On the Effects of Induced Earthquakes due to Fluid Injection at Hellisheidi Geothermal Power Plant, Iceland

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LISBOA 2012

SUMMARY:
Worldwide, induced earthquakes associated with geothermal projects have raised public concern on several occasions even though the seismicity has rarely had adverse physical effects. A recent sequence of induced seismicity due to fluid injection into the geothermal field at Hellisheidi Power Plant, southwest Iceland, culminated in two $M_L 3.8$ earthquakes on 15 October 2011. The earthquake ground motions and structural vibrations were widely felt, especially in the village of Hveragerdi (distance ~12 km), where the new ICEARRAY strong-motion small-aperture array produced recordings of 85 earthquakes on a total of 11 free-field three-component instruments. The largest horizontal PSA values in Hveragerði were 22% g and 17% g in the two largest events, respectively. This earthquake action is equal to, and in some cases higher than, the codified design demand applied to the majority of the building stock. These results may have important implications for future operations at the Hellisheidi geothermal plant.

Keywords: Strong-motion, ICEARRAY, earthquake action

1. INTRODUCTION

Iceland is a volcanic country rich in geothermal natural resources that have been utilised for centuries by the population. The systematic distribution of geothermal water for direct use and space heating commenced almost a century ago, but in recent decades geothermal power plants in Iceland have been increasingly utilized to produce electricity. In 2008 about 25% of the electricity generated in Iceland was of geothermal origin; the remainder was generated by hydroelectric power plants. The most recent geothermal development project in Iceland is the Hellisheidi Power Plant in southwest Iceland. Operations at the Hellisheidi plant commenced in 2006, but development and construction is still going on. Currently the plant produces 213 MW of electricity and 130 MW of thermal power[1], but the eventual production will be about 300 MW of electricity and 400 MW of thermal power (Hardarson *et al.* 2010; Gunnarsson 2011). The plant lies in the western part of the Hengill central volcanic system, which is characterized by its NNE-trending fissure swarm, postglacial lavas and widespread high-temperature geothermal resources; it is one of the most extensive in Iceland. The area is associated with continuous small magnitude earthquake activity and earthquake swarms (Foulger & Julian 1993; Foulger *et al.* 1995). The general tectonics in the area is characterized by the Hengill triple-junction of two active rift zones (Reykjanes Volcanic Zone towards the west and the Western Volcanic Zone towards the north-east) and a seismically active transform zone, the South Iceland Seismic Zone (SISZ) towards the east. Thus, normal faulting earthquakes associated with tectonic spreading, along with strike-slip earthquakes associated with the SISZ, can be expected on the triple junction.

The Hengill volcanic region lies at the western margin of the SISZ, which stretches across the lowlands of the south, a populous agricultural region in Iceland with numerous towns and villages. Historically, the SISZ is the source of the largest earthquakes (up to magnitude 7) that take place in South Iceland, with the entire zone breaking roughly once a century, often in earthquake sequences

[1] http://www.or.is/English/Projects/HellisheidiGeothermalPlant/

that can last for years. Such a sequence has been occurring since June 2000 when two earthquakes of magnitudes 6.4 and 6.5 occurred in the central SISZ, followed by many smaller events. Then in May 2008 a magnitude 6.3 earthquake took place in the western SISZ. Despite the high accelerations in the near-fault regions, most structures withstood the seismic effects without major structural damage (Sigbjörnsson & Ólafsson 2004; Sigbjörnsson, Ólafsson, & Snæbjörnsson 2007; Sigbjörnsson *et al.* 2009; Halldorsson & Sigbjörnsson 2009). While the earthquakes did not result in serious injury or loss of life, they caused notable psychological post-traumatic stress disorder for a certain fraction of the inhabitants (Akason, Ólafsson, & Sigbjörnsson 2006a; b).

It is a well-known and important fact that geothermal exploitation has induced earthquakes (Majer *et al.* 2007; Majer & Peterson 2007; Baisch *et al.* 2010; Evans *et al.* 2011). While such seismicity has rarely had adverse physical effects on operations or on surrounding communities, public concern about the number and magnitude of induced earthquakes in some cases delayed and/or threatened cancellation of geothermal projects worldwide (Majer *et al.* 2007; Baisch *et al.* 2010; Evans *et al.* 2011). While the number of geothermal plants in Iceland has steadily risen over the last quarter of a century, induced earthquakes have been a rare occurrence (Evans *et al.* 2011). The threat that induced earthquakes can pose to production, the built environment and the community is minimized through proper site selection, addressing community issues and operators' understanding of the underlying mechanisms causing the earthquakes (Majer *et al.* 2007). Therefore, this is an important and practical issue that should be taken into consideration in the development of geothermal projects, both for the sake of operation and community safety (Majer *et al.* 2012).

One of the basic requirements imposed on operations of the Hellisheidi geothermal plant is the reinjection of all wastewater into the geothermal reservoir for the purpose of (a) protecting the surrounding environment, (b) not contaminating groundwater reserves, and (c) maintaining pressure in the system (Hardarson *et al.* 2010; Gunnarsson 2011). Since operations at the Hellisheidi Power Plant commenced in 2006, reinjections into the geothermal reservoir have been accompanied by increased microseismicity. Recently, however, reinjection has been focused on a new location in the Reykjafell graben beneath Husmuli Mountain, which is constrained by two normal-faults. The wells, which are directionally drilled and target known active faults in the graben, have resulted in swarms of small earthquakes both during drilling, and especially during subsequent fluid reinjection tests (Hardarson *et al.* 2010; Gunnarsson 2011). The earthquakes associated with testing the reinjection wells were of small magnitude and had no adverse effects, and as a result received little attention by the operator and the community.

The Husmuli reinjection area became fully operational in early September 2011 when reinjection commenced at a rate of around 550 l/s. This was followed by immediate onset of induced microseismicity of about 1900 earthquakes during the period 10.09-16.10 (Orkustofnun 2011). The induced seismicity culminated in two $M_L 3.8$ earthquakes on 15 October 2011. These earthquakes are significant because they are (1) by far the largest ones on record in Iceland associated with geothermal exploitation, (2) larger than any induced earthquakes due to fluid injection in geothermal systems, as compiled from 41 European case histories (Evans *et al.* 2011), and (3) among the largest ones worldwide associated with fluid reinjection of enhanced geothermal systems (see Baisch *et al.* 2010).

Finally, the earthquakes are significant since the associated ground motions and structural vibrations were widely felt, from the village of Hella in the SISZ (distance ~50 km) and in the capital area in the west (distance ~20-30 km). Most notable, however, were the effects in the nearby villages of Hveragerdi (distance ~12 km, population 2316) and Selfoss (distance ~24 km, population 6476). These villages were the ones hardest hit in the magnitude 6.3 earthquake in May 2008 in the SISZ. Naturally, the induced earthquakes have caused public unrest and concern about their potential effects, not only as a result of current operations but future operations as well since production capabilities of the Hellisheidi geothermal power plant are expected to double in a few years.

The purpose of this study is to provide a preliminary assessment of the physical effects of the induced earthquakes on civil engineering structures and infrastructures in Hveragerdi using the acceleration

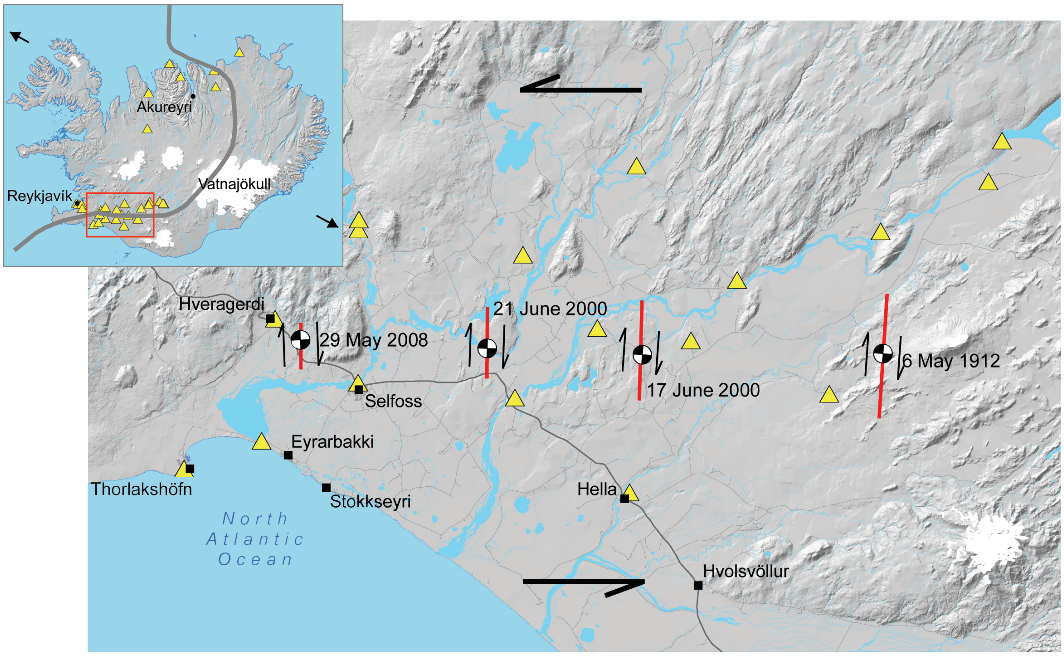

Figure 2.1. The approximate locations and fault alignment of damaging earthquakes larger than M6 over the last 100 years in the South Iceland Seismic Zone. The inset, top left, shows Iceland with respect to the present day active plate boundary and location of the Mid-Atlantic Ridge and the red rectangle indicates the area shown in the main picture. The triangles show the locations of the recording stations of the Icelandic Strong-motion Network.

records produced by the dense ICEARRAY network in Hveragerdi. The characteristics of the earthquake strong-motions are analysed and the earthquake action on structures estimated by evaluating the pseudo-spectral acceleration (PSA) of a 2% damped linear elastic simple oscillator. The largest horizontal PSA values in Hveragerði are compared with the codified design demand of the majority of the building stock, which has been increased several times during the last century. It is conceivable that the induced earthquakes may have caused some progressive damage, especially to older buildings and those that have already suffered intense near-fault motion during the May 2008 M_w6.3 earthquake. These results may have important implications for the future of operations at the Hellisheidi geothermal power plant as well as for the future of two planned geothermal projects in the Hengill region that would be situated considerably closer to the affected communities.

2. STRONG-MOTION MEASUREMENTS

2.1. Icelandic strong-motion network and the ICEARRAY

The Icelandic Strong-motion Network (IceSMN) of the Earthquake Engineering Research Centre (EERC) has been developed in Iceland over the last 25 years (see Figure 2.1, yellow triangles). The largest part of the network is in operation in the SISZ, where most of the recording sites are located in single-storey residential buildings, but important buildings and lifeline systems (hospitals, municipal buildings, bridges, hydroelectric power plants, and dams) are also instrumented as a part of the IceSMN. The latest development in strong-motion monitoring in Iceland is the ICEARRAY, a new small-aperture urban array of accelerographs, located in the town of Hveragerði, South Iceland (see Figure 2.2, red dots). Even though only recently deployed (in 2007), it has already created considerable research opportunities as it recorded the extreme near-fault earthquake ground shaking due to the magnitude 6.3 Ölfus earthquake on 29 May 2008 (Sigbjörnsson *et al.* 2009; Halldorsson & Sigbjörnsson 2009), along with a large number of its aftershocks (Douglas & Halldorsson 2010). The characteristics of the main shock motion as captured by the ICEARRAY and IceSMN recording stations in the near-fault region are large amplitude and long-period velocity pulses and intense high-

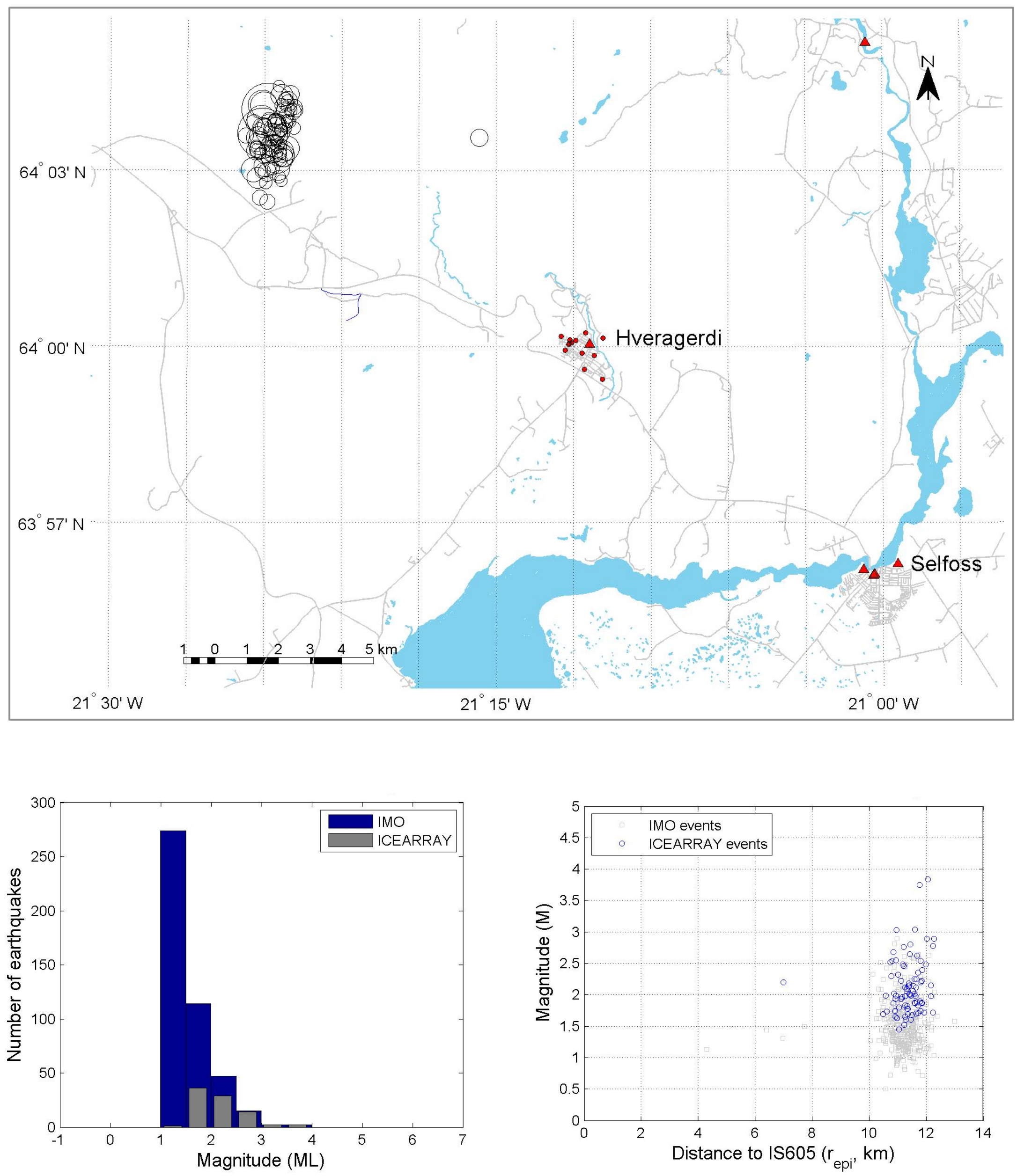

Figure 2.2. Top: Map of epicentral distribution (black circles) of the induced earthquakes and the sites of the ICEARRAY in Hveragerdi (red dots) and the IceSMN (red triangles). Bottom: histogram of earthquake magnitudes (M_L>1) (left) and magnitude-distance distribution (right) reported by the IMO (grey) and recorded by ICEARRAY (blue), respectively.

frequency accelerations that attenuate rapidly with distance from the faults (Sigbjörnsson *et al.* 2009; Halldorsson & Sigbjörnsson 2009). Moreover, the ground motion was associated with permanent tectonic displacement, both in the strike-parallel and strike-normal directions (Halldorsson *et al.* 2010; Rupakhety, Halldorsson, & Sigbjörnsson 2010). The earthquake caused considerable damage in the neighbouring towns of Hveragerði and Selfoss, but fortunately no lives were lost, and the vast majority of structures withstood the strong-motion without significant visual structural damage, primarily due to the predominant building style (low-rise reinforced shear wall concrete or wood frame) and the short duration of strong-motion (Sigbjörnsson *et al.* 2009).

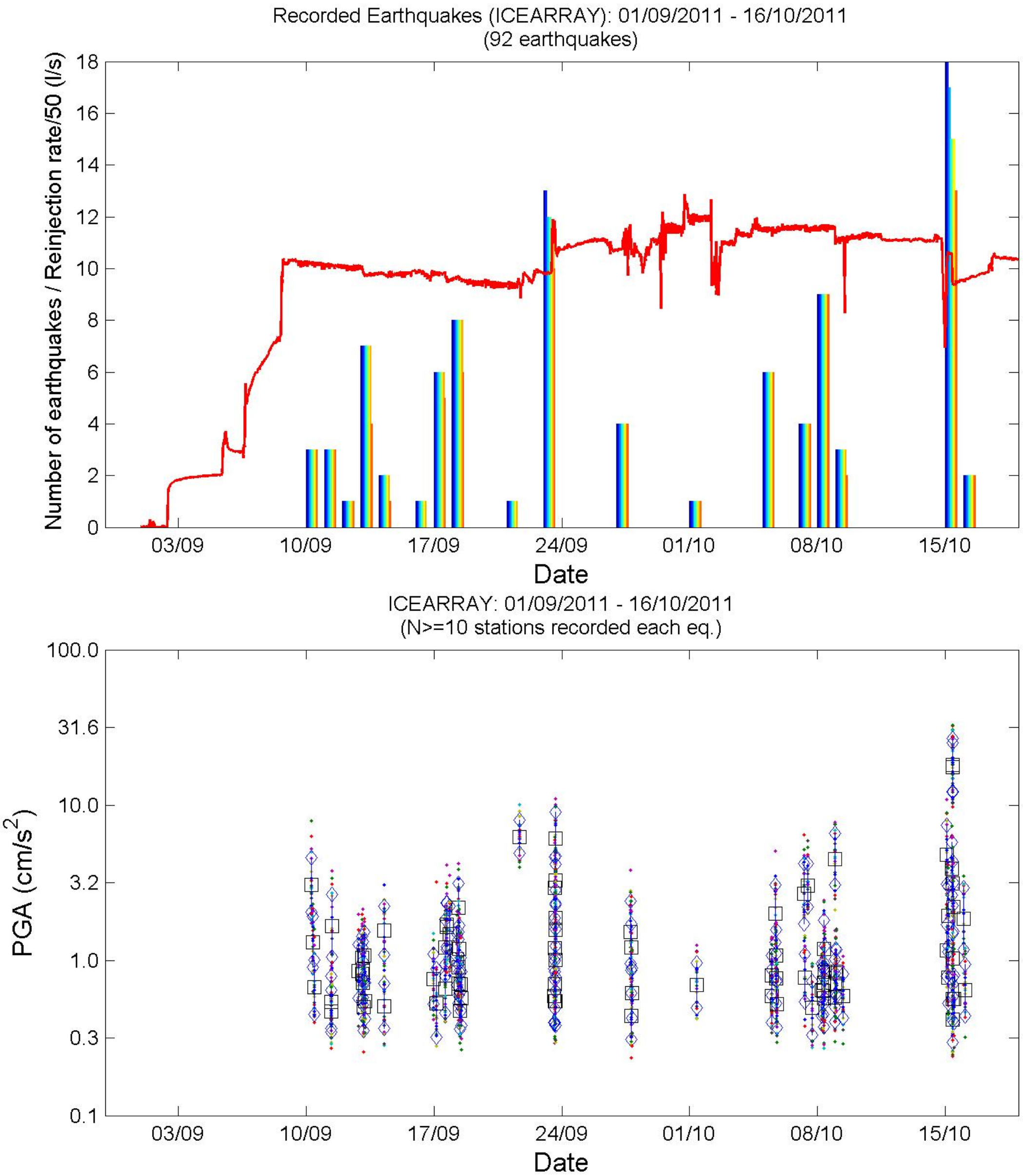

Figure 2.3. Top: number of ICEARRAY global triggers over time. The red line denotes the reinjection rate (divided by a factor of 50). Bottom: recorded peak ground accelerations (PGA) on individual ICEARRAY stations (small dots) plotted vs. time, along with the mean value (square) and ± 1 standard deviation of the distribution of PGA values for each event.

2.2. Earthquake sequence near Hellisheidi geothermal plant September-October 2011

In September 2011 new reinjection wells had become fully operational near the power plant in the Husmuli area with a wastewater cumulative reinjection rate of over 500 l/s, via multiple boreholes. The induced seismic sequence that followed immediately culminated on 15 October 2011 with two M_L3.8 earthquakes at 9:02 and 9:45 UTC. The induced earthquakes, the majority of which were minor and not felt, were monitored by the SIL (South Iceland Lowland) weak-motion national network of the Icelandic Meteorological Office (IMO), along with the IceSMN and ICEARRAY strong-motion networks of the EERC. Figure 2.2 gives an overview of the ICEARRAY recordings from 1 September to 16 October 2011. The map shows the geometry of the epicentral distribution of the induced earthquakes relative to the closest recording stations of the ICEARRAY in Hveragerdi and the IceSMN. Hveragerdi is the closest town affected by the induced seismicity. In particular, Figure 2.2 shows the histogram of the magnitudes of the earthquakes recorded by the IMO (shown in blue columns) and the ICEARRAY (shown in grey columns). Due to lower sensitivity of the

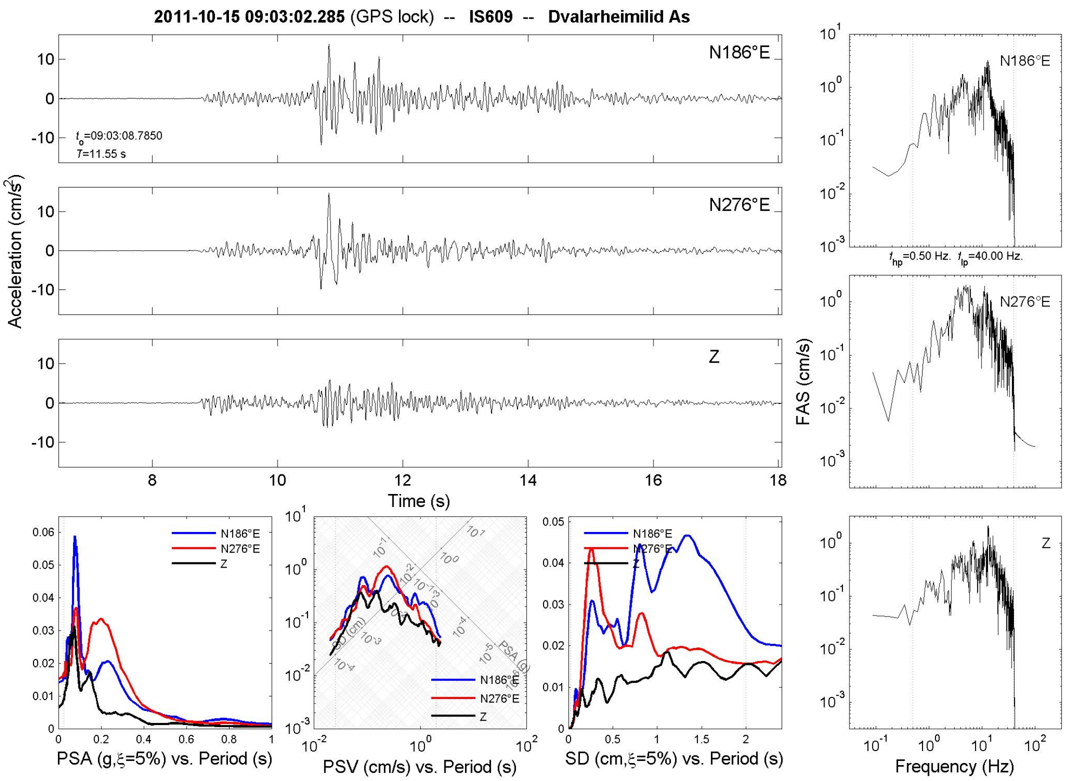

Figure 2.4. Ground acceleration during the 15 October 2011 9:02 $M_l3.8$ earthquake as recorded on ICEARRAY station IS609 on three-components, along with their respective Fourier amplitude spectra and 5% damped response spectra.

accelerographs of the ICEARRAY, the recordings become less complete at smaller magnitude (i.e., lower ground motions). Also shown is the magnitude-epicentral distance distribution of the events recorded by the ICEARRAY (blue circles).

The reported reinjection rate increased steadily from a total of zero to approximately 500 l/s during 3-8 September and subsequently remained fairly constant until mid-October 2011 (Orkustofnun 2011), as shown in Figure 2.3. The earthquake occurrence was, however, not evenly distributed over time during the reinjection phase, as can be seen in in Figure 2.3 where the frequency of recorded ground motions on the ICEARRAY is plotted vs. time. Similarly, the distribution of ground motion intensity was irregular as well, represented by peak ground accelerations (PGA) recorded on ICEARRAY stations as shown in Figure 2.3. For each triggered earthquake, the individual PGA values at each ICEARRAY station are denoted by the small dots and their log-mean value by a square, along with its ± 1 standard deviation.

2.3. ICEARRAY recordings

The ICEARRAY monitors strong-motions in Hveragerdi from earthquakes in the South Iceland Seismic Zone and the nearby fracture and volcanic zones. It is controlled by a common-triggering system that maximises the recording efficiency of the array while minimizing the efforts of an analyst in reviewing the recorded data and sorting out events vs. local noise and disturbances (Halldorsson & Avery 2009). Since 2009 the ICEARRAY has occasionally recorded ground motions in Hveragerdi due to earthquakes with epicentres near the Hellisheidi geothermal power plant. The earthquakes had been few and their ground motions weak and had therefore only attracted minor attention. During the recent seismic sequence of induced earthquakes the common-triggering system sent out 92 global triggers i.e., instances of more than two instruments triggering within the same 5-second time window, resulting in the activation of all ICEARRAY instruments (in case local man-made vibrations at some stations had compromised the triggering criteria). In some cases not all instruments could be activated

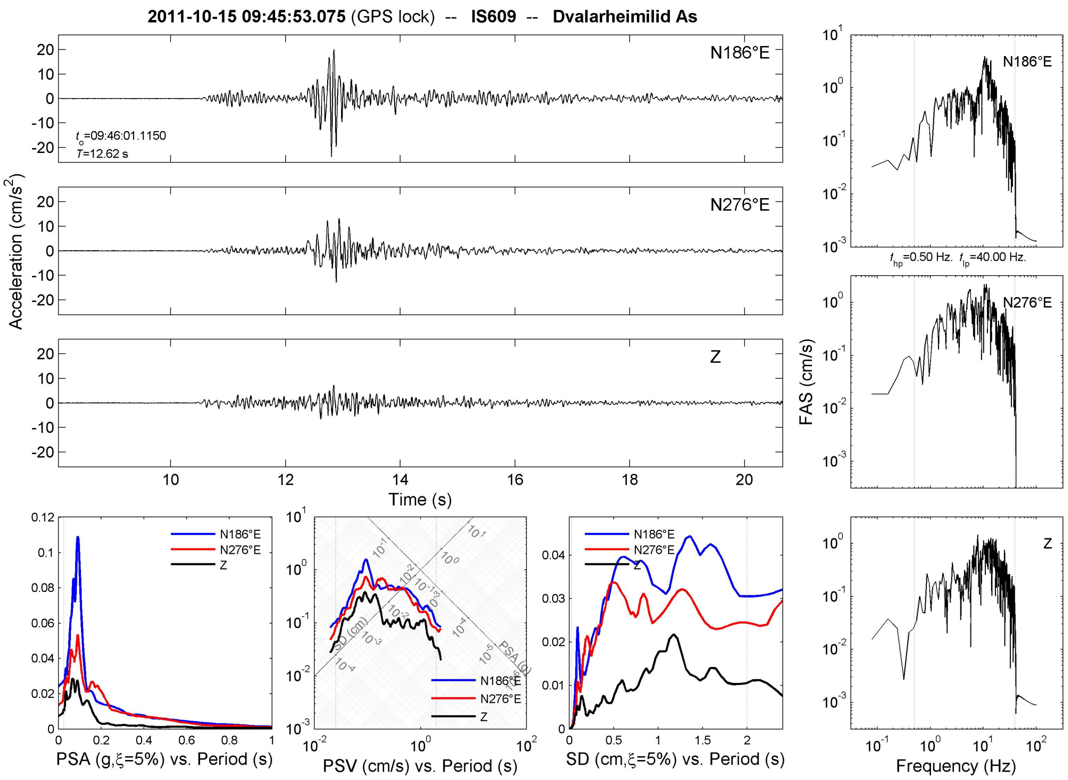

Figure 2.5. Ground acceleration during the 15 October 2011 9:45 $M_l3.8$ earthquake as recorded on ICEARRAY station IS609 on three-components, along with their respective Fourier amplitude spectra and 5% damped response spectra.

due to communication issues in the wireless telecommunication system. For this reason we confine our discussion of data to those events recorded on 10 stations or more on the ICEARRAY. Additionally, as the array system does not routinely locate earthquakes, we matched recording times on the array, accounting for time-shift due to wave propagation, with the origin times of earthquakes in the vicinity of the geothermal power plant as reported by IMO. This resulted in 85 matched events the data of which we analyze in this study. The three-component records of ground acceleration at ICEARRAY station IS609 for the two largest events are shown in Figure 2.4 and Figure 2.5, along with each component's absolute Fourier amplitude spectrum and 5% damped response spectra (pseudo-spectral acceleration, PSA; pseudo-spectral velocity, PSV; and spectral displacement, SD).

The recorded PGA values in Hveragerdi during the sequence of induced earthquakes are shown vs. time in Figure 2.3. In Figure 2.6 we show the mean PGA values (black curve) and the corresponding range of PGA values (gray shade, denoting minimum and maximum values) plotted vs. record index, where the record having the largest PGA mean value is assigned an index value of 1, and the record having the lowest has the largest index value). The figure shows that the maximum mean PGA in Hveragerdi was 17-18 cm/s^2 during the $M_L3.8$ earthquakes on 15 October 2011 at 9:02 and 9:45 (record indexes 1 and 2). The recorded PGA in Hveragerdi varied to the extent shown by the gray shaded area in the figure. We represent the variability of recorded PGA in Hveragerdi by its standard deviation for each event. The relative variability is constant regardless of the PGA amplitude, with a value of $\sigma_{\log A} = 0.16$. This is a result previously pointed out by Douglas & Halldorsson (2010) from their analysis of (a part of) the aftershock data from the 29 May 2008 Ölfus earthquake. The maximum PGA values recorded in Hveragerdi during the earthquake sequence were 32.2-32.5 cm/s^2 (3.3%g) during the $M_L3.8$ earthquakes on 15 October 2011 at 9:02 and 9:45.

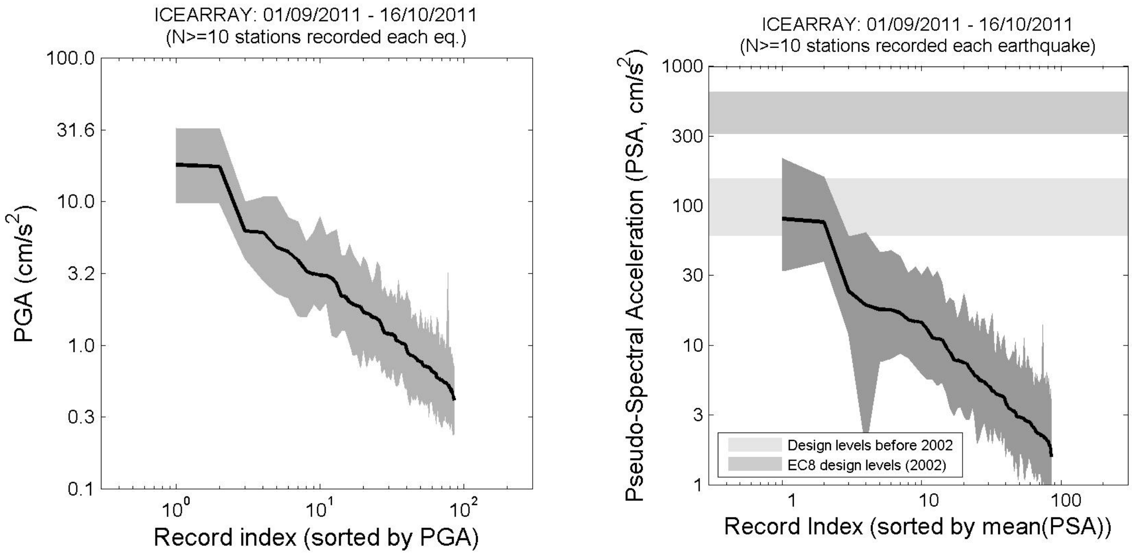

Figure 2.6. Left: The range of horizontal peak ground acceleration recorded on the ICEARRAY (grey shaded region) plotted vs. record index (sorted by descending mean horizontal PGA value for each event, denoted by the black curve). Right: The maximum horizontal PSA values (for 2% damping, grey shaded region) vs. record index (sorted by the mean PSA for each event, denoted by the black curve).

3. EARTHQUAKE ACTION ON STRUCTURES

Earthquake provisions were first formally incorporated into building standards in Iceland in 1976 and have been improving since then. Earlier, however, in the design of important and/or multi-storey structures, the earthquake effect was accounted for by requiring the design to alleviate an equivalent static horizontal earthquake force equal to 1/15th of the building weight. In 1976 the first seismic design code in Iceland, the Icelandic Standard IST-13, was put into effect and was based on the California Uniform Building Code. For seismically active areas like the South Iceland Seismic Zone, buildings were required to withstand an equivalent static horizontal force of up to 20% g. Currently, the building authorities are adopting Eurocode 8, including the necessary National Application Documents, as the future basis for earthquake-resistant design of buildings in Iceland. According to this standard, the horizontal earthquake design load is now based on a PGA value of 40% g (392.4 cm/s^2).

The building stock in rural Iceland is predominantly low-rise, 1-2 storey single houses constructed from reinforced concrete and/or wood. In terms of their dynamic characteristics, the natural frequency of oscillation can therefore be expected to be relatively high, especially for those made of concrete (~5-10 Hz). Additionally, the structural damping is expected to be low, on the order of 2% (Snæbjörnsson & Sigbjörnsson 2006). In terms of ductility factors, older concrete structures have relatively lower ductility than newer structures. In Hveragerdi, the vast majority of structures were built prior to the implementation of Eurocode 8 design requirements for building construction. Also, a considerable portion of the structures were built with no earthquake design provisions (prior to 1976).

As a first estimate of the earthquake action on structures in Hveragerdi during the induced earthquakes, we calculate the 2% damped pseudo-spectral acceleration for each component of ground acceleration at each recording station, and for all of the events recorded on at least 10 ICEARRAY stations during the seismic sequence between 10 September and 16 October 2011. This resulted in over 2,550 individual response spectra. Both due to the lack of space and for conciseness in presentation of the results, we show in Figure 2.6 the maximum PSA value for the horizontal components of ground motion plotted vs. event index, where the event associated with the largest PSA value has an index value of 1, while the event associated with the lowest PSA value has the highest index value. For reference we denote by light grey areas the ranges of the maximum values of the earthquake design provisions for two periods: before (light-grey) and after (mid-grey) the implementation of the Eurocode 8 design criteria. The maximum design values are selected from the plateau of the design spectral shape (around an undamped natural period of 0.2 seconds). The range shown for both design criteria are based on (a) the different design requirements that were in effect before 2002 (pre-IST-13; IST-13 of 1976; IST-13 update in 1989), and (b) different structural behaviour factors of typical building classes.

4. CONCLUSIONS

The commencement of operations in the Husmuli reinjection area of the Hellisheidi geothermal power plant in southwest Iceland in early September 2011 resulted in a relatively intense sequence of induced earthquakes that were felt in the neighbouring communities, causing unrest and fear in the population. The sequence culminated in two $M_L 3.8$ earthquakes on 15 October 2011, which were widely felt, therewith raising questions regarding the potential effects of the operations of the geothermal plant on future earthquake occurrence and in particular, their potential effects.

We have analyzed the recorded data and estimated the earthquake action on buildings by evaluating the pseudo-spectral acceleration of a 2% damped linear elastic oscillator, which resembles the predominant building types in the affected region. The largest horizontal PSA values in Hveragerði were 22% g and 17% g in the two largest events, respectively. This earthquake action is equal to, and in some cases higher than, the codified design demand applied for the majority of the building stock. Thus, the induced earthquakes may have caused some progressive damage, especially to older buildings and to those that suffered the intense near-fault motion during the May 2008 $M_w 6.3$ earthquake. These results may have implications for the future of operations at the Hellisheidi geothermal plant. In particular, they could affect the plans for two geothermal projects in the Hengill region, the location of which would be considerably closer to the communities of Hveragerdi and Selfoss.

ACKNOWLEDGEMENTS
This study was supported by the Earthquake Engineering Research Centre (EERC) of the University of Iceland, in Selfoss, Iceland (www.eerc.hi.is) and the Research Fund of University of Iceland. The ICEARRAY was supported by the 6th Framework of the European Commission through the Marie Curie International Re-integration Grant (no. MIRG-CT-2006-036564), the Icelandic Centre for Research (RANNIS) Project Grants (No. 60043021-3, 90049021-3). Furthermore, the Icelandic Strong-motion Network is supported by Landsvirkjun, the Icelandic Road Authority and the City of Reykjavik. The first author is grateful to Dr. Gunnar Gunnarsson of Reykjavik Energy (Orkuveita Reykjavíkur) for providing and granting permission to use the reinjection data.

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