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AN OVERVIEW ON STRONG MOTION MONITORING AND RECORDINGS IN ICELAND

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ABSTRACT

The paper describes a strong motion network run by the Engineering Research Institute of the University of Iceland. The objectives of the system are stated, and the geophysical and seismological background is explained. The network comprises ground response stations as well as structural response systems in power plants, dams, bridges and buildings. The more significant recordings made by the network are outlined and the basic processing procedure discussed. An overview of the analysis, interpretation and applications of the recorded data is given. A short presentation of other earthquake monitoring systems in Iceland is also included.

KEYWORDS

Ground acceleration; Iceland; monitoring systems; strong motion; strong motion attenuation; strong motion network; strong motion recordings; structural response systems.

INTRODUCTION

Iceland is a country of moderate seismicity. On the average it is struck by two severe earthquakes, that can reach a magnitude of seven or even more, every century (Björnsson and Einarsson, 1980). These earthquakes have caused considerable damage in settled areas over the centuries. For example in this century two earthquakes, occurring in 1934 and 1976 of magnitude 6 ¼ and 6 ½ respectively, caused significant damage in two small villages on the coast of North Iceland (Thráinsson and Sigbjörnsson, 1994). Further, seismologists have predicted that there is a high probability that a major earthquake will strike the South Iceland Lowland within the next decades (Halldórsson et al. 1984). This forecast has spurred increased research within seismology and earthquake engineering, including several monitoring projects.

All major destructive earthquakes in Iceland have had epicentres within two regions, one in the South and another in the North, as indicated by the shaded areas in Fig. 1. These seismic areas may be characterised as fracture zones that are related to the shifting of the Mid-Atlantic Ridge towards east when passing Iceland. Earthquakes that have occurred outside these areas are commonly characterised as intraplate earthquakes (Einarsson, 1991). They are apparently smaller and not as frequent as earthquakes within the seismic areas mentioned.

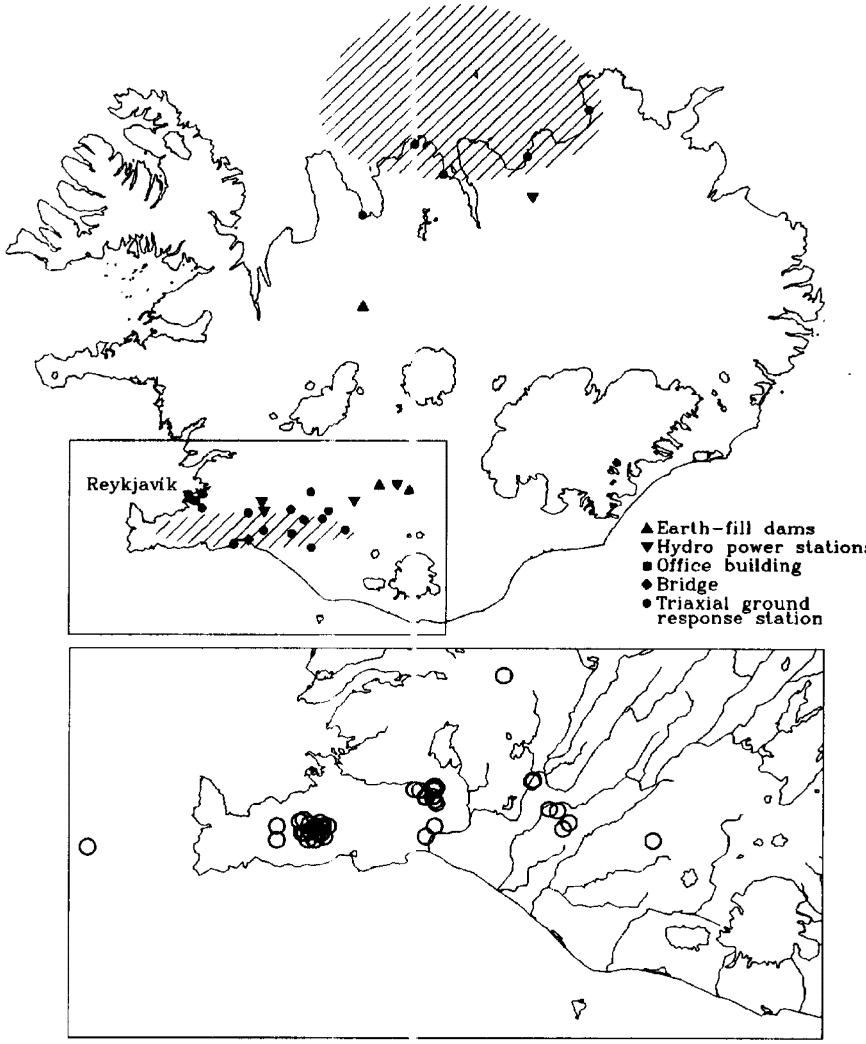

Fig. 1. The major seismogenic zones (shaded areas) in Iceland (redrawn after Thráinsson 1992) and the strong motion network operated by the Engineering Research Institute of the University of Iceland (top). Location (indicated by circles) of earthquakes measured by the strong motion network in the southern part of Iceland (bottom).

The source mechanism of major earthquakes in Iceland, obtained by fault plane solutions, is characterised as a strike-slip mechanism. The transform motion anticipated for the southern seismic area on the basis of plate tectonics, that is left lateral on an east-west striking fault, is however not visible on the surface. On the contrary it appears, at least in the South Iceland Lowland, that the motion can be visualised as a series of parallel north-south striking right lateral faults. This is supported by geological evidence in the form of fault traces on the surface as well as the north-south elongated shape of the mapped destruction zones of large historical earthquakes (Björnsson and Einarsson, 1980; Einarsson, 1991). In the northern seismic area the characteristics of the transform motion is not as obvious mainly because the epicentral area is mostly offshore.

THE STRONG MOTION NETWORK AND OTHER MONITORING SYSTEMS

Recording of earthquakes in Iceland started in the beginning of this century. The first seismometer was installed in the year 1909. There are sporadic recordings from 1909 to 1927 but from 1927 the observations are almost continuous (Sólnes, 1988). Currently three earthquake monitoring systems are operated in Iceland (see for instance Thráinsson, 1994). They are:

- A network of seismometers distributed throughout the country and operated by the Science Institute of the University of Iceland (Einarsson and Björnsson, 1987).

- The SIL-system (South Iceland Lowland system) consisting of 17 stations, each equipped with a short period seismometer, connected to a central computer in Reykjavík. Despite the name some of the stations are located within the northern seismic zone. The SIL-system is operated by the Icelandic Meteorological Office (Stefánsson et al., 1993).

- The strong motion network run by the Engineering Research Institute of the University of Iceland (see the following section).

The main purposes of the two networks mentioned first are geophysical research and earthquake prediction while the objective of the strong motion network is earthquake engineering research.

The strong motion network was initiated in 1984 and was originally based on a small-scale network proposed and installed by professor J. Sólnes (Sigbjörnsson, 1990). The objectives of the network are to establish earthquake engineering data required for rational structural design and risk management. The operation and maintenance of the network are supported by the National Power Company, the Public Road Authorities and the City Engineer in Reykjavík. At present the network consists of:

- 34 ground response stations, each with a triaxial sensor, including ground channels of structural systems.

- 3 earth-fill dams (30 channels),

- 2 hydro power stations (32 channels),

- a fourteen story office building in Reykjavik (8 channels),

- a 375 m long bridge with seismic base isolation (8 channels).

The locations of the ground response stations and the monitoring systems in structures are shown in Fig. 1. It is seen that the ground response stations are distributed within and close to the major seismic areas and in Reykjavik the capital. The capital region is the most densely populated area in Iceland. Within the South Icelandic Seismic Zone (SISZ) the standalone instruments are mostly located inside farm houses and public buildings in small villages. It is considered necessary to locate the instruments inside buildings due to severe climatic conditions, even though the buildings may affect the recordings. Further details of the network can be found in Table 1.

The network runs with a high degree of automation using digital instruments with the exception of five analogue instruments recording on film. The standalone instruments are of the following types: Kinemetrics SMA-1, Teledyne Geotech A-700, Terra DCA-333 and Kinemetrics SSA-1. The instrumentation systems in hydro power plants use single axis acceleration sensors of the type Kinemetrics FBA-11 and triaxial sensors of the type Kinemetrics FBA-23 and data acquisition equipment and computers from Hewlett Packard (see Table 1).

RECORDINGS AND BASIC PROCESSING OF DATA

To date 52 earthquakes have been recorded by the network, during which the acceleration of ground response channels has exceeded 0.4 per cent of the acceleration of gravity (g). In these quakes 294 time-series

Table 1. An overview of the strong motion network run by the Engineering Research Institute of the University of Iceland. Listed are ground response stations and structural response networks in buildings and structures, referred to as *system* in the table. Each ground response station contains one sensor. They are located in buildings or structures on firm ground. In some cases site dependent magnification has been observed. Sensors from Kinemetrics are applied in structural response networks (ch. denotes channel). The trigger thresholds are in the range 0.002 to 0.009 g, but in most cases around 0.005 g.

No.	*Site name*	*Geographic coordinates*		*Instrument type*	*Structure*
		Long. (°W)	*Lat.* (°N)		
100	Reykjavík	21.96	64.14	Kinemetrics SMA-1	Three story univ. building
101	Selfoss	21.00	63.94	Terra DCA-333	Hospital
102	Hveragerði	21.20	64.04	Kinemetrics SMA-1	Church
103	Kaldárholt	20.48	64.00	Terra DCA-333	Two story farm house
104	Thorlákshöfn	21.38	63.86	Kinemetrics SMA-1	Single story school building
105	Hella[1)]	20.39	63.84	Geotech A-700	Single story school building
106	Flagbjarnarholt	20.24	64.01	Kinemetrics SSA-1	Two story farm house
107	Thjórsártún	20.64	63.92	Geotech A-700	Two story farm house
108	Minni-Núpur	20.16	64.05	Geotech A-700	Two story farm house
109	Sólheimar[1)]	20.65	64.06	Geotech A-700	Two story school building
110	Hvítárbakki	20.39	64.16	Geotech A-700	Single story farm house
111	Selsund[1)]	19.95	63.94	Kinemetrics SMA-1	Single story farm house
201	Dalvík	18.53	65.97	Kinemetrics SSA-1	Three story office building
202	Húsavík	17.34	66.05	Kinemetrics SSA-1	Three story building
203	Sauðárkrókur	19.64	65.74	Terra DCA-333	Two story school building
204	Siglufjörður	18.91	66.15	Kinemetrics SSA-1	Retirement home
205	Kópasker	16.45	66.30	Terra DCA-333	Single story house
301	Búrfell	19.84	64.10	System (16 ch.)[4)]	Hydro power station
302	Hrauneyjarfoss	19.27	64.20	System (16 ch.)[5)]	Hydro power station
303	Sultartangi	19.57	64.19	System (18 ch.)[4)]	Earth-fill dam
304	Sigalda	19.10	64.16	Terra DCA-333 (6 ch.)[6)]	Earth-fill dam
305	Írafoss	21.01	64.09	Kinemetrics SSA-1 (4 ch)[6)]	Hydro power station
306	Ljósafoss	21.01	64.09	Kinemetrics SMA-1	Hydro power station
310	Laxárvirkjun	17.31	65.81	Kinemetrics SSA-1	Hydro power station
311	Blöndustífla	19.78	65.20	System (6 ch.)[6)]	Earth-fill dam
401	Reykjavík[2)]	21.90	64.13	System (8 ch.)	Fourteen story office building
402	Reykjavík	21.79	64.13	Kinemetrics SSA-1	Two story school building
403	Reykjavík	21.76	64.08	Kinemetrics SSA-1	Well-house/pump station
501	Óseyrarbrú[3)]	21.21	63.89	System (8 ch.)	Bridge[3)]

[1)] Site dependent magnification observed
[2)] The Commerce Building
[3)] 375 m long bridge with seismic base isolation
[4)] Including 3 ground response stations
[5)] Including 2 ground response stations
[6)] Including 1 ground response station

have been recorded, including both ground and structural response channels recordings. In addition to these series, recordings of numerous earthquake induced time-series have been made as a result of structural response triggered acceleration. At present the data base contains over 400 time-series recorded in earthquakes with magnitudes in the range 2 to 5.8 and epicentral distances ranging from nearly zero up to 80 km for ground response triggered recordings and nearly 300 km for structural response triggered recordings. Figure 2 shows the epicentral distance and magnitude for earthquakes triggering ground response stations. In Fig. 1 epicentral locations of earthquakes recorded by the strong motion network in the southern zone are shown. Table 2 shows parameters for earthquakes, of magnitude greater than 4.0, recorded so far. Only earthquakes triggering ground response channels are shown. The table shows time and date, location, hypocentral depth and various magnitude values for the earthquakes. Depth values in parenthesis indicate values where estimates based on measurements are not available.

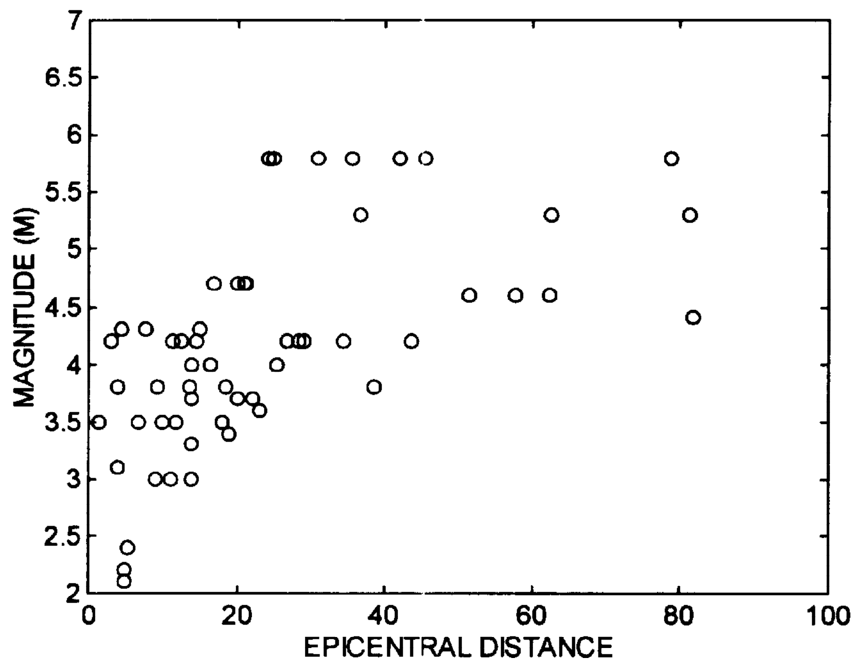

Fig. 2. Magnitude and epicentral distance of earthquakes recorded by the strong motion network in Iceland. Included are only earthquakes triggering ground response stations.

The highest ground channel acceleration recorded so far is 12 per cent of g, induced by a 4.3 magnitude earthquake with an epicentral distance of 4.5 km. The highest structural response channel acceleration recorded to date is about 15 per cent of g on the top floor of the instrumented office building in Reykjavik. The corresponding ground channel acceleration was 3.2 per cent of g. This was induced by an earthquake of magnitude 4.7 and a 20 km epicentral distance.

A basic data processing procedure is applied to evaluate the quality of recorded data and to perform necessary corrections. First the time series are visually inspected and a time interval for processing is selected. Then they are corrected for sensor characteristics, baseline errors and trends. After correcting the data velocities and displacements are calculated and peak values determined. Finally Fourier acceleration spectra and linear earthquake response spectra for pre-selected natural periods and critical damping ratios are calculated. The data processing procedure applies to digital recordings as well as analogue recordings after digitisation. The digitisation of analogue recordings is carried out after the lines described by Trifunac and Lee (1973). The sampling rate of the digitised analogue recordings is approximately 100 Hz while the sampling rate of the digital recordings is either 100 Hz or 200 Hz depending on the recording instrument.

Table 2. Earthquakes of magnitude greater than 4.0 recorded by the Icelandic strong motion network after triggering ground response channels.

Date	*Time*	*Magnitude* [1]					*Epicentre*		*Depth*
	GMT	M_L	M_T	m_b	M_s	M_w	*Latitude*	*Longitude*	*km*
26. 08. 1986	4:00:00		4,0				63,960	20,320	(5,00)
25. 05. 1987	11:31:54		5,5	5,8	5,8	5,9	63,909	19,779	11,30
09. 09. 1988	14:40:41	4,9	4,4	4,4	4,2		66,660	17,910	(5,00)
19. 03. 1990	10:46:31	4,7	4,7				63,950	21,930	(5,00)
19. 03. 1990	10:48:12	4,0	3,7				63,950	21,880	(5,00)
30. 01. 1991	7:43:44	4,6					64,383	20,746	4,98
23. 04. 1991	10:26:48	4,3					63,995	20,395	5,05
27. 12. 1992	12:23:22	4,2					64,016	21,179	(5,00)
28. 08. 1993	19:59:08	4,2					65,971	17,941	5,04
08. 02. 1994	3:27:52	5,3					66,451	19,245	(5,00)
19. 08. 1994	19:18:41	4,0					64,034	21,249	1,33

[1] M_L - local magnitude, M_T - magnitude based on duration of the seismic signal on local seismograms, m_b - body wave magnitude, M_s - surface-wave magnitude, M_w - moment magnitude.

INTERPRETATION OF DATA

The recorded data have been studied emphasising attenuation of ground motion and structural response, duration of shaking, spectral content of ground motion, spatial coherence of ground acceleration and structural behaviour under earthquake excitation. Some of the studies will be referred to in the following discussion.

The attenuation of peak ground acceleration is dealt with by Sigbjörnsson (1990) and Sigbjörnsson and Baldvinsson (1992). The analysis of the data was performed along the lines given by Joyner and Boore (1981) and Ambraseys and Bommer (1991). The main result was (Sigbjörnsson and Baldvinsson, 1992) that the observed peak ground acceleration was always lower than the acceleration predicted by the Joyner-Boore formula (1981). The same result was obtained in the majority of cases using the Ambraseys-Bommer formula (1991). An example of an attenuation formula with parameters derived using Icelandic data is displayed in Fig. 3. This formula is based on horizontal acceleration components induced by earthquakes of magnitude (M) greater than 4 and it is assumed valid for $4 \leq M \leq 6$. The dashed curves in Fig. 3 are the mean curve plus/minus one standard deviation which was estimated as 0.3 in the regression. In Fig. 3. data from all earthquakes of magnitude 2.0 or greater recorded by the strong motion network is plotted for comparison.

By comparing attenuation predicted by commonly applied formulas with the suggested formula derived using Icelandic data it is seen that the anelastic attenuation in Iceland as predicted by the formula tends to be somewhat higher than the attenuation predicted by the Joyner-Boore and Ambraseys-Bommer attenuation formulas (see also formulas in Ambraseys (1995) and Ambraseys and Bommer (1995)). It should be pointed out that the suggested formula lies close to the minus one standard deviation limit of the Joyner-Boore formula yielding lower acceleration values than derived by the above mentioned formulas. It is also worth mentioning that the Brillinger-Preisler formula (Brillinger and Preisler, 1985) gives a fair approximation to the Icelandic data if the mean value is reduced by one standard deviation (Sigbjörnsson, 1990).

The apparently high attenuation values derived from the data may be due, at least partly, to the fact that the data are obtained by sensors that are not spread uniformly around the epicentres of the recorded earthquakes. The data set is dominated by recordings obtained by sensors with azimuth angles that in many cases are roughly perpendicular to the causative fault. This raises the question of the necessity of accounting for the azimuth in the attenuation model. Otherwise it is difficult or nearly impossible to simulate the shape of the destruction zones characteristic for the historic Icelandic earthquakes. An approach that models such a directional dependence and accounts for the earthquake source is described by Sigbjörnsson et al. (1995).

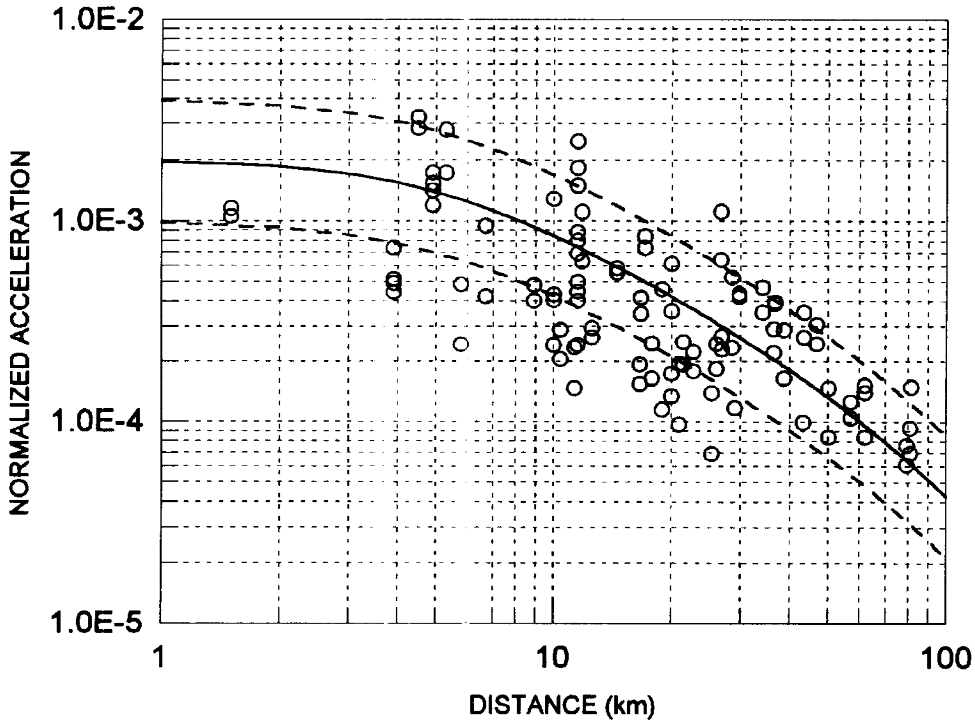

Fig. 3. Tentative attenuation formula for Iceland compared to all available Icelandic data.

The attenuation of earthquake response spectra have been dealt with by Sigbjörnsson and Baldvinsson (1992). Further the attenuation of standard deviation of acceleration and duration of shaking are dealt with by Ólafsson and Sigbjörnsson (1995) who also treat linear and nonlinear probabilistic response spectra.

The spatial coherence of acceleration has been studied (Baldvinsson et al., 1995) using data obtained in a hydro power station where two sensors are located on the ground floor with a separation distance of 78 m. The result indicates that the spatial variation of ground motion and loss in coherence are of importance for the power house involved in this study and other buildings and structures with large horizontal dimensions. The behaviour of structures subjected to earthquake acceleration has also been investigated. Snæbjörnsson and Sigbjörnsson (1993) deal with system identification and response of a 14-story office building in Reykjavík where the recorded acceleration has exceeded 15 per cent of g. Finally Snæbjörnsson et al. (1994) deal with the earthquake response of a hydro power plant.

FINAL REMARKS

A strong motion network recently installed in Iceland has been presented. This network has now been operational for eleven years. During this short time many recordings have been made including two earthquakes of magnitude greater than 5. Some of the more significant events are summarised in table 2. Location of events recorded by the network in the southern part of Iceland are shown in Fig. 1.

The apparently higher attenuation values derived from Icelandic strong motion data may be due to the fact that the data are obtained by sensors that are not spread uniformly around the epicentres of the earthquakes. For engineering hazard and risk assessment in Iceland it is found necessary to account for the azimuth angle in the attenuation model.

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