Near-source decay of seismic waves in Iceland

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SUMMARY:
The main focus of this investigation is the ground motion in the near-field and the application of GMPE that uses a geometric spreading function that assumes an increased rate of decay close to the source. The GMPE is theoretical and is based on Brune's source model. Most of the parameters are obtained by fitting the model to the Fourier spectra of the ground motion records. Records from three earthquakes in South Iceland, (M_w = 6.5, 6.4, 6.3), are applied to obtain an estimate of the duration function that is used in the model, the rate of attenuation close to source, governed by the exponent n, and a parameter that defines how far from the source this zone of faster decay extends. The estimated value for the near-field decay exponent is found to be close to the theoretical value of n = 2 and the study confirms the neccessity of accounting for this faster rate of decay in the GMPE.

Keywords: Near-source, attenuation, gmpe, geometrical spreading function, source model

1. INTRODUCTION

The first instruments of the Icelandic Strong Motion Network were installed in South Iceland in 1985. Soon after the first strong motion data was obtained from the network and attenuation curves were plotted it became apparent that rate of attenuation seemed to be different from what was predicted by main-stream attenuation relations from other areas such as the western part of North America (Sigbjörnsson, 1990). Attenuation curves based on the Icelandic data under-predicted the ground motion at short distances and over-predicted the ground motion further away as compared to the main-stream attenuation formulas. In order to obtain a better fit to the Icelandic data a theoretical attenuation relationship was derived based on a source model (Ólafsson and Sigbjörnsson, 1999; Ólafsson, 1999; Sigbjörnsson and Ólafsson, 2004). To account for the fact that the rate of attenuation is faster in the near-field than further away a geometric spreading function was included in the model with a rate of attenuation in the near-field of R^{-2} vs. R^{-1} further away. This resulted in piecewise continuous attenuation curves that gave a better fit than the attenuation models that were most common in the literature. This better fit is especially important in the near-field region where the damage potential of the earthquake is greatest.

It is interesting to note that the theoretical model was developed based very limited data from shallow strike slip earthquakes in South Iceland, where the largest earthquake was a M_w6 earthquake in Vatnafjöll in 1987. In spite of this the model provided a good fit to the attenuation of PGA from records of horizontal acceleration in two M_w6.5 earthquakes in South Iceland earthquake in June 2000.

In this study the proposed theoretical model is applied, by means of nonlinear optimization, to the PGA values obtained in earthquakes of similar magnitude from South Iceland with magnitudes M_w = 6.5, 6.4 and 6.3. The main objective is to determine the parameters that are difficult to obtain by fitting the source model to the spectra of the ground motion records. The three parameters that we intend to determine are the rate of decay in the near field (n), the depth parameter (h) and the parameter defining the range of the near-field region (D_2). Furthermore the duration (T_d), which represents a neccessary parameter in the theoretical attenuation model, will be studied. The near-field Brune model will also be studied and examined if it can be used for constraining the model in the near-field. But first the applied theoretical model (GMPE) is presented, furthermore, it is outline how the same model can be applied to simulate ground motion with the stochastic approach.

2. STRONG MOTION DATA

The largest earthquakes in Iceland occur in two transform zones one off the shore of North Iceland and the second one in the populated area of the lowland in South Iceland and is named the South Iceland Seismic Zone (SISZ). The largest earthquakes can reach up to around magnitude 7 and have strike-slip mechanism. Closer to Reykjavík there is a volcanic zone (Western Volcanic Zone) and the Reykjanes Peninsula (RP) where the earthquakes can exceed magnitude 6. The earthquakes there may have a more complex mechanism. These seismic zones are within 100 km distance from Reykjavík and surrounding urban areas and have been extensively studied. The SISZ is a rather well defined, 70 km long and 20 km wide, and reflects the basic kinematic features referred to as bookshelf tectonics with shallow right lateral strike-slip earthquakes on near vertical faults (Einarsson, 1991).

Detailed mapping of the most noteworthy faults in the SISZ exists. Several studies have been performed in the past decades profiling the crustal structure. Historical records in Iceland regarding earthquakes and damage, dating back several centuries, have been preserved. A database of instrumental teleseismic data for the period 1896-1996 has been compiled (expanded to 2012).

The Icelandic Strong-Motion Network (ISMN) is run by the Earthquake Engineering Research Centre of the University of Iceland. Figure 1 shows the location of the strong-motion stations of the network. Strong-motion records obtained in earthquakes in Iceland by the ISMN have been included in the Internet Site for European Strong-Motion (Ambraseys et al., 2004) and can be freely downloaded.

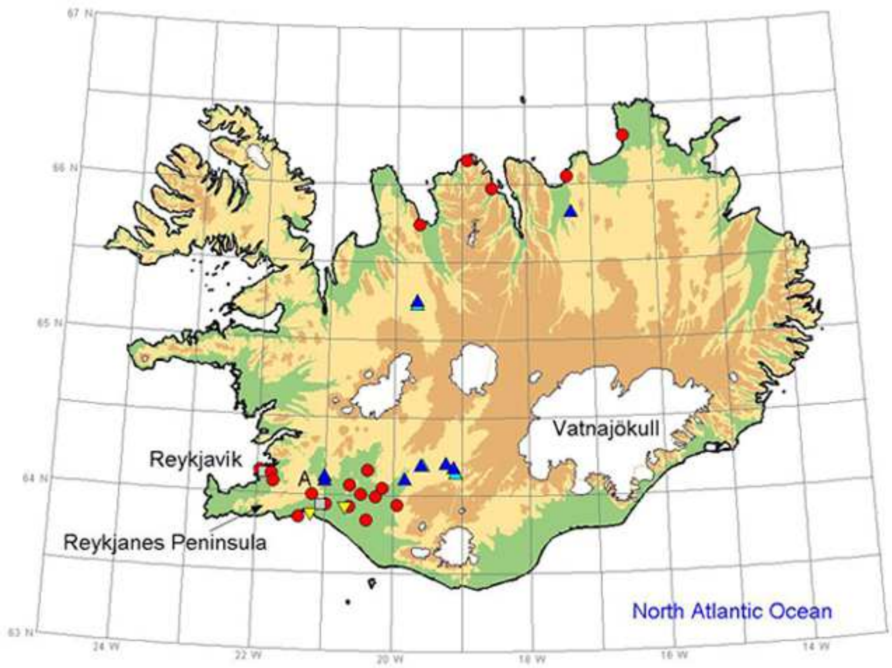


Figure 1. The Icelandic Strong-motion Network. Markers indicate: free field stations (red circles); bridges (yellow inverted triangles); buildings (grey squares); earth-fill dams (blue triangles); and power plants (aqua triangles pointing right). Topographical shading shows height above sea level: green for coastal areas at –200 m; yellow 200-600 m; and orange over 600 m. The white areas inland are glaciers.

3. THEORETICAL GROUND MOTION PREDICTION EQUATION (GMPE)

The theoretical GMPE model is based on Brune's far-field source model (Brune, 1970) and is derived by using Parsevals theorem, which equates rms-acceleration with an integral of the acceleration Fourier spectra squared. Similarly Brunes's model in the near-field is used for determining a closed form equation for the rms-acceleration in the near-field. The attenuation model or GMPE is derived based on the far-field model and the near-field model can be used to constrain the theoretical attenuation model close to the source, especially for those magnitudes where near-filed data is not available.

3.1. Far-field model

The Fourier amplitude spectrum in the far-field is given as follows, where Brune's model is extended with an exponential term to account for the spectral decay at higher frequencies:

$$\left|A(\omega)\right| = \frac{2C_P R_{\theta\phi} M_0}{4\pi\beta^3\rho R} \frac{\omega^2}{(1+(\omega/\omega_c)^2)} \exp(-\tfrac{1}{2}\kappa\omega) \tag{3.1}$$

where M_0 is the seismic moment; $R_{\theta\phi}$ is the radiation pattern; C_p is a reduction factor accounting for the partitioning of the energy into two horizontal components; R is the distance to the fault; β is the shear-wave velocity; ω_c (= $2\pi f_c$) is the corner frequency, and ρ is the material density of the crust. Furthermore, it is assumed, as an engineering approximation, that the spectral decay parameter, $\kappa = R/Q\beta$ (Q is a path-averaged quality factor), increases very slowly with distance and is near constant within a certain radius of the earthquake source. The geometrical spreading function $G(R)$ is here assumed to represent ($2C_P R_{\theta\phi} M_0 / 4\pi\beta^3\rho R$). The distance to the fault, R, can, for example, be taken to represent the hypocentral distance or the closest distance to the fault. More detailed models would take into account a faster rate of attenuation close to the fault than $1/R$.

$$\log_{10}(a_{rms}) = \log_{10}\left(\frac{(2\sqrt{7})^{2/3}}{2\sqrt{\pi}} \frac{C_P R_{\theta\varphi} \Delta\sigma^{2/3}}{\beta\rho\sqrt{\kappa}}\right) + \frac{1}{2}\log_{10}\left(\frac{\Psi}{T_d}\right) + \frac{1}{3}\log_{10}(M_o) - \log_{10}(R) \tag{3.2}$$

here T_d represents the strong-motion duration, M_0 represents the seismic moment, β is shear wave velocity, $R_{\theta\phi}$ is the radiation pattern, C_p is a partitioning factor $(2)^{-1/2}$, 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. The peak ground acceleration can be evaluated as $a_{peak} = pa_{rms}$ by using a peak factor p obtained by applying the theory of locally stationary Gaussian processes (Vanmarke and Lai, 1980). The dispersion function Ψ can be represented in closed form as:

$$\Psi = 1 - \frac{1}{2}\lambda\,\mathrm{ci}(\lambda)\left(\lambda\cos(\lambda) + 3\sin(\lambda)\right) - \frac{1}{2}\lambda\,\mathrm{si}(\lambda)\left(\lambda\sin(\lambda) - 3\cos(\lambda)\right) \tag{3.3}$$

Here, ci(•) and si(•) represent cosine and sine integrals with $\lambda = \kappa\omega_c$ where ω_c is the corner frequency of the Brune spectrum.

3.2. 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, Eqn. 3.4, is used. Hence, the near-field acceleration spectrum can be approximated as follows, accounting for the free surface and partitioning of the energy into two horizontal components:

$$\left|A(\omega)\right| = \frac{7}{8}\frac{C_p M_0}{\rho\beta r^3}\frac{\omega}{\sqrt{\omega^2 + \tau_R^{\ -2}}}\exp(-\tfrac{1}{2}\kappa_o\omega) \tag{3.4}$$

Here, κ_o is the spectral decay of the near-field spectra and τ_R is the rise time. Otherwise the same notation is used as above. An approximation for the rms and PGA is now obtained by applying the Parseval theorem and, then, carrying out the integration. The result is:

$$\log_{10}(a_{rms}) = \log_{10}\left(\frac{1}{\sqrt{\pi}}\frac{7}{8}\frac{C_p}{\rho\beta r^3\sqrt{\kappa_o}}\right) + \frac{1}{2}\log_{10}\left(\frac{\Psi_o}{T_o}\right) + \log_{10}(M_0) \tag{3.5}$$

Here, the duration is denoted by T_o, i.e. the source duration, and Ψ_o is a dispersion function given as:

$$\Psi_o = 1 - \lambda\big(\mathrm{ci}(\lambda)\sin(\lambda) - \mathrm{si}(\lambda)\cos(\lambda)\big) \tag{3.6}$$

where $\lambda = \kappa_o / \tau_R$ It is seen that the PGA predicted by this equation is independent of the epicentral distance and hence should give an estimate on the upper-bound of PGA. The rms-acceleration for the near-field can be written in terms of the seismic stress drop and is found to be directly proportional to the stress drop. That is:

$$a_{rms} = \frac{2}{\sqrt{\pi}}\frac{C_p\,\Delta\sigma}{\rho\beta\sqrt{\kappa_o}}\sqrt{\frac{\Psi_o}{T_o}} \tag{3.7}$$

This indicates that assuming constant stress drop the ground acceleration in terms of the rms value can decrease with increasing earthquake magnitude (Sigbjörnsson and Ólafsson, 2004).

3.3. Geometrical spreading function

The following expression is suggested for the geometrical spreading function (Ólafsson, 1999):

$$R = \begin{cases} D_2^{1-n}\, D^n & D_1 < D \le D_2 \\ D & D_2 < D \le D_3 \end{cases} \tag{3.8}$$

where $1 < n \le 2$ and R is a distance defined as:

$$D = \sqrt{d^2 + h^2} \tag{3.9}$$

Here, d is the epicentral distance and h is a depth parameter. The parameters D_1, D_2 and D_3 are used to set the limits for the different zones of the spreading function. The first zone can be thought of as a crude approximation for the intermediate field. Hence, the quantity D_1 can be approximated by h; D_2 quantifies the size of the zone representing the intermediate field, which is related to the magnitude of the earthquake (as represented by the seismic moment) and the thickness of the seismogenic zone; while D_3 can be thought of as the distance where cylindrical waves begin to dominate the wave field.

3.4. Duration function

A necessary component of the presented models is duration, T_d. For the near-field model the duration is the time it takes for the fault to break, that is the source duration termed T_o. Further away from the fault there is an increase in the duration with distance due to the dispersion of the seismic waves. The following simplified relationship describes this increase in the duration with respect to epicentral distance, d:

$$T_d = c_1 \frac{r}{\beta} + c_2 d^{c_3} + \sigma_T \tag{3.10}$$

Here r and c_1, c_2, c_3 are regression coefficients, σ_T is the standard deviation, r is the radius of the dislocation and β the shear wave velocity.

The first term in the relation represents the source duration and the second term represents the increasing duration with distance from source. The duration of the earthquake is very important when estimating structural damage and is a key parameter for simulation of earthquake time series.

3.5. Simulation of ground motion

The stochastic method is based on the ω-square model for the description of the spectrum of seismic source and assumes constant stress-drop following the work of Brune (1970) and Aki (1980) among others. Hanks and McGuire (1981) and Boore (1983) demonstrated that representing ground motion as a Gaussian process with power spectral density, based on Brune’s source model, produced results in good agreement with recorded ground motions. This method is especially well suited for higher frequencies where a stochastic description of the source is called for. Their models are of the following type:

$$A(\omega) = G(\mathrm{R}) \cdot B(\omega) \cdot E(\omega) \cdot S(\omega) \cdot D(\omega) \tag{3.11}$$

where $G(R)$ is the geometrical spreading function, with R being the measure of distance from source to site; $A(\omega)$ is the Fourier amplitude spectrum of ground motion; ω represents frequency; $B(\omega)$ is the ω-squared source model; $E(\omega)$ is the spectral decay function, and $S(\omega)$ represents site amplification; $D(\omega)$ is a differentiation operator ($D(\omega) = \omega^2$ if $A(\omega)$ represents acceleration). This model can be used for simulation by interpreting Eqn. 3.2 as a filter or sequence of filters. The simulated strong-motion can be obtained by using band-limited Gaussian noise as an input to the filter resulting in stationary time series. Therefore, usually an envelope function is also applied to the simulated time series to account for the change in variance with time.

The simulation with the stochastic method using Eqn. 3.10 is also possible using a discrete time version of the filter. An account of using discrete time models or recursive filters for the simulation process is presented in Ólafsson and Sigbjörnsson (2011). In Table 3.1 the discrete source model is shown. Simulated ground motion records are obtained by applying white noise as an input to the filter equations in Table 3.1.

The parameters that are not defined in Table 3.1 are $\alpha = T_S/T_c$ here $T_c = 1/f_c$ where f_c is the corner frequency and $f_c = 2.34\beta/2\pi r$, here $T_s = 1/f_s$ where f_s is the sampling frequency (f_s = 200 Hz for the accelerographs). For the soil amplification filter then r_c is the reflection coefficient and τ is the travel time in the single soil layer that the model represents. For more information on the site amplification filter see Safak (1995). In the present study it is assumed that there is no site amplification as most of the sites in South Iceland are classified as rock or stiff ground.

Table 3.1 Time and frequency domain equations for filters representing discrete ground motion model**.**

Sub-filter	Time domain	Frequency domain
$B(\omega)$	$x_1(k) = 2\mathrm{e}^{-\alpha} x_1(k-1) - \mathrm{e}^{-2\alpha} x_1(k-2) + \alpha^2 w(k)$	$\dfrac{\alpha^2}{(1-\mathrm{e}^{-\alpha} z^{-1})^2}$
$D(\omega)$	$x_2(k) = \dfrac{1}{T_S^2}(x_1(k) - 2x_1(k-1) + x_1(k-2))$	$(1-z^{-1})^2 / T_S^2$
$E(\omega)$	$x_3(k) = \dfrac{\kappa}{2\pi} \sum_{n=1}^{2N_p+1} \dfrac{z^{-n}}{(nT_S)^2 + (\kappa/2)^2} x_2(k-n)$	$\sum_{n=-\infty}^{\infty} \dfrac{\kappa}{2\pi} \dfrac{z^{-n}}{(nT_S)^2 + (\kappa/2)^2}$
$S(\omega)$	$x_4(k) = -r_c x_4(k-n) + (1+r_c) x_3(k-m)$	$\dfrac{(1+r_c) z^{-\tau/T_S}}{1+r_c z^{-2\tau/T_S}}$

4. ESTIMATION OF PARAMETERS

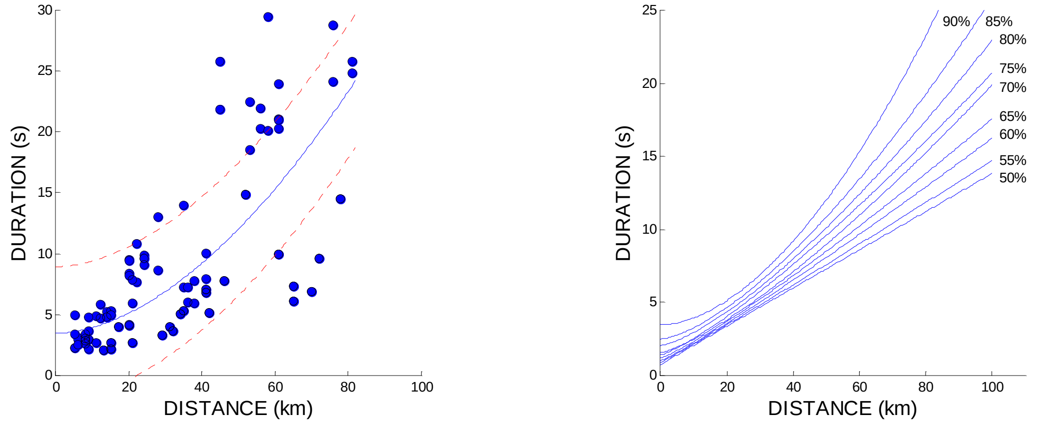
The strong-motion records from the three earthquakes in South Iceland on 17 June 2000 ($\underline{M}_w$ = 6.5), 21 June 2000 ($\underline{M}_w$ = 6.4) and on 29 May 2008 ($\underline{M}_w$ = 6.3) are used to obtain the parameters for the attenuation model. The source parameters, κ and r, for these earthquakes have been obtained before by applying the source model to the spectra of the ground motion records (see for example Ólafsson et al., 1998 and Sigbjörnsson and Ólafsson, 2004). Other parameters that characterize the area (for example β and ρ) have been obtained from studies by several research group on the tectonic structure of Iceland. The parameters for the GMPE of Eqn. 3.2 that will be estimated here are n, D_2 and h.

These parameters will be obtained by applying nonlinear optimization to fit Eqn. 3.2 to the PGA values of horizontal ground acceleration recorded in the three earthquakes. Another parameter that needs to be determined is the duration T_d and this will be done by applying the functional form of Eqn. 3.10 to the duration obtained from the ground motion records.

4.1. Estimation of duration

Duration is an important characteristic of strong motion for analysis of structures and it is also icluded in the GMPE in Eqn. 3.2. There have been several methods proposed for determining duration (see for example Trifunac, 1975 and Ólafsson, 1999). In this study duration is defined in terms of a fraction of the total cumulative energy. Trifunac and Brady (1975) for example suggested using 70% or 90% duration. For this study we computed duration for all the horizontal components from the three earthquakes that were based on different fractions of the total cumulative energy i.e. 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85% and 90%. For all the duration intervals the starting point was selected based on 5% of the total cumulative energy of the record. For example the 70% duration was selected by discarding the points of the records containing the initial 5% and last 25% of the total cumulative energy and the 90% duration by cutting the record poins contining the initial 5% and the last 5% of the total cumulative energy of the record. The duration function represented by Eqn. 3.10 was then fitted to the duration computed for all the records, based on the different fractions of the total cumulative energy. An example of fitting Eqn. 3.10 to the 90% duration computed for all the horizontal component from the records is displayed in Fig. 2a). The parameters of Eqn. 3.10 were estimated by applying non-linear optimization and are: (c_1, c_2, c_3, σ_T) = (1.8519, 0.0080, 1.7840, 5.4832). In the Fig.

2a) the blue dots represent the 90% duration of strong motion and solid curve is the mean value represented by Eqn. 3.10 and the dotted red curves are the mean value +/– one standard deviation (+/–1σ). In Fig. 2b) the mean value of the duration function of Eqn. 3.10 is plotted with parameters estimated based on the different fractions of cumulative energy (50% to 90%).



a) b)

Figure 2. a) Duration based on 90% cumulative energy with fitted Eqn. 3.10 (solid blue curve). The dotted red curve represent mean value +/– one standard deviation (+/–1σ). b) The curves represent the duration function of Eqn. 3.10 for different fractions of total cumulative energy (50%, 55%, 60%, 65%, 70%, 75%, 80%, 85% and 90%).

4.2. Estimation of parameters for the GMPE model

The parameters were estimated for GMPE that is represented by Eqn. 3.2 by fitting the equation to PGA values for the horizontal components of ground motion recorded in the three earthquakes, applying non-linear optimization. The parameters that are assumed know are the following, with the values used in the study: $\beta = 3.5$ km/s , $\rho = 2.8$ g/cm^3, $\Delta\sigma = 100$ bar, $\kappa = 0.04$ s, $r = 6.5$ km, $M_0 = 6.3\times10^{25}$ dyn cm, $C_p = (2)^{-1/2}$, $R_{\theta\phi} = 0.63$, $p = 2.94$ and T_d is duration function in Eqn. 3.10 with parameters estimated based on different fractions of the total cumulative energy. The parameters that we wanted to estimate are the following: h, D_2 and n. Where h is the depth parameter and D_2 is the parameter that defines the break in the geometrical attenuation function, assumed to be related to the radius of the dislocation i.e. $D_2 = Gr$ (where G is the quantity to be estimated). The parameter n is the exponent in the geometrical spreading function (Eqn. 3.8) and defines the rate of geometrical attenuation close to the fault. In the estimation process the three parameters h, G and n were estimated using the duration functions (in terms of different fraction of cumulative energy) estimated in the previous section (see Fig. 2b)). The results are presented in Table 4.1.

Table 4.1 Estimated values of the parameters h, G, and n applying the duration function of Eqn. 3.20 (with parameters c_1, c_2, c_3, σ_T) in terms of different fractions of the total cumulative energy. Also shown is the PGA at epicentral distance of 1 km (PGA_0).

Cumulative energy	c_1	c_1	c_3	σ_T	h (km)	G	n	σ	PGA_0 (g)
50%	0.3915	0.1325	0.9977	1.9472	15.5034	5.6848	1.9976	0.2872	0.8049
55%	0.4721	0.1130	1.0442	1.9309	15.1629	5.5282	1.9967	0.2868	0.7772
60%	0.5394	0.0926	1.1084	1.9424	15.0573	5.4360	1.9949	0.2863	0.7554
65%	0.6383	0.0767	1.1651	2.0717	14.7577	5.3421	1.9936	0.2858	0.7333
70%	0.8402	0.0446	1.3072	2.3974	14.0419	5.0856	1.9924	0.2851	0.6976
75%	0.7524	0.0642	1.2395	2.7453	14.6322	5.2775	1.9909	0.2848	0.7164
80%	1.1013	0.0371	1.3760	3.1754	13.5552	5.0906	1.9897	0.2842	0.6849
85%	1.3357	0.0255	1.4812	3.8608	13.0368	4.8847	1.9855	0.2847	0.6762
90%	1.8519	0.0080	1.7840	5.4832	12.2003	4.8697	1.9853	0.2833	0.6671

Estimated parameters h, G and n for the duration models (c_1, c_2, c_3 and σ_T also shown in Table 4.1) based on different fractions of cumulative energy are shown in Table 4.1. Estimated parameters for the GMPE with duration the function based on diffent definitions are also shown graphically in Fig. 3.

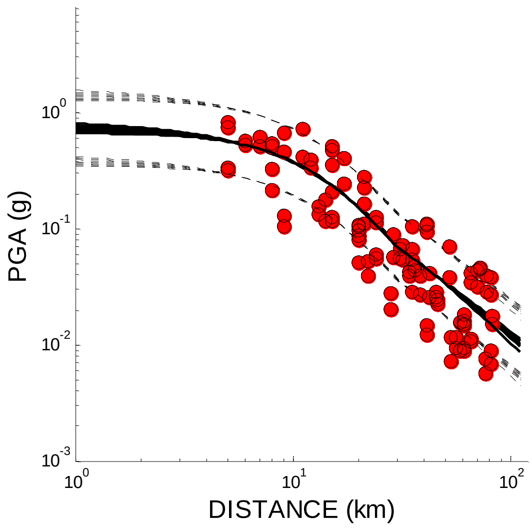


Figure 3. PGA for the horizontal components recorded in the three earthquakes (M_w = 6.5, 6.4, 6.3) with the GMPE represented by Eqn. 3.2 (solid black line representing the mean value) shown here with the duration represented by Eqn. 3.10 and several values of cumulative energy (in the range 50% to 90%). The dotted curves represent the mean value of the GMPE +/– one standard deviation.

It can be observed from Fig.3 that the variability in the results given by the GMPE is greatest at short and large distances from the fault. From Table 4.1 it can be seen that the PGA value (PGA_0) is 0.8049 for the 50% duration and is 0.6671 for the 90% duration. The variance of the estimate, σ, also becomes smaller for the higher percentage duration models. An estimate of PGA using the near-field model (Eqn. 3.7) with an estimate of source duration as $T_o = 1.5r/\beta = 2.78$ s and a rise time, $\tau_R = 0.1\ T_o$, a PGA value of 0.66 g is obtained. An estimate of T_o using the 90% duration model gives $T_o = 3.4$ s and a PGA value of 0.61g using the near-field model (Eqn. 3.7). The GMPE represented by Eqn. 3.2 and using the 90% duration is shown in Figs. 4 in a) log-log and b) linear scales plotted with the PGA obtained from the horizontal ground motion records from the three earthquakes used in the study.

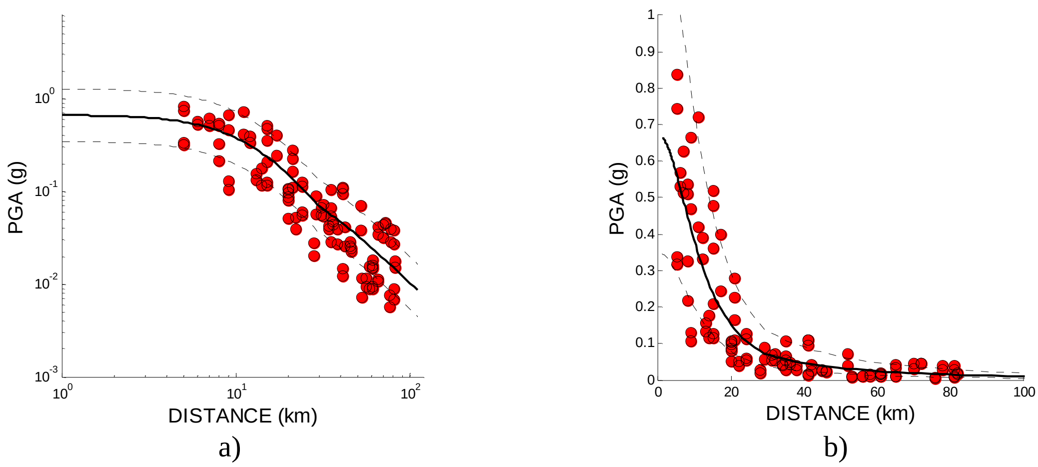


Figure 4. The GMPE represented by Eqn. 3.2, in log-log a) and linear scales b) using the 90% duration is shown here plotted with the PGA (filled red circles) obtained from the horizontal ground motion records from the three earthquakes used in the study.

It is interesting to note that estimated value of the parameter *n* obtained by non-linear optimization and is shown in Table 4.2, is very close to the theoretical value of 2 (see for example Aki, 1980) for all the applied duration models. This result shows clearly the importance of the geometrical spreading function in the GMPE representing a higher rate of attenuation in the near-field. A GMPE that assumes the same rate of attenuation close to the fault as further away will underestimate the ground motion in the near-field.

The parameter D_2 was also estimated and it is assumed here that there is a linear relationship with the radius of dislocation, that is $D_2 = Gr$. The estimates for G using the different duration models and it can be seen from Table 4.2 that $G = 5$ is a good approximation of the results. For the 90% duration model (bottom line in Table 4.1) the estimated value for D_2 is 31.2 km which is close to value of 30 km used in Sigbjörnsson and Ólafsson (2004).

Finally the depth parameter, *h*, was estimated and as can be seen from Table 4.1 it ranges from 15.5 km to 12.2 km. This is a larger value than used in prior modeling using Eqn. 3.2 (Sigbjörnsson and Ólafsson, 2004) where it was assumed that *h* represented the depth to the centroid of the dislocation.

5. CONCLUSIONS

The model parameters (h, D_2 and n) for a theoretical GMPE that has been developed for earthquakes in Iceland have been reevaluated based on ground motion records from three earthquakes in South Iceland with magnitudes $M_w \in [6.5, 6.4, 6.3]$. The strong motion duration has been calculated from the records based on a definition of a fraction of total cumulative energy contained in the records. A functional form for duration, represented by Eqn. 3.10, has been fit to the duration for different fraction of total cumulative energy in the strong motion records (ranging from 50% to 90%). The parameters (c_1, c_2, c_3, σ_T) for these different versions of the duration function are shown in Table 4.1. The GMPE model parameters have been estimated using the duration function defined in terms of different fractions of cumulative energy and are displayed in Table 4.1.

The parameter *n* defines the rate of attenuation for the geometrical spreading function which is included in the theoretical GMPE, that has been developed for Iceland, and is based on Brune's source model. This parameter has been estimated to be very close to the theoretical rate of attenuation, $n = 2$, for ground motion in the near-field (see Table 4.1). The parameter D_2 in the geometrical spreading function defines the distance from the fault where the attenuation changes from being proportional to R^{-2} to R^{-1}. The parameter was estimated as being close to $D_2 = 30$ km and assuming that D_2 is proportional to the radius of dislocation, $D_2 = Gr$, the resuls of the estimation shows that $D_2 = 5r$ is a reasonable approximation. The depth parameter, *h*, was also estimated and the estimates range from 15.5 km to 12.2 km. This is a bit surprising result because intuitively one would expect a value closer to the hypocentral depth. The three earthquakes used in this study were, however, so large that the fault reached all the way to the surface and down to the lower boundary of the upper crust or seismogenic layer.

As can be observed in Table 4.1 the standard deviation, σ, is lowest for the estimation using the 90% duration. This result and the result from the near-field model seem to favour the use of the 90% duration model for the GMPE. Hopefully the result obtained in this study can be useful for adjusting the GMPE to earthquakes in Iceland in other magnitude ranges for which limited strong motion data exists.

AKCNOWLEDGEMENTS

The operation and maintenance of the Icelandic Strong-motion Network are supported by the National Power Company, the Public Road Authorities, the City Engineer of Reykjavik, the Energy Authority and municipalities in northern and southern Iceland. The work presented herein was supported by a grant from the University of Iceland Research Fund. This study was co-financed by the EU - Civil Protection Financial Instrument, in the framework the European project "**U**rban disaster **P**revention **Strat**egies using **MA**croseismic Fields and **FA**ult Sources" (UPStrat-MAFA - Num. 230301/2011/613486/SUB/A5), DG ECHO Unit A5.

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