardoni, Armen Der Kiureghian, and Khalid M. Mosalam. June 2002.

PEER 2002/12 *Effects of Fault Dip and Slip Rake on Near-Source Ground Motions: Why Chi-Chi Was a Relatively Mild M7.6 Earthquake*. Brad T. Aagaard, John F. Hall, and Thomas H. Heaton. December 2002.

PEER 2002/11 *Analytical and Experimental Study of Fiber-Reinforced Strip Isolators*. James M. Kelly and Shakhzod M. Takhirov. September 2002.

PEER 2002/10 *Centrifuge Modeling of Settlement and Lateral Spreading with Comparisons to Numerical Analyses***.** Sivapalan Gajan and Bruce L. Kutter. January 2003.

PEER 2002/09 *Documentation and Analysis of Field Case Histories of Seismic Compression during the 1994 Northridge, California, Earthquake*. Jonathan P. Stewart, Patrick M. Smith, Daniel H. Whang, and Jonathan D. Bray. October 2002.

PEER 2002/08 *Component Testing, Stability Analysis and Characterization of Buckling-Restrained Unbonded Braces^{TM}*. Cameron Black, Nicos Makris, and Ian Aiken. September 2002.

PEER 2002/07 *Seismic Performance of Pile-Wharf Connections.* Charles W. Roeder, Robert Graff, Jennifer Soderstrom, and Jun Han Yoo. December 2001.

PEER 2002/06 *The Use of Benefit-Cost Analysis for Evaluation of Performance-Based Earthquake Engineering Decisions*. Richard O. Zerbe and Anthony Falit-Baiamonte. September 2001.

PEER 2002/05 *Guidelines, Specifications, and Seismic Performance Characterization of Nonstructural Building Components and Equipment*. André Filiatrault, Constantin Christopoulos, and Christopher Stearns. September 2001.

PEER 2002/04 *Consortium of Organizations for Strong-Motion Observation Systems and the Pacific Earthquake Engineering Research Center Lifelines Program: Invited Workshop on Archiving and Web Dissemination of Geotechnical Data, 4–5 October 2001*. September 2002.

PEER 2002/03 *Investigation of Sensitivity of Building Loss Estimates to Major Uncertain Variables for the Van Nuys Testbed*. Keith A. Porter, James L. Beck, and Rustem V. Shaikhutdinov. August 2002.

PEER 2002/02 *The Third U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*. July 2002.

PEER 2002/01 *Nonstructural Loss Estimation: The UC Berkeley Case Study.* Mary C. Comerio and John C. Stallmeyer. December 2001.

PEER 2001/16 *Statistics of SDF-System Estimate of Roof Displacement for Pushover Analysis of Buildings.* Anil K. Chopra, Rakesh K. Goel, and Chatpan Chintanapakdee. December 2001.

PEER 2001/15 *Damage to Bridges during the 2001 Nisqually Earthquake.* R. Tyler Ranf, Marc O. Eberhard, and Michael P. Berry. November 2001.

PEER 2001/14 *Rocking Response of Equipment Anchored to a Base Foundation.* Nicos Makris and Cameron J. Black. September 2001.

PEER 2001/13 *Modeling Soil Liquefaction Hazards for Performance-Based Earthquake Engineering*. Steven L. Kramer and Ahmed-W. Elgamal. February 2001.

PEER 2001/12 *Development of Geotechnical Capabilities in OpenSees*. Boris Jeremić. September 2001.

PEER 2001/11 *Analytical and Experimental Study of Fiber-Reinforced Elastomeric Isolators*. James M. Kelly and Shakhzod M. Takhirov. September 2001.

PEER 2001/10 *Amplification Factors for Spectral Acceleration in Active Regions.* Jonathan P. Stewart, Andrew H. Liu, Yoojoong Choi, and Mehmet B. Baturay. December 2001.

PEER 2001/09 *Ground Motion Evaluation Procedures for Performance-Based Design.* Jonathan P. Stewart, Shyh-Jeng Chiou, Jonathan D. Bray, Robert W. Graves, Paul G. Somerville, and Norman A. Abrahamson. September 2001.

PEER 2001/08 *Experimental and Computational Evaluation of Reinforced Concrete Bridge Beam-Column Connections for Seismic Performance*. Clay J. Naito, Jack P. Moehle, and Khalid M. Mosalam. November 2001.

PEER 2001/07 *The Rocking Spectrum and the Shortcomings of Design Guidelines.* Nicos Makris and Dimitrios Konstantinidis. August 2001.

PEER 2001/06 *Development of an Electrical Substation Equipment Performance Database for Evaluation of Equipment Fragilities*. Thalia Agnanos. April 1999.

PEER 2001/05 *Stiffness Analysis of Fiber-Reinforced Elastomeric Isolators.* Hsiang-Chuan Tsai and James M. Kelly. May 2001.

PEER 2001/04 *Organizational and Societal Considerations for Performance-Based Earthquake Engineering*. Peter J. May. April 2001.

PEER 2001/03 *A Modal Pushover Analysis Procedure to Estimate Seismic Demands for Buildings: Theory and Preliminary Evaluation*. Anil K. Chopra and Rakesh K. Goel. January 2001.

PEER 2001/02 *Seismic Response Analysis of Highway Overcrossings Including Soil-Structure Interaction*. Jian Zhang and Nicos Makris. March 2001.

PEER 2001/01 *Experimental Study of Large Seismic Steel Beam-to-Column Connections.* Egor P. Popov and Shakhzod M. Takhirov. November 2000.

PEER 2000/10 *The Second U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*. March 2000.

PEER 2000/09 *Structural Engineering Reconnaissance of the August 17, 1999 Earthquake: Kocaeli (Izmit), Turkey.* Halil Sezen, Kenneth J. Elwood, Andrew S. Whittaker, Khalid Mosalam, John J. Wallace, and John F. Stanton. December 2000.

PEER 2000/08 *Behavior of Reinforced Concrete Bridge Columns Having Varying Aspect Ratios and Varying Lengths of Confinement*. Anthony J. Calderone, Dawn E. Lehman, and Jack P. Moehle. January 2001.

PEER 2000/07 *Cover-Plate and Flange-Plate Reinforced Steel Moment-Resisting Connections.* Taejin Kim, Andrew S. Whittaker, Amir S. Gilani, Vitelmo V. Bertero, and Shakhzod M. Takhirov. September 2000.

PEER 2000/06 *Seismic Evaluation and Analysis of 230-kV Disconnect Switches.* Amir S. J. Gilani, Andrew S. Whittaker, Gregory L. Fenves, Chun-Hao Chen, Henry Ho, and Eric Fujisaki. July 2000.

PEER 2000/05 *Performance-Based Evaluation of Exterior Reinforced Concrete Building Joints for Seismic Excitation*. Chandra Clyde, Chris P. Pantelides, and Lawrence D. Reaveley. July 2000.

PEER 2000/04 *An Evaluation of Seismic Energy Demand: An Attenuation Approach*. Chung-Che Chou and Chia-Ming Uang. July 1999.

PEER 2000/03 *Framing Earthquake Retrofitting Decisions: The Case of Hillside Homes in Los Angeles.* Detlof von Winterfeldt, Nels Roselund, and Alicia Kitsuse. March 2000.

PEER 2000/02 *U.S.-Japan Workshop on the Effects of Near-Field Earthquake Shaking*. Andrew Whittaker, Editor. July 2000.

PEER 2000/01 *Further Studies on Seismic Interaction in Interconnected Electrical Substation Equipment.* Armen Der Kiureghian, Kee-Jeung Hong, and Jerome L. Sackman. November 1999.

PEER 1999/14 *Seismic Evaluation and Retrofit of 230-kV Porcelain Transformer Bushings*. Amir S. Gilani, Andrew S. Whittaker, Gregory L. Fenves, and Eric Fujisaki. December 1999.

PEER 1999/13 *Building Vulnerability Studies: Modeling and Evaluation of Tilt-up and Steel Reinforced Concrete Buildings*. John W. Wallace, Jonathan P. Stewart, and Andrew S. Whittaker, Editors. December 1999.

PEER 1999/12 *Rehabilitation of Nonductile RC Frame Building Using Encasement Plates and Energy-Dissipating Devices*. Mehrdad Sasani, Vitelmo V. Bertero, James C. Anderson. December 1999.

PEER 1999/11 *Performance Evaluation Database for Concrete Bridge Components and Systems under Simulated Seismic Loads*. Yael D. Hose and Frieder Seible. November 1999.

PEER 1999/10 *U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures*. December 1999.

PEER 1999/09 *Performance Improvement of Long Period Building Structures Subjected to Severe Pulse-Type Ground Motions*. James C. Anderson, Vitelmo V. Bertero, and Raul Bertero. October 1999.

PEER 1999/08 *Envelopes for Seismic Response Vectors.* Charles Menun and Armen Der Kiureghian. July 1999.

PEER 1999/07 *Documentation of Strengths and Weaknesses of Current Computer Analysis Methods for Seismic Performance of Reinforced Concrete Members*. William F. Cofer. November 1999.

PEER 1999/06 *Rocking Response and Overturning of Anchored Equipment under Seismic Excitations*. Nicos Makris and Jian Zhang. November 1999.

PEER 1999/05 *Seismic Evaluation of 550 kV Porcelain Transformer Bushings.* Amir S. Gilani, Andrew S. Whittaker, Gregory L. Fenves, and Eric Fujisaki. October 1999.

PEER 1999/04 *Adoption and Enforcement of Earthquake Risk-Reduction Measures.* Peter J. May, Raymond J. Burby, T. Jens Feeley, and Robert Wood. August 1999.

PEER 1999/03 *Task 3 Characterization of Site Response General Site Categories*. Adrian Rodriguez-Marek, Jonathan D. Bray and Norman Abrahamson. February 1999.

PEER 1999/02 *Capacity-Demand-Diagram Methods for Estimating Seismic Deformation of Inelastic Structures: SDF Systems*. Anil K. Chopra and Rakesh Goel. April 1999.

PEER 1999/01 *Interaction in Interconnected Electrical Substation Equipment Subjected to Earthquake Ground Motions*. Armen Der Kiureghian, Jerome L. Sackman, and Kee-Jeung Hong. February 1999.

PEER 1998/08 *Behavior and Failure Analysis of a Multiple-Frame Highway Bridge in the 1994 Northridge Earthquake*. Gregory L. Fenves and Michael Ellery. December 1998.

PEER 1998/07 *Empirical Evaluation of Inertial Soil-Structure Interaction Effects.* Jonathan P. Stewart, Raymond B. Seed, and Gregory L. Fenves. November 1998.

PEER 1998/06 *Effect of Damping Mechanisms on the Response of Seismic Isolated Structures*. Nicos Makris and Shih-Po Chang. November 1998.

PEER 1998/05 *Rocking Response and Overturning of Equipment under Horizontal Pulse-Type Motions*. Nicos Makris and Yiannis Roussos. October 1998.

PEER 1998/04 *Pacific Earthquake Engineering Research Invitational Workshop Proceedings, May 14–15, 1998: Defining the Links between Planning, Policy Analysis, Economics and Earthquake Engineering*. Mary Comerio and Peter Gordon. September 1998.

PEER 1998/03 *Repair/Upgrade Procedures for Welded Beam to Column Connections*. James C. Anderson and Xiaojing Duan. May 1998.

PEER 1998/02 *Seismic Evaluation of 196 kV Porcelain Transformer Bushings.* Amir S. Gilani, Juan W. Chavez, Gregory L. Fenves, and Andrew S. Whittaker. May 1998.

PEER 1998/01 *Seismic Performance of Well-Confined Concrete Bridge Columns.* Dawn E. Lehman and Jack P. Moehle. December 2000.

ONLINE PEER REPORTS

The following PEER reports are available by Internet only at http://peer.berkeley.edu/publications/peer_reports_complete.html.

PEER 2012/103 *Performance-Based Seismic Demand Assessment of Concentrically Braced Steel Frame Buildings.* Chui-Hsin Chen and Stephen A. Mahin. December 2012.

PEER 2012/102 *Procedure to Restart an Interrupted Hybrid Simulation: Addendum to PEER Report 2010/103.* Vesna Terzic and Bozidar Stojadinovic. October 2012.

PEER 2012/101 *Mechanics of Fiber Reinforced Bearings.* James M. Kelly and Andrea Calabrese. February 2012.

PEER 2011/107 *Nonlinear Site Response and Seismic Compression at Vertical Array Strongly Shaken by 2007 Niigata-ken Chuetsu-oki Earthquake.* Eric Yee, Jonathan P. Stewart, and Kohji Tokimatsu. December 2011.

PEER 2011/106 *Self Compacting Hybrid Fiber Reinforced Concrete Composites for Bridge Columns.* Pardeep Kumar, Gabriel Jen, William Trono, Marios Panagiotou, and Claudia Ostertag. September 2011.

PEER 2011/105 *Stochastic Dynamic Analysis of Bridges Subjected to Spacially Varying Ground Motions.* Katerina Konakli and Armen Der Kiureghian. August 2011.

PEER 2011/104 *Design and Instrumentation of the 2010 E-Defense Four-Story Reinforced Concrete and Post-Tensioned Concrete Buildings.* Takuya Nagae, Kenichi Tahara, Taizo Matsumori, Hitoshi Shiohara, Toshimi Kabeyasawa, Susumu Kono, Minehiro Nishiyama (Japanese Research Team) and John Wallace, Wassim Ghannoum, Jack Moehle, Richard Sause, Wesley Keller, Zeynep Tuna (U.S. Research Team). June 2011.

PEER 2011/103 *In-Situ Monitoring of the Force Output of Fluid Dampers: Experimental Investigation.* Dimitrios Konstantinidis, James M. Kelly, and Nicos Makris. April 2011.

PEER 2011/102 *Ground-Motion Prediction Equations 1964–2010.* John Douglas. April 2011.

PEER 2011/101 *Report of the Eighth Planning Meeting of NEES/E-Defense Collaborative Research on Earthquake Engineering.* Convened by the Hyogo Earthquake Engineering Research Center (NIED), NEES Consortium, Inc. February 2011.

PEER 2010/111 *Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings.* Task 7 Report for the Tall Buildings Initiative - Published jointly by the Applied Technology Council. October 2010.

PEER 2010/110 *Seismic Performance Assessment and Probabilistic Repair Cost Analysis of Precast Concrete Cladding Systems for Multistory Buildlings.* Jeffrey P. Hunt and Božidar Stojadinovic. November 2010.

PEER 2010/109 *Report of the Seventh Joint Planning Meeting of NEES/E-Defense Collaboration on Earthquake Engineering. Held at the E-Defense, Miki, and Shin-Kobe, Japan, September 18–19, 2009.* August 2010.

PEER 2010/108 *Probabilistic Tsunami Hazard in California.* Hong Kie Thio, Paul Somerville, and Jascha Polet, preparers. October 2010.

PEER 2010/107 *Performance and Reliability of Exposed Column Base Plate Connections for Steel Moment-Resisting Frames.* Ady Aviram, Božidar Stojadinovic, and Armen Der Kiureghian. August 2010.

PEER 2010/106 *Verification of Probabilistic Seismic Hazard Analysis Computer Programs.* Patricia Thomas, Ivan Wong, and Norman Abrahamson. May 2010.

PEER 2010/105 *Structural Engineering Reconnaissance of the April 6, 2009, Abruzzo, Italy, Earthquake, and Lessons Learned.* M. Selim Günay and Khalid M. Mosalam. April 2010.

PEER 2010/104 *Simulating the Inelastic Seismic Behavior of Steel Braced Frames, Including the Effects of Low-Cycle Fatigue.* Yuli Huang and Stephen A. Mahin. April 2010.

PEER 2010/103 *Post-Earthquake Traffic Capacity of Modern Bridges in California*. Vesna Terzic and Božidar Stojadinović. March 2010.

PEER 2010/102 *Analysis of Cumulative Absolute Velocity (CAV) and JMA Instrumental Seismic Intensity (I_{JMA}) Using the PEER–NGA Strong Motion Database.* Kenneth W. Campbell and Yousef Bozorgnia. February 2010.

PEER 2010/101 *Rocking Response of Bridges on Shallow Foundations.* Jose A. Ugalde, Bruce L. Kutter, and Boris Jeremic. April 2010.

PEER 2009/109 *Simulation and Performance-Based Earthquake Engineering Assessment of Self-Centering Post-Tensioned Concrete Bridge Systems.* Won K. Lee and Sarah L. Billington. December 2009.

PEER 2009/108 *PEER Lifelines Geotechnical Virtual Data Center.* J. Carl Stepp, Daniel J. Ponti, Loren L. Turner, Jennifer N. Swift, Sean Devlin, Yang Zhu, Jean Benoit, and John Bobbitt. September 2009.

PEER 2009/107 *Experimental and Computational Evaluation of Current and Innovative In-Span Hinge Details in Reinforced Concrete Box-Girder Bridges: Part 2: Post-Test Analysis and Design Recommendations.* Matias A. Hube and Khalid M. Mosalam. December 2009.

PEER 2009/106 *Shear Strength Models of Exterior Beam-Column Joints without Transverse Reinforcement*. Sangjoon Park and Khalid M. Mosalam. November 2009.

PEER 2009/105 *Reduced Uncertainty of Ground Motion Prediction Equations through Bayesian Variance Analysis.* Robb Eric S. Moss. November 2009.

PEER 2009/104 *Advanced Implementation of Hybrid Simulation.* Andreas H. Schellenberg, Stephen A. Mahin, Gregory L. Fenves. November 2009.

PEER 2009/103 *Performance Evaluation of Innovative Steel Braced Frames.* T. Y. Yang, Jack P. Moehle, and Božidar Stojadinovic. August 2009.

PEER 2009/102 *Reinvestigation of Liquefaction and Nonliquefaction Case Histories from the 1976 Tangshan Earthquake.* Robb Eric Moss, Robert E. Kayen, Liyuan Tong, Songyu Liu, Guojun Cai, and Jiaer Wu. August 2009.

PEER 2009/101 *Report of the First Joint Planning Meeting for the Second Phase of NEES/E-Defense Collaborative Research on Earthquake Engineering.* Stephen A. Mahin et al. July 2009.

PEER 2008/104 *Experimental and Analytical Study of the Seismic Performance of Retaining Structures.* Linda Al Atik and Nicholas Sitar. January 2009.

PEER 2008/103 *Experimental and Computational Evaluation of Current and Innovative In-Span Hinge Details in Reinforced Concrete Box-Girder Bridges. Part 1: Experimental Findings and Pre-Test Analysis.* Matias A. Hube and Khalid M. Mosalam. January 2009.

PEER 2008/102 *Modeling of Unreinforced Masonry Infill Walls Considering In-Plane and Out-of-Plane Interaction.* Stephen Kadysiewski and Khalid M. Mosalam. January 2009.

PEER 2008/101 *Seismic Performance Objectives for Tall Buildings.* William T. Holmes, Charles Kircher, William Petak, and Nabih Youssef. August 2008.

PEER 2007/101 *Generalized Hybrid Simulation Framework for Structural Systems Subjected to Seismic Loading*. Tarek Elkhoraibi and Khalid M. Mosalam. July 2007.

PEER 2007/100 *Seismic Evaluation of Reinforced Concrete Buildings Including Effects of Masonry Infill Walls*. Alidad Hashemi and Khalid M. Mosalam. July 2007.

The Pacific Earthquake Engineering Research Center (PEER) is a multi-institutional research and education center with headquarters at the University of California, Berkeley. Investigators from over 20 universities, several consulting companies, and researchers at various state and federal government agencies contribute to research programs focused on performance-based earthquake engineering.

These research programs aim to identify and reduce the risks from major earthquakes to life safety and to the economy by including research in a wide variety of disciplines including structural and geotechnical engineering, geology/seismology, lifelines, transportation, architecture, economics, risk management, and public policy.

PEER is supported by federal, state, local, and regional agencies, together with industry partners.

PEER Core Institutions:
University of California, Berkeley (Lead Institution)
California Institute of Technology
Oregon State University
Stanford University
University of California, Davis
University of California, Irvine
University of California, Los Angeles
University of California, San Diego
University of Southern California
University of Washington

PEER reports can be ordered at http://peer.berkeley.edu/publications/peer_reports.html or by contacting

Pacific Earthquake Engineering Research Center
University of California, Berkeley
325 Davis Hall, Mail Code 1792
Berkeley, CA 94720-1792
Tel: 510-642-3437
Fax: 510-642-1655
Email: peer_editor@berkeley.edu

ISSN 1547-0587X