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A Comparison of NGA Ground-Motion Prediction Equations to Italian Data

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Abstract Ground-motion prediction equations (GMPEs) have recently been developed in the Next Generation Attenuation (NGA) project for application to shallow crustal earthquakes in tectonically active regions. We investigate the compatibility of those models with respect to magnitude scaling, distance scaling, and site scaling implied by Italian strong motion data. This is of interest because (1) the Italian data are principally from earthquakes in extensional regions that are poorly represented in the NGA dataset, and (2) past practice in Italy has been to use local GMPEs based on limited datasets that cannot resolve many significant source, path, and site effects. We find that the magnitude scaling implied by the Italian data is compatible with four NGA relations. However, the Italian data attenuate faster than implied by the four NGA GMPEs at short periods; the differences are statistically significant. Comparison with the fifth one was not possible because it was developed for rock conditions only. Three regression coefficients are reevaluated for the four NGA GMPEs to reflect the faster attenuation: a constant term, a term controlling the slope of distance attenuation, and a source fictitious depth term. The scaling of ground motion with respect to site shear wave velocity is consistent between the NGA models and Italian data. Moreover, the data are found to contain a nonlinear site effect that is generally compatible with NGA site terms. The intraevent scatter of Italian data is higher than in the NGA models, although interevent scatter is comparable to NGA recommendations when the faster distance attenuation is considered. On the basis of these findings, we recommend using the NGA relations, with the aforementioned minor modifications, to evaluate ground motions for seismic hazard analysis in Italy.

Introduction

The characterization of earthquake ground motions for engineering applications generally involves the use of empirical models referred to as ground-motion prediction equations (GMPEs). Ground-motion prediction equations describe the variation of the median and lognormal standard deviation of intensity measures (such as peak acceleration, spectral acceleration, or duration) with magnitude, site-source distance, site condition, and other parameters. A review of GMPEs for peak acceleration and spectral acceleration published prior to 2006 is given by Douglas (2003, 2006).

In recent years a number of GMPEs have been redefining the state of practice for probabilistic seismic hazard analysis (PSHA) in many earthquake-prone regions. For European applications, Ambraseys *et al.* (2005) and Akkar and Bommer (2007a, b) have introduced GMPEs that are considerably more sophisticated than widely used previous relations such as Ambraseys *et al.* (1996) and Sabetta and Pugliese (1996). The Next Generation Attenuation (NGA) project developed a series of GMPEs intended for application to geographically diverse regions; the only constraint is that the region be tectonically active with earthquakes occurring in the shallow crust. The NGA GMPEs are presented by Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), and Idriss (2008).

An important issue for many practical applications is whether ground motions or GMPEs for one region can be applied to another. For example, this issue prompted considerable study for the Senior Seismic Hazard Analysis Committee Level 4 PSHA (Budnitz *et al.*, 1997) performed for the PEGASOS project in Switzerland (Abrahamson *et al.*, 2002). The subject region for the PEGASOS project had relatively few ground-motion recordings; hence, GMPEs were borrowed from other areas for use in PSHA. Cotton *et al.* (2006) describe how source characteristics, path effects related to geometric spreading and anelastic attenuation, and site effects can vary from region to region. Those underlying physics ideally should be manifest in how a GMPE represents the scaling of a particular ground-motion intensity measure (IM) with respect to magnitude, distance, and site condition. Those issues are explored subsequently in this article.

The database used to develop the NGA GMPEs is large (3551 recordings from 173 earthquakes; subsets used for particular GMPEs) relative to those developed for relatively local regions, as is common in Europe. As mentioned previously, the NGA database is international, with most recordings derived from Taiwan, California, and Europe/Turkey (Chiou *et al.*, 2008). As noted by Stafford *et al.* (2008), because of the large size and high quality of the NGA database, certain effects are well resolved in some of the NGA GMPEs that could not be evaluated using only Italian (or European) data. Examples include the effects of depth to top of rupture and nonlinear site response. The NGA data also provide the opportunity to constrain relatively complex functional forms for magnitude and distance scaling as compared with models typically used in Europe, as described subsequently in this article.

Because of the relative sophistication of the NGA GMPEs, it is of interest to evaluate whether they can be applied in specific geographic regions such as Italy. This issue has been examined in a number of previous studies, the results of which are summarized in the next section. Our objective is to examine this issue by specifically testing the ability of the NGA models to capture the magnitude scaling, distance scaling, and site effects represented in the Italian dataset. This testing is of interest for two reasons: (1) to evaluate whether it is appropriate to apply NGA GMPEs for PSHA in Italy and elsewhere in Europe and (2) to check NGA GMPEs against a dataset principally populated by extensional (normal fault) earthquakes, which are poorly represented in the NGA database.

Our focus on Italian data is a matter of convenience; it does not reflect any opinion that ground motions should be examined on the basis of political boundaries. Our focus on Italy is predicated on the reevaluation of the Italian dataset according to standards similar to those used for the NGA database presented by Scasserra *et al.* (2009).

Recent Studies Comparing European and California Strong Ground Motions

Three general approaches have been used to compare ground motions or GMPEs between regions: (1) direct comparison of median predictions of particular IMs from GMPEs for different regions (Campbell and Bozorgnia, 2006; Stafford *et al.*, 2008); (2) analysis of variance (Douglas, 2004a, b); and (3) evaluation of the consistency of data distributions with respect to a GMPE (Scherbaum *et al.*, 2004; Stafford *et al.*, 2008) using likelihood concepts.

Comparison of Medians from GMPEs

Figure 1 shows an example of the first approach. Estimates of peak horizontal acceleration (PHA) and 5% damped pseudo-spectral acceleration at 2.0 sec from the Akkar and Bommer (2007a) and Ambraseys *et al.* (2005) models are compared with those from the NGA models of Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008). As shown by Campbell and Bozorgnia (2006) and Stafford *et al.* (2008), the European and NGA predicted medians generally compare well over the range of distances and magnitudes well constrained by the data. The bands of results for the two magnitudes generally show reasonably consistent vertical offsets from model to model (e.g., the difference between M 7 and 5 peak ground acceleration (PGA) at $R_{\mathrm{jb}} = 30$ km is reasonably consistent across models). This suggests generally consistent levels of magnitude scaling. The slopes of the median PGA curves for a given magnitude are generally steeper for the European relations than the NGA relations, suggesting faster distance attenuation. This potential difference in the distance attenuation was not noted by Campbell and Bozorgnia (2006) and Stafford *et al.* (2008).

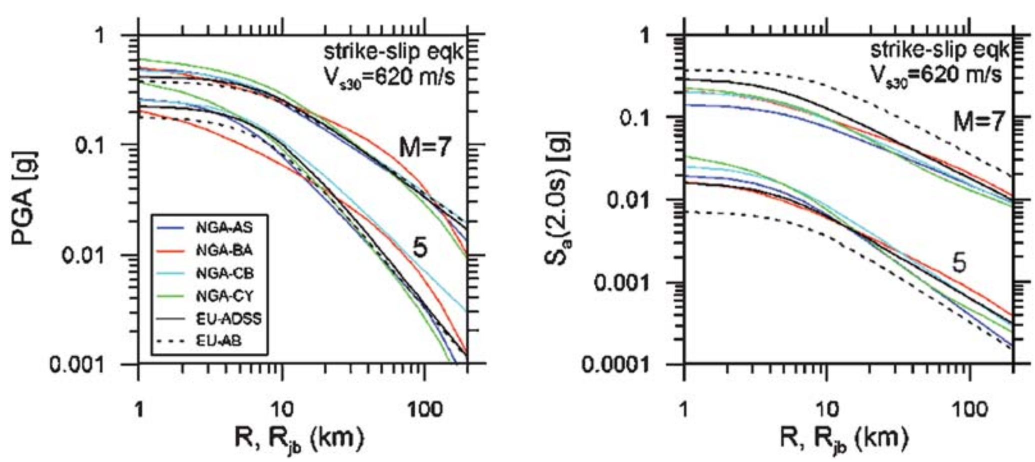

Figure 1. Comparison of median predictions of average horizontal component of peak ground acceleration (PGA) and 2.0 sec pseudo-spectral acceleration for strike-slip earthquakes and soft rock site conditions from NGA and European GMPEs. Assumed condition is vertically dipping fault with zero depth to top of rupture, for which $R = R_{\mathrm{jb}}$. AS: Abrahamson and Silva (2008); BA: Boore and Atkinson (2008); CB: Campbell and Bozorgnia (2008); CY: Chiou and Youngs (2008); ADSS: Ambraseys *et al.* (2005); AB: Akkar and Bommer (2007a). Ambraseys *et al.* (2005) median values adjusted from maximum component to average horizontal per Beyer and Bommer (2006).

Analysis of Variance

The approach termed analysis of variance was applied by Douglas (2004a) to compare ground motions for five local regions within Europe; Douglas (2004b) compared ground motions from Europe, New Zealand, and California. The procedure involved calculating the mean (μ) and variance (σ^2) of the log of data inside particular magnitude and distance bins (M-R bins) for two different regions (e.g., Europe and California) and combined data for those regions. The distance metric used by Douglas was the closest distance to the surface projection of the fault for $M > 6$ and epicentral distance otherwise. Individual data points were adjusted for a linear site factor from Ambraseys *et al.* (1996) before the calculation of mean and variance. These results were then used in two ways. First, for a given M-R bin and pair of regions, the variance of the combined data for both regions [termed $(\sigma^2)_{\text{interregion}}$] was compared to the within-region variance [termed $(\sigma^2)_{\text{intraregion}}$] using statistical tests that evaluated whether the datasets were significantly distinct. If $(\sigma^2)_{\text{interregion}} > (\sigma^2)_{\text{intraregion}}$ in a statistically significant way, there were likely to be significantly different means between regions. Second, the binned results were used to plot means for each M-R bin together for pairs of regions.

Using this approach, Douglas (2004a) found similar variances for the various regions in Europe, indicating a lack of regional variations. Accordingly, Douglas (2004b) combined all of the European data into a single category for comparison with the New Zealand and California data. The Europe–California comparisons indicated that approximately half of the M-R bins demonstrated significantly different inter- and intraregion variances. The distinction was toward larger ground motions in California (Douglas, 2004b). Careful analysis of figure 1 of Douglas (2004b) indicates that the California and European means for most M-R bins have similar amplitudes in short distance bins (< 20 km), whereas California amplitudes are larger at larger distances (> 30 km). Thus, Douglas's (2004b) finding of larger California ground motions could be alternatively expressed as more rapid distance attenuation in Europe. Offsets between California and European means within a given well-populated distance category (e.g., 10–15 km) do not vary significantly across magnitude bins, suggesting similar levels of magnitude scaling.

Overall Goodness-of-Fit of Model to Data

This approach, developed by Scherbaum *et al.* (2004), provides an evaluation of overall goodness-of-fit of a GMPE to a dataset. A normalized residual is calculated for recording j from event i in a dataset

$$Z_{T,ij} = \frac{\ln(\text{IM}_{\text{obs},ij}) - \ln(\text{IM}_{\text{mod},ij})}{\sigma_T}, \qquad (1)$$

where $\ln(\text{IM}_{\text{obs},ij})$ represents the IM value from the record; $\ln(\text{IM}_{\text{mod},ij})$ represents the median model prediction for the same magnitude, site-source distance, and site condition of the record; and σ_T represents the total standard deviation of the model (combination of inter- and intraevent standard deviations). If the data are unbiased with respect to the model and have the same dispersion, the normalized residuals (Z_T) should have zero mean and standard deviation of one (i.e., the properties of the standard normal variate). Accordingly, in simple terms, the procedure of Scherbaum *et al.* (2004) consists of comparing the actual Z_T distribution to that of the standard normal variate. Note that this procedure tests both misfit of the median and standard deviation.

Stafford *et al.* (2008) extended this method to consider both inter- and intraevent variability. They compared European data to the NGA relation of Boore and Atkinson (2008) and the European models of Ambraseys *et al.* (2005) and Akkar and Bommer (2007a, b). The Boore and Atkinson (2008) relation was shown to match the median of the European data nearly as well as European GMPEs. The Boore and Atkinson standard deviation, however, was lower than values from the European relations. This discrepancy was attributed to the magnitude dependence of the European GMPE standard deviation models, whereas the Boore and Atkinson standard deviation was homoscedastic (constant with respect to magnitude).

Interpretation

It should be emphasized that the Scherbaum *et al.* (2004) approach assesses model performance in an overall sense. All aspects of the model (magnitude scaling, distance scaling, site effects) are evaluated in a lumped manner. If one of these model components was in error, that effect could be obscured through compensating errors in the analysis of normalized residuals. Accordingly, while the results of Stafford *et al.* (2008) are certainly promising with respect to the application of NGA relations in Europe, they do not specifically address whether individual components of the NGA models are adequate with respect to European data. Because there is some evidence of faster distance attenuation of European data relative to California data (Douglas, 2004b) and active regions generally (Fig. 1), a formal analysis of the adequacy of the NGA relations with respect to magnitude scaling, distance scaling, and site effects is needed. We address these issues in the remainder of this article.

Attributes of NGA and European Ground-Motion Prediction Equations

GMPEs are formulated with varying degrees of complexity in their functional form as a result of author preference and database size. The NGA models include two relatively simple models (Boore and Atkinson, 2008; Idriss, 2008) and three more complex models (Abrahamson and Silva, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008). Attributes of the NGA models and several European relations with respect to magnitude, distance, and V_{S30} scaling are summarized in this section. The European models considered are Ambraseys *et al.* (2005) and Akkar and Bommer (2007a).

Magnitude scaling varies from linear (Idriss, 2008; Ambraseys *et al.*, 2005) to nonlinear functions expressed as second-order polynomials (Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Akkar and Bommer, 2007a), piecewise linear relations (Campbell and Bozorgnia, 2008), and bilinear relations with smooth transitions (Chiou and Youngs, 2008). As shown in Stewart *et al.* (2008), the variation with magnitude of PGA and $T = 2.0$ sec 5% damped spectral acceleration are similar for the NGA and European GMPEs at a site-source distance of 30 km.

Table 1 shows the forms of the distance-attenuation functions in the selected GMPEs. Many of the models (Abrahamson and Silva, 2008; Campbell and Bozorgnia, 2008; Akkar and Bommer, 2007a; Ambraseys *et al.*, 2005) use a relatively simple form consisting of the product of a linear function of magnitude and the natural log of the square root of sum of squares of distance and a fictitious source depth term (denoted by h in Table 1). The linear term accounts for the decrease of attenuation with increasing magnitude (the intercept is negative and the coefficient for the change of slope with magnitude is positive). The Chiou and Youngs (2008) model produces a similar trend using a magnitude-dependent fictitious depth. The Chiou and Youngs (2008) model also accounts for the variation of distance attenuation with distance to capture the dominant effects of body waves at distances $<$40–70 km and *Lg* waves at larger distances. The Boore and Atkinson (2008) model has a similar change of rate of attenuation in this distance range, which is attributed to anelastic attenuation. Additional anelastic attenuation terms (represented by $\gamma(M)$) are included by Chiou and Youngs (2008) and Idriss (2008). Figure 1 compares the distance attenuation of NGA and European models. As noted previously, the slopes from European models are slightly greater. Among the NGA models, the steepening of the slope of the median curve for PGA at distances exceeding about 70 km is apparent in Figure 1 from the Boore and Atkinson (2008) and Chiou and Youngs (2008) models, whereas the Abrahamson and Silva (2008) and Campbell and Bozorgnia (2008) slopes at large distance are constant. Also noteworthy are the relative slopes in the 10–70 km distance range, where much of the data lie. In this range, the steepest slope is Chiou and Youngs (2008), the flattest is Boore and Atkinson (2008), while Abrahamson and Silva (2008) and Campbell and Bozorgnia (2008) are intermediate. These differences have implications with respect to the Italian data, as discussed subsequently.

The models by Abrahamson and Silva (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008) include hanging wall terms, which account for the larger ground motions observed on the hanging wall of dipping faults. As shown in Table 1, a distance parameter used to evaluate this effect for the Abrahamson and Silva (2008) and Chiou and Youngs (2008) models is R_x, which is defined in Figure 2. Additional terms used to evaluate hanging wall effects include depth to top of rupture (Z_{tor}), dip angle (δ), and down-dip fault width (W).

The site terms utilized in the GMPEs vary in complexity. All NGA models except Idriss (2008) use V_{S30} as a predictor of site effects. The level of amplification for weak input motions (corresponding to nearly linear conditions) increases with decreasing V_{S30}. In the Abrahamson and Silva (2008) and Campbell and Bozorgnia (2008) GMPEs, the reference rock parameter used with the nonlinear components of the site terms is $\widehat{\mathrm{PGA}}_{1100}$, which is roughly the median peak acceleration on rock with $V_{S30} = 1100$ m/sec. (Boore and Atkinson [2008] similarly used PGA on rock with $V_{S30} = 760$ m/sec.) The Chiou and Youngs (2008) site model replaces $\widehat{\mathrm{PGA}}_{1100}$ with the median rock spectral acceleration at the period of interest. The slopes of the amplification functions relative to $\widehat{\mathrm{PGA}}_{1100}$ become flatter with increasing V_{S30}. The Ambraseys *et al.* (2005) and Akkar and Bommer (2007a) site terms are linear and constant for qualitative site descriptors (soft soil, stiff soil, rock). In addition to V_{S30}, the Abrahamson and Silva (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008) site models include a basin depth term, which is taken as the depth to a particular shear wave velocity isosurface. The Abrahamson and Silva (2008) and Chiou and Youngs (2008) models take this depth as $Z_{1.0}$ (depth to $V_S = 1.0$ km/sec), whereas the Campbell and Bozorgnia (2008) model takes this depth as $Z_{2.5}$ (depth to $V_S = 2.5$ km/sec).

We consider each of the GMPEs listed in Table 1 except Idriss (2008). That model is excluded due to its lack of a site term. A significant fraction of the Italian data has soil site conditions and, hence, requires the use of a site term.

Database

The database used in this study is presented by Scasserra *et al.* (2009). The strong motion data were corrected and uniformly processed by the same seismologists (Walter Silva and Robert Darragh) who prepared the data for NGA. During this process, about 50% of the Italian motions were screened out because of *S*-triggers and other problems. Figure 3 shows the number of available recordings with $M > 4$ as a function of the maximum usable period, taken as the inverse of $1.25 \times f_{HP}$, where f_{HP} is the high-pass corner frequency used in the data processing, which varies from accelerogram to accelerogram according to signal characteristics. Note that there is a significant drop-off in the data for periods $>$2–3 sec.

Source parameters were compiled from databanks maintained by the Italian Institute of Geology and Vulcanology (INGV; see the Data and Resources section), and included moment magnitude, focal mechanism, and hypocenter location for 52 of the 89 events. The other 37 events were small magnitude (M_L 3–5); for those events M_L was taken as an estimate of M_w. For events with magnitudes $>$ ~5.5, finite source parameters were compiled from INGV. Closest distance (R), Joyner–Boore distance (R_{jb}), and a hanging wall index were evaluated by Brian Chiou (personal communication, 2008) using the source parameters and site locations in the database.

Table 1

Distance-Scaling Functions Used in NGA and Recent European GMPEs

	GMPE	R-Scaling*	Notes	Parameters†
NGA	Abrahamson and Silva (2008)	$[a_2 + a_3(M - M_r)] \times \ln(\sqrt{R^2 + h^2})$	Additional hanging wall, depth to top of rupture, and large distance-scaling terms	R, R_{jb}, R_x, Z_{tor}, W, δ
NGA	Boore and Atkinson (2008)	$[c_1 + c_2(M - M_r)] \times \ln(\frac{\sqrt{R_{jb}^2+h^2}}{R_{ref}}) + c_3(\sqrt{R_{jb}^2 + h^2} - R_{ref})$	None	R_{jb}
NGA	Campbell and Bozorgnia (2008)	$(c_4 + c_5 M) \times \ln(\sqrt{R^2 + h^2})$	Additional hanging wall term with functional dependence on δ and Z_{tor}	R, R_{jb}, Z_{tor}, δ
NGA	Chiou and Youngs (2008)	$c_4 \ln[R + c_5 \cosh\{c_6 \max(M - M_r, 0)\}] + (c_{4a} - c_4)\ln(\sqrt{R^2 + c_{RB}^2}) + \gamma(M) \times R$	Additional hanging wall terms with functional dependence on δ and Z_{tor}	R, R_{jb}, R_x, Z_{tor}, δ
NGA	Idriss (2008)	$-(\beta_1 + \beta_2 M) \times \ln(R + 10) + \gamma(T)R$	None	R
European	Akkar and Bommer (2007a)	$(b_4 + b_5 M) \times \ln(\sqrt{R_{jb}^2 + h^2})$	None	R_{jb}
European	Ambraseys *et al.* (2005)	$(a_3 + a_4 M) \times \ln(\sqrt{R_{jb}^2 + h^2})$	Separate style of faulting term	R_{jb}

*a, c, and β terms format retained from original model; h and M_r variables used here to show compatibility across models. These terms do not necessarily match those in the source publications. R_{ref} is specific to Boore and Atkinson (2008).

†R = rupture distance; R_{jb} = closest distance to horizontal projection of rupture plane; R_x defined in Figure 2; Z_{tor} = depth to top of rupture; W = fault width; δ = dip angle.

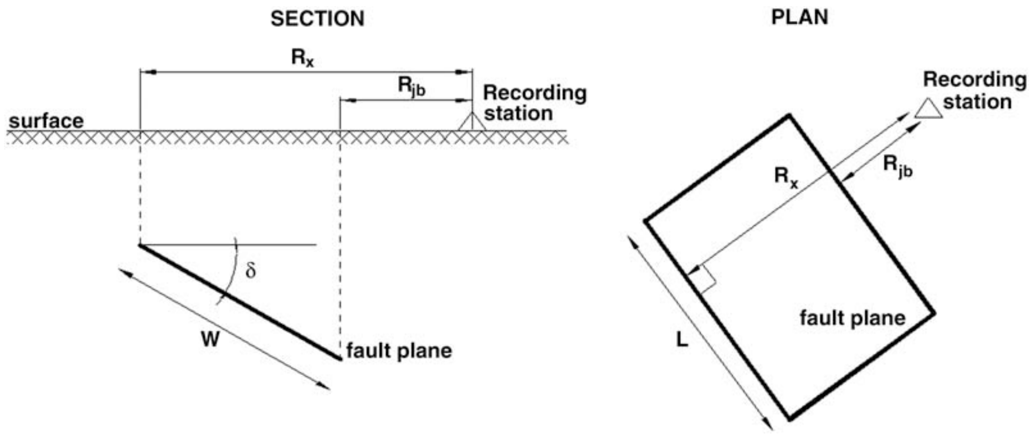

Figure 2. Schematic illustration of dipping fault and measurement of R_x parameter used in hanging wall terms for the Abrahamson and Silva (2008) and Chiou and Youngs (2008) GMPEs.

Where available, distance R was taken to the fault rupture plane and R_{jb} to the surface projection of the fault rupture plane. For small magnitude earthquakes without a finite fault model, R was taken as the hypocentral distance and R_{jb} was taken as the epicentral distance. Because the only events without finite fault models were small in magnitude and, hence, had small fault dimensions, this approximation was considered to be reasonable. For one event with unknown hypocentral depth and focal mechanism, those parameters were estimated based on available data from the local region.

The hanging wall index compiled by Chiou indicates whether a site is located on the hanging wall, footwall, or in a neutral (side) position relative to a dipping fault. For hanging wall sites, parameter R_x is estimated as

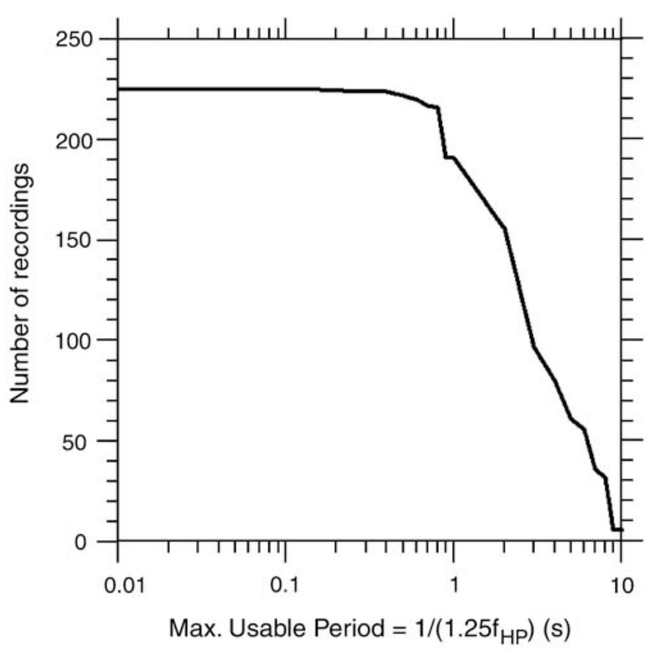

Figure 3. Variation of number of available recordings with $M > 4$ in the Italian database with the maximum usable period, which is taken as the inverse of $1.25 \times f_{\mathrm{HP}}$ (f_{HP} = high pass corner frequency used in data processing).

$$R_x \approx R_{\mathrm{jb}} + W\cos(\delta), \tag{2}$$

where W = fault width and δ = dip angle. Parameters W and δ are compiled by Scasserra *et al.* (2009) for earthquakes with finite source models. For other events where these parameters were needed, they were estimated using empirical models for W (Wells and Coppersmith, 1994) and dip angles for nearby faults (for δ). The approximation in equation 2 is because R_x is strictly measured normal to the fault strike, as shown in Figure 2, whereas R_{jb} is not measured normal to the fault strike for sites beyond the ends of the fault but within the hanging wall region. As indicated in Table 1, another parameter needed for some of the NGA hanging wall terms is depth to top of rupture (Z_{top}). As with dip angle, this is taken from the finite fault database where available and otherwise is calculated assuming the hypocenter is at mid-width as equation (3) shows

$$Z_{\mathrm{top}} \approx Z_{\mathrm{hyp}} - \frac{W}{2}\sin(\delta), \tag{3}$$

where Z_{hyp} = hypocentral depth. Additional adjustments are made on a case by case basis as needed (e.g., if $Z_{\mathrm{top}} < 0$ by assuming the hypocenter is at mid-width, it is moved down).

Figure 4 shows the magnitude distance scattergram relative to that in the NGA database described by Chiou *et al.* (2008). Relative to the NGA data, the Italian data are generally sparse for $R_{\mathrm{epi}} < 10$ km and $M > 6.5$. There is a reasonable degree of overlap in the datasets for $R_{\mathrm{epi}} = 10$–70 km and M 4.5–6. The Italian data are richer than NGA for $M < 4.5$, which occur because the NGA models are intended for application to $M > 5$ earthquakes. An important distinction between the NGA and Italian databases concerns the preponderance of normal fault earthquakes in the Italian data (44 of 89 events). In contrast, the NGA database has only 13 normal fault earthquakes with 87 recordings (2.5% of total). Accordingly, comparison of NGA relations to Italian data provides the opportunity to test their applicability for a

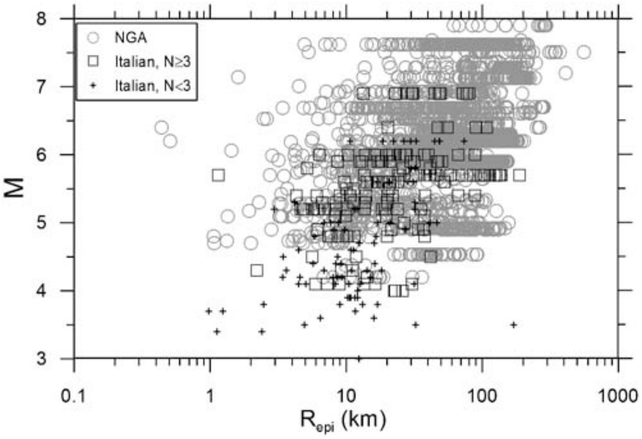

Figure 4. Distribution of NGA and Italian data with respect to magnitude and epicentral distance.

predominantly extensional region (although we do not claim the results to be applicable to extensional regions generally).

Scasserra *et al.* (2009) present V_{S30} parameters for all Italian sites utilized in the present analysis. Basin depth term $Z_{1.0}$ is taken from velocity profiles where available. Otherwise $Z_{1.0}$ is estimated from V_{S30} using the following function proposed by Chiou and Youngs (2008):

$$\ln(Z_{1.0}) = 28.5 - 0.4775 \ln(V_{S30}^8 + 378.7^8), \quad (4)$$

where $Z_{1.0}$ is in m and V_{S30} is in m/sec. It is not possible to validate equation (4) using existing data from sites in Italy. Depth term $Z_{2.5}$ is evaluated from $Z_{1.0}$ using the following relation similarly derived from the NGA data by Campbell and Bozorgnia (2007):

$$Z_{2.5} = 0.519 + 3.595 Z_{1.0}, \quad (5)$$

where both depths are in kilometers. Use of equation (5) implies similar velocity gradients in rock for California and Italian sites, which may not be the case.

We recognize that these empirical sediment depth estimates may not apply to Italy. By using median depths that are dependent on V_{S30} for the majority of sites, we are essentially using the average basin effect in the NGA GMPEs. If we are significantly in error, it would be expected to produce bias at long periods, where the basin effects are most pronounced. This is evaluated subsequently in the article.

Data Analysis

Overall GMPE Bias and Standard Deviation Relative to Italian Data

We begin by evaluating residuals between the data and a particular GMPE referred to with index k. Residuals are calculated as

$$(R_{i,j})_k = \ln(\mathrm{IM}_{i,j})_{\mathrm{data}} - \ln(\mathrm{IM}_{i,j})_k. \quad (6)$$

Index i refers to the earthquake event and index j refers to the recording within event i. Hence, $(R_{i,j})_k$ is the residual of data from recording j in event i as calculated using GMPE k. Term $\ln(\mathrm{IM}_{i,j})_{\mathrm{data}}$ represents the GMRotI50 parameter (Boore *et al.*, 2006) computed from recording j (similar to geometric mean). Term $\ln(\mathrm{IM}_{i,j})_k$ represents the median calculated using GMPE k in natural log units.

Residuals are calculated using equation (6) for six GMPEs: Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), Chiou and Youngs (2008), Akkar and Bommer (2007a), and Ambraseys *et al.* (2005). The analysis of residuals with respect to magnitude, distance, and site scaling requires that event-to-event variations be separated from variations of residuals within events. This is accomplished by performing a mixed effects regression (Abrahamson and Youngs, 1992) of residuals according to the following function:

$$(R_{i,j})_k = c_k + (\eta_i)_k + (\varepsilon_{i,j})_k, \quad (7)$$

where c_k represents a mean offset (or bias) of the data relative to GMPE k, η_i represents the event term for event i (explained in the following section), and $\varepsilon_{i,j}$ represents the intraevent residual for recording j in event i. Event term η_i represents approximately the mean offset of the data for event i from the predictions provided by the GMPE median (after adjusting for mean offset c_k, which is based on all events). Event terms provide a convenient mechanism for testing the ability of a GMPE to track the magnitude scaling of a dataset. Event terms are assumed to be normally distributed with zero mean and standard deviation $= \tau$ (in natural log units). Intraevent error ε is also assumed to be normally distributed with zero mean and standard deviation $= \sigma$.

Figure 5 shows the distribution of event terms from the Italian data as a function of the number of recordings per event. The scatter of event terms is large for sparsely recorded events (1–2 recordings), but it is relatively stable for events with three or more recordings. Accordingly, for subsequent

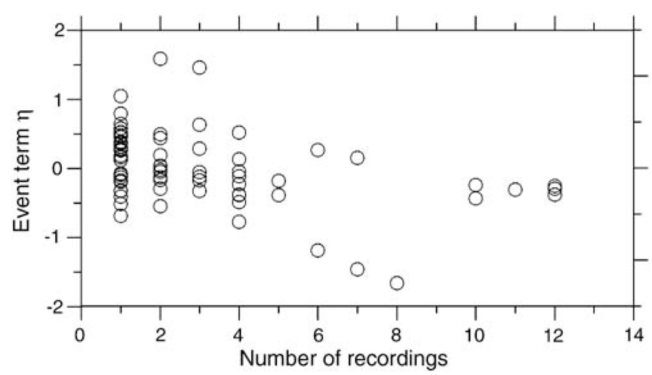

Figure 5. Variation of PGA event terms for Abrahamson and Silva (2008) GMPE with number of recordings, showing decrease of scatter for events with more recordings. Data from 1- and 2-recording events are not used in this study because of large scatter of event terms.

analysis we remove from the dataset events with only one or two recordings. The three outlier events with large negative event terms (with 6, 7, and 8 recordings) are recorded predominantly at large distance (the events are Molise, M_w 5.7, 31 October 2002 and M_w 5.7, 1 November 2002; Trasaghis–Friuli, M_L 4.1, 28 May 1998). The large negative event terms for these events are attributed in part to a distance-attenuation bias in the NGA GMPEs described subsequently. The Molise events also appear to have had low stress drops (Calderoni *et al.* 2010).

Using the dataset for earthquakes with three or more recordings, mixed effects regressions were performed using equation (7) for the aforementioned six GMPEs and five IMs: peak acceleration and 5% damped pseudo-spectral acceleration (S_a) at periods of 0.2, 0.5, 1.0, and 2.0 sec. Additional results are tabulated in Stewart *et al.* (2008). Figure 6a shows the average misfit of Italian data to the NGA GMPEs as expressed by parameter c, along with 95% confidence intervals. Parameter c is not generally significantly offset from zero, nor does it have a significant trend with period. An exception is Campbell and Bozorgnia (2008), for which c is consistently and significantly negative for $T > \sim 0.2$ sec. Negative values of c indicate an average overprediction of the Italian data by the CB GMPE. The general lack of significantly nonzero values of c at long periods suggests that, in a crude first-order sense, the basin depth estimates applied to the Italian data are not introducing significant bias when used in the NGA GMPEs.

Figures 6b–c plot the inter- and intraevent standard deviations (τ and σ, respectively) versus periods as evaluated from the regressions performed using equation (7). Results are shown for the NGA GMPEs only. Also shown in Figures 6b–c are the ranges of τ and σ provided by a representative NGA GMPE (Chiou and Youngs, 2008) and a European GMPE (Akkar and Bommer, 2007a) for M 5–7. The standard deviation terms from the Italian data are significantly larger than those provided by Chiou and Youngs (2008) and the other NGA relations. Intraevent standard deviation σ is similar to values obtained previously by Akkar and Bommer (2007a) for Europe, but our τ terms are much larger. This is strongly influenced by the aforementioned three events with large negative event terms (Fig. 5), and is reduced by modifications to the GMPEs described subsequently in this article. Differences between the Italian and NGA σ terms are relatively stable and are discussed further in the following section.

Distance Scaling

We next turn to the question of how well the selected GMPEs capture the distance scaling of the Italian dataset. Distance scaling is tested by examining trends of intraevent residuals $\varepsilon_{i,j}$ as a function of distance. Recall that per equation (7), $\varepsilon_{i,j}$ is the remaining residual after mean error (c) and event term (η_i) are subtracted from the total residual. Figure 7 shows ε_{ij} for IMs of PGA, 0.2 sec S_a, and 1.0 sec S_a.

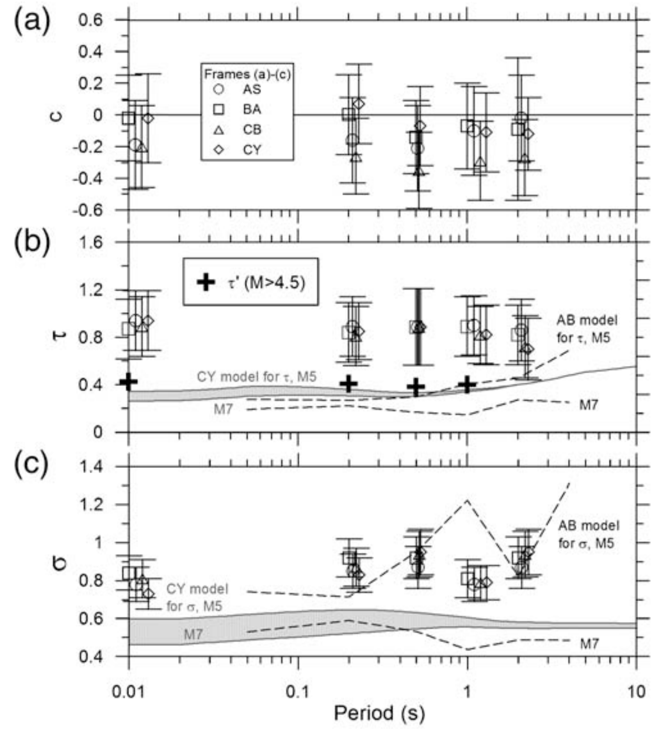

Figure 6. Variation with period of mean bias parameter c, interevent dispersion τ, and intraevent dispersion σ evaluated from regression of NGA residuals relative to Italian data with equation (7). Values of τ' in (b) are derived from modified NGA GMPEs.

To help illustrate trends, we also plot a fit line and its 95% confidence intervals, the fit being made according to:

$$\varepsilon_{i,j} = a_R + b_R \ln(R_{i,j}) + (\kappa_R)_{i,j}. \quad (8)$$

Parameters a_R and b_R are regression parameters and κ_R is the residual of the fit for recording j from event i. Subscript k has been dropped in equation (8), which strictly holds for GMPEs using rupture distance. For Boore and Atkinson (2008), Akkar and Bommer (2007a), and Ambraseys *et al.* (2005), R_{jb} replaces R as the distance parameter. Slope parameter b_R represents approximately the misfit of the distance scaling in the Italian dataset relative to the selected GMPEs. The statistical significance of the distance-dependence of intraevent residuals is assessed using sample t statistics to test the null hypothesis that $b_R = 0$. This statistical testing provides a significance level $= p$ that the null hypothesis cannot be rejected. For clarity of expression, we show values of 1-p in Figure 7, which we refer to as a rejection confidence for a zero slope model. Also shown in Figure 7 are median residuals within overlapping distance bins nominally 1/4 of a distance log cycle in width (overlap is 1/8 of a distance log cycle on either side).

The results in Figure 7 indicate mixed findings with respect to misfits between the NGA distance scaling and the Italian data. For example, NGA GMPEs other than Boore

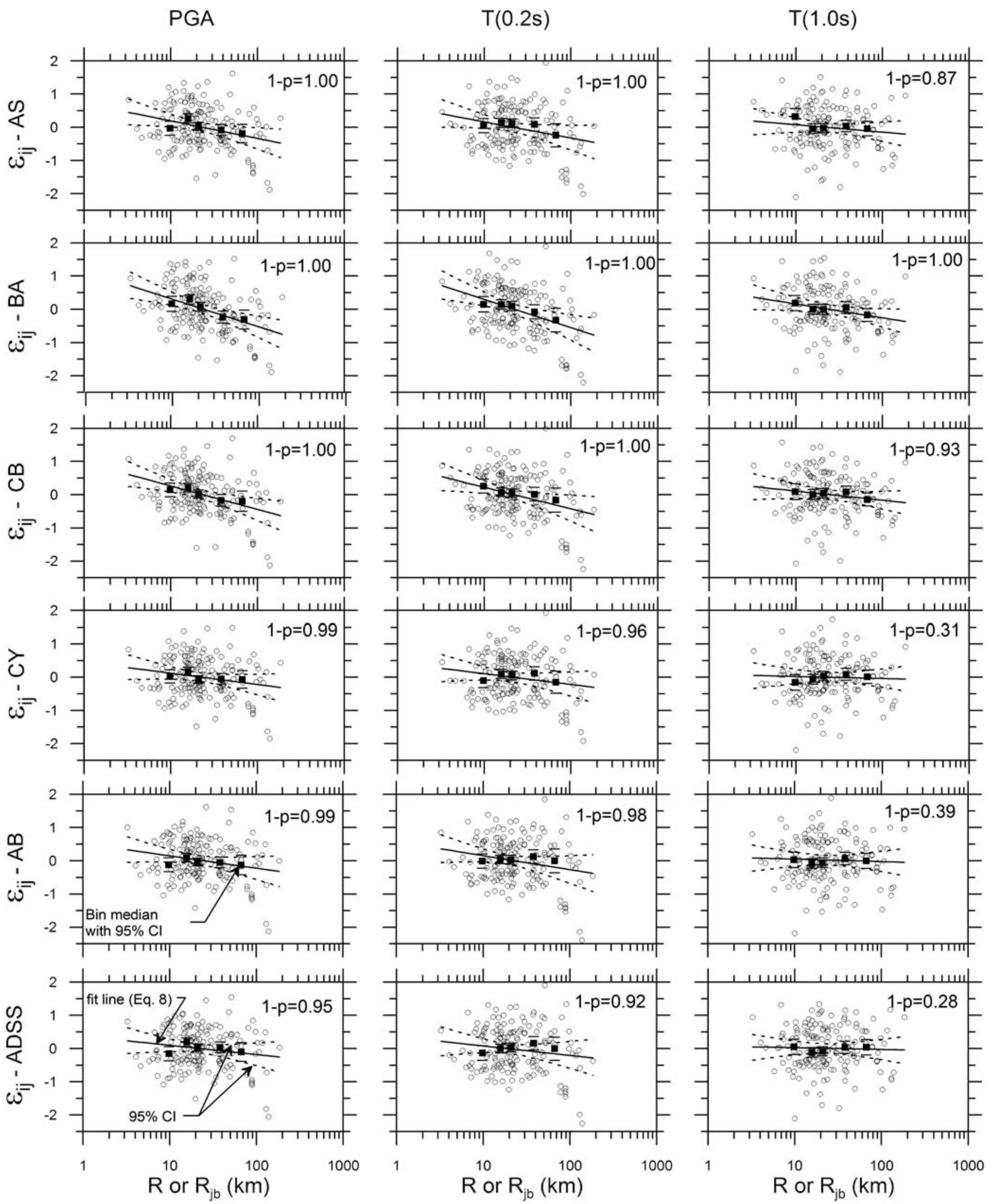

Figure 7. Variation of intraevent residuals for Italian data with distance for PGA, 0.2 sec S_a, and 1.0 sec S_a.

and Atkinson (2008) have unbiased distance attenuation at long period ($T \geq 1.0$ sec), as evidenced by low rejection confidence for the zero slope null hypothesis. On the other hand, NGA GMPEs produce statistically significant values of b_R ranging from approximately -0.15 to -0.4 at short periods (PGA and 0.2 sec S_a). These negative values of b_R at short periods indicate faster distance attenuation of the Italian data relative to these GMPEs. The smallest b_R values (in an absolute sense) occur for the Chiou and Youngs (2008) model, which is consistent with its steeper IM distance slope in the 10–70 km range relative to the other NGA GMPEs (Fig. 1). The largest b_R values occur for the Boore and Atkinson (2008) model, which has the slowest distance attenuation, with Abrahamson and Silva (2008) and Campbell and Bozorgnia (2008) being intermediate cases. As shown in Figure 7, the bin medians generally track the fit lines for distance bins beyond 10 km, where bin populations are largest. This indicates that the trend lines provide a reasonable measure of the data trend (at least for distances > 10 km).

The European models (Ambraseys *et al.*, 2005 and Akkar and Bommer, 2007a) also indicate mixed results. As shown in Figure 7, slope parameter b_R is insignificant to marginally significant at short periods (PGA and 0.2 sec) for Ambraseys *et al.* (2005) but significant (at the 95% level) for Akkar and Bommer (2007a). At $T = 1.0$ sec, Akkar and Bommer (2007a) and Ambraseys *et al.* (2005) have insignificant values of b_R. We interpret these results to suggest reduced distance-attenuation bias of the European GMPEs relative to NGA, which might be expected because Italian ground motions contributed data to the European GMPEs.

To further examine the distance-attenuation misfit of the NGA models, we regress the Italian data against the NGA functional forms to reevaluate selected coefficients controlling the distance attenuation, with the results shown in Table 2. Recalling the distance-attenuation functions from Table 1, the principal coefficient that is reevaluated is the term expressing the magnitude-independent slope of the distance attenuation (a_2 for Abrahamson and Silva (2008), c_1 for Boore and Atkinson (2008), c_4 for Campbell and Bozorgnia (2008), and c_{4a} for Chiou and Youngs, 2008). In general, the constant term must also be changed to fit the data (a_1 for Abrahamson and Silva, 2008; c_0 for Campbell and Bozorgnia,

Table 2
Summary of Modified GMPE Parameters for Constant and Distance-Scaling Terms*

GMPE	Period (sec)	Regression Coefficients: Constant Term†		Slope Term		h Term		Error Terms: $\Delta\sigma$‡	τ'	τ'
Abrahamson and Silva (2008)		a_1	a'_1	a_2	a'_2	c_4	c'_4		all M	$M > 4.5$
	PGA	0.80	2.12 ± 0.60	−0.97	−1.42 ± 0.16	4.5	6.6	0.07	0.64	0.47
	0.2	1.69	2.71 ± 0.64	−0.97	−1.34 ± 0.19	4.5	6.0	0.02	0.56	0.42
	0.5	1.40	1.92 ± 0.62	−0.85	−1.11 ± 0.18	4.5	5.0	0.06	0.59	0.43
	1	0.92	n/c§	−0.81	n/c	4.5	n/c	0.10		
	2	0.19	n/c	−0.80	n/c	4.5	n/c	0.18		
Boore and Atkinson (2008)		e_0	e'_0	c_1	c'_1	h			all M	$M > 4.5$
	PGA	0.00	0.11 ± 0.54	−0.66	−0.79 ± 0.16	1.35	1.50	0.27	0.53	0.45
	0.2	0.00	n/c	−0.58	−0.67 ± 0.08	1.98	1.75	0.21	0.53	0.47
	0.5	0.00	0.10	−0.69	−0.78 ± 0.07	2.32	n/c	0.14	0.45	0.36
	1	0.00	0.10	−0.82	−0.89 ± 0.07	2.54	n/c	0.04	0.51	0.39
	2	0.00	n/c	−0.83	n/c	2.73	n/c	0.11		
Campbell and Bozorgnia (2008)		c_0	c'_0	c_4	c'_4	c_6	c'_6		all M	$M > 4.5$
	PGA	−1.72	1.20	−2.12	−2.58 ± 0.07	5.60	7.14	0.18	0.51	0.39
	0.2	−0.49	n/c	−2.22	−2.26 ± 0.07	7.60	7.00 ± 4.00	0.23	0.49	0.40
	0.5	−2.57	n/c	−2.04	−2.03 ± 0.07	4.73	n/c	0.19	0.51	0.37
	1	−6.41	n/c	−2.00	n/c	4.00	n/c	0.13		
	2	−9.70	n/c	−2.00	n/c	4.00	n/c	0.25		
Chiou and Youngs (2008)		c_1	c'_1	c_{4a}	c'_{4a}	c_{RB}	c'_{RB}		all M	$M > 4.5$
	PGA	−1.27	3.3 ± 2.1	−0.5	−1.64 ± 0.50	50	45	0.08	0.57	0.39
	0.2	−0.64	4.8 ± 2.2	−0.5	−1.85 ± 0.54	50	n/c	0.11	0.45	0.33
	0.5	−1.47	n/c	−0.5	n/c	50	n/c	0.10		
	1	−2.25	n/c	−0.5	n/c	50	n/c	0.12		
	2	−3.41	n/c	−0.5	n/c	50	n/c	0.26		

*Original coefficients are shown without primes and modified coefficients with primes (′).
†Modified for Abrahamson and Silva (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008). Constant term for Boore and Atkinson (2008) is e_1 to e_4 (dependent on source type); e_0 is an additive term for any focal mechanism.
‡Additive intraevent standard deviation term.
§n/c = no change in recommended coefficient.

2008; c_1 for Chiou and Youngs, 2008), which are evaluated through regression simultaneously with the distance attenuation term. In the case of Boore and Atkinson (2008), the constant term depends on focal mechanism, taking on values of $e_1 - e_4$. The Italian data are not sufficiently voluminous to check the scaling of ground motion with focal mechanism, so we retain the $e_1 - e_4$ values and simply provide an additive term (e_0) that could be applied to each (e.g., the new constant term for strike-slip would be $e_0 + e_1$). Finally, we constrain the resulting modified GMPEs to match reasonably closely to the original GMPEs at close distance (R or $R_{\mathrm{jb}} < 3$ km). This is done because the Italian data cannot constrain ground motions in that range, so we rely on the constraint provided by the NGA models. If the modified NGA models do not provide this match from the regression on the identified coefficients, then we enforce the match through minor manual adjustment of the fictitious depth term along with an occasional added adjustment to the constant term, as shown in Table 2. All other coefficients in the GMPEs are fixed at the published values.

An alternative approach to that previously mentioned (modification of magnitude-independent slope term) would have been to modify the parameters controlling the change of attenuation rate with magnitude (e.g., a_3 in Abrahamson and Silva, 2008). By increasing such parameters, we could accomplish faster attenuation at low magnitude and retain the approximate NGA rate of attenuation at larger magnitudes. The choice of approach is arbitrary because the Italian data are not sufficient to resolve both terms. More discussion on the implication of this approach is provided in the Interpretation and Conclusions section.

In Table 2, values established through regressions are shown with 95% confidence intervals, whereas values fixed manually have no confidence intervals. The absolute values of the modified distance-attenuation terms (a_2' for Abrahamson and Silva (2008), c_1' for Boore and Atkinson (2008), c_4' for Campbell and Bozorgnia (2008), c_{4a}' for Chiou and Youngs, 2008) are larger than the original values, consistent with the faster distance attenuation in the Italian data. This can also be seen in Figure 8, which shows the distance attenuation of the original and modified Boore and Atkinson

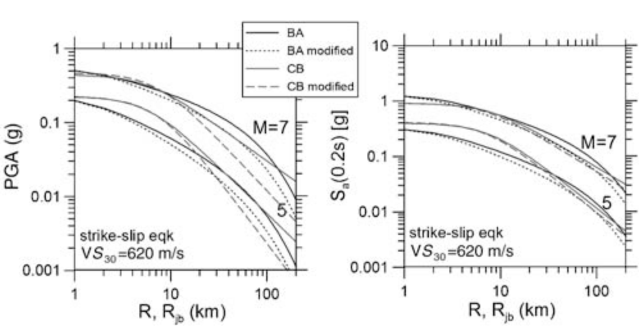

Figure 8. Variation of median ground motions with distance and magnitude from NGA and modified NGA relations developed in this study.

(2008) and Campbell and Bozorgnia (2008) GMPEs for PGA and 0.2 sec S_a for soft rock site conditions ($V_{S30} = 620$ m/sec) and magnitudes of M 5 and 7. Similar trends occur for the Abrahamson and Silva (2008) and Chiou and Youngs (2008) GMPEs.

After adjusting the constant and distance terms as described previously, the distance dependence of intraevent residuals ($\varepsilon_{i,j}'$) were checked and found to be negligible. The intraevent standard deviation of the modified GMPEs (σ) is only slightly affected by the distance adjustments and remains higher than the original NGA values; the $\Delta\sigma$ values in Table 2 are the offset between the intraevent standard deviations and the NGA values. The standard deviation of event terms for the modified GMPEs (τ') is reduced because events with predominantly large-distance recordings show less bias. Those values of τ' are listed in Table 2 (under heading "τ' all M").

Magnitude Scaling

Magnitude scaling is tested by examining trends of event terms versus magnitude. The event terms presented are recomputed using the modified GMPEs where applicable (denoted as η_i'); for IMs without modified GMPEs the original GMPE is used to evaluate event terms (denoted as η_i). The modified GMPEs are used so that distance bias is not mapped into event terms. Figure 9 shows event terms for the IMs of PGA, 0.2 sec S_a, and 1.0 sec S_a. Event terms are shown separately for normal fault earthquakes and other mechanisms (generally strike-slip). To help illustrate trends, we also plot a fit line (for all of the data) and its 95% confidence intervals, the fit being made according to

$$\eta_i' = a_M + b_M M_i + (\kappa_M)_i. \tag{9}$$

Separate regressions are performed for each GMPE. Parameters a_M and b_M represent the regression coefficients and $(\kappa_M)_i$ is the residual of the fit for event i. If slope b_M is nonzero and significant, it suggests the magnitude scaling in the model does not match the data. Slope b_M cannot capture higher-order (e.g., quadratic) dependence of residuals on magnitude, although visual inspection of Figure 9 does not suggest the presence of such higher-order trends in the data.

While the slopes of the trend lines (b_M) in Figure 9 are nonzero, we find that they are generally not statistically significant at the 95% confidence level. To the extent that trends in the data exist, they are generally strongest at $T = 1.0$ sec (e.g., for the Abrahamson and Silva, 2008; Campbell and Bozorgnia, 2008; Ambraseys *et al.*, 2005 GMPEs). On the basis of hypothesis testing for slope parameter b_M, we conclude that the GMPEs (some original; some modified) adequately capture the magnitude scaling of the Italian dataset. However, it is visually apparent in Figure 9 that the fit is not as good and the scatter is relatively large at low magnitudes ($M > 4.5$), which is beyond the intended range of the NGA models. Although not shown in Figure 9, the trends with

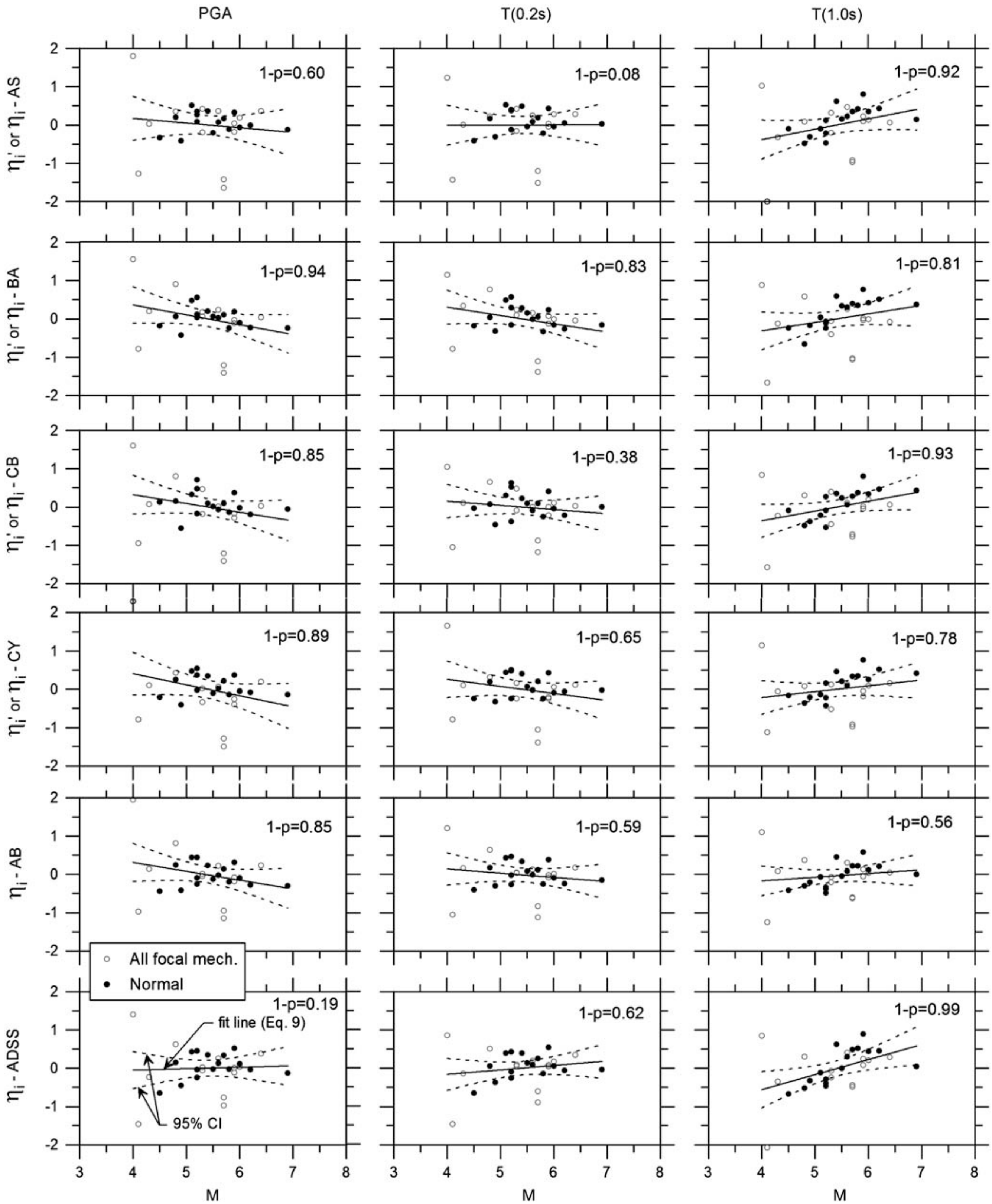

Figure 9. Variation of event terms for Italian data with magnitude for PGA, 0.2 sec S_a, and 1.0 sec S_a.

magnitude weaken (lines become flatter) when only data with $M > 4.5$ are used in the equation 9 regression. Table 2 shows that the standard deviation of event terms is reduced significantly when only events with $M > 4.5$ are considered (compare terms under headings "all M" and "$M > 4.5$" in Table 2). As shown in Figure 6, τ' values averaged across the four GMPEs for $M > 4.5$ are similar to published values. Hence, the NGA GMPEs can be applied with greater confidence for a limiting magnitude of approximately 4.5 to 5.0 (5.0 is the minimum magnitude in the NGA relations).

We do not consider the Italian data to be adequately large to formally test focal mechanism terms in the NGA GMPEs. Accordingly, the residuals analysis (equation 6) used NGA focal mechanism terms. As a rough check, we see in Figure 9 that event terms for normal fault earthquakes (the most common focal mechanism in the Italian data) are not visually distinct from the data as a whole, which supports our use of the NGA focal mechanism terms.

Site Effects

We evaluate the scaling of ground motions with V_{S30} using the modified NGA GMPEs (for appropriate spectral periods) so that distance bias is not mapped into the analysis of V_{S30}. In Figure 10, we examine trends of intraevent residuals (ε_{ij} or $\varepsilon'_{i,j}$) as a function of V_{S30} for the IMs of PGA, 0.2 sec S_a, and 1.0 sec S_a. Trends are illustrated with a fit line

$$\varepsilon'_{i,j} = a_V + b_V \ln(V_{S30})_{i,j} + (\kappa_V)_{i,j}. \tag{10}$$

Parameters a_V and b_V are regression parameters; κ_V is the residual of the fit for recording j from event i. Equation (10) strictly holds for the modified GMPE; for original models,

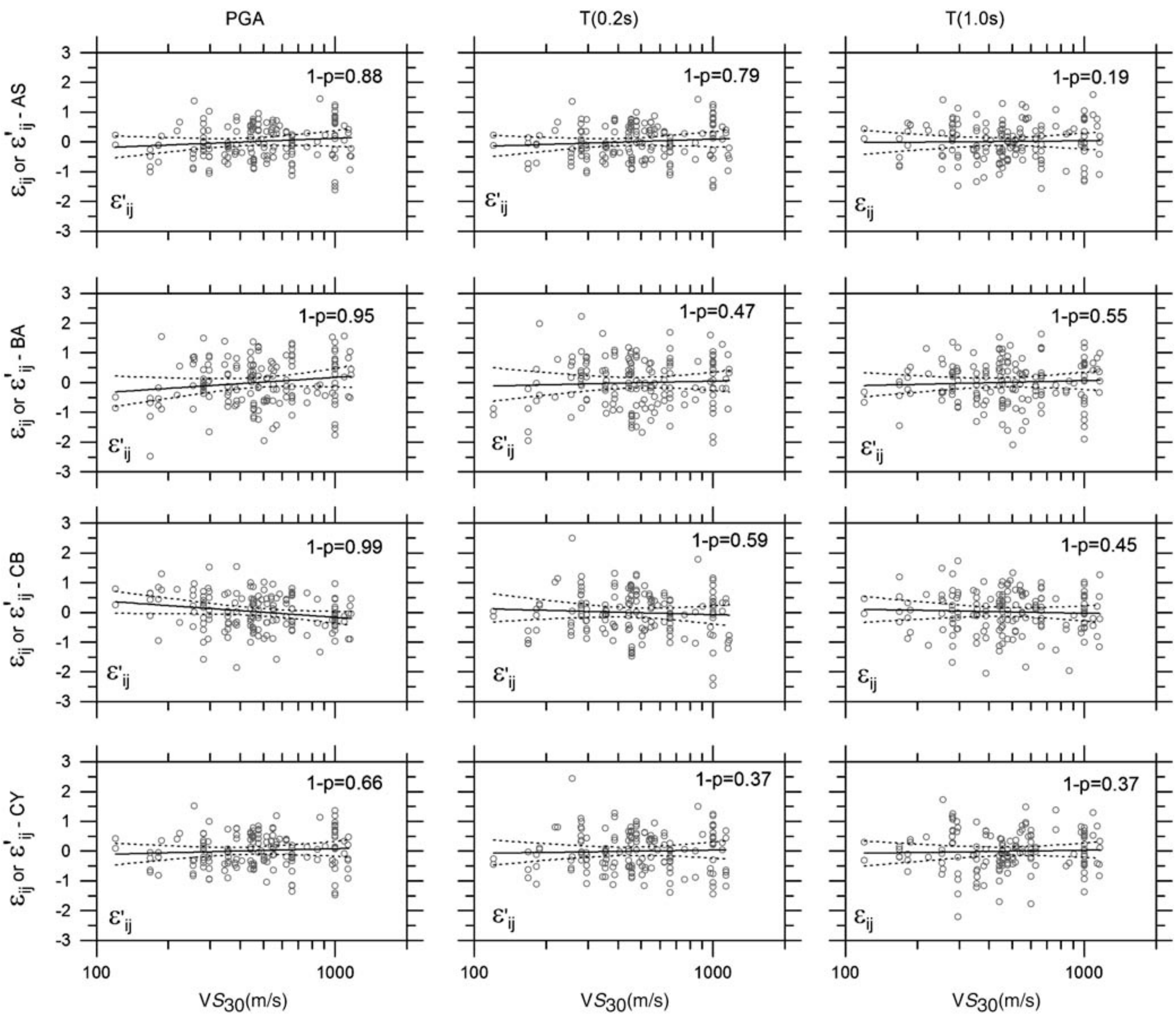

Figure 10. Variation of intraevent residuals with average shear wave velocity in upper 30 m (V_{S30}). Residuals are for original GMPE when shown without prime (ε_{ij}) and for modified GMPE when shown with prime (ε'_{ij}).

$\varepsilon_{i,j}$ replaces $\varepsilon'_{i,j}$. Slope parameter b_V represents approximately the misfit of the V_{S30}-scaling in the GMPEs relative to the Italian dataset. Table 3 shows values of b_V, their 95% confidence intervals, and the rejection confidence for a $b_V = 0$ model (1-p) from hypothesis testing. The results in Figure 10 and Table 3 indicate a general lack of statistically significant trends with V_{S30}. This suggests that the V_{S30}-based site terms in the NGA GMPEs may be compatible with the Italian data.

Because of the established use of linear site terms in European GMPEs, we explore more deeply the nonlinearity of site effects implied by the Italian data. This analysis begins by reevaluating residuals in a manner similar to equation (6), but with modified GMPEs (as appropriate) and with V_{S30} fixed at a reference value of 1100 m/sec, basin depth $Z_{1.0}$ set to zero, and $Z_{2.5}$ set to 0.52 km (per equation 5). Residuals evaluated in this manner are written as $\varepsilon_{i,j}^{1100}$ and are calculated as

$$(\varepsilon_{i,j}^{1100})_k = \ln(\mathrm{IM}_{i,j})_{\mathrm{data}} - [\ln(\mathrm{IM}_{i,j}^{1100})_k + \eta'_i], \qquad (11)$$

where $(\mathrm{IM}_{i,j}^{1100})_k$ indicates the prediction of GMPE k for the reference rock conditions described previously (using modified GMPEs where appropriate) and η'_i is the event term evaluated for the modified GMPE where applicable (which is replaced with the event term from equation 7 otherwise). Those residuals are then grouped into two categories, one corresponding to recordings made on firm rock site conditions ($V_{S30} = 800$ to 1100 m/sec) and the other to soft to medium-stiff soil conditions ($V_{S30} = 180$ to 300 m/sec). Figure 11 shows those residuals plotted as a function of $\widehat{\mathrm{PGA}}_{1100}$, which is the median peak acceleration from the respective GMPEs for the magnitude, distance, and other parameters associated with the recordings. We illustrate trends in the results with fit lines regressed according to equation (12) for data in each category

$$\varepsilon_{i,j}^{1100} = a_{\mathrm{PGA}} + b_{\mathrm{PGA}} \ln(\widehat{PGA}_{i,j}^{1100}) + (\kappa_{\mathrm{PGA}})_{i,j}, \qquad (12)$$

where a_{PGA} and b_{PGA} are the regression parameters and $(\kappa_{\mathrm{PGA}})_{i,j}$ is the misfit of the line to the residual for recording j from event i. Those coefficients are given in Table 3.

For each of the GMPEs considered, the results show (1) for low values of $\widehat{\mathrm{PGA}}_{1100}$, larger residuals occur for the soil category than the rock category, and (2) the slope of the $\varepsilon_{i,j}^{1100}$-$\widehat{\mathrm{PGA}}_{1100}$ relationship (b_{PGA}) is significantly negative, as established by hypothesis test results, for the soil category but is not significantly different from zero for the rock category. These results demonstrate a nonlinear site effect for the IMs of PGA and S_a for $T \leq 1.0$ sec. Moreover, the difference between the $\varepsilon_{i,j}^{1100}$ fit for soil and rock represents an implied site effect inherent to the Italian data relative to the $V_{S30} =$ 1100 m/sec site condition adopted as a reference in equation (11). That implied site effect is compared with the V_{S30}-based site term in the Abrahamson and Silva (2008), Boore and Atkinson (2008), and Campbell and Bozorgnia (2008) GMPEs in Figure 12. Although the absolute position of the implied site term varies somewhat relative to the GMPE site term, the slopes are generally similar. In the few cases where the slopes appear dissimilar (e.g., Boore and Atkinson [2008] and Campbell and Bozorgnia [2008] at $T = 1.0$ sec), the slopes of the implied site term are not significant, as indicated by the wide confidence intervals. This suggests that the NGA site terms are providing approximately the correct level of nonlinearity for these Italian soil sites.

Interpretation and Conclusions

We have investigated the compatibility of strong motion data in Italy with ground-motion prediction equations (GMPEs) established by the Next Generation Attenuation (NGA) project for shallow crustal earthquakes in active regions. Using a mixed effects procedure, we evaluated event terms (interevent residuals) and intraevent residuals of the Italian data relative to the NGA GMPEs.

Table 3
Summary of Slope Terms Indicating Lack of Trend of Intraevent Residuals with V_{S30} and Fit Coefficients for Rock and Soil Categories with Specified V_{S30} Ranges

GMPE	Period (sec)	V_{S30}-Scaling (modified GMPE) b_v	$1-p$	Rock (V_{S30} = 800–1100 m/sec) a_{PGA}	b_{PGA}	$(1-p)_b$	Soil (V_{S30} = 180–300 m/sec a_{PGA}	b_{PGA}	$(1-p)_b$
Abrahamson and Silva (2008)	PGA	0.1396 ± 0.1780	0.88	0.60	0.15	0.74	−0.68	−0.33	1.00
	0.2	0.1102 ± 0.1751	0.79	0.32	0.09	0.45	−0.12	−0.07	0.64
	1	0.0225 ± 0.1894	0.19	0.09	0.18	0.60	−0.36	−1.33	0.97
Boore and Atkinson (2008)	PGA	0.2267 ± 0.2326	0.95	0.89	0.14	0.65	−0.33	−0.26	1.00
	0.2	0.0774 ± 0.2443	0.47	−0.11	−0.08	0.35	−1.08	−0.44	1.00
	1	0.0824 ± 0.2180	0.55	0.17	−0.03	0.14	−0.96	−0.25	1.00
Campbell and Bozorgnia (2008)	PGA	−0.2444 ± 0.1770	0.99	0.67	0.16	0.76	−0.73	−0.31	1.00
	0.2	−0.0901 ± 0.2205	0.59	0.66	0.23	0.88	−0.49	−0.21	1.00
	1	−0.0624 ± 0.2099	0.45	−0.23	−0.02	0.11	−0.38	−0.22	1.00
Chiou and Youngs (2008)	PGA	0.0823 ± 0.1740	0.66	0.66	0.12	0.69	0.67	−0.35	1.00
	0.2	0.0481 ± 0.1996	0.37	−0.05	0.02	0.14	1.14	−0.26	1.00
	1	0.0486 ± 0.2004	0.37	0.62	0.16	0.66	−0.10	−0.29	0.99

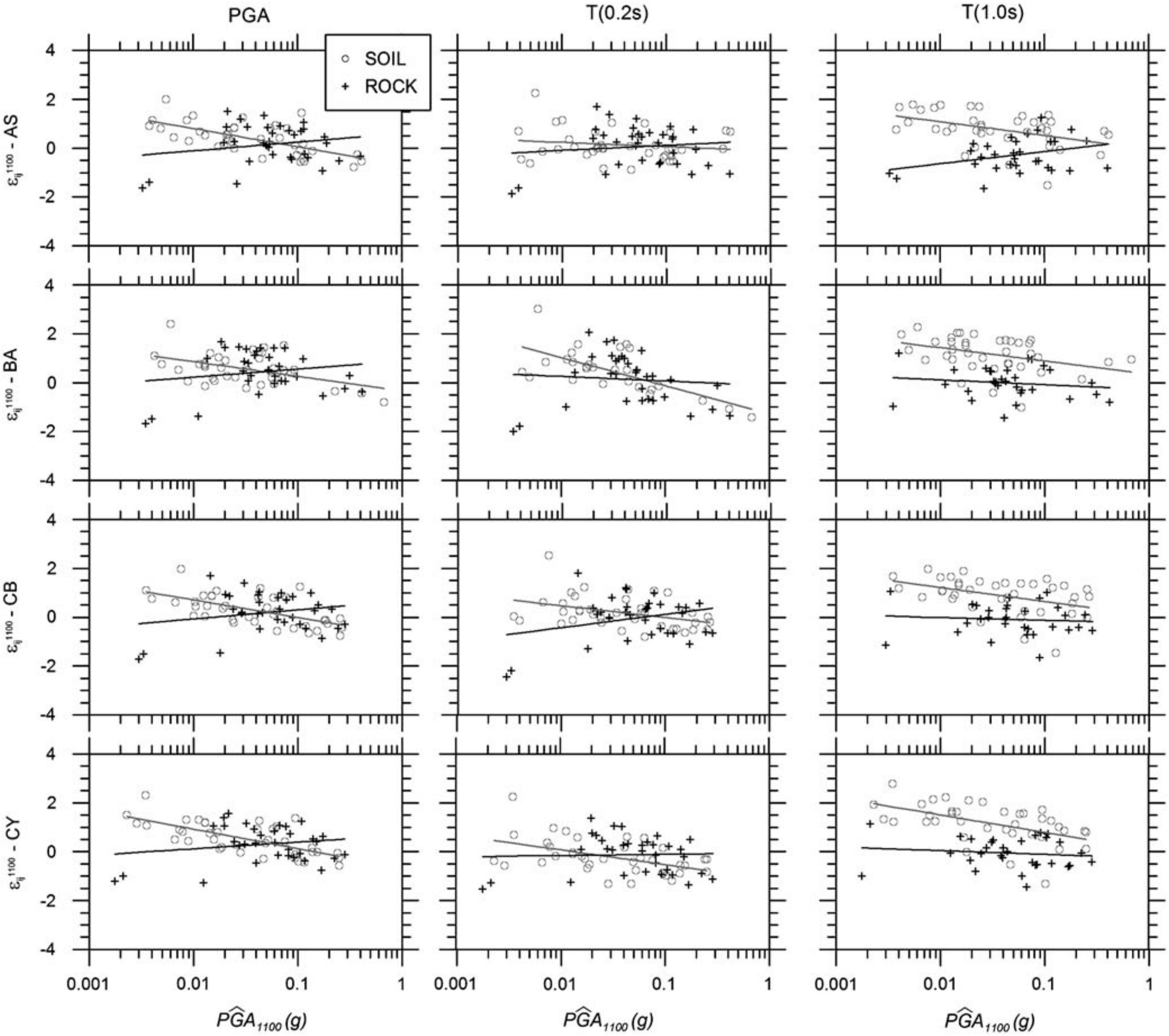

Figure 11. Variation of reference-site intraevent residuals (defined using equation 11) with median anticipated reference site peak acceleration, $\widehat{\mathrm{PGA}}_{1100}$.

Distance scaling was investigated by examining trends of intraevent residuals with distance. For the four NGA relations considered (Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008), the residuals demonstrated a statistically significant trend with distance for short periods ($T \leq 0.2$–0.5 sec), which was suggestive of faster attenuation of Italian data. For two recent European GMPEs, the residuals demonstrated mixed trends with distance, but the trends were weaker than those for the NGA GMPEs . Parameters in the NGA GMPEs that accounted for magnitude independent distance attenuation were adjusted through regression, which detrends the residuals. As noted previously, a different approach could have been adopted in which the rate of attenuation was adjusted for low magnitude earthquakes only (through adjustment of terms controlling the rate of change of attenuation with magnitude). Such an approach has been advocated recently to account for observed fast attenuation of some low magnitude California data (e.g., Chiou, personal communication, 2009). Either approach would have produced reasonable results for the present study, which contains a significant amount of data with $M_w < 5.5$. However, it is interesting to note that the 2009 M_w 6.3 L'Aquila earthquake data (which became available following the writing of this article) is consistent with the rate of attenuation in the modified Boore and Atkinson (2008) GMPE from this study (Di Capua *et al.*, 2009). Had the adjustment to faster attenuation been concentrated at low magnitudes, this fit may not have been achieved.

The observed faster attenuation of Italian data relative to many of the NGA GMPEs was consistent with previous work

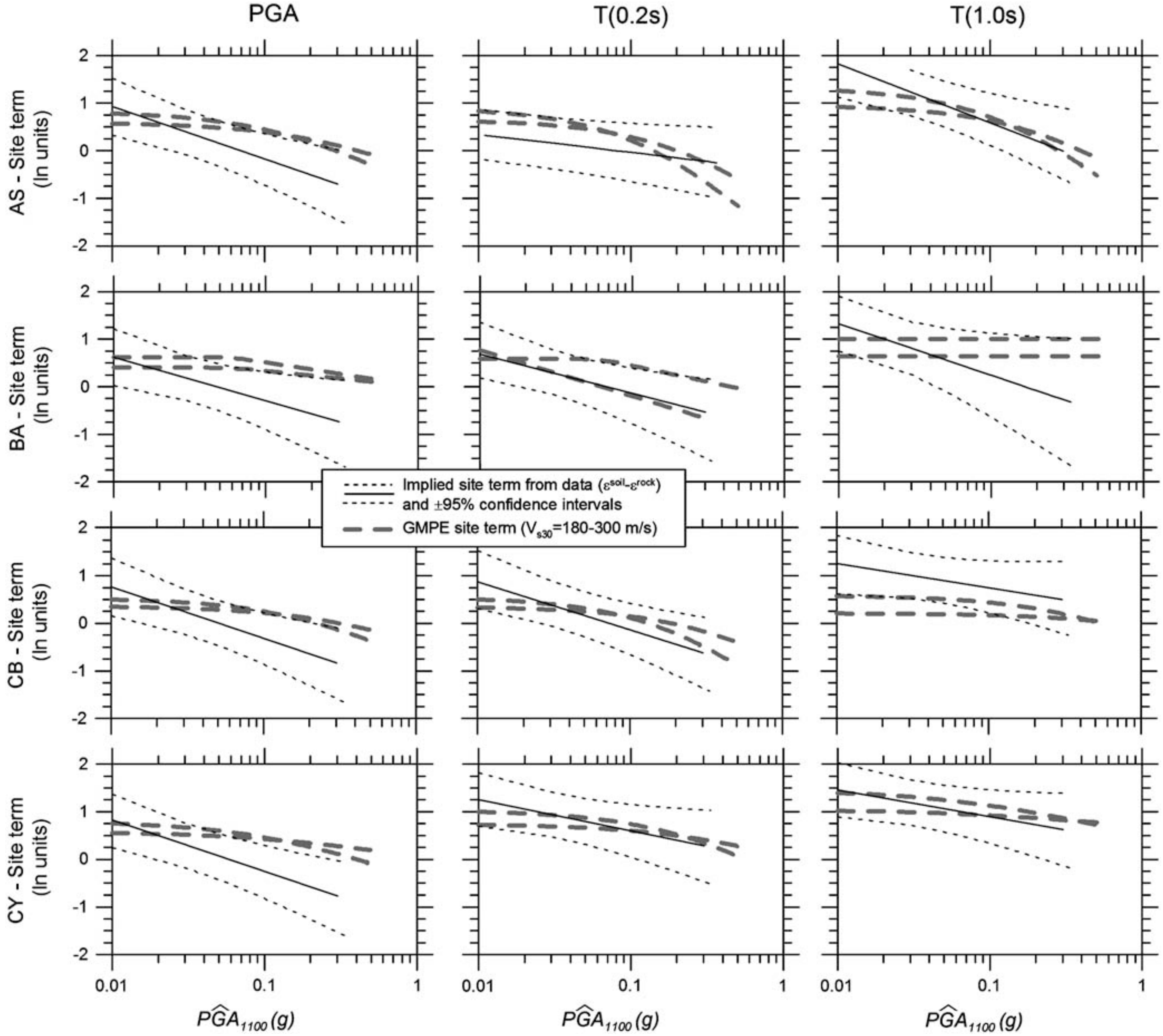

Figure 12. Comparison of range of GMPE site terms for $V_{S30} = 180$ and 300 m/sec sites to approximate site effect inferred from Italian data relative to $V_{S30} = 1100$ m/sec reference condition.

that showed faster distance attenuation of European data relative to California data (e.g., Douglas, 2004b). Moreover, as shown in Figure 13, our finding of faster attenuation of Italian data was consistent with higher crustal damping as represented by lower frequency-dependent Q values from the Umbria/Apennines region of Italy (which contributed about 2/3 of the Italian recordings) relative to values for central and southern California (which contributed much of the NGA data).

Event terms from the NGA GMPEs (modified as appropriate to remove the biased distance attenuation) did not show a statistically significant trend with magnitude, indicating that the magnitude scaling was generally compatible with Italian data. The two European GMPEs were also compatible with magnitude scaling implied by the Italian data.

Scaling with respect to site condition was investigated by plotting intraevent residuals versus average shear wave velocity in the upper 30 m (V_{S30}). Those residuals were calculated relative to modified NGA GMPEs as applicable. The results indicated no general trend with V_{S30}, suggesting that the NGA site terms were compatible with Italian data. Because the NGA site terms were nonlinear, which was inconsistent with the linear site terms in European GMPEs, we also investigated whether the Italian data supported the use of a nonlinear site term. This was done by examining residuals of Italian data relative to the NGA GMPEs evaluated for a reference firm rock condition. A group of data on firm rock showed no trend of residuals with $\widehat{\mathrm{PGA}}_{1100}$, which represented the median amplitude of shaking expected on firm rock. However, a group of data from soil sites showed a

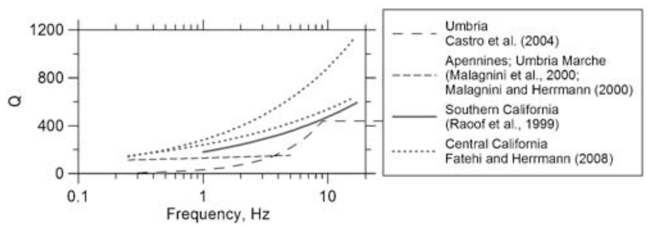

Figure 13. Comparison of relatively large Q values from California with smaller values from Apennines region of Italy, indicating higher crustal damping in the Italian region producing most of the recordings in the present database.

statistically significant trend with $\widehat{\mathrm{PGA}}_{1100}$. The differences between these trends for firm rock and soil implied a nonlinear site term having a slope relative to $\widehat{\mathrm{PGA}}_{1100}$ that was generally consistent with the NGA site terms. Accordingly, we concluded that nonlinear site response should be incorporated into site terms for European GMPEs.

Turning next to data dispersion as represented by standard deviation terms, we found the event-to-event variability as expressed by the standard deviation of event terms (τ) to be compatible with NGA recommendations when the modified GMPEs were used and the lower bound magnitude was set to 4.5. Intraevent standard deviation (σ) was larger in Italian data than in NGA, but by amounts on the order of $\Delta\sigma = 0.05$ to 0.3.

In summary, we recommend that the Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008) NGA GMPEs for median ground motions be utilized for hazard analysis in Italy along with existing European models (especially Ambraseys *et al.*, 2005 and Akkar and Bommer, 2007a). However, we recommend modification of (generally) two or three parameters in the evaluation of median ground motions from the NGA models: one being a constant term, the second representing attenuation from geometric spreading and anelastic attenuation, and the third representing the source fictitious depth term. Those parameters and the recommended new coefficients are given in Table 2. The associated functional forms for distance attenuation are given in Table 1. With respect to standard deviation terms, we recommend the use of the τ terms (representing interevent variability) in the original NGA equations. We recommend σ (representing intraevent variability) be taken as the sum of the NGA values and the $\Delta\sigma$ values given in Table 2. The revised GMPEs are considered valid over the magnitude range 4.5 to 7.0 and for distances (R or R_{jb}) under 200 km.

Finally, while this work has focused on Italy, we believe ground motions know nothing of political boundaries; the results presented here may be applicable elsewhere in Europe. The applicability of the results to extensional regions generally remains an open question. We anticipate that future work will formally evaluate data from other regions in a manner similar to what is described here.

Data and Resources

The strong motion data utilized in this study are available at http://sisma.dsg.uniroma1.it/ (last accessed May 2009). Metadata associated with the recordings is given in Scasserra *et al.* (2009). Source parameters were compiled from databanks maintained by the Italian Institute of Geology and Vulcanology (INGV, www.ingv.it, last accessed September 2008).

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