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# Ground Motion Amplitudes for Earthquakes in Puerto Rico

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## Abstract

We explore ground-motion amplitudes for earthquakes in Puerto Rico using the Referenced Empirical approach. The technique is based on the use of residual analysis to model discrepancies between ground-motion observations for Puerto Rico and a reference ground-motion prediction equation (GMPE). The reference GMPE is that of Boore and Atkinson (2008) for shallow crustal earthquakes in active tectonic regions (as modified by Atkinson and Boore (2011) to improve the fit for small-to-moderate events). Amplitudes are examined for both shallow (depth<30km) and deep (40 to 200 km) earthquakes in Puerto Rico. Overall, we conclude that ground motions in Puerto Rico are consistent in amplitude level and attenuation with those in other active regions, for shallow events. Furthermore, deeper events have amplitudes that are also consistent with typical GMPEs for shallow events, if the greater distance of the events due to their depth is considered.

## 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 direct approach to the development of GMPEs is to perform a regression analysis of a database of recorded strong ground motions for the region of interest (e.g. Power et al., 2008 and references therein). In regions that do not have sufficient data in the magnitude-distance range of interest, alternative methods need to be considered. One such method is the Referenced Empirical approach (Atkinson, 2008). In the Referenced

Empirical approach, we use the limited empirical data for the region of interest (the target region) to develop suitable modifications to empirical GMPEs 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 complex source and distance scaling effects that are present in the data. 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.

In this study, we explore use of the Referenced Empirical approach to the development of GMPEs for Puerto Rico. Our aim is to propose only those changes to existing well-constrained empirical GMPEs that are required by the regional data. This approach is motivated by growing evidence that regional differences in ground motions may not be as profound as once believed (Douglas, 2004; Bommer et al., 2007; Allen and Wald, 2009). For example, Bommer et al. (2007) have shown that the PEER-NGA equations (see Power et al., 2008 and references therein), developed for shallow crustal earthquakes in active tectonic regions using a global database, do as well at modeling European observations as do regional relations developed specifically for Europe. The regional GMPEs for Europe were developed for relatively small regions, based on limited datasets, and the resulting equations may not be well-constrained at the large magnitudes and close distances that are most critical to engineering applications. A similar situation exists for Puerto Rico, where most of the available ground-motion data are for moderate events at regional distances. Thus it makes sense to begin with well-constrained global GMPEs that might be applicable, and evaluate what changes, if any, are warranted for Puerto Rico.

## The Ground-Motion Database for Puerto Rico

Puerto Rico has a sparse but growing database of ground-motion observations, containing recordings from shallow crustal earthquakes (at depths up to 33km) and deeper events related to subduction processes (at depths up to 200 km). Figure 1 is a map of events used in this study and recording stations; see the Data and Resources section for details of how the data were

obtained. Figure 2 plots the database used in magnitude/distance space, distinguishing between shallow (depth h<34 km) and deeper (35 to 200 km) events. We use only those events for which moment magnitude (**M**) is known (see Data and Resources section) or can be reliably determined (as described in the next section). Table 1 lists event parameters for the study events. In this study, acceleration response spectra were computed for 280 three-component acceleration time series and 1284 three-component velocity seismograms. In general, the processing of records involved digital filtering and baseline correction as described by Boore and Bommer (2005), in order to compile instrument-corrected three-component response spectra (pseudo acceleration, PSA, 5% damped) at frequencies from 0.2 to 20 Hz. For each record, the shear-wave portion of the signal was windowed using a 5% cosine taper on each end of the signal. The instrument response was removed, and then the Fourier and response spectra were obtained; we retained data only for those frequencies with a signal to noise ratio greater than 2 (in the frequency domain).

We used the geometric mean of the horizontal components of PSA as the primary ground-motion variable of interest. Event size is characterized by moment magnitude. Distance measures include hypocentral distance ($R_{hyp}$) and epicentral distance ($R_{epi}$). For the events included in this study, which have **M**<6.2, and distances that are mostly>50 km, we made the simplifying (and sufficient) assumption that the closest distance to the rupture surface ($R_{cd}$) is equal to Rhyp, while the closest distance to the surface projection of the rupture ($R_{jb}$) is equal to $R_{epi}$. Site classes for the Puerto Rico Seismic Network (PRSN) were obtained from the Puerto Rico $V_{s30}$ maps compiled by Feliciano and Santaella (2008) and Odum et al. (2007). Most of the recording sites are classified as NEHRP Site Class C, while a few are listed as "unknown". We therefore assume that the database is indicative of C conditions overall.

### *Determination of Moment Magnitude*

A significant challenge in comparing the Puerto Rico database to the predictions of GMPEs involved obtaining estimates of moment magnitude (**M**). Moment magnitudes were available for some of the study events from catalogue sources (see Table 1; these are the events with the catalogue magnitude listed as "Mw", which is often used in catalogues as the designation for **M**). For most events, however, the catalogue magnitude is mb (body-wave magnitude) or mD (duration magnitude), and they are too small to have **M** estimates available from global catalogues such as the Global CMT catalogue.

To obtain estimates of **M** for as many events as possible, we used a calibration approach based on PSA amplitudes at 1 Hz, recorded at regional distances (150 to 400 km). This is motivated by the observation that 1-Hz spectral amplitudes correlate well with seismic moment (e.g. Chen and Atkinson, 2002; Motazedian and Atkinson, 2005). The calibration approach was selected after examining PSA plots versus distance, and determining that 1-Hz PSA amplitudes in the distance range from 150km to 400km trend smoothly with distance. Amplitudes are typically well behaved as such regional distances, for which the details of crustal propagation effects have been smoothed through multi-pathing effects. A stable amplitude estimate for the mid-point of this distance range (at 245km in log distance space) can be determined from as few as three observations, by fitting a straight line of log $(PSA)_{1Hz}$ versus log hypocentral distance, for data in the range from 150 to 400 km. The vertical component is used for calibration as it is less affected by site effects.

Events with known **M,** having at least 3 ground-motion observations in the 150 to 400 km distance range are the calibration events; there are 19 such events. For each calibration event, a linear trend is fit in log-log space for 1-Hz PSA (vertical) from 150 km to 400 km. The reference amplitude for the event is determined at the mid-point of this line segment (245 km). Figure 3 shows a few typical examples of determination of the mid-point reference amplitudes of PSA at 1 Hz (=A245). The method is stable because we focus on the mid-point of the determined line segment. Thus even though the slopes of particular events may scatter quite widely (with typical slopes ranging from -1.5 to -3.5), the amplitude in the middle of the distance range is well determined, even when data are relatively sparse.

On Figure 4, the reference amplitudes are plotted versus **M** for the calibration events. A least-squares fit gives the predictive relationship to obtain **M** from A245:

$$\mathbf{M} = 6.85 + 0.58 \log A245 \qquad (2)$$

where A245 is in m/s. This fit shows no significant dependence on the depth of the event. The standard deviation of residuals for predicted **M** values from the equation is 0.2. The scaling of the 1-Hz amplitudes at regional distances is also compared (on Figure 4) with that predicted from GMPEs, such as Motazedian and Atkinson (2005) for Puerto Rico, or Boore and Atkinson (2008, updated in 2011, BA08'). It is noted that the scaling trend of the GMPEs is similar in the main magnitude range of interest (4.5 to 5) to which Equation 2 will be applied; however the Puerto

Rico amplitudes are systematically lower in amplitude than predicted. We will return to this observation in the next section.

For events with unknown **M**, we can use Equation (2) to estimate **M** from the 1-Hz PSA values (vertical) at regional distances. To ensure stable and reliable estimates, we determine **M** only for those events having at least 5 PSA observations in the 150 to 400 km distance range, and showing "reasonable" attenuation behavior as based on typical event slopes within this distance range; "reasonable" attenuation is defined as a decrease in amplitude from 150 to 400 km that is within the range from 0.3 to 3.0 log units. This range of amplitude drop over the distance range corresponds to that expected for the range of typical slopes that are seen in the data (-1.5 to -3.5).

## Application of the Referenced Empirical Approach to Puerto Rico

### *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 (in this case the Puerto Rico ground motions), and a set of reference equations (in this case the GMPEs of Boore and Atkinson (2008) for active tectonic regions, as modified by Atkinson and Boore, 2011, to reduce their bias at moderate magnitudes). The most important underlying assumption is that the magnitude scaling of ground motions is the same for the target region(Puerto Rico) as that exhibited for shallow crustal earthquakes elsewhere, as is the overall near-source behavior with distance. If this assumption holds, we can use the empirical data for Puerto Rico 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 potentially accommodate such factors as regional variations in stress drop and event type, including the effects of focal depth, while adjustments to the distance coefficient can accommodate regional attenuation.

The database for the study is the Puerto Rico ground-motion dataset described in the previous section (geometric-mean of horizontal components). The reference ground motion prediction equations used in this study are the Boore and Atkinson (2008) relations for shallow

crustal earthquakes in active tectonic regions, developed in the PEER-NGA project (Power et al., 2008) for the orientation-independent horizontal component (which is similar to the geometric mean), for an unspecified focal mechanism; they have been modified by Atkinson and Boore (2011) to improve their agreement with moderate-magnitude (**M**<6) PSA data from California. These modified GMPEs, referred to as BA08', are selected for their simplicity and convenience. We use the BA08' GMPEs to evaluate what modifications may be required to better match Puerto Rico PSA values.

The BA08' equations are used to predict the mean horizontal ground motion for each magnitude and distance in the Puerto Rico database. Due to the limited information available on Puerto Rico site conditions, we initially ignore the complications posed by site conditions. We assume that any difference between the average site amplification for the Puerto Rico stations (believed to be C in most cases) and the B/C boundary reference site condition of BA08' will be determined, on average, by the analyses - and represented by a constant offset (bias). Thus we compute the residuals (in log units) for each record, defined as the log(base10) of the ratio of observed Puerto Rico motions to those predicted by BA08' (i.e. log residual = log (observed Puerto Rico amplitude) – log (predicted amplitude from BA08')). Figure 5 plots the residuals for 4 selected frequencies as a function of epicentral distance ($R_{epi}$), for events of **M**>4.5.For sub-crustal events, we have adjusted the BA08' predictions for the effect that depth has on the overall distance from the source. The idea of the adjustment is to scale the predicted amplitudes by the attenuation factor that represents the amplitude decay in the BA08' model over the added distance involved in going from a typical crustal focal depth in California (~8km) to the focal depth of the deeper Puerto Rico event. Following the attenuation of amplitudes in BA08', this scaling factor (S) by which to multiply the BA08' predictions in order to obtain predictions for deeper events, is:

$$S = \min\left(1, (R_{hyp}'/R_{hyp})^{0.8}\right) \qquad (3)$$

where $R_{hyp}' = \sqrt{(R_{epi}^2 + 8^2)}$. This factor has a value near 1 except for deep events (>35 km) at moderate distances. It is seen in Figure 5 that, with the inclusion of this correction, the residuals show a similar behavior for shallow (<30 km), intermediate (30 to 100 km) and deep (100 to 200 km) events. Inspection of Figure 5 reveals no compelling difference in attenuation rates with distance between BA08' and the Puerto Rico data. However, the Puerto Rico PSA values

generally have lower amplitudes, especially at lower frequencies (0.5 to 1 Hz). On Figure 6, we examine the average residual for each event of **M**>4.5, for stations within 300 km, as a function of focal depth. This comparison reinforces the impression that there are no apparent depth trends in the average event residuals, after correction of BA08' by the depth scaling factor, S.

In Figure 7, we examine the average event residuals (**M**>4.5, stations <300 km) versus moment. There is a significant trend, with a suggestion that larger magnitude events are approaching the BA08' predicted amplitudes, while smaller events have low amplitudes relative to BA08'. To examine this magnitude trend in more detail, we focus on a cluster of shallow events, ranging in magnitude from 4.5 to 6.1, which occurred near 19N, 65W (see Figure 1). The path to each station is repeated for every event within the cluster, facilitating an evaluation of the magnitude scaling in the Puerto Rico data relative to that in BA08'. To examine the magnitude scaling, we correct observed amplitudes at each station by the BA08' scaling factor of Equation (3), to the reference distance of R=h (where h is the effective depth in BA08'). Since the distance from each event in the cluster to a specific station is approximately constant, these distance corrections will affect the overall amplitude level for each station, but not its scaling behavior with magnitude. Figure 8 shows the distance-scaled magnitude scaling behavior of the events in this cluster, in comparison to the BA08' magnitude scaling (for R=h). Regardless of which distance range of stations we examine, we see that the magnitude scaling of the Puerto Rico data is steeper than that for BA08'. However, it is potentially significant that the largest event in the cluster, the **M**6.1 event, has amplitudes in accord with those predicted by BA08'. This suggests that perhaps no adjustment of the BA08' GMPE is needed in order for it to be applicable to Puerto Rico events (aside from the depth factor adjustment to distance for sub-crustal events, as discussed earlier).

It is known that GMPEs developed for moderate-to-large earthquakes often do a poor job at modeling amplitudes from smaller events (Bommer et al., 2007; Atkinson and Morrison, 2009; Chiou et al., 2010; Cotton et al., 2008). The BA08' GMPE has been adjusted to improve the fit to smaller events in California at lower magnitudes, but these adjustments do not completely solve the small-magnitude problem, leaving significant residuals for small events even for California (Atkinson and Boore, 2011). Thus it may be useful to compare small-to-moderate event data for Puerto Rico directly with corresponding data for California (rather than just comparing to GMPEs). Figures 9 and 10 present such a comparison. The PSA amplitudes for

shallow crustal events in Puerto Rico, for events of**M**4.5 to 5.0 (Figure 9) and **M**5.0 to 5.5 (Figure 10), are overlain on plots showing corresponding amplitude data from California, corrected to B/C site conditions (from the ShakeMap database utilized by Atkinson and Boore, 2011; see Data and Resources). No adjustments for site condition have been made to the Puerto Rico data. It is observed that the Puerto Rico amplitudes appear generally similar to those from California at high frequencies. At low frequencies, the Puerto Rico amplitudes appear to be lower than those from California. This may be due to different site conditions, with the Puerto Rico sites not being as influenced by an underlying crustal structure that amplifies lower frequencies. There may also be some effects of data bias, with the ShakeMap database from which the California PSA data were drawn being unreliable at lower frequencies. Inconsistencies in the relative small-event amplitudes between southern and northern California, as noted in previous studies (Chiou et al., 2010) are also apparent. Overall, the amplitudes of ground motions in Puerto Rico do not appear to be significantly different than those for similar-sized events in California. Thus the PEER-NGA equations for shallow active tectonic regions may be applied to predict ground motions in Puerto Rico, with suitable adjustments to account for focal depth for sub-crustal earthquakes.

Finally, in Figure 11 we compare the GMPE developed for Puerto Rico by Motazedian and Atkinson (2005), using a stochastic finite-fault approach, to the BA08' GMPE, which is proposed on the basis of this study to be a reasonable empirical GMPE model for Puerto Rico events. Both models are plotted for shallow events on B/C site conditions. It is observed that the models are actually quite similar, with the Motazedian and Atkinson model featuring somewhat slower amplitude decay with distance. The current study results support steeper attenuation than that found by Motazedian and Atkinson (2005), more similar to the attenuation rates in the BA08' model, at least for distances beyond 100 km.

## Conclusion

Earthquake ground motions in Puerto Rico are consistent in amplitude level and attenuation with those in other active regions, for shallow events. Furthermore, deeper events have amplitudes that are also consistent with typical GMPEs for shallow events, if the greater distance of the events due to their depth is considered. Ground motions may be predicted

reasonably well using the empirical PEER-NGA equations (e.g. such as the BA08' model), or the stochastic Puerto Rico model of Motazedian and Atkinson (2005).

## Data and Resources

The seismograms used in this article were obtained from the Incorporated Research Institutions for Seismology (IRIS) official web site and Puerto Rico Seismic Network (PRSN). The strong motion time series were obtained from the Puerto Rico Strong Motion Network (PRSMN). The waveform records were processed using SAC2000 and *redseed*. Moment magnitudes were obtained from the Global Centroid Moment Tensor project (www.globalcmt.org) and from the Advanced National Seismographic System catalogue (www.ncedc.org/anss/catalog-search.html). The small-to-moderate ShakeMap database for California was provided by Brian Chiou (see Chiou et al., 2008), and modified to reflect a uniform site condition as described by Atkinson and Boore (2011).

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*Table 1* – Ground-motion database for earthquakes in Puerto Rico

| iyr | imo | iday | ihr | Mw-assigned | Depth (km) | latitude | longitude | Mcat | M_type |
|---|---|---|---|---|---|---|---|---|---|
| 1999 | 1 | 18 | 7 | 5.00 | 33 | 18.86 | -67.15 | 5 | MW |
| 2003 | 3 | 9 | 5 | 4.77 | 25 | 19.15 | -68.7 | 4.2 | mb |
| 2003 | 3 | 11 | 10 | 4.68 | 128 | 19.02 | -68.81 | 4.2 | MD |
| 2003 | 3 | 21 | 1 | 5.07 | 97 | 18.07 | -68.13 | 5.1 | MW |
| 2003 | 5 | 30 | 3 | 4.62 | 126 | 18.08 | -69.35 | 4 | MD |
| 2003 | 7 | 23 | 6 | 4.01 | 33 | 18.3 | -68.07 | 4.1 | mb |
| 2004 | 2 | 26 | 2 | 4.56 | 184 | 18.85 | -68.81 | 4 | MD |
| 2004 | 12 | 11 | 7 | 5.20 | 54 | 18.65 | -64.72 | 5.2 | MW |
| 2005 | 2 | 27 | 10 | 4.49 | 144 | 18.5 | -68.72 | 4.1 | MD |
| 2005 | 3 | 10 | 1 | 4.55 | 118 | 19.52 | -68.93 | 4.2 | MD |
| 2005 | 4 | 8 | 12 | 4.74 | 14 | 19.08 | -69.08 | 4.1 | mb |
| 2005 | 4 | 28 | 6 | 4.57 | 25 | 17.25 | -69.46 | 4.1 | MD |
| 2005 | 6 | 1 | 12 | 4.89 | 148 | 18.46 | -68.75 | 4.2 | mb |
| 2005 | 8 | 20 | 5 | 4.21 | 142 | 18.32 | -69.01 | 4 | MD |
| 2005 | 9 | 3 | 6 | 4.52 | 98 | 19.4 | -68.92 | 4 | MD |
| 2005 | 9 | 8 | 4 | 4.31 | 143 | 19.33 | -68.65 | 4 | MD |
| 2005 | 12 | 30 | 3 | 4.51 | 34 | 19.49 | -65.36 | 4.1 | mb |
| 2006 | 1 | 12 | 1 | 4.54 | 75 | 18.92 | -64.27 | 4 | MD |
| 2006 | 1 | 13 | 4 | 4.74 | 54 | 18.68 | -65.04 | 4.2 | mb |
| 2006 | 1 | 25 | 4 | 4.31 | 33 | 19.31 | -67.28 | 4.2 | mb |
| 2006 | 2 | 24 | 12 | 4.94 | 137 | 19.24 | -69.27 | 4.2 | mb |
| 2006 | 2 | 25 | 6 | 4.68 | 160 | 18.26 | -68.43 | 4.4 | MD |
| 2006 | 3 | 2 | 11 | 5.46 | 24 | 19.36 | -63.79 | 5.6 | Mw |
| 2006 | 3 | 2 | 11 | 4.81 | 5 | 19.15 | -63.8 | 4.4 | mb |
| 2006 | 3 | 3 | 9 | 4.66 | 21 | 19.26 | -63.6 | 4.1 | mb |
| 2006 | 3 | 3 | 1 | 5.08 | 39 | 19.06 | -63.68 | 5.1 | Mw |
| 2006 | 3 | 4 | 8 | 4.44 | 16 | 19.27 | -63.84 | 4 | mb |
| 2006 | 3 | 4 | 3 | 4.76 | 5 | 19.22 | -63.81 | 4.2 | mb |
| 2006 | 3 | 26 | 2 | 4.97 | 28 | 19.26 | -64.81 | 4.4 | mb |
| 2006 | 4 | 13 | 2 | 4.77 | 51 | 19.12 | -64.36 | 4 | MD |
| 2006 | 4 | 15 | 4 | 4.49 | 55 | 19.11 | -64.32 | 4 | MD |
| 2006 | 4 | 20 | 12 | 4.53 | 40 | 19.51 | -62.65 | 4.3 | mb |
| 2006 | 6 | 5 | 8 | 4.91 | 69 | 18.18 | -68.37 | 4.5 | mb |
| 2006 | 6 | 14 | 1 | 4.42 | 197 | 18.61 | -68.46 | 4 | MD |
| 2006 | 6 | 17 | 10 | 5.01 | 49 | 18.99 | -64.79 | 4.6 | mb |
| 2006 | 6 | 24 | 8 | 4.58 | 17 | 18.88 | -67.25 | 4 | mb |
| 2006 | 6 | 29 | 9 | 4.49 | 10 | 18.21 | -67.43 | 4 | MD |
| 2006 | 8 | 6 | 11 | 4.56 | 96 | 18.07 | -68.01 | 4.3 | mb |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2006 | 8 | 13 | 11 | 4.30 | 161 | 18.31 | -68.89 | 4.1 | MD |
| 2006 | 8 | 14 | 1 | 5.30 | 21 | 19.02 | -64.64 | 5.3 | Mw |
| 2006 | 8 | 23 | 11 | 4.25 | 38 | 19.28 | -63.29 | 4 | MD |
| 2006 | 9 | 2 | 2 | 4.44 | 12 | 19.62 | -63.67 | 4 | mb |
| 2006 | 9 | 18 | 6 | 4.03 | 166 | 18.51 | -68.38 | 4 | MD |
| 2006 | 10 | 20 | 9 | 4.75 | 161 | 17.98 | -68.52 | 4.6 | mb |
| 2006 | 11 | 3 | 10 | 4.09 | 25 | 19.45 | -63.32 | 4 | MD |
| 2006 | 12 | 14 | 9 | 4.87 | 32 | 18.62 | -62.13 | 4.2 | mb |
| 2006 | 12 | 16 | 9 | 4.53 | 171 | 18.58 | -68.5 | 4.1 | mb |
| 2007 | 1 | 7 | 3 | 4.59 | 28 | 19.31 | -65.16 | 4.2 | mb |
| 2007 | 1 | 7 | 6 | 4.95 | 64 | 19.26 | -65.11 | 4.7 | mb |
| 2007 | 1 | 10 | 9 | 4.88 | 89 | 19.13 | -69.32 | 4.3 | mb |
| 2007 | 1 | 16 | 9 | 4.54 | 174 | 18.86 | -68.59 | 4.2 | mb |
| 2007 | 2 | 13 | 5 | 4.66 | 10 | 18.7 | -63.33 | 4.4 | mb |
| 2007 | 3 | 9 | 8 | 4.99 | 96 | 18.19 | -68.73 | 4.9 | mb |
| 2007 | 4 | 8 | 4 | 4.98 | 17 | 18.96 | -67.69 | 4.7 | mb |
| 2007 | 4 | 16 | 2 | 4.87 | 10 | 19.09 | -64.66 | 4.4 | mb |
| 2007 | 4 | 16 | 3 | 4.61 | 10 | 19.12 | -64.76 | 4 | MD |
| 2007 | 6 | 17 | 9 | 4.89 | 19 | 19.19 | -64.83 | 4.8 | mb |
| 2007 | 8 | 3 | 7 | 4.32 | 38 | 19.47 | -69.6 | 4.1 | MD |
| 2007 | 8 | 12 | 9 | 4.59 | 15 | 18.24 | -63.5 | 4.2 | mb |
| 2007 | 8 | 13 | 2 | 4.21 | 24 | 19.34 | -69.6 | 4 | MD |
| 2007 | 9 | 6 | 12 | 4.87 | 66 | 17.31 | -68.4 | 4.8 | mb |
| 2007 | 9 | 13 | 5 | 4.97 | 86 | 18.09 | -68.41 | 4.8 | mb |
| 2007 | 9 | 14 | 6 | 4.89 | 94 | 18.38 | -64.45 | 4.8 | mb |
| 2007 | 9 | 16 | 11 | 4.59 | 12 | 19.14 | -64.66 | 4.5 | mb |
| 2007 | 10 | 5 | 2 | 4.35 | 42 | 19.43 | -68.39 | 4 | MD |
| 2007 | 10 | 7 | 12 | 5.01 | 70 | 19.31 | -69.7 | 4.5 | mb |
| 2007 | 10 | 13 | 11 | 4.31 | 107 | 18.99 | -68.65 | 4 | MD |
| 2007 | 10 | 19 | 8 | 4.57 | 133 | 18.99 | -70.23 | 4.6 | mb |
| 2007 | 11 | 22 | 7 | 4.94 | 134 | 18.17 | -64.53 | 4.4 | mb |
| 2007 | 12 | 16 | 8 | 4.62 | 99 | 18.85 | -69.41 | 4.4 | mb |
| 2007 | 12 | 19 | 1 | 5.23 | 8 | 19.2 | -64.65 | 5.3 | Mw |
| 2007 | 12 | 19 | 2 | 4.69 | 5 | 19.19 | -64.7 | 4.5 | mb |
| 2007 | 12 | 19 | 3 | 4.66 | 39 | 19.4 | -64.57 | 4.6 | mb |
| 2007 | 12 | 28 | 3 | 5.12 | 14 | 19.23 | -64.68 | 5.2 | Mw |
| 2007 | 12 | 28 | 6 | 4.88 | 65 | 19.2 | -64.52 | 4.6 | mb |
| 2008 | 1 | 12 | 4 | 4.24 | 35 | 19.43 | -69.6 | 4.2 | MD |
| 2008 | 1 | 14 | 2 | 4.28 | 29 | 17.8 | -63.27 | 4.1 | mb |
| 2008 | 1 | 16 | 4 | 4.55 | 61 | 17.76 | -67.97 | 4.1 | mb |
| 2008 | 2 | 1 | 7 | 4.41 | 36 | 19.18 | -63.21 | 4.1 | MD |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2008 | 2 | 4 | 7 | 5.50 | 14 | 19.03 | -66.9 | 5.5 | MW |
| 2008 | 4 | 24 | 10 | 4.48 | 45 | 20.05 | -65.01 | 4.4 | mb |
| 2008 | 5 | 3 | 6 | 4.52 | 49 | 19.36 | -64.17 | 4.5 | mb |
| 2008 | 5 | 4 | 11 | 4.77 | 35 | 20.06 | -65.04 | 4.5 | mb |
| 2008 | 5 | 4 | 11 | 4.18 | 149 | 19.21 | -68.79 | 4 | MD |
| 2008 | 6 | 7 | 4 | 4.96 | 29 | 19.76 | -64.21 | 4.9 | Mw |
| 2008 | 7 | 10 | 1 | 4.67 | 97 | 19.36 | -65.25 | 4.1 | mb |
| 2008 | 7 | 18 | 10 | 4.31 | 78 | 18.22 | -68.23 | 4.1 | MD |
| 2008 | 7 | 22 | 1 | 4.51 | 127 | 18.64 | -68.34 | 4.1 | MD |
| 2008 | 10 | 11 | 10 | 6.10 | 23 | 19.16 | -64.83 | 6.1 | Mw |
| 2008 | 11 | 2 | 8 | 4.83 | 10 | 17.14 | -62.38 | 4.8 | mb |
| 2008 | 11 | 2 | 8 | 5.26 | 10 | 19.43 | -66.38 | 5.4 | Mw |
| 2008 | 11 | 2 | 9 | 4.38 | 21 | 19.65 | -66.28 | 4.8 | mb |
| 2008 | 11 | 8 | 1 | 3.96 | 28 | 19.4 | -66.35 | 4.2 | mb |
| 2008 | 11 | 13 | 2 | 4.39 | 15 | 19.48 | -66.35 | 4.6 | mb |
| 2008 | 11 | 15 | 11 | 4.66 | 157 | 18.55 | -68.34 | 4.5 | mb |
| 2008 | 11 | 23 | 9 | 4.81 | 47 | 19.49 | -66.32 | 5 | Mw |
| 2008 | 11 | 27 | 10 | 4.58 | 125 | 19.2 | -69.36 | 4.1 | MD |
| 2008 | 12 | 2 | 12 | 4.53 | 35 | 19.5 | -66.36 | 4.6 | mb |
| 2008 | 12 | 14 | 5 | 4.45 | 39 | 18.61 | -64.24 | 4 | mb |
| 2009 | 2 | 13 | 4 | 4.66 | 35 | 19.63 | -66.3 | 4.5 | mb |
| 2009 | 2 | 14 | 7 | 5.00 | 121 | 18.67 | -68.92 | 5 | Mw |
| 2009 | 3 | 4 | 10 | 4.89 | 163 | 18.29 | -68.56 | 5 | mb |
| 2009 | 4 | 14 | 9 | 4.44 | 56 | 19.35 | -65.07 | 4 | MD |
| 2009 | 5 | 20 | 3 | 4.76 | 18 | 19 | -65.5 | 5 | mb |
| 2009 | 6 | 1 | 4 | 5.01 | 41 | 19.57 | -63.48 | 4.8 | mb |
| 2009 | 7 | 21 | 7 | 4.83 | 30 | 19.12 | -64.8 | 4.7 | mb |
| 2009 | 8 | 13 | 2 | 4.91 | 38 | 19.31 | -65.78 | 4.9 | mb |
| 2010 | 4 | 18 | 8 | 5.00 | 84 | 18.22 | -68.48 | 5 | MW |
| 2010 | 5 | 16 | 5 | 5.80 | 113.1 | 18.4 | -67.07 | 5.8 | MW |
| 2010 | 6 | 5 | 6 | 4.45 | 77 | 18.64 | -67.98 | 4.1 | mb |
| 2010 | 7 | 2 | 4 | 5.01 | 172 | 18.32 | -68.86 | 4.4 | mb |
| 2010 | 7 | 7 | 3 | 4.88 | 2 | 19.12 | -64.83 | 4.5 | Mw |
| 2010 | 7 | 22 | 12 | 4.97 | 123 | 18.48 | -64.95 | 4.5 | mb |
| 2010 | 10 | 4 | 5 | 4.45 | 88 | 18.05 | -68.56 | 4 | MD |
| 2010 | 10 | 19 | 3 | 4.75 | 35 | 19.28 | -68.2 | 4.2 | mb |
| 2010 | 10 | 29 | 4 | 4.43 | 50 | 18.13 | -67.73 | 4.3 | Mb |
| 2010 | 11 | 13 | 4 | 5.55 | 94 | 17.88 | -68.54 | 5.4 | Mw |
| 2010 | 11 | 24 | 1 | 4.44 | 62 | 18.07 | -68.47 | 4 | mb |
| 2010 | 12 | 23 | 9 | 4.52 | 10 | 19.62 | -65.21 | 4 | MD |
| 2010 | 12 | 24 | 11 | 5.00 | 102.9 | 18.26 | -66.14 | 5 | MW |

## Figures

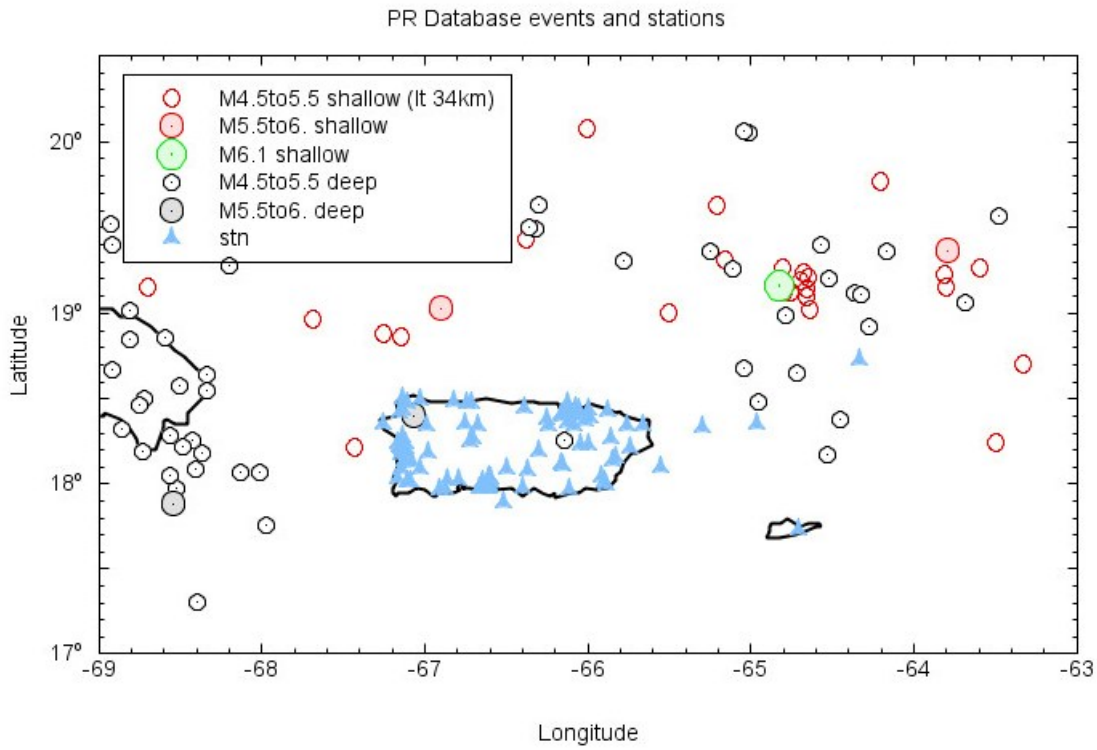


*Figure 1* – Earthquakes and stations for study events. Shallow events are at <34 km. Deep events range in depth from 35 to 200 km.

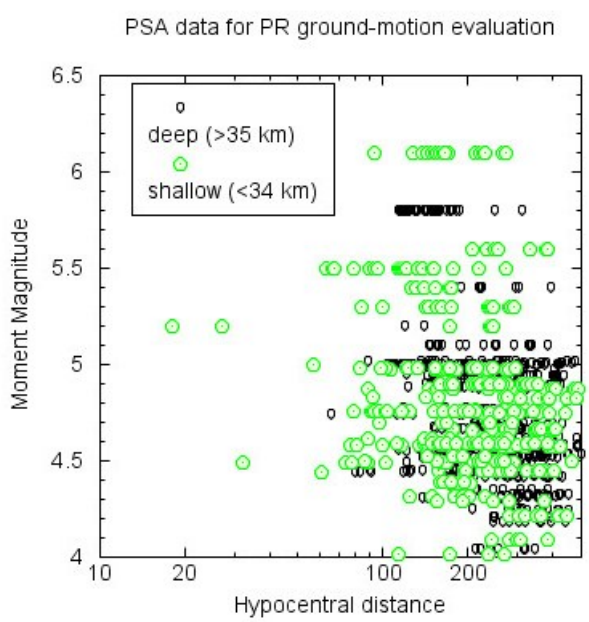


*Figure 2* – Distribution of Puerto Rico ground-motion database in **M** and hypocentral distance.

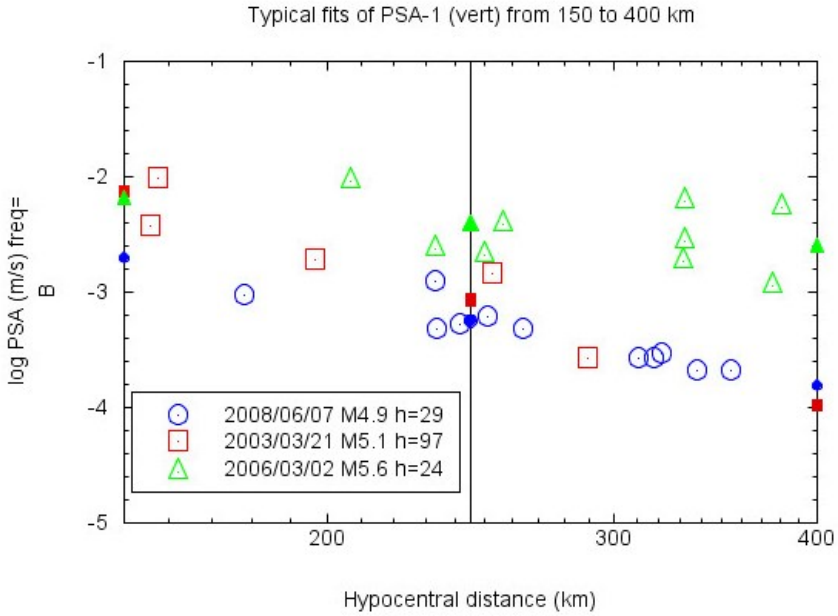


*Figure 3* – Three examples of finding A245 (PSA 1 Hz, vertical, at 245 km) by linear fit to data from 150 to 400 km. Filled symbols show values of A245, as defined at mid-point of line segment fits, as well as values at end-points of the line segments.

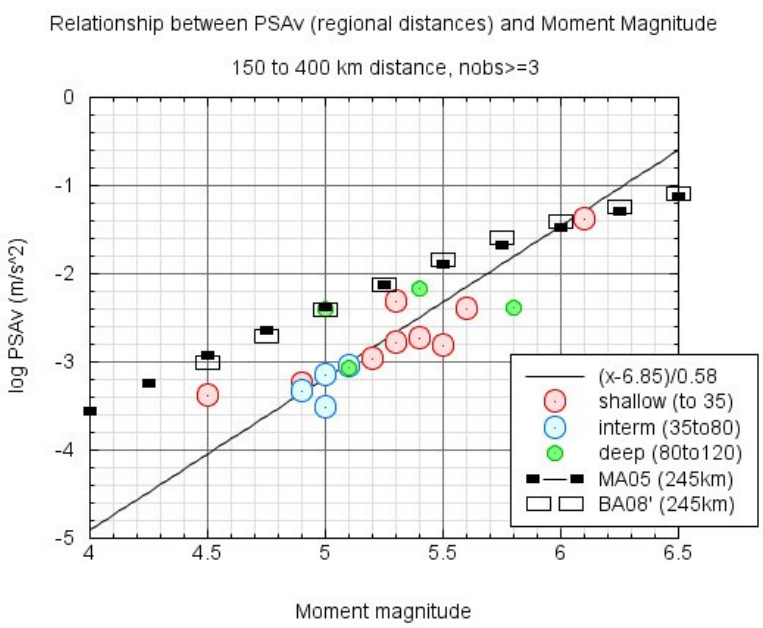


*Figure 4* – Relationship between A245 (PSA 1-Hz, vertical, at reference distance of 245 km) and moment magnitude, with fitted prediction line for **M** (Equation 2). The predicted PSA values (horizontal, B/C boundary) from two GMPEs, Motazedian and Atkinson (2005) for Puerto Rico (MA05) and Boore and Atkinson (2008, 2010) (BA08') are also shown for comparison of scaling behavior.

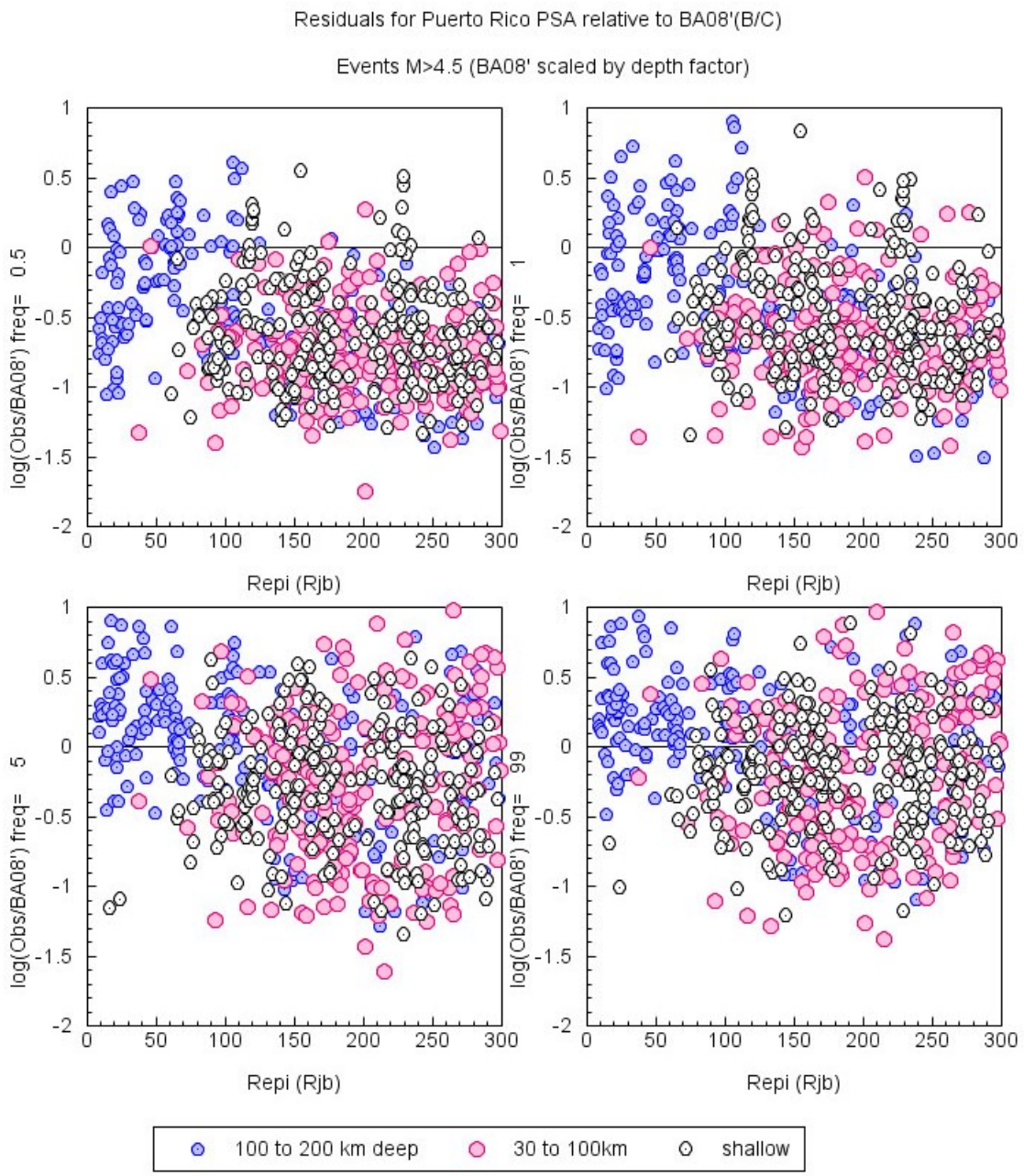


*Figure 5* – Residuals for Puerto Rico ground-motion data compared to BA08' reference equations (log10 units), for PSA at frequencies 0.5, 1, 5Hz and PGA. BA08' predictions have been scaled by Equation 3.

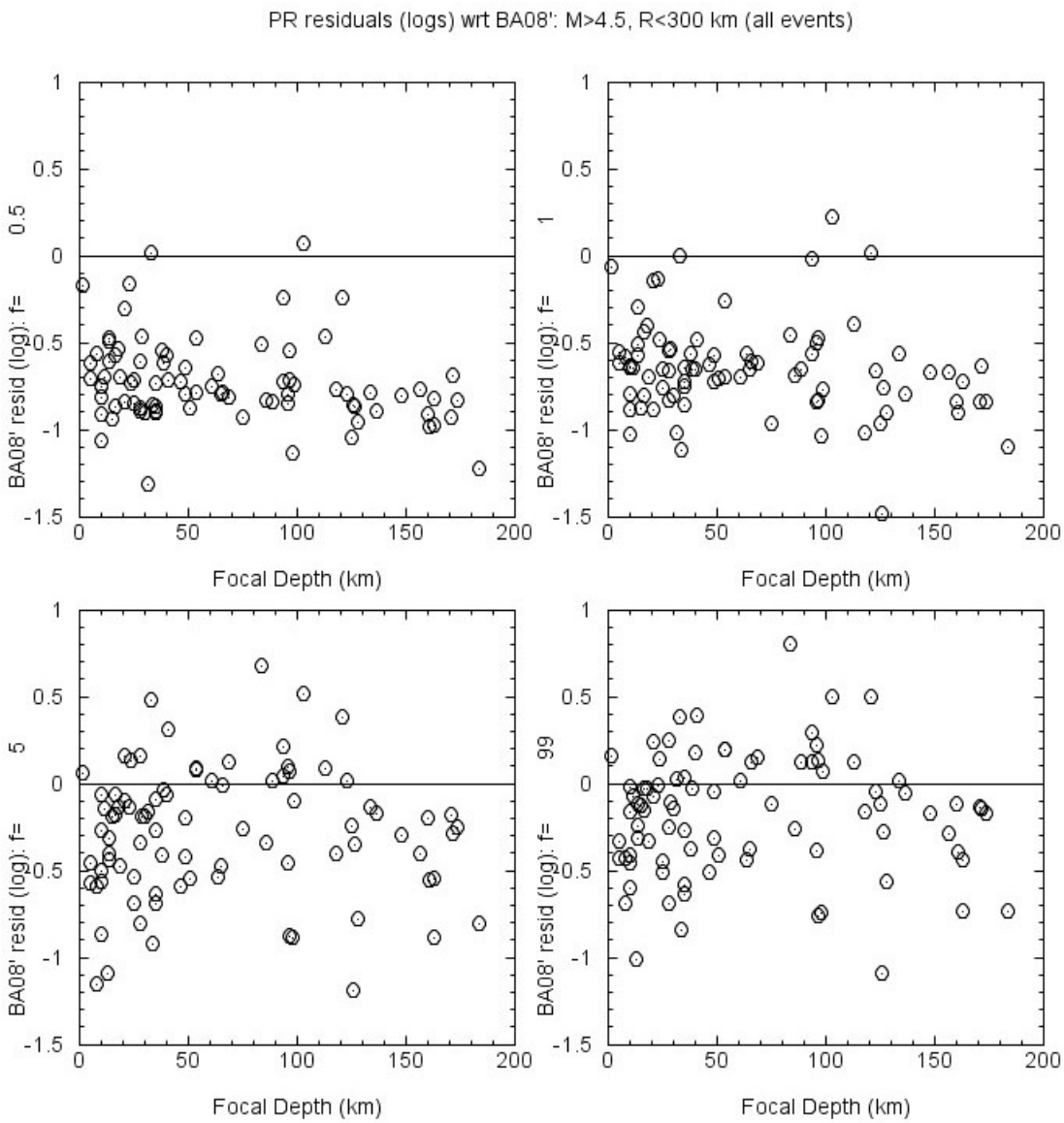


*Figure 6* – Dependence of average event residuals, for M>4.5 at $R_{epi}$<300km, on focal depth.

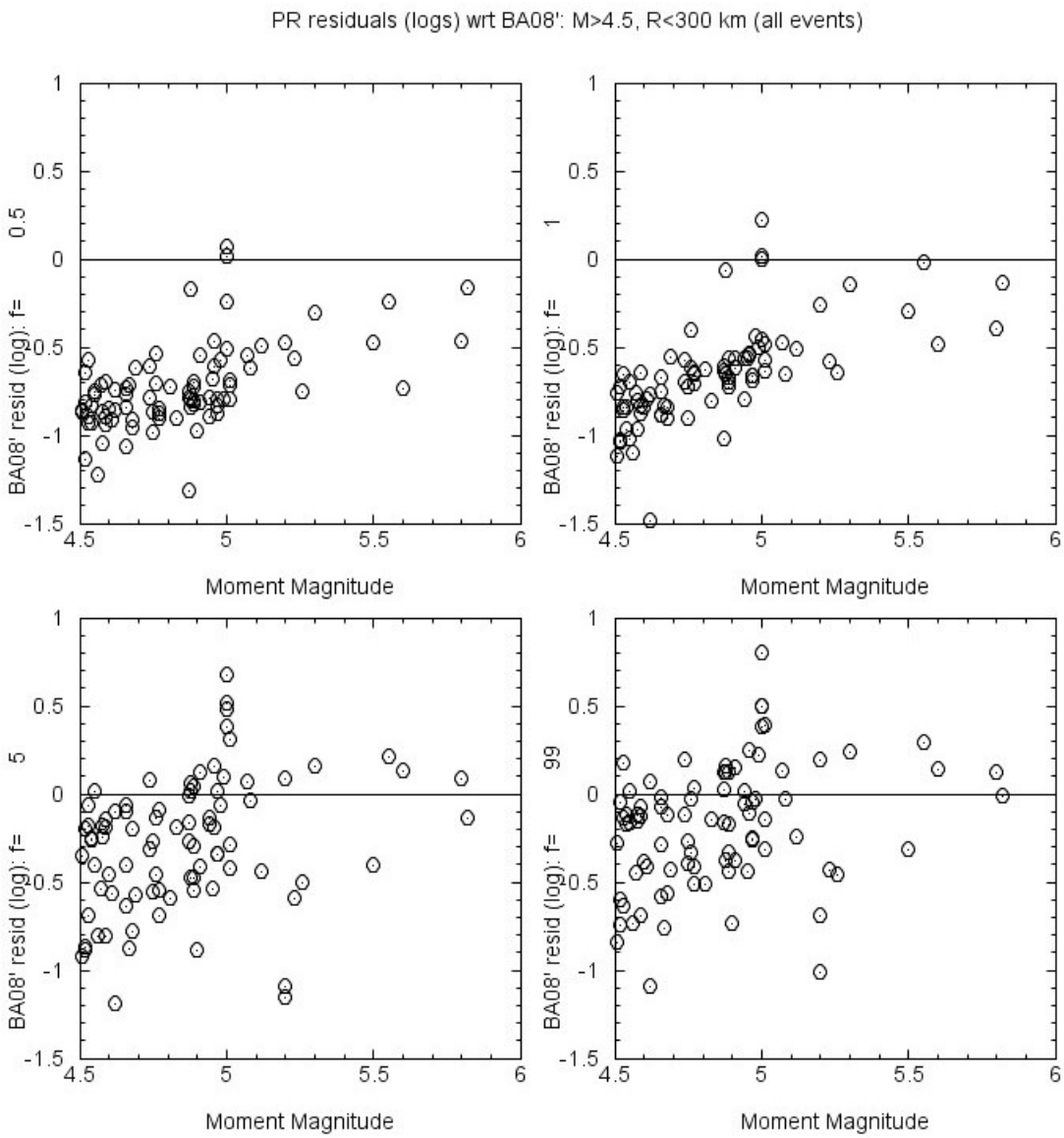


*Figure 7* – Dependence of average event residuals, for M>4.5 at $R_{epi}$<300km, on magnitude.

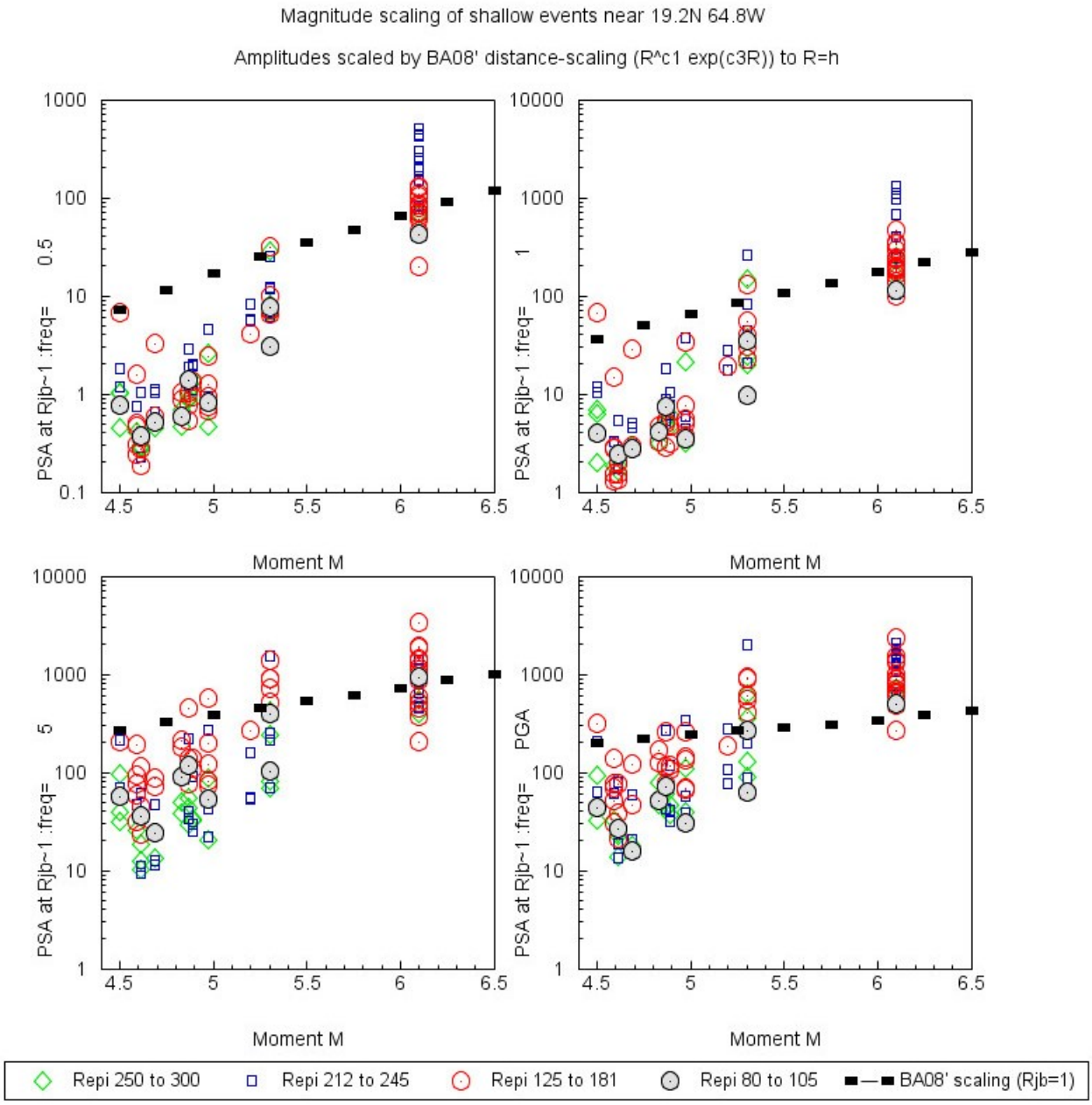


*Figure 8* – Magnitude scaling of distance-corrected PSA for a cluster of shallow events near 19N 65W. BA08' magnitude scaling shown for reference.

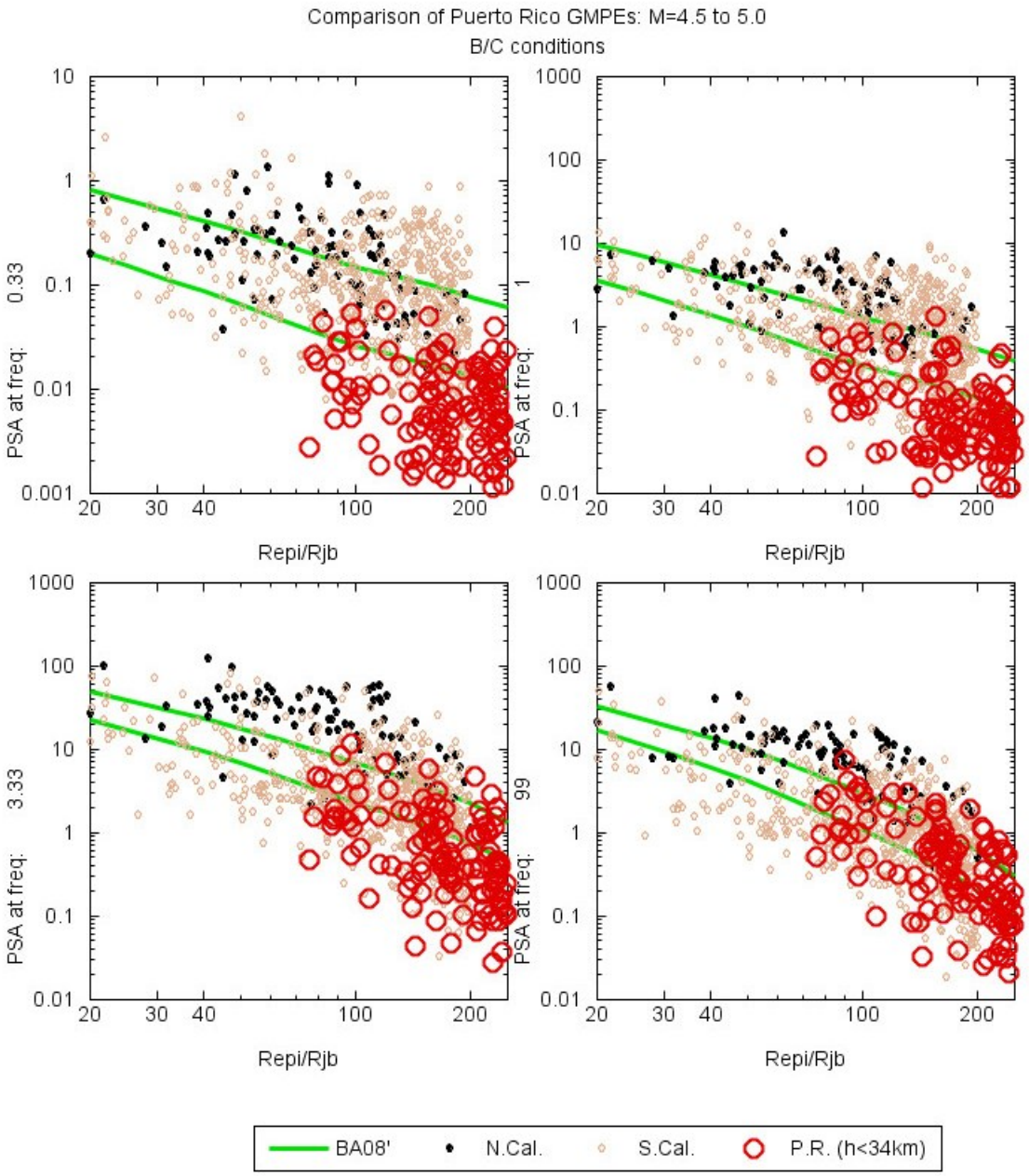


*Figure 9* – Comparison of PSA at 0.3, 1, 3Hz and PGA for shallow crustal earthquakes in Puerto Rico and California, **M**4.5 to 5.0. BA08' GMPEs also shown, for **M**4.5 and **M**5.0.

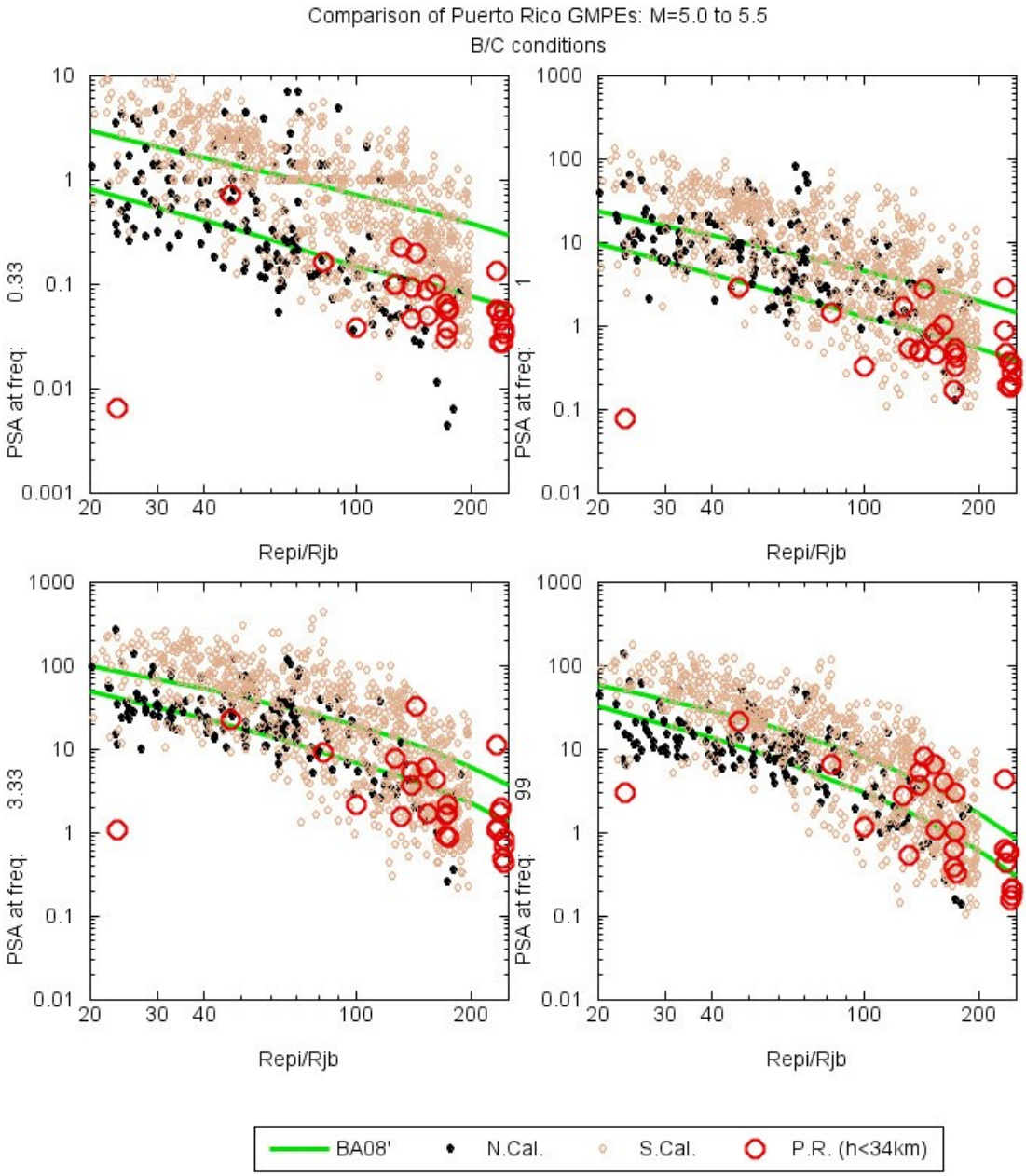


*Figure 10* – Comparison of PSA at 0.3, 1, 3Hz and PGA for shallow crustal earthquakes in Puerto Rico and California, **M**5.0 to 5.5. BA08' GMPEs also shown, for **M**5.0 and **M**5.5.

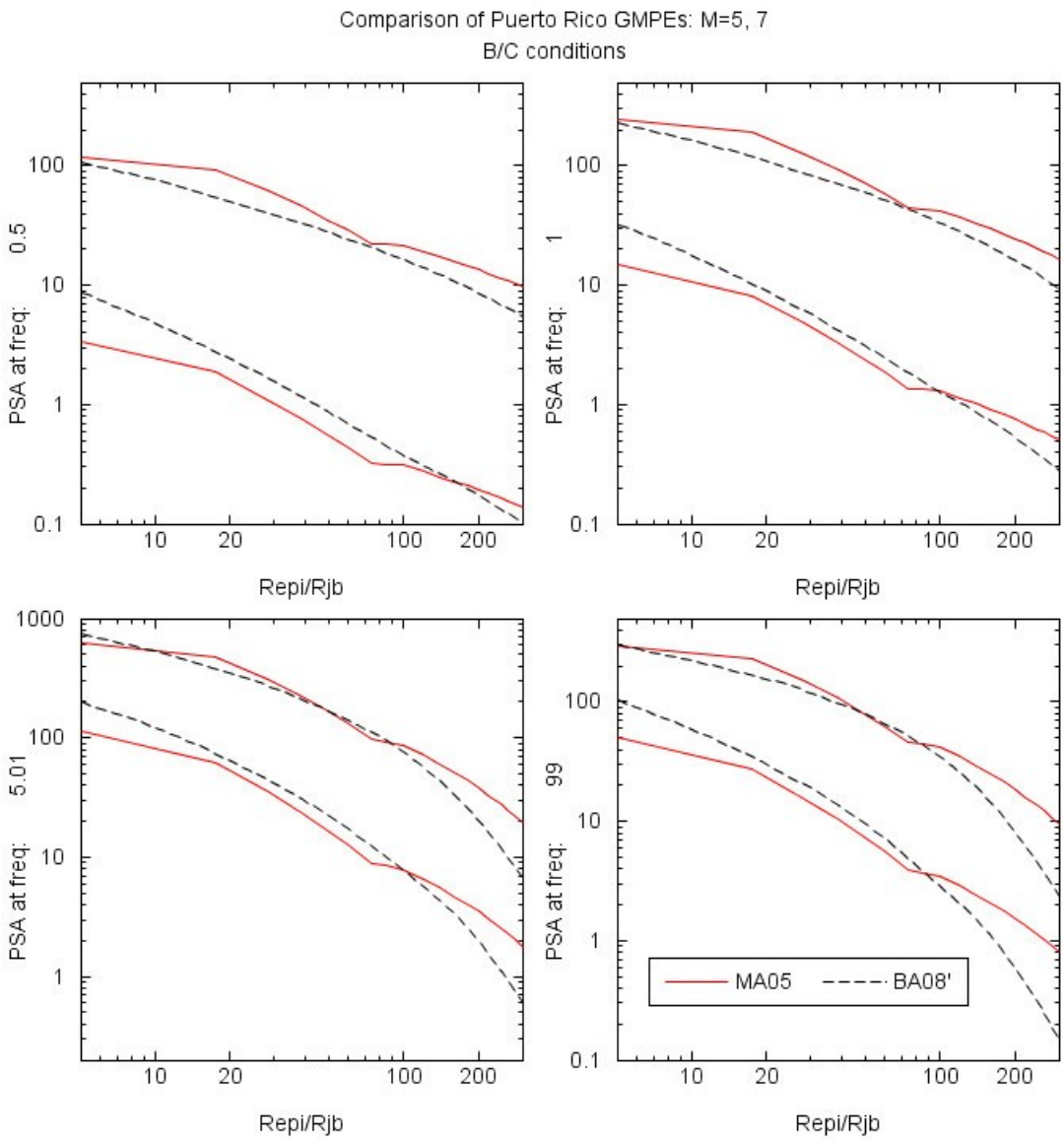


*Figure 11* – Comparison of example PEER-NGA GMPE of Boore and Atkinson (BA08'), and stochastic-model GMPE for Puerto Rico of Motazedian and Atkinson (2005) (MA05), for shallow events, B/C site conditions, for earthquakes of **M**=5 and **M**=7.