THE IMPORTANCE OF CRUSTAL STRUCTURE IN EXPLAINING THE OBSERVED UNCERTAINTIES IN GROUND MOTION ESTIMATION

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ABSTRACT

In this paper, the possible reduction in standard deviation of empirical ground motion estimation equations through the incorporation of crustal structure is assessed through the use of ground-motion simulations. Simulations are computed for different source-to-site distances, focal depths, focal mechanisms and for crustal models of the Pyrenees, the western Alps and the upper Rhine Graben. Through the use of the method of equivalent hypocentral distance introduced by Douglas et al. (2004) to model the effect of crustal structure in empirical equations the scatter associated with ground motion estimation equations derived using these simulated data could be reduced to zero if real-to-equivalent hypocentral distance mapping functions were derived for every combination of mechanism, depth and crustal structure present in the simulated dataset. This is, obviously, unrealistic for a practical use of the method. The relative importance of each parameter in affecting the decay of ground motions is assessed here. It is found that variation in focal depth is generally more important than the effect of crustal structure when deriving the real-to-equivalent hypocentral distance mapping functions.

***Keywords**:* *Ground motion estimation, attenuation relations, crustal structure, uncertainties, ground motion simulation.*

1. INTRODUCTION

Douglas *et al.* (2004) introduce a new distance metric, which seeks to capture in empirical ground motion estimation equations (GMEEs) the effect on the decay rate of the layered structure of the crust. The layered structure of the crust leads to a much more complex decay of ground motions with distance than is currently captured in any GMEE. Also the differences in crustal structures between regions cause correspondingly different decay rates, which could be responsible for some of the variability in observed ground motions. This variability is shown by the large aleatory uncertainties (measured by the standard deviations of the equations) associated with GMEEs, which are not significantly decreasing with time despite increasing data and complexity of analysis (e.g. Douglas, 2003). In order to test their proposed distance metric, Douglas *et al.* (2004) conducted a small test based on observed data from Umbria-Marche and south Iceland, which are areas with considerable different crustal structures and hence theoretically different decay rates. The data was combined together with and without correction for the effect of the crust and simple ground motion estimation equations were derived. Disappointingly, and surprisingly, the standard deviations of the equations derived having corrected for the different effects of the crust in the two regions were higher than those of the equations derived having neglected the different effects of the crust.

Possible reasons for this disappointing result are the following. Firstly, the crustal structure models used for the wave velocities, densities and Q values used for the two regions were not completely appropriate. It is likely that this is an important factor because there is still uncertainty in the true structure of the crust for the two examined regions, which is demonstrated by the wide dispersion in the three crustal structures for south Iceland displayed in Figure 4 of Douglas *et al.* (2004). In addition, the values of Q used for the computation of the synthetics for the two regions were taken from global relations connecting velocity and anelastic attenuation and therefore probably are not completely appropriate. The second possible reason for no reduction in the scatter of ground motions after having tried to remove the effect of the crust is that the real-to-equivalent hypocentral distance mapping functions used for the two regions by Douglas *et al.* (2004) were for a specific magnitude (M_w 5), focal depth (5 km), azimuth (22.5°) and focal mechanism (pure strike-slip) whereas the observational data they used for testing the method were from earthquakes with differing magnitudes, focal depths and focal mechanisms and from stations at different azimuths. All of these additional factors have an effect on the decay rate of ground motions, particularly the focal depth [see Figure 9 of Douglas *et al.* (2004)]. Therefore the distance mapping functions used by Douglas *et al.* (2004) were not wholly correct for all the used data. Possibly the effect of one or more of the ignored factors (magnitude, focal depth, focal mechanism or azimuth) on the decay is more important than the difference in the decay rate caused by the differing crusts in the two regions.

If real-to-equivalent hypocentral distance mapping functions were derived for all combinations of magnitude, focal depth, focal mechanism and azimuth present in the observed data sets using a highly accurate model of the crustal structure in the two regions then the scatter caused by the effect of the crust could be reduced to practically zero. Obviously computing real-to-equivalent hypocentral distance mapping functions for every combination of magnitude, focal depth, focal mechanism and azimuth is unrealistic when using the concept of equivalent hypocentral distance in practice. Hence the purpose of this paper is to assess how close one can get to this theoretical value of zero by neglecting different factors that affect the decay of ground motions (magnitude, focal mechanism, focal depth, azimuth and crustal structure).

2. SELECTED REGIONS AND CRUSTAL STRUCTURE MODELS

Three regions of metropolitan France (the Pyrenees, the upper Rhine Graben and the western Alps) were selected for study. These three regions were chosen because they are the most seismically active parts of metropolitan France and because the crusts in these three areas are considerably different from one another.

Crustal velocity structures for these three regions could be obtained from the global model CRUST5.1 (Mooney *et al.*, 1998) or its update CRUST2.0 (Laske *et al.*, 2005) or from the European model EurID (Du *et al.*, 1998). However, it was shown in Douglas *et al.* (2004) that a better fit between synthetic and observed accelerograms is obtained by using a local crustal velocity structure. Therefore in this study we only use crustal structure models that have been derived for the specific regions studied and not compiled from large scale models.

For the Alps, the crustal velocity structure model of Costa *et al.* (2003) is used. For the Pyrenees, the structure derived by Souriau and Granet (1995) is chosen. For the upper Rhine graben the recent crustal structure derived by Lopes Cardozo (2003) is used. Unfortunately, the profiles chosen for the Pyrenees and the upper Rhine Graben do not provide information on the velocities in the top few kilometres because of the type of data used for their derivations. Therefore, in order to have realistic near-surface velocities in the used structures the generic rock profiles provided by Boore and Joyner (1997) were appended to the top of adopted structures. By comparing the structure for the upper Rhine graben to the two generic profiles provided by Boore and Joyner (1997) at depths greater than 2km it was decided to append their 'generic rock site' profile (their Table 1) since this closely matches the adopted profile at common depths. Similarly by comparing the crustal structure models for the Pyrenees to the two profiles of Boore and Joyner (1997) the velocities for a 'generic very hard rock site' was found to provide a close match at common depths, therefore it was appended. These findings are consistent with the statement of Boore and Joyner (1997) that sites with their 'very hard rock site profile' are found in areas where glaciers have scoured the weathered and cracked near-surface materials; such areas are common in the Pyrenees whereas they are less common in the Rhine graben region.

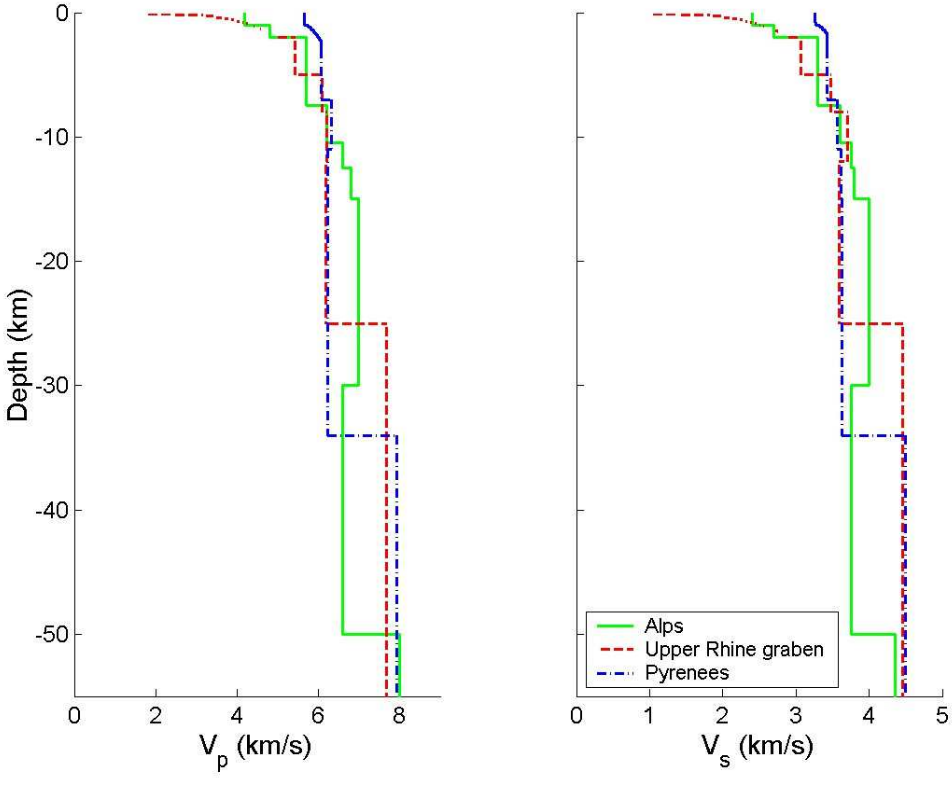

Figure 2.1: Comparison of the V_p and V_s crustal structures used for the simulations for the three regions.

The geographical distribution of the travel-paths of strong-motion recordings from the Réseau Accélérométrique Permanent (RAP) of France was examined to choose a 1D velocity that is representative of the travel paths of recordings in the three regions. Figure 2.1 compares the crustal structures used for the three regions.

Published density estimates for the chosen regions are not common. Therefore, and also because it is commonly adopted, the relation of Gardner *et al.* (1974), i.e. $\rho = 1.741V_p^{0.25}$, where V_p is P-wave velocity in km/s and ρ is density in g/cm^3, has been used here. Minor changes in the density values will not significantly affect the results.

3. GROUND MOTION SIMULATIONS

Wave propagation for the different scenarios was calculated using a finite difference scheme within an elastic volume of 34×34×25 km^3 at equally spaced points every 100m using a time step of 0.005 s. Simulations have been conducted for a point source of magnitude M_w 5.0, three focal depths (5, 10 and 15km) and two mechanisms: pure normal (λ=-90°, δ = 60°) and pure strike-slip (λ=0°, δ = 90°). Ground motions are extracted at ideally located surface stations whose azimuths from the strike of the earthquake are between 250° and 340° in steps of 15° at 11 different epicentral distances (0 km to 45 km).The mechanism-independent equations of Wells and Coppersmith (1994) estimate a subsurface fault length of 3.3km therefore, assuming a rupture velocity of 2.5 km/s, this gives a rupture duration of 1.3s, which was used as a local support of B-spline function of order 4 (degree 3) assumed as the moment source time function in all the simulations.

Because the assumed source model (point source with a simple smooth time function) does not well model the high frequency content of the motions it was decided to study the decay of peak ground velocity (PGV).

4. RESULTS

In Douglas *et al.* (2004) a new distance metric called the equivalent hypocentral distance is introduced. The true hypocentral distance is converted to the equivalent hypocentral distance that would experience the same amplitude decay as a station on a homogenous crust. For each strong-motion record in the set of records selected for analysis, a theoretical decay curve is defined through ground motion simulations for the region where the earthquake occurred. The true hypocentral distance is then mapped to the equivalent hypocentral distance and this equivalent distance is used for the regression analysis, in which the geometrical decay is constrained to 1/r. Data from regions with different crustal structures can then be combined because equivalent hypocentral distance is used, which incorporates the effect of crustal structure, rather than true hypocentral distance, which neglects these effects. The advantage of this method is that a complex form of the equation is not needed; the effect of crustal structure being handled by using a better distance metric. It removes the need to use simple functional forms to handle Moho bounce or a change to surface-wave decay because they are implicitly handled by the distance metric.

As an example of the variability in PGVs present in the simulations due to different crustal structures, focal depths, azimuths and mechanisms Figure 4.1 displays the simulated PGVs for all scenarios against distance. As can be seen the scatter in PGVs is considerable. To measure of this scatter an equation with functional form: $\log PGV=a+b\log d_h+cd_h$, where d_h is hypocentral distance, was fitted to the simulated points and the standard deviation of this equation was computed. The standard deviation computed was 0.27 corresponding to a factor of 1.86 between the median and 84 percentile ground motions, which compares well to the uncertainty associated with empirical ground motion estimation equations for PGV, e.g. the standard deviation of 0.28 associated with the PGV equation of Tromans & Bommer (2002). The simulations in this study, however, do not include the scatter due to variation in the earthquake source propagation or variation due to local site conditions, both of which contribute to the scatter in empirical GMEEs.

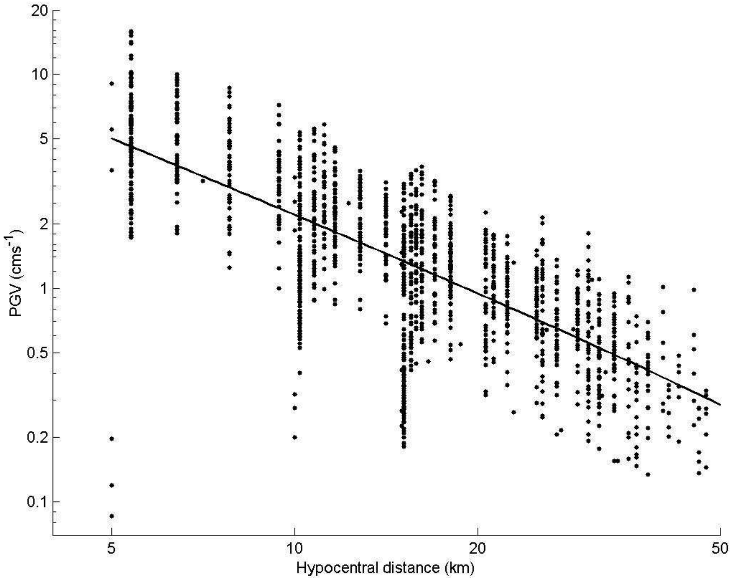

Figure 4.1: Decay of simulated PGVs for all scenarios against hypocentral distance.

In this study, equivalent hypocentral distances are calculated using a reference point of 15km so that they could be computed consistently for all three studied focal depths (5, 10 and 15km). Therefore the mapping function is: $r_{equivalent}$=15 y(15km)/y(r_{real}) where $y(x)$ is the simulated acceleration at a real hypocentral distance of x. These mapping functions were derived independently for each scenario, which makes the implicit assumption that the average ground motions at 15km for each scenario is the same and only the decay function varies with scenario. Figure 4.2 shows the computed real-to-equivalent distance mappings for the three regions for each of the three depths for normal faulting for an azimuth of 295°. The large variations in these mappings is noticeable. In particular, the three mapping functions for the same region but for different depths show large differences.

In order to assess the ability of the equivalent hypocentral distance technique to lead to a reduction in ground motion scatter due to regional crustal differences, the standard deviation of the mean real-to-equivalent hypocentral distance mapping functions for a region (i.e. neglecting focal depth) and for a focal depth (i.e. neglecting region) were computed. These standard deviations measure the importance of assuming either a single mapping function for a region (regardless of focal depth) or a single mapping function for a focal depth (regardless of region). Figure 4.3 shows these computed standard deviations with respect to real hypocentral distance. It shows that the standard deviations of the equivalent hypocentral distance mapping functions computed with respect to the three regions are, in general, higher than the standard deviations computed with respect to the three focal depths showing that focal depth within a given region is more important than regional differences in crustal structure for a given focal depth. This is thought to be due to similarities in the crustal structural models of the three regions at depths between 10 and 15km (see Figure 2.1). For shallow earthquakes (h=5km) the effect of region is more important because the three crustal models are significantly different at shallow depths.

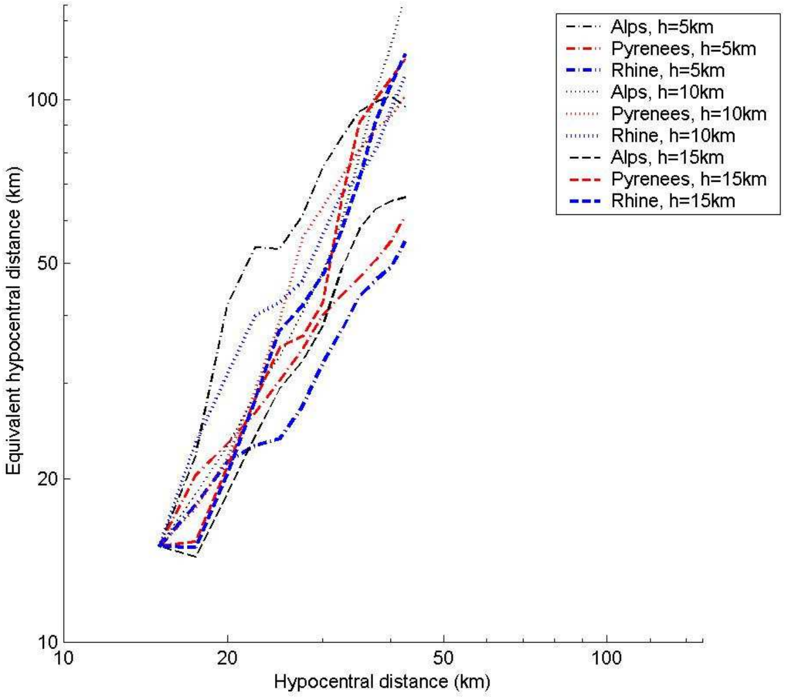

Figure 4.2: Real-to-equivalent hypocentral distance mappings for the three regions for each of the three depths for normal faulting for an azimuth of 295°.

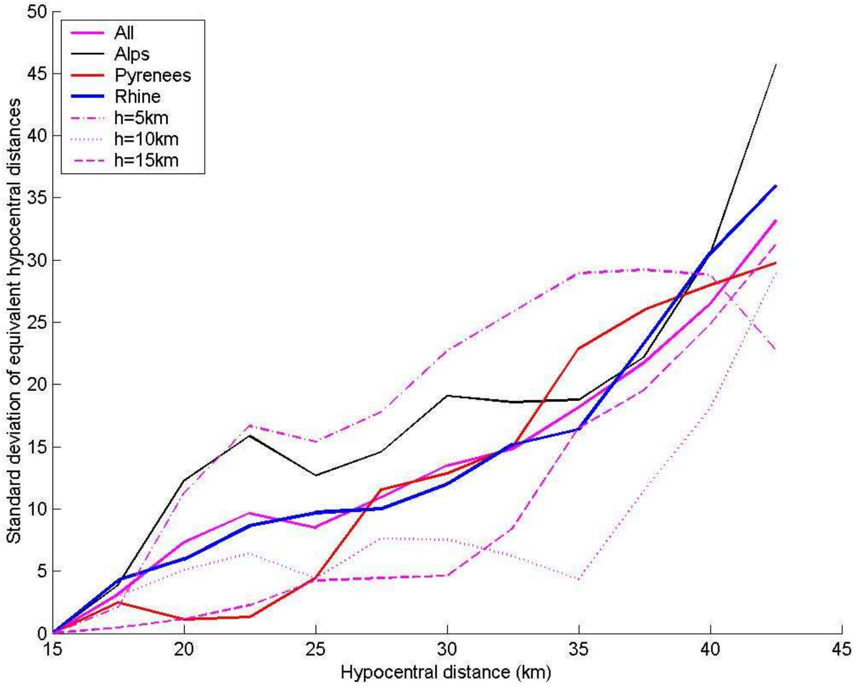

Figure 4.3: Standard deviations of the mean real-to-equivalent hypocentral distance mapping functions overall, for a region and for a focal depth with respect to distance for normal faulting.

5. DISCUSSION AND CONCLUSIONS

In this brief article, a number of ground motion simulations have been conducted in order to assess the utility of the equivalent hypocentral distance technique introduced by Douglas *et al.* (2004) to capture the possible regional dependence of ground motions caused by differences in crustal structure. For the three regions studied (the western Alps, the Pyrenees and the upper Rhine Graben) it has been found that focal depth is more important in explaining the variation in decay of the simulated ground motions than differing crustal structures. This finding needs to be verified for other regions.

If in two regions the earthquakes occur within a narrow depth range, with similar mechanisms and are recorded at similar azimuths then the differences in crust between the two regions would dominate over these confounding effects and the real-to-equivalent hypocentral distance technique should lead to a significant reduction in the scatter observed when the two sets of data are combined.

It is planned to extend this study by computing simulations for different magnitudes and focal mechanisms to assess the need to derive real-to-equivalent distance mapping functions to account for differences in decay due to these factors. It is planned to publish these further results in a journal article.

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