ATTENUATION IN ICELAND COMPARED WITH OTHER REGIONS

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SUMMARY

In this paper strong-motion models that are based on ground acceleration data measured in earthquakes from different regions in the world are compared with a ground motion model based on strong ground motion in Iceland, The purpose it to assess if there are similarities in the attenuation of ground motions in Iceland and other regions with shallow strike-slip earthquakes characteristic for Iceland. The ground motion estimation model derived from the Icelandic earthquake data is based on a point source approximation and is described in the paper. The model is applied to strong motion data from two M_w 6.5 earthquakes that occurred in June 2000 in Iceland. Peak ground acceleration (PGA) data from earthquakes with similar magnitudes from different regions are compared with the Icelandic data as well as strong motion estimation equations based on data from different region of the world. In the study the ground motion estimation relations based on data from other regions did not in general provide all that good a match with the PGA obtained from earthquakes measured in Iceland. When comparing peak ground acceleration data from earthquakes with similar magnitudes, source mechanism and crustal thickness it is observed that the data from Europe and North-America have higher PGA than observed in Iceland corresponding to a factor of approximately 1.4. This confirms earlier studies of the acceleration data from Iceland. The possible reasons for this difference are examined. The conclusion is that the difference in acceleration levels can be attributed to dissimilarities in tectonic environments and crustal structure.

1. INTRODUCTION

Through the years it has been a common practice in earthquake engineering design, for areas with none or only a few measured strong motion records, to use information gathered from other regions. The study of regional dependency of strong motion models has therefore an important practical side in addition to the purely academic aspect of acquiring basic scientific knowledge and promoting better understanding of the phenomena. In Iceland, for example, a strong motion measurement program was initiated 20 years ago [Sigbjörnsson, 1990; Sigbjörnsson, et al., 2004b]. By that time Californian strong motion measurement programs had already been in operation for several decades. Strong motion accelerograms and attenuation relations based on Californian earthquakes were therefore used in Iceland for earthquake engineering design and hazard studies. It is aim of this study to examine the feasibility of this practice as it relates to the attenuation of PGA. The main focus is on comparing the attenuation of PGA for two M_w 6.5 earthquakes that occurred on June 2000 in South Iceland with strong motion data from other regions as well as a few strong motion attenuation relations based on data from other regions that have shallow crustal earthquakes. A theoretical strong motion estimation model, based on point source approximations, has been fit to the earthquakes. The theoretical model is described in this paper. It is formulated in term of a few model parameters that have direct physical meaning and are not obtained by

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regression analysis of the PGA data but can instead be estimated from the accelerograms by applying a physical model of the source process and wave propagation [Ólafsson, and Sigbjörnsson, 1999; Ólafsson, et al., 1998].

We will begin by a brief description of the study area, Iceland, and the earthquakes that are used as a benchmark in this study, the June 2000 earthquakes in South Iceland (M_w 6.5). The theoretical ground motion model that has been fit to the Icelandic data is then described. A few empirical attenuation relations from different regions worldwide, with shallow strike slip earthquakes, are then introduced. Finally the attenuation relations are compared with PGA values from the Icelandic earthquake and the applied theoretical model.

2. THE STUDY AREA IN ICELAND

Iceland is located just south of the Arctic Circle in the middle of the North Atlantic Ocean, roughly between 63°N and 67°N latitude and 25°W to 13°W longitude. The island covers an area approximately 500 km long from West to East and almost 400 km from South to North totally equal to 103,000 km^2. Around the main island there are numerous small islands, a few of which are inhabited. The geological environment of Iceland can be characterised as volcanic, volcanic activity being the main internal process forming the landscape. The volcanic activity is rather high, with several major eruptions in the last century.

The Icelandic Strong-Motion Network was established in the early eighties [Sigbjörnsson et al., 2004b]]. Up to now it has recorded more than 300 earthquakes, some of which are noteworthy. In June 2000 the South Iceland Lowland was hit by a devastating earthquake sequence. The biggest events in this sequence were recorded on 17 June and 21 June. In the June 2000 earthquake sequence, about 80 events where recorded on the Icelandic Strong-Motion Network, resulting in about 750 ground response time series. Further information on these earthquakes can be found in [Ambraseys, et al., 2002].

3. GROUND MOTION MODEL

The theoretical model, described in the following, was first presented by the authors of this paper in [Ólafsson et al., 1999]. A description of the model can also be found in [Ólafsson et al., 1999; Ólafsson, and Sigbjörnsson, 2006; Sigbjörnsson, and Ólafsson, 2004a]. The estimation of the parameters in the models is described in [Ólafsson et al., 1998] and the use of models for stochastic simulation of ground motion is discussed in references .

The model is based on the Brune source spectra for the near- and far-field [Brune, 1970; Brune, 1971] that have been extended with an exponential term to account for anelastic attenuation. Using Parseval's theorem the rms-acceleration can be written as integrals that can be solved so they result in closed form solutions. The result is a model comprised of two equations, one for the far-field, Eq. (1), and one for the near-field, see Eqs. (3), where the form of each equation resembles a traditional attenuation relation, the main difference being that the coefficients of a traditional attenuation relation are obtained by regression analysis of the ground motion data. The coefficients of Eqs. (1) and (3) are instead physical parameters which is possible to estimate using accelerometric records. The main rationale behind this model is to obtain a model based on simple physical principles of the earthquake source process and propagation of the earthquake waves that can be used to estimate strong ground motion. The model is based on a point source approximation and has been found to give a good fit to Icelandic earthquakes, where the largest earthquakes have a magnitude of $M_w = 6.5$. The model has also been tried on ground acceleration data from larger earthquakes where the point source approximation, strictly speaking, does not apply. Even in these cases the fit has been found to be reasonably good.

In addition to consisting of two parts that model the near- and a far-field, the geometric attenuation function (represented by $\mathcal{R}$ in Eq. (1)) for the far-field model is divided into two parts (see Eq. (2)). The geometric-attenuation term is described in section 3.2. The left hand sides of Eq. (1) and (3) have the variable a_{rms} that represent RMS acceleration. In order to obtain PGA acceleration that is commonly used quantity in attenuation relations a peak factor is introduced (see Section 3.4).

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3.1 Far-field model

The theoretical attenuation relation for the far-field can be written as follows, where a_{rms} are the rms-value of the ground acceleration:

$$\log_{10}(a_{\text{rms}}) = \log_{10}\left(\frac{1}{\sqrt{\pi}}\left(\frac{7}{16}\right)^{1/3}\frac{2C_P\langle R_{\theta\phi}\rangle \Delta\sigma^{2/3}}{\beta\rho\sqrt{\kappa}}\right) + \frac{1}{2}\log_{10}\left(\frac{\Psi}{T_d}\right) + \frac{1}{3}\log_{10}(M_o) - \log_{10}(\mathcal{R}) \tag{1}$$

here T_d represent the strong motion duration, M_o represents the seismic moment, β is shear wave velocity, $R_{\theta\phi}$ is the radiation pattern, C_p is a partitioning factor ($1/\sqrt{2}$), ρ is the density of the crust, $\Delta\sigma$ is the seismic stress drop and Ψ represents a dispersion function of the variable $\lambda = \kappa\omega_c$, and can be evaluated by a closed form expression [Sigbjörnsson et al., 2004a]. The peak ground acceleration can be evaluated as $a_{\text{peak}} = pa_{\text{rms}}$ by using a peak factor p obtained by applying the theory of locally stationary Gaussian processes [Vanmarcke, and Lai, 1980].

3.2 Geometric attenuation function

The distance from source to site, $\mathcal{R}$, is modelled by the following expression

$$\mathcal{R} = \begin{cases} D_2^{1-n}\ D^n & D_1 < D \leq D_2 \\ D & D_2 < D \leq D_3 \end{cases} \tag{2}$$

here $D = \sqrt{d^2 + h^2}$, d is the epicentral distance and h is a depth parameter. In this case h should not be interpreted as a hypocentral depth but ought to be taken as a scaling factor. The parameters D_1, D_2 and D_3 are used to set the limits for the different zones of the spreading function. The parameter n is in the range 1 to 2 but is assumed to have the value 1.41 in the present study.

3.3 Near-field model

The model described in the previous section is not valid in the near-field and can, therefore, not be expected to describe the peak ground acceleration accurately close to the fault. To be able to obtain an approximation valid for shear waves in the near-fault area, it is suggested that the Brune near-field model is used. An approximation for the RMS and PGA is now obtained by applying the Parseval theorem and, then, carrying out the integration. The result is:

$$\log_{10}(a_{rms}) = \log_{10}\left(\frac{1}{\sqrt{\pi}}\frac{7}{8}\frac{C_p}{\rho\beta r^3\sqrt{\kappa_o}}\right) + \frac{1}{2}\log_{10}\left(\frac{\Psi_o}{T_o}\right) + \log_{10}(M_o) \tag{3}$$

Here, κ_o represents the spectral decay of the near-field spectra, r is radius of the fault, duration is denoted by T_o and Ψ_o is a dispersion function presented in closed form [Sigbjörnsson et al., 2004a].

3.4 Response spectra and peak factor

Similarly as for a_{rms} a closed form solution can be obtained for the response spectra. Using Parseval's theorem and the extended Brune source spectrum for the far-field, the rms response of a second order system can be represented by the following approximate expression, which holds for lightly damped systems in the far-field [Snæbjörnsson, et al., 2004]:

$$x_{rms}(t) \approx \frac{1}{\omega_o^2}\sqrt{I_F + \frac{1}{\pi T_d}|A_F(\omega_o)|^2\left(\frac{\pi\omega_o}{4\zeta} - 1\right)} \tag{4}$$

where ω_o denotes the undamped natural period, ζ is the critical damping ratio, T_o is the source duration $|A_F|$ is the far-field spectrum represented by the modified or extended Brune source spectrum [Snæbjörnsson et al., 2004] and I_F is represented by:

$$I_F = \frac{1}{\pi}\left(\frac{7}{16}\right)^{2/3}\left(\frac{C_P\, R_{\theta\phi}\, \Delta\sigma^{2/3}}{\beta\rho\, R}\right)^2 \frac{\Psi}{T_d\, \kappa} M_o^{2/3} \tag{5}$$

Similar expressions can be derived for the near field. The peak response can be obtained applying the random vibration theory as outlined by Vanmarcke and Lai [Vanmarcke et al., 1980]. Hence, introducing the peak factor, p, the response spectrum for a linear elastic sdof system can be expressed as follows:

$$S_D\left(\omega_o,\zeta\right) = \max_{t\in T} x(t) = p\cdot x_{rms}(t) \tag{6}$$

It should be noted that the peak factor will generally be a function of the duration, effective frequency and bandwidth of the system, in other words, it depends on the effective number of peaks within the time window considered. Furthermore, the peak factor depends on the probability of exceedance referred to the time window under consideration. However, in the following a median value is used for the peak factor, which is close to the most probable value, corresponding to positive zero crossings:

$$p \cong \sqrt{2\ln\left(2.8 T f_o / 2\pi\right)} \tag{7}$$

where f_o is the natural frequency of the system. A thorough treatment of the peak factor is given in [Vanmarcke, 1976].

3.5 Comparison

The model that is presented here above is fit to PGA data from two M_w 6.5 earthquakes in South-Iceland. This is demonstrated in Figure 1. The black curve shows Eq. (3) and Eq. (1) with the above mentioned geometric attenuation function, Eq. (2). This model is giving higher rate of attenuation closer than 25 km from the source than further out. The red curve represents the model with $n = 1$ giving $1/R$ geometric attenuation for all distances from the source. The black curve is in agreement with the higher rate of attenuation in the near- to intermediate-field that is more apparent in the linear scale (see Figure 1b)).
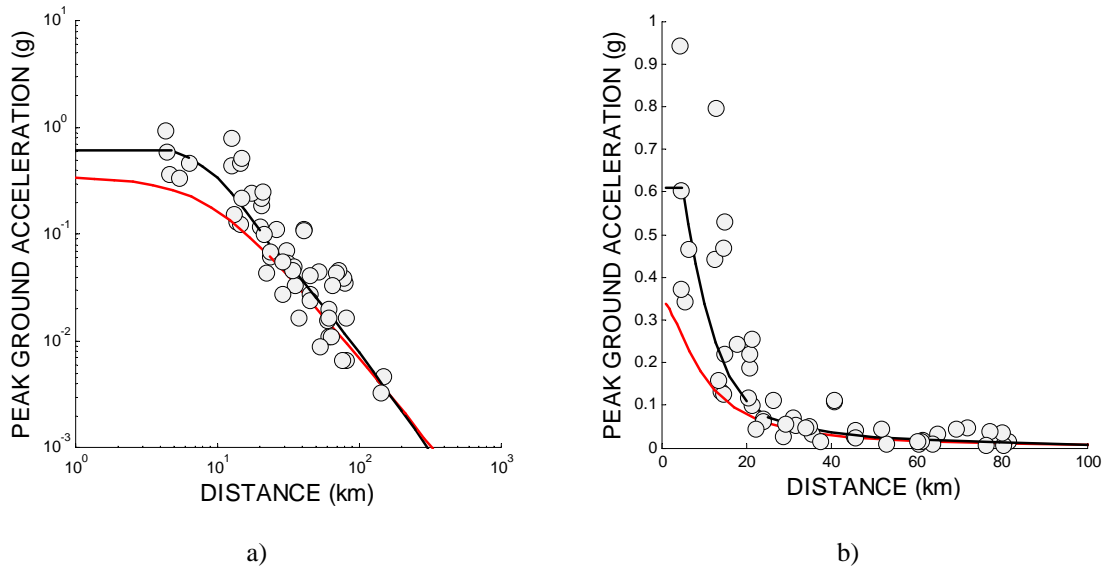
Figure 1: Model fit to PGA data from an M_w 6.5 earthquake in South-Iceland in a) log-log scale and linear scale. For black curve $n = 1.4$ and the red curve $n = 1$ for Eq. (2).

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4. GROUND MOTION MODELS FROM OTHER REGIONS

In the past three decades or so, numerous ground motion attenuation relationships have been put forward in the literature. When these attenuation relations are studied, the disagreement between them is apparent (see, for example [Douglas, 2003b] for a recent comprehensive review). These attenuation relations are in most cases similar in form, with magnitude and distance from source to site as the independent variables. Many relations have additional terms representing anelastic attenuation, depth and soil type and even directivity. The parameters are estimated by fitting the relations to the data (in most cases PGA) by means of regression analysis.

It is know that many additional factors influence the strength of the ground motion. For example the type of source mechanism is one and some models have factors that account for this. The depth of the earthquakes is also clearly a factor that affects the strength of the ground motion. Subduction earthquakes originate at greater depths than crustal earthquakes and they do produce stronger ground motions. The disagreement of models is partly due to the difference between the data sets from which the models are derived and also due to different modelling, processing and estimation techniques. Although the modelling approach is in general the same, that is fitting a parametric equation to data by means of linear- or non-linear regression, there is a multitude of functional forms that have been proposed. Preparation of the data and the regression methods can also influence the results. Some use one-stage regression approach and others two-stage. Several definitions are used for the distance of the measurement station from the source or fault. In addition various methods are used for dealing with the two horizontal components of PGA, for example the larger of two is selected or the geometrical mean is applied. The composition of the earthquakes database with respect to magnitude and distances can also affect the results. Often there is a lack of data for short distances and during the non-linear regression process the data points further away from the fault can affect the attenuation curve at short distances. Outliers can also greatly influence the regression curves and are therefore often removed from the dataset. The location of the accelerometers, i.e. whether they are located inside buildings or in free field can have an effect on the results. The after-shocks are also often grouped separately from the main-shocks as they often have lower stress drop than the main-shocks. Considering all these different factors that can influence the outcome, it is clear that a comparison of different attenuation relations can be difficult.

The PGA data from two M_w 6.5 earthquakes that occurred in June 2000 in South Iceland will be used as a benchmark in the following. The attenuation relations from other regions that will be compared to the Icelandic data will therefore have to be from shallow crustal earthquakes, have strike-slip mechanism and be recorded on stiff ground or firm sites. Four attenuation relations were selected and are mainly based on data from New Zealand, Europe and North-America. The attenuation relations are the following:

New Zealand: Expressions have been obtained for crustal and subduction zone earthquakes in New Zealand. [McVerry, et al., 2006]. High attenuation has been observed for earthquake waves that cross the volcanic zone and a term has been added to the models to account for this. The functional form of the models is similar to the models by Abrahamson and Silva [Abrahamson, and Silva, 1997].

Europe and the Middle East: Ambraseys and co-workers have derive equations based on data from Europe and the Middle East for the estimation of horizontal and vertical strong ground motion caused by shallow crustal earthquakes with $M_w > 5$ and the distance to the surface projection of the fault less than 100 km [Ambraseys, et al. 2005 A factor of 1.25 is used to lower the PGA values given by the models so they are comparable with data given by both components.

Extensional Regimes: A revised relation called SEA99 is presented by Spudich an his co-workers for horizontal ground motion derived from data in extensional regimes [Spudich, et al., 1999]. They define extensional regimes as follows: "Extensional regions are regions in which the lithosphere is expanding areally". The earthquakes in the database are mainly from North- and South-America, Europe and the Middle East. The model SEA99 is a revision of a prior model, SEA96, that was presented in [Spudich, et al., 1997].

California: These relationships are based strong motion data primarily from shallow crustal earthquakes in California. The relationship was presented in an article [Sadigh, et al., 1997] in a special issue of *Seismological Research Letters* dedicate to estimation of ground motion where several workgroups presented their attenuation equations for different regions but mainly based on data from USA. Five of these teams are expected to present new attenuation relationships for shallow crustal earthquakes in the western U.S. by the end of May 2006, as part of a project called the "Next Generation of Ground Motion Attenuation Models" or NGA project [Power, et al., 2006].

In the NGA project the PEER database has been expended and updated [PEER, 2006]. In addition to earthquakes from North-America, earthquakes from Kocaeli and Duzce events in Turkey, the 1999 Chi-Chi earthquakes in Taiwan have been added. An extensive effort has been made to provide additional supportive information (metadata) on earthquake sources, travel paths and local site conditions [Power et al., 2006].

5.   RESULTS

The ground motion model presented in Section 3 has been compared with two different datasets: (1) Icelandic strong-motion data from South Iceland earthquakes in June 2000 and (2) shallow earthquakes from Europe and North-America that are chosen according to the conditions of depth < 15 km and any magnitude in the range 6.3 to 6.7. The data from the European earthquakes are obtained from ISESD [Ambraseys et al., 2002] and the North American data is obtained from the Pacific Earthquake Engineering Research Centre strong-motion database [PEER, 2006]. The records chosen are from rock or stiff soil sites. A total of 124 records of horizontal acceleration come from these two regions. The focal mechanism for the Icelandic earthquakes is strike-slip but for the European and North-American earthquakes chosen here the mechanism is normal and oblique in addition to strike-slip (for a list of earthquakes in the dataset see [Ólafsson et al., 2006]). The data from the Icelandic earthquakes is composed of 98 horizontal components of accelerations from two earthquakes occurring on June 17th (M_S 6.6) and June 21st (M_S 6.5) 2000. The data from the earthquakes are available in the ISESD database [Ambraseys et al., 2002].

Figure 2a) shows PGA for the Icelandic strong motion data with the applied ground motion model represented by a solid curve. Figure 2b) shows PGA of the data from Europe and North-America. The triangles represent strike-slip earthquakes and the filled circles represent earthquakes with other types of source mechanisms. In the figures the solid curve represent the mean values calculated from the theoretical model and the dotted curves represent the mean values $+/-$ one standard deviation.

a)   b)
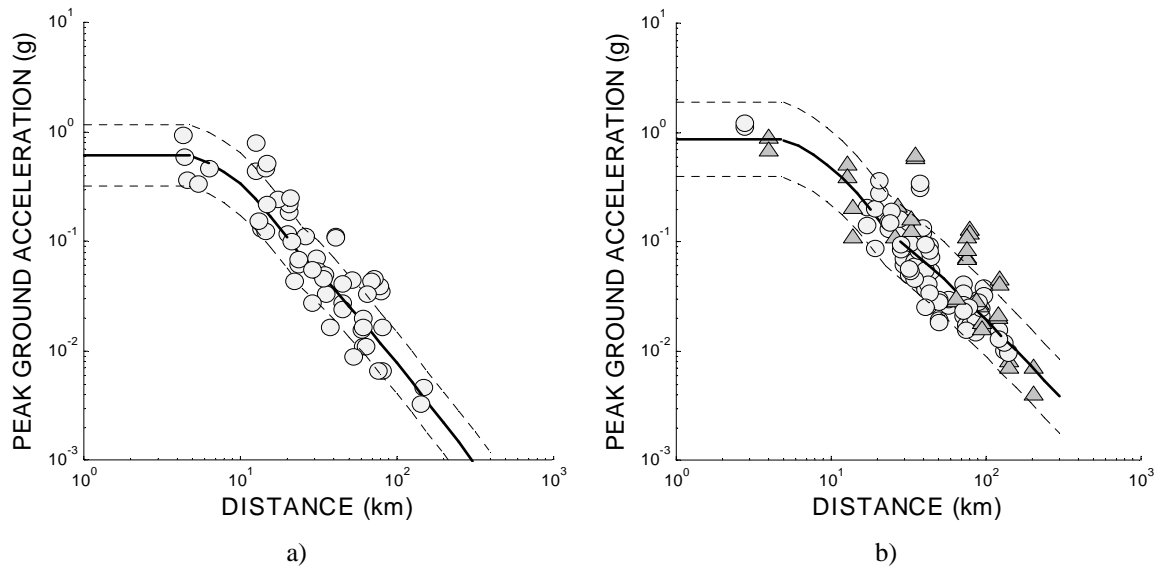
Figure 2:   **a) PGA attenuation of the June 2000 earthquakes in Iceland. b) PGA attenuation of several earthquakes from Europe and North-America with magnitudes in the range 6.3 to 6.7. Earthquakes with strike-slip source mechanism are shown as triangles and other with circles.**

The theoretical model is seen to fit the PGA data from the European and North-American region equally well as the data from the Icelandic earthquakes, as can see by comparing Figs. 1a) and 1b). The same form of the attenuation curve is seen to fit both data sets equally well. The curve for the Icelandic data is however lower by a factor 1.4 compared with the curve for the data from North-America and Europe.

In Figure 3 four ground motion models from regions outside of Iceland, presented in the previous section, were compared with the two Icelandic earthquakes that occurred in June 2000 in South-Iceland. Values of PGA are represented by dots and the solid curve represents the applied model presented in Section 3. The four relations are plotted as dashed curves in red and are as follows: a) New Zealand model [McVerry et al., 2006]. b) Europe and Middle East model [Ambraseys, et al., 2005]. c) Extensional regimes, SEA99 [Spudich et al., 1999]. d) Californian relation [Sadigh et al., 1997]. In the comparison of the attenuation relationships it was assumed that the soil types were, soft-rock or harder (with the mean shear wave velocity in the top 30 m, $v_{30} > 350$ m/s). The source mechanism is strike-slip. For the relations where the larger component is used instead of both, the results are lowered by a factor 1.25. For the relationships where the resultant PGA is a geometric mean of both horizontal components, no correction is applied [Douglas, 2003a].
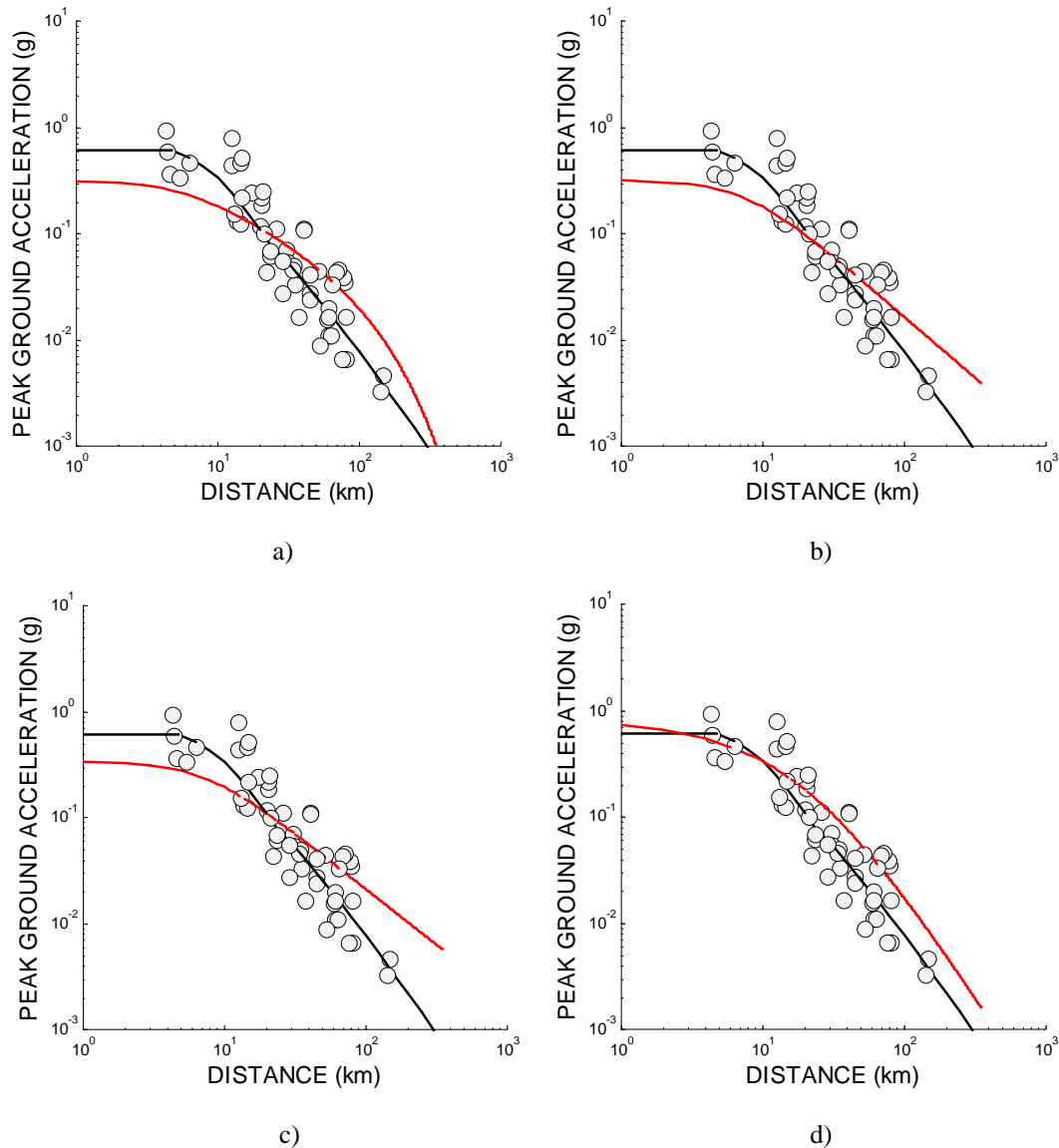
Figure 3: **Attenuation relations compared with PGA for both components of horizontal acceleration from two Icelandic earthquakes (M_w 6.5). Attenuation relations, red curves, based on data from a) New-Zealand b) Europe and Middle East (Ambraseys et al.) c) Extensional regimes (SEA99). d) Californian data.**

6. DISCUSSION AND CONCLUSIONS

By observing Fig. 3 it is obvious that most of the attenuation relations from regions outside Iceland do not give a good fit to the Icelandic strong motion data represented by the two M_w 6.5 earthquakes. The curves do not have same slope as the data, with the exception of the [Sadigh et al., 1997] relation, and do therefore not represent the rate of attenuation. The tendency is therefore to under-predict the ground motion at short distances and over-predict further away from the source. Of all 4 models, the best fit is provided by the model derived using the Californian data, see Fig. 3d). The slope of the curve for the Californian model is seen to be very similar as for the Icelandic model. In the near-field the agreement is also quite good. The PGA levels are, however, higher for the Californian model by a factor of around √2 for distances of 25 to 100 km. The shape of Californian curve, Fig. 3d), is also consistent with the data from California and Europe as seen in Fig. 3b). It is, however, surprising that the curve based on data from Europe and the Middle East, Fig. 3b), does not fit the Icelandic data better, because that model is based on some of the same data and even the Icelandic data is included in the applied dataset.

It is interesting to note from Fig.2 that PGA data from Europe and North-America has a similar rate of attenuation as the Icelandic data. The PGA is higher for the data from Europe and North-America by a factor of 1.4. Reasons for the lower acceleration levels for the Icelandic data as compared with the data from California and Europe could be lower stress drop or higher anelastic attenuation. The ground motion model derived for the Icelandic data (Section 3) shows that there is trade-off between the stress drop parameter and the spectral decay factor [Boore, et al., 1992]. Different pair of Δσ and κ can therefore give the same results. Instead of lowering the κ-values the radius could be decreased, which increased the stress drop. As has been observed in New Zealand [McVerry et al., 2006], the PGA of measured acceleration is lower for the volcanic zones than for zones with older crust. Using this rationale the young crust in South-Iceland should attenuate the seismic waves more rapidly than the older crust in California. The stress drop is a more difficult parameter to compare and although it is usually obtained from the spectra, it is a poorly defined parameter. We agree with researchers arguing that slip velocity would be a more suitable physical parameter to characterize the strength of high-frequency radiation from earthquakes [Beresnev, 2001; Beresnev, and Atkinson, 2002].

We are aware that it is difficult to compare different attenuation relations exactly, due to the various premises and assumptions that are used in deriving them. It is, nonetheless, interesting to note how different the general shape of the attenuation curves are, even for relations that are derived from similar datasets. The choice of functional forms, processing of data and applied regression techniques could weigh heavily in determining the shape of the curves

The ground motion model derived for the Icelandic data, described in Section 3, is meant to provide an approximation that would be useful for engineering purposes. This model can be used for simulation of accelerograms as well as for modelling attenuation. It is based on a point source approximation and depends on relatively few parameters and is therefore applicable for smaller and medium sized earthquakes. In spite of this it has provided surprisingly good results when applied to larger earthquakes. Models that more accurately describe the earthquake process exist. They depend on a number of parameters, some of which are not accurately known, and, therefore, it is questionable whether complex models provide good predictions of future ground motion.

Attenuation relations from other regions with shallow crustal earthquakes have been compared with strong motion data from Icelandic earthquakes (M_w 6.5) and a model that has been derived based on the data. In general these attenuation relationships, from regions outside Iceland, have not provided a good fit to Icelandic PGA data. In general the shape of the attenuation curves and rate of attenuation with respect to distance are not similar to the Icelandic attenuation curve. Furthermore, the curves tend to under-estimate the ground motion at short distance and over-estimate for larger distances. The attenuation curve based on data from shallow Californian data have similar rate of attenuation as the Icelandic model and the fit is also quite good in the near-source area. The curve, however, over-estimates the PGA by 40 percent for distances 25 to 100 km. This seems to confirm higher attenuation for strong ground motion in South-Iceland compared with ground motion from Californian earthquakes. A possible explanation for this could be that the young crust in Iceland has greater attenuation of earthquakes waves compared with the older crust in California.

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