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Assessment of Earthquake Hazard and Seismic Risk in Iceland

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The early settlers from Norway and other Nordic countries were soon acquainted with the harsh and sometimes hostile nature in Iceland. Coming from lands where the earth is relatively quiet, and upheaval, such as earthquakes and volcanic outbursts, is practically unknown, they must have been shocked to experience sudden eruptions with lava flows destroying land and raising havoc with the livestock, not to mention sudden earthquakes, in which farmhouses collapsed with sometimes-considerable loss of life. From chronicles and the Sagas, it is evident that many farms, especially those located in the South Iceland Earthquake Zone (SISZ), were extremely vulnerable to earthquakes. Thus, for instance, it is reported that the farm Hjalli in Ölfus at the western end of the zone, and Haukadalur in Rangárvellir at the eastern boundary, collapsed or were partially destroyed about once every century in severe earthquakes. In the South Iceland earthquakes of 1784, damage and destruction of farmhouses in the first shock of August 14th was particularly severe and widespread. Even the sturdy buildings of the bishopric at Skálholt were not spared, with the result that the episcopal see and school, over 700 years after its establishment as the main cultural centre of Iceland, were relocated to the emerging national capital Reykjavik, some 70 km to the west,. The two bishops in Skálholt had local office holders compile reports on the damage of all farmhouses after the earthquakes. For the first time in Icelandic history, the affected, impoverished farmers received relief funds in proportion to the reported damage provided by the Danish King, a kind of catastrophe insurance, as we know it today. (*Júlíus Sólnes et al*., 2013, pp. 549, 574).

Our forefathers were not in a position to do much about the earthquake risk, nor did they apprehend the hazard. At the end of the 18th century, many Icelandic scholars started to compile list of historical earthquakes, the most prominent of those, Jónas Hallgrímsson, poet and natural scientist, whose Earthquake History of Iceland (*Hallgrímsson*, 1839) is found at the end of his handwritten manuscript on the history of Icelandic volcanos. Þorvaldur Thorodssen continued Hallgrímsson's work in the late 19th century, inspired by the 1896 south Iceland earthquakes, which caused extensive damage in the middle and eastern part of the SISZ (*Júlíus Sólnes et al*., 2013, pp. 579).

Thoroddsen became the first scholar to use the compiled list of historical earthquakes for producing an earthquake hazard map for Iceland (Fig. 1, *Thoroddsen*, 1905–1906). He defines five distinct earthquake zones, where large earthquakes can be expected, without considering their strength nor the actual seismic risk. No further attempts of analysing seismic risk nor providing new hazard maps were carried out until after World War II, except that *Thorarinsson* (1937) proposed a sixth zone, extending north of Dalvík on both sides of Eyjafjörður, after his studies of the 1934 Dalvík earthquake (Fig. 1).

In the late 1950s, the State Research Council entrusted a three-man commission (Eysteinn Tryggvason, seismologist, Sigurður Þórarinsson, geologist, and Sigurður Thoroddsen, civil engineer)

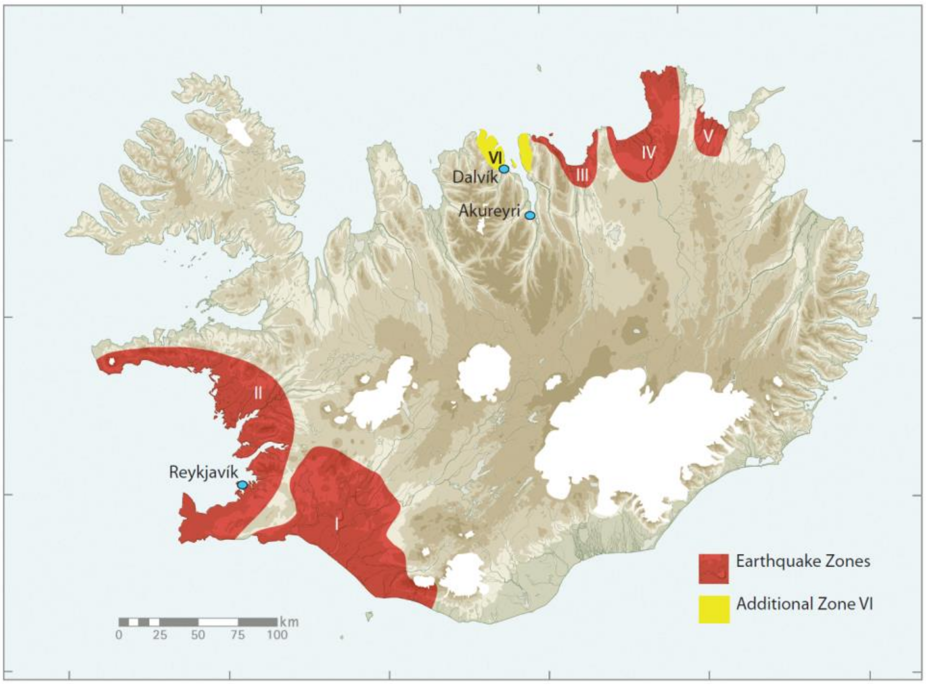

Figure 1. "Bruchlinien des Islands". The earthquake hazard map of Þorvaldur Thorodssen from 1905. He defines five different earthquake zones: I and II in South Iceland, and III, IV and V in the north. Sigurður Þórarinsson proposed to add one more zone (VI), extending from Dalvík to the north on both sides of Eyjafjörður, after the Dalvík earthquake of 1934.

to assess earthquake hazard in Iceland and produce an acceleration map suitable for defining earthquake forces acting on civil structures (*Tryggvason et al*., 1958).

The 1958 hazard map is based on Modified Mercalli intensity maps for 100, 1000 and 10.000 years, as proposed by the first author. However, actual peak acceleration calculations were not carried

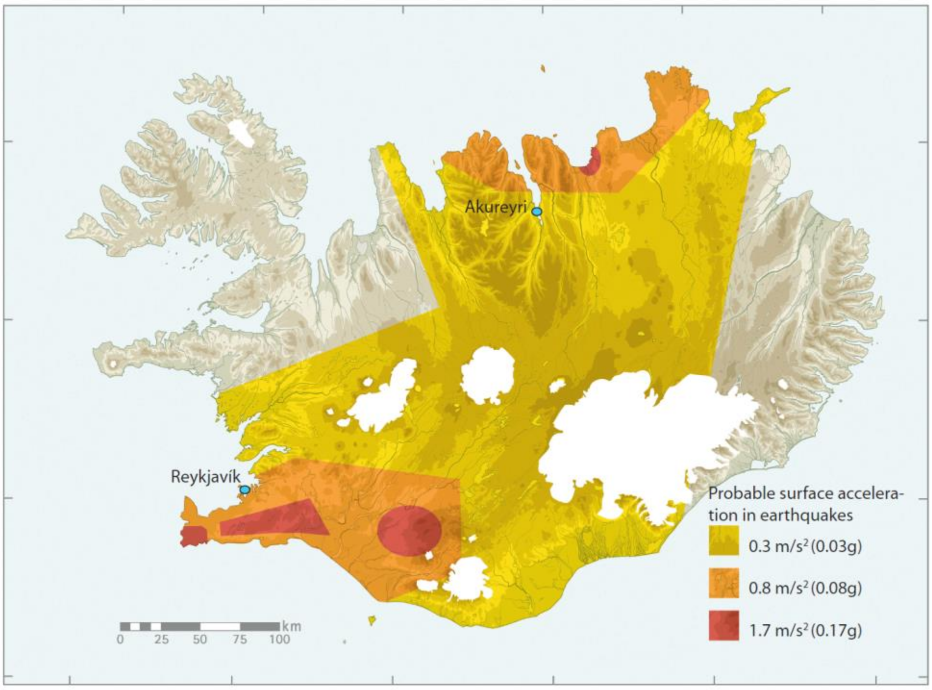

Figure 2. An earthquake hazard map proposal, showing probable maximum surface design accelerations, submitted by the Earthquake Hazard Commission 1958. No measured surface accelerations in earthquakes had been obtained in any Icelandic earthquakes at that time.

out. Thus, the map is speculative in nature, as many other earthquake hazard maps that were introduced in the following years.

The first Icelandic earthquake resistant design provisions were formally adopted in 1976 as part of the Icelandic Building Standards. A hazard map dividing the country into three earthquake exposure zones with different earthquake load factors accompanied the provisions. In 1989, the provisions were modified and a new hazard map introduced with four different load factors.

In the 1990s, preparation for implementing the new Eurocodes called for a new and more sophisticated approach to hazard assessment. The Eurocode 8 earthquake resistant design provisions are based on design peak accelerations that have 10% probability of being exceeded in a 50-year period. This is equivalent to saying that within a time interval of 475 years, the maximum surface acceleration in an earthquake in any given place will be equivalent or higher than the design peak acceleration. In other words, it has a recurrence period of 475 years.

Páll Halldórsson (1996) published one of the first hazard maps with calculated peak accelerations, which was later introduced in a slightly modified version as a suitable Icelandic attachment to Eurocode 8. This map was criticized for paying undue attention to singular events, such as the Hvítársíða earthquake of 1974 and the Vatnafjöll earthquake of 1987, which dominate parts of the map. A final version of the map was published in 2002 under the auspices of the Ministry for the environment (*Halldórsson & Sveinsson*, 2003), and formally adopted as an Icelandic annex to Eurocode 8. Although much improved, the new map shows similar weakness as the original version of 1996, according to earthquake scientists of the University of Iceland, who produced a well-documented hazard map the same year (*Sólnes, Sigbjörnsson & Elíasson, 2004*). This map has been well received by the international earthquake research community. It is based on innovative theoretical calculations, where the Brune's spectrum of an earthquake is calculated for its focal area. Applying Ólafsson´s and Sigbjörnsson's attenuation model for Icelandic earthquakes (*Ólafsson*, 2013), a corresponding Brune's spectrum may be calculated at each point in the countrywide grid, and a corresponding peak acceleration derived. Thus for all known and well-documented historical earthquakes (after 1700), and adding future simulated events as well (*Sólnes*, 1997), a series of peak accelerations are obtained for each grid point, from which statistical parameters, such as the 475 year recurrence value, are calculated.

In 2009–2010, in the aftermath of the damaging 2008 South Iceland earthquake, Viðlagatrygging (Iceland Catastrophe Insurance) organised a thorough revision of the seismic risk in Iceland in collaboration with its re-insurance broker Guy Carpenter in London. Icelandic scientists under supervision of the Catastrophe Fund's special adviser Dr Scott Steedman participated in this endeavour. The Icelandic participants collected the precisely reported loss data from the 2008 South Iceland earthquake (data from the 2000 earthquakes was also used) and helped set up a complete damage prediction model, which is connected to all buildings and structures, registered in the Official Property registry of Iceland. With this model, the expected insured damage in any earthquake scenario can be rapidly calculated (*Bessason et al*., 2012, 2014).

In order to provide a seismic risk map, which addresses the expected losses rather than the earthquake design forces, Guy Carpenter solicited the services of Dr Mohammad Zolfaghari, who provided a new seismic risk map for Iceland (Figure 3). Dr Zolfaghari used a different and unconventional approach for estimating maximum effects of earthquakes in any given area. The country was divided into 26 sub-regions to cover all known earthquake sources. A two-dimensional

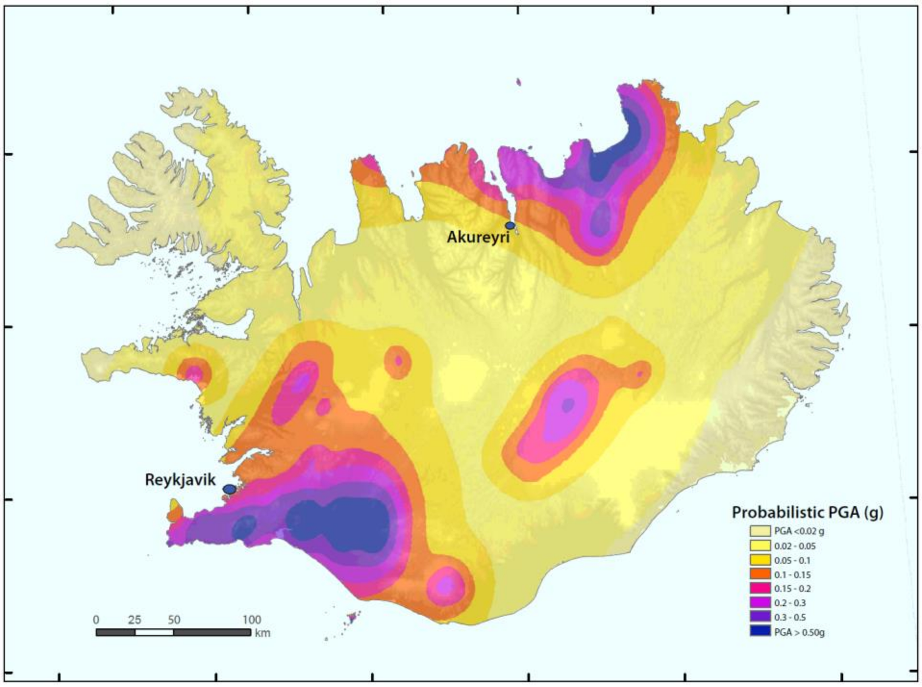

Figure 3. The Zolfaghari seimsic risk map, which has been converted to portray the probabilistic maximum peak acceleration with a 475 year recurrence period.

normal distribution is applied to simulate focal co-ordinates of possible earthquakes, using the Gutenberg-Richter magnitude-frequency relationship with different parameters as appropriate for different areas. In all, Dr Zolfaghari simulated over 27 thousand earthquakes, characteristic for the seismicity of the country. The accelerations from these earthquakes were then calculated for different grid points, using the attenuation law of *Ólafsson and Sigbjörnsson* (2013) in a similar manner as for the 2004 earthquake hazard map (*Sólnes et al*., 2004).

This work has been continued under the auspices of Iceland Catatrophe Fund, and a thorough revision of the Zolfaghari map, by refining the earthquake origins and source mechanism, is under way (*Bjarnason et al.*, 2016).

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