

## Seismic hazard and recordings of strong ground motion in Iceland

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**ABSTRACT:** A recently installed network for strong motion recording is presented. Up to now recordings of 39 earthquakes have been made. Recorded accelerations are compared to predicted accelerations using known attenuation relationships. Tentative attenuation relationships for horizontal peak ground acceleration based on available Icelandic data are investigated. Earthquake response spectra based on the same data are presented. The data and the results obtained are used to assess tentatively the seismic hazard in Iceland.

### 1 INTRODUCTION

Iceland is located on the Mid-Atlantic plate boundary, which marks the border between the North American Plate and the Eurasian Plate. This boundary runs across Iceland from southwest to north, but is shifted towards east through two major fracture zones, one in the south, that is the Reykjanes and the South Iceland Seismic Zone, and another mostly outside the north coast, termed the Tjörnes Fracture Zone (Einarsson 1991).

All the major earthquakes in Iceland have occurred within these zones. Events exceeding magnitude six, which have occurred since the year 1700, are depicted in Fig.1 (Björnsson and Einarsson 1980).

It has been assessed, that the largest earthquakes

zone and in 1963 in the north zone, both of magnitude seven.

The fault plane solutions obtained for earthquakes in these zones indicate strike-slip faulting. The transform motion anticipated on the basis of plate tectonics, that is left lateral in the South Iceland Seismic Zone and right lateral in the Tjörnes Fracture Zone, is however not visible on the surface in either zone, in terms of a major fault. On the contrary the motion appears to be right lateral in the South Iceland Seismic Zone and left lateral in the Tjörnes Fracture Zone. In the South Iceland Seismic Zone this is supported by geological evidences regarding direction of surface faults as well as the north-south elongated ellipsoidal shape of the destruction zones of major historic earthquakes (Björnsson and Einarsson 1980, Einarsson 1991).

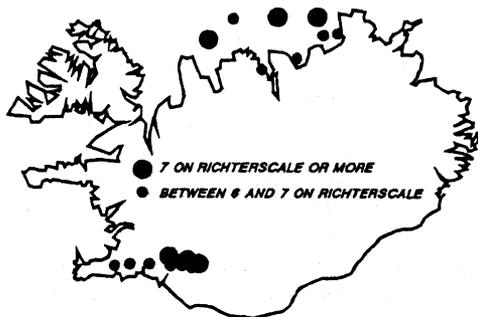


Fig.1 Major earthquakes in Iceland since the year 1700.

in Iceland exceed magnitude seven. The largest recorded earthquake occurred in 1912 in the south

### 2 STRONG MOTION NETWORK

Even though the earthquake history of Iceland contains documentations of destructive earthquakes (Björnsson and Einarsson 1980, Sólnes 1988), no strong motion recordings are available from such events. In order to obtain strong motion data, a measurement program was set up in 1984. It was based on a small scale network initiated by professor J. Sólnes and run by the Engineering Research Institute of the University of Iceland.

The main objective of this program was to establish earthquake engineering data required for rational structural design and risk management. At present the strong motion network consists of 28 ground response stations (3 channels each) including ground

channels of structural systems (for instance power houses), 2 earthfill dams (24 channels), 2 power houses (32 channels), 1 office building (8 channels) and 1 bridge (8 channels). In most cases the sensors are located inside buildings or rural houses. This is considered necessary due to severe climatic conditions, even though the buildings may affect the recordings made. The network runs with a high degree of automatization using digital instruments, with the exception of five instruments recording on film.

The locations of the stations are shown on Fig.2. They are distributed within the aforementioned seismic zones (see Fig.1) as well as the most densely populated areas.



Fig.2 Location of strong motion recording stations operated by the Engineering Research Institute of the University of Iceland.

### 3 RECORDINGS

Up to now, recordings of 25 earthquakes have been made by the network, in which the recorded acceleration of ground response channels has exceeded 0.4 per cent of  $g$  ( $g$  being the acceleration of gravity). In these quakes a total of 138 time series have been recorded. This includes both ground response channels and structural response channels.

The most significant event recorded so far is the Vatnafjöll Earthquake, which occurred on May 25th 1987 (Sigbjörnsson et al. 1987). The magnitudes of this quake have been estimated as 5.8 ( $m_b$ ), 5.8 ( $M_s$ ) and 5.9 ( $M_w$ ) and the seismic moment equal to  $9 \cdot 10^{24}$  dyn cm. The epicentre was on  $63.91^\circ$  North and  $19.78^\circ$  West, and the hypocentre depth was approximately 11 km. For further details a reference is made to Bjarnason and Einarsson (1991). As a sample of recordings from this quake, Fig.3 displays acceleration time series from a station with approximately 25 km epicentre distance. On Fig.4 response spectra calculated from recordings at four different stations are shown. The response spectra are normalized to peak ground acceleration of 10 per cent of  $g$ .

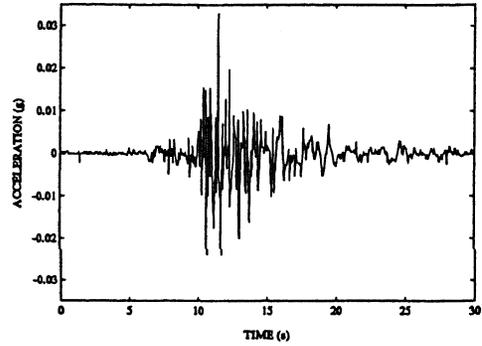


Fig.3 A sample of recorded acceleration from the Vatnafjöll Earthquake on May 25th 1987.

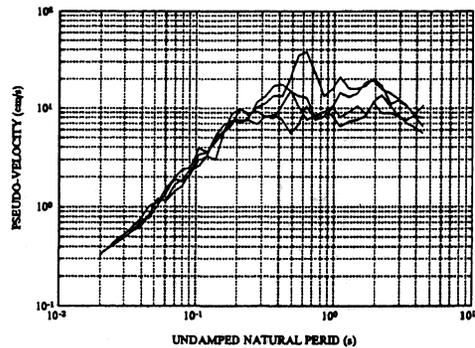


Fig.4 Normalized pseudo-velocity response spectra computed from recordings of the Vatnafjöll Earthquake at four different locations.

The highest ground channel acceleration recorded up to now is 12 per cent of  $g$  on April 23rd 1991 induced by a 4.3 magnitude earthquake at a station with 4.5 km epicentre distance. On the other hand, the highest structural response acceleration recorded so far is 14.8 per cent of  $g$  on March 19th 1990 at the top floor of a 14 story office building in Reykjavik. The corresponding ground channel acceleration of 3.2 per cent of  $g$  indicates a magnification factor on the order of 4.6 for this building. This was due to a 4.7 magnitude earthquake with 20 km epicentre distance.

In addition to these aforementioned data, recordings of response triggered acceleration, a total of 124 time series, have been made. Currently our database contains 262 time series recorded in 39 earthquakes over the last seven years.

#### 4 ATTENUATION

The basis for hazard and risk assessment is the attenuation of strong motion quantities and their relation to relevant earthquake and propagation variables. Herein the strong motion quantities chosen for investigation are peak ground acceleration and linear earthquake response spectrum, represented by pseudo-acceleration. In both cases the following simplified model is applied (Joyner and Boore 1981, Ambraseys and Bommer 1991, Sigbjörnsson 1990):

$$\log A = \alpha + \beta M - \log R + bR + \sigma P \quad (1)$$

Here,  $A$  denotes the strong motion quantity;  $M$  is the magnitude of the earthquake;  $R = \sqrt{(d^2 + h^2)}$ , where  $d$  is the shortest distance to the surface projection of causative fault and  $h$  is a depth parameter.  $\alpha$ ,  $\beta$  and  $d$  are parameters to be determined;  $\sigma$  is the standard error of  $\log A$  and  $P$  is a suitable fractile in the standardized normal distribution ( $P = 0$  for the mean value).

The available Icelandic data described in section 3 have been compared to attenuation formulas of this type reported in the literature. Fig.5 shows such a comparison to the Joyner-Boore formula (1981) using the only earthquake of magnitude 5 or greater. Further, in Fig.6 the data from earthquakes of magnitude 4 or greater are compared to the Ambraseys-Bommer formula (1991) where  $h = 6$  km. Similar results are obtained for the Ambraseys-Bommer formula (1991) where  $h$  is the focal (hypocentre) depth.

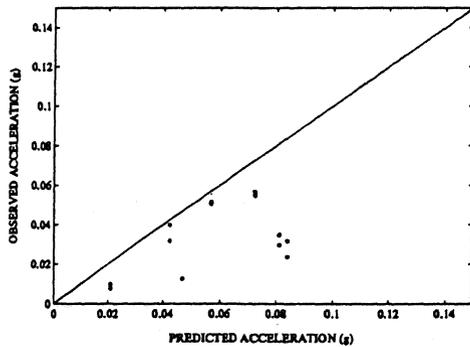


Fig.5 Comparison of observed peak horizontal accelerations in the Vatnafjöll Earthquake and that predicted by the Joyner-Boore attenuation formula.

In both cases it is seen that these formulas tend to overestimate the peak ground acceleration. The same tendency seems to be the case for other formulas (Campell 1985, Fukushima et al. 1988) tested. A

study by Halldórsson et al. (1984) on the attenuation of intensity lead to comparable results.

This indicates the necessity of developing a formula for peak ground acceleration which fits the Icelandic data. This has been attempted using a two step regression procedure similar to that of Joyner and Boore (1981) (Sigbjörnsson 1990).

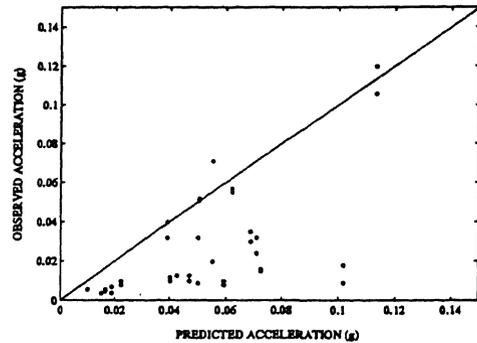


Fig.6 Comparison of observed peak horizontal accelerations in earthquakes exceeding magnitude 4 and that predicted by the Ambraseys-Bommer attenuation formula with  $h = 6.0$  km.

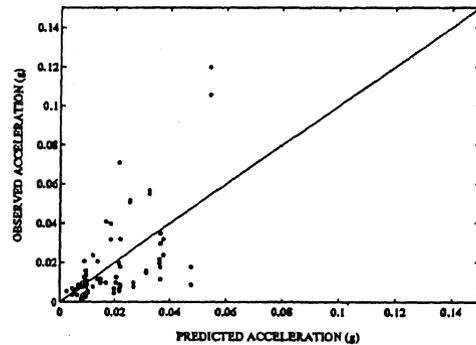


Fig.7 Comparison of observed peak horizontal accelerations and that predicted by a tentative attenuation formula based on available Icelandic data using  $h = 5.0$  km.

To make the prediction more applicable in hazard assessment only data from earthquakes of magnitude 4 or greater were used in the regression. Following Dahle et al. (1990), (see also Ambraseys and Bommer 1991) the depth parameter was taken to be the estimated hypocentre depth of the earthquakes. Further, both horizontal components were included. The results were:

$$\log(a) = -1.98 + 0.365M - \log R - 0.0039R + 0.30P$$

$$4.0 < M < 6.0 \quad (2)$$

where  $a$  denotes the average of the peak acceleration of the two horizontal components.

On Fig.7 all available Icelandic data are compared to peak horizontal acceleration predicted by Eq.(2). The curve resulting from Eq.(2) is plotted in Fig.8 along with the data used in the regression, normalized with respect to magnitude, and in Fig.9 along with all available data. It is seen that the curve fits the data reasonably well and that the small quakes, with magnitude less than 4, are in most cases below this tentative attenuation curve.

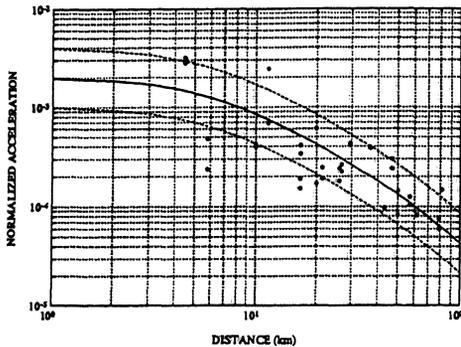


Fig.8 Normalized horizontal acceleration calculated by Eq.(2) compared to observed values from earthquakes with magnitude greater than 4.

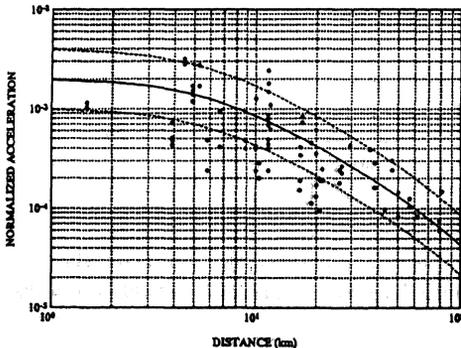


Fig.9. Normalized horizontal acceleration calculated by Eq.(2) compared to all observed values.

A similar regression was made using only the larger component of the horizontal acceleration. This was done in an attempt to derive a formula more comparable to formulas reported in the literature (Joyner and Boore 1981, Ambraseys and Bommer

1991). This lead to the following equation:

$$\log(a) = -1.72 + 0.327M - \log R - 0.0043R + 0.30P$$

$$4.0 < M < 6.0 \quad (3)$$

where  $a$  in this case refers to the larger horizontal component of the acceleration.

The resulting curve is plotted in Fig.10 along with the data used in the regression, and in Fig.11 along with all available data.

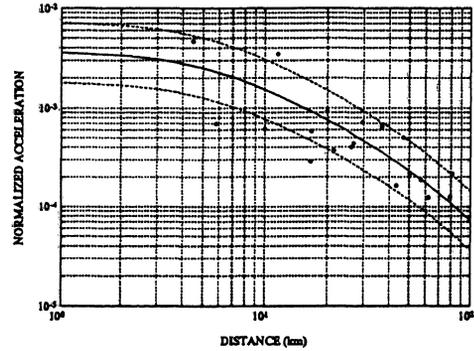


Fig.10 Normalized horizontal acceleration calculated by Eq.(3) compared to observed values of the larger horizontal component from earthquakes with magnitude greater than 4.

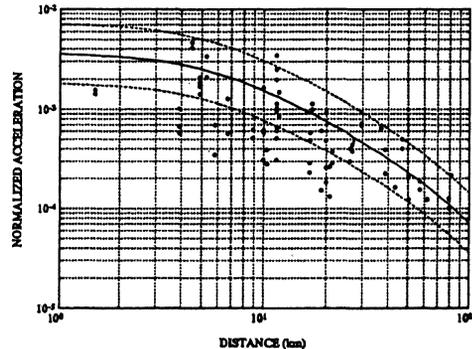


Fig.11 Normalized horizontal acceleration calculated by Eq.(3) compared to all observed values.

It is seen that the curve fits the data reasonably well and that the parameters are of the same magnitude as in the former case. Further, the anelastic attenuation parameter  $b$  is greater than reported by Joyner and Boore (1981) and Ambraseys and Bommer (1991). Also in this case (Fig.11) the data from small quakes, with magnitude less than 4, are mostly below the attenuation curve.

If the small quakes are included in the analysis the anelastic attenuation parameter tends to be positive, which does not seem realistic. The results obtained using all the data and setting  $b = 0$  were:

$$\log(A) = -2.28 + 0.386M - \log R + 0.29P$$

$$2.0 < M < 6.0 \quad (4)$$

Here  $a$  refers to both components of horizontal acceleration.

The resulting curve is plotted in Fig.12 along with all data. The histogram of the logarithm of the ratio of predicted to observed peak acceleration is plotted in Fig.13. The results in Fig.13 seem to support the normality hypothesis.

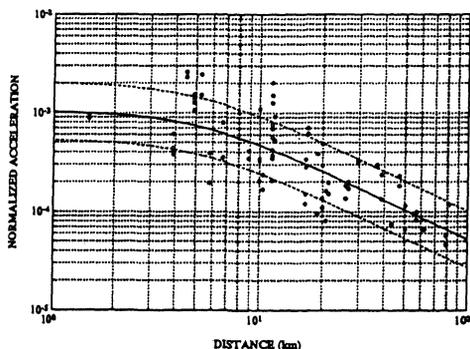


Fig.12 Normalized horizontal acceleration calculated by Eq.(4) compared to all observed values.

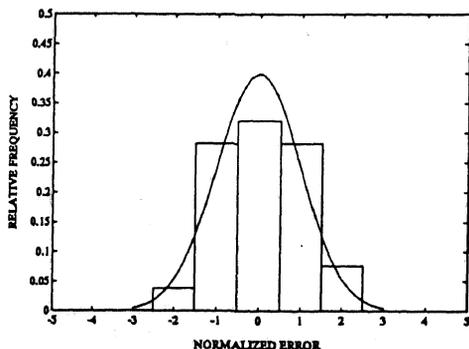


Fig.13 Histogram of the logarithm of the ratio of predicted to observed peak acceleration compared to standardized normal distribution.

The regression analysis was also performed taking the depth  $h$  as a parameter and optimizing it by minimizing  $\sigma$ . The result was similar to the results reported above.

The procedure described has also been applied to the earthquake response spectrum, which is believed to be a more suitable strong motion quantity, from the engineering point of view, than the peak ground acceleration. First the response spectra were computed for five different damping ratios using accelerograms from earthquakes of magnitude 4 or greater. Then an average response was computed from ten values for undamped natural periods in the range 0.1 to 0.4 seconds. This range of periods seems to be typical for low rise buildings and representative for the top level of the acceleration response spectra. Finally the regression parameters are obtained using Eq.(1) and a two step procedure. The results in terms of pseudo-acceleration are plotted in Fig.14 for a magnitude 6 earthquake. In this case the anelastic attenuation seems to be somewhat higher than reported in the literature (see for instance Dahle et al. 1990).

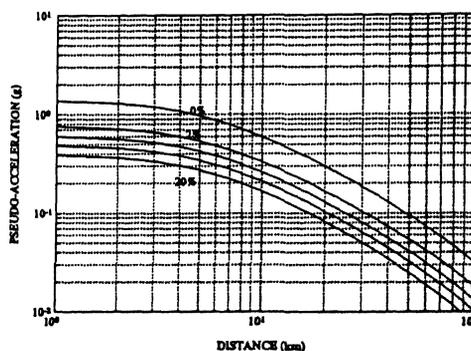


Fig.14 Predicted pseudo-acceleration response for undamped natural periods in the interval 0.1 to 0.4 seconds for a magnitude 6 earthquake, based on available Icelandic data for earthquakes of magnitude greater than 4. The damping ratios are 0, 2, 5, 10 and 20 per cent of the critical damping.

The hypocentre depth for the bigger Icelandic earthquakes is of the order of 10 km, while the hypocentre depth for the smaller ones, used in this study, are close to 5 km on the average. It is necessary to keep this in mind when comparing Eq.(2), (3) and (4) to attenuation formulas based on a fixed depth parameter. Further, it should be stressed that the data applied are limited and these formulas should therefore be treated as tentative.

## 5 ASSESSMENT OF SEISMIC HAZARD

An attempt has been made to assess the seismic hazard in Iceland (Sigbjörnsson 1990). The results

are exemplified in Fig.15, which shows a tentative contour map for horizontal peak ground acceleration (referred approximately, to 0.2 per cent yearly probability of exceedance). The map was obtained using extrapolations based on Eq.(2), with  $P = 0$ , and the shortest distance to the surface projection of causative fault. The size of the fault could, however, only be approximated roughly, by using available mapping of destruction zones (Björnsson and Einarsson 1980). It is worth stressing that the error term in Eq.(2) has significant effects on hazard predictions.



Fig.15 A tentative seismic hazard map for Iceland.

## 6 CONCLUSIONS

This study seems to indicate that the attenuation of strong ground acceleration in Iceland is somewhat higher than in the western part of USA and Europe as a whole. Further, only moderate seismic hazard is predicted for the capital region which is the most densely populated area in Iceland. Finally, it should be underlined that the available data are limited and therefore a definite conclusion has not been reached.

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