Final Technical Report

Ground Motion Prediction Equations for Hawaii from a Referenced Empirical Approach

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Non-technical Summary

Ground-motion prediction equations for Hawaii are developed to estimate the strength of ground shaking from earthquakes of different magnitudes and distances. These equations are important for improving assessment of seismic hazard in Hawaii, and thereby enabling better protection of people and vulnerable infrastructure from damaging earthquakes.

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Abstract

Ground-motion prediction equations (GMPEs) for Hawaii are developed using the Referenced Empirical approach. The technique is based on the use of residual analysis that models discrepancies between ground-motion observations for Hawaii and a reference GMPE, in this case the GMPE of Boore and Atkinson (2008) for shallow crustal earthquakes in active tectonic regions. The Referenced Empirical approach provides GMPEs for Hawaii that are in agreement with regional ground-motion observations, while being constrained to follow the overall scaling behavior of ground motion that is observed in better-instrumented regions. GMPEs are developed for both shallow (depth<20km) and deep (35 to 40 km) earthquakes in Hawaii.

Introduction

Ground-motion prediction equations (GMPEs), providing estimates of peak ground motion and response spectral amplitudes as a function of earthquake magnitude and distance, are a key input to seismic hazard analysis. These equations allow us to estimate the average ground shaking effects for future earthquakes. The classical approach to the development of GMPEs is to perform a regression analysis of a database of recorded strong ground motions. An example is the prediction equations developed for shallow crustal earthquakes in active tectonic regions by the "PEER-NGA" (Pacific Earthquake Engineering Research Center – Next Generation Attenuation) project (Power et al., 2008); many other such examples that have been commonly used in seismic hazard applications in western North America (eg. Boore et al., 1997; Abrahamson and Silva, 1997; Sadigh et al., 1997).

In regions that do not have a rich strong-motion database from which to derive GMPEs, alternative methods need to be considered. For example, in eastern North America (ENA), GMPEs have often been derived based on performing simulations, with the model parameters calibrated with available data (eg. Atkinson and Boore, 2006). An alternative approach is the Referenced Empirical approach (Atkinson, 2008). In the Referenced Empirical approach, the aim is to use empirical data for the region of interest (the target region) to develop suitable modifications to empirical ground-motion relations developed from a larger database (the reference GMPE). The approach is similar in concept to the Hybrid Empirical approach of Campbell (2003), in that it is based on making adjustments to empirical equations from other regions. The rationale for such an approach is that empirical equations presumably capture important but complex source and distance scaling effects that are present in the data, but may be missing in a simple seismological model. By making regional adjustments to empirical GMPEs, we anchor our predictions to real experience from data-rich regions. The difference between the Referenced Empirical approach and the Hybrid Empirical approach is that the regional

adjustment factors for the Referenced Empirical approach are derived directly from the target-region ground-motion database. By contrast, in the Hybrid Empirical approach the regional adjustment factors are based on a seismological model.

The Referenced Empirical approach appears particularly well-suited to the development of GMPEs for Hawaii. There is a reasonable strong-motion database for Hawaii, as seen from its distribution in magnitude and distance in Figure 1. This database is sufficient to allow evaluation of regional ground motions in comparison to a reference GMPE, but is too sparse for a reliable direct development of regional GMPEs for Hawaii. An issue that complicates ground motion modeling in Hawaii is the depth distribution of events, which is extended due to the volcanic origin of the earthquake processes. The hazard comes both from shallow crustal earthquakes (depth<20 km) and from deeper events (35 to 45 km). The active volcanism of the region may also influence source and propagation characteristics; it is thus unclear whether GMPEs for shallow crustal earthquakes in other tectonic environments would necessarily be applicable. These are important questions, as Hawaii has a significant seismic hazard and a growing population and infrastructure base (Klein et al., 2001).

The Ground-Motion Database for Hawaii

Hawaii has a sparse but growing database of strong-motion observations, which was greatly enriched by the occurrence of the **M**6.7 Kiholo Bay and **M**6.0 Hawi earthquakes in 2006. Figure 1 plots available data in magnitude/distance space, distinguishing between shallow (depth h<20 km), intermediate (20 to 35 km), and deeper (35 to 40 km) events. Table 1 lists the events and the number of records available for each. The database was compiled from several sources, as listed in the Data and Resources section. I used corrected response spectra data when available, re-processing time histories to calculate corrected response spectra only as required. For events that have occurred since 2000, corrected ground-motion data and response spectra were downloaded from COSMOS. For the events of 1973 and 1975, corrected data were available from the U.S. Geological Survey (Seekins et al., 1991). For an event in 1983, only uncorrected time series data were available; the time series for this event were downloaded from a U.S. Geological Survey site linked to the Seekins et al. report. Processing for the 1983 event involved digital filtering and baseline correction as described by Boore and Bommer (2005). The database was compiled at 20 frequencies from 0.2 to 30 Hz, though the reliability of the older data at frequencies less than 0.5 Hz is suspect.

The basic data downloaded from the ground-motion database sources included the ground motions, location of the events and the recording stations, the event depth, and a magnitude measure. For the evaluation of GMPEs, we need the moment magnitude and depth for each event, the average near-surface shear-wave velocity of each recording station (V30, the time-averaged shear-wave velocity over the top 30 m), and a fault-distance measure for each observation. Fault-distance measures used in GMPEs include the closest distance from the station to the earthquake fault surface (R_{cd}), and the Joyner-Boore distance (R_{jb}), which is the closest distance from the station to the surface projection of the fault. For small events, R_{cd} is approximately equal to the hypocentral distance, while R_{jb} is approximately equal to the epicentral distance. For large earthquakes, the fault-distance measures will be less than the corresponding point-source distance on average. Thus the compilation of a useful ground-

motion database involves evaluation of a number of parameters. This evaluation is described in the following, with the data sources listed in the Data and Resources section.

Moment Magnitude: To obtain estimates of moment magnitude (**M**), I first searched the Global CMT catalog; this provided **M** values for events 3, 7, 8, 12, 13, 14, 15 and 16. For events 1 and 2 (the 1973 and 1975 events), it was assumed that **M**= Ms, following Munson and Thurber (1997) and Klein et al. (2001). For the 1975 event of Ms7.2, it is noted that there have been several studies that estimated **M**, with values in the range of 7.3 to 7.7 being reported (Nettles and Ekstrom, 2004). As 3 of 4 studies reported **M** of 7.3 or 7.4, the adopted value of 7.2 based on Ms appears reasonable, but may be slightly low; because GMPEs depend only weakly on magnitude for **M**>7, and there are few recordings of this event, this uncertainty is not significant. For the remaining events, I followed the approach of Klein et al. (2001) in using catalog magnitudes to represent **M**. After considering various alternative measures, the value of mb obtained from the ANSS catalog was assumed to be approximately equivalent to **M**. This assumption was based on plotting alternative magnitude values versus **M** for those events having multiple measures available. As shown in Figure 2, mb appears to be a reasonable estimate of **M** (though there are few events) from magnitude 4.5 to 6. Other magnitude measures available in the ISC catalogue, including duration magnitude (Md), Ms and ML were also considered, but mb appears to provide the most stable correlation with **M**. An empirical relationship between Md and M provided by Zuniga et al. (1988) was noted, but it is calibrated only for events of Md<4, which is below the magnitude range for the events of this study. An exception to the use of mb as an estimate of **M** was made for event 10, for which the mb value (3.9) appears unusually low relative to the Md value (4.7) reported by the Hawaii Volcano Observatory (HVO). For this event the average of the mb and Md estimates was adopted. It was noted that depth estimates provided by alternative catalogue sources (CMT, ANSS, HVO) are consistent, suggesting the depth estimates are reasonably reliable.

Distance measures: The geometry of the fault plane is not generally known for Hawaiian earthquakes, and most of the events are sufficiently small that this is not a major issue. Approximate value of R_{cd} and R_{jb} were calculated by using the empirical relationships of Wells and Coppersmith to estimate fault width and length based on moment magnitude. It was assumed that the hypocenter occurred at the center of a vertical fault with these dimensions, and the distance measures R_{cd} and R_{jb} were calculated according to this geometry. Epicentral and hypocentral distances were also calculated.

Site shear-wave velocity: Detailed site-specific information on shear-wave velocity profile is not available for the recording sites. However, Wald and Allen (2007) have developed a model that estimates V30 for sites using correlations between V30 and topography. The estimated V30 values for each of the recording stations in Hawaii, based on its latitude and longitude and regional topography, was provided by T. Allen (pers. comm., 2008) through application of this model. Estimated V30 values for the database sites are between 330 m/s and 740 m/s, with the average value over all records being 450 m/s.

The compiled database including all of the above parameters is available as an excel spreadsheet at the author's website: www.seismotoolbox.ca. The database contains 105 3-component records (see Figure 1). For this study, I focus on the geometric mean of the response spectra of the two horizontal components as the ground-motion parameter of interest. Peak ground acceleration is also considered.

Application of the Referenced Empirical Approach to Hawaii

Basis of the Method

The idea behind the Referenced Empirical approach is to use the target-region ground-motion database in concert with GMPEs from data-rich regions, in order to make the best use of both region-specific data and global experience from better-instrumented regions. The key inputs are the target-region ground-motion database, and a set of reference equations. In this study, the target region is Hawaii, and the reference equations are the GMPEs of Boore and Atkinson (2008) (BA08) for shallow crustal earthquakes in active tectonic regions (unspecified focal mechanism).

The most important underlying assumption is that the magnitude scaling of ground motions is the same for the target region (Hawaii) as that exhibited for shallow crustal earthquakes elsewhere, as is the overall near-source behavior with distance. Note that although the scaling is assumed to be similar, no such assumption is made regarding overall levels. The scaling assumption is reasonable based on ground-motion scaling principles (eg. constancy of stress drop; see Boore, 1983), and can be verified to a reasonable extent with the Hawaiian data, as will be shown. In this case, we can use the empirical data for Hawaii to make modifications to GMPEs from another environment, by deriving appropriate adjustment factors to reference equations that will modify the overall level of the curves, and possibly their shape as a function of distance. Adjustments to the overall level can accommodate such factors as regional variations in stress drop and event type, including the effects of focal depth, while adjustments to the distance coefficient accommodate regional attenuation. Thus we develop new GMPEs for Hawaii that are referenced to those that were derived from a larger database, richer in observations at large magnitudes and close distances.

The database for the study is the Hawaiian ground-motion dataset described in the previous section (geometric-mean-horizontal component). The reference ground motion prediction equations used in this study are the Boore and Atkinson (2008) (BA08) relations (unspecified mechanism) for shallow crustal earthquakes in active tectonic regions, developed in the PEER-NGA project (see Power et al., 2008) for the orientation-independent horizontal component (which is similar to the geometric mean). They are selected for their simplicity and convenience. Other reference relations from amongst the recent PEER-NGA equations could also be used, and would provide slightly different results, corresponding to the level of differences between the alternative PEER-NGA equations (see Abrahamson et al., 2008).

The BA08 equations are used to predict the mean horizontal ground motion for each magnitude, distance and V30 in the Hawaiian database. I then compute the residuals for each record, defined as the log(base10) of the ratio of observed Hawaii motions to those predicted by BA08 (ie. log residual = log (observed Hawaii amplitude) – log (predicted amplitude from BA08)). Figure 3 plots the residuals for 4 selected frequencies as a function of Joyner-Boore distance (R_{jb}), using different symbol types to distinguish magnitude levels and focal depths. Inspection of this figure suggests that the residuals have a linear trend with log distance at low frequencies, and are approximately independent of distance at high frequencies. There appears to be no significant dependence of residuals on magnitude level, but there appears to be a focal depth effect, with deeper events having higher residuals at high frequencies. These trends

suggest that the adjustment factor should provide for a linear dependence in log distance (for each frequency), with a possible difference in amplitude level based on focal depth.

Fitting the Observed Residuals

To define the residual trends noted in Figure 3, we seek an overall distance trend, and a level that may depend on focal depth. This can be achieved using Stage 1 of a two-stage regression procedure, as described by Joyner and Boore (1993). Linear regression with dummy variables is performed in order to extract the average-event-residual term of each earthquake and the distance scaling shape, using:

$$\log A_{ij} = \sum (c_0)_i \; E_i + c_1 \; (R_{jb})_{ij} \qquad (1)$$

where A_{ij} are the observed ground-motion residuals (earthquake i at station j), and $E_i = 1$ for earthquake i and 0 otherwise. The c_{0i} terms are the average-event-residual for each event (this is the source term, or amplitude level at 1 km). Figure 4 plots the c_{0i} terms versus focal for 4 selected frequencies, using different symbols to distinguish small (**M**4 to 5.5) from larger (**M**5.5 to 7.2) events. This confirms that there is no significant trend with magnitude, but that focal depth appears to be a significant factor in determining the overall level, at least for some frequencies. The residuals versus focal depth can be grouped into those for shallow events (h<20 km) and deep events (h>35 km), with a single event at intermediate depth (28 km). There is an anomalous shallow event which has a very low residual (-1 log units); the PSA values from this event (**M**5.2 at 14 km depth, on 2006/12/3), recorded on 6 stations near 100 km, all appear too low in amplitude. To avoid biasing the results, these data are not considered further in deriving the overall residual factors.

The c_{0i} terms from the shallow earthquakes (h<20 km) are used to calculate a weighted-average residual value, denoted $x_0(h<20)$, where the weights are based on the number of observations per event. The c_{0i} terms from the deep events (h>35 km) are used to calculate the corresponding weighted average residual $x_0(h>35)$. These weighted-average residual source terms are plotted versus frequency on Figure 5, along with the distance coefficients, c_1 (from Equation 1, as determined in the Stage 1 regression). Error bars show the standard errors of the coefficients. From these coefficients, I define smooth functions that describe the overall behavior of the residuals with frequency (f). The residuals (log A) are well-described by:

$$\log A = x_0 + x_1 \log R_{jb} \qquad (2)$$

where

$$x_1 = \min(-0.18 + 0.17 \log(f), 0) \qquad (3)$$

$$x_0(h<20) = \max(0.217-0.321 \log(f), 0) \qquad (4a)$$

$$x_0(h>35) = \min(0.263+0.0924 \log(f), 0.35) \qquad (4b)$$

$$x_0(20 \le h \le 35) = 0.2 \qquad (4c)$$

For convenience, Table 2 lists the values of x_0 and x_1 at selected frequencies. Note that the value of x_0 for intermediate depths (20 to 35 km) has been assigned to provide an intermediate behavior between shallow and deep events; there is only 1 intermediate event in the dataset so no attempt was made to "fit" this class. To define the functions in Equations (3) and (4), bilinear functions were fit to the residual term trends with frequency, as they appear to change smoothly

and systematically with frequency up to a frequency of 5 to 10 Hz, and are then approximately constant at higher frequencies – including PGA, which is plotted at 50 Hz on Figure 5.

The regional correction factor to predict Hawaii ground motions from the BA08 equations is log A as defined in Equation (2); this describes the log factor that must be added to the BA08 predictions to provide ground motions in agreement with the Hawaii database. Thus the predicted ground-motion amplitude for Hawaii is simply:

$$\log Y_{Hawaii} = \log Y_{BA08} + \log A \qquad (5)$$

where Y_{BA08} is the predicted amplitude from BA08 for the corresponding magnitude, distance, V30 and ground-motion parameter (eg. PSA at a given frequency, or PGA or PGV). For PGA, a nominal frequency of 50 Hz (or any value above 10 Hz) may be assigned for use in Equations (3) and (4). PGV was not specifically examined, but typically behaves as PSA at 2 Hz. Thus the correction factor for 2 Hz PSA could be applied for the prediction of PGV (eg. assume log A (PGV) = log A (PSA at 2 Hz). Predictions can be made for an unknown fault mechanism, or for the specific applicable mechanism if this is known.

Evaluation of Results

The derived Referenced Empirical GMPEs for Hawaii (for shallow and deep events) are plotted at 4 example frequencies, for **M**5.5 and M7.5, on Figure 6, in comparison to the reference GMPEs for active tectonic regions of BA08. An unknown focal mechanism is assumed. The Hawaii GMPEs for shallow events are very similar to the BA08 reference equations for high frequencies (f≥5 Hz), but larger amplitudes are predicted in Hawaii for deep events at high frequencies. At low frequencies (<2 Hz), the Hawaii curves have steeper attenuation, with higher amplitudes suggested near source for shallow events, in comparison to those of BA08. The differences in predicted amplitudes for the Hawaii and BA08 equations does not appear dramatic, but note that in some cases (deep events at high frequencies) it is as much as a factor of two. These differences have important implications for seismic hazard from deep events (35 to 45 km) in Hawaii.

Figure 7 plots the residuals for the Hawaii GMPEs (Equation 5) for 4 frequencies. The residuals are close to zero on average (<0.05 log units) at all frequencies. The standard deviation, listed in Table 2, increases from 0.23 log units at low frequencies to about 0.33 log units at high frequencies. These values are indicative of less low-frequency variability, and greater high-frequency variability, in comparison to the corresponding values from BA08 (also listed in Table 2). It is noted that the trend of increasing residuals with increasing frequency runs counter to typical GMPE variability trends. As the BA08 values are based on a more robust database and detailed regression procedure, they may be more representative of the actual physical variability of ground-motion amplitudes (ie. the model error component of sigma may be smaller in general for BA08). It is thus recommended to use the BA08 values of sigma in conjunction with the Hawaii GMPEs.

Conclusion

The Referenced Empirical approach provides GMPEs for Hawaii that are in agreement with regional strong-motion observations, while being constrained to follow the overall scaling behavior of ground motion that is observed in better-instrumented active tectonic regions. Equations are provided for events of shallow depth (<20 km) and also for deeper events (35 to 40 km); the prediction equations are applicable for moment magnitudes 4 to 7.5, at distances out to 200 km. The most significant potential limitation of the GMPEs for Hawaii is that the response spectra database may be insufficient to properly model all the effects that are important. On the other hand, the developed equations are not dramatically different from the reference equations of BA08, which were based on a rich database. At high frequencies, the Hawaii and BA08 GMPEs agree quite closely for shallow events. At low frequencies, the Hawaii GMPEs suggest somewhat steeper attenuation and larger near-source amplitudes. A significant finding is that amplitudes for deep events in Hawaii at high frequencies (≥5 Hz) exceed those predicted by equations developed in other regions (BA08) by as much as a factor of two. This finding has important implications for seismic hazard assessment in Hawaii.

Data and Resources

Ground motion data were obtained from COSMOS at www.cosmos-eq.org (last accessed Jan. 2009) and from an open-file report from the U.S. Geological Survey by Seekins et al. (1991). Magnitude information was obtained from the Global CMT at www.globalcmt.org (last accessed March 2009), the Advanced National Seismic System (http://www.ncedc.org/anss/, last accessed March 2009) and the International Seismological Center Bulletin at www.isc.ac.uk (last accessed March 2009). Estimates of V30 were extracted (courtesy of Trevor Allen) from the Global V30 map given at http://earthquake.usgs.gov/research/hazmaps/interactive/vs30/predefined.php (last accessed Nov. 2008)

Acknowledgements

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Tables

Table 1 – Ground-motion database for earthquakes in Hawaii

Index	Year	month	day	Moment M	Depth(km)	Latitude	Longitude	#records
1	1973	4	26	6.2	38.7*	19.865	-155.153	2
2	1975	11	29	7.2	9.2	19.339	-155.004	4
3	1983	11	16	6.6	11.0	19.429	-155.452	15
4	2000	4	2	4.9	4.0	19.346	-155.208	6
5	2003	8	27	4.6	10.0	19.325	-155.207	7
6	2004	10	12	4.2	9.4	19.339	-155.118	2
7	2005	7	15	5.3	7.8	20.436	-155.138	4
8	2005	7	17	5.1	28.4	18.809	-155.446	7
9	2005	11	30	4.4	9.9	19.330	-155.110	4
10	2006	1	19	4.3	40.0	19.013	-155.450	5
11	2006	2	17	4.4	10.0	19.336	-155.212	4
12	2006	10	15	6.7	38.9	19.878	-155.935	10
13	2006	10	15	6.0	18.9	20.129	-155.983	10
14	2006	11	23	5.2	37.7	19.890	-155.979	9
15	2006	12	3	5.2	14.1	19.980	-155.998	6
16	2007	8	14	5.4	9.7	19.346	-155.066	10

* An alternative depth estimate by Unger and Ward (1979) places this event deeper, at 48 km.

Table 2 – Example values of coefficients x_0 and x_1 for Equation (2), and variability (sigma, log10, total) for the Hawaii GMPE and that of the reference GMPE of BA08.

frequency	x1	x0(h<20)	x0(h20to35)	x0(h>35)	Sigma(Hawaii)	Sigma(BA08)
0.2	-0.299	0.438	0.200	0.199	0.23	0.32
0.5	-0.231	0.319	0.200	0.233	0.23	0.31
1	-0.180	0.237	0.200	0.281	0.27	0.28
2	-0.129	0.082	0.200	0.264	0.28	0.27
5	-0.061	0.009	0.200	0.339	0.33	0.26
10	-0.010	0.007	0.200	0.421	0.36	0.26
20	0.000	-0.021	0.200	0.331	0.32	0.26
PGA	0.000	-0.047	0.200	0.280	0.32	0.25

Figures

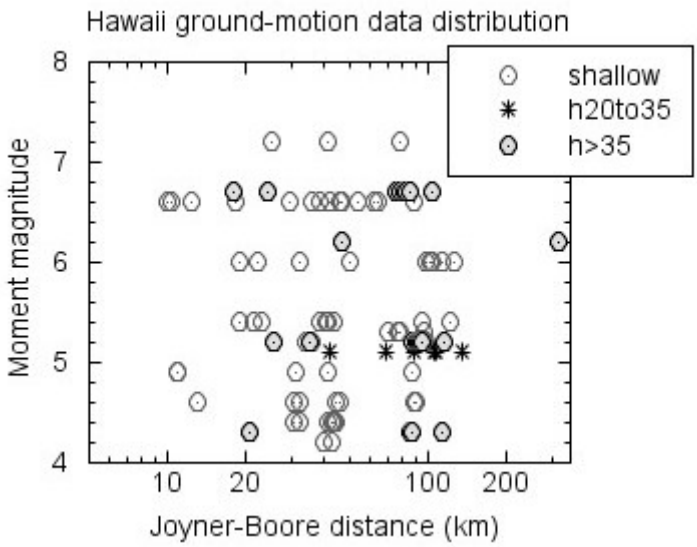

Figure 1 – Distribution of Hawaiian ground-motion database in moment magnitude and Joyner-Boore distance (closest distance to surface projection of fault).

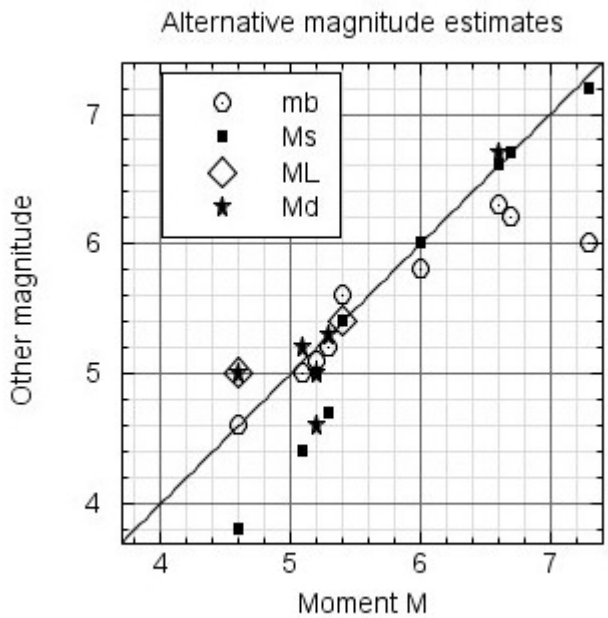

Figure 2 – Alternative magnitude estimates for the Hawaiian earthquakes for which ground-motion data are available.

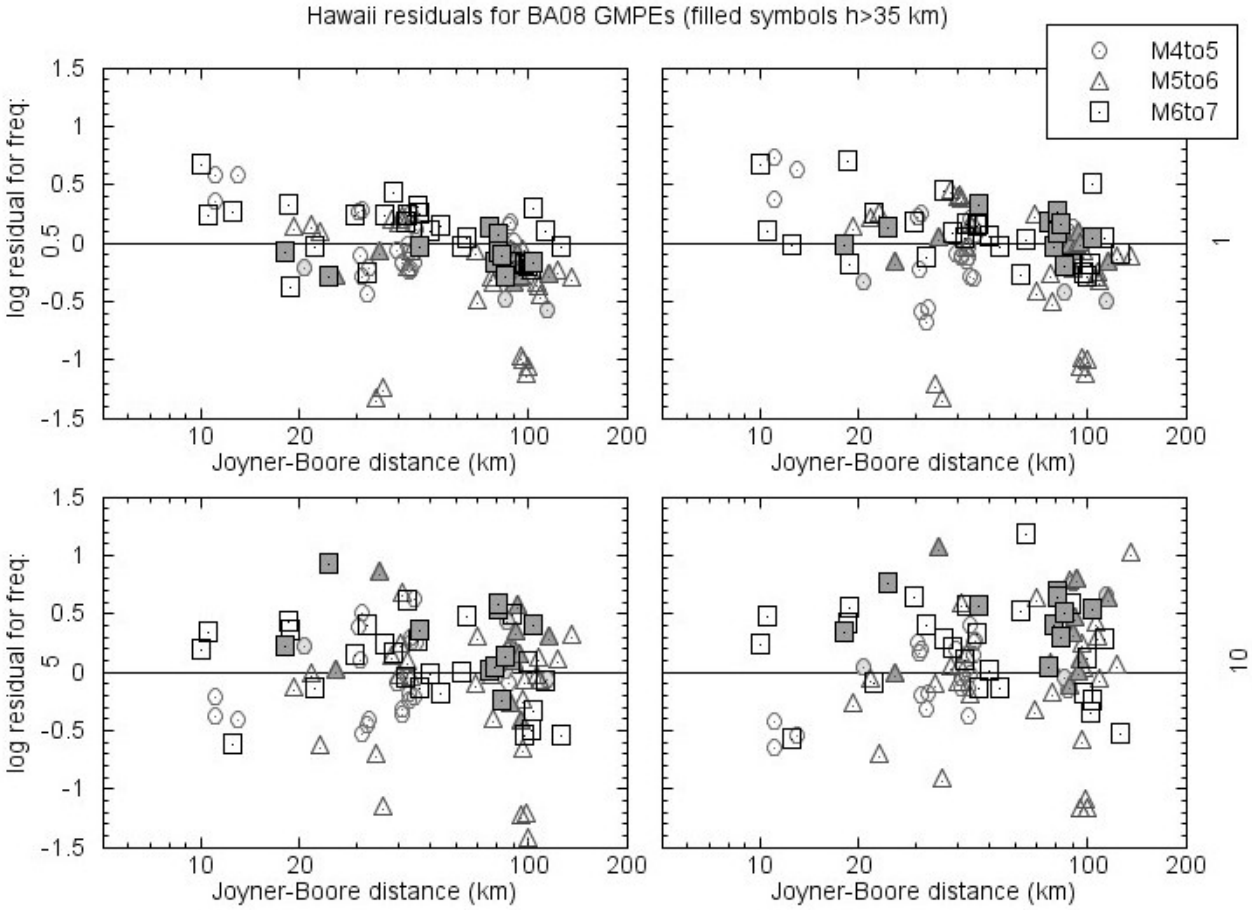

Figure 3 – Residuals for Hawaii ground-motion data compared to BA08 reference equations (log10 units), for PSA at frequencies 0.5, 1, 5 and 10 Hz. Filled symbols for events with depth > 35 km.

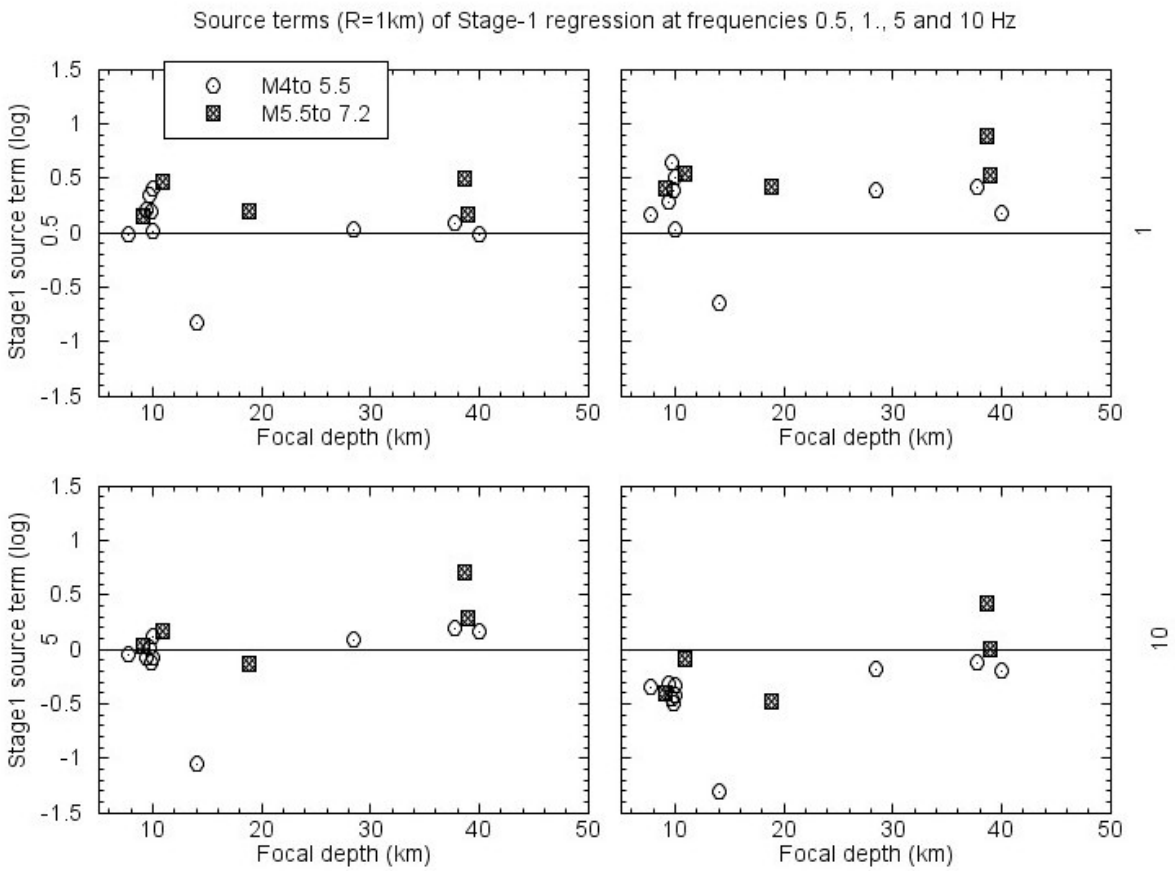

Figure 4 – Source terms (Stage-1 regression) for Hawaii residuals at frequencies 0.5, 1, 5 and 10 Hz.

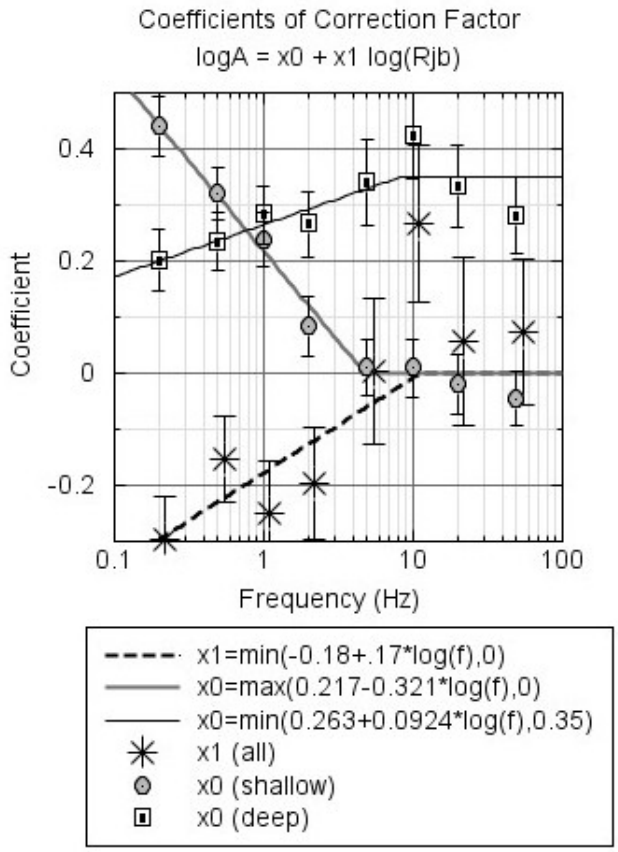

Figure 5 – Coefficients x_0 (all events) and x_1 (separate functions for shallow and deep events) for Hawaii region-specific correction factors of Equation (2).

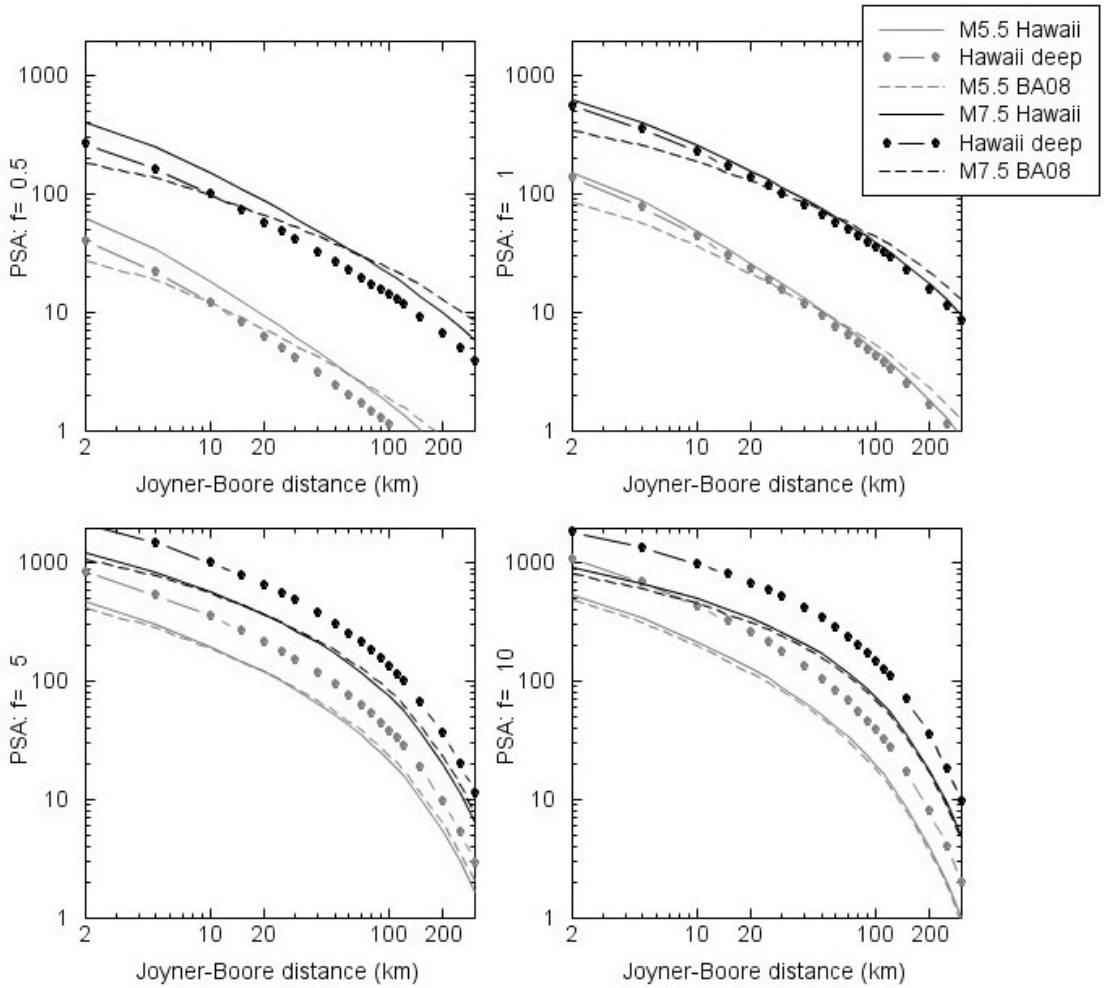

Figure 6 – Comparison of predicted ground motions (PSA) for Hawaii, for shallow (h<20km) and deep (h>35 km) events, to those of the BA08 GMPEs, for **M**5.5 and 7.5, at frequencies of 0.5, 1, 5 and 10 Hz.

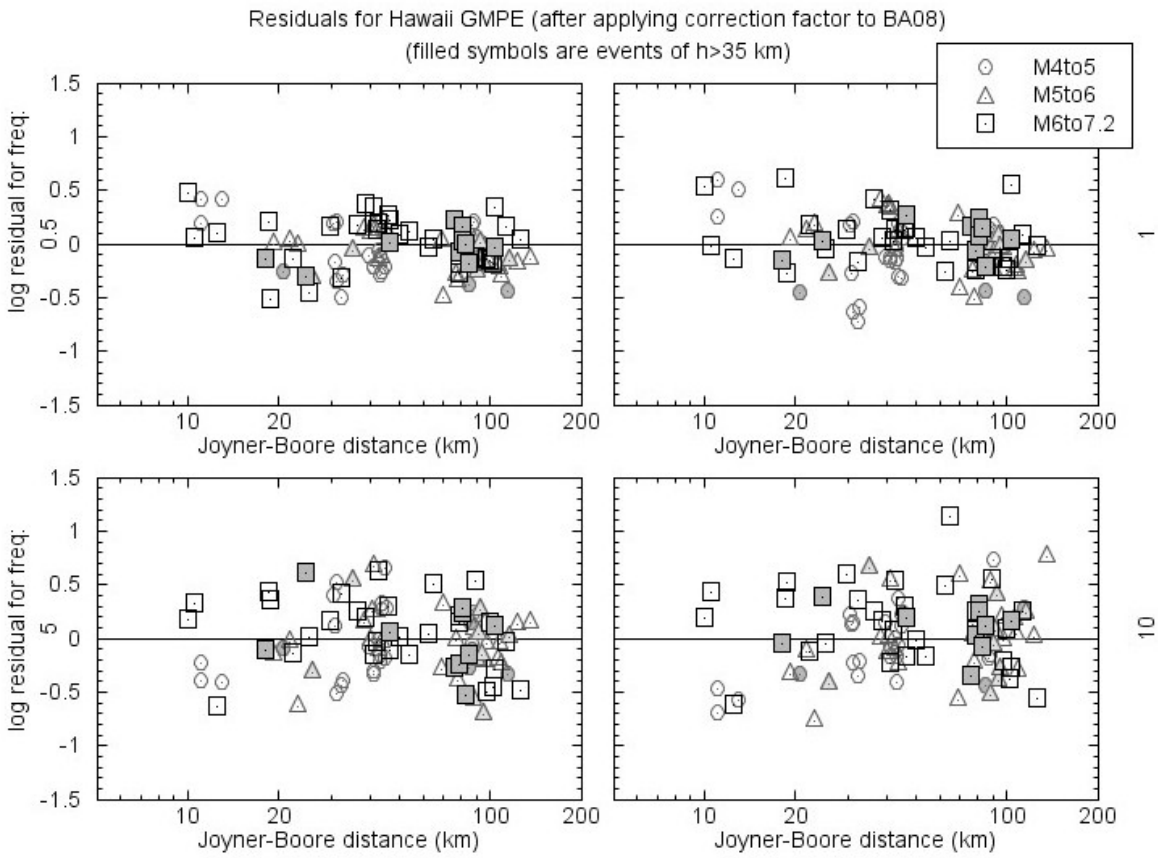

Figure 7 – Residuals for Empirical-Reference Hawaii GMPEs (after adding regional correction factors). Filled symbols are events of depth >35 km.