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ON THE PROBABILISTIC SEISMIC HAZARD ESTIMATE FOR HUSAVIK, NORTH ICELAND, ON THE BASIS OF MONTE CARLO METHODS

M. Kowsari(1), B. Halldorsson(2), J. Þ. Snæbjörnsson(3)

(1) *Ph.D. Student, Earthquake Engineering Research Centre & Faculty of Civil and Environmental Engineering, School of Engineering & Natural Sciences, University of Iceland, Selfoss, Iceland. milad@hi.is*

(2) *Research Professor & Director of Research, Earthquake Engineering Research Centre. Faculty of Civil and Environmental Engineering, School of Engineering & Natural Sciences, University of Iceland, Selfoss, Iceland, skykkur@hi.is*

(3) *Professor, School of Science and Engineering, Reykjavík University, Iceland. jonasthor@ru.is.*

Abstract

Húsavík, the second largest town in North Iceland, is effectively located, directly on top of the Húsavík–Flatey Fault (HFF), the largest transform fault in Iceland. The diverse geology and topography under the town is likely to contribute to localized differences in site effects and spatially variable earthquake strong-motions, indicating significant relative differences in seismic risk to its inhabitants. Previous earthquake hazard estimates of this region have relied on a single ground motion model and incorporated uncertainties in a limited way, but pointing out several ways to improve the hazard estimates. In this paper, a probabilistic seismic hazard analysis (PSHA) of the area of Húsavík in terms of peak ground acceleration (PGA) and spectral accelerations (SA) is presented using the Monte-Carlo (MC-PSHA) and Cornell-McGuire (CM-PSHA) methods, respectively. We considered different ground-motion models and selected the best model based on data-driven approaches. Both aleatory and epistemic uncertainties are taken into account. Moreover, the disaggregation of the seismic hazard is carried out to identify hazard-dominating events. The presented results shed further light on the earthquake hazard of Húsavík with implications for the associated seismic risk.

Key words: Húsavík, PSHA, Monte Carlo method.

1. Introduction

Probabilistic seismic hazard analysis (PSHA) is a relatively straightforward process for the estimation of long term probabilities of ground motion exceedance at a given site over a given recurrence interval. Different source of uncertainties can be identified, quantified and combined through a rational framework provided by PSHA [1]. Consequently, these useful information are transferred into seismic risk studies to mitigate the destructive impact of earthquakes, risk management and decision making. The current approach of PSHA evaluates the probability of exceeding the intensity measures of interest focusing on delineation of seismic sources, definition of seismicity and ground motion models (GMMs). The input parameters for such an analysis are seismicity parameters which are derived from an earthquake catalogue of the region under study. However, most earthquake catalogues are contaminated by uncertainties associated with size, space and time of earthquakes, which might result to the imprecise estimation of seismic hazard. To overcome this problem, Monte-Carlo simulation can be used to generate and extend the earthquake catalogue, thus reducing historical bias. The Monte-Carlo PSHA (MC-PSHA) involves taking a standard seismic source model and using it to generate a large number of synthetic catalogue representing possible future outcomes of regional seismicity in a period representing the lifetime of the structure being designed [2]. The MC-PSHA has been comprehensively used in different parts of the world [2–9]. The solution provided is the same as the Cornell-McGuire approach (CM-PSHA) [10–12], which uses a numerical integration but there are some advantages to the MC-PSHA in terms of flexibility and transparency [13].

Iceland is one of the few places on Earth where a divergent plate boundary can be observed on land [14]. The interaction of the Mid-Atlantic plate boundary between the Eurasian plate and the North American plate along with the Icelandic Hot Spot mantle plume under the middle of Iceland are responsible for the present day tectonic situation. The most significant feature is the eastward ridge-jump in Iceland which has caused to major transform zones, the South Iceland Seismic Zone (SISZ) in the south-western lowlands and the Tjörnes Fracture Zone (TFZ) in north-eastern Iceland. The vast majority of strong earthquakes in Iceland have occurred within these zones. MC-PSHA has been conducted by several researchers in Iceland for the two commonly used strong-motion parameters earthquake hazard is characterized, namely peak ground acceleration (PGA) and pesudo-spectral acceleration (PSA). Sigbjornsson et al. [15] developed seismic hazard maps for SISZ using stochastic simulation of the Fourier spectral density of the ground motion accelerations obtained based on the Brune [16] source model. Solnes et al. [17,18] presented the hazard maps of the Reykjavik area and whole country, respectively, using the theoretical attenuation relationship proposed by Olafsson and Sigbjornsson [19,20] for the near-, intermediate- and far-field spectra including an exponential term to account for anelastic attenuation. Snæbjornsson and Sigbjornsson [21,22] and Sigbjornsson and Snæbjornsson [22] assessed the seismic hazards at four geothermal power plants (i.e., Krafla, Theistareykir, Gjástykki and Bjarnarflag) located within the fissure swarms in the Northern Volcanic Zone (NVZ) and at an industrial site (i.e., Bakki) near Husavik which is located in TFZ.

The TFZ is a broad and complex region and cannot be associated with a single fault or clearly identified plate boundary. Instead, Snæbjornsson and Sigbjornsson in [21,22], based on the geological and geophysical findings, have associated the seismicity along linear seismic delineations: the Grímsey lineament (A), the Husavik-Flatey Fault (HFF) (3 segments) (B1, B2 and B3), the Dalvík lineament (C) are three parallel WNW trending lines, the Krafla zone (D), Theistareykir zone (E), the Fremri-Námur zone (F) and the Askja zone (G) are four lines trending NNE represent the main fissure swarms of the NVZ which are shown in Figure 1. The HFF is the largest transform fault in Iceland and is for the most part offshore. On land however, it has an additional normal component of faulting, resulting in an extensional basin where the town of Húsavík is located, effectively directly on top of the fault. The diverse geology and topography under the town is likely to contribute to spatially variable earthquake strong-motions, manifested in part as localized differences in site effects which may lead to increased relative differences in seismic risk.

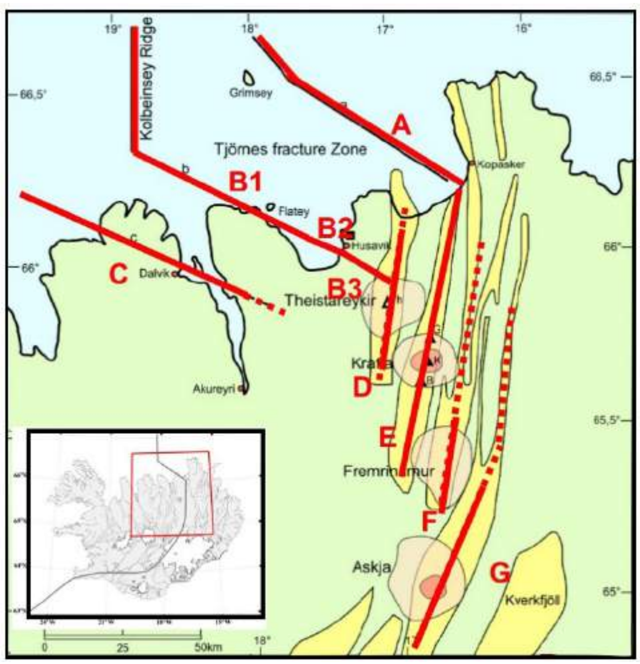

Fig. 1–The seismic source zones applied in probabilistic seismic hazard analysis. The small map inset at bottom left shows Iceland and the area under study. The solid red lines indicate seismic source zones producing earthquakes with magnitude greater than or equal to 4 and the dotted lines refer to source zones where event magnitude does not exceed 4 [23].

The Icelandic seismic catalogue used is from Ambraseys and Sigbjornsson [24] and covers earthquakes from 1896 to 1996 based on the teleseismic data obtained from station bulletins, books, periodicals, newspapers and public domain reports. The catalogue lists 422 events with surface-wave magnitudes, including 276 events with recalculated surface-wave magnitudes and maximum observed magnitude of 1910, the largest recorded earthquake in the Iceland area, reaching a magnitude of 7.2. [25]. Due to uncertainties associated with this catalogue, it might not be appropriate for hazard assessment in North Iceland where the earthquakes were less destructive than Southwest events and also many of them occurred off-shore and may not have been mentioned in the historical annals. For this reason, all previous hazard studies in Iceland have applied the MC-PSHA approach. However, the previous earthquake hazard estimates of this region have relied on a single ground motion model and incorporated uncertainties in a limited way. Therefore, it is both timely and important, especially in light of the fast growing heavy industry planned for the region, to revise the earthquake hazard estimate for the region. In this study, we have selected a number of different GMMs and evaluated them based on data-driven approaches to consider epistemic uncertainty. Moreover, we used Markov Chain Monte Carlo (MCMC) method to recalibrate the selected GMMs for Iceland. Finally, both CM-PSHA and MC-PSHA approaches are considered and the disaggregation of the seismic hazard is also carried out to identify hazard-dominating events.

2. Uncertainties in PSHA

To provide a precise portrayal of the hazard at the given region, PSHA should quantify various sources of uncertainties, which are usually categorized as either aleatory or epistemic. Aleatory uncertainty arises because of natural, unpredictable variation in the performance of the system that can not be eliminated with increasing knowledge and information while epistemic uncertainty is due to the lack of knowledge about the behaviour of the system that is conceptually resolvable [26]. This seperation is important in assessing performance over time, even though such a categorization is somewhat idealistic, in that some of the aleatory variability could be due to systematic effects and thereby being a source of epistemic uncertainty [27–29]. Notwithstanding the popularity of this distinction, over time one should therefore expect that uncertainties may slowly migrate from aleatory to epistemic, as our knowledge of the system and related processes may increase [30,31]. Uncertainties can be found in all PSHA steps; characteristics of the seismic sources, distribution describing seismicity parameters and in GMMs [12]. However, the uncertainty associated with the GMM tends to exert a greater influence on the hazard results than other sources of uncertainty related to the underlying seismicity model [28,30]. Furthermore, since a very long catalogue (e.g. a million years) is simulated in MC-PSHA to cover all the possible situations, uncertainties related to seismicity parameters are lower than CM-PSHA approach where the recorded earthquake catalogue is used. Therefore, the main source of uncertainty should be found in GMM.

In GMMs, variability of amplitudes about a median values is aleatory in nature and is represented by the standard deviation of the residuals. This aleatory uncertainty can be handled easily by integrating over the distribution of ground motion amplitudes about the median in PSHA studies [32]. On the other hand, the uncertainty about the correct value of the median is considered as epistemic. In PSHA, epistemic uncertainty has been modelled by the use of alternative equations in a logic tree framework which it is not necessarily the best way to deal with uncertainties [33–35]. Recently, representative suite approach is introduced to offer more flexibility in expressing the epistemic uncertainty than any weighted combination of the available GMMs [35,36]. Based on the observation that the epistemic uncertainty for shallow crustal events in active tectonic regions grows with distance [37], a log factor is recommended to add and subtract from the central GMM to construct the upper and lower GMM curves, respectively. The representative suite approach facilitates explicit judgment regarding magnitude and distance scaling and enables greater control over how the median GMMs and their uncertainty will satisfy data constraints and behave across regions [35,36]. However, in both approaches, selection of appropriate GMMs is still a major challenge, particularly for regions where an appropriate local GMM does not exist, either due to the low seismicity or limited observational data or both [38]. In this study, two data-driven methods, the likelihood-based [39] and the Euclidean distance-based ranking [40] are used to reduce epistemic uncertainties. Finally, nine candidate GMMs including Olafsson et al. [41], Ol14; Rupakhety and Sigbjornsson [42], RS09; Akkar and Bommer [43], AB10; Ambraseys et al. [44], Am05; Danciu and Tselentis [45], DT07; Gulkan and Kalkan [46], GK02; Zhao et al. [47], Zh06; Lin and Lee [48], LL08 are selected for further analysis.

We develop the site-specific GMMs by means of recalibrating the existing models with Icelandic observations using the MCMC algorithm and assess their performance. The selected GMMs are regional models corresponding to Europe and Middle East data sets and models from Japan and Northern Taiwan. We recalibrated all these models to the Icelandic ground motions dataset using the MCMC method that forms the backbone of modern Bayesian posterior inference. Figure 2 shows the attenuation of PGA from a magnitude M_w 6.4 for the selected GMMs models before and after recalibrating in two distinct site types. The blue circles and green diamonds are the recorded PGAs of the 2000 and 2008 earthquakes with M_w 6.5, 6.4 and 6.3 at rock and stiff soil sites, respectively (which is generally the site classification of strong-motion stations in Iceland).

As expected, after recalibrating, the selected GMMs fit the observations better. However, while not shown here, we note that for larger earthquakes and at near-fault distances (for which no data exists), the recalibrated GMMs diverge significantly from one another relative to what is shown in Figure 2 for M 6.4, and as a result the epistemic uncertainty drastically increases with magnitude. That observation has important effects on hazard estimates on the basis of these GMMs, and is one of the main reasons for considering many different forms of GMMs in this study. In particular those that include magnitude and distance dependent scaling terms in their functional forms [48,49] that ideally should be calibrated using physical models [49–51].

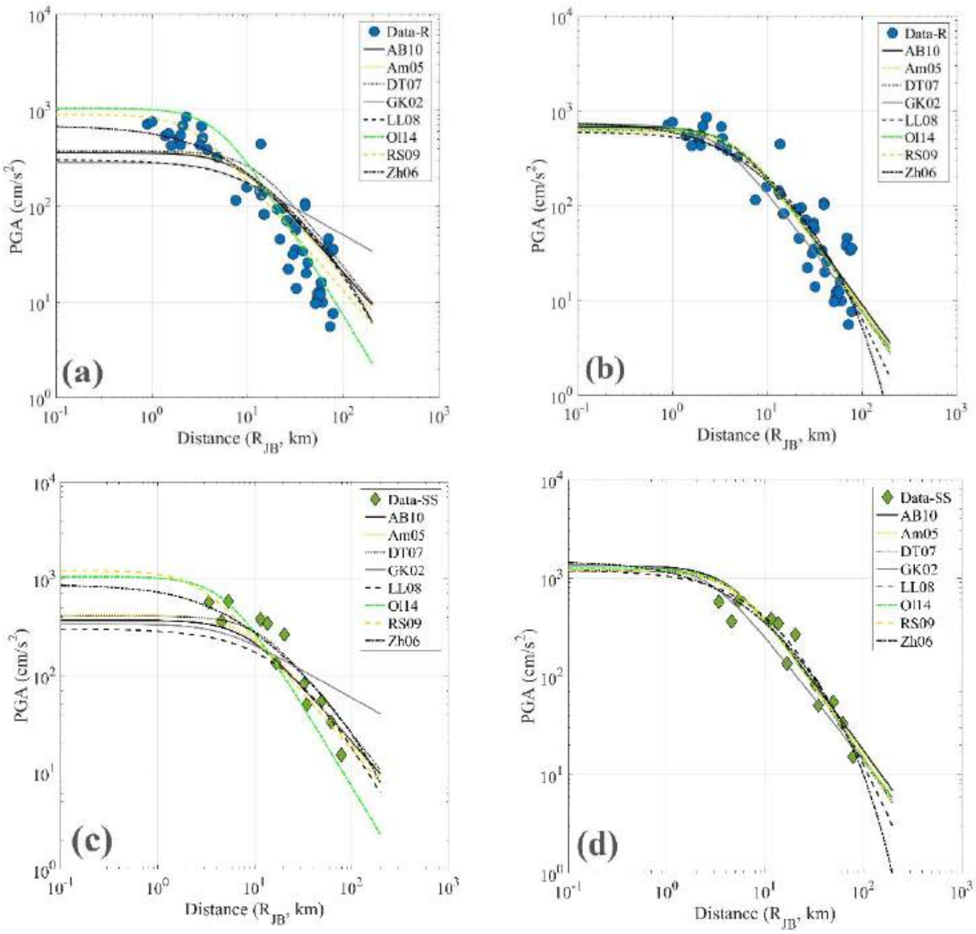

Fig. 2–Attenuation of PGA from a magnitude Mw=6.4 earthquake with distance for the selected GMMs before (a, c) and after (b, d) recalibrating. The blue circles and green diamonds are the recorded PGAs of the 2000 and 2008 earthquakes with Mw=6.5, 6.4 and 6.3 at rock and stiff soil sites, respectively.

3. Monte Carlo simulation

MC-PSHA is a relatively straightforward approach for the assessment of seismic hazard as illustrated schematically in Figure 3. One of the prominent advantages of MC-PSHA is its compatibility with different models of seismicity. In other words, the characteristic, time-dependent, non-Poissonian and Markovian seismicity models can be adopted easily within the framework of the MC-PSHA [4]. First, a user specified number of synthetic subcatalogues are generated for each seismic source. These subcatalogues contain the Monte Carlo draws for magnitude, distance and epsilon (the number of standard deviations by which an observation differs from the mean value of prediction).

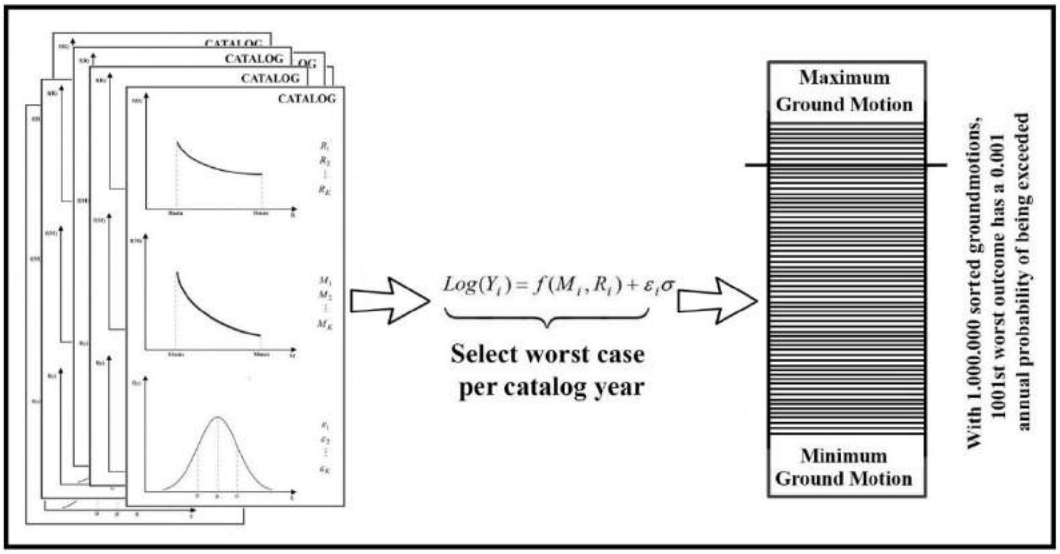

Fig. 3– Schematic representation of the MC-PSHA.

For a line seismic source for example, its seismicity is assumed to be uniformly distributed over the length of the fault (L), and as a result, the probability density function of site to source distance is given by $f_R(r) = r(r^2 - r_{min}^2)^{-1/2}L^{-1}$ [52]. With the Poissonian assumption of the temporal occurrence of earthquakes, the doubly truncated Gutenberg-Richter distribution can be considered for earthquake magnitude. This distribution is truncated between maximum magnitude (Mmax) and minimum magnitude (Mmin) with Mmax related to the tectonic setting, geometry, and type of the seismic source whereas Mmin is usually related to events that are relatively small and do not have damaging effects on engineered structures. Also, the normalized residual (ε) represents a measure of the goodness-of-fit of the GMM which is generally assumed to be normal with a mean zero and a standard deviation (σ) [53]. The predicted distributions are used to generate the synthetic earthquake catalogue. For each generated set of magnitude, distance and epsilon, the ground motion intensity measure of interest (here, the PGA) can be estimated by the selected GMMs. This process is repeated for a specified number of subcatalogues. For example, 10000 simulations of 100 years of seismicity gives the effect of one million years of data. Then, the worst case ground motion from each of these one million years is selected and sorted. The ground shaking value can then be determined with a 0.001 annual probability of being exceeded by just picking the 100lst value in the sorted list.

4. Results and Discussions

A Monte Carlo basis approach was used to seismic hazard assessment in Husavik, North Iceland. Due to uncertainties in Icelandic earthquake catalogue, especially in TFZ, the MC-PSHA that simulates synthetic catalogues based on the geophysical characteristics of the seismic zones, is preferred over classical CM-PSHA. Identification of seismic sources is the first step of PSHA. In this study, we used the seismic source zones proposed by Bjornsson et al. [23] which is shown in Figure 1. Mmin as the lower bound magnitude on each seismic source is set equal to 4.0 where no engineering-significant damage is expected. Mmax or the upper bound magnitude is required for each source zone to avoid the inclusion of unrealistically large earthquakes [54]. The seismic source zones and their Mmax are used based on the study of Bjornsson et al. [23] which are shown in Table 1. The considered seismic sources are the Grímsey lineament (A), the Husavik Flatey fault (3 segments) (B1, B2 and B3), the Dalvík lineament (C), the Krafla zone (D), the Theistareykir zone (E), the Fremri-Námur zone (F) and the Askja zone (G). The a- and b-value which provide information about the seismicity of a region, the occurrence of events and the magnitude distribution [55] are shown in Table 1 [21,22]. Results of a simulation are given in Figure 4, revealing the histogram of distance, magnitude and epsilon for Grimsey lineament.

Table 1– The applied seismicity parameters for PSHA in TFZ [21,22].

Seismicity parameter	Seismic source								
	A	B1	B2	B3	C	D	E	F	G
Length	89	68	18	19	72	42	90	31	55
Mmax	7.3	7.3	7.3	6.5	7.3	5.5	5.5	5.5	5.5
Mmin	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
b-value	0.7	0.7	0.7	0.7	0.7	1.0	1.0	1.0	1.0
a-value	5.3	5.0	4.2	4.0	4.6	5.8	5.2	5.0	6.3

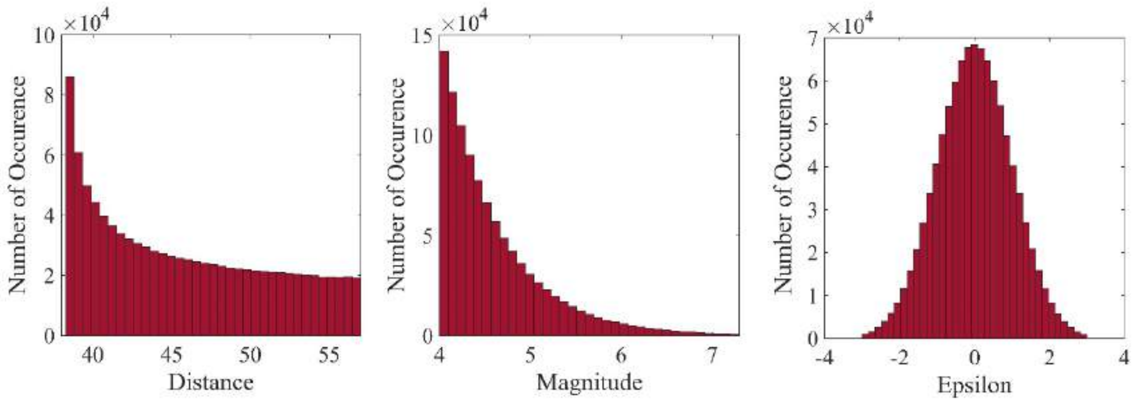

Fig. 4– Histograms for distance, magnitude and epsilon, respectively, in the synthetic earthquake catalogue for the Grimsey lineament.

GMMs have a major impact on seismic hazard estimates and should be carefully selected for such an analysis. Since sites of interests in the TFZ are in the extreme near-fault region of major earthquake faults (e.g., Husavik and zone B, Kopasker and zone A, and Dalvik and zone C), the GMMs with magnitude-dependent distance scaling term were considered in this study. The selected models are the AB10, Am05, Zh06 and LL08. To reduce epistemic uncertainty, a logic tree is applied in which for simplicity equal weights for each GMM have been assigned. The seismic hazard is calculated for PGA and spectral acceleration at T=0.2, 0.3, 1.0 and 2.0 s. The results are shown in Table 2 for different level of exceedance at a rock site.

Table 2– Seismic hazard estimates at different periods based on MC-PSHA for rock site.

Mean return period (years)	Annual probability of exceedance %	Probability of exceedance in 50 years %	Spectral Acceleration (g)				
			T=0.0s (PGA)	T=0.2s	T=0.3s	T=1.0s	T=2.0s
72	1.39	50	0.26	0.57	0.43	0.06	0.02
95	1.05	40.9	0.29	0.64	0.49	0.07	0.03
475	0.21	10	0.52	1.19	0.98	0.18	0.08
1000	0.1	4.88	0.63	1.52	1.28	0.25	0.13
2475	0.04	2.0	0.81	2.04	1.74	0.36	0.17
3000	0.03	1.65	0.87	2.24	1.89	0.39	0.19
4975	0.02	1.0	0.95	2.50	2.14	0.45	0.23
9975	0.001	1.65	1.94	5.52	4.74	1.05	0.65

For completeness the CM-PSHA method is also utilized and its results, shown in Figure 5 compared with the MC-PSHA. As expected, the results are consistent between the two approaches. The PGA level corresponding to a 10% probability of exceedance in 50 years (APE=0.0021, horizontal line in Figure 5) are are within 10% of one another for the CM- and MC-PSHA.

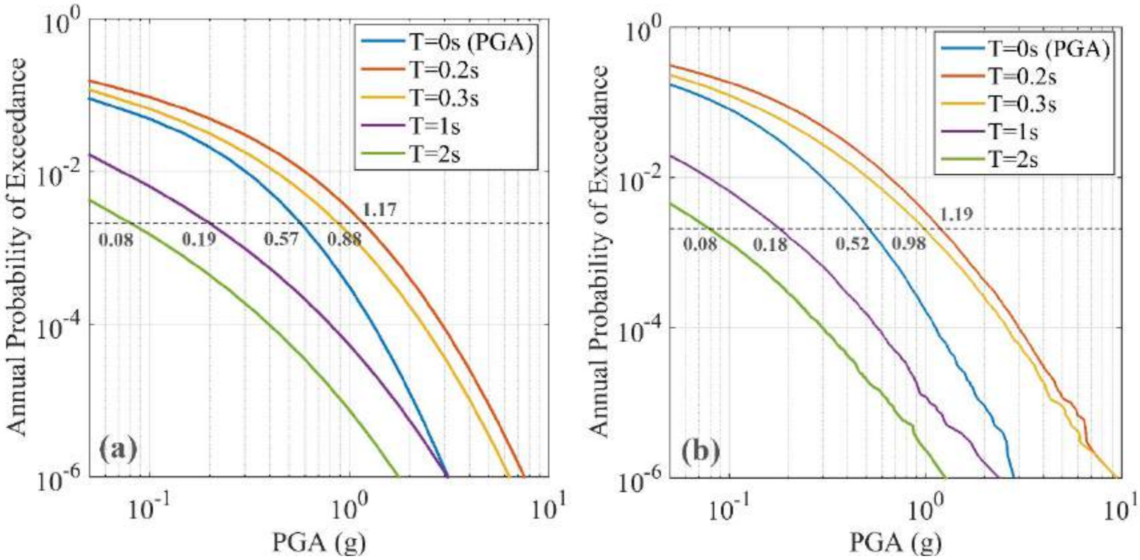

Fig. 5– The hazard curves at different periods based on CM-PSHA (a) and MC-PSHA for rock site. The dashed line crosses the hazard curves at annual probability of exceedance equal to 0.0021 (T=475 yrs).

One of the primary advantages of PSHA is, for a given site, to take into account the ground motions from the full range of earthquake magnitudes that are assumed to take place on each seismic source. However, this advantage which results from the integrative nature of PSHA, could be also a disadvantage since it obscures the most important magnitude and distance combinations [4]. To overcome this problem, the disaggregation of seismic hazard has been introduced [3–5]. Disaggregation is used to identify the individual earthquake scenarios that contribute most to the hazard at a given site for the selected annual probability of exceedance. Here, we skipped the effect of epsilon and just magnitude and distance are considered for contributing the hazard. The ground motions in Húsavík for short return periods are governed by both B2 and B3 segments with 4.8-7.0 magnitude and 4-15 km distance range. The ground motions at long return periods are mostly governed by segment B2 with the contributing magnitudes M>6.8 at short distances.

This study builds on previous hazard studies for Iceland, specifically on the delineation of seismic sources, seismicity parameters and the GMMs. These assumptions need to be carefully analysed and possibly revised. In particular, selection of GMMs and the uncertainty associated with them tend to exert a great influence on the hazard results. In this study, we showed that some of the selected GMMs in previous PSHA studies in Iceland may not necessarily be appropriate. Despite the fact that the current data-driven methods select some of them as the appropriate models, Figure 1 shows that the recalibrated models are promising candidates to be applied in future hazard studies in Iceland. Further studies are needed however, as the high obtained hazard levels for Husavik show, since their reliability may be limited in the extreme near-fault region due to the lack of near-fault recordings from earthquakes greater than 6.5 in Iceland. Further hampering this issue are the great variations that synthetic near-fault motions exhibit in the near-fault region from dynamic earthquake rupture models [54,55].

5. Acknowledgements

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