Assessment of Ground Motion Models: A Case Study of the Earthquake 29 May 2008 (M_w 6.3) in South Iceland

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ABSTRACT:
In this study an assessment is made of a ground motion model that has been developed for Iceland. For this purpose the focus will be on applying the model to ground motion records obtained in an earthquake that occurred on 29 May 2008 in the Olfus District in South Iceland. The earthquake struck at 15:45 UTC and has been estimated to have a moment magnitude M_w 6.3. The ground motion model is derived from a source model and its main purpose is to estimate ground motion for engineering purposes. The model has been applied to Icelandic earthquakes and parameters have been estimated from the data by means of inversion. In the current study the model is applied to the 29 May earthquake and an assessment is made of the fit to PGA data, from recorded ground motion, using estimated model parameters.

Keywords: Ground motion, source model, strong motion data, attenuation, Iceland

1. INTRODUCTION

On 29 May 2008 a damaging earthquake (M_w 6.3) occurred in South Iceland with an epicentre a few km east of the village Hveragerdi. In this paper strong-motion recordings from that event are studied by applying a strong-motion model that has been developed for earthquakes in Iceland and is based on the Brune source model.

The model has simple functional forms representing the physical processes of ground motion. The data are classified according to magnitude and site conditions. The parameters of the model are estimated for each class directly from the strong-motion records and the attenuation is studied.

In Iceland, which is in the North Atlantic on the boundary of two tectonic plates, there are two major transform zones where the largest earthquakes occur, one in North Iceland called the Tjornes Fracture Zone and one in South Iceland called the South Iceland Seismic Zone. The earthquakes in these zones can be characterised as shallow, moderate to strong, with a predominant strike-slip faulting mechanism. The fault planes of the largest earthquakes are in all cases close to vertical and the rupture typically propagates to the surface.

2. EARTHQUAKE ON 29 MAY 2008

An earthquake occurred on 29 May 2008 and originated on a fault in the western part of the South Iceland Seismic Zone in a densely populated area (see Figure 1). The earthquake struck at 15:45 UTC and was widely recorded both locally and in other parts of the world. Amongst the stations that measured the earthquake are the United States Geological Survey (USGS) and the Instituto Nazionale di Geofisica e Vulcanologia (INGV) in Italy, which both estimated the magnitude of the event as 6.3. The earthquake can be characterised as a shallow crustal earthquake on a north trending right-lateral strike-slip fault. The basic properties of this event are found to be similar to the South Iceland earthquakes in 2000 where two M_w 6.5 events occurred, the first one on 17 June and the second on 21 June (Sigbjörnsson and Ólafsson, 2004; Sigbjörnsson, Ólafsson and Snæbjörnsson, 2007; Halldórsson, Ólafsson and Sigbjörnsson, 2007). No clear evidence was found that the earthquake fault reached the surface on 29 May, in contrast to the 2000 events where there was considerable surface faulting.

The recorded acceleration in the epicentral area was high and the earthquake action on buildings may have exceeded the codified design action. The damage was widespread and significant, even though the majority of buildings withstood the high accelerations without visible damage. The damage to household articles and building contents was extensive in the near-fault region. Only 28 people suffered physical injury due to the earthquake, and fortunately there were no fatalities. Some damage to roads and bridges in the area has been observed after the earthquake. Furthermore, the water supply systems in the area were affected by the event which resulted in leakages and cloudy drinking water, at least temporarily. No interruption occurred in the supply of electricity during the earthquakes (Sigbjörnsson et al. 2009).

3. STRONG MOTION RECORDINGS

The earthquake on 29 May 2008 was the third largest earthquake to be recorded by the Icelandic Strong-motion Network (see Table 3.1). Other notable events recorded by the network are the M_w 5.9 Vatnafjöll earthquake in 1987 (Ólafsson, Sigbjörnsson and Einarsson, 1998) and the two M_w 6.5 earthquakes on 17 and 21 June 2000 (Sigbjörnsson and Ólafsson, 2004). The peak ground acceleration (PGA) recorded in the two villages close to the epicentre was high. In the town of Selfoss, towards the southeast of the epicentre, the horizontal acceleration reached 50% g. Selected recordings from this event are available through the ISESD database at the website http://www.isesd.hi.is.

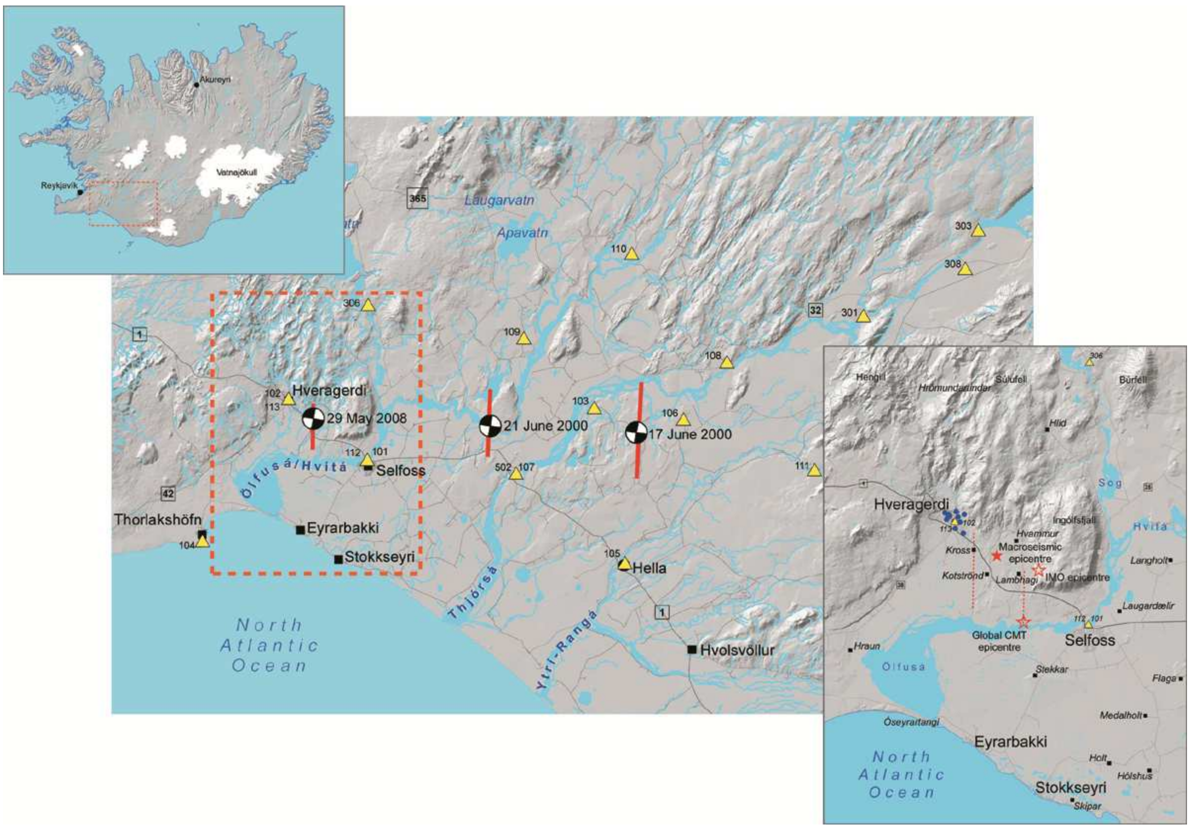


Figure 1. Fault lines of the three most recent damaging earthquakes in South Iceland. They are, from east to west, 17 June 2000 (M_w 6.5), 21 June 2000 (M_w 6.5) and 29 May 2008 (M_w 6.3).

In the village of Hveragerdi, towards the north-northwest of the epicentre, the horizontal and the corresponding vertical acceleration reached 85% g in some locations. In the vicinity of the epicentre there was an indication that the vertical acceleration had exceeded 100% g. In Hveragerdi the newly installed ICEARRAY network (Halldórsson and Sigbjörnsson, 2006), which is a small-aperture array located in Hveragerdi, recorded the earthquake on several accelerometers. The ICEARRAY exhibited a pronounced long-period component that manifests as a near-fault velocity pulse. In the Reykjavik area, roughly 40 km from the epicentre, the horizontal PGA was less than 4% g. The ICEARRAY measurements are presented in (Halldorsson and Sigbjornsson, 2009).

Table 3.1. PGA of measured ground motion for the earthquake on 29 May 2008 at 15:45.

Station	**Coordinates**		**Distance** (km)	**PGA (g)**		
	°W	**°N**		**L**	**V**	**T**
Hveragerdi retirement home	21.19	64.00	2.8	0.666	0.468	0.472
Selfoss – City hall	21.00	63.94	9.1	0.538	0.266	0.334
Selfoss – Hospital	21.00	63.94	9.5	0.211	0.171	0.529
Ljosifoss - Powerplant	21.01	64.10	14.6	0.131	0.072	0.106
Thjórsárbrú	20.65	63.93	25.5	0.081	0.026	0.098
Reykjavík – Heidmörk	21.76	64.07	31.3	0.038	0.016	0.028
Reykjavík – Foldaskóli	21.79	64.13	35.0	0.013	0.009	0.015
Hella	20.39	63.84	40.7	0.047	0.019	0.043
Húsavík	17.36	66.05	286.9	0.00035	0.0005	0.00033

4. STRONG MOTION MODEL

The model is based on the Brune source spectra for the near- and far-field (Brune, 1970) 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 and one for the near-field (see Sigbjörnsson and Ólafsson. 2004).

The far-field equation can be written as follows, where a_{rms} is the rms-value of the ground acceleration:

$$\log_{10}(a_{\text{rms}}) = \log_{10}\left(\frac{1}{\sqrt{\pi}}\left(\frac{7}{16}\right)^{1/3}\frac{2\mathrm{C_P}\left\langle \mathrm{R}_{\theta\phi}\right\rangle \Delta\sigma^{2/3}}{\beta\rho\sqrt{\kappa}}\right) + \frac{1}{2}\log_{10}\left(\frac{\Psi}{T_{\text{d}}}\right) + \frac{1}{3}\log_{10}(M_{\text{o}}) - \log_{10}(R) \qquad (4.1)$$

here T_{d} represents the strong-motion duration, M_{o} represents the seismic moment, β is shear wave velocity, $\mathrm{R}_{\theta\phi}$ 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 $\lambda = \kappa\omega_{\text{c}}$, and can be evaluated by a closed form expression. 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 (Vanmarke and Lai, 1980). The dispersion function Ψ can be represented in closed form as:

$$\Psi = 1 - \frac{1}{2}\lambda\, ci(\lambda)\big(\lambda\cos(\lambda) + 3\sin(\lambda)\big) - \frac{1}{2}\lambda\, si(\lambda)\big(\lambda\sin(\lambda) - 3\cos(\lambda)\big) \qquad (4.2)$$

Here, ci(•) and si(•) represent cosine and sine integrals with $\lambda = \kappa\omega_{\text{c}}$ where ω_{c} is the corner frequency of the Brune spectrum. The geometrical spreading function is defined as follows:

$$R = \begin{cases} D_2^{1-n}\ D^n & D_1 < D \le D_2 \\ D & D_2 < D \le D_3 \end{cases} \qquad (4.3)$$

Where $D = (d^2 + h^2)^{1/2}$ and d is the epicentral distance and h is the depth parameter.

For the near-field the following model has been derived:

$$\log_{10}(a_{rms}) = \log_{10}\left(\frac{1}{\sqrt{\pi}}\frac{7}{8}\frac{C_p}{\rho\beta r^3\sqrt{\kappa_o}}\right) + \frac{1}{2}\log_{10}\left(\frac{\Psi_o}{T_o}\right) + \log_{10}(M_o) \quad (4.4)$$

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 (see Sigbjörnsson and Ólafsson, 2004).

A necessary component of the models is the 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:

$$T_d = 1.5\frac{r}{\beta} + \left(\frac{d}{12}\right)^2 \quad (4.5)$$

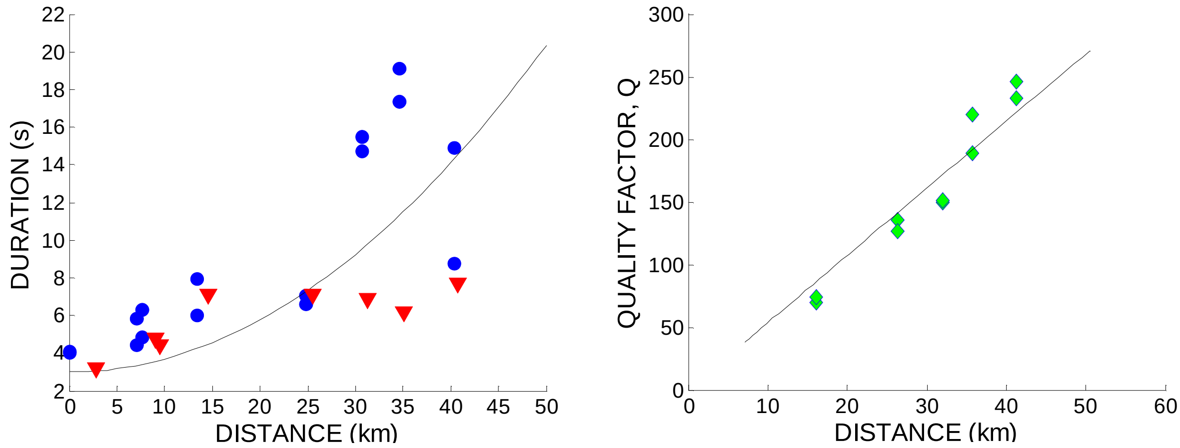
The first term in the relation represents the source duration and the second term represents the increasing duration with distance from source. The duration of the earthquake is very important when estimating damage and is a key parameter for simulation of earthquake time series.

The ground motion model described in this section has the advantage, with respect to the more commonly used regression equations, of using relatively few physically intuitive parameters that can be estimated from the acceleration time series. The model has been applied to Icelandic earthquakes with good results (Ólafsson and Sigbjörnsson, 1999; Sigbjörnsson and Ólafsson, 2004) which are predominantly shallow with a strike-slip source mechanism. It is based on a point source approximation and depends on relatively few parameters and is therefore applicable for minor to moderate sized earthquakes. In spite of this it has provided surprisingly good results when applied to larger earthquakes. In the current model the site effects are disregarded and the ground motion is estimated for stiff or rock sites. Another advantage with this model is that it can be used for generating ground acceleration time sequences using the stochastic method (Boore, 1983).

5. ESTIMATION OF PARAMETERS

The parameters of the model in Eqn. 4.1 were estimated by fitting the model to the dataset in Table 3.1. Two methods are applied to estimate the parameters. The first one involves estimating the parameters by fitting Brune's displacement spectrum to the displacement spectra computed from ground acceleration records obtained in the earthquakes. The second method consists of using the spectral moment to obtain the corner frequency and seismic moment (Andrews, 1986; Ólafsson, 1999). In this study the results using the second method are presented, as it tends to give more stable results. In Table 5.1 the average values of the parameters are shown. The parameters were only computed for five of nine stations, leaving out three of the closest stations and also the most distant station.

The S-wave time window used for estimating the parameters was selected by visual inspection of the acceleration records. For simulating a time series the duration can be selected based on a certain fraction of the cumulative energy of the record. In Figure 2(a) the source duration is shown as triangles, the duration representing 95% of the cumulative energy is shown as dots and the solid curve represents the duration model of Eqn. 4.5.



(a) (b)

Figure 2 (a) Duration of the earthquake with respect to time. The red triangles represent source duration (S-wave windows), the solid blue circles represent the 95% duration and the solid curve represents the duration model in Eqn. 4.5. (b) Quality factor Q with respect to distance. The Q factors for each record are represented by green diamonds and the line indicates a linear regression model applied to the measurements.

The quality factor Q is assumed constant in the frequency range of 2 to 25 Hz. The acceleration spectra are dominated by the exponential term $e^{-\omega R/2Q\beta}$ at high frequencies. The Q values can be estimated by fitting a linear model ($-\omega R/2Q\beta$) to the acceleration spectra between 2 and 25 Hz. Figure 2(b) shows the estimated Q as a function of epicentral distance. As a first order approximation a relationship between the Q and hypocentral distance R can be considered linear. By means of linear regression the value for κ = 0.05 s is obtained.

The parameters f_c and M_o were estimated using spectral moments, as mentioned above (see Andrews 1986; Ólafsson 1999). The values used in the estimation were β = 3.5 km/s, ρ = 2.8, h = 7 km, n = 2 and D_2 = 25 km (note that using Eqn. 4.1, cm are used instead of km and M_o in units of dyne cm to obtain PGA in cm/s^2). Geographic coordinates of the earthquakes epicentre are approximated as: 21.16 °W and 63.98 °N. The average values of the parameters, M_o, f_c, r, $\Delta\sigma$, u, Q and κ are shown in Table 5.1. The moment magnitude, M_w, in Table 5.1 is obtained by applying the Hanks-Kanamori (Hanks and Kanamori, 1979) relation and the average seismic moment, $M_o = 3.4\times10^{18}$ N m. The value obtained for the moment magnitude is M_w = 6.26 that can be approximated as M_w 6.3.

The value obtained for the stress drop, $\Delta\sigma$, is 73×10^4 Pa (i.e. 73 bar). This is lower than the value obtained for the earthquake in South Iceland on 17 June 2000, which was close to 100 bar. The mean value obtained for κ is 0.05 s, similar to the values obtained for the year 2000 earthquakes.

Table 5.1 Average values estimated for the 29 May 2008 earthquake.

Parameter	Units	Estimated Value
M_o	$\times10^{18}$ N m	3.4
M_w		6.26
f_c	Hz	0.24
r	km	6.4
κ	s	0.053
$\Delta\sigma$	$\times10^4$ Pa	73.0
u	cm	79.4

The closest stations were not included in the estimation of the parameters. These are the stations in Hveragerdi and two stations in Selfoss. With epicentral distances of approximately 3 km and 9 km (see Table 3.1) we considered them too close to apply the far-field approximation. The estimation of the source parameters was also computed based on the P-waves obtained from the vertical components of acceleration. The average seismic moment was similar to that estimated from the S-waves (M_o = 3.18×10^{18} N m) with M_w = 6.30. The estimate of the corner frequency, however, resulted in a larger radius (r = 7.6 km) and therefore resulted in lower values of stress drop and fault displacement ($\Delta\sigma$ = 27.8 bar and u = 38.1 cm). The dispersion in the estimates was much greater than for the S-waves but this is to be expected because the signal-to-noise ratio is considerably lower for the P-waves.

6. ASSESSMENT OF GROUND MOTION

As stated in the previous section the model parameters estimated for prior earthquakes and, in particular, the earthquakes of June 2000 in South Iceland were similar to the parameters estimated for the earthquake on 29 May 2008. The ground motion model therefore provided a good estimate of the peak ground acceleration and its attenuation for the earthquake. This can be seen in Figure 3, where the dots represent the PGA from the records measured in the earthquake on 29 May, the solid line represents the mean values of the far-field ground motion model of Eqn. 4.1 and the dashed lines represent the mean value given by the model +/– one standard deviation. The standard deviation of the difference between recorded values and the mean value is found to be 0.25. The far-field model is not applied any closer to the epicentre than a distance that is equivalent to the radius of the dislocation ($d = r$ = 6.4 km). The PGA values for shorter distances are then considered constant.

A comparison to strong motion models in other countries has been done with several of the empirical attenuation relations that have been presented in the literature. The fit to the Icelandic data has been found to be rather poor and often the acceleration levels are underestimated for short distances and overestimated for larger distances (Ólafsson and Sigbjörnsson, 2006).

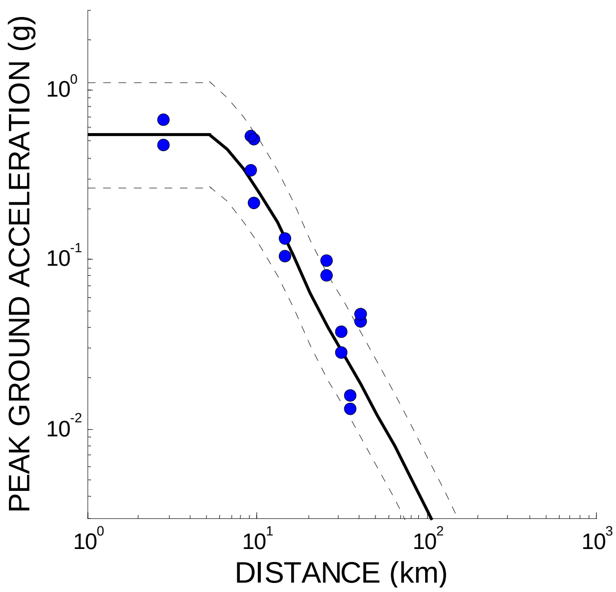


Figure 3. Horizontal peak ground acceleration as a function of epicentral distance. Each dot denotes a recorded PGA single component and the solid black curve indicates the ground estimation model presented in section 4 of this paper. The dashed lines are obtained as the solid black curve (mean values given by model) +/– one standard deviation of the difference between the recorded values and the black solid curve.

6. CONCLUSIONS

A recent earthquake in the Olfus District in South Iceland, which occurred on 29 May 2008, has been described and the strong-motion records obtained by the Icelandic Strong-motion Network. In this study the strong-motion measurements from the earthquake have been used to assess how well a strong-motion model estimates the peak ground acceleration. The main result is that the model manages to describe the data very well using parameters from prior earthquakes.

The model parameters estimated using the strong-motion measurement from the 29 May earthquake are found to be similar to the parameters obtained from prior earthquakes in South Iceland. The estimated parameters are as follows: seismic moment, $M_o = 3.4\times10^{18}$ N m; stress drop, $M_w = 6.26$, $\Delta\sigma = 73\times10^4$ Pa; fault displacement, $u = 79$ cm; radius of the fault, $r = 6.4$ km; and the spectral decay parameter, $\kappa = 0.05$ s. In the estimation process only the far-field model is applied. Applying the near-field model is still very difficult due to the lack of near-field data and physical processes in the near-field that make it challenging to model.

The main purpose of using the applied model is to develop a model that can estimate ground motion in Icelandic earthquakes for engineering purposes. The model has few parameters that are physically intuitive and can be estimated consistently using measured ground acceleration records.

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