2012 Update of the Campbell-Bozorgnia NGA Ground Motion Prediction Equations: A Progress Report

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SUMMARY:
In 2008, we published a ground motion prediction equation (GMPE) appropriate for estimating peak and response spectral ground motion parameters from shallow crustal earthquakes in active tectonic regions. The GMPE was developed as part of the Next Generation Attenuation (NGA) program (now called NGA-West1) coordinated by the Pacific Earthquake Engineering Research Center. As successful as the original NGA-West1 program was, there were several ground motion issues that could not be addressed because of time constraints, which we are subsequently including in our updated GMPE as part of the NGA-West2 program. We also are making several improvements to our GMPE including: (1) a better method for incorporating magnitude saturation in near-source large magnitude ground motions, (2) incorporation of hypocentral depth as a scaling parameter, (3) additional and improved estimates of sediment depth, (5) additional spectral periods for a smoother predicted response spectrum, and (6) incorporation of an anelastic attenuation term.

Keywords: Ground motion prediction equation, NGA, attenuation, site response, magnitude saturation

1. INTRODUCTION

In 2008, we published a ground motion prediction equation (GMPE) that we considered to be appropriate for estimating peak ground acceleration (PGA), peak ground velocity (PGV), and 5%-damped pseudo-absolute acceleration response spectra (PSA) from shallow crustal earthquakes in active tectonic regions (Campbell and Bozorgnia, 2007, 2008). We also developed a preliminary GMPE for peak ground displacement (PGD). The GMPE was developed as part of the Next Generation Attenuation (NGA) program (Power et al., 2008) coordinated by the Pacific Earthquake Engineering Research Center (PEER). This program is now called NGA-West1 in order to distinguish it from a subsequent follow-on study (NGA-West2) and a similar study for eastern North America (NGA-East) also coordinated by PEER. Many researchers, practitioners, and organizations located throughout the world are using our NGA-West 1 GMPE together with the other NGA-West1 GMPEs (Abrahamson et al., 2008; Power et al., 2008) in engineering seismology applications. Part of the program's success is that subsequent studies have shown that the NGA-West1 GMPEs are generally consistent with recordings of moderate-to-large magnitude ground motions and with other GMPEs in shallow tectonically active regions throughout the world, including Europe and the Mediterranean region (Campbell and Bozorgnia, 2006; Stafford et al., 2008; Peruša and Fajfar, 2010), Taiwan (Lin, 2007), Italy (Scasserra et al., 2009), and Iran (Shoja-Taheri et al., 2009). Unpublished results from similar ongoing studies have found similar results for shallow crustal earthquakes in western Canada, New Zealand, Japan, and Latin America.

As successful as the original NGA-West1 program was, there were several ground motion issues that could not be addressed because of time constraints, which we are subsequently including in our updated GMPE as part the NGA-West2 program. These issues include the incorporation of: (1) source directivity effects, (2) horizontal component directionality, (3) vertical ground motion, (4) small-magnitude ($3.0 \le \mathbf{M} < 6.0$) recordings from California; (5) recent moderate- and large-magnitude

($6.0 \leq \mathbf{M} \leq 7.9$) recordings from around the world, (6) PSA scaling with damping, (7) epistemic uncertainty, and (8) improved site-response characterization (Bozorgnia et al., 2012). The small-magnitude database includes several tens of thousands of recordings from earthquakes in California in order to better constrain small-magnitude scaling and to allow a comparison of our predictions with small-magnitude data in other regions of the world where moderate and large magnitude recordings are not available. Some of the significant recent earthquakes that are included in the updated moderate and large magnitude database are 2003 Bam (Iran, **M** 6.7), 2004 Parkfield (California, **M** 6.0), 2007 Niigata Chuetsu-oki (Japan, **M** 6.7), 2008 Wenchuan (China, **M** 7.9), 2009 L'Aquila (Italy, **M** 6.3), 2010 El Mayor-Cucapah (Mexico, **M** 7.2), 2010 Darfield (New Zealand, **M** 7.1), 2011 Christchurch (New Zealand, **M** 6.1), as well as many others. Fig. 1.1 shows the distribution of this latter database with respect to moment magnitude (**M**) and closest distance to fault rupture (R_{RUP}).

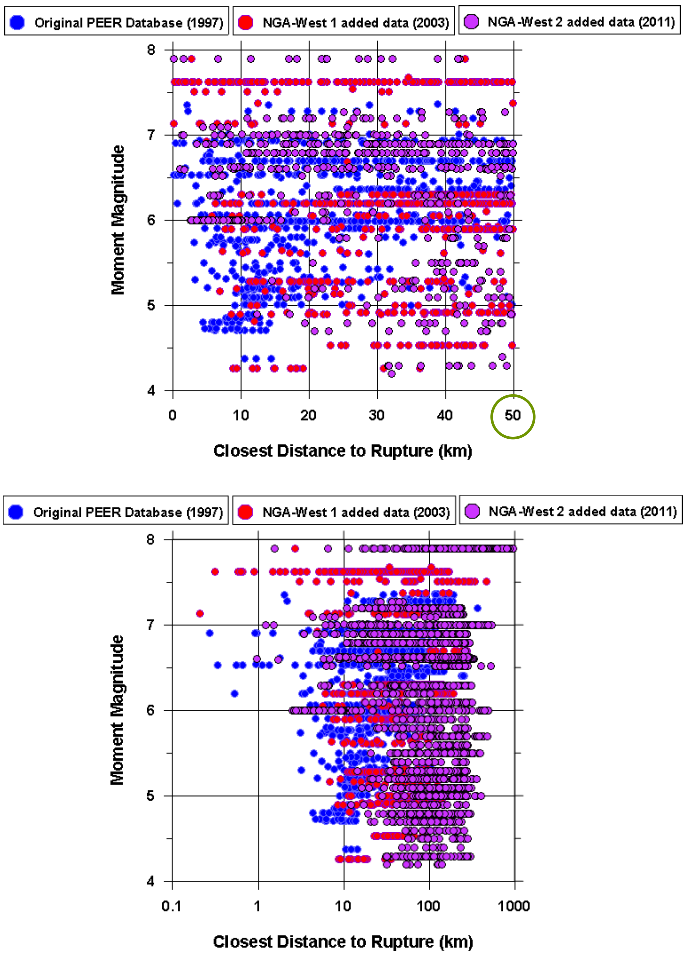

Figure 1.1. Magnitude-distance distribution of earthquakes in the NGA-West2 moderate-to-large magnitude database for near-source distances (top) and all distances (bottom)

We also are making several improvements and enhancements to our NGA-West 1 GMPE. Some of the more important of these that have been incorporated to date include: (1) implementing a better method for modelling magnitude saturation in the prediction of near-source large-magnitude ground motions, (2) including hypocentral depth as a scaling parameter, and (3) incorporating a regionally independent geometric attenuation term. These items are discussed in more detail below. Other issues that are currently being explored, but which are not far enough along to be presented at this time, include: (4) incorporating additional spectral periods for a smoother predicted response spectrum, (5) improved and additional sediment depths for a better constrained basin response term, (5) a regionally dependent long-distance attenuation term for better constrained far-source predictions, (6) a depth-dependent shallow site-response term parameterized in terms of the shear-wave velocity in the top 30 m of a site (V_{S30}), and (7) a regionally dependent shallow site-response term also parameterized in terms of V_{S30}.

2. NEAR-SOURCE MAGNITUDE SATURATION

The functional form we used previously included a magnitude-dependent geometric attenuation term given by the relationship

$$f_{dis} = (c_4 + c_5\mathbf{M}) \ln \sqrt{R_{RUP}^2 + c_6^2} \tag{2.1}$$

We found that this relationship caused "oversaturation" (inverse scaling with magnitude) of PGA and short-period PSA at large magnitudes and short distances. The only way that this oversaturation could be prevented was by constraining the large-magnitude coefficient in the magnitude scaling term

$$f_{mag} = \begin{cases} c_1\mathbf{M}; & \mathbf{M} \le 5.5 \\ c_1\mathbf{M} + c_2(\mathbf{M} - 5.5); & 5.5 < \mathbf{M} \le 6.5 \\ c_1\mathbf{M} + c_2(\mathbf{M} - 5.5) + c_3(\mathbf{M} - 6.5); & \mathbf{M} > 6.5 \end{cases} \tag{2.2}$$

to the equality $c_3 = -(c_1 + c_2 + c_5 \ln c_6)$. However, this constraint changes the magnitude scaling at all distances and not just in the near-source region where the oversaturation occurs.

In order to limit the correction for oversaturation to only those near-source distances where it occurs, we modified the distance scaling term to the equation

$$f_{dis} = \begin{cases} [c_4 + c_5(\mathbf{M} - 6.5)] \ln \sqrt{R_{RUP}^2 + c_6^2}; & \mathbf{M} < 6.5 \\ c_4 \ln \sqrt{R_{RUP}^2 + \{c_6 \exp[c_6'(\mathbf{M} - 6.5)]\}^2}; & \mathbf{M} \ge 6.5 \end{cases} \tag{2.3}$$

where,

$$c_6' = \begin{cases} -(c_1 + c_2 + c_3)/c_4; & c_1 + c_2 + c_3 + c_4 c_6' < 0 \\ c_6'; & \text{Otherwise} \end{cases} \tag{2.4}$$

The first line in Eqn. 2.4 is the constraint when oversaturation occurs. The key to this new saturation term is constraining the geometric attenuation coefficient to be independent of magnitude and the pseudo-depth term to be an exponential function of magnitude for $\mathbf{M} \ge 6.5$ (the lower term in Eqn. 2.3). When the condition in the upper term of Eqn. 2.4 is not met, the equation can range from partial to no saturation. This behaviour is demonstrated in Fig. 2.1.

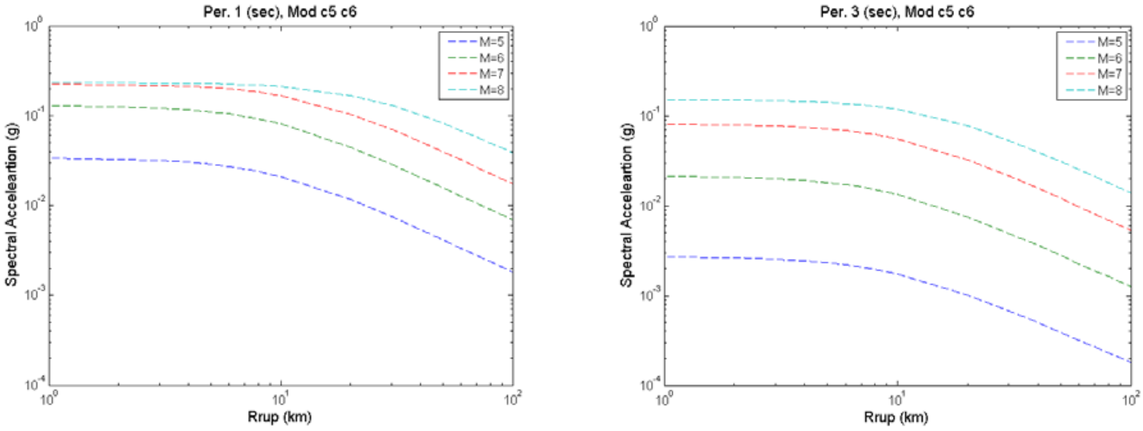

Figure 2.1. New near-source magnitude saturation term showing total (left) and partial (right) saturation

3. HYPOCENTRAL DEPTH

Several of the NGA-West1 GMPEs incorporated a source-depth term that was parameterized in terms of the depth to the top of the rupture plane, Z_{TOR} (Abrahamson et al., 2008). In our previous mode, we included source depth only as part of our fault mechanism term through the equation

$$f_{flt} = c_7 F_{RV} f_{flt,Z} + c_8 F_{NM} \tag{3.1}$$

where F_{RV} is the reverse-faulting parameter, F_{NM} is the normal-faulting factor, and

$$f_{flt,Z} = \begin{cases} Z_{TOR}; & Z_{TOR} \leq 1\,\text{km} \\ 1; & \text{Otherwise} \end{cases} \tag{3.2}$$

Using the expanded NGA-West2 database, we found that there was a strong dependence of short-period ground motion on hypocentral depth. The resulting relationship is given by the equation

$$f_{hyp} = \begin{cases} 0; & Z_{HYP} < 10\,\text{km} \\ c_{13} Z_{HYP} - 10; & Z_{HYP} \geq 10\,\text{km} \end{cases} \tag{3.3}$$

which is valid up to the depth limit of the data (about 25–30 km). This also allowed us to remove depth from the source mechanism term resulting in a simpler fault mechanism term given by

$$f_{flt} = c_7 F_{RV} + c_8 F_{NM} \tag{3.4}$$

Fig. 3.1 shows the impact of including the hypocentral depth term in the GMPE for strike-slip events. Figs. 3.2 and 3.3 show the same impacts for reverse-faulting and normal-faulting events, respectively.

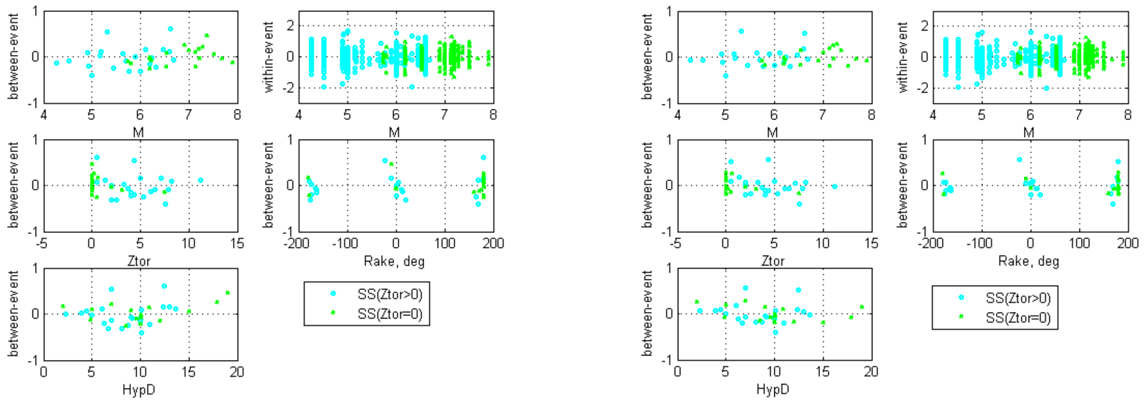

Figure 3.1. Inter-event residuals excluding (left) and including (right) the new hypocentral depth term for strike-slip-faulting mechanisms (smaller green symbols refer to surface-faulting events)

In all cases, the inclusion of the new hypocentral-depth and fault-mechanism terms (Eqns. 3.3 and 3.4) remove the biases and trends in the residual plots of the inter-event (between-event) residuals (i.e., source terms) plotted against magnitude and hypocentral depth. Even the residual trends with respect to Z_{TOR} are improved, although the results are more statistically significant when Z_{HYP} (HypD in the plots) is used in the GMPE. Also shown in these plots are the intra-event (within-event) residuals plotted against magnitude and the inter-event residuals plotted against rake angle (the angle between the strike of the fault and the direction of slip on the fault plane). The smaller symbols (green for strike-slip faults and black for reverse faults) indicate those events with surface rupture. There is no obvious bias between surface-rupture and buried faults once hypocentral-depth scaling is incorporated.

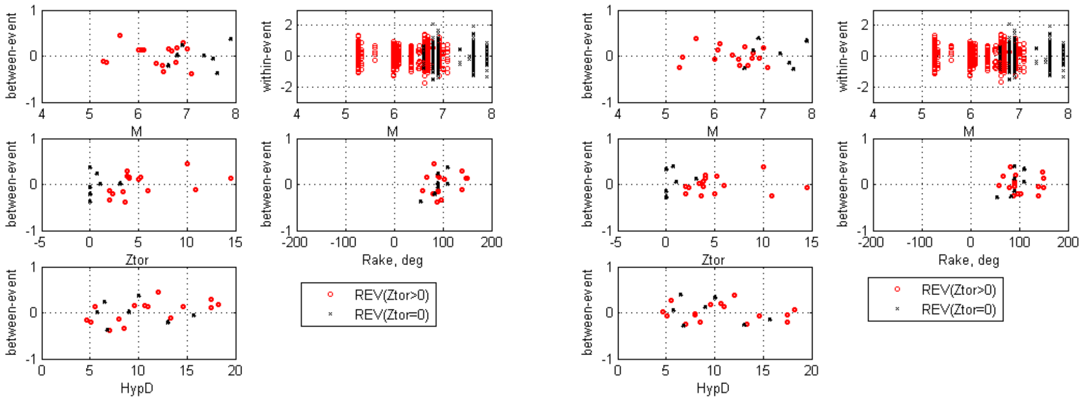

Figure 3.2. Inter-event residuals excluding (left) and including (right) the new hypocentral depth term for reverse-faulting mechanisms (smaller black symbols refer to surface-faulting events)

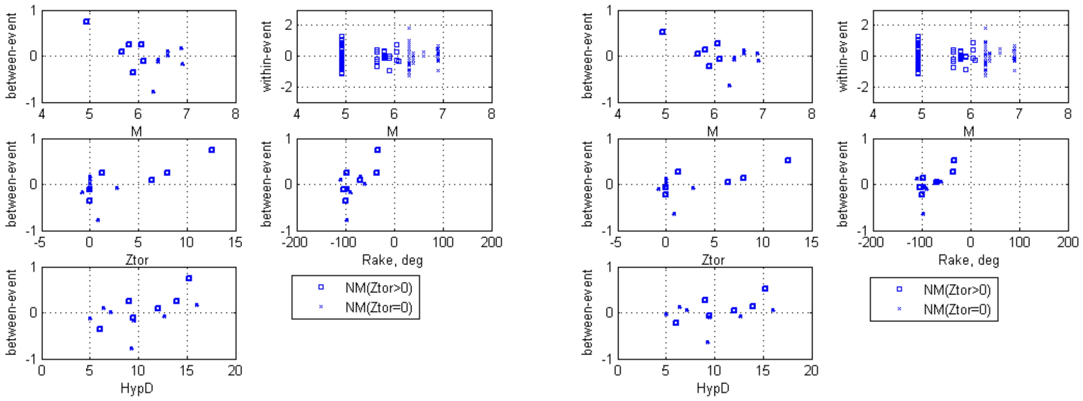

Figure 3.3. Inter-event residuals excluding (left) and including (right) the new hypocentral depth term for normal-faulting mechanisms (smaller symbols refer to surface-faulting events)

4. REGIONAL DIFFERENCES IN GEOMETRICAL ATTENUATION

Geometrical attenuation, or what seismologists often call the spreading term, models the rate of decay of ground motion at relatively close distances to the source, where the effects of other attenuation mechanisms, such as anelastic attenuation and scattering (effective *Q*), are negligible. It is well known that *Q* is regionally dependent with, for example, far-source ground motion decay being much greater in western North America than in central and eastern North America. One of the important questions we have addressed in the NGA-West2 project is whether geometrical attenuation is regionally dependent. In order to investigate this, we used our previous magnitude-scaling functional form and our new distance-scaling functional form (Eqns. 2.3 and 2.4), together with the NGA-West2 recordings within a rupture distance of 80 km, to investigate potential regional differences in geometrical attenuation. Intra-event residuals from this analysis are shown in Fig. 4.1 for earthquakes in California, Japan, Italy, Taiwan (Chi-Chi earthquake), China (Wenchuan earthquake), and Greece.

Inspection of Fig. 4.1 indicates that geometrical attenuation for PGA and 1.0-s spectral acceleration appears to be independent of the region in which the earthquakes occur. This implies that this part of the GMPE functional form can be calibrated using data from all active tectonic regions and that only attenuation at longer distances (the *Q* term or what some call anelastic attenuation) must be modelled as being regionally dependent. Observations of intra-event residuals at distances longer than 80 km indicates that long-distance attenuation related to *Q* is very strong in Japan and Italy, possibly due to travel paths through hotter crust associated with volcanic regions and very weak from the Wenchuan

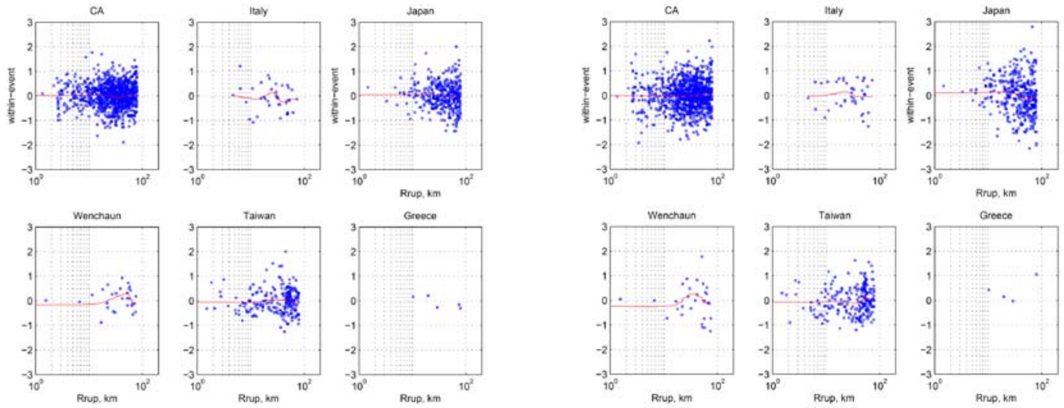

Figure 4.1. Intra-event residuals from a GMPE developed for PGA (left) and 1.0-s PSA (right) from recordings obtained within 80 km of the fault rupture plane showing no apparent regional dependence of geometric attenuation

earthquake due to propagation of ground motion primarily to the east through the stable continental region of China. The Chi-Chi (Taiwan) earthquake has very strong azimuthal differences in ground motion decay, but this attenuation behaves on average (i.e., averaging over all azimuths) like that from similar magnitude earthquakes in California.

5. OTHER OBSERVATIONS

There are several other observations that we or others have noted during the NGA-West2 project as of the writing of this manuscript. We will consider these observations when revising our GMPE. Some of the more important of these observations are as follows:

1. The shallow site-response (V_{S30}) term is very different in Japan, and perhaps in other regions, e.g., Italy, than it is in California. This could be due to fundamentally different upper crustal profiles in these regions. For example, Japan and Italy have profiles that have relatively soft deposits at shallow depths that grade rapidly to high-velocity deposits at relatively shallow depths. Such profiles will generally demonstrate relatively high narrow-band amplification that demonstrates generally less nonlinear behaviour than typical sites in California. We need to decide whether we will exclude these recordings from our update or modify our shallow site-response term to be regionally dependent.

2. The deep site-response parameterized in terms of the depth to the 2.5 km shear-wave velocity horizon ($Z_{2.5}$) is also very different in Japan, the only region outside of California where there are enough depths to this horizon for comparison, than in California. These depths tend to be much shallower for the same value of V_{S30}, which leads to different predicted amplification effects. As with the shallow site-response term, we need to decide whether we will exclude these recordings from our update or modify our deep site-response term to be regionally dependent.

3. The Southern California Earthquake Center (SCEC) has developed two competing Community Velocity Models: CVM4 and CVM-H. We need to evaluate the sediment-depth ($Z_{2.5}$) values from each of these models and decide which ones to use in our deep site-response term. Alternatively, we might use both sets in order to incorporate uncertainty between these two competing models.

4. Magnitude and distance scaling characteristics of small-magnitude ($3.0 \leq \mathbf{M} \leq 5.5$) ground motions collected during the NGA-West2 project are different from those predicted by extrapolating our NGA-West1 GMPE. We and others had already noted this using a more

limited small-magnitude dataset (Campbell, 2008, 2011; Atkinson and Morrison, 2009; Chiou et al., 2010; Atkinson and Boore, 2011), but now we have an extensive, uniformly processed database to reliably extend our GMPE to smaller magnitudes. This will allow others to compare our small-magnitude predictions with recordings from other regions, which are often only from small-magnitude earthquakes, in order to determine whether our GMPE can be used in these regions.

6. CONCLUSIONS

We are currently in the process of updating our NGA-West1 GMPE as part of the PEER NGA-West2 project. Besides using an extensive updated moderate-to-large magnitude database, we are also using several tens of thousands of recordings from small-magnitude earthquakes in order to extend our GMPE to earthquakes as small as **M** 3.0. As of the writing of this manuscript, we have (1) modified our functional form in order to provide a more realistic means of incorporating near-source magnitude saturation at larger ($\mathbf{M} > 6.5$) events, (2) discovered that geometric attenuation for ground motions with $R_{RUP} \leq 80$ km is regionally independent, and (3) added a hypocentral-depth term for $Z_{HYP} > 10$ km that removes both a distance bias noted in short-period ground motions from all fault mechanisms and allows us to remove the distance term in our existing reverse-faulting mechanism term. Current observations indicate that we will also need to consider that (1) both the shallow and deep site-response term is likely to be regionally dependent, (2) long-distance attenuation (*Q* effects) are stronger in volcanic regions than in other regions, and (3) small-magnitude ground motions have stronger scaling with both magnitude and distance than is predicted by our NGA-West1 GMPE.

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