COMPARATIVE STUDY OF UNIFORM HAZARD SPECTRA DERIVED USING DIFFERENT GROUND MOTION ESTIMATION MODELS: A CASE STUDY

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ABSTRACT :

The aim of this paper is to compare the effects of different strong-motion estimation equations on the uniform hazard spectra. Three models are used in the comparison, which are the Campbell and Bozorgnia (2007) model, the Ambraseys et al. (2005) model and the Sigbjörnsson and Ólafsson (2004) model. The reliability of ground motion estimation equations is based on the quality of the available strong-motion data. In Iceland recorded strong-motion data is limited with the most significant seismic events recorded in being the South Iceland Lowland earthquake sequences of June 2000 and May 2008. A trend that appears to be consistent for Icelandic strong-motion data is that the recorded peak ground acceleration is very high in the near-fault zone but appears to attenuate more rapidly than models commonly applied in earthquake engineering hazard studies. The hazard curves are derived by generating a synthetic earthquake catalogue, thereby calculating the strong-motion effects induced by each event applying an appropriate ground motion estimation model and then order statistics, which can be repeated to enhance the computational stability of the results. The main findings are that, even though the deviation between the ground motion estimation models applied may seem considerable, the difference in the uniform hazard is not necessarily all that much for the study site, except in the case of models based solely on Icelandic data. Furthermore, it is found that the Eurocode 8 model spectrum of type 2 can be applied with confidence for the study area.

KEYWORDS: Hazard curves, ground motion estimation model, uniform hazard spectrum, Eurocode 8

1. INTRODUCTION

The objective of this paper is to study the effects of different strong-motion estimation equations on the uniform hazard spectra. The uniform hazard spectra are derived using Monte Carlo simulation. The main steps of the computational procedure are the following: (1) generation of a synthetic earthquake catalogue; (2) derivation of a hazard curve for the earthquake response spectrum ordinates; and (3) representation of the uniform hazard spectrum for selected mean return periods. The comparison is carried out using the difference between the uniform hazard spectra.

The ground motion estimation models considered are: (1) an analytical model based on the Brune source spectrum, originally derived using Icelandic strong-motion data; (2) the model presented by Ambraseys et al. (2005) based on an extensive strong-motion dataset for Europe and the Middle East; and (3) two models from the New Generation Attenuation of Ground Motion (NGA) Project. The models chosen are by Boore and Atkinson (2006) and Campbell and Bozorgnia (2007). They are based on a common database of worldwide strong-motion recordings provided for developers within the NGA-project (PEER-NGA database, 2007)

The study site selected is the City of Reykjavík and surrounding townships. They are located about 20 km north of the seismic delineation of the Reykjanes Peninsula where the Mid Atlantic Ridge enters the island from the southwest. Moreover, the South Iceland Seismic Zone is within 30-50 km towards the southeast. Considerable earthquake activity has been reported in the area in ancient and recent chronicles. The origin of this activity is the nearby Mt. Hengill area at the boundary of the South Iceland Seismic Zone to the east, Mt. Brennisteinsfjoll and the Sveifluhals area on the Reykjanes Peninsula. Fortunately, the earthquakes on the Reykjanes Peninsula are characterised as minor to moderate while the earthquakes originating within the South Iceland Seismic Zone are moderate to major. The faulting mechanism is predominantly strike-slip.

2. BACKGROUND

The Mid-Atlantic Ridge, the boundary between the North American and Eurasian plates, transects Iceland from the Reykjanes Peninsula in the west to the Northern Rift Zone in the northeast. On the Reykjanes Peninsula the ridge runs along it in an easterly direction delineating an area of minor to moderate seismic activity approximately 2 km wide. The peninsula, see Figure 1, is also a region of active volcanism, which is evident by the significant post-glacial lava fields, volcanic systems and fissure swarms (Thordarson and Larsen, 2007).

2.1 Volcanic systems

The Hengill Volcano is the easternmost of a series of four closely spaced basaltic fissure systems that cut diagonally across the Reykjanes Peninsula. It lies at the triple junction of the Reykjanes Peninsula Volcanic Zone, the Western Volcanic Zone, and the South Iceland Seismic Zone. Postglacial lava flows cover much of the volcanic system. The latest eruption was radiocarbon dated to about 1900 years before present. The Hengill Volcanic System, cutting through Thingvallavatn Lake, consists of a series of northeast to southwest-trending fissure vents, crater rows and small shield volcanoes occupying a strongly faulted graben.

Towards the west, the Brennisteinsfjöll Mountains are another volcanic system located east of Kleifarvatn Lake on the Reykjanes Peninsula and consist of a series of northeast to southwest-trending crater rows and small shield volcanoes. Postglacial and historical basaltic lavas cover a wide area surrounding the volcanic system. An eruption in 1000 AD was dated by its occurrence at the time of a meeting of the Icelandic Parliament at Thingvellir. The most recent eruption at the Brennisteinsfjöll Mountains took place in the 14th Century.

Further west the Krýsuvík Volcanic System is a group of northeast to southwest-trending basaltic crater rows and small shield volcanoes in the central part of the Reykjanes Peninsula west of Kleifarvatn Lake. Several eruptions have taken place since the settlement of Iceland, including a large lava flow from the Ögmundargigar craters around the 12th Century. Similar to Brennisteinsfjöll, the latest eruption from Krýsuvík Volcano also took place during the 14th Century.

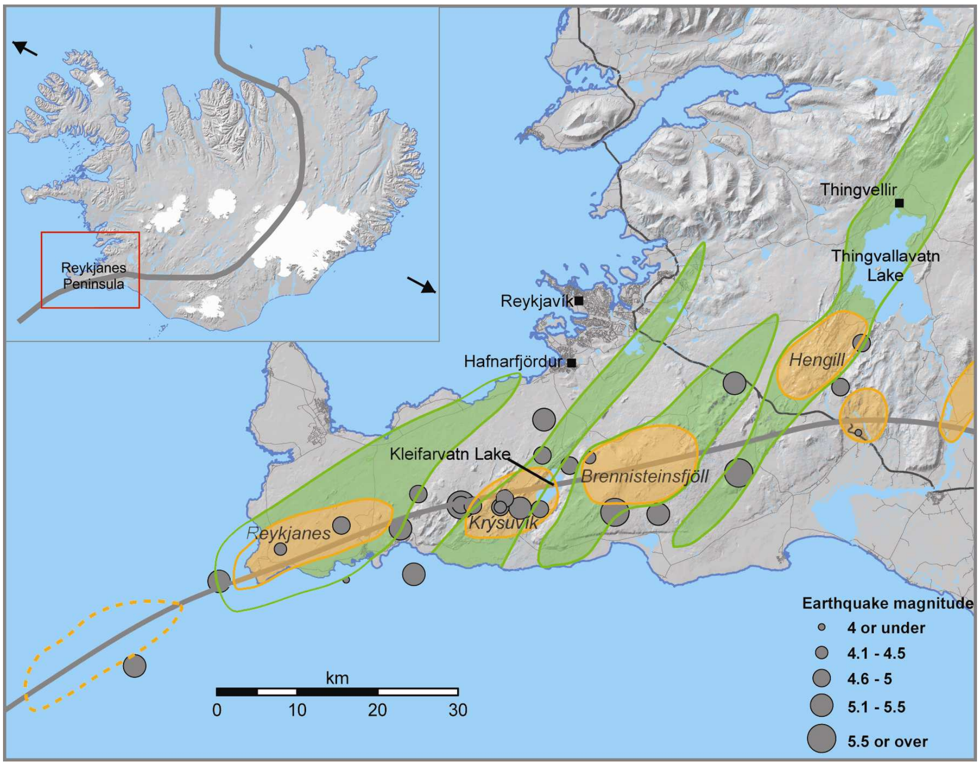


Figure 1 The Reykjanes Peninsula. Shown are main volcanic systems (orange) and fissure swarms (green) along with epicentres of significant earthquakes (grey circles). The boundary between the North American and Eurasian plates is shown in the main figure and inset (grey line). The inset map shows relative plate motions of the North American and Eurasian plates (arrows) and glaciers in white. Major roads and rivers are shown in the main figure.

The Reykjanes Volcanic System is the westernmost of the four fissure systems that extend diagonally along the Reykjanes Peninsula. Most of the volcanic system is covered by Holocene lavas and eruptions have occurred in historical times during the 13th Century at several locations on the northeast to southwest-trending fissure system. The Reykjanes Volcanic System is located on the southwest tip of the Reykjanes Peninsula, where the Mid Atlantic Ridge rises above sea level. It comprises a broad area of postglacial basaltic crater rows and small shield volcanoes.

2.2 Earthquake activity

Earthquake activity in the region can mainly be attributed to the following areas, which are judged to be of some importance to our study site:

- Offshore of the Reykjanes Ridge towards the southwest of the tip of the Reykjanes Peninsula, i.e. the Reykjanes Volcano
- The Reykjanes Volcano and the area towards the Krýsuvík Volcano
- The Krýsuvík Volcano and the area towards the Brennisteinsfjöll Mountains
- The Brennisteinsfjöll Mountains towards the Mt. Hengill area.

The offshore earthquakes originate in the rift zone of the Mid-Atlantic Ridge. These earthquakes are rather small, with magnitudes that seldom exceed 5. On land the earthquake magnitude increases towards the east. Based on experience, earthquakes with epicentres at the Brennisteinsfjöll Mountains may exceed magnitude 6, while earthquakes around Krýsuvík Volcano and Reykjanes Volcano are significantly smaller. Due to volcanism and geothermal activity the tectonic strain in the subterranean heated rock is relaxed, whereby the accumulated strain energy released during an earthquake is smaller than otherwise expected. Earthquakes in this area can be characterised as having a predominant strike-slip faulting mechanism.

Seismic activity on the Reykjanes Peninsula has been significant during the last two centuries but mainly consisting of minor to moderate sized earthquakes. In the period of instrumental recordings, a few moderate sized significant earthquakes have occurred on Reykjanes Peninsula. The most noteworthy are listed below and identified by year, date, time of origin, epicentre (latitude and longitude) and surface wave magnitude (Ambraseys and Sigbjörnsson, 2000):

1920 May 14 17:57 64.00 -22.00 5.16
During the period of 14 to 30 May, an earthquake sequence shook Southwest Iceland. In Reykjavík the main shock overturned loose objects. No significant damage was reported.

1924 Sep 04 16:01 63.90 -22.05 5.26
An earthquake was widely felt in Southwest Iceland. It was preceded and followed by many smaller earthquakes. In Krýsuvík, the motion was so violent that people outdoors could not stand. However, no significant damage to buildings was reported. A new solfatara formed south of Kleifarvatn Lake. In Reykjavík, the earthquake was described as rather strong and people were woken up. In Hafnarfjördur, south of Reykjavík, people were startled and evacuated their houses. The macroseismic epicentre was close to Krýsuvík.

1924 Dec 12 02:20 63.80 -22.80 5.24
An earthquake was felt on Reykjanes Peninsula and in Reykjavík, followed by smaller earthquakes. Its effects are described as slight in Reykjavík. Some damage was reported at the Reykjanes lighthouse. The macroseismic epicentre was probably located southwest of Reykjanes (not far from the lighthouse).

1929 Jan 6 00:02 63.70 -23.00 5.41
An earthquake was widely felt on the Reykjanes Peninsula and was perceptible in Reykjavík (MMI IV) but not mentioned in local newspapers. A series of earthquakes preceded and followed it.

1929 Jul 23 18:43 63.90 -21.70 6.31
An earthquake was felt throughout large areas of south, west and north Iceland. The effects in Reykjavík are described as strong or very strong. Buildings in Reykjavik made of stone (dolerite) sustained some damage. Some cracks developed in walls and slabs of concrete buildings. A few chimneys fell down. Windows broke in some places, and a lot of glassware was destroyed. People ran outdoors. The pier in the harbour was damaged. A wave was observed in Thingvallavatn Lake moving northeast with great speed. The macroseismic epicentre of this earthquake was in Brennisteinsfjöll Mountains. The earthquake was followed by several aftershocks, the largest of which was a magnitude 5.35.

1933 Jun 10 12:07 63.90 -22.20 5.69
A series of earthquakes was felt in Southwest Iceland. The biggest earthquake was felt as far north as approximately 250 km away and as far east as around 80 km away. The greatest impact was on a farm near Krýsuvík. The maximum effects experienced in Reykjavík were MMI V.

1968 Dec 5 09:44 63.90 -21.81 5.97
An earthquake with its epicentre on Reykjanes Peninsula was felt from throughout west and south Iceland, as far east as approximately 200 km away. The earthquake did not cause any significant damage in Reykjavík or Hafnarfjördur, just south of Reykjavík. A blackout occurred in Hafnarfjördur, lasting a few minutes after the earthquake.

3. METHODOLOGY

The methodology applied follows the main stream in seismic hazard analysis (McGuire, 2004). The hazard curves are derived by generating a synthetic earthquake catalogue, thereby calculating the strong-motion effects induced by each event applying an appropriate ground motion estimation model and then order statistics. This procedure can be repeated many times to enhance the computational stability of the results.

The generation of the synthetic earthquake catalogue depends on reliable earthquake catalogue data. In the current case the available data is primarily the catalogue compiled by Ambraseys and Sigbjörnsson (2000) covering the period after 1896. For this period we have instrumental data which gives a catalogue for the study area with a reasonable degree of completeness. However, the period is too short to give a catalogue with the desired reliability. The main parameters characterising the seismicity of the study site are taken to be the following (see Ambraseys and Sigbjörnsson, 2000): the Gutenberg-Richter parameters are $\alpha = 10.31$ (referred to 100 years) and $\beta = 1.57$. Furthermore, the maximum magnitude is assumed to be 6.5 and the minimum magnitude applied is 4. These parameters are, without doubt, disputable but are believed to give a reasonable basis for the current comparative study emphasising various ground motion estimation models.

The reliability of the ground motion estimation equation is based on quality of the available strong-motion data. It must be stressed that the strong-motion data recorded in Iceland is limited. The first major event recorded by the Icelandic Strong-motion Network was a magnitude 6 earthquake in 1987 with its epicentre south of Mt. Hekla. By far the most important seismic events recorded in Iceland to date are the South Iceland earthquake sequences in June 2000 (Sigbjörnsson et al., 2007) and May 2008 (Sigbjörnsson et al., 2008). The strong-motion data is available online at the Internet Site for European Strong-motion Data (ISESD) www.isesd.hi.is (Ambraseys et al., 2004). Altogether the database contains only four events with a magnitude equal to or greater than 6, all with epicentres in the South Iceland Lowland. On the Reykjanes Peninsula there are only small recorded earthquakes west of the Hengill area. We have therefore assumed that the ground motion models applicable to the South Iceland Lowland can also be applied to earthquakes originating on the Reykjanes Peninsula.

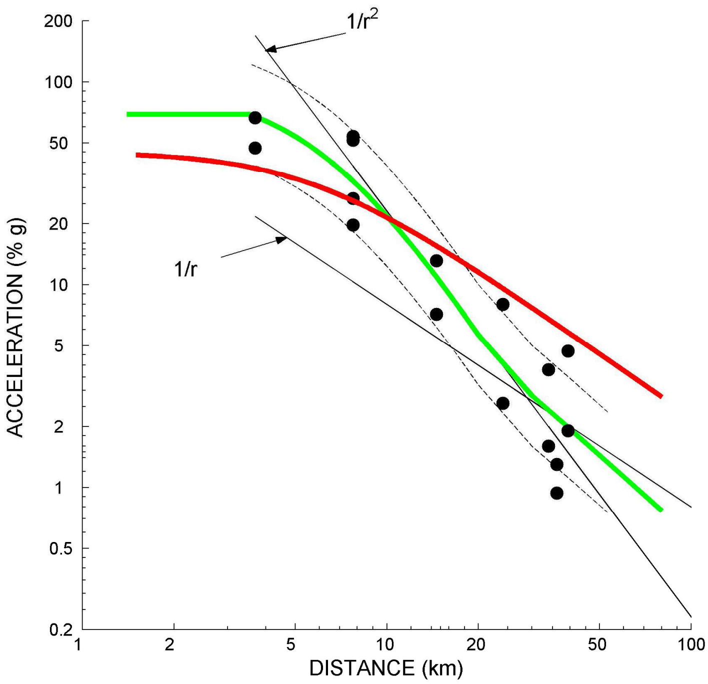


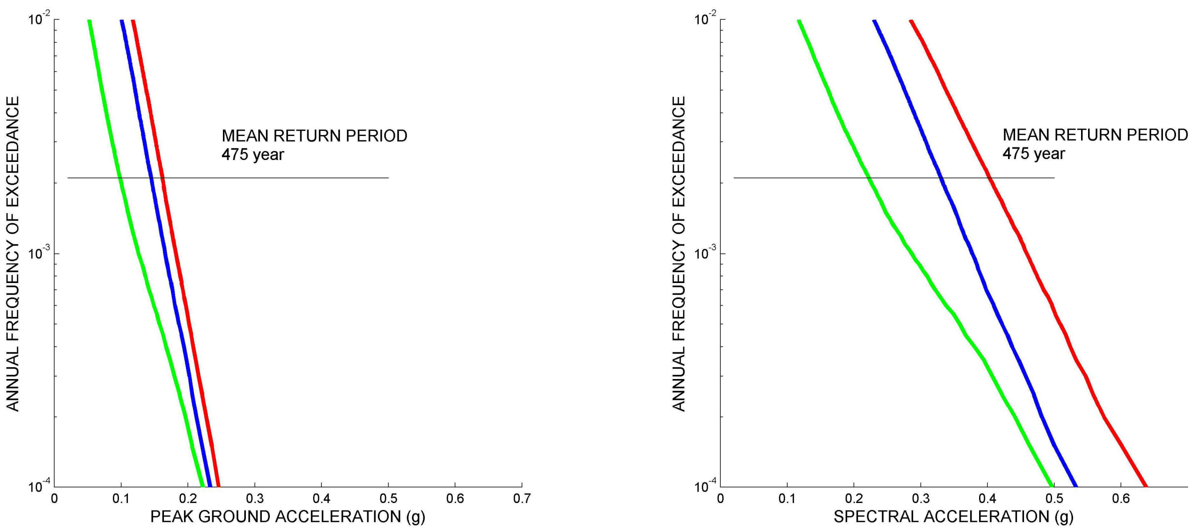
Figure 2 Ground motion estimation equation and accelerometric data (black dots) recorded by the Icelandic Strong-motion Network in the 29 May 2008 M_w 6.3 earthquake (Sigbjörnsson et al., 2008). The green curve is a theoretical model suggested by Sigbjörnsson and Ólafsson (2004), the black dashed curves indicate root mean square error of the data, the black lines indicate typical slopes of the attenuation curves (r being a distance measure), and the red curve is the new generation attenuation model by Campbell and Bozorgnia (2007).

Figure 2 indicates the trend that appears to be consistent for Icelandic strong-motion data. Here we see that the recorded peak ground acceleration is very high in the near-fault zone but appears to attenuate more rapidly than models commonly applied in earthquake engineering hazard studies (Douglas, 2003). In the figure these models are represented by the 'new generation attenuation' equation by Campbell and Bozorgnia (2007). The tendency is to underestimate the acceleration for short distances and overestimate it for long source distances. The model developed especially for shallow, strike-slip earthquakes in Iceland (Sigbjörnsson and Ólafsson, 2004) seems, on the other hand, to fit the data fairly well. To take the limited Icelandic strong-motion data into account we have therefore included in this study the models developed by Ambraseys et al. (2005), which are derived using a dataset containing the Icelandic data.

4. RESULTS

The obtained hazard curves are exemplified in Figure 3, showing peak ground acceleration values and response spectrum values, respectively. We observe that the model of Ambraseys et al. (2005) (blue curves) on one side and Campbell and Bozorgnia (2007) (red curves) on the other appear to give fairly consistent results for peak ground acceleration (PGA) (see Figure 3a). The model by Sigbjörnsson and Ólafsson (2004) gives significantly smaller PGA values, except for the longest mean return period considered. For a mean return period equal to 475 years (typical for Eurocode 8) this value is only 2/3 of the value obtained by the Campbell and Bozorgnia model.

The response spectrum values are exemplified in Figure 3b for a system with a 5 Hz natural period and 5% critical damping ratio. This natural period is taken to be representative for Icelandic low-rise buildings and the selected damping ration is in accordance with the reference value in Eurocode 8. In this case a significant difference is emerging between the hazard curves obtained by the Ambraseys et al. (2005) model (blue curves) on one side and the Campbell and Bozorgnia (2007) model (red curves) on the other. Also, in this case the Sigbjörnsson and Ólafsson (2004) model gives the lowest values, which are only roughly half of those obtained by the Campbell and Bozorgnia model. This difference calls for a more thorough study.



(a) (b)

Figure 3 Hazard curves. (a) Peak ground acceleration. (b) Spectral acceleration for a system with a 5 Hz natural period and 5% critical damping ratio. The following colour legend is used: red – Campbell and Bozorgnia (2007) model; blue – Ambraseys et al. (2005) model; and green - Sigbjörnsson and Ólafsson (2004) model for shallow strike-slip earthquakes in Iceland.

A comparison of the obtained uniform hazard spectra and the Eurocode 8 model spectra is given in Figure 4. Here it is seen that the uniform hazard spectrum obtained using the Campbell and Bozorgnia (2007) model falls between the Eurocode type 1 and 2 model spectra. The Ambraseys et al. (2005) model on the other hand gives a uniform hazard spectrum that is close to the Eurocode type 2 model. Taking into consideration the limited Icelandic strong-motion data it seems that the Eurocode type 2 model might be applicable for our study site, which seems reasonable, taking into consideration that the area can be characterised as a low to moderate seismic area.

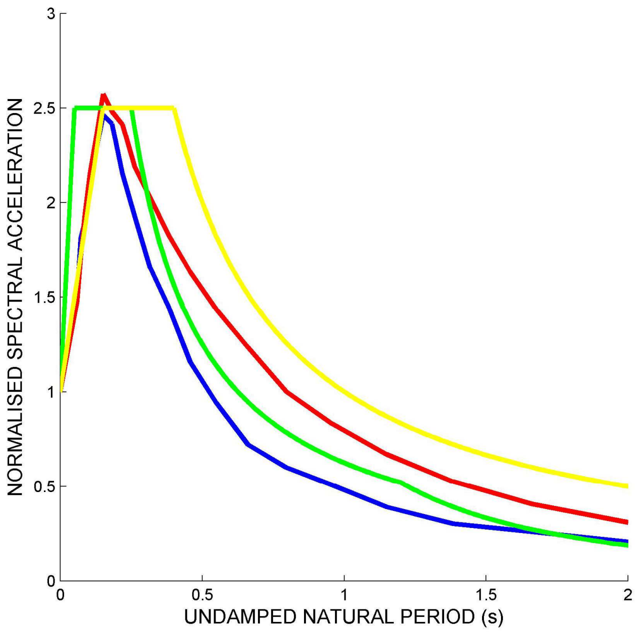


Figure 4 Comparison of normalised uniform hazard spectral acceleration to the Eurocode 8 spectral curves. The following colour legend is used: red – Campbell and Bozorgnia (2007) model; blue – Ambraseys et al. (2005) model; yellow – Eurocode 8 type 1 spectrum; and green - Eurocode 8 type 2.

5. CONCLUSION

The Ambraseys et al. (2005) and the Campbell-Bozorgnia (2007) ground motion estimation models appear to give, broadly speaking, similar results for the peak ground acceleration hazard, even though the Campbell-Bozorgnia model tends to give slightly higher acceleration, especially for the spectral acceleration. The ground motion models derived from Icelandic data give, on the other hand, significantly lower peak ground acceleration values, which apparently also applies to other similar models derived using comparable internationally based data sets.

The behaviour of Icelandic earthquakes differs from that predicted by models describing shallow strike-slip earthquakes in that the recorded peak ground acceleration is very high in the near-fault zone but appears to attenuate more rapidly than models commonly applied in earthquake engineering hazard studies. In these studies there seems to be a tendency to underestimate the acceleration for short distances and to overestimate it for long distances.

If the attenuation reflected in the Icelandic strong-motion data describes the reality, the economic consequences might be significant taking this into consideration instead of using mainstream ground motion estimation models, although the damage in epicentral areas could be less than expected using mainstream models. For areas that are more than 15-20 km outside the epicentral area of moderate sized earthquakes peak ground acceleration is seen to attenuate to less than 20% g according to the Sigbjörnsson and Ólafsson (2004) model, which fits the data fairly well. Finally, the comparison indicates that the Eurocode 8 model spectrum of type 2 is more appropriate for the study site than type 1 spectrum.

ACKNOWLEDGEMENTS

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