Investigating possible regional dependence in strong ground motions

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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 ground motions 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 aleatory variabilities of ground motions also similar? In this brief article, some of the recent literature with relevance to these questions is summarized. It is concluded that although some regions seem to show considerable differences in shaking it is currently more defensible to use well-constrained models, possibly based on data from other regions, rather than use local, often poorly-constrained, models. In addition, it is noted that the presence of 'pseudo-regional dependency' due to differences in, for example, focal depths, average shear-wave velocity profiles or focal mechanisms can lead to apparent variations between areas when these variations could be captured in well-characterized ground-motion prediction equations.

1. Introduction

One of the main topics of debate in the recent engineering seismology literature is the question of whether strong ground motions show dependence on the region or country in which they occur or in other words 'Have strong-motion data a nationality?' Whether median earthquake ground motions and their variabilities for the same magnitude and distance show a significant dependence on the area in which they were recorded is a fundamental but still open question. Almost all parts of the world and, in particular, the Euro-Mediterranean region do not have sufficient strong-motion data from which to derive robust estimates of median ground motions based solely on instrumental data from a small geographical area. Therefore, for many projects, including the Global Earthquake Model (GEM) and Seismic Hazard Harmonization in Europe (SHARE), whether ground-motion models derived for one region can be safely transferred for the prediction of shaking in another is a pressing issue. Recent articles on this topic include Douglas (2007), on which this current paper is based, and Bommer et al. (2010).

This article presents evidence taken from the available literature from both sides of the debate. No new results are shown but it seeks to provide a summary of recent studies on this topic. Drawing conclusions either for or against regional dependency based on visual inspection of median response spectra from published ground-motion prediction equations (GMPEs) (e.g. Douglas, 2003a) should be avoided since such comparisons can often be interpreted in support of either side of the argument due to the large epistemic uncertainties associated with GMPEs. Therefore, in the following other more objective methods are preferred.

2. Pseudo-regional differences

Before beginning the review of evidence for or against regional dependency, I will discuss what I am entitling 'pseudo-regional dependency'. This refers to an apparent dependence of ground motions on region that should disappear (or become negligible) if a GMPE that is sufficiently well characterized is used to estimate shaking. This idea is discussed in more detail in Douglas (2007), where actual examples are given.

For example, in two regions the average focal depths (an important earthquake characteristic controlling shaking particularly for small events) could differ thereby leading to a difference in median ground motions if a distance metric (such as Joyner-Boore distance, r_{jb}) that does not take into account the depth of the earthquake is used. If, however, a metric, such as rupture distance (r_{rup}), is employed the variation in ground motions due to differences in depths between the two regions could be modeled. Similarly, if in one region reverse-faulting earthquakes are prevalent whilst in another normal-faulting earthquakes are most common then this could lead to a difference of 10-40% in ground motions since shaking in reverse-faulting events are generally significantly higher than those in normal or strike-slip earthquakes (e.g. Bommer et al., 2003). However, if a GMPE was used that had terms modeling style-of-faulting effects then this apparent regional dependence would disappear. As a final example, differences in the average soil profiles in one region could lead to differences in median ground motions. For example, if a GMPE used site classes based on broad ranges of average shear-wave velocities in the top 30m, V_{s30}, (e.g. the Eurocode 8 or NEHRP classifications) then if in one region rock sites were harder on average than those in another area then this could lead to overprediction of shaking but if V_{s30} was used directly this difference could be captured.

A difficulty that can complicate comparisons between ground motions, particularly of smaller events, in various regions is the requirement for a consistent magnitude scale. Douglas (2003b) notes that above roughly magnitude 5 earthquakes generally have moment magnitude (M_w) estimates reported by global or regional data centers (e.g. Global CMT or the National Earthquake Information Center) but for smaller events only local magnitudes (M_L) are available, which can be highly network dependent. For example, Scherbaum et al. (2004) list various M_L estimates for the St Dié 2003 earthquake that occurred in France close to the Swiss and German borders. The M_L estimates range from 5.4 (LED, Germany) to 5.8 (LDG, France) (whereas the M_ws reported are 4.7-4.8). Therefore, comparisons between ground motions from French or German earthquakes associated with only M_Ls from the local networks should account for a possible difference of up to, for this case, 0.4 magnitude units. Such a large difference in magnitude scales would obviously have a significant effect on predicted ground motions.

3. Previous studies

The following sections summarize evidence for and against regional dependency of ground motions. The next section deals with evidence based on physical differences between regions and those based on macroseismic intensities; the mapping of these differences to instrumental strong motion can be difficult. The subsequent section discusses evidence based on weak ground motion, which is becoming increasingly abundant with the installation of high-quality digital instruments and the consideration of combined accelerometric and broadband datasets. The final section presents evidence based on strong-motion data.

3.1 Evidence from physical reasoning or macroseismic intensities

Variations in certain physical properties of Earth's crust could be thought to lead to differences in strong ground motions, such as anelastic attenuation parameters (Q) measured by, for example, Mitchell and co-workers for many parts of the world (e.g. Baqer & Mitchell, 1998) and crustal structural velocities (e.g. Mooney et al., 1998). However, although variations in these physical properties will affect the shaking at long distances (>50km) they do not seem to significantly affect ground motions close to the source, where such estimates are vital for engineering purposes.

Similarly a number of authors have evidenced clear variations in the attenuation of macroseismic intensities in different parts of the world (e.g. Bakun & McGarr, 2002) (Figure 1). Using macroseismic intensities to examine regional differences is attractive since for many parts of the globe these are the only observations of large earthquakes currently available. Differences in observed intensities generally become greater as source-to-site distance increases and they are clearest when comparing the felt areas (i.e. intensity III) of earthquakes in various regions. However, close to the source (<100km) observed macroseismic intensities appear to be similar in different areas (e.g. Hanks & Johnston, 1992).

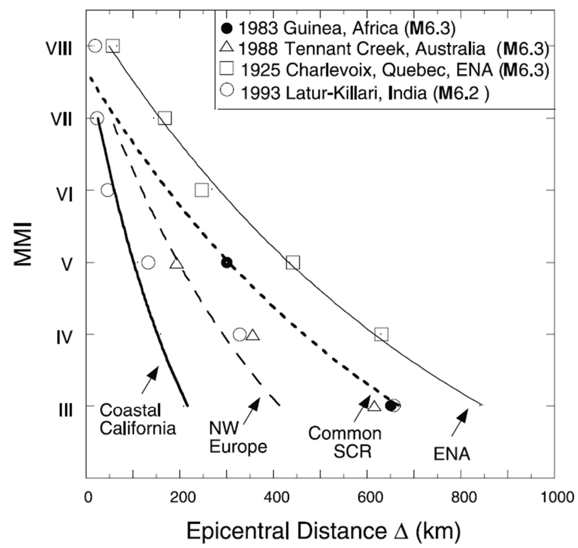

Fig. 1. Comparison between attenuation of Modified Mercalli intensity (MMI) in four different regions (from Bakun & McGarr, 2002)

3.2 Evidence from weak-motion data

One of the richest sources of evidence for regional dependence of ground motions are recent studies using weak-motion records from high-quality digital accelerometric and broadband networks that have been installed in the past couple of decades in many parts of the world. An early study is Campbell (1989) who finds that near-source peak ground accelerations (PGAs) from small earthquakes in eastern North America (ENA) are consistent with a GMPE derived using data from small events in California, once differences in site effects and magnitude scales (see earlier comments) are accounted for. This study demonstrates two important points. Firstly, the importance of reducing 'pseudo-regional differences', such as general site variations between two areas, and, secondly, comparing weak motions in one region to weak motions in another. As shown by, for example, Bommer et al. (2007) and Cotton et al. (2008) ground motions from small earthquakes scale differently with respect to magnitude and source-to-site distance in small and large events and this effect must be accounted for when examining variations between ground motions in one region and those in another.

Two studies that reach contrasting conclusions on the similarity of shaking in two different areas of Australia and ENA are those by Allen et al. (2006) who find that on average ground motions in ENA are higher than those in *south-western Western* Australia whereas Allen & Atkinson (2007) conclude that motions are similar between ENA and *south-eastern* Australia. They conclude, therefore, that it is valid to combine data from ENA and south-eastern Australia when deriving models for use in either area or stable continental regions in general.

Bommer et al. (2007) derive a set of GMPEs that are valid down to M_w 3 and examine inter- and intra-event residuals with respect to their model for four countries (Greece, Italy, Spain and Switzerland) in the M_w 3 to 5 range. They find that none of these sets of residuals shows a clear bias (Figure 2). Consequently, apparent differences in GMPEs derived using data from these regions can be related to data coverage (particularly magnitude range), choices of functional form and regression techniques and, therefore, the strongest evidence for or against regional dependency comes from using the observations directly.

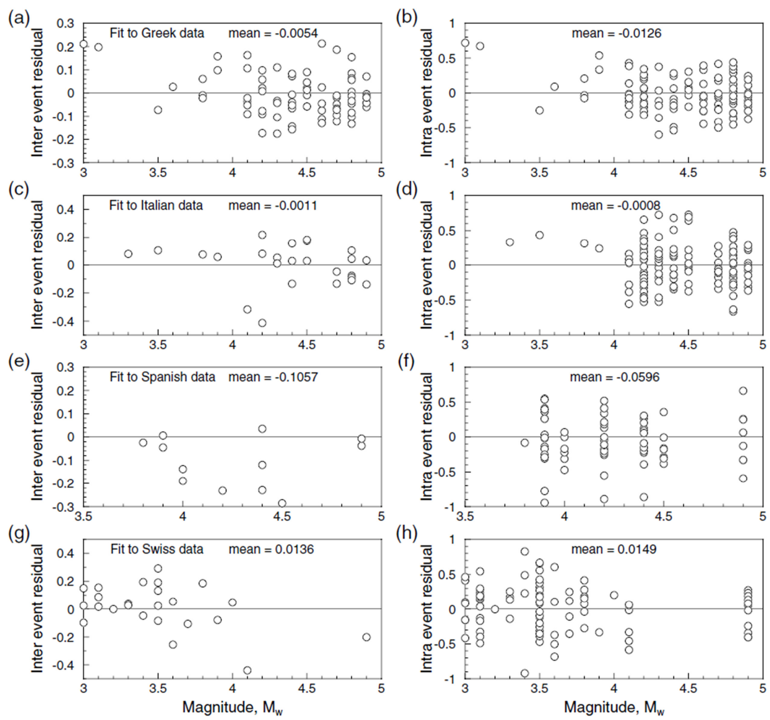

Fig. 2. Residuals with respect to the PGA GMPE of Bommer et al. (2007) for four national subsets (from Bommer et al., 2007).

Douglas (2004) developed such a technique based on analysis of variance (ANOVA) within small magnitude and distance bins that can be used to statistically test the null hypothesis of no difference between observed ground motions in two areas. This technique has been applied for different areas (see Douglas, 2007 for a summary) and some tests clearly demonstrated a difference in ground motions between regions. For example, observed shaking in Umbria-Marche and Molise (two areas of central Italy) was shown by Douglas (2007) using the ANOVA technique to be significantly different at various periods and for a number of magnitudes and distances. However, these tests are weakened by the small size of the datasets available and since the data used comes from one earthquake sequence in Umbria-Marche in 1997-1998 and one in Molise in 2002-2003 and hence it is not clear if the difference is strictly regional or whether these sequences are special cases for their areas.

An informative example of regional variation between two areas that are invariably combined when deriving GMPEs is the difference between average ground motions in small earthquakes ($M<5.5$) between southern and northern (central) California shown by Atkinson & Morrison (2009) and Chiou et al. (2009). Median ground motions from southern Californian small earthquakes are up to two times those from northern events of the same size recorded at the same distance at a wide range of periods (Figure 3), which has been related by Chiou et al. (2009) to variations in stress drop between the two areas. However, for larger earthquakes, which are the main focus of seismic hazard assessments the clear differences in ground motions between the two regions become negligible. This leads Chiou et al. (2009) to make this clear statement on the difficulty of using weak motions to examine regional dependency for strong motions (SMM is small-to-moderate magnitude range, NGA is Next Generation Attenuation, CCal is central California and SCal is southern California):

> 'Our results suggest that regional difference derived from small-to-moderate earthquake data is not an infallible indicator of regional difference expected in the moderate-to-large magnitude range of primary importance to the quantification of seismic hazard to civil structures. Differences observed in SMM range between the locally recorded data and California data should therefore be used with caution to infer NGA model applicability or to adjust NGA models for use in seismic hazard analysis. Finally, the insignificant difference in large-magnitude median motions between CCal and SCal is in agreement with the working hypothesis of NGA project, that is ground motions from moderate-to-large magnitude earthquakes in different active tectonic regions are similar.'

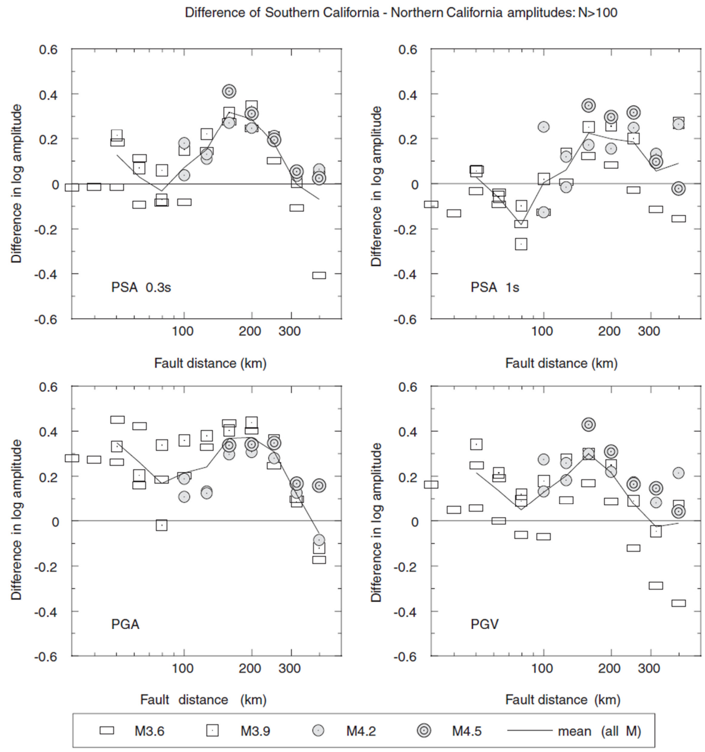

Fig. 3. Difference in log (base 10) amplitudes between southern and northern California ground motions for PGA, peak ground velocity (PGV) and pseudo-spectral accelerations (PSA) at two periods (from Atkinson & Morrison, 2009).

3.3 Evidence from strong-motion data

Two large geographical regions that have tended to develop roughly independent GMPEs are western North America (WNA) and Europe, Mediterranean and Middle East (EMME). The recent set of NGA GMPEs (e.g. Abrahamson et al., 2008) do use some data from EMME but the models are not highly dependent on these data. Stafford et al. (2008) quantitatively examine, using an extended Scherbaum et al. (2004) technique, the ability of one of the NGA models (Boore & Atkinson, 2008) to predict observed ground motions in EMME. They conclude that this model provides a good match to the observed median shaking.

In a similar, but larger scale, study Allen & Wald (2009) compute average residuals for a worldwide strong-motion dataset from shallow crustal earthquakes (containing data from most active regions with strong-motion networks) with respect to a number of recent robust GMPEs for WNA and EMME. They find that most models do a good job of predicting median ground motions and their variabilities within the magnitude-distance range of validity.

Douglas (2007) shows that aleatory variabilities (standard deviations, sigmas) of empirical GMPEs derived using data from small geographical zones are not lower, and in many cases are higher, than those associated with GMPEs derived from combining data from many parts of the globe. If ground motions show a clear regional dependency then this variation between regions should show up as larger sigmas in GMPEs derived from global datasets. Bragato (2009) calculates, using a large Italian weak-motion dataset (M_L 2.7-4.5), that regional variations in ground motions contributes only 4% to the total observed sigma.

The technique of Scherbaum et al. (2004) for quantitatively comparing observed and predicted ground motions has been applied to numerous datasets. Some of these (e.g. Hintersberger et al., 2007) have found that none of the models tested provide good predictions for some earthquakes outside their geographical zone of origin whereas others (e.g. Drouet et al., 2007) have found some GMPEs closely predict observations from completely different geographical zones. The good or poor match between observations and predictions can often be related to the magnitude and distance ranges of validity of the considered GMPEs and different average site effects between regions.

4. Discussion and conclusions

This brief article has sought to summarize some of the recent literature that has a bearing on the question of regional differences in earthquake ground motions. There are a number of recent studies showing strong evidence for differences in ground motions from small and moderate earthquakes occurring in different areas and also at long distances. However, these differences for weak motions rarely seem to carry over to shaking of engineering significance, i.e. close (<50km) to earthquakes of magnitudes greater than roughly 5. Evidence for regional dependency from weak motions does not imply regional dependency for strong motions. Due to the large and rapidly growing databanks of weak motions in many parts of the world, it is tempting to develop local GMPEs based on these data in the hope that they are more appropriate for that region than models derived for other locations. This temptation, however, should be resisted since a number of recent studies (e.g. Bommer et al., 2007; Cotton et al., 2008) have demonstrated that the extrapolation of GMPEs derived from weak-motion data are likely to significantly over-estimate ground motions in future large earthquakes. Therefore, it is more defensible to make the assumption that ground motions from large earthquakes do not show a significant regional dependency and hence adopt GMPEs that are robust at high magnitudes even if local data was not used in their derivation. In order to match observations from small events in the local area adjustments for small magnitudes like those made by Chiou et al. (2009) or Scasserra et al. (2009) could be applied.

As shown by Douglas (2010) ground-motion prediction is still affected by large, and only slowly decreasing, uncertainties even for well-instrumented areas with long histories of strong-motion observation (e.g. California). These large epistemic uncertainties caused by a lack of data and knowledge means that it is not currently possible to make firm conclusions on regional dependency of earthquake shaking. Consequently, the null hypothesis of no regional dependency cannot be rejected. In Scottish law a 'Not proven' verdict would probably be returned.

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