Bull Earthquake Eng (2009) 7:113–126
DOI 10.1007/s10518-008-9087-0

ORIGINAL RESEARCH PAPER

A note on the M_w 6.3 earthquake in Iceland on 29 May 2008 at 15:45 UTC

R. Sigbjörnsson · J. Th. Snæbjörnsson · S. M. Higgins · B. Halldórsson · S. Ólafsson

Received: 16 June 2008 / Accepted: 23 August 2008 / Published online: 26 September 2008
© Springer Science+Business Media B.V. 2008

Abstract This preliminary study aims to investigate a M_w 6.3 earthquake that occurred in South Iceland on Thursday 29 May 2008 at 15:45 UTC. The epicentre was in the Olfus District between the towns of Selfoss and Hveragerdi. This study examines the data recorded and the damage observed immediately after the event. Horizontal accelerations of up to 80% g were recorded in the epicentral region and there is visual evidence that the vertical acceleration exceeded 1 g. The PGA data is compared to a ground motion estimation model developed for the South Iceland earthquakes in June 2000. In general the basic properties of this event are found to be similar to the characteristics of the South Iceland earthquakes in June 2000. The duration of strong-motion is short and the intensity attenuates rapidly with increasing distance. The earthquake action resisted by buildings in the near fault area is inspected through evaluation of elastic as well as inelastic response spectra. The vast majority of structures seemed to withstand the strong-motion fairly competently and without significant visual damage due firstly to the low-rise, predominantly reinforced concrete or timber, style of buildings. Secondly, the short duration of strong-motion contributed to the endurance of structures.

Keywords Iceland · Strong-motion · Acceleration · Attenuation · Earthquake action · Response spectra · Damage

1 Introduction

A damaging earthquake occurred in South Iceland on Thursday 29 May 2008 at 15:45 UTC. The epicentre was in the Olfus District between the towns of Selfoss and Hveragerdi. The moment magnitude of the earthquake was 6.3 according to the Global Centroid Moment

R. Sigbjörnsson (✉) · J. Th. Snæbjörnsson · S. M. Higgins · B. Halldórsson · S.Ólafsson
Earthquake Engineering Research Centre, University of Iceland, Austurvegur 2a, 800 Selfoss, Iceland
e-mail: Ragnar.Sigbjornsson@hi.is

Tensor (CMT) database[1] and the Instituto Nazionale di Geofisica e Vulcanologia (INGV).[2] The earthquake can be characterised as a shallow crustal earthquake on a north–south trending right-lateral strike-slip fault. The basic properties of this event are found to be similar to the characteristics of the South Iceland earthquakes in June 2000 (Ambraseys et al. 2004; Sigbjörnsson and Ólafsson 2004; Sigbjörnsson et al. 2007; Halldórsson et al. 2007).

The recorded acceleration in the epicentral area was high and the earthquake action on buildings may have exceeded the codified design loading. The damage was widespread and significant, even though the majority of buildings withstood the high accelerations without visible damage. There are several cases of totally damaged buildings, i.e. buildings that are not economically feasible to repair. 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 luckily there were no fatalities out of roughly ten thousand people living in the epicentral area. Landslides and rock-falls were significant. Geothermal areas were affected and new hot springs were formed. 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.

The seismic activity in the wake of this earthquake produced numerous events that may have augmented the structural damage and the post-earthquake stress of the people living in the affected area, as observed after the June 2000 earthquakes (Ákason et al. 2006a,b).

2 Strong-motion recordings

The event was recorded by the Icelandic Strong-motion Network and the newly installed ICEARRAY network (Halldórsson et al. 2008), which is a small-aperture array located in the epicentral area. The peak ground acceleration (PGA) recorded close to the epicentre was high. In the town of Selfoss, towards the southeast of the epicentre, the horizontal acceleration reached 50% g. In the village of Hveragerdi, northwest of the epicentre, the horizontal and the corresponding vertical acceleration reached 85% g at some locations. Near the epicentre there was an indication that the vertical acceleration had exceeded 1 g. In the Reykjavik area, roughly 40 km from the epicentre, the horizontal PGA was less than 4% g. Table 1 summarises the preliminary findings on PGA. Furthermore, Fig. 1 gives a geographical overview of the location of the strong-motion stations, as well as assessed epicentres of the current event. For comparison the epicentres of the June 2000 earthquakes have been added.

There are no clear indications of a single causative fault to be found at the surface, which can, at least partly, be explained by thick sediments overlying the bedrock. There is also an indication that the recorded earthquake waves were not generated by a single causative fault but, rather, of two parallel faults rupturing almost simultaneously. Following this observation the initial rupture was a north–south trending fault corresponding to the location given by the Global Centroid Moment Tensor (CMT) database[1] (63.94°N and 21.09°W). Then about 1 s later the second rupture started on another north–south trending fault approximately 3.5 km west of the first fault. This is substantiated by the aftershocks recorded,[3] which also indicate north–south trending faults.

1 http://www.globalcmt.org/CMTsearch.html.

2 http://www.ingv.it.

3 http:/www.vedur.is.

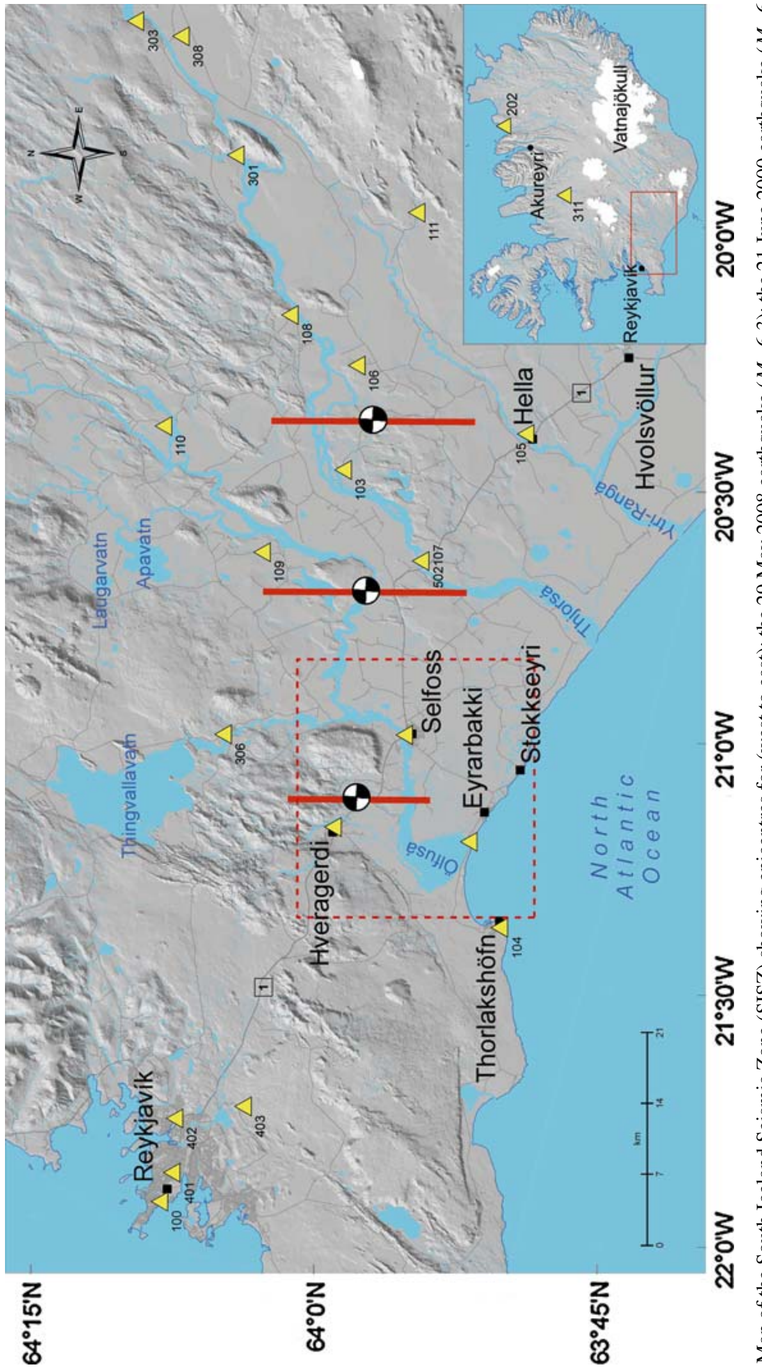

Fig. 1 Map of the South Iceland Seismic Zone (SISZ) showing epicentres for (west to east): the 29 May 2008 earthquake (M_w6.3); the 21 June 2000 earthquake (M_w6.4); and the 17 June 2000 earthquake (M_w6.5). Epicentres are indicated by beachball plots. Red lines indicate the orientation and length of causative faults. Yellow triangles indicate locations of Icelandic Strong-motion Network stations. Inset map shows the location of the SISZ in Iceland. White areas are glaciers

Table 1 Peak ground acceleration (PGA) recorded by the Icelandic Strong-motion Network

Id. No.	Station name	Geographic location		Peak ground acceleration (g)			*D*(km)
		(°W)	(°N)	*L*-axis	*T*-axis	*V*-axis	
113	Hveragerdi—Retirement Home	21.19	64.00	0.666	0.472	0.468	3
112	Selfoss—City Hall	21.00	63.94	0.538	0.334	0.266	8
101	Selfoss—Hospital	20.99	63.94	0.211	0.529	0.171	9
306	Ljosafoss—Power-house	21.01	64.10	0.131	0.106	0.072	15
403	Reykjavik—Heidmork (Jadar)	21.76	64.07	0.038	0.028	0.016	33
502	Thjorsarbru	20.65	63.93	0.081	0.098	0.026	36
402	Reykjavik—Foldaskoli	21.79	64.13	0.013	0.015	0.009	36
105	Hella	20.39	63.84	0.047	0.043	0.019	39
311	Blanda Dam	19.67	65.23	0.0075	0.0066	0.0044	156
202	Husavík	17.36	66.05	0.00035	0.0005	0.00033	290

Earthquake date: 29 May 2008; origin time: 15:45 UTC; moment magnitude: 6.3; macroseismic epicentre: 63.98°N and 21.13°W. The *V*-axis is vertical, orientation of *L*- and *T*-axes are not uniform. *D* is the distance from the recording station to the macroseismic epicentre

To substantiate the location of the initial rupture the inter-arrival time of the P-wave at six stations equipped with absolute GPS timing was used to estimate the epicentre applying the least squares technique. Due to the nature of the faulting described above, there was no clear distinction in the recorded time series between the P- and the S-waves. Using a P-wave velocity of 6.8 km/s (Fedorova et al. 2005) the initial epicentre was located at 63.97°N and 21.09°W. As seen in Fig. 2, this location is approximately inline with the location given by the CMT database.

In view of the above described scenario, as well as the lack of clear surface manifestation of a causative fault, we have chosen to use the macroseismic epicentre, 63.98°N and 21.13°W, as a reference for the distance measure applied and the distances reported in Table 1. This location is obtained by minimising the rms-error obtained as the difference between the recorded data and the model presented for the June 2000 earthquakes (Sigbjörnsson and Ólafsson 2004), applying the parameters listed in Fig. 3, and a variable epicentre. It is seen that this macroseimsic epicentre falls in between the two causative faults (as indicated on Fig. 2).

The PGA data available is plotted in Fig. 3 along with model estimates. The peak ground motion estimation equation represented by the blue curve in Fig. 3 consists of three main parts or zones. Firstly, the near-source zone denoted by the horizontal line for epicentral distances less than approximately 3.5 km. Secondly, the intermediate-source zone for epicentral distances in the range 3.5–25 km. This zone is characterised by rapid attenuation that is roughly proportional to $1/r^2$, r referring to the source distance. Thirdly, there is the far-source zone for epicentral distances above 25 km. In this zone the rate of attenuation decreases towards 1/r according to the model applied. It is worth noting that the standard deviation of the difference between the recorded values and the blue curve, (see Fig. 3), equals 0.236 (log-scale), furthermore that the mean difference is slightly below zero or −0.049.

These results are comparable to the attenuation obtained for the June 2000 earthquakes (Sigbjörnsson and Ólafsson 2004). The main finding in both cases is that the attenuation

Fig. 2 SPOT satellite image of the epicentral area of the 29 May 2008 earthquake showing the location of the macrosiesmic epicentre (solid red star) and the epicentre according to the Global Centroid Moment Tensor database (hollow red star labelled CMT). Our estimate of the location of the epicentre, based on strong-motion data, is indicated by the hollow star near to Lambhagi. Dashed red lines indicate proposed causative faults. Yellow triangles indicate locations of the Icelandic Strong-motion Network stations. Some of the towns and villages affected are shown. The location shown by the figure is indicated in Fig. 1 by the dashed red outline

is rapid and, furthermore, more rapid than predicted by the commonly used ground motion estimation equation (for a comprehensive overview, see Douglas 2003). In addition, the current recordings reveal a short duration of strong ground shaking. It is worth pointing out that the recordings on the ICEARRAY network exhibited a long-period component that manifests as a near-fault velocity pulse. Selected recordings from this event are available through the Internet Site for European Strong-motion Data (ISESD) database (Ambraseys et al. 2004).

3 Observed damage

No catastrophic collapse of residential buildings or other structures occurred during the event of 29 May 2008. However, damage was extensive and insured damage is believed to exceed that of the June 2000 earthquakes. This is largely due to the fact that the May 2008 epicentral area is more densely populated than those of the 2000 earthquakes. Furthermore, three

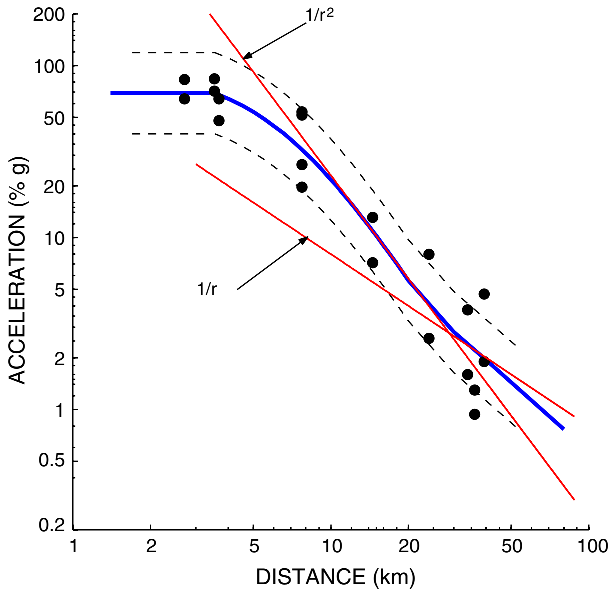

Fig. 3 Horizontal peak ground acceleration (PGA) as a function of epicentral distance. Each dot denotes a recorded PGA single horizontal component and the solid blue curve indicates a ground estimation model suggested by Sigbjörnsson and Ólafsson (2004). The dashed lines are obtained as the blue curve +/− one standard deviation of the difference between the recorded values and the blue curve (standard deviation of the difference = 0.236 and mean difference = −0.049). The red lines indicate attenuation proportional to $1/r^2$ and 1/r, respectively, where r refers to the source distance. The following data are assumed deriving the blue curve: moment magnitude, $M_w = 6.3$; shear wave velocity, $\beta = 3.5$ km/s ; density of rock, $\rho = 2.9\,g/cm^3$; stress drop, $\Delta\sigma = 90$bar; partitioning parameter, $C_P = 1/\sqrt{2}$; peak factor, $p = 2.94$; spectral decay in the near-field, $\kappa_o = 0.04$ s; duration used in near-field model, $T_o = 1.5 \cdot r/\beta$; characteristic dimension of the intermediate-field, $R_2 = 25$ km; depth parameter, $h = 6.3$ km; exponent describing attenuation in the intermediate-field, $n = 2$. The macroseismic epicentre, 63.98°N and 21.13°W, is obtained by minimising the rms error

villages were strongly affected by the 2008 event, which are Hveragerdi, Selfoss and Eyrarbakki (see Fig. 2). The exposure of the built area is therefore greater, even though the earthquake magnitude was smaller (see Fig. 1). Over 2000 buildings were damaged to some extent, but only about 25 were uninhabitable after the earthquake. Twenty four buildings have since been declared unfit for repair and will be demolished. The buildings most severely damaged are most commonly older concrete or masonry buildings with little or no reinforcement. An example of such a building is shown in Fig. 4c. Several buildings sustained some tilting or cracking related to differential soil-foundation settlements. The church tower in the town of Selfoss was damaged, as shown in Fig. 4a. As seen in Fig. 4b the tower is linked to a lower building and therefore there is a change in stiffness. Furthermore, the natural frequency of the tower is about 0.4 s, which corresponds to a peak in the response spectra recorded in the Town Hall some 300 m away (see Fig. 6).

An additional 2000 incidences of damage to building interiors have been reported. The damage varies significantly in its severity, but may have stronger psychological effects on people than minor visual structural damage. It is also a fact that people in Iceland are more likely to be injured by falling interior objects such as loose bookshelves or closets than by collapsing buildings. Figure 4d shows the effects of the earthquake on secondary systems located inside a building, as seen after the earthquake.

There was some damage to roads, mostly due to subsidence of the fill and the underlying sediments causing mainly longitudinal fracturing along the roads. There was also subsidence in roads where structures intersect the roadway, such as at culverts. There was also some

Fig. 4 Examples of earthquake damage to buildings and their interior. (**a**) The church of Selfoss and the approximately 20 m high tower. (**b**) Fracture in the Selfoss church tower. (**c**) Extensively fractured masonry building in the town of Hveragerdi. (**d**) Archives in the town of Selfoss

damage to the water supply systems in the towns of Hveragerdi and Selfoss. One bridge suffered minor visual damage as the horizontal movements of the bridge deck, which were in the order of 10 cm, exceeded the limit allowed for during construction. However, it was fully operational after the earthquake.

The earthquake caused extensive rock-falls from the surrounding mountains, and secondary faulting at mountain edges. Several instances were found where rocks and loose objects were thrown from their cavity to a new location some 10–20 cm away, indicating large vertical accelerations in the near-fault region.

The earthquake affected the natural waterways in the bedrock, new geysers were formed in the vicinity of the town Hveragerdi and, in general, geothermal activity was greater after the event. This was, however, not the case everywhere in the area, as hot water wells experienced a pressure drop in the area just east of the town Hveragerdi.

4 Earthquake action

Earthquake design provisions in Iceland have been improving gradually through time. Particularly after major damaging earthquakes, designers and engineers have tried to improve their methods. Construction of multi-story buildings increased after the Second World War. In the design of important buildings at that time, the effects of earthquakes were accounted for as a static horizontal force equal to 1/15 of the weight of the building. The first seismic design code was issued in 1976 as Icelandic Standard IST-13. These provisions were written using the California Uniform Building Code (UBC) as a model. According to IST-13 the buildings in the South Iceland Lowland had to withstand a horizontal seismic force up to 20% g. Currently, the building authorities are adopting Eurocode 8, including the necessary national application documents (NAD), as the future basis for the seismic design of buildings in Iceland. The horizontal design load has been increased for this area and is currently based on a PGA value equal to 40% g.

In view of the low seismic loading design applied to the majority of the buildings in the epicentral area and the high PGA recorded, greater damage might have been expected. The seemingly low damage rate is assigned to the short duration of strong ground shaking and the fact that the buildings are low-rise with the dominating building materials being reinforced concrete on the one hand and timber on the other. The more vulnerable unreinforced concrete and masonry type structures make up a much lesser proportion.

A detailed overview of the action that the buildings in the area had to resist can be obtained from ISESD. An example of recorded ground acceleration and structural response is given in Fig. 5, for a three-storey office building in the town of Selfoss. It is seen that the ground motion is not severely magnified by the structure as the peak acceleration level on the third floor is only about 1.4 times the PGA at base level for each horizontal direction. This corresponds to the dynamic characteristics of this building which has natural periods below 0.17 s, whereas the normalised response spectra (seismic coefficient) shown in Fig. 6 demonstrate that the horizontal earthquake action peaks at periods above 0.3 s. The fact that the low-rise buildings in the near-fault region did not pick up the peak earthquake action has been a contributing factor in limiting the potential damage caused by this event.

In the epicentral area linear acceleration spectra indicate that the base shear may be as high as 3 to 4 times the acceleration of gravity, while the vertical acceleration is of the same order of magnitude, in extreme cases. This implies that the behaviour of real structures in the near-source area cannot be predicted by linear models, especially as the seismic design

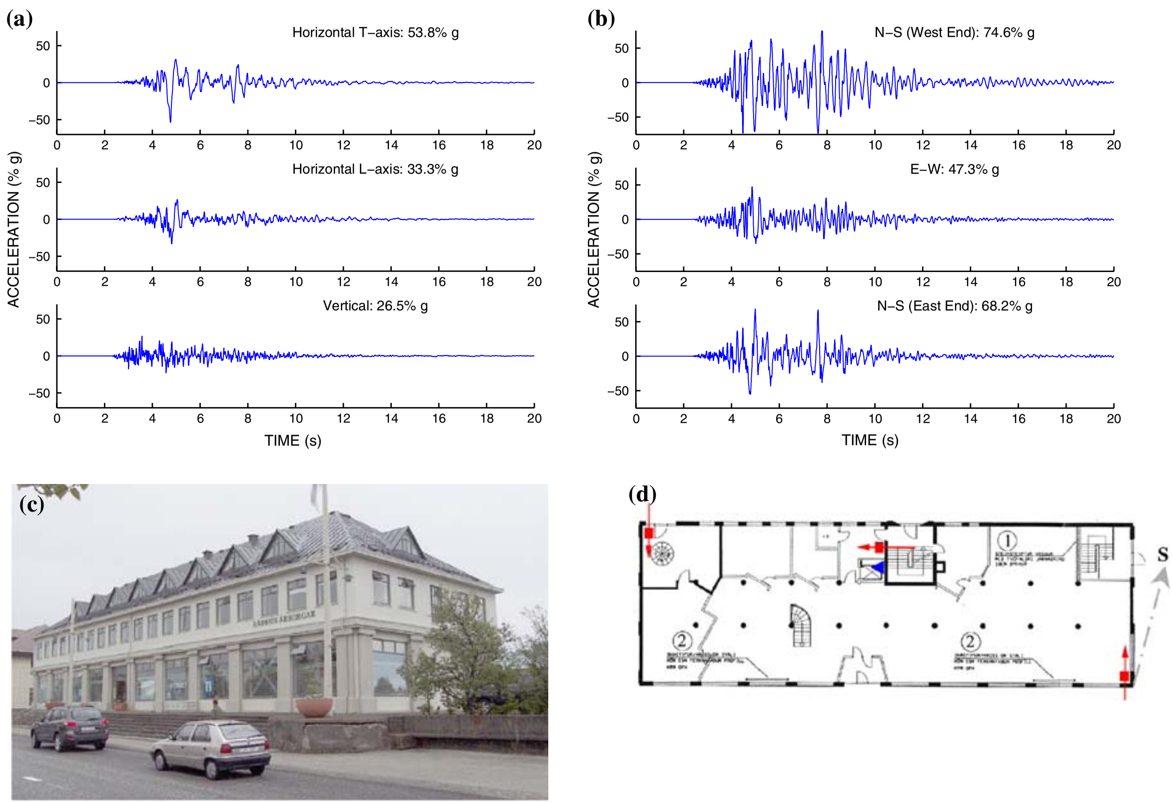

Fig. 5 Accelerations recorded in a three storey office building in the town of Selfoss: (**a**) ground acceleration components recorded in the basement; (**b**) horizontal acceleration recorded on the third floor, NS (West End) is the transversal component of the west end of the building, E–W is the longitudinal component and N–S (East End) is the transversal component of the east end of the building; (**c**) photo showing the north and west sides of the building; and (**d**) drawing showing the location of accelerometers. The red rectangles identify the locations of uni-axial accelerometers on the third floor while the arrows indicate the sensor directions. The blue triangle denotes a tri-axial accelerometer in the basement

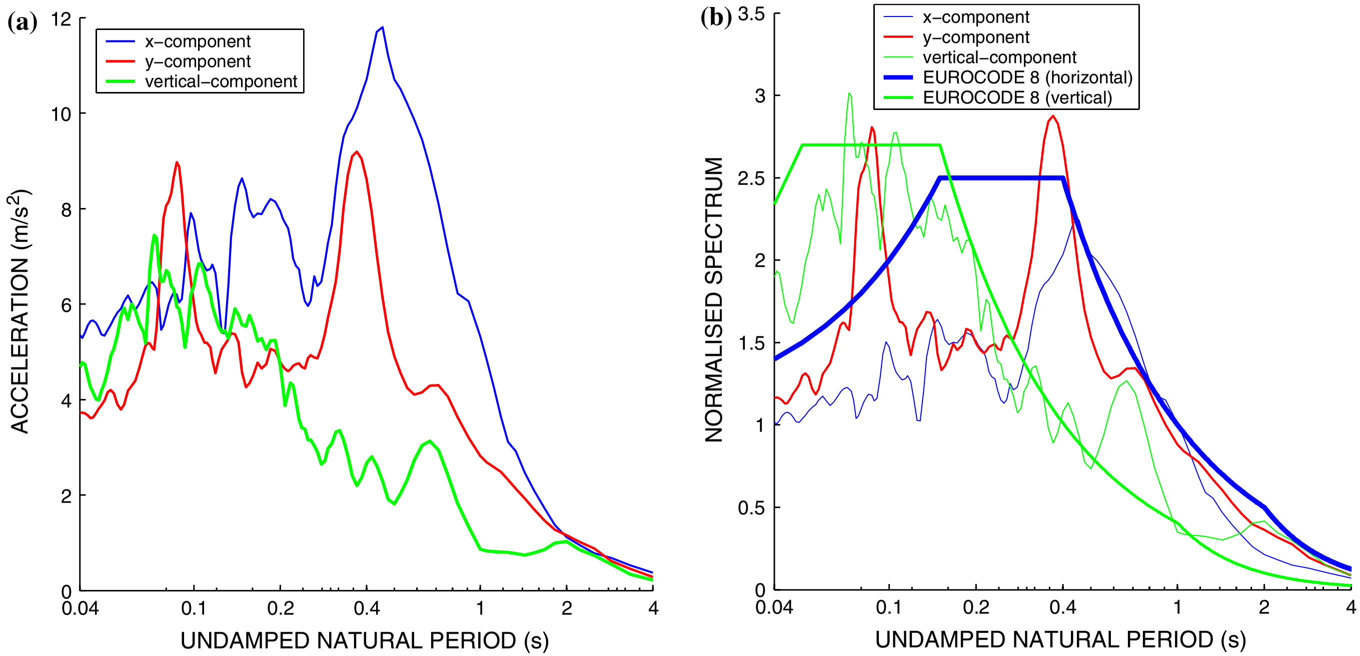

Fig. 6 Linear elastic earthquake response spectrum derived from ground acceleration components recorded in a three storey office building in the town of Selfoss: (**a**) Spectral acceleration for transverse (north–south) acceleration (blue line), longitudinal (east–west) acceleration (red line) and vertical acceleration (green line). (**b**) Normalised earthquake response spectrum (seismic coefficient) for transverse (north–south) ground acceleration (thin blue line), longitudinal (east–west) acceleration (red line) and vertical ground acceleration (thin green line). Eurocode 8 horizontal and vertical ground accelerations are indicated by the thick blue line and thick green line, respectively. Critical damping ratio is 5% in all cases

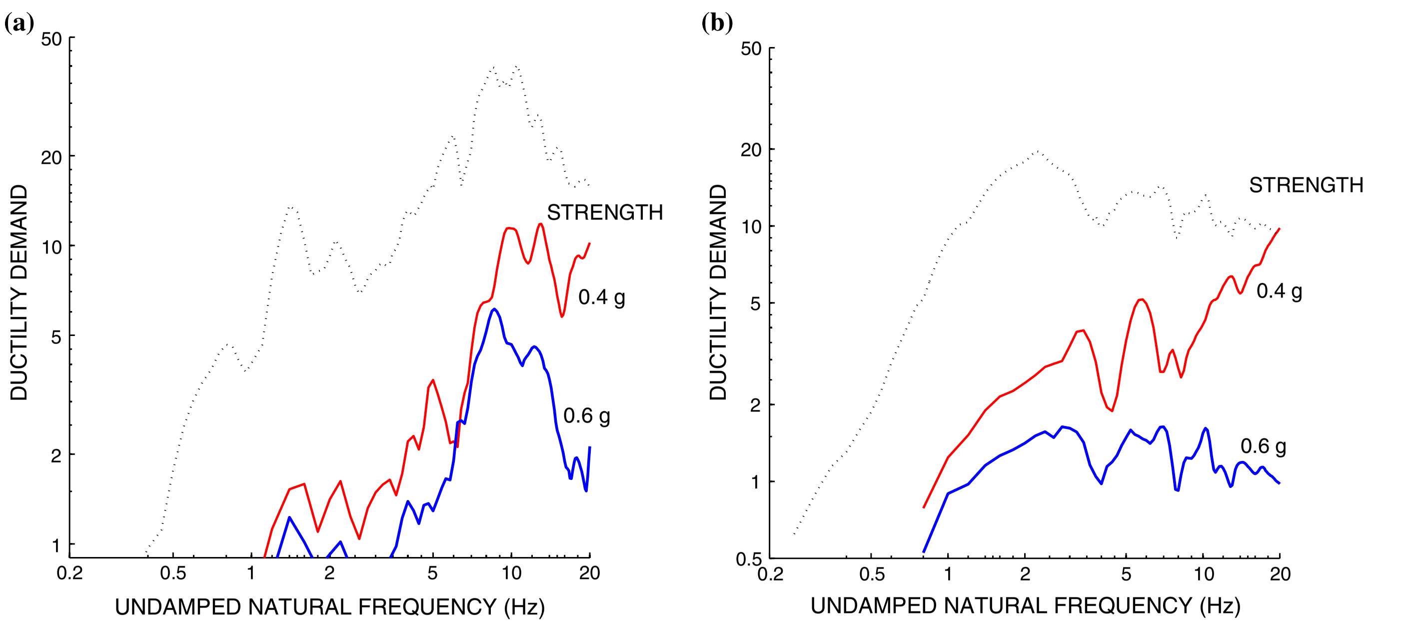

Fig. 7 Inelastic response spectra for constant strength, respectively, 0.4 g (blue curve) and 0.6 g (red curve). Solid curves indicate inelastic earthquake response spectra and dashed curve gives the linear elastic earthquake response spectra scaled by the yield displacement for a system with strength of 0.6 g. The critical damping ratio is 5% in all cases. (**a**) Hveragerdi–Retirement House (Id. No. 113), (**b**) Selfoss-Town Hall (Id. No. 112)

requirements are, in general, rather weak and even non-existent for older buildings. Therefore, to assess the required strength demand, inelastic spectra has been calculated. The results are exemplified in Fig. 7 for two recording stations. Only horizontal action is considered. The figures show the ductility demand for a prescribed strength, corresponding to yield strength equal to 0.4 and 0.6 g. The dotted curves, indicating the linear displacement spectra for a 5% critical damping ratio, are inserted for comparison. They are obtained by dividing the linear displacements by a yield displacement equal to f_u/ω^2, where f_u is the yield strength and ω is the undamped natural frequency in rad/s. The non-linear spectra show, in both cases, a tendency to well-known shifts in the characteristic spectral peaks. The shift is encountered for the weaker systems towards higher frequencies, relative to the characteristic peaks in the spectra for the stronger systems. These spectra indicate that low-rise buildings designed according to the minimum requirements of the seismic code, applied for the bulk of the buildings, are bound to suffer damage. These damages surface as cracks in the concrete and masonry partitions, yielding in reinforcements and significant deformations in timber elements.

The strength demand as a function of the ductility demand is displayed in Fig. 8 for the above-mentioned recording stations. Only structures with an undamped natural frequency equal to 2, 5 and 10 Hz, respectively, are considered. On average we see that the strength demand decreases with increasing ductility demand. The figure displays, however, some characteristic differences also seen in Fig. 6. The curve for a structure with a 10 Hz natural frequency at Station 113 indicates considerably higher action than the corresponding curve for Station 112. This can be attributed to the spectral characteristics of the ground acceleration reflected in the higher dominating frequency at Station 113 than 112. It is also seen that for high-resistant low-rise structures, for example with an undamped natural period of about 10 Hz and strength equal to 1 g, the ductility demand is low, i.e. in the range of 1.5–2 (see Fig. 8).

5 Discussion

When the damage in the epicentral area is assessed, it is necessary to take into consideration that many of the structures were built without any seismic provisions, and that the codified seismic design strength demand in this region was only about 20% g, until recently. This value refers to horizontal action, as vertical action is not taken into consideration. Hence, it may seem surprising that the damage to buildings was not more severe than it turned out to be in reality. The reasons for this may be many. The buildings in the area, which are made of concrete, masonry and timber, can be characterised as low-rise, with few buildings exceeding three storeys. The fundamental natural frequencies of these buildings are, in most cases, of the order of 10 Hz and in very few cases are they below 5 Hz. It seems obvious that the high natural strength of these low-rise buildings is a key factor. This high strength is first of all attributed to other design considerations than the rather weak seismic design requirements. Furthermore, it seems clear that the spectral characteristics of the earthquake action are, at least in some cases, favourable to stiff, low-rise buildings compared with more flexible multi-storey buildings. In addition, it is obvious, when the damage of a building is analysed, that the short duration of strong shaking contributed to the survival of the structure.

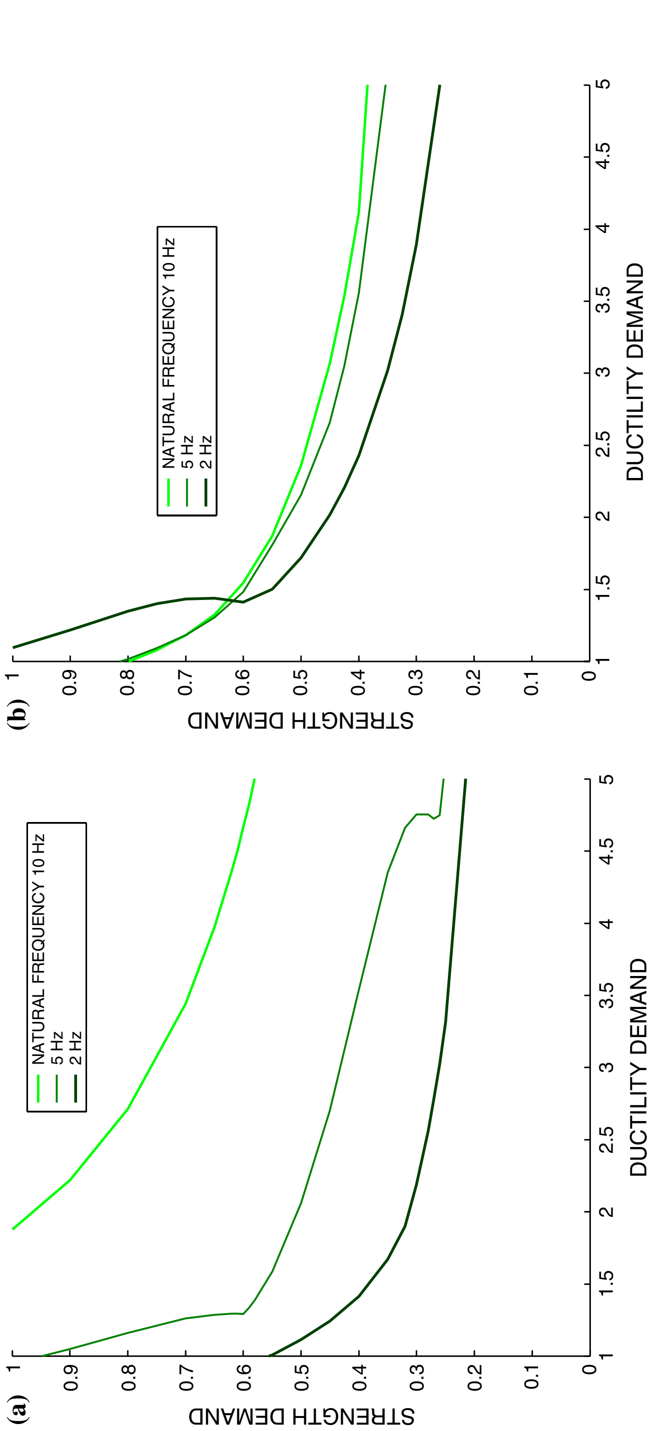

Fig. 8 Strength ductility demand for three selected undamped natural frequencies, 2, 5 and 10 Hz. The critical damping ratio is 5% in all cases. (**a**) Hveragerdi Retirement House (Id. No. 113), (**b**) Selfoss Town Hall (Id. No. 112)

6 Final remarks

The main findings of this preliminary study are the following:

- The recorded acceleration in the epicentral area was high
- The acceleration attenuated rapidly with increasing distance form the macroseismic epicentre
- The duration of the strong ground shaking was short
- The majority of buildings withstood the high accelerations without significant visible damage.

Recordings from the Icelandic Strong-motion Network are currently available through the ISESD (Ambraseys et al. 2004) including the raw data, corrected time series and linear elastic response spectra.

References

Ambraseys N, Smit PM, Douglas J, Margaris B, Sigbjörnsson R, Ólafsson S, Suhadolc P, Costa G (2004) Internet-site for European strong-motion data. Bollettino di Geofisica Teorica ed Applicata 45(3): 113–129

Ákason JB, Ólafsson S, Sigbjörnsson R (2006a) Perception and observation of residential safety during earthquake exposure: a case study. Saf Sci 44(10):919–933

Ákason JB, Ólafsson S, Sigbjörnsson R (2006b) Phases of earthquake experience: a case study of the June 2000 South Iceland earthquake. Risk Anal 26(5):1235–1246

Douglas J (2003) Earthquake ground motion estimation using strong-motion records: a review of equations for the estimation of peak ground acceleration and response spectral ordinates. Earth Sci Rev 61(1–2): 43–104

Fedorova T, Jacoby WR, Wallner H (2005) Crust–mantle transition and Moho model for Iceland and surroundings from seismic, topography, and gravity data. Tectonophysics 396:119–140

Halldórsson B, Ólafsson S, Sigbjörnsson R (2007) A fast and efficient simulation of the far-field and near-fault earthquake ground motions associated with the June 17 and 21, 2000, earthquakes in South Iceland. J Earthq Eng 11:343–370

Halldórsson B, Sigbjörnsson R, Schweitzer J (2008) ICEARRAY: the first small-aperture, strong-motion array in Iceland. J Seismol. doi:10.1007/s10950-008-9133-z

Sigbjörnsson R, Ólafsson S (2004) On the South Iceland earthquakes in June 2000: strong-motion effects and damage. Bollettino di Geofisica Teorica ed Applicata 45(3):131–152

Sigbjörnsson R, Ólafsson S, Snæbjörnsson JTh (2007) Macroseismic effects related to strong ground motion: a study of the South Iceland earthquakes in June 2000. Bull Earthq Eng 5(4):591–608