PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

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ABSTRACT

Conditional models for the horizontal and vertical peak ground velocity (PGV), given the pseudo-spectral acceleration $[PSA(T)]$ values, are developed for active crustal regions. The period of the $PSA(T)$ used in the conditional model, T_{PGV}, is magnitude dependent, which captures the effect of the magnitude dependence of the earthquake source corner frequency on the PGV. Conditional models can be used to estimate the PGV given a design spectrum and are applicable for magnitudes between 3.0 and 8.5, and for distances up to 200 km. The conditional PGV models can also be combined with appropriate GMMs for $PSA(T)$ to develop traditional GMMs for PGV that are consistent with the more complex scaling included in the $PSA(T)$ model. Unlike previous conditional PGV models, the slope on the $ln[PSA(T)]$ term is allowed to be different from unity. With this feature, an appropriate aleatory standard deviation of the resulting $ln(PGV)$ can be computed, avoiding the over-prediction of the aleatory standard deviation of the PGV seen in previous conditional PGV models.

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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 agencies or the Pacific Earthquake Engineering Research Center and the Regents of the University of California.

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1 Introduction

The most common ground-motion parameters used to develop design ground motions are horizontal-component elastic pseudo-spectral acceleration (PSA) values.

While the PSA values broadly represent the amplitude of the ground shaking important to the response of buildings, there are other ground-motion parameters that can significantly affect the response of different types of structures. Examples of secondary ground-motion parameters that are often considered when developing design ground motions are the duration, peak ground velocity (PGV), presence of a velocity pulse, Arias intensity (I_a), and cumulative absolute velocity (CAV).

There are two main approaches for estimating the secondary ground-motion parameters given a design earthquake scenario and a horizontal-component design spectrum. The first approach is to develop an empirical ground-motion model (GMM) for the secondary ground-motion parameters in a manner similar to the approach used to develop GMMs for the horizontal $PSA(T)$ values. The secondary parameter can be estimated using the design earthquake scenario (e.g., magnitude and distance) from the disaggregation of the hazard for the response spectral values at the periods important for the structure.

An alternative approach is to include the design $PSA(T)$ values as predictive parameters in the GMM for the secondary parameters in addition to the source, path, and site parameters used in traditional GMMs. For example, a GMM for secondary parameters may include the design $PSA(T = 1)$ sec) value as an input parameter. Abrahamson et al. (2016) used the term "conditional ground-motion model" for GMMs that include other ground-motion parameters as model input parameters. This is consistent with the term "conditional" used in the conditional mean spectrum (CMS) described by Baker and Cornell (2006). The CMS uses the design response spectral value at the conditioning period as input to compute the expected response spectral values at other spectral periods. The conditional GMM approach differs from the CMS approach in that the conditional GMM uses the design $PSA(T)$ value directly as an input parameter rather than using the normalized residual, ϵ, for the design $PSA(T)$ and the correlation coefficient between the ϵ values for the two spectral periods. Because the $PSA(T)$ value already includes magnitude, distance, and site scaling effects, conditional GMMs have weaker dependence on these parameters compared to traditional GMMs. In addiition, they have much smaller aleatory variability, making the regression more robust.

An advantage of using the conditional GMM approach is that it leads to estimates of the secondary parameters that are compatible with the design response spectral values. In contrast, using a traditional GMM approach can lead to estimates of the secondary parameters that are inconsistent with the design $PSA(T)$ values. For example, if the design $PSA(T)$ value from a probabilistic seismic hazard analysis corresponds to $\epsilon = 1.5$ (i.e., the 93th percentile spectral acceleration), then the common practice of computing the secondary parameter based on the 16th–84th percentile range for the controlling scenario from the disaggregation will lead to a target range of the values of the secondary parameter inconsistent with the design $PSA(T)$ values.

This inconsistency issue can be addressed using the correlation between the ϵ of the secondary parameter and the ϵ of spectral acceleration at the selected period, and computing the expected value of the secondary parameter given the ϵ of the design $PSA(T)$, similar to the approach for computing the CMS. It may seem easier to just follow this CMS-type approach; however, using the correlation approach implicitly assumes that the GMM for the secondary parameter has a consistent parameterization and consistent physical constraints on the extrapolation as the horizontal PSA GMM. This is the case for spectral accelerations at different periods from a single GMM, but it may not be the case for secondary parameters because the GMMs for the secondary parameters are often developed by different researchers, and there is less information available from analytical studies to provide physical constraints on the scaling for the secondary parameters.

A conditional GMM can be combined with a suite of GMMs for the median and standard deviation of the $PSA(T)$ values to develop a suite of GMMs for the secondary parameter that fully captures the aleatory variability as well as the magnitude, distance, and site scaling of the median of the secondary parameter. For example, the single conditional model for I_a, developed by Abrahamson et al. (2016), was combined with each of the five NGA-West2 GMMs per Gregor et al. (2014) for the PGA and $PSA(T = 1)$ values to produce five alternative GMMs for I_a. In this approach, the magnitude, distance, and site scaling for each $PSA(T)$ model is incorporated into a new I_a model. Because of the smaller aleatory variability and the simpler functional forms required, the coefficients of conditional models are stable and well constrained by the available empirical data.

Conditional GMMs have been considered as overly simplified models that should only be used if a traditional GMM is not available for the secondary parameter of interest. For example, Bommer and Alarcon (2006) have claimed that estimating PGV using traditional GMMs for PGV is preferable to estimating the PGV using conditional models based on the response spectral values. Furthermore, they recommended that conditional models should only be used for estimating a secondary parameter if there are no appropriate traditional GMMs available for the secondary parameter. We do not agree with this recommendation. More than just being a simplified model used as a last resort, there are several key advantages to using the conditional GMM approach.

1. Conditional GMMs may take advantage of the significant effort that has been put into developing constraints on the extrapolation in the PSA–GMM scaling using analytical modeling for effects not well constrained by the empirical data, such as short-distance saturation, hanging-wall (HW) effects, soil-depth effects, and nonlinear soil effects. For example, Abrahamson et al. (2016) showed that by combining a conditional GMM for I_a without HW effects with an NGA-West2 GMM that used seismological finite-fault simulations to constrain the HW effects, the resulting I_a model captured almost all of the HW effect on the I_a by using the PGA as an input parameter.

2. Regional differences in the scaling for the secondary parameters can be easily estimated by combining a global conditional model with region-specific GMMs for the $PSA(T)$ values. This leads to a region-specific model for the secondary parameters for the new region.

3. Using conditional GMMs leads to secondary parameters that are consistent with PSA GMM. Traditional GMMs for the secondary parameters are often developed by different researchers than those that developed the $PSA(T)$ GMM. As a result, they can have inconsistent scaling from the PSA GMM in terms of how the model extrapolates outside the empirical data range. So while the GMM for the secondary parameter fits the available data, it may give estimates that are inconsistent with the design $PSA(T)$ values if the models use different analytical and seismological constraints outside the range well constrained by the data.

4. The conditional GMMs have simpler functional forms and much smaller aleatory variability than traditional GMMs, so the coefficients of the conditional GMMs are better constrained than the coefficients for traditional GMMs.

1.1 PREVIOUS CONDITIONAL MODELS FOR PGV

Newmark and Hall (1982) developed a model for the ratio of the pseudo-spectral velocity (PSV) to the PGV for spectral periods in the velocity-controlled period range of the response spectrum. For 5% damping, the median $PSV(T)/PGV$ ratio in the velocity-controlled region given by Newmark and Hall (1982) is 1.65. While Newmark and Hall (1982) used this $PSV(T)/PGV$ ratio to estimate the $PSV(T)$ in velocity-controlled region given an estimate of the PGV, this ratio can be also used to develop a conditional ground-motion model for PGV given the $PSA(T)$. Converting the $PSV(T)$ in cm/sec to $PSA(T)$ in g and taking the natural logarithms, the Newmark and Hall (1982) scale factor for $PSV(T)/PGV$ can be rewritten as:

$$ln(PGV) = 4.55 - ln(T) + 1.0ln[PSA(T)] \tag{1.1}$$

where the PGV is in cm/sec, the $PSA(T)$ is in g, and the period, T, is the period representing the constant-velocity region.

Bommer and Alarcon (2006) evaluated the relationship between PGV and $PSA(T)$ at a range of spectral periods. They found that the $ln[PSA(T)]$ at a period of 0.5 sec had similar magnitude scaling as the $ln(PGV)$. Therefore, they developed a simple conditional model for PGV for crustal earthquakes in active regions based on the 5% damped PSA at $T = 0.5$ sec.

$$PGV = \frac{980PSA(T = 0.5)}{20} \tag{1.2}$$

where the PGV is in cm/sec, and the $PSA(T)$ is in g. A magnitude term was not included in this model because the magnitude scaling of the PGV and the $PSA(T = 0.5)$ were found to be similar. This $PGV - PSA$ relation can be written as:

$$ln(PGV) = 3.89 + 1.0ln\left[PSA(T = 0.5)\right]) \quad (1.3)$$

An issue with these models is the estimation of the standard deviation of the PGV. Bommer and Alarcon (2006) noted that GMMs developed for both PSA and PGV show that the standard deviation of $ln(PGV)$ is smaller than the standard deviation of $ln[PSA(T = 0.5)]$. In this case, adding the variance from the residuals of the conditional $ln(PGV)$ model to the variance of the $ln(PSA)$ model would add to the overestimation of the total standard deviation of $ln(PGV)$ already present due to the use of the standard deviation of $ln[PSA(T = 0.5)]$. Therefore, they recommended not including the standard deviation of the conditional model in estimating the aleatory variability of the resulting $ln(PGV)$.

Huang and Whittaker (2015) developed an updated conditional PGV model for use in seismic performance evaluations described in FEMA-58-1 (2018). Using ground-motion data from the NGA-West2 dataset for active crustal regions, they developed two alternative empirical models for the PSV/PGV ratio: one based on the PSV/PGV ratio averaged over the period range of 0.5 to 2 sec, and one based on the PSV/PGV ratio at a period of 1.0 sec. Their PSV/PGV model using the T=1 sec PSV is given by:

$$ln\left[\frac{PSV(T = 1)}{PGV}\right] = 1.3 - 0.13M \quad (1.4)$$

with a standard deviation of 0.43 natural log units. Converting the PSV in cm/sec to the PSA in g, their model can be written as:

$$ln(PGV) = 3.75 + 1.0ln\left[PSA(T = 1)\right] + 0.13M \quad (1.5)$$

For the model based on the $PSV(T)/PGV$ ratio averaged over the 0.5 to 2.0 sec period range, the standard deviation of $ln[PSV(T)/PGV]$ is reduced to 0.33 natural log units. This reduction in the standard deviation reflects that there is not a single predominant period for the PGV for all earthquakes; therefore, using the PSV averaged over a period range is a better parameter for predicting the PGV for a range of magnitudes. For computing the standard deviation of $ln(PGV)$, Huang and Whittaker (2015) add the variance of the conditional PGV model to the variance of the $ln[PSA(T)]$ model.

All three of the previous models for estimating PGV given the response spectral values are based on statistical modeling of the $PSV(T)/PGV$ or $PSA(T)/PGV)$ ratios, which is equivalent to constraining the slope on the $ln[PSA(T)]$ term to be unity; see Equations (1.1), (1.3), and (1.5). As discussed later in the model development section, constraining the slope to unity limits the ability to accurately compute the standard deviation of PGV.

In this study, we have developed conditional ground-motion models for the horizontal and vertical components of $ln(PGV)$ for active crustal regions. Our approach differs from the previous models in that the conditional PGV models are developed directly for the $ln(PGV)$ rather than developing the model for the $PSV(T)/PGV$ or $PSA(T)/PGV$ ratio, which allows the slope on the $ln[PSA(T)]$ term to be different from unity. This approach allows for the aleatory variability of $ln(PGV)$ for an earthquake scenario [i.e., without considering a given $PSA(T)$ value] to be accurately estimated by combining the conditional PGV model with the standard deviation of an appropriate GMM for the $PSA(T)$.

2 Datasets

For active crustal earthquakes, we used the NGA-west2 database (Ancheta et al., 2014) developed by the Pacific Earthquake Engineering Research Center (PEER). This database includes ground motions from earthquakes in active crustal regions around the world that have occurred between 1940 and 2011. The full database contains over 21,000 three-component recordings from 713 earthquakes. We used the same subset of this dataset as selected by Abrahamson et al. (2016) for their conditional ground-motion model for Arias intensity (AI). This subset consists of 11,353 recordings with distances between 0 and 340 km from 431 earthquakes, with magnitudes between 3.0 and 7.9.

Recordings with a usable long-period range that does not cover the spectral periods relevant to the PGV were removed. For the horizontal component, 47 recordings were removed due to the usable period-range constraint. For the vertical component, 427 recordings were removed. The magnitude and distance distribution of the 11,306 recordings from 427 earthquakes in the selected horizontal dataset is shown in Figure 2.1.

The distribution of the V_{S30} is shown in Figure 2.2. Most of the data are for V_{S30} between 200 and 800 m/sec. There are only a few recordings on hard-rock conditions. The sample from small and large magnitude is similar.

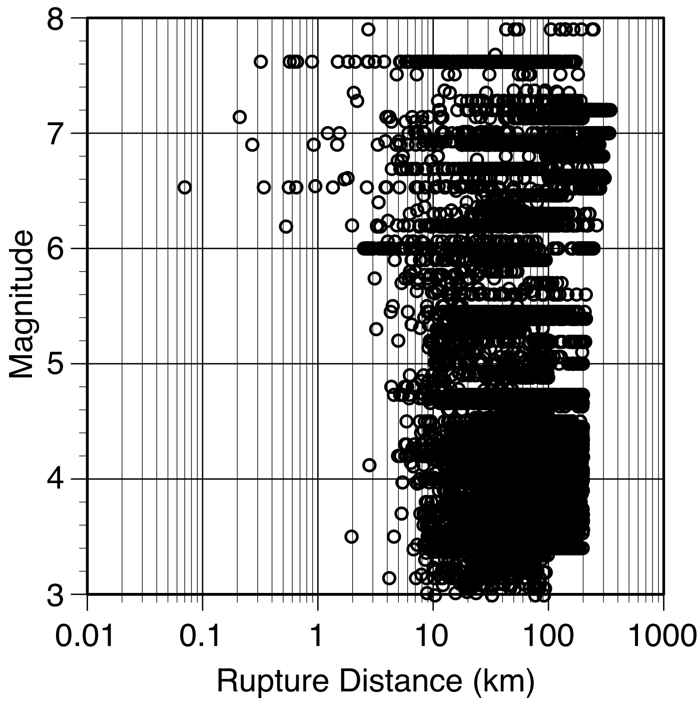

Figure 2.1: Magnitude-distance distribution of the selected dataset for crustal earthquakes.

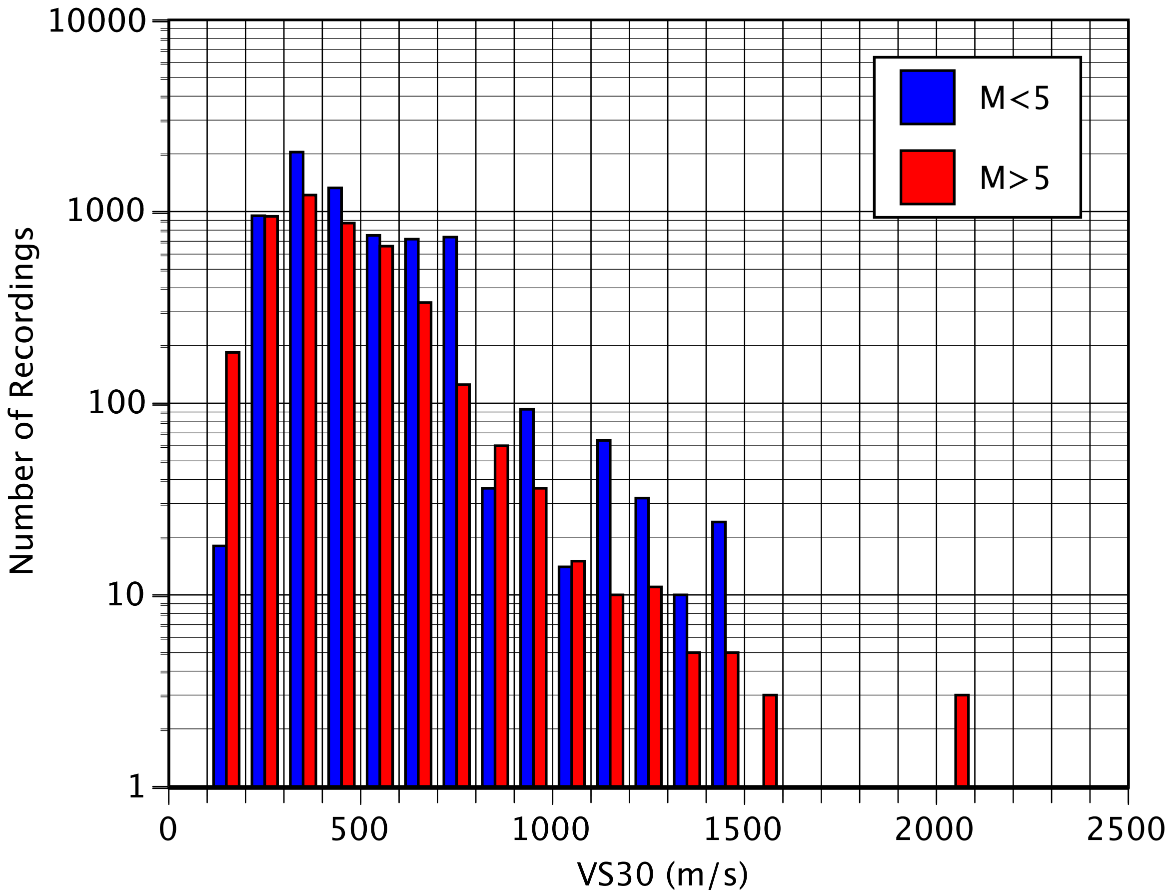

Figure 2.2: Distribution of V_{S30} for small and large magnitudes.

3 Conditional *PGV* Models

The development of good empirical GMMs for earthquake engineering applications is more than just a curve-fitting exercise. First, there should be a physical basis for the form of the model. Second, there should be appropriate constraints on the extrapolation of the model outside of the range constrained by the empirical data but that are important contributors to the seismic hazard. Given an appropriate functional form and appropriate constraints, the regression analysis is used to fit the model in the range covered by the empirical data.

3.1 PHYSICAL BASIS FOR THE PGV MODEL

For the relationship between $PSA(T)$ and PGV, the key physical constraint comes from the magnitude dependence of the source corner frequency in the Fourier amplitude spectrum (FAS) of ground motions. This change in frequency content can be seen in the magnitude scaling of the velocity FAS. Figure 3.1 shows the velocity FAS for **M**3 to **M**8 earthquakes in California based on the Bayless and Abrahamson (2019) FAS GMM. Due to the magnitude dependence of the corner frequency, there is an increase in the long-period content with increasing magnitude, and the predominant period of the peak velocity will increase as the earthquake magnitude increases. As a result, the period of the $PSA(T)$ that has the highest correlation between PGV and $PSA(T)$, denoted T_{PGV}, will also be magnitude dependent. The velocity time series for smaller magnitude earthquakes will have a smaller T_{PGV} values than for larger earthquakes.

The distance dependence on the frequency content of the velocity FAS is much weaker than the magnitude dependence. Figure 3.2 shows that velocity FAS for **M**6 at distances of 5, 20, 50, 100, and 200 km using the Bayless and Abrahamson (2019) FAS GMM. Compared to the large changes in spectral shapes for different magnitudes, the spectral shapes for the different distances are very similar. Therefore, we do not consider the distance dependence in the model for T_{PGV} for the distance range of up to 200 km considered in this study.

3.2 DEVELOPMENT OF THE CONDITIONAL PGV MODEL

The development of the conditional PGV model starts with the evaluation of the magnitude dependence of the correlation of the PGV and $PSA(T)$. The data are first divided into magnitude bins with a width of 1 magnitude unit. For each magnitude bin, the correlation between the $ln(PGV)$

and the $ln[PSA(T)]$ is computed for 104 spectral periods between 0.01 and 10 sec, as given in the PEER NGA-West2 dataset. Unlike the previous studies discussed above, the slope of the $ln(PSA)$ term is a free parameter rather than being fixed at unity:

$$ln(PGV) = c_1 + c_2 ln[PSA(T_{PGV})] \tag{3.1}$$

The inclusion of the slope, c_2, as a free parameter is important because it captures the difference in the standard deviation of the $ln(PGV)$ relative to the standard deviation of the $ln[PSA(T)]$ as shown below.

Using simple propagation of errors, the variance of the $ln(PGV)$ is given by

$$\sigma^2_{lnPGV} = \left(\frac{\partial lnPGV}{\partial lnPSA(T_{PGV})}\right)^2 \sigma^2_{lnPSA(T_{PGV})} + \sigma^2_{lnPGV|PSA(T_{PGV})} \tag{3.2}$$

in which σ_{lnPGV} and $\sigma_{lnPSA(T)}$ are the standard deviations of the residuals from traditional GMMs for $ln(PGV)$ and $ln[PSA(T)]$, respectively. For the simple model given in Equation (3.1), the partial derivative is just a constant:

$$\frac{\partial lnPGV}{\partial lnPSA(T_{PGV})} = c_2 \tag{3.3}$$

The standard deviation of the conditional PGV GMM is related to the standard deviation of the traditional PGV GMM through the correlation coefficient:

$$\sigma^2_{lnPGV|PSA(T_{PGV})} = (1-\rho^2)\sigma^2_{lnPGV} \tag{3.4}$$

where ρ is the correlation coefficient between the normalized residuals from a traditional GMMs for the $ln(PGV)$ and $ln[PSA(T)]$. Substituting Equation (3.3) and Equation (3.4) into Equation (3.2), the slope, c_2, is given by

$$c_2 = \rho \frac{\sigma_{lnPGV}}{\sigma_{lnPSA(T_{PGV})}} \tag{3.5}$$

The correlation coefficient must be less than or equal to 1.0, and from the Abrahamson et al. (2014) NGA-West2 GMM, $\sigma_{lnPGV} < \sigma_{lnPSA(T)}$ for all periods. Therefore, using Equation (3.5), c_2 will be less than 1.0. Figure 3.3 shows the relation between the log(PGV) and the $log[PSA(T = 1.5]$ for a subset of crustal data with magnitudes between 6.5 and 7.5 and rupture distances less than 50 km. As expected, the slope of 0.829 is less than unity.

The magnitude dependence of the T_{PGV} is evaluated using a subset of the dataset, with rupture distances less than 50 km to focus on the source-scaling effects. The distance and site dependence of the conditional PGV model is modeled in a later step using the full dataset. Using this subset, a contour plot of the standard deviation of the fit to Equation (3.1) is shown as a function of magnitude and spectral period in Figure 3.4 for the horizontal component.

The T_{PGV} value found for each magnitude bin is listed in Table 3.1. The magnitude dependence of the T_{PGV} is shown in Figure 3.5, which is similar for both the horizontal and vertical components. Also, the contours of the correlations shown in Figure 3.4 are broad. Therefore, the T_{PGV} values for the horizontal and vertical components are combined, and a single relation is developed for both horizontal and vertical components. Based on the binned values shown in Figure 3.5, a simple linear relation is used to model the magnitude dependence of the T_{PGV} for rupture distances less than 50 km:

$$ln(T_{PGV}) = b_1 + b_2 M \tag{3.6}$$

An ordinary least-squares fit to the combined horizontal and vertical data results in $b_1 = -4.09$ and $b_2 = 0.66$, with a standard deviation of 0.2 natural log units.

We can compare the magnitude dependence of T_{PGV} with the result of Bommer and Alarcon (2006), where T = 0.5 sec was the best single period to use for estimating the PGV from the $PSA(T)$. In the Abrahamson and Silva (1997) dataset used by Bommer and Alarcon (2006), the magnitudes range from **M**4.4 to **M**7.4. Using Equation (3.6), the spectral periods with the highest correlation for **M**4.4 to 7.4 range from 0.3 sec to 2.2 sec. The magnitude-independent value of $T_{PGV} = 0.5$ sec used by Bommer and Alarcon (2006) falls within this range.

Given the model for the magnitude dependence of T_{PGV}, a new ground-motion parameter, $PSA[T_{PGV}(M)]$, is computed from the NGA-West2 dataset. For T_{PGV} values that fall between the spectral periods in this dataset, the $PSA(T)$ value is computed using linear interpolation on the log-period and log-PSA values.

To fully take advantage of the conditional GMM approach, simple magnitude, distance, and site terms need to be included so that the slope of the $ln(PSA)$ term represents the product of the correlation and the ratio of the standard deviations, as shown in Equation (3.5). For slopes less than unity, the full magnitude, distance, and site scaling is not included in the $c_2\, ln(PSA)$ term. The difference in the magnitude, distance, and site dependence of the $ln(PGV)$ and that of the scaled $ln(PSA)$ is captured by the explicit magnitude, distance, and site terms.

The functional form used for the conditional PGV model is given by

$$\begin{aligned} ln(PGV) =& a_1 + f_1(M)\, ln\left[PSA(T_{PGV})\right] + a_4\,(M-6) + a_5(8.5-M)^2 \\ &+ a_6\, ln\left[R_{RUP} + 5e^{0.4(M-6)}\right] + \left[a_7 + a_8(M-5)\right]\, ln\left(\frac{V_{S30}}{425}\right) + \delta B + \delta W \end{aligned} \tag{3.7}$$

in which M is the moment magnitude, R_{RUP} is the rupture distance in kilometers, the PSA is the 5% damped spectral acceleration in g, V_{S30} is the time-averaged shear-wave velocity over the top 30 m in m/sec, and δB and δW are the between-event and within-event residuals, respectively. An initial analysis demonstrated that setting the finite-rupture saturation term at $5e^{0.4(M-6)}$ removed any short-distance trend in the residuals at large magnitudes. Because the period of the PSA used in the regression, T_{PGV}, is magnitude dependent, the V_{S30} scaling is also magnitude dependent. To reduce the trade offs in the coefficients, the regression was implemented in two steps.

1. The V_{S30} scaling terms (a_7 and a_8) are set to zero.
2. The within-event residuals are fit with just the (a_7 and a_8) terms.

As discussed earlier, the slope of the $ln[PSA(T_{PGV})]$ term, f_1, is related to the differences in the aleatory standard deviations for $ln(PGV)$ and $ln[PSA(T_{PGV})]$. The differences in the standard deviation for $ln[PSA(T_{PGV})]$ and $ln(PGV)$ from the Abrahamson et al. (2014) GMM are magnitude dependent. Therefore, the f_1 term is modeled as magnitude dependent. A simple tri-linear form is used for $f_1(M)$:

$$f_1(M) = \begin{cases} a_2 & \text{for } M < 5 \\ a_2 + (a_3 - a_2)(M - 5.0)/2.5 & \text{for } 5 \leq M \leq 7.5 \\ a_3 & \text{for } M > 7.5 \end{cases} \quad (3.8)$$

The coefficients are estimated using a random-effects regression analysis with a random effect for the earthquake; see Abrahamson and Youngs (1992). The standard deviations of the between-event and within-event residuals are denoted τ and ϕ, respectively. The total standard deviation is given by $\sigma = \sqrt{\phi^2 + \tau^2}$. The resulting coefficients and standard deviation terms are listed in Table 3.2. The $f_1(M)$ term for the vertical component is smaller than for the horizontal component, indicating that the correlation between PSA and PGV is weaker for the vertical component.

The $PSA(T)$, magnitude, and distance scaling of the conditional PGV model are shown in Figures 3.6 and 3.7. Both figures show a strong dependence of the PGV on the $PSA(T_{PGV})$. Figure 3.6 shows that the horizontal and vertical models are similar for **M**4, but they separate at larger magnitudes because the horizontal PGV has a stronger magnitude scaling than the vertical PGV. Note: Figure 3.7 shows that there is a shift to smaller PGV values for larger distances, but the scaling with distance is not strong.

3.3 EVALUATION OF RESIDUALS

The within-event residuals for the horizontal crustal data are shown as functions of the $PSA(T_{PGV})$ in Figure 3.8 and as a function of rupture distance in Figure 3.9. The residuals in these two figures are shown for subsets of the data by magnitude bin to check that there is not a trade off between the magnitude scaling and either the $PSA(T_{PGV})$ scaling or the distance scaling. In these figures, there are no clear trends seen in the within-event residuals. The within-event residuals are shown as a function of the V_{S30} in Figure 3.10. Again, there are no trends seen in the within-event residuals.

The between-event residuals are shown as a function of magnitude in Figure 3.11. There is no trend with magnitude in the between-event residuals, but there are two outlier events at **M**3.7 (EQIDs 1092 and 1100 in the NGA-West2 database). The event terms for $PSA(T = 0.2)$ from Abrahamson et al. (2014) for these two events are not outliers; therefore, we did not remove these two earthquakes. The residuals for the vertical component for crustal earthquakes are not shown, but no significant trends were observed in either the within-event residuals or the between-event residuals residuals for the vertical component.

To check the applicability of the conditional PGV model for near-fault directivity effects, the within-event residuals for recordings with near-fault velocity pulses are shown in Figure 3.12. The residuals are centered near zero: the mean residual for $M > 6.5$ is 0.06 natural log units. Similarly, to check the applicability of the conditional PGV model for HW effects, the within-event residuals for recordings from dipping faults–a dip less than 65 degrees–are shown in Figure 3.13 as a function of R_x (the horizontal distance measured perpendicular to fault strike). For $0 < R_x < 10$ km (HW side), the residuals are also centered near zero: the mean residual is 0.02 natural log units. These residual plots indicate that the near-fault effects on the PGV are captured in the observed $PSA(T_{PGV})$ values, and that the conditional PGV GMM is applicable to the near-fault region.

3.4 MODEL APPLICATION

The conditional PGV model developed in this study uses the $PSA(T)$ at different periods depending on the magnitude of the controlling earthquake, as given in Equation (3.6). Given a response spectrum, the value of the $PSA(T_{PGV})$ should be interpolated using log-log interpolation on the available $PSA(T)$ values.

The use of magnitude-dependent period is a strength of the model, but it also limits for applications in which the $PSA(T)$ values are only available for a few spectral periods. For example, design seismic hazard maps may only provide the PSA at a few spectral periods. In this case, the model based on the PSA at a single period needs to be used rather than using the magnitude-dependent period, $PSA(T_{PGV})$.

To be applicable to the case in which only PGA or $PSA(T = 1)$ values are available, the regression was repeated using the PGA and the $PSA(T = 1)$ values in place of the $PSA(T_{PGV})$ values. The PGV scaling using a fixed spectral period does not work well over a large magnitude range, so the dataset used for these two models was limited to earthquakes with $M > 5$. In addition, the standard deviation will become magnitude dependent due to the worse fit to the PGV data when using PGA and the $PSA(T = 1)$ values in place of the $PSA(T_{PGV})$. For example, using the PGA, the conditional GMM will provide a better fit to the smaller magnitudes because $T_{PGV}(M)$ is closer to the PGA for **M**5 than for **M**7. To capture this effect, the standard deviation of the within-event terms is modeled using a tri-linear form shown in Equation (3.9). This same functional form is used for the standard deviation of the between-event residuals, τ.

$$\phi(M) = \begin{cases} \phi_1 & \text{for } M < M_1 \\ \phi_1 + (\phi_2 - \phi_1)\frac{(M-M_1)}{(M_2-M_1)} & \text{for } M_1 \leq M \leq M_2 \\ \phi_2 & \text{for } M > M_2 \end{cases} \tag{3.9}$$

Table 3.3 lists the coefficients for the PGA-based and the $PSA(T = 1)$-based conditional PGV models for the horizontal component. Design maps are for the horizontal component only, so PGA-based and the $PSA(T = 1)$-based conditional PGV models are not included for the vertical component.

Given an estimate of the controlling magnitude and distance from disaggregation of the hazard, the models given in Table 3.3 can be used to estimate the PGV from either the PGA or the $PSA(T = 1)$. While not as accurate as the full conditional PGV model, this simplified approach still accommodates the differences in the aleatory variability between the $ln(PSA)$ and the $ln(PGV)$.

Table 3.1: Response spectral period with highest correlation to PGV by magnitude bin.

Mag Bin	Mean Mag	Horiz T_{PGV} (sec)	Vert T_{PGV} (sec)
3.0-3.5	3.4	0.20	0.15
3.5-4.5	4.0	0.28	0.22
4.5-5.5	5.0	0.40	0.32
5.5-6.5	6.1	0.95	1.1
6.5-7.5	6.9	1.4	1.3
7.5-8.5	7.6	2.8	3.0

Table 3.2: Conditional PGV model coefficients for crustal earthquakes.

Coeff	Horizontal	Std Err	Vertical	Std Err
a_1	5.39	0.06	5.51	0.06
a_2	0.799	0.004	0.763	0.004
a_3	0.654	0.008	0.538	0.010
a_4	0.479	0.056	0.131	0.060
a_5	-0.062	0.008	-0.106	0.008
a_6	-0.359	0.007	-0.431	0.008
a_7	-0.134	0.007	-0.089	0.008
a_7	0.023	0.005	0.017	0.006
ϕ	0.29		0.32	
τ	0.16		0.15	
σ	0.33		0.35	

Table 3.3: Coefficients for PGA-based and $PSA(T=1)$-based models for PGV for crustal earthquakes

Coeff	Horizontal PGA Model	Horizontal PSA(T=1) Model
a_1	4.77	4.80
a_2	0.738	0.82
a_3	0.484	0.55
a_4	0.275	0.27
a_5	-0.036	0.054
a_6	-0.332	-0.382
a_7	-0.44	-0.21
a_8	0.0	0.0
ϕ_1	0.32	0.28
ϕ_2	0.42	0.38
τ_1	0.12	0.12
τ_2	0.26	0.17
σ_1	0.34	0.30
σ_2	0.49	0.42
M_1	5.0	5.0
M_2	7.0	7.0

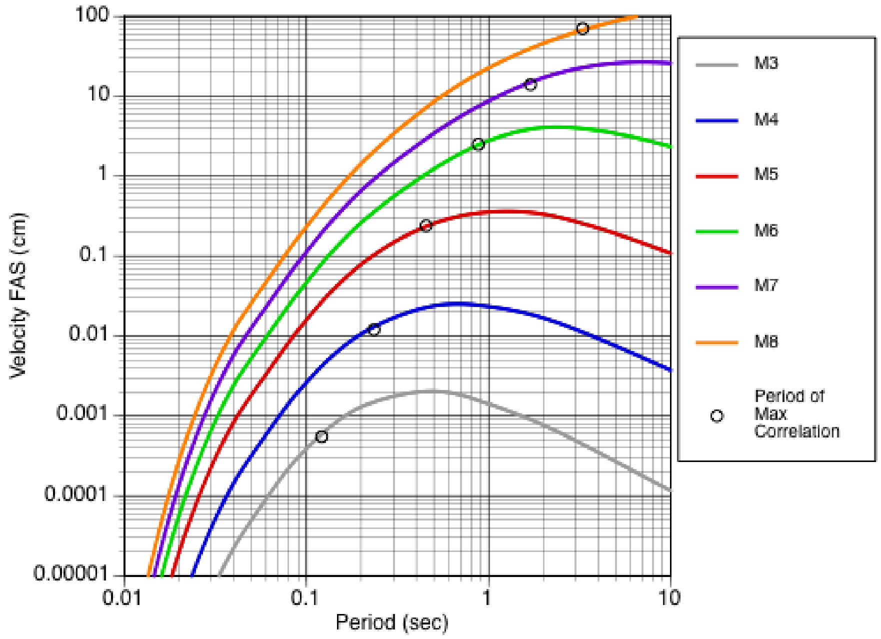

Figure 3.1: Horizontal velocity FAS for different magnitudes for crustal earthquakes at a distance of 30 km and for a site with V_{S30} = 400 m/sec from the Bayless and Abrahamson (2019) model. The circles show the period with the highest correlation between $ln(PGV)$ and $ln[PSA(T)]$.

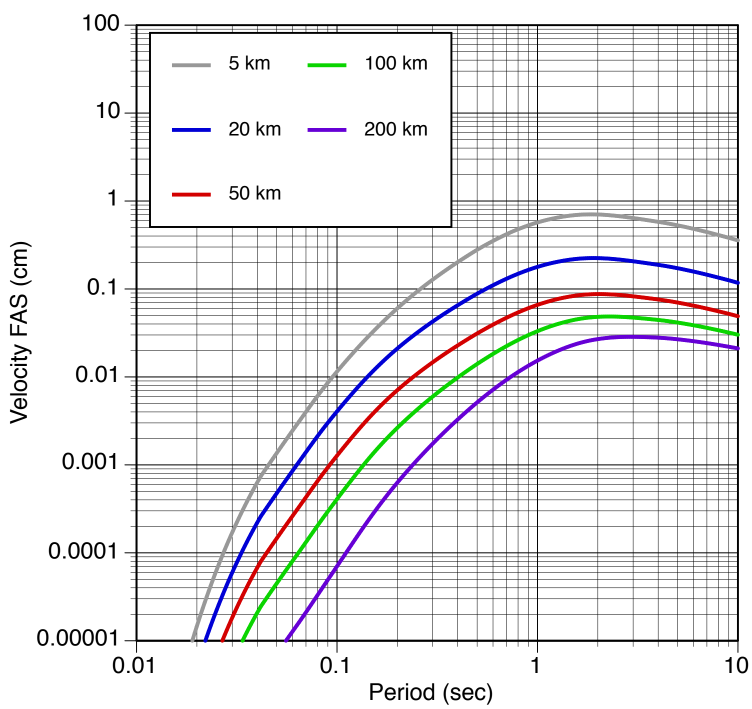

Figure 3.2: Horizontal velocity FAS for M6 at different rupture distances for a site with V_{S30} = 400 m/sec from the Bayless and Abrahamson (2019) model.

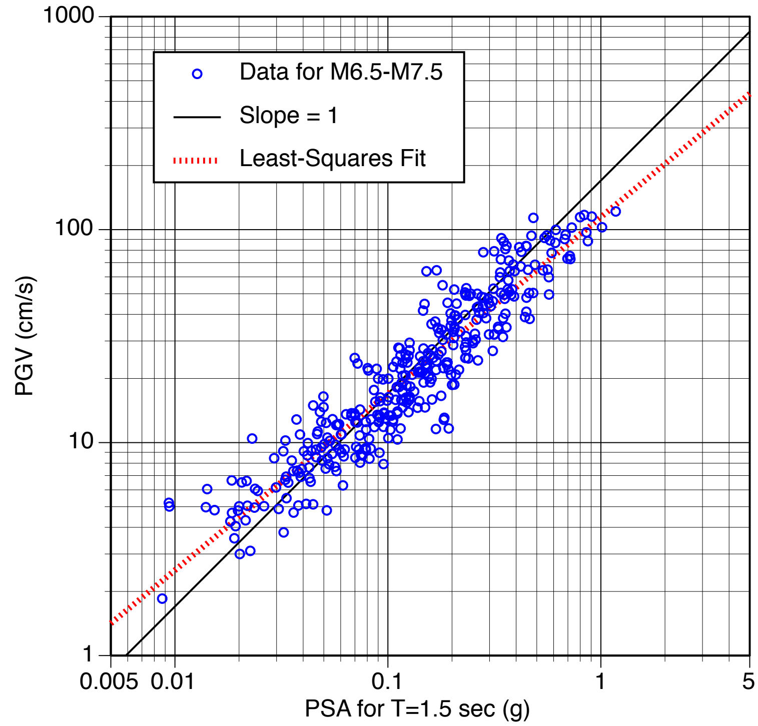

Figure 3.3: Example of the relation between the $ln(PGV)$ and $ln[PSA(T = 1.5)]$ for crustal earthquakes with magnitudes between 6.5 and 7.5 at distances less than 50 km. The slope is less than unity.

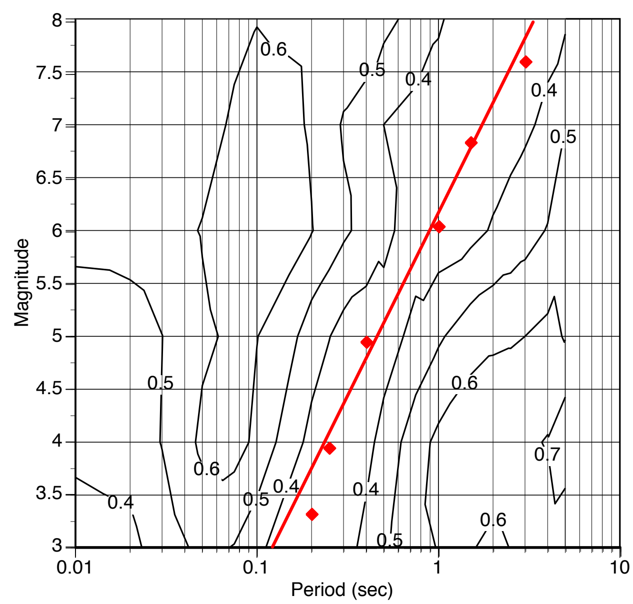

Figure 3.4: Standard deviation of the linear fit of $ln(PGV)$ for crustal earthquakes as a function of $ln[PSA(T)]$ computed by magnitude bin.

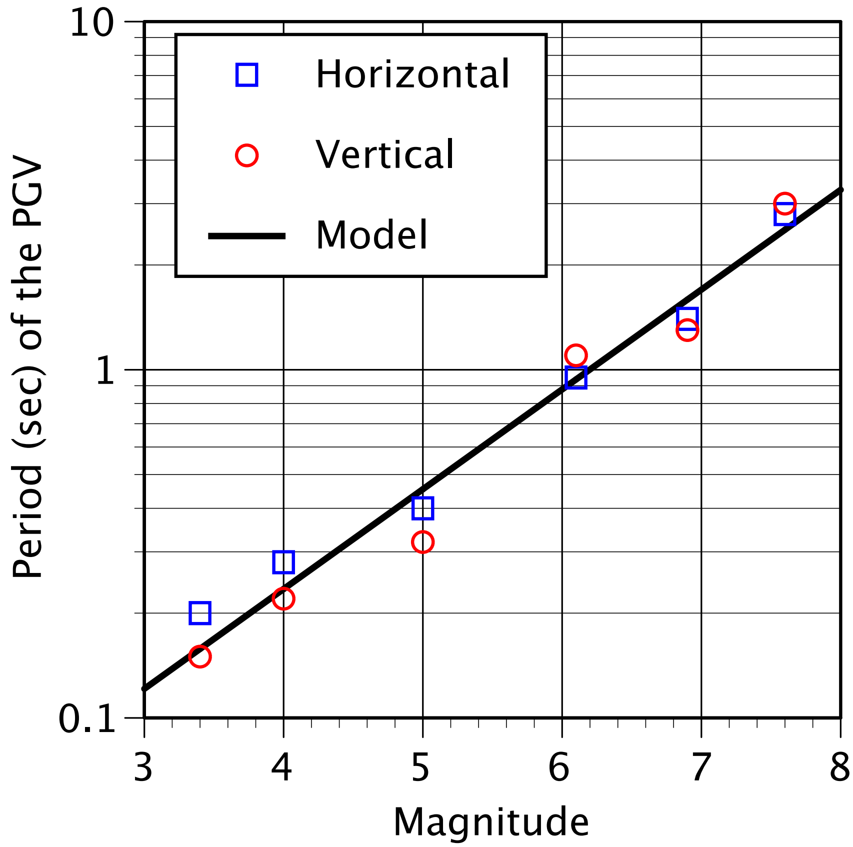

Figure 3.5: Magnitude dependence of the period with highest correlation between PGV and $PSA(T)$.

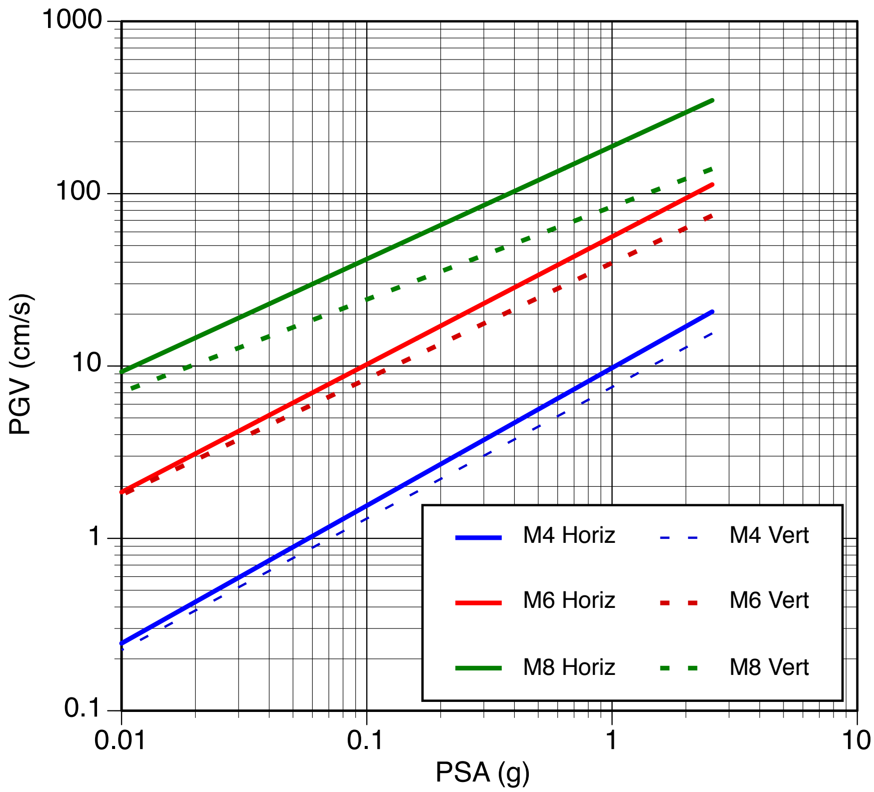

Figure 3.6: $PSA(T_{PGV})$ **scaling of the conditional** PGV **model for** R_{RUP} **= 10 km and** V_{S30} **= 425 m/sec for magnitudes M4 to M8 for both the horizontal and vertical components.**

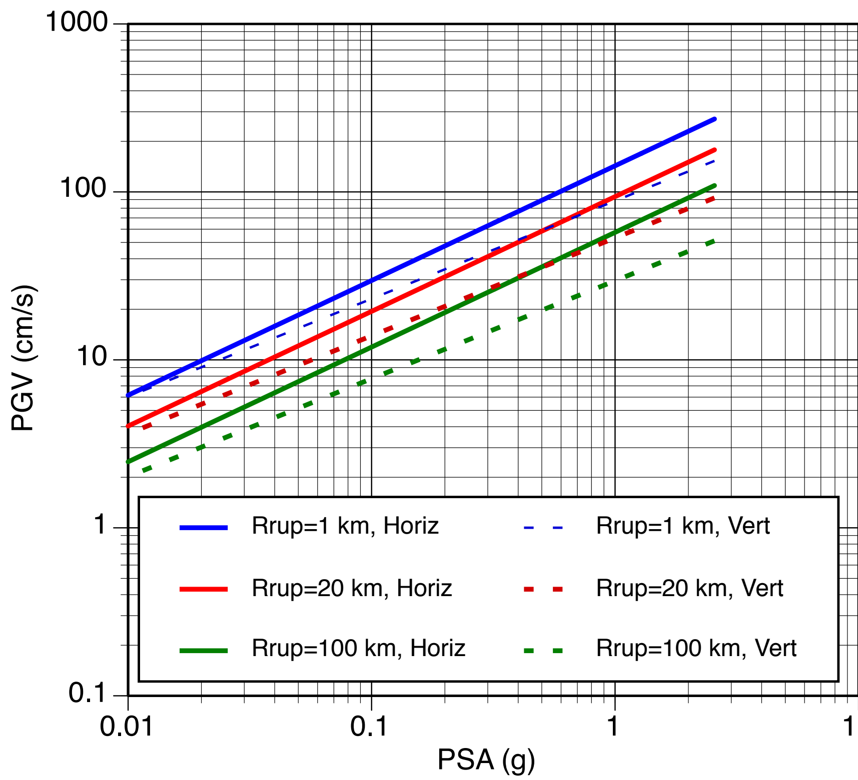

Figure 3.7: $PSA(T_{PGV})$ **scaling of the conditional** PGV **model for M = 7 and** V_{S30} **= 425 m/sec for** R_{RUP} **from 1 to 100 km for both the horizontal and vertical components.**

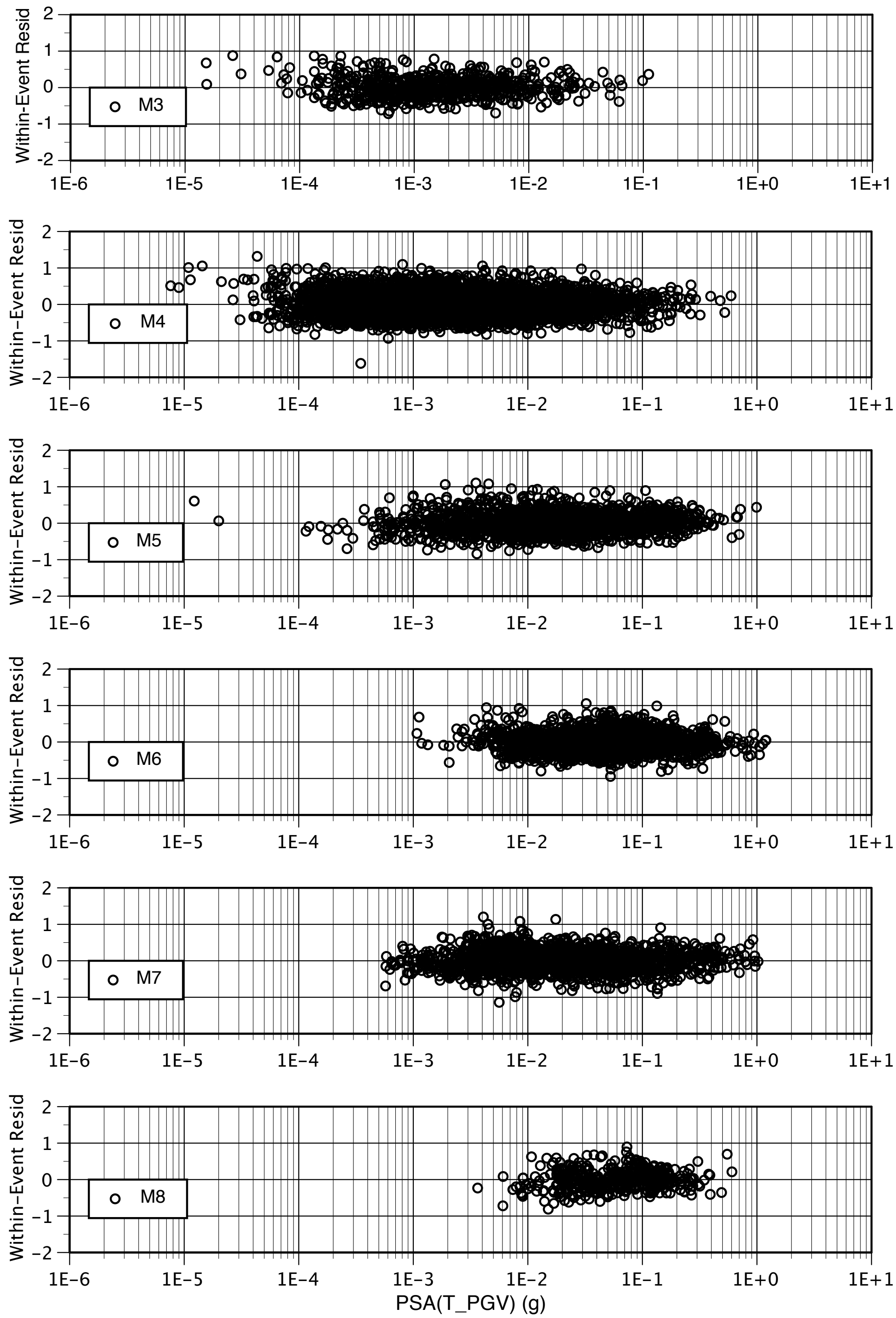

Figure 3.8: $PSA(T_{PGV})$ **dependence of the within-event residuals for the horizontal component.**

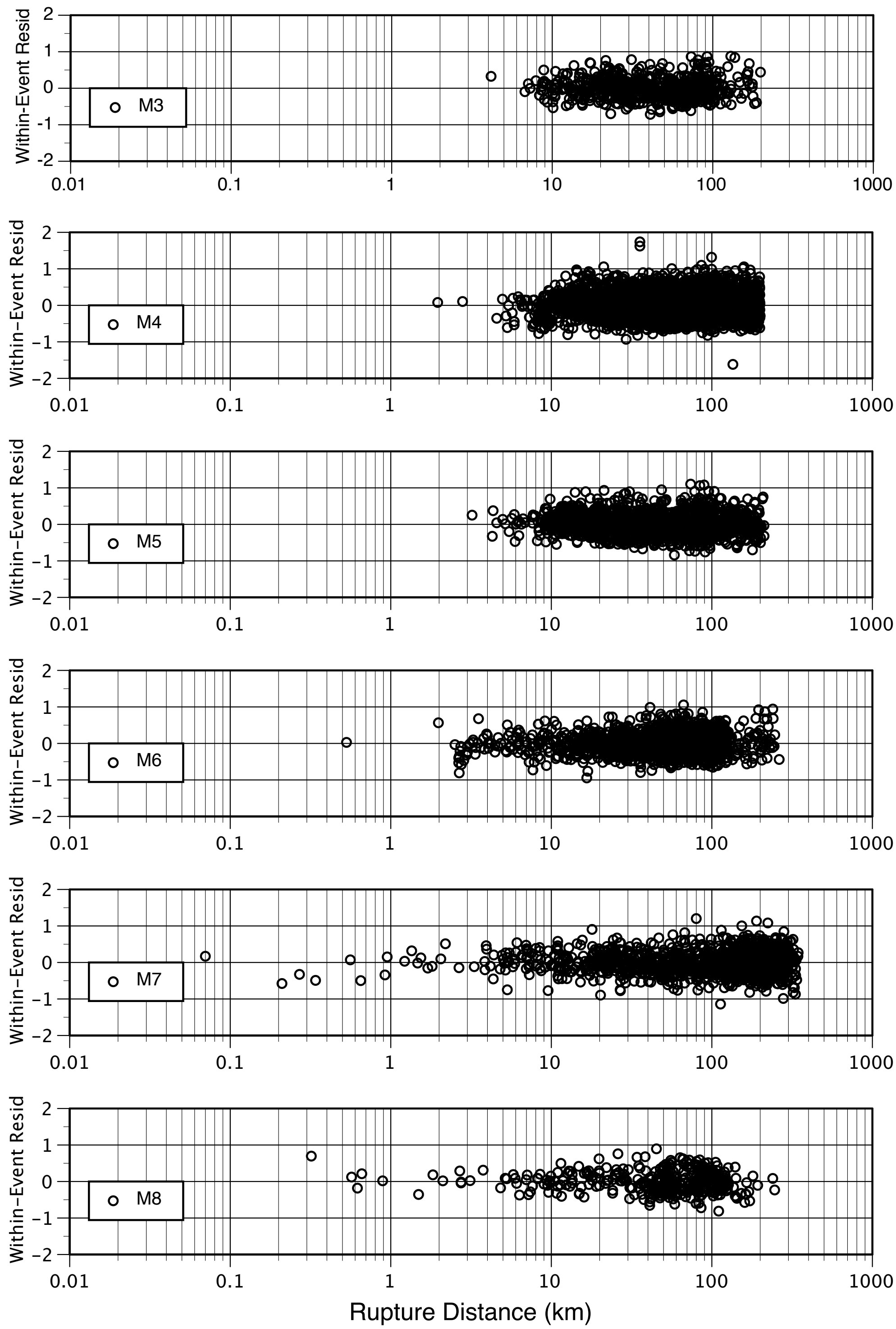

Figure 3.9: Distance dependence of the within-event residuals for the horizontal component.

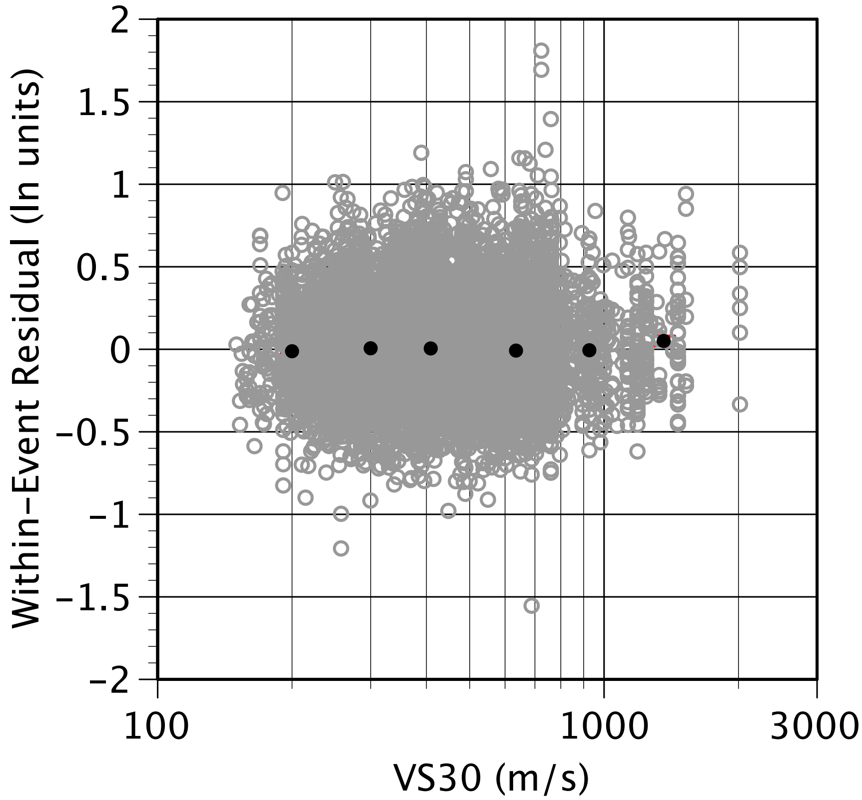

Figure 3.10: V_{S30} dependence of the within-event residuals for the horizontal component. The black symbols are the mean values by V_{S30} bin.

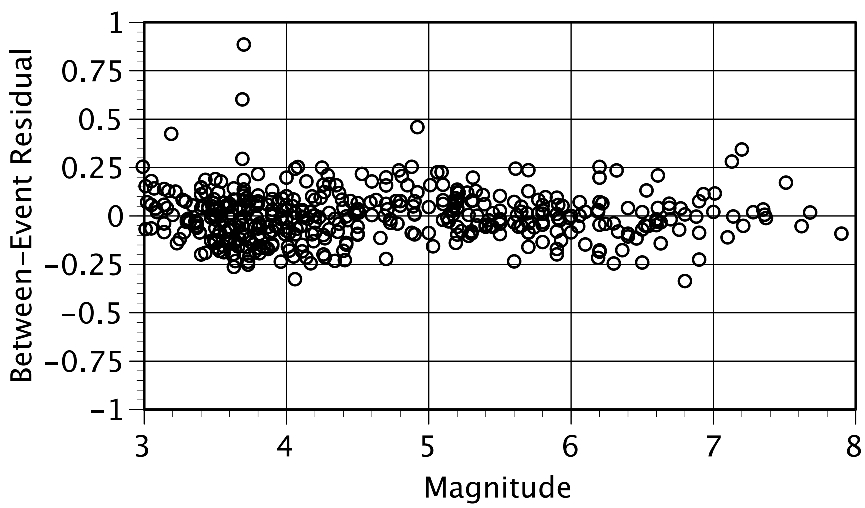

Figure 3.11: Between-event residuals for the horizontal component.

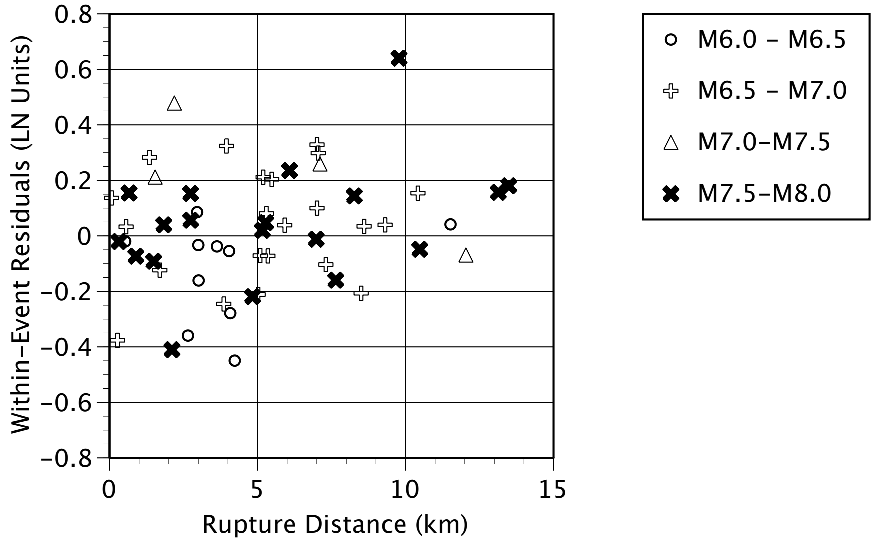

Figure 3.12: Within-event residuals of the conditional PGV model for near-fault ground motions with velocity pulses.

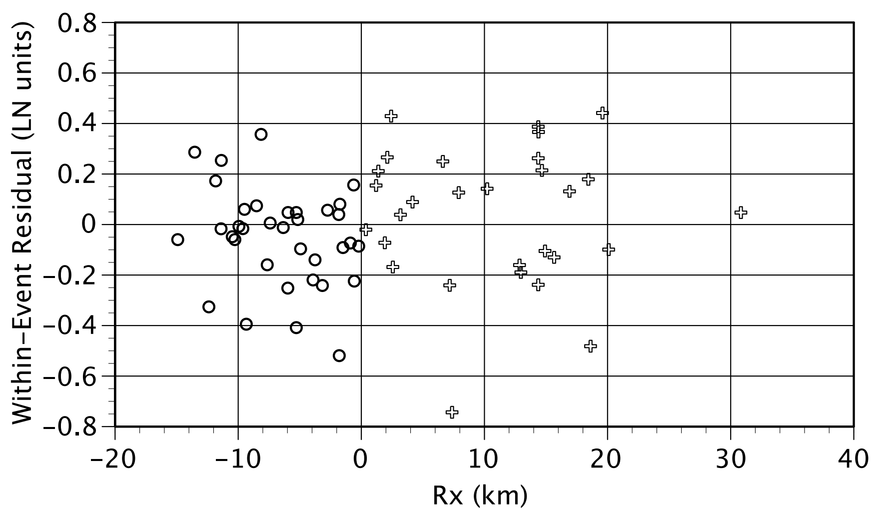

Figure 3.13: Within-event residuals of the conditional PGV model for near-fault ground motions for dipping faults. The sites with positive R_x are on the HW side and sites with negative R_x are on the footwall side.

4 Converting Conditional GMMs to Traditional GMMs

The conditional PGV model can be converted to a traditional scenario-based PGV model by combining it with a GMM for the $ln[SA(T_{PGV})]$ values. The median PGV is computed by using the median $PSA(T_{PGV})$ from the GMM as input to the conditional GMM for PGV. The aleatory variability is computed using the propagation of errors given in Equation (3.2).

4.1 MEDIAN MODEL

Figure 4.1 shows the resulting median PGV values from the conditional models compared to the geometric mean of the PGV from the four NGA-W2 PGV GMMs for strike–slip earthquakes with magnitudes between 3 and 8 for a rupture distance of 20 km and a stiff-soil site condition. For this example, the geometric mean of the RotD50 $PSA(T)$ values from the four GMMs is computed and combined with the previous conditional PGV models and the conditional PGV model developed in this study. The PGV estimates from all four conditional PGV models are similar for the **M**6.0 to **M**6.5 range, which is near the center of the data available for the previous studies. The Newmark and Hall (1982) and Bommer and Alarcon (2006) models do not include a magnitude term, which results in weaker magnitude scaling above **M**6.5 for these two models than observed in the GMMs. The Huang and Whittaker (2015) model includes a magnitude scaling term, and this model is consistent with NGA-W2 PGV GMMs for $M > 6$. The model developed in this study captures the magnitude scaling in the PGV GMMs over the full range of magnitudes.

Figure 4.2 shows the PGV resulting from the four individual scenario-based PGV models as a function of magnitude along with the median PGV from the four NGA-West2 GMMs. The four scenario-based models all capture the curvature in the magnitude scaling from **M**3 to **M**8. There is only a small epistemic range in the median PGV, given the $PSA(T_{PGV})$ values. For this distance, there is adequate data to constrain the GMMs, so the four GMMs yield similar $PSA(T)$ values. The largest epistemic range is related to differences in break points in the magnitude scaling for the four GMMs, causing kinks in the magnitude scaling.

4.2 ALEATORY VARIABILITY

The aleatory variability of the $ln(PGV)$ for a given earthquake scenario is computed using simple propagation of errors shown in Equation (3.2). With the functional form of the conditional PGV model given in Equation (3.7):

$$\frac{\partial lnPGV}{\partial lnPSA(T_{PGV})} = f_1(M) \tag{4.1}$$

The aleatory variability is then given by:

$$\sigma^2_{lnPGV} = f_1^2(M)\sigma^2_{lnPSA(T_{PGV})} + \sigma^2_{lnPGV|PSA(T_{PGV})} \tag{4.2}$$

Using the average of the NGA-West2 GMMs, the standard deviation of the $ln(PGV)$ and the $PSA(T_{PGV})$ are shown in Table 4.1 for magnitudes of 3, 4, 5, 6, 7, and 8 at a distance of 30 km. Using these values, the standard deviation of the $ln(PGV)$ given by the average of the NGA-West2 GMMs is compared to the standard deviation computed using Equation (4.2) in Figure 4.3. The standard deviation computed using the conditional PGV model shows a similar magnitude dependence of σ_{lnPGV} as given by the average of the four NGA-West2 GMMs for PGV.

Figure 4.3 also shows the standard deviations computed using the approaches recommended by Bommer and Alarcon (2006) and by Huang and Whittaker (2015). Bommer and Alarcon (2006) recommend using the standard deviation of the $PSA(T = 0.5)$ without considering the $\sigma_{lnPGV|PSA(T_{PGV})}$ term, whereas Huang and Whittaker (2015) recommend adding the variance of the conditional PGV model to the variance of the $PSA(T = 1)$. In this comparison, the standard deviations from the ASK14 model are used for the σ_{lnPSA} terms; see Abrahamson et al. (2014). The Bommer and Alarcon (2006) approach overestimates the standard deviation by 0.05 to 0.1 natural log units, which simply reflects the difference between the standard deviation of $ln(PGV)$ and $ln[PSA(T = 0.5)]$. The Huang and Whittaker (2015) approach overestimates the standard deviation of the PGV by about 0.2 natural log units. This large overestimation results from both the larger standard deviation of $ln[PSA(T = 1)]$ compared to $ln(PGV)$ and the addition of the variability from the conditional PGV model. This comparison demonstrates the value of allowing the slope of the $ln(PSA)$ term to be different from unity for computing appropriate standard deviations of the $ln(PGV)$ for a given scenario.

The results using the conditional model based on PGA or $PSA(T = 1)$ are shown in Figure 4.4. These models lead to similar PGV values, but they do not fit the scaling over the full magnitude range as well as the model using a magnitude-dependent period, T_{PGV}. The aleatory standard deviations computed using the PGA or the $PSA(T = 1)$ conditional models are shown in Figure 4.5. The conditional model based on $PSA(T = 1)$ gives similar standard deviations, but the conditional model based on PGA underestimates the standard deviation.

Table 4.1: Standard deviation for unconditional $ln(PGV)$ for crustal earthquakes, horizontal component.

			NGA-W2		σ_{lnPGV}	
Mag	T_{PGV}	$f_1(M)$	$\sigma_{ln[PSA(T_{PGV})]}$	$\sigma_{lnPGV\|PSA(T_{PGV})}$	This Study	NGA-W2
3	0.12	0.819	0.86	0.33	0.78	0.75
4	0.23	0.819	0.84	0.33	0.75	0.75
5	0.45	0.819	0.76	0.33	0.70	0.70
6	0.88	0.772	0.72	0.33	0.65	0.62
7	1.7	0.724	0.71	0.33	0.61	0.60
8	3.3	0.677	0.71	0.33	0.58	0.60

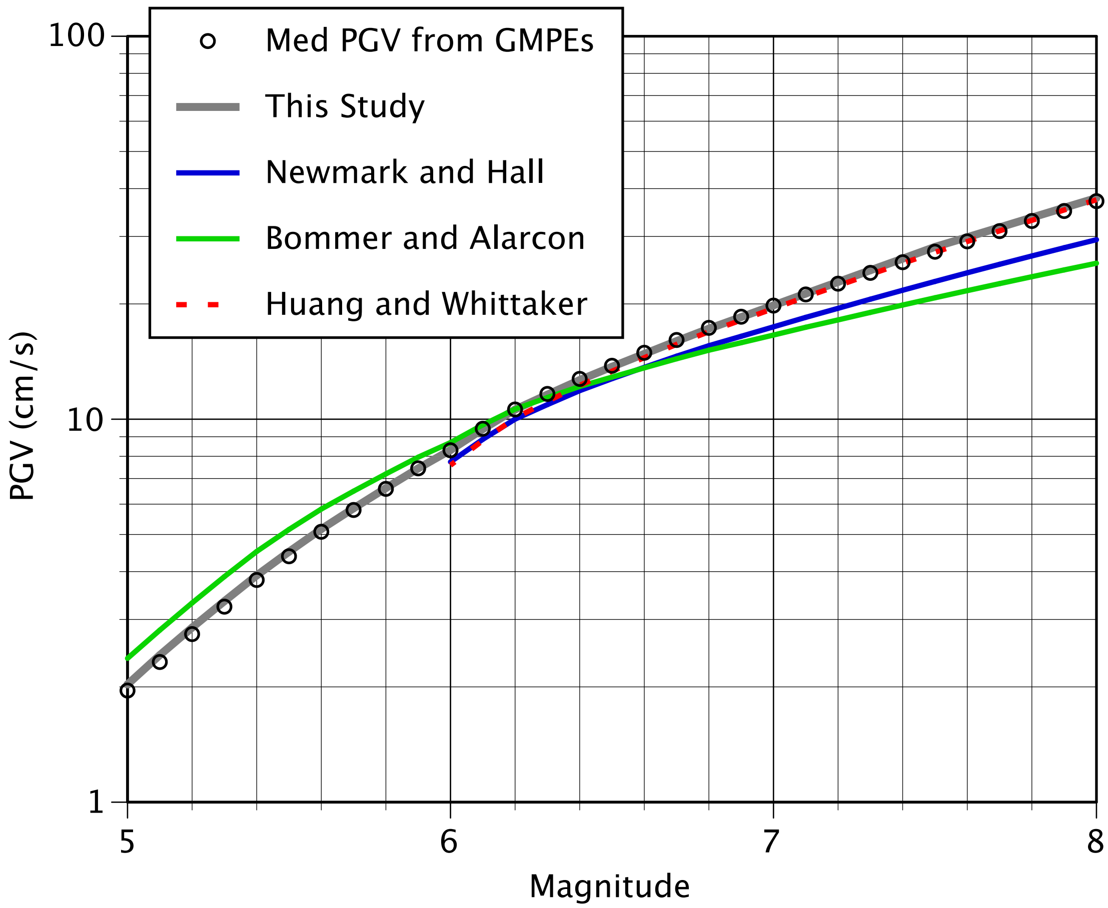

Figure 4.1: Comparison of the magnitude scaling for the conditional PGV model for the horizontal component. The $PSA(T)$ is for the median spectrum from four NGA-West2 GMMs from a strike–slip earthquake at a rupture distance of 20 km at a stiff-soil site conditions (V_{S30} = 400 m/sec).

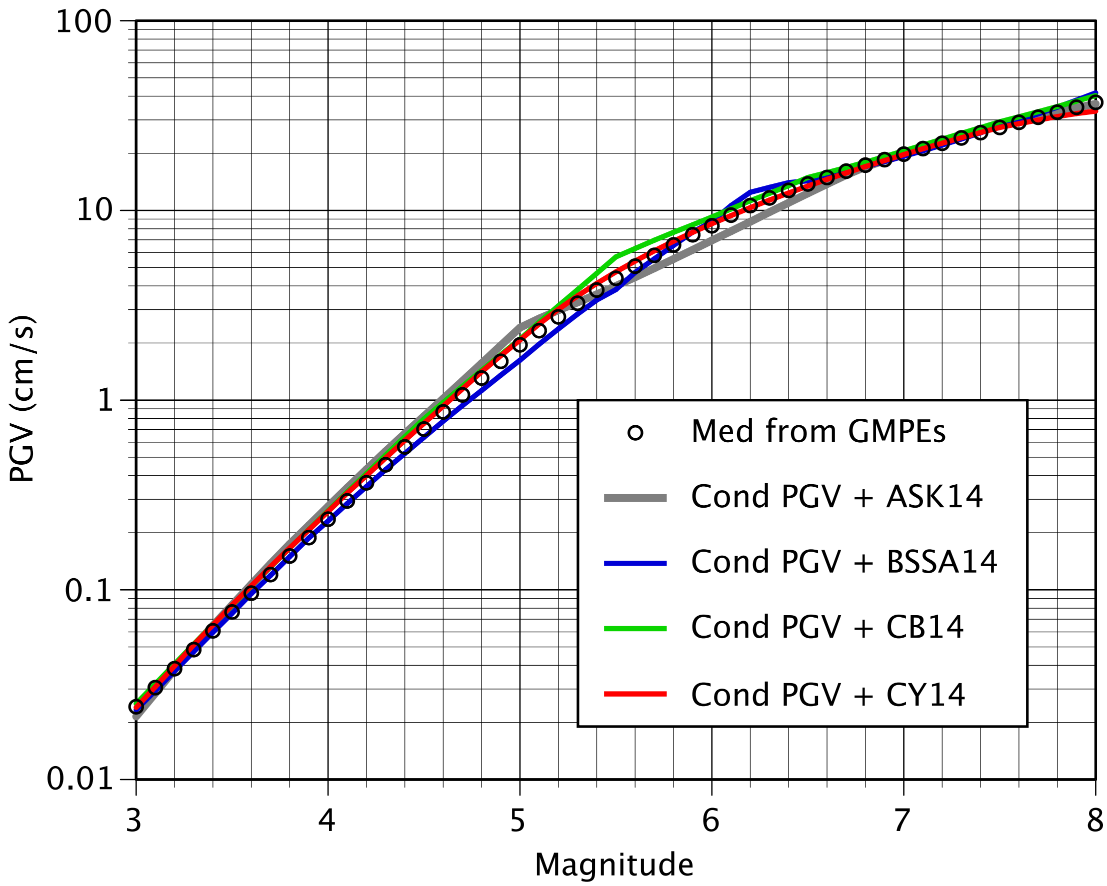

Figure 4.2: Comparison of the magnitude scaling for the horizontal component PGV using four different GMMs to compute the $PSA(T)$ values for the median spectrum from a strike–slip earthquake at a rupture distance of 20 km at a stiff-soil site conditions. The four GMMs used are: ASK14 = Abrahamson et al. (2014); BSSA14 = Boore et. al. (2014); CB14 = Campbell and Bozorgnia (2014); and CY14 = Chiou and Youngs (2014).

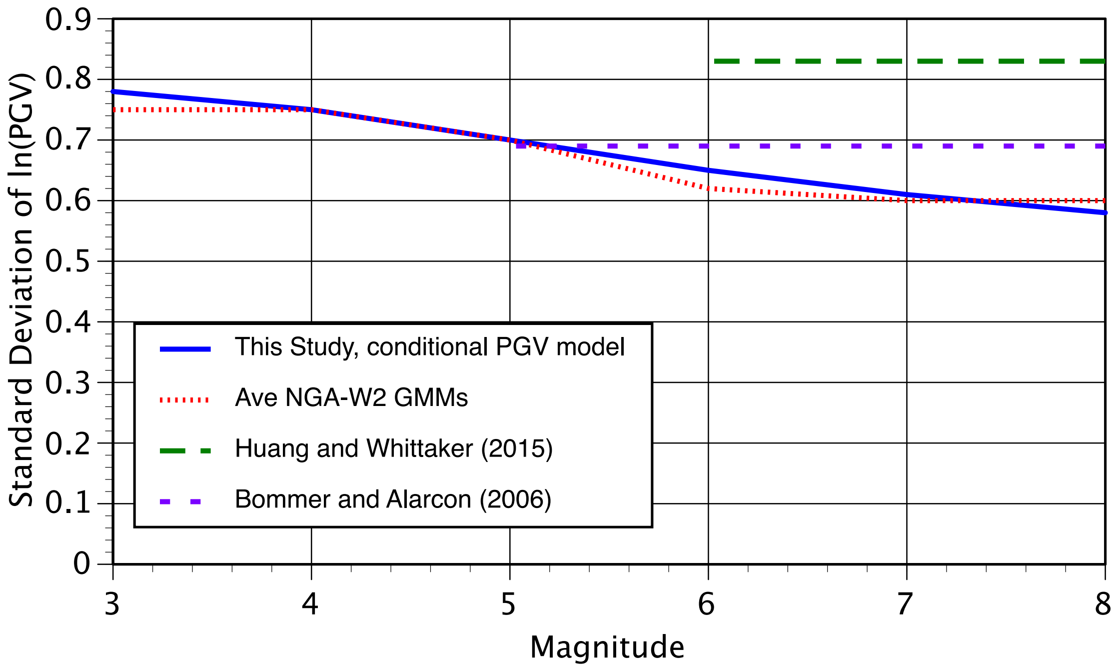

Figure 4.3: Magnitude dependence of the aleatory standard deviation for $ln(PGV)$ for crustal earthquakes, horizontal component for a distance of 20 km.

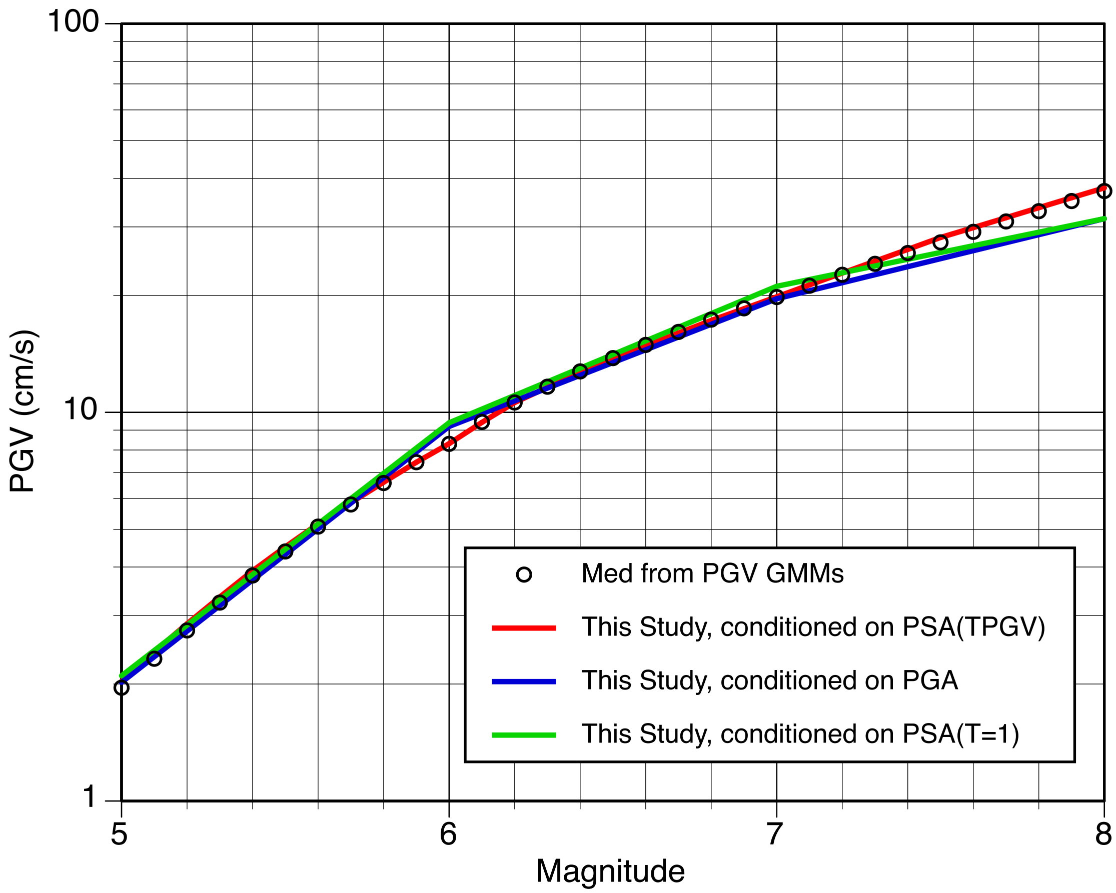

Figure 4.4: Magnitude scaling at a rupture distance of 20 km for the PGA and $PSA(T = 1)$ models compared to the scaling for model based on $PSA(T_{PGV})$.

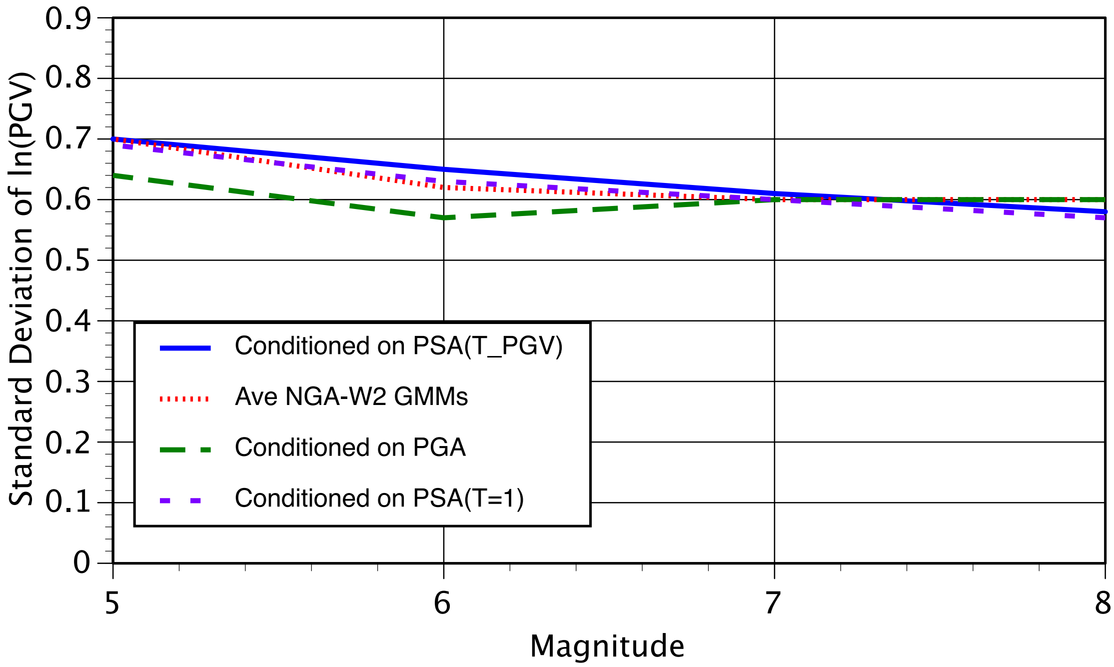

Figure 4.5: Comparison of the aleatory standard deviation computed using the models conditioned on PGA and $PSA(T = 1)$ compared to the standard deviation for the conditional model based on $PSA(T_{PGV})$.

5 Conclusions

Conditional ground-motion models are useful for developing design values for secondary ground-motion parameters consistent with the design response spectral values. While models for the $PGV/PSA(T)$ ratio have been developed in previous studies, our model uses a magnitude-dependent spectral period that captures a key physical behaviour of earthquake ground motion: the corner frequency is magnitude dependent. With a proper physical basis, the conditional models can be reliably extrapolated outside of the range that is constrained by the empirical data. For engineering applications, we judge that the conditional PGV models developed in this study can be reliably extrapolated up to **M**8.5 for crustal earthquakes based on the magnitude scaling of the corner frequency.

The conditional PGV models can also be combined with appropriate GMMs for $PSA(T)$ to develop traditional GMMs for PGV. Because the conditional models use the $PSA(T)$ values as predictive parameters, they show less regional differences than traditional GMMs. That is, the regional differences are captured in the $PSA(T)$ values; therefore, a global ergodic conditional GMM is more likely to be applicable to many different regions than a traditional GMM. Due to the use of non-unity slopes for the $ln[PSA(T)]$ dependence in our conditional GMM, an appropriate aleatory standard deviation of the resulting $ln(PGV)$ can be computed, avoiding the over-prediction of the aleatory standard deviation seen in previous models.

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