On the Regional Dependence of Earthquake Response Spectra

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Abstract

It is common practice to use ground-motion models, often developed by regression on recorded accelerograms, to predict the expected earthquake response spectra at sites of interest. An important consideration when selecting these models is the possible dependence of ground motions on geographical region, i.e. are median ground motions in the (target) region of interest for a given magnitude and distance the same as those in the (host) region where a ground-motion model is from? and are the aleatoric variabilities of ground motions also similar? These questions can be particularly difficult to tackle in many regions of the world where little observed strong-motion data is available since there are few records to validate the choice of model. Reasons for regionally-dependent ground motions are discussed and possible regional dependence of earthquake response spectra is examined using published ground-motion models, observed accelerograms and also by using ground motions predicted by published stochastic models. It is concluded that, although some regions seem to show considerable differences in spectra, it is currently more defensible to use well-constrained models possibly based on data from other regions rather use predicted motions from local, often poorly-constrained, models.

Keywords: ground-motion estimation, attenuation relationships, regional dependence, analysis of variance, stochastic method

INTRODUCTION

The selection of ground-motion estimation equations (e.g. Douglas, 2003) for use in estimating elastic earthquake response spectra at sites in most regions of the world (such as many parts of Europe and in India) is a challenging task due to the relatively short histories of quantitative recording of ground motions of engineering significance by strong-motion networks in these areas. For example, the French accelerometric network (the Réseau Accélérometrique Permanent, RAP) is only about ten years old and the seismicity level of metropolitan France is moderate therefore there are only a handful of records from earthquakes of magnitudes greater than

M_w5.0 and at source-to-site distances less than 100 km. Two recent empirical ground-motion models have been published based on French data (Marin et al., 2004; Souriau, 2006), however, these equations are only for the estimation of peak ground acceleration (PGA) and, in addition, are based on data from small earthquakes. Due to the observation that ground motions from small and large earthquakes scale differently with magnitude and distance (e.g. Pousse et al., 2007) these equations cannot be used for the estimation of ground motions from damaging earthquakes. In addition, as shown by Trifunac and Todorovska (2000) the extrapolation of ground-motion estimates for soil sites derived from weak motions may not be appropriate for large events due to nonlinear site amplifications.

Although the study of Douglas (2003) lists over 120 equations for the estimation of PGA [this list was updated in two recent reports (Douglas, 2004a, 2006) to over 200 equations] most of the equations in the literature have: a) been superseded by more recent equations from the same authors or by other studies for the region, b) fail one or more of the criteria listed by Cotton et al. (2006), or c) cannot be used for near-source distances or for moderate or large earthquakes due to the distribution with respect to magnitude and distance of the data used to derive the equation. After removing these equations the seismic hazard analyst is left with a choice of possibly twenty to thirty equations.

Criteria for the further narrowing down and weighting of these possible ground-motion models have been discussed by Scherbaum et al. (2004) and Scherbaum et al. (2005), specifically with respect to the selection of models for seismic hazard analysis in Switzerland, a country where the choice of ground-motion models is challenging for similar reasons to those discussed above (short history of quantitative observation and relatively low seismicity). Even following these articles there is still much debate over the selection of ground-motion estimation equations, especially for regions with limited observational data (e.g. Klügel, 2005; Musson et al., 2005).

An important consideration when selecting ground-motion models for seismic hazard analysis is the possible dependence of earthquake ground motions on geographical region, i.e. are average ground motions in the (target) region of interest for a given magnitude and distance the same as those in the (host) region where a ground-motion model is from? and are the aleatoric variabilities of ground motions also similar? This article investigates this problem mainly with respect to empirical ground-motion estimation. Estimated response spectra based on physically-based simulations explicitly model regional dependence by the choice of input parameters therefore the goal of such studies is to use input parameters that are appropriate for the considered region. The selection of such input parameters is not considered here.

The following section discusses possible reasons for a regional dependence of elastic earthquake response spectra. The next section of the article investigates regional dependence based on published empirical ground-motion estimation equations. In the following section, the method proposed by Douglas (2004b) based on analysis of variance is applied to two Italian regions (Umbria-Marche and Molise) where recent studies have suggested a large difference in ground motions. Due to the difficulty in developing robust empirical ground-motion models for many parts of the world a number of studies have investigated whether ground motions in one region are comparable to those in another region, see for example Douglas (2004b) and the references therein. However, many of the proposed methods rely on the availability of observed ground motion data from moderate and large earthquakes, which is often lacking. Therefore, later a different approach is taken that is less reliant on such data. The article ends with some conclusions and suggestions.

For many of the analyses presented, PGA is used because of the greater availability of predictive models and observation data for this strong-motion intensity measure. Since PGA equals elastic response spectral acceleration (SA) for an infinitely-stiff single-degree-of-freedom system it is often used as a basis of seismic design response spectra (e.g. Comité Européen de Normalisation (CEN), 2005). Note that some of the results presented here for PGA may not be directly applicable to the estimation of response spectra because of differences in the frequency range of the ground motions sampled by PGA and SAs. Regional dependence, or not, of PGA may not imply the same conclusion for SA at a given period.

REGIONAL DEPENDENCE

Earthquake response spectra are dependent on various factors that are commonly divided into source, path and site factors and include: earthquake magnitude, epicentral intensity, faulting mechanism, source depth, fault geometry, stress drop and direction of rupture; source-to-site distance, crustal structure, geology (e.g. sedimentary basins) along wave paths, radiation pattern and directionality; and site geology, topography, soil-structure interaction, nonlinear soil behaviour and site intensity. Within models for the prediction of response spectra the dependence of spectra on some of these factors (mainly magnitude, source-to-site distance, site geology and faulting mechanism) is considered, albeit often only simply (e.g. Douglas, 2003). The unmodelled effects, that can be important, are ignored and consequently predictions from the ground-motion models contain a bias due to the (unknown) distribution of records used to construct the model with respect to these variables. Therefore, if the ground-motion model was used to estimate the response spectra in another region where the distribution of scenarios was different to that used to create the model, the predictions would be biased.

An example of an unmodelled factor that can lead to a implicit inclusion of regional dependence within ground-motion models is focal depth. The depth at which an earthquake occurs can significant influence the resultant ground motions. The fact that the earthquake source is closer (for shallow events) or further (for deep events) away from a site is important due to differences in decay especially for small and moderate earthquakes, which are approximately point sources (e.g. Ambraseys and Bommer, 1991). This effect can be modelled by the use of a distance metric that includes a consideration of the depth of the earthquake source, such as hypocentral distance or the distance metric proposed by Gusev (1983) and used by, for example, Lee and Trifunac (1995) for the development of empirical ground-motion models. Models using a distance metric, such as distance to the surface projection of rupture (commonly known as Joyner-Boore distance) (Joyner and Boore, 1981), cannot model variations in ground motions due to focal depth and therefore if they are applied in a target region where the distribution of source depths is different that in the host region the predicted ground motions could be incorrect. However, the scaling of ground motions with focal depth is more complicated than that simply explainable by increased source-to-site distance for deep earthquakes. McGarr (1984) shows that, for the same hypocentral distance, ground motions from deep earthquakes can be higher than those from shallow earthquakes due to differences in stress conditions.

Another factor that, until recently was commonly unmodelled, but can have an impact on ground motions is faulting mechanism (often called style of faulting). Ground motions from reverse-faulting earthquakes are, on average, slightly higher (about 10-30% for PGA and for SAs at short periods) than those from strike-slip and normal-faulting earthquakes (e.g. Bommer et al., 2003). Therefore, if, for example, within a region only reverse-faulting earthquakes occur a ground-motion model developed using data from this region it will overpredict, on average, the shaking in a region where only strike-slip earthquakes occur (other effects being equal). The correction of this possible bias is the basis of the method developed by Bommer et al. (2003).

Similarly, another important effect that could lead to apparent regional dependence of strong ground motions are differences in average site conditions between host and target regions. For example, sites classified into a common soft soil category in the two regions may be underlain by, on average, deeper soil deposits in one region than in the other, thereby leading to differences in average site response. As an example of this, Atkinson and Boore (2003) find that ground-motion amplitudes differ from those in Japan by more than a factor of two for the same magnitude, distance and site class, which they relate to differences in the depth of soil profiles in the two regions. This type of regional difference could be modelled by using more sophisticated methods for capturing site effects, such as considering the depth of soil profiles (e.g. Seed et al., 1976; Trifunac, 1990) rather than only the average near-surface shear-wave velocity. Another factor that contributes to differences in the response of otherwise similar sites is geological age (e.g. Novikova et al., 1994). Such methods, however, rely on having sufficient high-quality data on site conditions, which is unfortunately often unavailable.

If much more complex ground-motion models were developed that explicitly include all the factors affecting response spectra then these models could be applied throughout the world without introducing regional bias, as long as the correct input parameters were used. A proposal of how empirical ground-motion models could be developed to incorporate the possibly important effect of regional differences in crustal structure is discussed by Douglas et al. (2004) and Douglas et al. (2007).

It is common practice within Europe to combine data from different countries together in order to obtain sufficiently large datasets for regression analysis (e.g. Berge-Thierry et al., 2003; Ambraseys et al., 2005). Due to increasing regional datasets from sensitive digital seismic networks there is a growing move towards the development of empirical ground-motion models developed using data from small geographical regions, e.g. north-eastern Italy (Bragato and Slejko, 2005; Costa et al., 2006), north-western Italy (Frisenda et al., 2005), Umbria-Marche (Zonno and Montaldo, 2002; Bindi et al., 2006), Molise (Luzi et al., 2006), France (Marin et al., 2004; Souriau, 2006) and north-western Turkey (Özbey et al., 2004). An idea of the difference in geographical scale between these small regions and the broader areas otherwise used as source of data is given by comparing the surface area of the State of California ($410\,000\,\mathrm{km}^2$) to the surface area of the Region of Molise ($4\,400\,\mathrm{km}^2$): a factor of almost 100. This comparison is not completely fair since models developed using Californian data have mainly employed data from well-instrumented relatively small zones (e.g. the Los Angeles Basin, San Francisco Bay Area and Imperial Valley). However, these models are usually applied for the prediction of motions at all sites in California (and often beyond).

Political boundaries do not usually follow seismotectonic boundaries: many countries feature various tectonic regimes (e.g. Greece includes extensional, compressional, volcanic and subduction regimes) and numerous countries share one tectonic regime (e.g. the extensional Upper Rhine Graben straddles the borders of France, Germany and Switzerland). Therefore, the number of countries that are the source of data for a ground-motion model is not important but rather whether the data come from similar tectonic regions. As is discussed below, lack of observed data and uncertainties and simplifications within empirical and stochastic ground-motion models means variations in ground motions from different tectonic regimes has not yet been clearly demonstrated.

If the practice of only using data from small geographical zones in order to develop more applicable ground-motion models was justified it could be expected that such models would be associated with lower aleatoric variabilities (standard deviations, σs) than models developed by combining records from many different areas, since regional dependence would be contributing to the scatter. However, this is not observed (see Table 1 comparing σs from regional models to those derived using data from larger areas). One reason that current equations developed based on data from small regions do not have lower σs is that they are mainly based on motions from small earthquakes ($M < 5$), which have been shown to be more variable than motions from larger earthquakes (e.g. Youngs et al., 1995). Although Youngs et al. (1995) and others find that σs are relatively constant for magnitudes below 5. Recently derived models from the PEER Next Generation Attenuation (NGA) project (Boore and Atkinson, 2006; Campbell and Bozorgnia, 2006; Chiou and Youngs, 2006) do not show magnitude-dependent σ. The previously reported dependence could have been due to a lack of strong-motion data from large events and also errors in the associated parameters (e.g. magnitudes and distances) of the strong-motion data for small earthquakes. The NGA models, however, are mainly based on data from earthquakes with $M > 5.5$ therefore σ could be magnitude dependent for small events.

[Table 1 about here.]

One possible way of investigating possible regional dependence is to compare recorded ground motions in one region with those predicted by models from other regions. In the past this type of comparison has often been made by visually comparing observations and predictions or through analyses of residuals (e.g. Boore, 2001), however, Scherbaum et al. (2004) suggest a statistically more rigorous method to undertake this task that has been applied. They compare recordings of the 2003 St Dié (France) earthquake at 13 rock stations to predicted motions from various models. This study has recently been extended by Hintersberger et al. (2007) and the same method has been applied by Drouet et al. (2007) for the Pyrenees. Douglas et al. (2006a) investigate the ground motions observed on the French Antilles from both shallow crustal and subduction earthquakes (considered separately) using this approach and find these motions are not well predicted by published equations developed for other regions. One difficulty with this method, which was faced by Douglas et al. (2006a), is that the available observations from the target region often are from magnitudes and distances that require extrapolation of the ground-motion models beyond their ranges of assumed applicability, creating uncertainties over the comparisons.

INVESTIGATION USING EMPIRICAL MODELS

It is common practice when presenting a new ground-motion model to compare its predicted ground motions to those estimated by earlier published models, both for same region and for other geographical areas. These comparisons are invariably made by graphically plotting the predicted levels of shaking (characterised, for example, by the elastic response spectra) for a number of magnitudes and distances. Then it is often stated that the predictions are similar or different without much statistical justification. Some researchers believe that there is clear evidence for regional dependence while others doubt that a clear conclusion can currently be drawn. For example, Sokolov (2000) states during a discussion of empirical models, '[a]t present, there is no doubt that these relations are different for different seismic regions, and "region and site-specific" models should be developed on the basis of available strong ground motion records' whilst Bommer (2006) believes, when presenting comparisons between empirical models developed for different European datasets, '[t]hese plots do not suggest that there are strong regional differences and this leads to the conclusion that it is not only acceptable but in fact desirable to ignore national borders when compiling datasets for the derivation of ground-motion prediction equations'. Previous discussions on this issue are those by Lee (1997) and Ambraseys et al. (1997) following the publication of the empirical ground-motion estimation equations of Ambraseys et al. (1996), who combined together data from numerous European, Middle Eastern and north African countries in order to derive their model.

Bommer (2006) compares ground motion predictions from various empirical models derived solely from Turkish data and finds larger differences between predicted median ground-motions from these models than between models derived from databanks containing data from many parts of Europe and the Middle East. Figure 1 shows a comparison between simple empirical models (Aman et al., 1995; Singh et al., 1996; Jain et al., 2000; Sharma, 1998; Sharma and Bungum, 2006) for the prediction of PGA based on data from the Indian Himalayas. These five studies basically used the same sparse poorly-distributed dataset (see Figure 2) but chose different functional forms and regression techniques. An earlier study that showed the large variations in median predictions possible simply by changing the functional form is that by McCann Jr. and Echezwia (1984). Figure 1 shows a similar finding to that for the Turkish models reported by Bommer (2006): a large dispersion in predicted median ground motions even between models derived for the same region. PGA estimates from the different models become slightly more coherent at 50-200 km where most of the available observations are located (Figure 2). This example shows that reaching conclusions on regional dependence of ground motions based solely on comparisons between empirical ground-motion models is difficult because of the large epistemic uncertainty in the models due to limited data. Many published empirical models could be rejected from consideration in a seismic hazard assessment due to problems in their underlying data, weaknesses in the analysis performed and since they are too simple with respect to the underlying physics.

[Figure 1 about here.]

[Figure 2 about here.]

One important question that is rarely asked when making these comparisons of curves derived through regression analysis on sets of data with differing underlying distributions is: what is the uncertainty in the prediction of the median ground motion? Note that this is different than asking: what is the uncertainty of a single ground-motion estimate? for which the answer is given by the reported standard deviations of the model. For example, the standard deviation of a mean is given by $\sigma/\sqrt{n}$ where σ is the standard deviation and n is the number of samples, showing that the mean becomes more precisely defined when more data is used (e.g. Moroney, 1990). The uncertainty in the median is due to the lack of sufficient data to precisely define the coefficients of the regression model whereas the uncertainty of a single ground-motion estimate is mainly caused by the simplicity of the physical model assumed (e.g. Douglas and Smit, 2001). Given a very large well-distributed dataset the uncertainty in the prediction of the median ground motion will tend to zero but the uncertainty of a single ground-motion estimate will tend to a constant non-negligible value unless additional independent parameters are included. This difference is related to that between epistemic uncertainty and aleatoric variability. The uncertainty in the median is important when comparing ground motions in two different regions.

In his survey of empirical ground-motion estimation Campbell (1985) presents this equation for the estimation of the confidence limits for the mean of n_0 observations for linear models:

$$\hat{y} \pm t_{\alpha/2,\nu}\sigma\sqrt{\frac{1}{n_0} + X_0' C X_0}$$

where $\hat{y}$ is the mean predicted ground-motion (in logarithms), $t_{\alpha/2,\nu}$ is the absolute value of the t-statistic associated with an exceedance probability $\alpha/2$ and $\nu = n-p-1$ degrees of freedom, n is the number of records used to derive the model, p is the number of coefficients in the model, σ is the standard deviation, X_0 is a vector containing specified values of model parameters (e.g. M and $\log R$) and C is the covariance matrix of the model coefficients. He notes that the usual assumption of simply multiplying the median ground motion by the antilogarithm of differing numbers of standard deviations in order to obtain the confidence limits (e.g. the 84% percentile by multiplying by the antilogarithm of one σ) is inappropriate since it is only valid for many degrees of freedom (not too serious for most recent ground-motion models for which many hundreds of records are used) but also since it neglects uncertainty in the mean prediction of $\hat{y}$, which is only true near the centroid of the data. Applying this formula in place of the usual formula for computation of confidence limits leads to marginally broader limits that are curved at short and long distances and small and large magnitudes (points distant from the centroid of the data). This type of curved confidence limits are shown by Boore et al. (1980) for predictions from their models but in very few other articles. McGuire (1977) reports that the consideration of these correctly computed confidence limits does not significantly affect the hazard computed by probabilistic seismic hazard analysis compared with the standard approach. However, this was for a site 40 km from a single line source, hence it may not be true for real situations where near-source events are important.

In order to compute confidence limits of the median ground motion, the covariance matrix, C, is required (as shown above) and, within the formula above, $n_0 \to \infty$. To my knowledge, the complete covariance matrix of a published ground-motion model has never been publicly reported (the diagonal elements of these matrices, the standard errors of the coefficients, are, however, occasionally reported). Therefore a number of published PGA datasets that have been used to derive ground-motion models have been re-regressed here using the standard one-stage regression method and a simple linear functional form in order to obtain and plot confidence limits on the median curves. The equations used for this analysis were selected from those that published their datasets. In total, these seven models published in peer-reviewed journals for the prediction of PGA from shallow crustal earthquakes were recomputed: Joyner and Boore (1981) and Boore et al. (1993, 1997) (western USA); Ambraseys et al. (1996) and Ambraseys et al. (2005) (Europe and Middle East); Ulusay et al. (2004) and Kalkan and Gülkan (2004) (Turkey); and Sabetta and Pugliese (1987) (Italy). Equations were derived for the larger horizontal component, M_w (derived by conversion from M_s using Equation 6.2 of Ambraseys and Free (1997) with $P = 0$ for Ambraseys et al. (1996)) and distance to the surface projection of rupture (except for Ulusay et al. (2004) for which epicentral distance was used). The simple functional form adopted was: $\log y = a_1 + a_2 M + a_3 \log \sqrt{d^2 + 5^2} + a_{3+i} S_i$ where S_i equals unity for site class i and zero otherwise (the same site classes as in the original equation are used). A fixed coefficient of 5 km (a rough average value for this coefficient for most models that adopt this functional form) inside the square root has been assumed in order to make the function linear. This functional form has been commonly adopted in the past and models the major dependencies on magnitude, distance and site class. In addition, the model is linear therefore it allows the easy computation of the confidence limits using the formula above. Note that the effect of style-of-faulting and other factors have been neglected. The idea of this analysis is not to develop ground-motion estimation equations to be used for seismic hazard assessments but to derive confidence limits on the median PGA and there after to examine possible regional dependence. 95% confidence limits are computed since it is common to examine the rejection of a null hypothesis (in this case that there is no regional dependence) at a 5% significance level (e.g. Moroney, 1990). Note that here it is assumed that PGAs are log-normally distributed, which was shown to be a valid hypothesis by Douglas and Smit (2001), however for response spectral amplitudes a log-normal distribution may not be appropriate (Lee and Trifunac, 1995).

Figure 3 displays the predicted median PGAs at rock sites and their 95% confidence limits from the various rederived models for M_w5.0, 6.5 and 8.0 events and for distances up to 200 km. Note that events of magnitude 5 and 8 are often outside the limits of the data used to derive these models but they are included in order to show how the median becomes less precisely defined when extrapolation is required. Similarly most dataset have few records from distances greater than 100 km therefore again this shows the effect of extrapolation. In order to emphasize the imprecision in the median ground motions the median is plotted using a dashed line and the 95% confidence limits as solid lines.

[Figure 3 about here.]

The confidence limits on the median ground-motion predictions for equations derived with limited data, especially when it is poorly-distributed with respect to magnitude and distance, (Ulusay et al., 2004; Kalkan and Gülkan, 2004; Sabetta and Pugliese, 1987) are much wider than those of models based on large well-distributed datasets (Joyner and Boore, 1981; Boore et al., 1993, 1997; Ambraseys et al., 1996, 2005) showing that their medians are more poorly defined. Generally for moderate magnitudes ($5.5 < M_w < 7$) and at moderate distances ($10 \leq d_f \leq 60$ km) the 95%-confidence limits of the median are narrow and are within bands 10–30% from the median. For smaller and larger earthquakes and particularly at shorter and longer distances the confidence limits become much wider, especially if extrapolation is required, and imply that the estimated median ground motion is only known (to 95% confidence) within a factor of roughly two. Parts of the dataspace away from the centroid (e.g. near-source and for large events) where the confidence limits of ground-motion models become much broader are also often where the various models diverge (and also the parts of log-log graphs where differences are most noticeable). Hence such divergence between different models should not necessarily be taken as proof of regionally-dependent ground motions.

The importance of increasing the quantity of near-source large magnitude data is demonstrated by comparing the confidence limits for the model based on the data of Joyner and Boore (1981) to those based on the data of Boore et al. (1993, 1997), who had new data from large magnitude events available, such as Loma Prieta (M_w6.9), Cape Mendocino (M_w7.1) and Landers (M_w7.3), and consequently the confidence limits are narrower at large magnitudes and at close distances. Similarly, but less pronounced, the confidence limits of the model derived using the data of Ambraseys et al. (2005) are slightly narrower for large magnitudes and at close distances than those using the data of Ambraseys et al. (1996) due to the presence of additional data, such as records from the Kocaeli (M_w7.6) and Düzce (M_w7.2) events. On their Figure 4 Sabetta and Pugliese (1987) give distance and magnitude ranges within which their model applies (because of sufficient data): roughly 1.5–30 km for M5, 4–100 km for M6 and 10–200 km for M7. The importance of these recommendations is demonstrated by the large confidence limits of the model derived using these data for distances and magnitudes outside these limits.

As an example of the problem in assessing regional dependence based on published empirical ground-motion models Figure 4 compares the predicted median PGAs at rock sites for a M_w6.5 earthquake using the equations derived from the data of Ulusay et al. (2004) (from north-western Turkey) and from the data of Sabetta and Pugliese (1987) (from Italy). This figure shows that if only the predicted median ground motions are considered (the dashed lines) then it appears that there is a difference in shaking between these two areas. However, if the 95% confidence limits are considered, in order to test the significance of this suspected difference, then the apparent variation between the two regions is not strong enough to reject the null hypothesis because the confidence limits of the medians of the two curves overlap (except at great distances, where there is very little data).

[Figure 4 about here.]

INVESTIGATION USING OBSERVED GROUND MOTIONS

Luzi et al. (2006) compare predicted ground motions using equations developed by Bindi et al. (2006) from Umbria-Marche data with those they develop using data from the Molise region and find large differences that they propose are due to real differences in ground motions between the two regions. Figure 5 compares predicted PGAs from the ground-motion model of Luzi et al. (2006) for Molise with those predicted by the models of Bindi et al. (2006) and Zonno and Montaldo (2002) for Umbria-Marche, showing that predicted shaking in Molise is much lower (by about an order of magnitude for M_L4.5) than those in Umbria-Marche. Molise and Umbria-Marche are geographically close regions within the Italian Apennines and therefore if ground motions in these two areas are truly different it would have serious implications for studies that combine data from various, often widely-separated, parts of the world.

[Figure 5 about here.]

One possible reason why the predicted ground motions from the model of Luzi et al. (2006) do not match those from the model of Bindi et al. (2006) is that Luzi et al. (2006) use data mainly from $2.8 \leq M \leq 5.2$ and $10 \leq d \leq 40$ km whereas the data of Bindi et al. (2006) mainly comes from $4.0 \leq M \leq 5.9$ and $d \leq 40$ km. Pousse et al. (2007) show, using data from the Japanese K-Net and Kik-Net, that ground-motion models developed by regression on data from small earthquakes poorly predict ground motions from large earthquakes and vice versa even for models derived for the same region, due to differences in scaling. Since the exact datasets used by Bindi et al. (2006) and Luzi et al. (2006) have not been published the confidence limits of the median predictions, as discussed in the previous section, cannot be assessed here.

To investigate further the differences in shaking between these two regions, strong-motion data from the Umbria-Marche 1997–1998 sequence on the CD ROM published by Servizio Sismico Nazionale — Monitoring System Group (2002) plus data available on the Internet Site for European Strong-motion Data (Ambraseys et al., 2004) for a 1979 earthquake in the same region were selected. The same set of records was employed by Douglas et al. (2004) during their validation of the modal summation ground-motion simulation technique, although the sub-crustal 26th March 1998 (focal depth of 48 km) event is excluded here. For the Molise region, the data available on the CD ROM of D.P.C., U.S.S.N. - Monitoring System Group (2004) was analysed. Analysis was confined to ground motions from larger events ($M \gtrsim 4$) in both sequences. All available time-histories were examined and those of too poor quality were rejected. Table 2 summarises the data selected. In total, 191 records from 22 earthquakes and 42 stations from the Umbria-Marche region and 70 records from 9 earthquakes and 31 stations in the Molise region were retained. Table 3 presents the distribution of records with respect to site class and style of faulting for the two regional datasets.

[Table 2 about here.]

[Table 3 about here.]

Figure 6 displays the normalized residuals, i.e. $\epsilon_i = (\log y_i - \log y_i')/\sigma_i$ where y_i is the observed ith ground motion value, y_i' is the predicted ith ground motion and σ_i is the predicted standard deviation of the ith ground motion, of the observed horizontal PGA and SA at 1.0 s for 5% damping with respect to the ground-motion model of Ambraseys et al. (2005) against distance and magnitude, for the two regions. Mean normalized residuals for the two regions are, for Umbria-Marche: −0.06 for PGA and −0.25 for SA at 1.0 s and for Molise: −1.71 for PGA and −1.60 for SA at 1.0 s. Figure 6 and these mean residuals show that PGA is, on average, well estimated for the Umbria-Marche events and over estimated for the Molise events and SA at 1.0 s is, on average, over estimated for both sequences although much less so for the Umbria-Marche events. Note that 88 records from eight Umbria-Marche events were used to derive the equations of Ambraseys et al. (2005) but no records from the Molise sequence were because they were not available at the time. Figure 6 makes apparent some of the difficulties in assessing regional differences based solely on comparisons with published ground-motion models. The equations of Ambraseys et al. (2005) were derived for earthquakes with $M_w \geq 5$ and from distances less than or equal to 100 km, therefore there are possible problems in extrapolating the equations to smaller magnitudes and greater distances but this is required here in order to obtain reasonably large datasets. This extrapolation could be responsible for some of the apparent trends in the residuals for $M_w < 5$ and distances greater than 100 km. In addition, the sets of records from the two regions have different magnitude-distance distributions: for Umbria-Marche most data is from distances less than 30 km and from $M_w \geq 4.5$ whereas for Molise there are many records from greater distances and from smaller magnitudes. Therefore it is difficult to compare the residual plots from the two regions. The following section presents another technique for assessing differences between the two regions without requiring an explicit ground-motion model.

[Figure 6 about here.]

Application of analysis of variance

In order to investigate further the possible differences in ground motion between these two zones the technique proposed by Douglas (2004b) based on one-way analysis of variance (e.g. Green and Margerison, 1979, pp. 149–154) is applied. Douglas (2004b) used the method to investigate variations in ground motions between five regions (south Iceland, Friuli, central Italy, Greece and the Caucasus region) and found little evidence for differences in ground motions in the different regions, although the analysis technique could only be applied to data from small events due to a lack of data. Differences in ground motions in California, Europe and New Zealand were examined by Douglas (2004c) using the same technique and some evidence for differences in motions between California and Europe was found.

In this technique, two estimates of the variance of the ground motions are calculated. One estimate is the between-region variance (with $n-1$ degrees of freedom, where n is the number of regions) and the other is the within-region variation (with $N-n$ degrees of freedom, where N is the total number of records within the bin). Whether or not the means of the ground motions for the different regions differ, the within-region variation will be an unbiased estimator of the true variance, σ_2; the between-region estimator, however, will only be unbiased if the means of the ground motions are equal, otherwise its expectation will be larger than σ_2. The ratio of the two estimates of the variance of the ground motions is compared to the critical value of F using an F-test. The null hypothesis that the median ground motions are equal is rejected if this ratio is greater than the critical value of F for the significance level used (in this study, 5%) (e.g. Green and Margerison, 1979, pp. 149–154). The observed data are analysed at four periods: 0.0 (PGA), 0.2, 0.5 and 1.0 using the larger horizontal component of each record for each intensity measure. The common (base 10) logarithm of the ground motion amplitudes is taken before the analysis of variance is performed since it has been demonstrated (e.g. Douglas and Smit, 2001) that this transformation is justified because the standard deviations of the untransformed ground motions are proportional to the mean of the ground motions. A logarithmic transformation removes this dependence (e.g. Draper and Smith, 1981, pp. 237–238).

In this study the data space was divided into small intervals within which an analysis of variance was performed. Intervals of 10 km $\times$ 0.25 M_w units were used for this analysis so that there were sufficient records within each bin. This is a larger interval size than used by Douglas (2004b), who used 5 km $\times$ 0.25 M_s units, because, unfortunately, there are not sufficient records available from Molise to use smaller bins. In each interval a one-way analysis of variance calculation is made to assess whether the means of the transformed ground motion amplitudes from the different regions are significantly different. Only bins with two or more records from each region were considered. A key assumption in analysis of variance is that the variances of each subset are equal. This seems reasonably justified because, for example, Table 1 shows that the developed ground-motion models for Umbria-Marche and Molise have similar standard deviations.

In order to approximately correct for local site response the site coefficients derived by Ambraseys et al. (2005) for the three site classes (soft soil, stiff soil and rock) were used to adjust the observed ground motions at non-rock sites to estimated ground motions on rock. Therefore SAs at non-rock sites were divided by the corrective factors reported in Table 4. There is not enough data available that the analysis could be repeated for an individual site class (e.g. rock). An analysis was conducted without applying corrective site factors and similar results were obtained.

[Table 4 about here.]

Figure 7 displays the means of the four transformed strong-motion intensity measures for each region and for each of the eight bins with sufficient data. On this figure the bins and intensity measures that display a significant difference in the means are indicated by crosses as opposed to dots when there is no significant difference. From this figure it can be seen that for most intervals there are significant differences between the ground motions in Molise and Umbria-Marche with PGA and SA in Umbria-Marche being significantly higher than in Molise, confirming the findings of Luzi et al. (2006) based on regionally-specific empirical equations and the analysis of residuals with respect to a common ground-motion model shown above. Interestingly the most distant bin (that at 40–50 km for $5.50 \leq M_w \leq 5.75$) shows no significant difference in ground motions between the two regions suggesting that the cause of the variation in shaking between the two regions may be a near-source effect (although two near-source bins: 20–30 km for $4.25 \leq M_w \leq 4.50$ and 0–10 km for $4.50 \leq M_w \leq 4.75$ also show similar ground motions in the two regions).

[Figure 7 about here.]

Possible reasons for observed differences

One possible cause for lower ground motions within the Molise 2002–2003 sequence compared to earthquakes in Umbria-Marche is the difference in average focal depths of the two sequences. Bindi et al. (2006) report the focal depths of the 45 Umbria-Marche events they study; they range between 1 and 9 km (not including the single sub-crustal event of depth 48 km) with most between 3 and 6 km. This contrasts with the deeper focal depths of the Molise events reported by Chiarabba et al. (2005) who find that the events occurred at depths between 8 and 20 km. The effect of these greater focal depths on ground motions could be partly modelled with empirical equations by using a distance measure that accounts for depth of the source but this will not predict large differences in motions especially distant from the source where the effect of depth on source-to-site distances is small. For example, Luzi et al. (2006) find that the Molise ground motions were lower than those predicted by the model of Bindi et al. (2006) even when hypocentral distance was used.

Differences in local site response for stations within the two areas could be responsible for some of the observed differences (e.g. if rock sites in Molise were, on average, much harder than those in Umbria-Marche). An average local site amplification for horizontal PGA for Molise stations on soil is estimated by Luzi et al. (2006) via regression as: 1.33. Bindi et al. (2006) also present average local site amplifications for four site classes in Umbria-Marche via regression. They report factors for PGA of between: 1.10 (for deep soft soil sites) to 2.75 (for sites with shallow soft soil overlying rock). Due to the similarity between these estimated site effects in the two regions it is unlikely that regional differences in average site conditions is the main cause of the observed variations.

Different predominant faulting mechanism in the two sequences (mainly normal faulting for the Umbria-Marche sequence and mainly strike-slip for the Molise events) is also unlikely to be responsible for the large differences in observed ground motions since as noted by Bommer et al. (2003) ground motions are not strongly dependent on style of faulting (average factors between shaking from events with different mechanisms are 10–30%). In fact, spectral ordinates from normal faulting earthquakes are generally similar or slightly lower (about 10%) than those from strike-slip events (Bommer et al., 2003).

Via ground-motion modelling Di Luccio et al. (2005) and Vallée and Di Luccio (2005) have calculated quite slow rupture velocities for the Molise mainshock of 1.1 km/s and 2.0 km/s, respectively. These relatively low ruptures velocities contrast with more usual rupture velocities reported by, for example, Capuano et al. (2000) for the main Umbria-Marche events of 2.6 km/s to 3.0 km/s. These differences in velocities should have an important effect on ground motions due to more prominent directivity effects in faster rupturing earthquakes. Also slow rupture velocities could imply a sparse distribution of asperities and therefore a larger fault area for the same magnitude, which could explain differences for intermediate and long periods (M. D. Trifunac, written communication, 2007).

An important question is whether the ground motions observed in the Molise and Umbria-Marche sequences are typical for their regions. If so then corrective factors to adjust ground-motion models derived for other regions would need to be applied in these parts of Italy in order to avoid general over- or under-estimation of shaking. Chiarabba et al. (2005) note that earthquakes of the Molise 2002 sequence were deeper than is usual in the southern Apennines normal fault belt therefore the data from this sequence may not be sufficient to develop such corrective factors because the ground motions observed may be atypical.

INVESTIGATION USING STOCHASTIC MODELS

The stochastic method (Boore, 2003) has become a widely-used technique for the simulation of ground motions especially for regions lacking observational data from damaging earthquakes, such as eastern North America, because the parameters required can be estimated using data from standard seismological networks. Following Boore (2003), 'stochastic model' refers here to the parameters used within the stochastic method for a particular application.

In the stochastic method a Fourier spectrum of ground motion is estimated using a model of the source source spectrum that is transferred to the site by considering geometric decay and anelastic attenuation. The parameters that define the source spectrum and the geometric and anelastic attenuation are based on simple physical models of the earthquake process and wave propagation and these parameters are estimated by analysing many seismograms. After the Fourier spectrum at a site is estimated time-histories can be computed by adjusting and enveloping white noise to give the desired spectrum and duration of shaking. The main input parameters in this method that make the stochastic model regionally-dependent are (divided into source, path and site factors): the source spectral amplitude and shape and the source duration; the geometric decay rates with respect to distance, the anelastic attenuation with respect to frequency and the path duration with respect to distance; and the local site amplification and attenuation. Since the method does not account for phase effects due to propagating rupture or wave propagation the results in the near-source region may not be appropriate. In addition, there is much debate over the shape of source spectra for moderate and large events (M_w greater than roughly 6) where the commonly-used one corner frequency spectrum of Brune (1970, 1971) for body waves may not be appropriate (e.g. Gusev, 1983; Joyner, 1984; Atkinson and Silva, 2000). Since only body waves are usually considered long-period ground motions could be poorly estimated by this method (see Trifunac (1993) on the estimation of long-period spectral ordinates). The reader is referred to the comprehensive review article by Boore (2003) for details of the stochastic method and a discussion of its limitations.

In this article, comparisons are made of the elastic response spectra predicted using stochastic models developed for different regions that are classified into a number of broad seismotectonic categories: stable continental regions (low strain rates) and regions of moderate and high strain rates. If such a classification of regions is justified with respect to the ground motions estimated for the same magnitude and distance then variations between ground motions predicted using models from different tectonic categories should be larger than those predicted from models within the same tectonic class. For example, predictions of ground motions from different models for stable continental regions should be closer together than predictions from various models for high-strain-rate regions, i.e. the intra-region variation should be less than the inter-region variation.

Sokolov (2000) also makes comparisons of ground motions predicted by various stochastic models (for the Racha and Spitak regions of the Caucasus region and Taiwan) and concludes that there are regional variations in ground motions between the three regions compared. However, the models compared by Sokolov (2000) were based on strong-motion datasets of different distributions in terms of magnitude and distance, which could have strongly contributed to the variation in predicted motions. Stochastic models are subjected to large uncertainties due to trade-offs between different parameters (e.g. Bay et al., 2005) and it is important that this epistemic uncertainty is appreciated when make comparisons between models. One difficulty in making comparisons between predicted median ground motions from different stochastic models is that the uncertainties in the median predictions are rarely given. Unlike empirical models that are derived by regression and where the uncertainty can be easily computed using the difference between observed and predicted ground motions, stochastic models are derived through complex analysis and hence it is difficult to estimate uncertainties.

In an earlier study using stochastic models, Chen and Atkinson (2002) compared apparent earthquake source radiation for six different regions: Japan, Mexico, Turkey, California, British Columbia (western Canada) and eastern North America and they concluded that there is little evidence for inter-regional differences.

Stochastic models considered

Due to the possible trade-off between parameters (e.g. Bay et al., 2005) within stochastic models, only studies that report all required parameters of the stochastic model are considered here. Therefore studies, such as Castro et al. (2004) who study the attenuation in southern Italy but do not provide estimates of $\Delta\sigma$ are excluded. Also excluded are those models that have adopted all or some of the main parameters of their stochastic models, such as $\Delta\sigma$, from studies for other regions (e.g. Douglas et al., 2006b). Finally, models developed for use in stochastic methods that include finite fault effects (e.g. Beresnev and Atkinson, 1998) have not been included since their parameters may not be appropriate for use in the standard stochastic approach. The model of Allen et al. (2006) from Western Australia is not included since it is developed from data from earthquakes with $2.2 \leq M_w \leq 4.6$ therefore its suitability for predictions of ground motions from larger earthquakes is not known. The model of Sokolov et al. (2005) for earthquakes occurring in the Vrancea region of Romania is not considered due to the large depths (60–170 km) of these events.

A quantitative comparison of epistemic and aleatoric variabilities of these stochastic models is not possible since to correctly estimate the aleatoric variabilities within ground motions simulated using the stochastic method requires that each parameter within the stochastic model has a range of possible values in order that the complete range of ground motions is computed (e.g. Sigbjörnsson and Ambraseys, 2003). In this study, the epistemic uncertainty within the expected ground motions for broad seismogenic domains is approximated by the variation between different models for regions classified within common domains.

To separate ground-motion models by their seismotectonic regime the global map of second-invariant strain rates published by Kreemer et al. (2003) has been used. Since within the regions covered by the considered stochastic models the strain rates vary, an average strain rate is given within Table 5. Strain rates for the models given in Table 5 fall into three broad categories: $0 \times 10^{-9}\mathrm{yr}^{-1}$ (stable continental regions), between 0 and $100 \times 10^{-9}\mathrm{yr}^{-1}$ and $> 100 \times 10^{-9}\mathrm{yr}^{-1}$

therefore these three classes have been used for the analysis. If a fault length of 100 km is assumed then this classification corresponds to the classification of earthquakes proposed by Scholz et al. (1986), namely: 'intraplate (mid-plate)', 'intraplate (plate boundary related)' and 'interplate'. The distribution of number of models with respect to the different classes is: six for the high strain rate class, eight for the intermediate class and four for the low class.

As discussed in Bommer et al. (2003) and mentioned above, the faulting mechanism of an earthquake can have an measurable impact on the observed strong ground motions. Since this effect could be important when comparing stochastic models studied here, Table 5 also reports the predominant faulting mechanism of earthquakes within the region for which the model was derived. This information is taken, either from the articles themselves or from the World Stress Map (Reinecker et al., 2005).

[Table 5 about here.]

Comparisons between different models

The computer program SMSIM (Boore, 2005) was used to compute elastic response spectra on generic rock sites. Simulations were computed for each model for M_ws of: 4.5, 5.5 and 6.5 and for hypocentral distances: 5, 10, 20 and 50 km. The reliability of some of the stochastic models studied here at larger magnitudes is questionable for two reasons. Firstly, many studies used data from small and moderate earthquakes so it is not known if the parameters of the models, particularly $\Delta\sigma$, are applicable for larger earthquakes (e.g. Ide and Beroza, 2001). Secondly, for larger earthquakes and especially for short source-to-site distances finite fault effects, which are not modelled using the standard stochastic method, become important. Therefore, comparisons for $M_w > 6.5$ are not made. Ground motions at distances greater than 50 km are rarely of engineering interest due to their low amplitudes therefore no far-source comparisons are made.

Figures 8 to 10 display the predicted median response spectra from the studied stochastic models grouped with respect to the strain rate categories defined above. Within each category there are some models that systemically predict greatly different response spectra than the others for that regime, which probably demonstrates regional dependence for the areas covered by these models. For the models from stable continental regions, the predictions from eastern North America (Campbell, 2003) are much higher than those from the other three regions, especially at short periods, whereas predicted spectra from the other three models are generally similar considering the uncertainties in median predictions. Note, however, that predicted spectra (especially at short periods) are highly sensitive to the choice of parameters in the models (particularly $\Delta\sigma$, near-surface attenuation, e.g. the value of κ, and near-surface shear-wave velocities) as Campbell (2003) shows for predicted spectra from eastern North America.

The spectra predicted by the model of Campbell (2003), which is for a very hard rock site with low near-surface attenuation, need modification for other types of site with lower near-surface shear-wave velocities and greater attenuation. The predictions from the models for moderate strain regions are approximately separated into two groups: higher amplitudes predicted from the models for eastern Sicily (Scognamiglio et al., 2005), the Apennines (Malagnini et al., 2000a) and the western Alps (Morasca et al., 2006) and lower amplitudes predicted for north-east Italy (Malagnini et al., 2002), Spitak (Sokolov, 1998), Racha (Sokolov, 1997), Utah (Jeon and Herrmann, 2004) and Umbria-Marche (Malagnini and Herrmann, 2000). Spectra predicted for the high strain regions show large dispersion of factors of more than 10 times (for example, compare the predicted spectra for Taiwan and Erzincan for M_w6.5 at 5 km). Such large dispersion is not observable in strong-motion data from these high strain regions, which are often combined when deriving empirical models.

[Figure 8 about here.]

[Figure 9 about here.]

[Figure 10 about here.]

Interestingly, the variation in predicted response spectra between models that could be considered to have been developed for comparable tectonic regions is similar to the variation between models from tectonically different regions. This suggests that the stochastic models are not well enough developed to be able to draw definitive conclusions regarding the regional dependence of ground motions based on stochastic modelling. This does not necessarily mean that ground motions are not regionally dependent but that the stochastic models are not yet sufficiently accurate. Due to the large variation in the predicted spectra for each group it is not currently possible to clearly observe whether variations in faulting mechanism between regions within each tectonic group are responsible for the differences in estimated ground motions. As mentioned above, observations from analysis of recorded strong ground motions show that, although measurable differences in spectra due to differing faulting mechanism exist, the effect of mechanism is relatively small (usually 10–30%) (e.g. Bommer et al., 2003). Therefore other variations in the stochastic models could be obscuring this effect.

One important parameter within the regional stochastic models that could be obscuring a regional dependence in response spectra due to source or path differences is that the stochastic models have been derived for different average rock conditions. For example, for stable continental regions: Campbell (2003) proposes his model for very hard rock sites (average shear-wave velocities in upper 30 m of 2800 m/s) with high near-surface shear-wave velocities and low attenuation ($\kappa = 0.006$ s) that are common in eastern North America whereas the model of (Bay et al., 2005) is for sites in the Swiss Alpine foreland of softer rock (average shear-wave velocities in upper 30 m of 750–1500 m/s) and higher attenuation ($\kappa = 0.0125$ s).

CONCLUSIONS

This article has investigated the question of whether average ground motions for the same magnitude and source-to-site distance show significant regional variations. A number of different techniques are employed to examine this question: comparison of published empirical and stochastic ground-motion models, comparison of empirical models considering the confidence limits on the median predictions, residual plots and analysis of variance.

It is shown that predictions from empirical models derived through regression analysis are associated with large epistemic uncertainties due to insufficient data to constrain the median prediction, especially for magnitudes and distances where earthquake ground motions could be of engineering concern. These epistemic uncertainties are shown by large variations in median predictions even when basically the same set of records is used but the functional form and the regression method is varied. This article presents the 95% confidence limits of ground-motion models derived by regression on various sets of records and shows that the predicted median ground motions are not well constrained away from the centroid of the data, especially for sparse data sets. Therefore conclusions concerning regional dependence based on apparent differences in predicted median ground motions should be made with great caution unless the confidence limits of the models are known. It is suggested that developers of ground-motion models report the confidence limits of their models in order to more reliably make comparisons between predicted median spectra. In the distant future when large well-distributed datasets become available the medians of predicted earthquake response spectra will become perfectly constrained through the reduction of epistemic uncertainties and the confidence limits of the medians will be very narrow. These precisely-known confidence limits will improve the reliability of conclusions based on comparisons between empirical models.

Residual analysis of spectral ordinates with respect to well-constrained ground-motion models provide an attractive approach for the investigation of regional dependence since it does not rely on the availability of large numbers of records. However, comparing two regions by examining their residuals can be difficult if the distribution of records with respect to their independent variables (e.g. magnitude, distance and site class) is not similar and/or does not match the distribution of records used to derive the ground-motion model.

If data was sufficient, comparisons between earthquake response spectra from different regions should ideally be solely made by comparing observed spectra, in order to reduce uncertainties due to differences in the distributions of datasets from the various regions. In this article, an approach based on analysis of variance of observed spectra is applied to two close-together Italian regions (Umbria-Marche and Molise), having been already used in previous studies for various regions in Europe, California and New Zealand. The results confirm the observations made using other techniques.

Finally, numerous stochastic models for the prediction of strong motions were examined. Such models have the advantage of not requiring as much strong-motion data in order to constrain their parameters due to the underlying physical model. Hence, they appear to be an appealing method for comparing ground motions in different regions with insufficient data to apply other methods. By comparing estimated median response spectra for various regions separated into three broad tectonic regimes based on their average strain rates, it is found that some regions seem to display significantly higher or lower spectra than others, however, most models within each type of regime predict similar spectra especially when considering the (unknown) uncertainties of models. There is no strong evidence for large differences between spectra from different tectonic regimes.

From the evidence discussed in this article and other studies, it currently seems to be more defensible for many parts of the world where observational data is limited to use well-constrained ground-motion models possibly developed using data from other regions than to base design ground-motion estimates on local models, which are often less robust. An important question is whether the ground motions observed during short observational histories (about a decade for many parts of the world) are typical for their regions. It is important to carefully study possible differences in ground motions between regions using, for example, the techniques discussed here but rather than systemically assuming regional dependence of shaking once a new dataset becomes available, physical reasons for regional dependence should be sought. For example, Dowrick and Rhoades (2004) present an analysis of relations between magnitude and fault rupture dimensions (length, width, area, slip and aspect ratio) and find strong evidence for regional differences within relations between these parameters. The differences were statistically significant between New Zealand and California, New Zealand and Japan, New Zealand and China, and Japan and California. These differences in gross features of earthquakes should translate into differences in strong ground motions since they will affect static stress drops.

If it is found that ground motions vary significantly between regions then the hybrid method introduced and applied by Campbell (2003) for eastern North America and applied by Douglas et al. (2006b) for sites in southern Spain and southern Norway could be useful for the development of robust predictive models. This technique seeks to combine the benefits of empirical and stochastic modelling. Another method that could model the effect of crustal structure on ground motions, which is a potentially important source of regional dependence, is the use of equivalent hypocentral distance introduced by Douglas et al. (2004).

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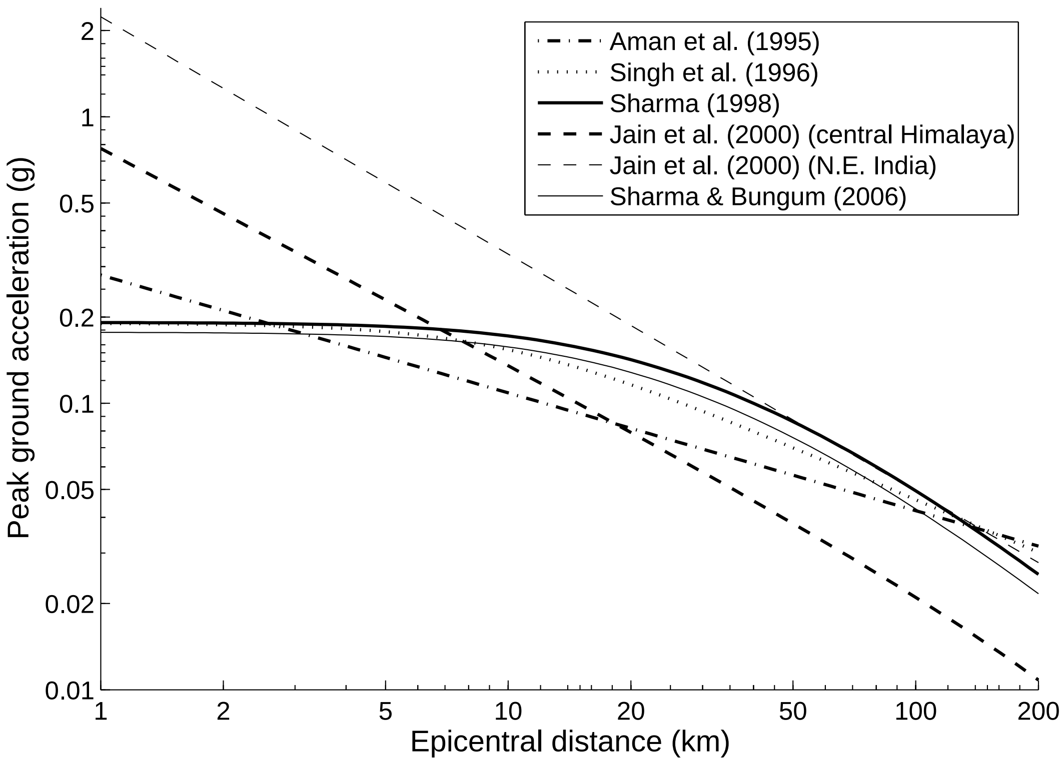
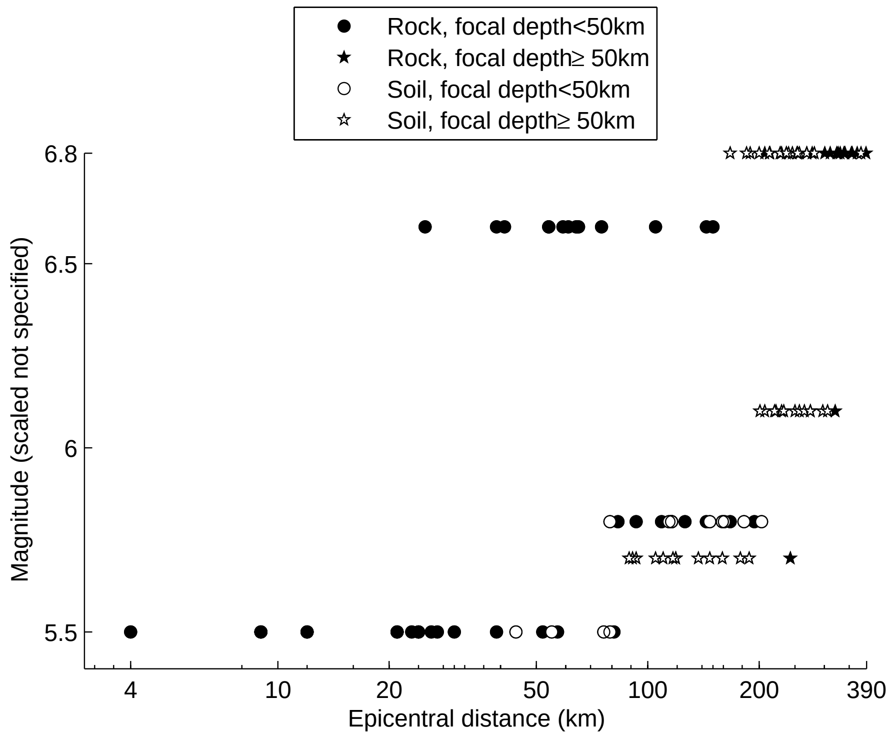


Figure 1: Comparison of horizontal PGA predicted by various empirical ground-motion models developed using Indian strong-motion data for an $M_w6.0$ [$m_b5.6$, using the magnitude-conversion formula of Castellaro et al. (2006): $m_b = (M_w + 1.272)/1.291$] earthquake with a focal depth of 10 km.



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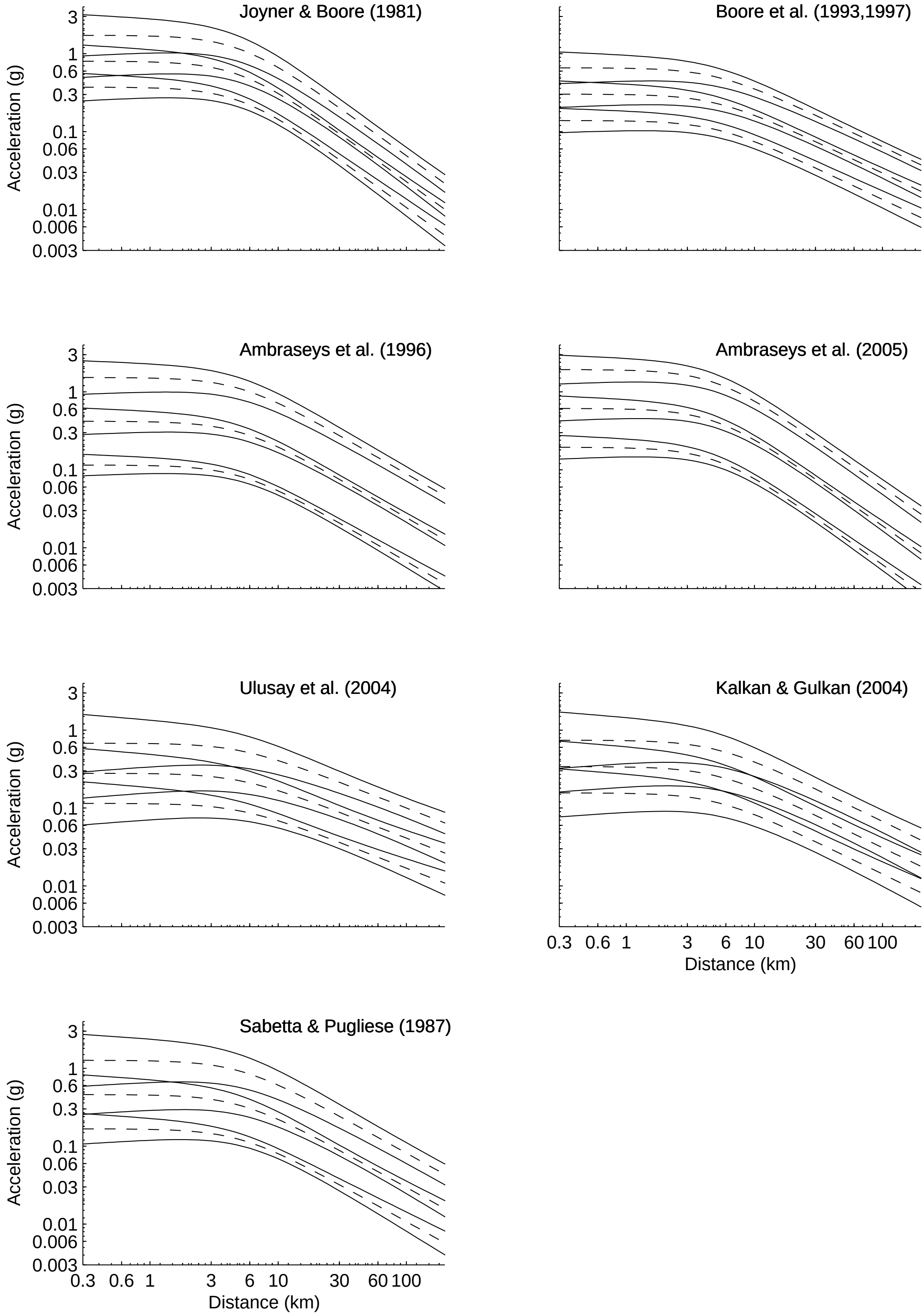
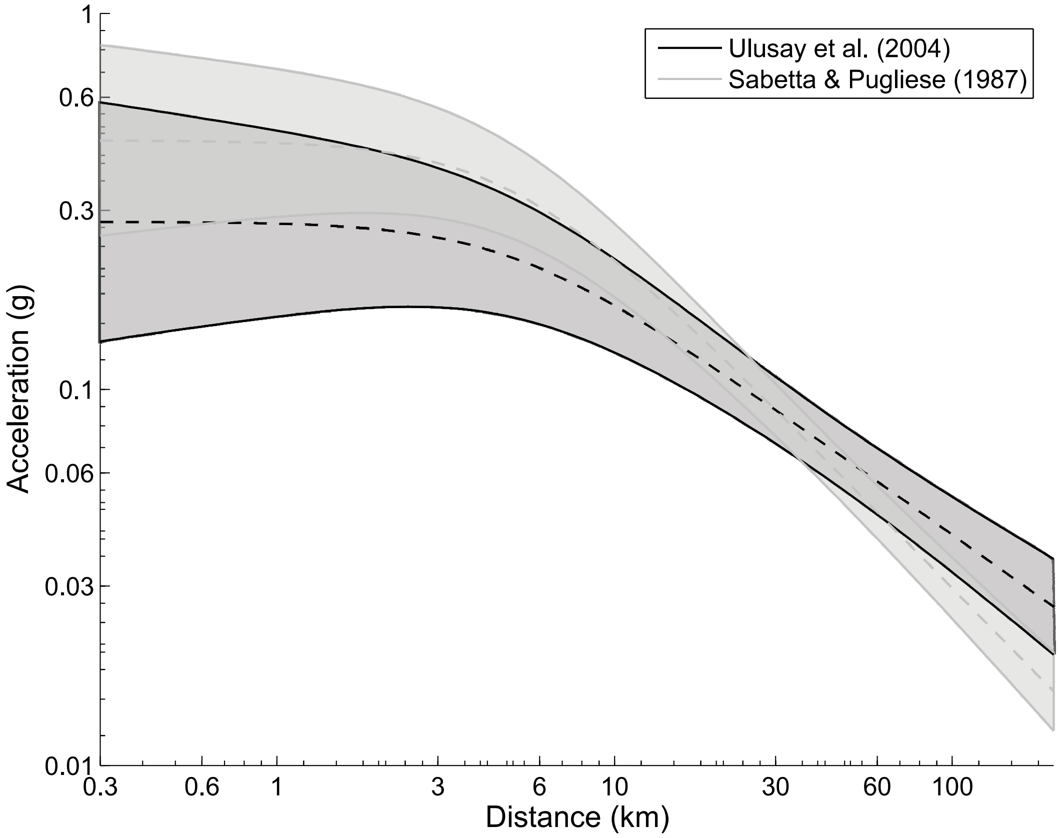


Figure 3: Predicted median PGAs (dashed lines) at rock sites for M_w5.0, 6.5 and 8.0 earthquakes and their 95% confidence limits (solid lines) for ground-motion models derived using various datasets. Note that the names in this figure refer to the datasets, not to the equations, of the respective authors.



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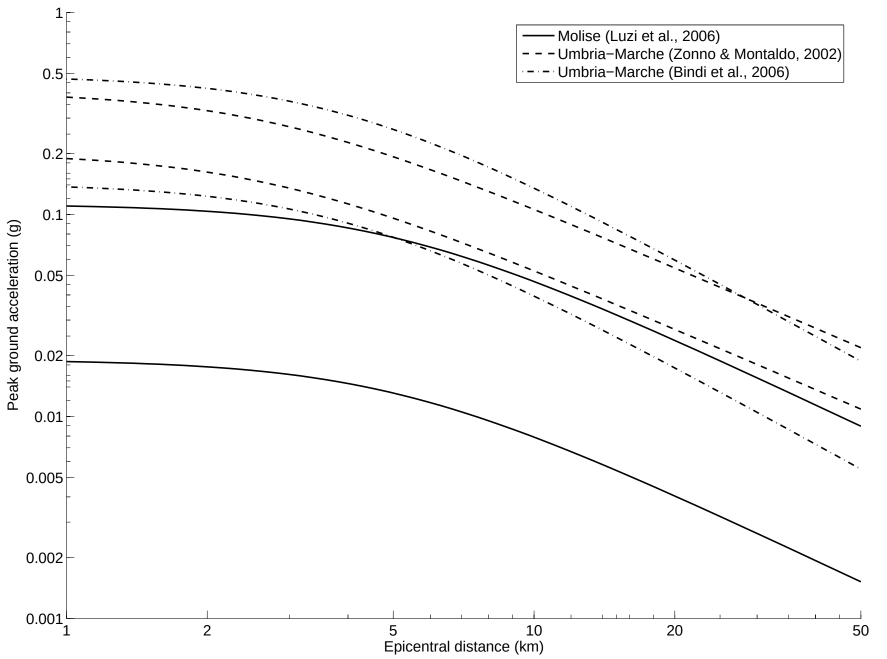

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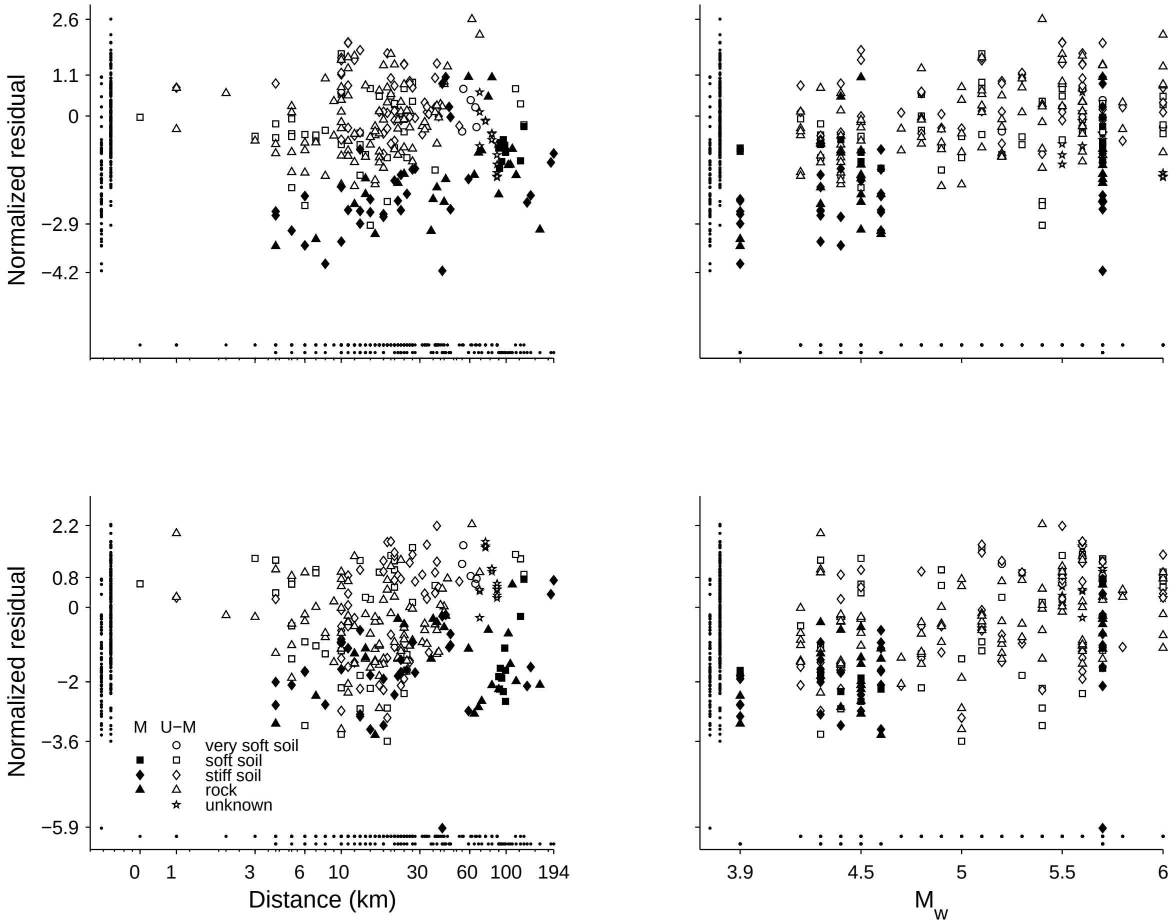


Figure 6: Normalized residuals for PGA (upper graphs) and SA at 1 s for 5% damping (lower graphs) for data from Umbria-Marche (unfilled symbols) and Molise (filled symbols) and the ground-motion model of Ambraseys et al. (2005) with respect to source-to-site distance and M_w. Residuals for records with unknown site classes (for Umbria-Marche) have been computed with respect to predicted rock motions. Residuals for unknown mechanisms (for Molise) have been computed with respect to predicted strike-slip motions (the predominant mechanism for these events). Also shown, as small dots close to the x and y axes, are the marginal distributions.

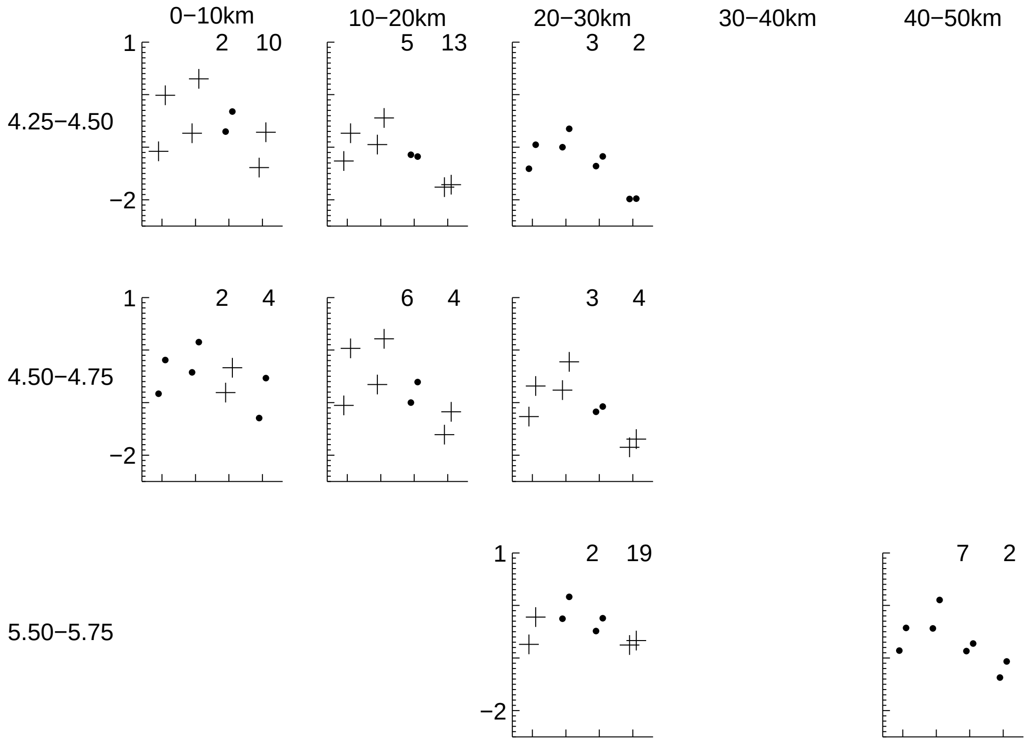


Figure 7: Graphs for each bin where analysis of variance was performed to compare ground motions in Molise and Umbria-Marche. Each small graph displays the means of the transformed ground motions for each of the four strong-motion intensity measures considered (the first two points are PGA, the second two points are SA at 0.2 s, the third two points are SA at 0.5 s and the final two points are SA at 1.0 s). The ordinate of the small graphs is logarithm of acceleration in m/s^2. Therefore they can be thought of as response spectra with only four ordinates. The left point in each pair is for Molise and the right point is for Umbria-Marche. If the difference in means was found to be significant at the 5% significance level using the F-test then the marker is a cross rather than a dot. The two numbers in the top right corner are the total number of records in the bin from each region (the left number is for Molise and the right number is for Umbria-Marche). The small graphs are arranged in an overall plot showing the magnitude (on the y-axis) and distance (on the x-axis) ranges of the bins. Since no comparisons could be performed due to insufficient data, the magnitude range between 4.75 and 5.50 is not shown.

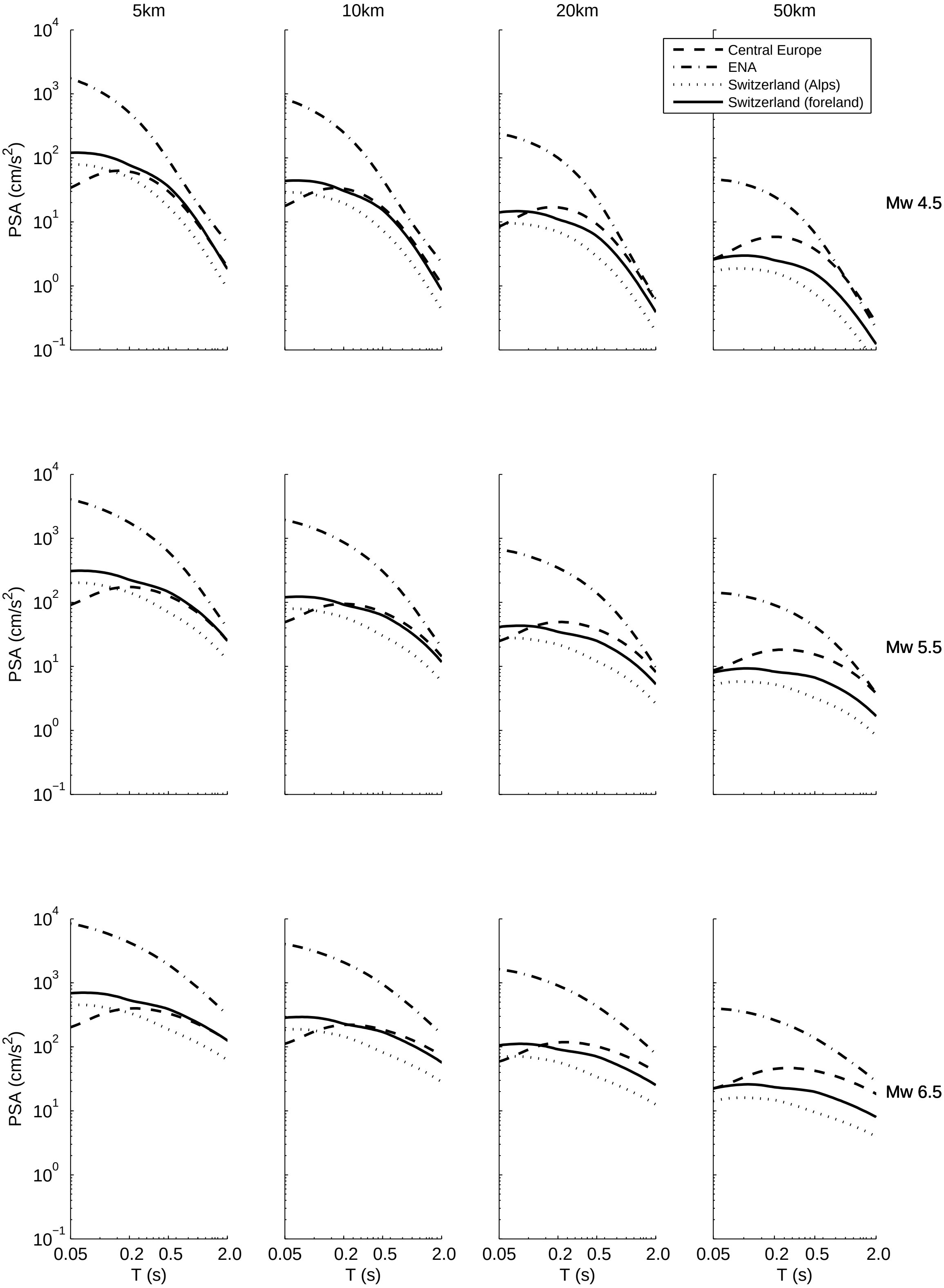
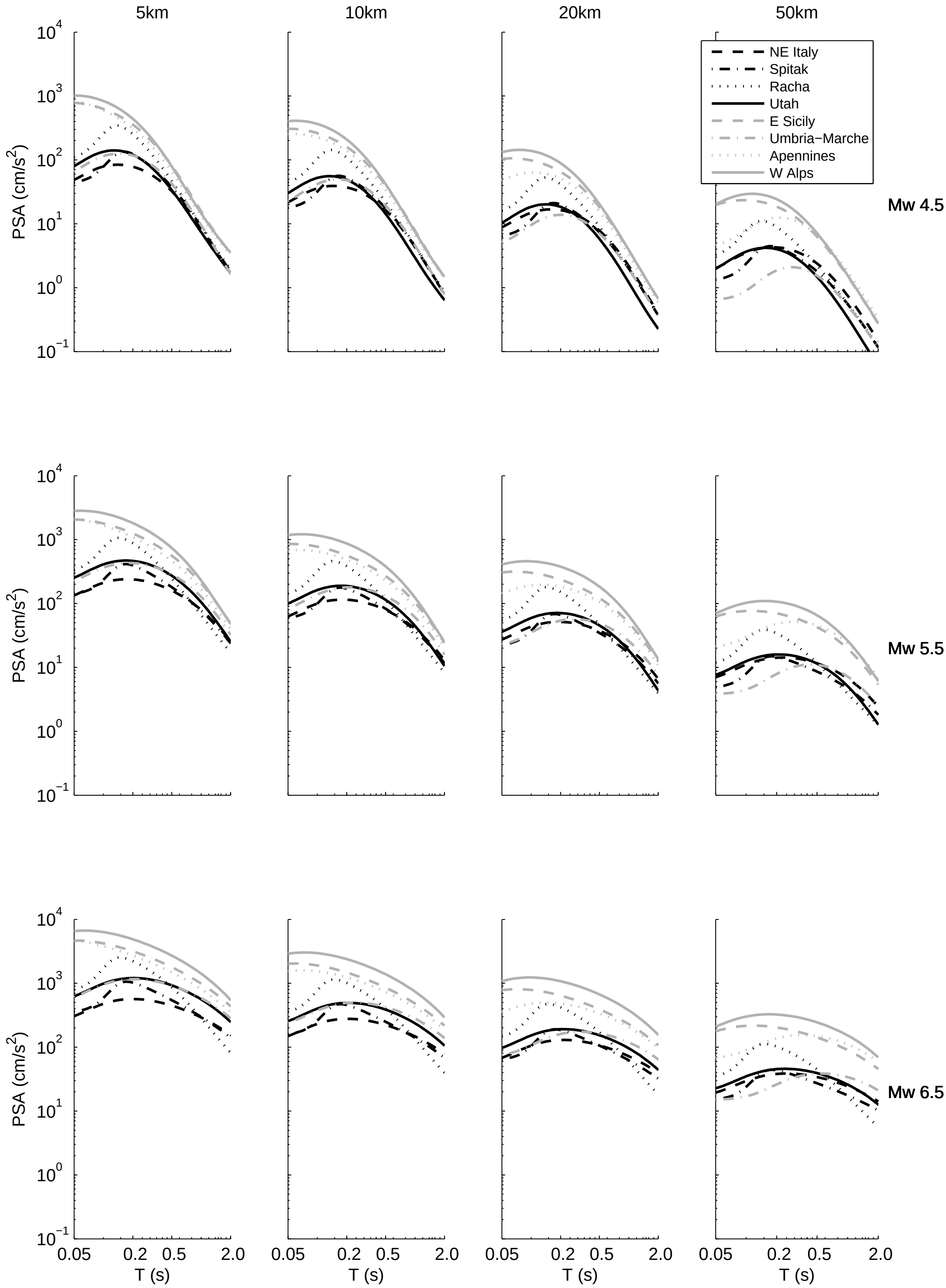


Figure 8: Comparison of the elastic acceleration response spectra predicted using stochastic models for stable continental regions: central Europe (Malagnini et al., 2000b), eastern North America (Campbell, 2003) and Switzerland (Alps and foreland) (Bay et al., 2005), for different magnitudes (rows) and distances (columns).



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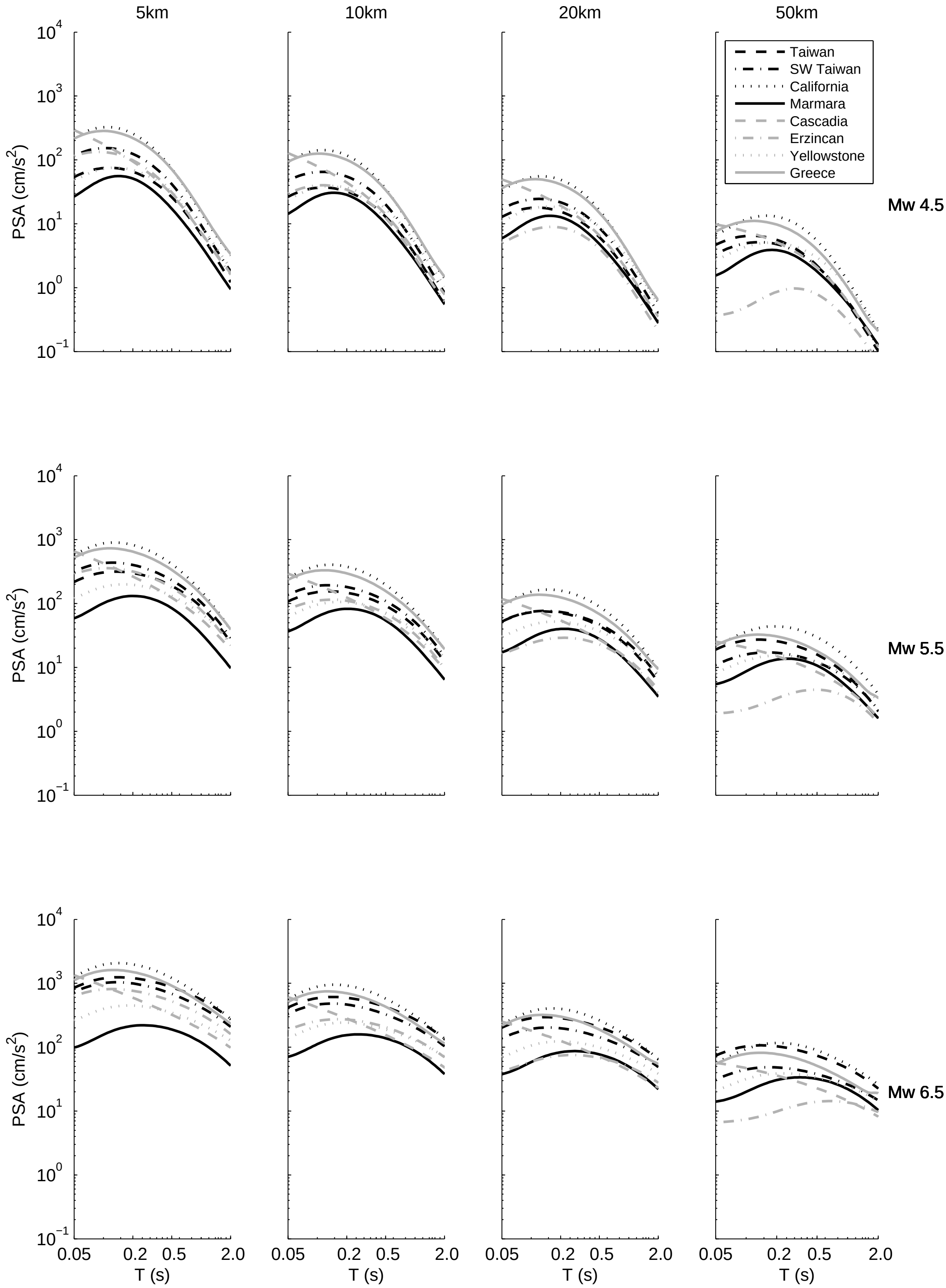

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Table 1: Standard deviations in common logarithms (σ) of selected empirical ground-motion models for prediction of PGA from strike-slip shallow-crustal earthquakes at rock sites, the regions used as sources of accelerograms and the number of accelerograms (T) and earthquakes (E) and the magnitude and distance ranges (d_e is epicentral distance, d_f is distance to surface projection of rupture, d_h is hypocentral distance, d_r is distance to rupture and d_s is distance to seismogenic rupture) of data used for the deviation of the model. Standard deviations given for Abrahamson and Silva (1997), Ambraseys et al. (2005), Campbell and Bozorgnia (2003) and Sadigh et al. (1997) are for $5.0 \leq M_w \leq 7.5$ since the authors report magnitude-dependent σs.

Reference	Region	T	E	M range	d range (km)	σ
			Small regions			
Bindi et al. (2006)	Umbria-Marche	239	45	$4.0 \leq M_L \leq 5.9$	$1 \leq d_e \leq 100$	0.27
Bragato and Slejko (2005)	Eastern Alps	1402	240	$2.5 \leq M_L \leq 6.3$	$0 \leq d_f \leq 130$	0.36
Costa et al. (2006)	Friuli	900	123	$3.0 \leq M_L \leq 6.5$	$1 \leq d_e \leq 100$	0.34
Frisenda et al. (2005)	NW Italy	6899	1152	$0.0 \leq M_L \leq 5.1$	$0 \leq d_h \leq 300$	0.32
Kalkan and Gülkan (2004)	Mainly NW Turkey	112	57	$4.0 \leq M_w \leq 7.4$	$1 \leq d_f \leq 250$	0.27
Luzi et al. (2006)	Molise	886	N/A	$2.6 \leq M_L \leq 5.7$	$5 \leq d_h \leq 55$	0.35
Marin et al. (2004)	France	63	14	$2.6 \leq M_L \leq 5.6$	$5 \leq d_h \leq 700$	0.55
Özbey et al. (2004)	NW Turkey	195	17	$5.0 \leq M_w \leq 7.4$	$5 \leq d_f \leq 300$	0.26
Sabetta and Pugliese (1987)	Italy	95	17	$4.6 \leq M_s, M_L \leq 6.8$	$1 \leq d_f \leq 179$	0.17
Zonno and Montaldo (2002)	Umbria-Marche	161	15	$4.5 \leq M_L \leq 5.9$	$2 \leq d_e \leq 100$	0.28
			Broad regions			
Abrahamson and Silva (1997)	Mainly California	655	58	$4.4 \leq M_w \leq 7.4$	$0 \leq d_r \leq 220$	0.19–0.31
Ambraseys et al. (1996)	Europe & Middle East	422	157	$4.0 \leq M_s \leq 7.9$	$0 \leq d_f \leq 260$	0.25
Ambraseys et al. (2005)	Europe & Middle East	595	135	$5.0 \leq M_w \leq 7.6$	$0 \leq d_f \leq 99$	0.19–0.36
Berge-Thierry et al. (2003)	Europe & Middle East	802	403	$4.0 \leq M_s \leq 7.9$	$4 \leq d_h \leq 330$	0.29
Boore et al. (1997)	Mainly California	271	20	$5.1 \leq M_w \leq 7.7$	$0 \leq d_f \leq 118$	0.23
Campbell and Bozorgnia (2003)	Mainly California	443	36	$4.7 \leq M_w \leq 7.7$	$2 \leq d_s \leq 60$	0.17-0.25
Joyner and Boore (1981)	Mainly California	182	23	$5.0 \leq M_w \leq 7.7$	$0 \leq d_f \leq 370$	0.26
Lussou et al. (2001)	Japan	3011	102	$3.7 \leq M_{\mathrm{JMA}} \leq 6.3$	$4 \leq d_h \leq 600$	0.32
Sadigh et al. (1997)	Mainly California	960	119	$3.8 \leq M_w \leq 7.4$	$0 \leq d_r \leq 305$	0.17–0.30
Spudich et al. (1999)	Worldwide extensional regimes	142	39	$5.1 \leq M_w \leq 7.2$	$0 \leq d_f \leq 99$	0.20

Table 2: Details of earthquakes from the Umbria-Marche and Molise region analysed in this study. Y is year, M is month, D is day, T is time, M_w is moment magnitude (those in italics have been converted from m_b using the conversion formula of Castellaro et al. (2006)), N is number of records and d range is the distance range of records selected (epicentral unless in italics when it is distance to surface projection).

Y	M	D	T	M_w	Mechanism	N	d range
				Umbria-Marche			
1979	09	19	21:35	5.8	N	4	1–37
1997	09	03	22:07	4.5	N	2	4–13
1997	09	26	00:33	5.7	N	15	*0–122*
1997	09	26	09:40	6.0	N	17	*1–128*
1997	09	26	13:30	4.5	N	2	3–26
1997	09	27	08:08	4.4	N	4	4–31
1997	10	03	08:55	5.3	N	8	5–37
1997	10	04	16:33	4.7	N	3	11–23
1997	10	06	23:24	5.5	N	17	5–88
1997	10	07	01:24	4.2	N	4	10–16
1997	10	07	05:09	4.5	O	6	3–39
1997	10	12	11:08	5.2	O	12	4–54
1997	10	13	13:09	4.4	N	3	9–25
1997	10	14	15:23	5.6	N	29	9–114
1997	10	16	12:00	4.3	S	6	1–12
1997	10	19	16:00	4.2	N	5	5–17
1997	11	09	19:07	4.9	N	8	7–37
1998	02	07	00:59	4.4	N	7	6–16
1998	03	21	16:45	5.0	O	8	5–19
1998	04	03	07:26	5.1	N	14	6–38
1998	04	03	07:59	4.3	N	6	7–25
1998	04	05	15:52	4.8	N	11	8–39
				Molise			
2002	10	31	10:32	5.7	S	11	22–194
2002	11	01	15:08	5.7	S	10	24–187
2002	11	01	15:20	*3.8*	U	1	90–90
2002	11	01	17:21	4.5	O	1	94–94
2002	11	04	00:35	*4.3*	U	9	4–93
2002	11	12	09:27	4.6	S	11	5–91
2002	12	02	20:52	*3.8*	U	9	4–99
2003	06	01	15:45	4.4	S	6	6–96
2003	12	30	05:31	4.5	S	12	14–160

The method of Frohlich and Apperson (1992) has been used to classify earthquakes by faulting mechanism, i.e.: earthquakes with plunges of their T axis greater than 50° are classified as thrust (T), those with plunges of their B axis or P axis greater than 60° are classified as strike-slip (S) and normal (N), respectively, and all other earthquakes are classified as odd. U stands for unknown faulting mechanism.

Table 3: Distribution of data used with respect to local site class and faulting mechanism for the two regions (left-hand number refers to Umbria-Marche and right-hand numbers to Molise).

	Very soft soil		Soft soil		Stiff soil		Rock		Unknown		Total	
Normal	4	0	32	0	43	0	65	0	15	0	159 (83%)	0 (0%)
Strike-slip	0	0	1	7	1	22	4	21	0	0	6 (3%)	50 (71%)
Thrust	0	0	0	0	0	0	0	0	0	0	0 (0%)	0 (0%)
Odd	1	0	4	1	7	0	14	0	0	0	26 (14%)	1 (1%)
Unknown	0	0	0	3	0	12	0	4	0	0	0 (0%)	19 (27%)
Total	5	0	37	11	51	34	83	25	15	0	191	70
	(3%)	(0%)	(19%)	(16%)	(27%)	(49%)	(43%)	(36%)	(8%)	(0%)		

Sites have been classified in terms of the categories proposed by Boore et al. (1993), i.e.: very soft soil $V_{s,30} \leq 180$ m/s, soft soil $180 < V_{s,30} \leq 360$ m/s, stiff soil $360 < V_{s,30} \leq 750$ m/s and rock $V_{s,30} > 750$ m/s.

Table 4: Corrective factors applied to adjust non-rock accelerations (PGA or SA) to approximate rock accelerations (from Ambraseys et al. (2005)). The factor in *italics* was found not to be statistically significant different than unity, at the 5% level, by Ambraseys et al. (2005).

Period (s)	Soft soil	Stiff soil
PGA	1.37	*1.12*
0.2	1.33	1.17
0.5	1.95	1.36
1.0	2.28	1.63

Table 5: Stochastic models considered in this study, average strain rate in the region from Kreemer et al. (2003), region type (S is subduction, SC is shallow crustal, V is volcanic and SCR is stable continental region) and the region's predominant faulting mechanism (N is normal, R is reverse and SS is strike-slip).

Study	Region	Strain rate ($\times10^{-9}$yr^{-1})	Region type	Mechanism
Sokolov et al. (2000)	Taiwan (shallow)	500	S/SC	R
Chung (2006)	SW Taiwan	500	S/SC	R
Campbell (2003)	California	200	SC	SS/R
Akinci et al. (2006)	Marmara	200	SC	SS/N
Atkinson (1995) & Atkinson (1996)	Cascadia	100	S/SC	R/SS
Akinci et al. (2001)	Erzincan	100	SC	SS
Jeon and Herrmann (2004)	Yellowstone	100	V	N
Margaris and Boore (1998) & Margaris and Hatzidimitriou (2002)	Greece	100	SC	N/SS
Malagnini et al. (2002)	North-east Italy	20	SC	R
Sokolov (1998)	Spitak, Caucasus	20	SC	R
Sokolov (1997)	Racha, Caucasus	20	SC	R
Jeon and Herrmann (2004)	Utah	20	SC	N
Scognamiglio et al. (2005)	Eastern Sicily	20	SC	N/R/SS
Malagnini and Herrmann (2000)	Umbria-Marche	10	SC	N
Malagnini et al. (2000a)	Apennines	10	SC	N
Morasca et al. (2006)	Western Alps	5	SC	R/N/SS
Malagnini et al. (2000b)	Central Europe	0	SCR	SS
Campbell (2003) (modal parameters)	Eastern North America	0	SCR	R
Bay et al. (2005)	Switzerland (Alps/foreland)	0	SCR	SS/N