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Learning from recent destructive earthquakes in Iceland

Apprendre des récents séismes destructeurs en Islande

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ABSTRACT: In June 2000 two Mw6.5 earthquakes occurred in the middle of the largest agricultural region in Iceland and in May 2008 the region was hit again by a Mw6.3 event. The maximum inter-epicentral distance between these quakes was 38 km. The geology in Iceland is young and quite special and there are sites where stiff lava overlays sediments or soft sediment layers are sandwiched between lava layers. Strong motion data were recorded at a number of stations in the 2000 and 2008 events and valuable information about ground motion attenuation and site amplification were obtained. Furthermore, in each case nearly 5000 residential buildings were affected. A great deal of damage occurred but no residential buildings collapsed and there were no fatalities. Insurance against natural disasters is compulsory for all buildings and all properties are registered in a comprehensive inventory database. Therefore, to fulfil insurance claims, a field survey was carried out and a complete building-by-building loss database was established after the 2000 events and the 2008 quake which is international unique. Based on the loss databases seismic vulnerability models have been developed. The loss data and the models show that the overall seismic performance of the Icelandic buildings was outstanding. Timber buildings behaved best, then the RC buildings, whilst the masonry buildings were most vulnerable.

RÉSUMÉ: En juin 2000, deux tremblements de terre de Mw6,5 se sont produits au centre de la plus grande région agricole d'Islande et, en mai 2008, ils ont de nouveau été frappés par un événement de Mw6,3. La distance interépique maximale était de 38 km. La géologie est jeune et assez particulière et il existe des sites où de la lave raide recouvre des sédiments ou des couches de sédiments mous sont prises en sandwich entre les couches de lave. Des données de mouvement fortes ont été enregistrées sur le nombre de stations obtenues lors de ces événements et des informations précieuses sur l'amplification de site, l'amplification de site. De plus, dans chaque cas (c'est-à-dire en 2000 et 2008), près de 5000 bâtiments résidentiels ont été touchés. De nombreux dégâts ont été causés, mais aucun immeuble résidentiel ne s'est effondré et aucun décès n'est survenu. L'assurance contre les catastrophes naturelles est obligatoire pour tous les bâtiments et ils sont tous enregistrés dans une base de données complète sur les biens. Par conséquent, pour compléter les réclamations d'assurance, une enquête sur le terrain a été effectuée et une base de données complète des pertes par bâtiment a été créée après les événements de 2000 et le tremblement de terre de 2008. Sur la base de la perte de bases de données, des modèles de vulnérabilité séismique ont été développés. Les modèles, reflétant les données, montrent que la performance globale des bâtiments islandais était exceptionnelle. Les bâtiments en bois se sont bien comportés, puis les bâtiments du CR, tandis que les bâtiments en maçonnerie étaient les plus vulnérables.

Keywords: Seismic hazard, attenuation, site amplification, vulnerability, fragiltiy, low-rise buildings.

1 INTRODUCTION

In north Europe seismic hazard is highest in Iceland and comparable to what is experienced in South Europe (Italy, Greece, Romania and Turkey). The seismicity in Iceland is related to the Mid-Atlantic divergence plate boundary that crosses the country with an average relative plate movement of 2 cm/year (Einarsson 1991; 2008). Since 1700 about 25 earthquakes in the magnitude range 6.0-7.0 have occurred in the country and caused extensive damage to buildings and infrastructure (Halldórsson et al. 2013; Bessason & Rupakhety, 2018). The last three destructive earthquakes struck in 2000 and 2008 in the built environment in South Iceland and caused extensive damage to buildings and infrastructure, although no buildings collapsed and there were no fatalities. The geology of Iceland is quite special due to volcanism and glacier impact, including rapid sediment transport and build-up in sub-glacial outburst floods as well as sandwiched lava and sediment layers. On a geological scale both rock and sediments are quite young. All this affects seismic wave propagation, attenuation, soil amplification, liquefaction potential and in general seismic site response. The main aim of this paper is to give an overview of lessons learned from recent destructive earthquakes from a geotechnical and earthquake engineering point of view.

2 SEISMIC HAZARD

Within Iceland most of the damaging earthquakes are strike-slip events at shallow depth (<10km) occurring in two complex fracture zones. The first is called the South Iceland Seismic Zone (SISZ) and is in the middle of the largest agricultural region in the country. The second is called the Tjörnes Fracture Zone (TFZ) and is mainly offshore in north-east Iceland (Einarsson 1991; 2008). Since 1700 around 25 destructive earthquakes in the range of magnitude 6.0 to 7.0 have occurred in these two zones (Fig.1). They tend to occur in sequences and therefore structures may be exposed to strong ground motion from more than one event within a few days. For instance, in 1896 five destructive earthquakes ($M_S \geq 6.0$) occurred in two weeks with a maximum inter-epicentral distance of 40 km.

According to Eurocode 8 and the Icelandic National Annexes for Eurocodes (2010) the reference peak ground acceleration in both these zones is $a_{R,g}$=0.5g and refer to a seismic event with a 475 year return period.

In June 2000 two destructive earthquakes struck in the SISZ and in May 2008 another strong earthquake hit the region. Time series and response spectra from these events recorded by the Icelandic Strong Motion Network are available in the ISESD database (Ambrayses et al., 2002)

2.1 The two June 2000 earthquakes

In June 2000 two shallow earthquakes of Mw6.5 struck in the SISZ (Fig. 1). The first occurred on 17 June, 2000, 15:41, (GMT) in the eastern part of the zone. It was a right-lateral strike-slip quake, with fault striking in the north-south direction and had a focal depth of 6.3 km. The second earthquake, also Mw6.5, struck on 21 June, 2000, at 00:52, (GMT) further west. It was also a right-lateral strike-slip quake, with the fault striking in the north-south direction and with a focal depth of 5.3 km. The highest recorded PGA in these two events was 0.84g (Thorarinsson et al. 2002).

2.2 The May 2008 earthquake

In May 29, 2008, a shallow Mw6.3 earthquake struck in the western part of the SISZ, called the Ölfus earthquake (Fig. 1). It consisted of a slip on two separate faults. The first was initiated on the eastern fault, and the wave propagation from it triggered a slip on the western fault about one second later. In the Icelandic Strong Motion Network, the maximum PGA recorded was 0.66 g in Hveragerdi, whilst in the village of Selfoss the recorded PGA was 0.54 g. However, in the new small-aperture strong-motion array in the village of Hveragerdi, ICEARRAY, values as high as 0.88 g, were recorded (Halldórsson, Sigbjörnsson, 2008).

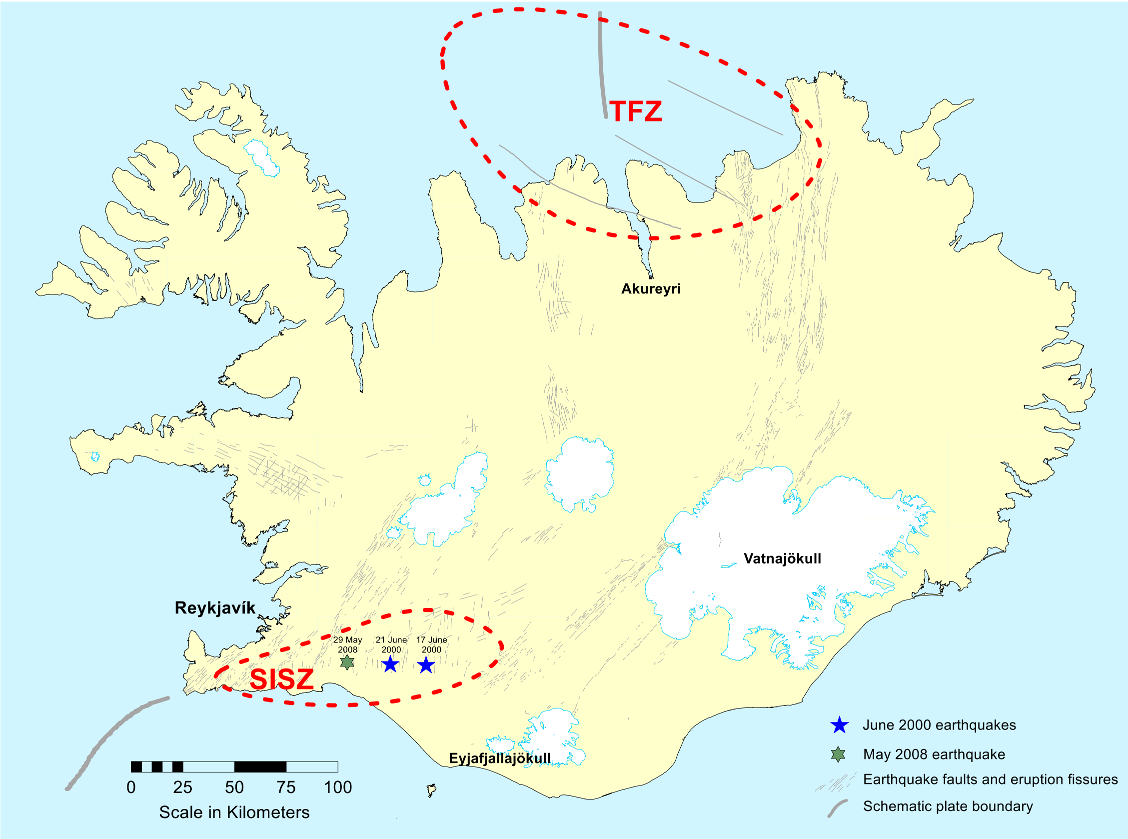

Figure 1. Map of Iceland showing the South Iceland Seismic Zone (SISZ) and the Tjörnes Fracture Zone (TFZ) along with epicentre of the 2000 and 2008 earthquakes in the SISZ. The map is based on data from the National Land Survey of Iceland.

3 LEARNING FROM EARTHQUAKES

The three destructive earthquakes in June 2000 and May 2008 in the SISZ gave valuable data that have been studied and analysed by different research groups focusing on different research topics. Lessons from these events are of great value for disaster planning, in preparation for mitigation and retrofit programmes, as well as to improve seismic design and increase the resilience of the built environment.

3.1 Attenuation models

Recorded data from the Icelandic strong motion acceleration array have been used in recent years to develop site-specific ground motion prediction models (GMPE). The main characteristic of these models is that they predict relatively high peak ground accelerations (PGA) in the near fault area whilst the attenuation with distance is more than generally found GMPE from other regions. This higher attenuation with distance in Iceland has been explained by the existence of young, fissured and relatively weak rock in the seismic source area that dampens the propagating seismic waves faster than in more solid rock (Sigbjörnsson et al., 2009; Rupakhety, Sigbjörnsson, 2009; Ólafsson 2013; Kowsari et al., 2019).

3.2 Near fault effects

In both the June 2000 Mw6.5 earthquakes strong near-fault pulses were observed at a number of strong ground motion stations in the SISZ (Halldórsson et al., 2007). Such pulses are of particular of concern for structures with long natural periods like long span bridges and high rise buildings. In the May 2008 earthquake (Mw6.3) near fault pulses were also observed (Rupakhety, Sigbjörnsson, 2011). The base-isolated Óseyrar Bridge, located at the south end of the western fault of the 2008 Ölfus earthquake (see Fig. 1), experienced some damage which was related to near-fault motion (Jonsson et al. 2010).

According to Eurocode 1998-1:2004 (*Seismic Rules for Buildings*) near source effects should be taken into account for base-isolated buildings belonging to Importance class IV if they are located at a distance less than 15 km from the nearest potentially active fault where earthquakes of magnitude $M_S \geq 6.5$ can be expected. These examples from South Iceland indicate that lower magnitude earthquakes (<6.5) are also generating near-fault pulses which are of concern for structures. Fortunately, most of the buildings in the near-fault region in the SISZ and TFZ are low rise with short natural periods and were therefore not affected by this phenomenon.

3.3 Site amplification

The geology of Iceland is special. There are sites where lava overlays sediments or where soft sediments layers are sandwiched between lava layers. The overall site response is then controlled by the sediment layers, and the average property of the profile becomes irrelevant. The average shear wave velocity in the upper 30 m, the $V_{s,30}$ parameters, used in the present version of Eurocode 8, is then quite misleading. This was demonstrated in a case study after the June 2000 earthquakes (Bessason, Kaynia, 2002). At one strong motion measurement site, the Thjorsa Bridge site, the geology is quite different on the two sides of the 80 m wide river canyon. Geotechnical borings have shown that on the east side there is solid bedrock all the way to the surface, whilst on the west side a 10 m thick lava layer overlays 18-20 thick alluvial sediments (Fig. 2). The ground motion was monitored on both sides of the canyon by triaxial accelerometers during the June 2000 earthquakes when the main shocks as well as a number of aftershocks were recorded. The study presented by Bessason and Kaynia (2002) showed that the ground motion was significantly more intense on the site with lava-rock overlying the alluvial deposits compared to the one with a classical bedrock site. The study used recorded acceleration time histories from both the two main earthquakes (Mw6.5 and 6.5) and eight

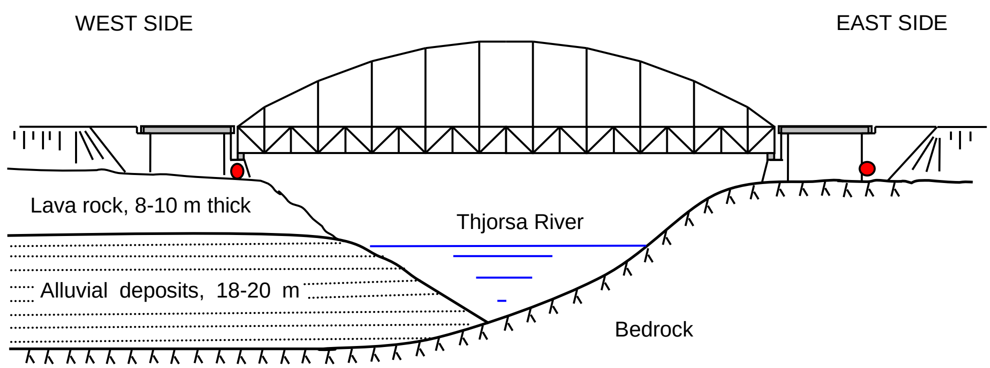

Figure 2: Schematic drawing of the Thjorsa Bridge site showing the different soil profiles on each side of the river. The red dots (•) show the location of triaxial accelerometers in the abutments.

aftershocks in the magnitude range of 3.1 to 5.0. The study affected the selection of the site for a new bridge crossing the Thjorsa which was located about 700 m downstream from the old bridge where the same type of bedrock was found on both sides of the river canyon.

More recent studies have shown similar effects on sandwiched lava sites (Rapheyna et al., 2017, Sigurdsson et al. 2017).

3.4 Liquefaction and landslides

Liquefaction and landslides have not been a major problem in historical or more recent earthquakes. However, in the old sagas and documents there are some descriptions of the phenomenon. In 1749, for instance, it is revealing that a church in South Iceland had a settlement of more than 1 m. In the 2000 earthquakes there were some very few examples of damage due to the settlement of the foundations of power transmission masts as well as damage to road fillings due to lateral spreading. Marks of sand boils were also observed close to the Ölfus River in the aftermath of the May 2008 event (Solnes et al. 2013). Finally, it can be mentioned that both rock falls and landslides, and even snow avalanches, have occurred during major earthquakes, but mostly, due to spread settlement and low population, these events have not caused losses or fatalities (Solnes et al. 2013).

3.5 Seismic vulnerability

3.5.1 Buildings

The SISZ crosses the South Iceland lowland, which is the largest agricultural region in Iceland, with number of small towns, farms, and all the infrastructure of modern society. Although this area has been hit by a number of destructive earthquakes since the settlement of Iceland around 900 AD the total population has always been low on an international scale and consequently fatalities, injuries and losses have always been low. Single-storey turf and stone houses dominated before 1900 AD (Fig. 3) and, although these houses collapsed, they were easily rebuilt and the losses were limited.

Construction of modern types of buildings started in the twentieth century, along with denser settlement (Fig. 4). In 2008, when the last destructive earthquake (Mw6.3) hit the area. the population was around 18,000. The great majority of the buildings have been built after 1940, though the oldest one is from around 1875.

Figure 3: Turf and stone building from 1900.

Figure 4: RC wall building from around 2000.

Those built before 1940 are mostly timber houses. Between 1940 and 1960 it was common to build RC buildings as well as special buildings of hollow pumice blocks which can be classified as masonry or brick buildings and have some similarities with South European masonry buildings. After 1960 RC buildings and timber dominated. The majority of the structures are in-situ-cast or in-situ-built buildings, although buildings using prefabricated elements exist. The lateral load-bearing system is dominated by structural walls. The first seismic codes were implemented in Iceland in 1976 and the Eurocodes were implemented in 2002. Most of the buildings are low-rise single-family dwellings or town houses, with one to two storeys being dominant. A few buildings can be classified as multi-family apartment blocks and of those none is taller than five storeys.

All buildings in Iceland are registered in a comprehensive official property database which contains information about construction age, main building material, number of storeys, geographical coordinates and official replacement value (www.skra.is). In 2000 around 50% of all residential buildings in the SISZ were low rise RC buildings, 40% low rise timber buildings, and 10% low rise masonry buildings. Taking the country as a whole, the percentages differ and the RC buildings dominate (Bessason, Rupakhety, 2018).

Insurance against earthquakes is compulsory for all buildings in Iceland (www.nti.is). Therefore, to evaluate insurance claims, field surveys are carried out after destructive earthquakes to estimate damage and repair costs of all affected structures.

The property database and the insurance loss surveys make it possible to map damage accurately in the aftermath of earthquakes and construct dwelling-by-dwelling or building-by-building loss databases. This was done in the aftermath of the June 2000 and May 2008 earthquakes where nearly 5000 residential buildings were affected in each case, i.e. where the estimated PGA was ≥ 0.05g based on site-specific GMPE. A great deal of damage occurred but no residential buildings collapsed, and there was no loss of life. These complete loss databases have been used to study the vulnerability of low-rise Icelandic buildings (Bessason et al. 2012; Bessason et al. 2014; Bessason, Bjarnason, 2016; Bessason, Rupakhety 2018; Ioannou et al. 2018). The overall performance of the Icelandic buildings has been outstanding. Timber buildings behaved best, then the RC buildings, whilst the masonry buildings were most vulnerable. This is reflected in vulnerability curves presented by Bessason and Bjarnason (2016) and Bessason and Rupakhety (2018) (Fig. 5). The damage factor, DF, on the vertical axis is defined as the ratio of estimated loss divided by replacement value. As an example, when the PGA=0.4g the DF is close to 3% for both post-1980 (built after 1980), RC and timber buildings, whilst it is close to 10% for masonry buildings.

In general, the scatter of damage between buildings even in the same area was quite high and, whilst a number of buildings had no losses, others suffered total loss (70 -100% loss) and had to be demolished and rebuilt after the earthquakes, even though they had not collapsed.

A detailed analysis of the losses showed that non-structural damage dominated the estimated repair cost for all building typologies and at all intensity levels. This was mainly cosmetic surface damage of partition walls which required paintwork, as well as damage to flooring that required replacement (Bessason, Bjarnason, 2014).

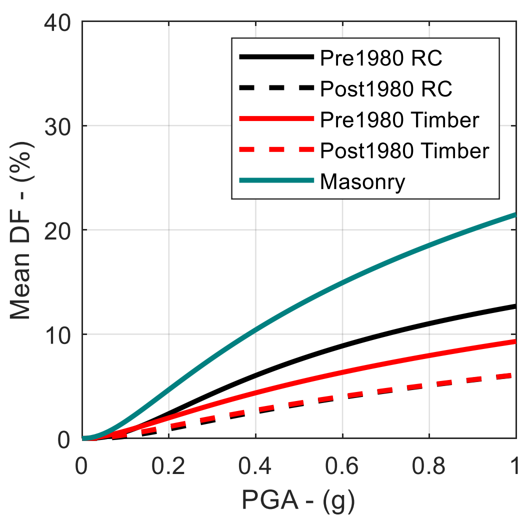

Figure 5: Empirical vulnerability curves for low-rise RC, timber and masonry residential buildings in Iceland. Pre-1980 are buildings built before 1980 and Post-1980 after 1980.

3.5.2 Bridges and roads

There are no long span bridges in the SISZ. The longest spans are less than 85 m. Most of them are short span RC beam bridges. The longest one is 360 m in 8 spans. There are also two suspension bridges (80 m span), and a steel arch bridge. No bridges collapsed during the South Iceland earthquakes of June 2000 and May 2008. There was only minor damage to a very few bridges. All main bridges built after 1980 in the SISZ are base-isolated with lead-rubber bearings. Six of them were subjected to a PGA ≥0.1 g in these events (the max PGA, 0.84 g, was recorded at the Thjorsa Bridge site. The damage was negligible to minor in all cases and all of the bridges were open for traffic immediately after these events. (Bessason, et al. 2019; Jonsson et al. 2010; Bessason, Haflidason, 2004). Some roads were damaged, especially those that were crossed by fault movements, but they were rapidly fixed and there were no road closures.

3.6 Infrastructure

There was some damage to cold water distribution systems. In the 2000 events the main pipeline between the villages, Hella and Hvolsvöllur, in the SISZ, an old brittle underground asbestos water pipeline, broke in pieces and had to be renewed with steel pipes. In the 2008 events there were also damage in the form of leakage and pollution of water springs. There was also some disturbance to communication systems, but overall this damage was minor (Solnes et al. 2013).

4 CONCLUSIONS

Recent three destructive earthquakes (Mw6.5, 6.5 and 6.3) in Iceland have given valuable information on ground motion attenuation, site response, seismic hazard, and seismic vulnerability of buildings, structures and infra-structure. In summary, all these items showed outstanding seismic performance. Larger magnitude earthquakes, up to Mw7.0 or even 7.2 can be expected in Iceland, however, and caution is needed when predicting the behaviour of structures and infrastructure in larger events. Geology, wave propagation, as well as building characteristics, differ between regions and countries and therefore it is important to learn from destructive earthquakes in each case, gather new information and disseminate it in order to reduce seismic risk and increase the resilience of the society for the benefit of the succeeding generations.

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