1. Information about the project

Name of the project: Physics-based revision of the seismic hazard in Southwest Iceland

Grant number: 1800-947

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2. Participants and their role in the project

Benedikt Halldorsson, Research Professor, Faculty of Civil and Environmental Engineering, School of Engineering and Natural Sciences, University of Iceland (SENS-UI). *Role: Principal Investigator.*

Bjarni Bessason, Professor, Faculty of Civil and Environmental Engineering, School of Engineering and Natural Sciences, University of Iceland (SENS-UI). *Role: Co-proposer, supervising and quality control of the results.*

Jónas Þór Snæbjörnsson, Professor, Department of Civil and Structural Engineering, Reykjavík University, Iceland. *Co-proposer, supervising and quality control of the results.*

Milad Kowsari, PhD, Faculty of Civil and Environmental Engineering, School of Engineering and Natural Sciences, University of Iceland (SENS-UI). *Role: Co-proposer, postdoctoral researcher.*

3. Objectives and work packages of the project

The **long-term objective** of this study is the comprehensive revision of PSHA for Iceland using new state-of-the-art models, methods, and earthquake source zonations. Moreover, this will include the implementation of the first physics-based approach to PSHA, with a focus on the earthquake near-fault region of southwest Iceland. Therefore, **the short-term objective** of this specific proposal is to carry out a comprehensive PSHA using Monte Carlo simulations of finite-fault earthquake rupture using a new and complete physics-based earthquake source model of southwest Iceland. Thus, the project will be split into the following Work Packages (WPs) to optimize feasibility:

WP1- Selection of appropriate GMMs and quantified epistemic uncertainties

WP2- Seismic hazard maps for Southwest Iceland, on the basis of a new physics-based finite-fault earthquake catalogue

WP3- Sensitivity and uncertainty analyses to quantify different sources of uncertainty in PSHA for Southwest Iceland

WP4- Relative comparisons of the new PSHA map with previous maps, including the European Seismic Hazard Models of 2013 and 2020.

4. Progress of the project and the main results

Iceland is the subareal manifestation of a localized oceanic plate uplift due to the Iceland hot spot. Its collocation and interaction with the Mid-Atlantic Ridge, the extensional tectonic plate margin that separates the Eurasian and North American Plates drives the intense volcanic and seismic activity of this most seismically active region in northern Europe. The Mid-Atlantic Ridge crosses Iceland from Southwest to north but due to a ridge-jump caused by the hot spot, the ridge is displaced towards the east, forming two major transform zones, the South Iceland Seismic Zone (SISZ) and the Reykjanes Peninsula Oblique Rift (RPOR) in the southwest and the Tjörnes Fracture Zone (TFZ) in northwest. They are the regions with the greatest potential for occurrence of large earthquakes in Iceland. The SISZ is collocated with the South Iceland Lowland, a relatively flat and populated agricultural region with all the critical infrastructures and lifelines of a modern society such as hydroelectric and geothermal power plants, dams, above-ground pipelines and electrical transmission lines. The RPOR, however, is a relatively remote high basaltic plain. In these zones, strong earthquakes have repeatedly taken place on a dense array of separate but parallel near vertical north-south trending right-lateral strike slip faults that in fact is continuous from the SISZ across the Hengill triple junction and to the relatively uninhabited RPOR (Einarsson 1991, 2008, 2014; Einarsson et al. 2020; Steigerwald et al. 2020).

As a result, the earthquake hazard is the highest in this region, the SISZ in particular, and the investigation of earthquake strong-motion and its effects on manmade environments is of particular interest and vital for seismic risk assessment and its mitigation (Tryggvason et al. 1958; Sigbjörnsson et al. 1995; Solnes et al. 2004). For this purpose, probabilistic seismic hazard analysis (PSHA) is used to quantify the probability of levels of earthquake ground motion parameters being exceeded over a specified time period at any given location (e.g., Cornell 1968; Reiter 1991; McGuire 2004).

In order to produce a reliable PSHA, a careful estimation of its inputs and their uncertainty is of paramount importance. The seismicity parameters and selection of appropriate ground motion models (GMMs) are the key PSHA inputs affecting the hazard levels (e.g., Cramer et al. 1996; Cramer 2001; Lombardi et al. 2005; Sabetta et al. 2005). A rigorous assessment of the uncertainties of these inputs is therefore required. In the scientific literature, such uncertainties are divided into two major categories, aleatory variability and epistemic uncertainty (Toro et al. 1997). The aleatory variability is related to the natural unpredictability of the earthquake process whereas the epistemic uncertainty arises from incomplete knowledge and limited data. In the current practice of PSHA, the different estimates of the median ground motions predicted by empirical GMMs are attributed to epistemic uncertainty. In this regard, classical PSHA deals with the epistemic uncertainty in ground motion estimates using a logic tree framework (Kulkarni et al.

1984). Different ground motion predictions by different GMMs have the largest contributions to the overall epistemic uncertainty, in particular at long return periods. Therefore, selection of appropriate GMMs to reduce the epistemic uncertainty is vital for application in PSHA and this can be achieved by using data-driven GMM-ranking methods. The data-driven methods reduce subjectivity in the selection process and thus have an advantage over the classical residual analysis method (Scherbaum et al. 2009).

The data-driven method is based on the Deviance Information Criterion (DIC) and selects the most suitable GMM for application in PSHA. The main advantage of the DIC is to introduce the posterior sigma as a key unknown measure in order to rank the models objectively. The posterior distribution of sigma is then obtained based on the observed ground motions and shows the deviance of predicted values from the observed ground motions that is representative of the aleatory variability in the region under study. In this way, the DIC ranks models more favorably when they are associated with a smaller bias and the corresponding posterior sigma is close to the aleatory variability of the ground motions in the region under study, for the given dataset. In the context of the Bayesian statistical framework, the posterior sigma is conditioned on the observed ground motions obtained from the region under study.

In this study, a recently developed data-driven GMM-ranking method has been applied to rank several candidate GMMs developed from local, regional, and worldwide datasets (Kowsari et al. 2019b). The final GMMs are the following: The ones calibrated in Kowsari et al. (2020b) to the Icelandic strong-motion dataset using Bayesian inference with informed priors, named as Kea20-1 to Kea20-6. Each of them has a different functional form, and together they facilitate the estimation of epistemic uncertainty. Then, the regional GMMs such as Ambraseys et al. (2005), Aea05; Zhao et al. (2006), Zh06; Akkar and Bommer (2010), AB10; Kotha et al. (2016), Kea16; and the NGA-West2 GMMs including Abrahamson et al. (2014), ASK14; Boore et al. (2014), BSSA14; Chiou and Youngs (2014), CY14; Campbell and Bozorgnia (2014), CB14; Idriss (2014), I14. On the other hand, in order to apply the data-driven GMM-ranking method, we used the earthquake strong-motion data recorded on 30 stations of the Icelandic strong-motion network from six strike-slip mainshock earthquakes that occurred in the SISZ between 1987 and 2008 covering magnitude range of 5.1–6.5, with a distance range of 1–80 km (Sigbjörnsson et al. 2014). In addition, we used the extreme near-fault array recordings of ICEARRAY I during the 2008 Ölfus earthquake (Halldorsson et al. 2009; Halldorsson and Sigbjörnsson 2009). In Iceland, the recording stations are classified according to the Eurocode 8 classification scheme into the rock class (V_{S30}>800 m/s) and the stiff soil class (360 m/s<V_{S30}<800 m/s) (Sigbjörnsson et al. 2014).

Figure 1 shows the attenuation of the selected GMMs versus distance for PGA and PSA at T=0.3, 1.0 and 2.0 s. The GMMs are evaluated at M_{w} 5.5 and 6.5 on rock site class. The color scheme shows the different groups of GMMs: Yellow-to-orange colors represent the local Kea20 1-6 models, blue colors represent NGA-West2, and green colors represent regional GMMs and the purple is Zh06. The red circles are the observed strong-motion data in the two magnitude bins, dominated by recordings of the M_{w}6.5 and M_{w}6.4 earthquakes in 2000 and the M_{w}6.3 2008 earthquakes. From this figure, it is qualitatively clear that the Kea20 models fit the recorded data well in the magnitude and distance range where data is available. The regional and NGA-West2 GMMs appear to exhibit a strong bias against the Icelandic strong-motion data primarily due to the failure of capturing the high near-fault motions and rapid attenuation of strong-motion (Kowsari et al. 2019a, 2020). As a result, they underestimate the Icelandic strong-motions in the near-fault region and overestimate them in the far-field region.

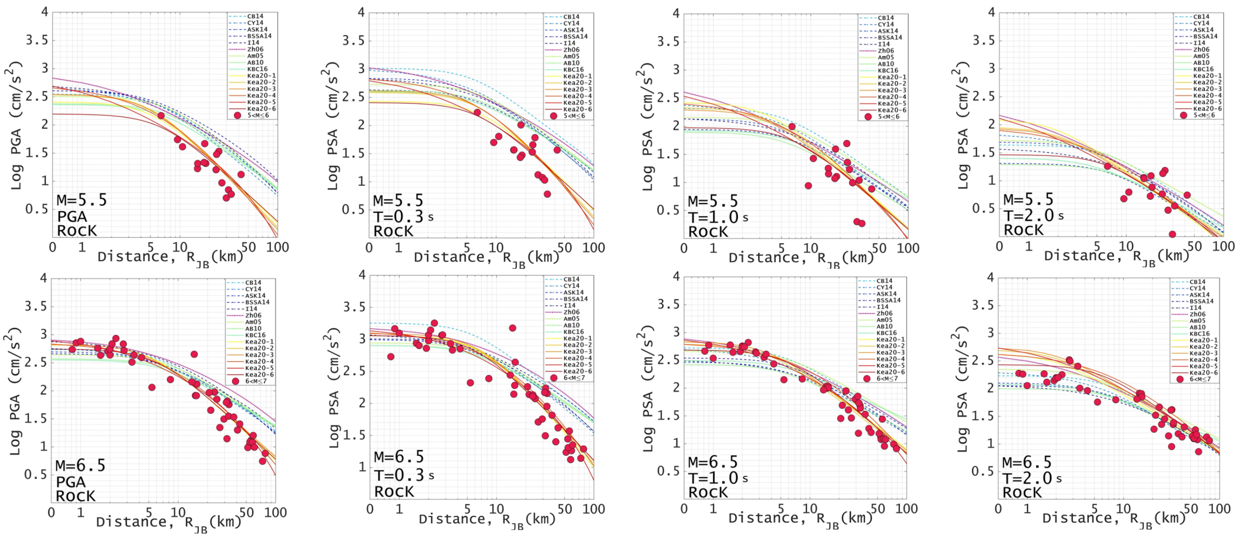

Figure 1. The attenuation of the candidate GMMs versus distance for PGA and PSA at $\boldsymbol{T}$*=0.3, 1.0 and 2.0 s (columns left to right, respectively). The GMMs are evaluated at* $\boldsymbol{M_w}$*5.5 (top row) and 6.5 (bottom row) for rock. The red circles are the observed strong-motion data.*

Error! Reference source not found. shows the results of the DIC ranking against the strong-motion data, presented for PGA and PSA at different oscillator periods of T = 0.3, 1.0, and 2.0 s for the two site classes (i.e., rock vs. stiff soil). We indicate the results of the ranking by the arrangement of these 15 GMMs from 1, the best ranked, to 15, the least ranked, from left to right. Not surprisingly, the results show that the Kea20 GMMs are ranked best almost at all periods (except for PSA at T=2.0 s at stiff soil). The ranking also indicates that NGA-West2 models are much less favorable GMMs to describe Icelandic ground motions. More interestingly however, in most cases the regional GMMs that had been applied in the previous seismic hazard studies in Iceland were shown to represent the least favored models. This is consistent with recent results showing that they are strongly biased against the Icelandic dataset and therefore, the results of previous seismic hazard studies in Iceland using these GMMs are cast in serious doubt.

Therefore, for performing a classical PSHA, the logic tree is populated with six Bayesian GMMs with different functional forms (i.e., Kea20 GMMs) that were all calibrated to the Icelandic strong-motions.

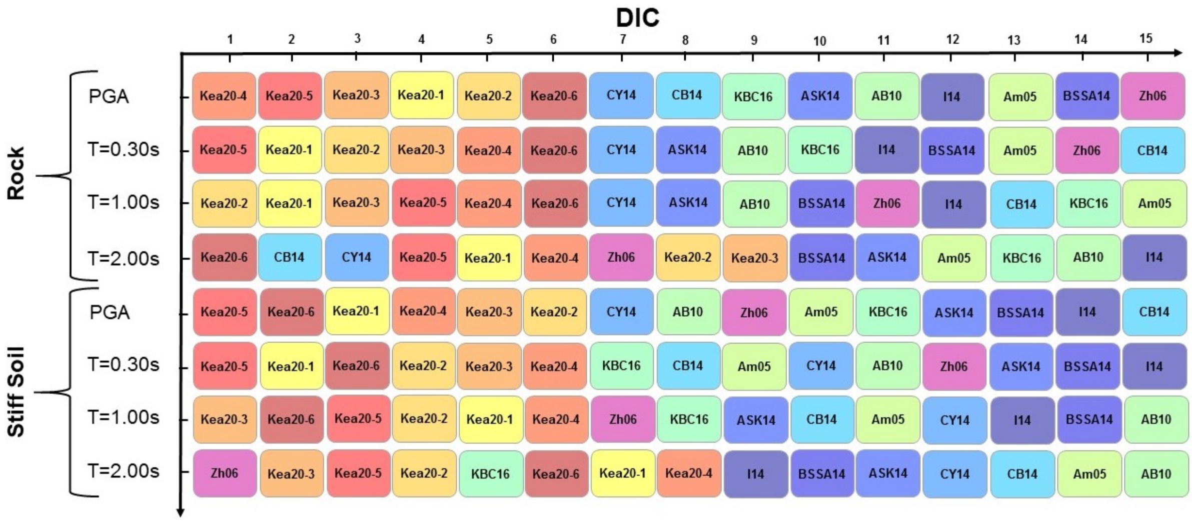

Figure 2. Ranking of the selected GMMs against the Icelandic strong-motions using the DIC method for PGA and PSA at different periods of T = 0.3, 1.0, and 2.0 s for rock (top) and stiff soil (bottom) site classes. The color scheme shows the different groups of GMMs: Yellow-to-orange colors represent Kea20, blue colors represent NGA-WEST2, and green colors represent regional GMMs and the purple is Zh06.

The study region is southwest Iceland where the transform motion of the eastward jump of the Mid-Atlantic Ridge is taken up by a complex “bookshelf” faulting system i.e., an array of near vertical dextral transform faults across the SISZ and the RPOR (Einarsson et al. 1981, 2020; Einarsson 1991, 2008, 2014; Steigerwald et al. 2020). This bookshelf system characterizes the occurrence of strong earthquakes in the SISZ and has recently been shown to be continuous across the Hengill Triple Junction and along the RPOR (Steigerwald et al. 2020). There are five volcanic systems in the RPOR in which normal faulting seismicity occurs episodically during (very rare) intense rifting episodes between which transcurrent motion dominates (Sæmundsson et al. 2020). Moreover, the corresponding maximum earthquake magnitudes associated with rifting episodes are believed to be approximately M_w4.5-5, and as such they are considered to have a minimum contribution to the seismic hazard. In this region, the hypocentral depth of earthquakes gradually increases from west to east. It is generally at 1-5 km in the western part of the RPOR and down to 12-14 km depth in the easternmost part of the SISZ (Stefánsson and Halldórsson 1988; Stefansson et al. 1993; Panzera et al. 2016; Steigerwald et al. 2020). For the transform faults in this region, the maximum magnitude is estimated to vary from $\sim M_w$ 5.5 in the westernmost part of the RPOR to $\sim M_w$ 7 in the easternmost part of the SISZ. Thus, the seismogenic potential increases towards the east as confirmed by the historical catalogue and observational reports in annals (Tryggvason et al. 1958; Halldórsson et al. 1984; Stefansson et al. 1993; Ambraseys and Sigbjörnsson 2000). For PSHA purposes therefore the relevant source zone in Southwest Iceland is the transform fault system of SISZ and RPOR.

Recently, Bayat et al. (2022) proposed a new physics-based finite-fault system model for the transform fault systems of the SISZ and the RPOR. Constrained by known historical and mapped fault locations, historical and instrumental seismicity, geophysical information e.g. on maximum seismogenic depth in the region, they modelled the SISZ-RPOR transform zone as an array of finite-size "bookshelf" strike-slip faults of systematically varying seismic potential and accounted for variability in interfault distances guided by fault mapping by field surveys and relative relocations of seismic swarms (e.g., Hjaltadóttir 2009; Einarsson et al. 2020; Steigerwald et al. 2020). The activity of the fault system is calibrated to the velocity of plate tectonic extension in the region as reported by long-term deformation studies (Sigmundsson et al. 1995; Hreinsdóttir et al. 2001; Sigmundsson 2006; Decriem et al. 2010; Einarsson et al. 2020). The resulting model is completely specified in terms of suites of 3D finite-fault strike-slip faults in the zone along with their corresponding annual slip rates, thus fully capturing the salient tectonic characteristics of the transcurrent faults in the region that dominate the seismic hazard.

We took advantage of the availability of these models and simulated multiple finite-fault earthquake catalogues for the entire bookshelf system that are both compatible with the earthquake faulting and the long-term seismicity in the region. One realization of the synthetic 3D fault system is shown in Figure 3. It models 3000 years of strike-slip fault activity in the region limited with a minimum magnitude of $M_{\mathrm{w}}5$. The magnitude-frequency distribution of these synthetic earthquakes in each zone is consistent with the activity rate derived from the 3D fault system modelesented. This figure shows one realization, the vertical surface projection of these randomly distributed fault planes with colors indicating magnitude bins (minimum magnitude of 5), clearly reflecting the expected increase in maximum possible magnitudes from west to east.

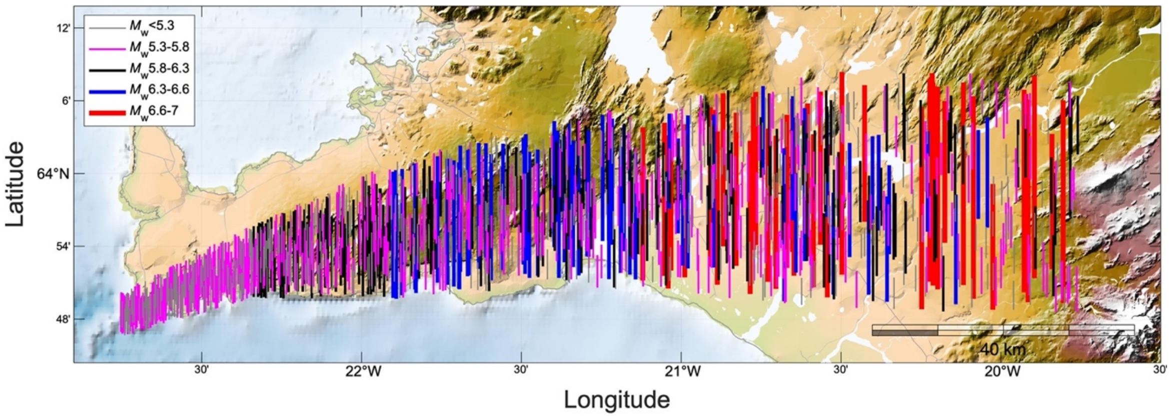

Figure 3. One realization of a hypothetical 3D fault system model for each zone consistent in activity with the magnitude frequency distribution of the zone, as derived from the 3D fault system model realizations. This synthetic finite-fault catalogue results in a collective zone-average fault slip-rates that is consistent

with that postulated by the 3D fault system model. The locations of the faults are allowed to vary randomly, and the colors indicate the distribution of magnitudes.

Therefore, this synthetic finite-fault catalogue now enables us to perform the first comprehensive physics-based PSHA in the SISZ-RPOR. For that purpose, we employ a Monte-Carlo PSHA that takes different realizations of the synthetic physics-based finite-fault catalogue. We grid the entire region with a dense grid of hypothetical stations and calculate the horizontal distance to the vertical surface projection of each fault, from each hypothetical station. Figure 4 shows the mean hazard map at 10% probability of exceedance in 50 years for PGA. The hazard is calculated based on the six Icelandic Bayesian GMMs on bedrock. These maps are the mean hazard values from different realizations of the finite-fault catalogue.

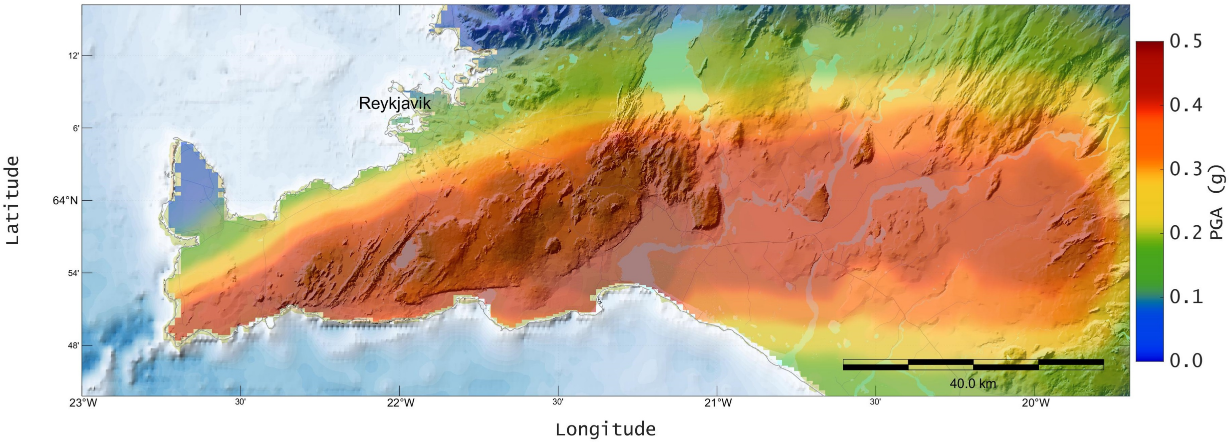

Figure 4 – PSHA hazard map for the 10% probability in 50 years of PGA, based on the finite-fault catalogue of 3000 years.

The results of this study are compared with the two latest published earthquake hazard maps for Iceland from the European seismic hazard model, ESHM13 (Woessner et al. 2015) and ESHM20 (Danciu et al. 2021) which are shown in Figure 5. There was no formal Icelandic participation in the ESHM13 project and as a result, local knowledge was missing in the detailed scrutiny of the supporting documents. This resulted in a hazard map that showed a remarkable inconsistency compared to the Icelandic National Annex to Eurocode 8 (Halldorsson and Sveinsson 2003; European Committee for Standardization 2004). This inconsistency is due to the coarse and inappropriate seismic source models that were defined within the country as well as the use of inappropriate GMMs that have been shown to be biased against Icelandic recorded strong-motions (Kowsari et al. 2019a, 2020). In this unreliable hazard estimate, the hazard values for the capital area increased from ~10%g to ~50%g.

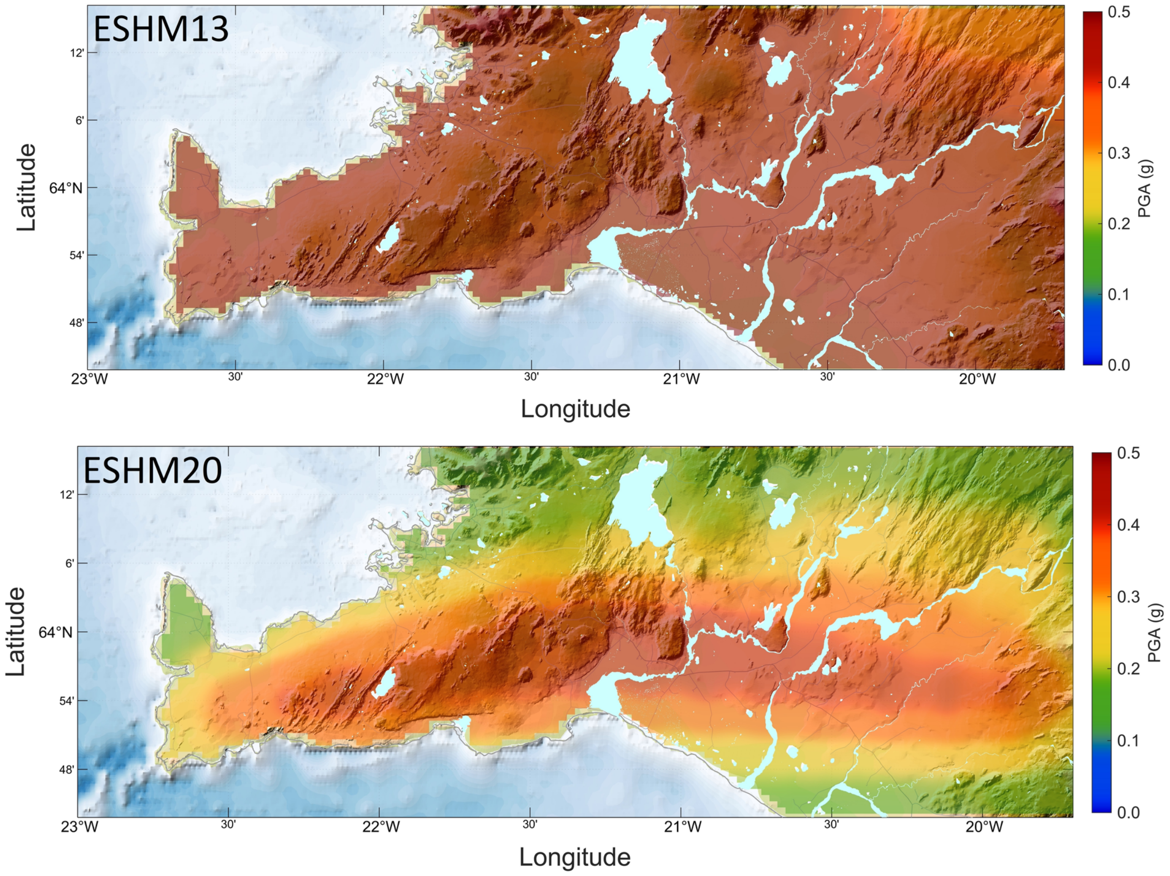

Figure 5 – The PSHA hazard map of the ESHM13 (top) and ESHM20 (bottom) for the 10% in 50 years probability of exceedance of peak ground acceleration (PGA).

The ESHM20 seismic hazard maps, are drastically different from the ESHM13, showing more realistic hazard values that are spatially much more similar to those in the Icelandic National Annex. However, since our influence was ultimately limited by time and other constraints, the final incorporation of the ESHM20 of our input differed unexpectedly from what we provided in terms of the sub zonation of the southwest Iceland transform zone, which specified varying maximum magnitudes and different activity rates (Halldorsson et al. 2022).

5. Impacts

The results of this project will find direct application in aseismic design, urban planning, risk mitigation strategies and catastrophe insurance for major earthquake occurrences in Iceland. The results will directly affect the revision of PSHA for Iceland in the form of the preparation of a new Icelandic National Annex to Eurocode 8, which is currently in progress at the Icelandic Standardization Committee (Staðlaráð), as a part of the revision efforts of the European Committee for Standardization's. This revision is of dire need as the design requirements have not changed in two decades despite considerable new and relevant information and methods.

6. Publications

1. Bayat F, Kowsari M and Halldorsson B (2024) A simplified seismicity model of the bookshelf fault system of the Southwest Iceland transform zone, accepted in *Bulletin of Earthquake Engineering*
2. Kowsari M, Bayat F and Halldorsson B (2024) Physics-based Probabilistic Seismic Hazard Assessment Using Finite-fault Earthquake Catalogue for Southwest Iceland, manucript compeleted
3. Bayat F, Kowsari M and Halldorsson B (2024) Near-fault ground motion models from physics-based synthetic data for the Southwest Iceland transform zone, manucript compeleted

The following are the publications in the peer-reviewed conferences:

4. Kowsari M, Bayat F & Halldorsson B (2024) Towards physics based PSHA for Southwest Iceland, 18th World Conference on Earthquake Engineering (WCEE2024), Milan, Italy, 30th June to 5th July 2024.
5. Bayat F, Kowsari M, Halldorsson B, Rojas O, Abril C, Monterrubio-Velasco M & de la Puente J (2024) On the Bayesian hierarchical modeling of the near-fault seismic ground motion models from synthetic data, 18th World Conference on Earthquake Engineering (WCEE2024), Milan, Italy, 30th June to 5th July 2024.
6. Davari H, Kowsari M, Sonnemann T, Darzi A, Rahpeyma & Halldorsson (2024) Towards a consistent weak-to-strong empirical seismic ground motion model for Southwest Iceland, 18th World Conference on Earthquake Engineering (WCEE2024), Milan, Italy, 30th June to 5th July 2024.

7. Summary

In southwest Iceland, the largest earthquakes that have been reported in historical annals have repeatedly taken place in the South Iceland Seismic Zone (SISZ) and caused damage. However, it has recently been shown that the unique bookshelf earthquake fault system of the SISZ is continuous towards the west, over the Hengill triple junction, and all along the Reykjanes peninsula. This new information reveals that the entire capital region and multiple small towns, with their infrastructures and lifelines of our modern society are in much greater proximity to large bookshelf faults. The foundation of our society's efforts to mitigate seismic risk is the earthquake resistant design of structures according to Eurocode 8, which in turn is based on the Icelandic National Annex for Eurocode 8 which is a seismic hazard map of Iceland. In light of the above, a comprehensive revision of the PSHA of Iceland is clearly needed. It is also needed because past PSHA studies carried out for Iceland suffered from several and significant limitations: They were not subjected to peer-review or published in scientific journals, the treatment of uncertainties was not in line with international standard practice, they used various versions of the Icelandic earthquake catalogue, the ground motion models (GMMs) that were used in many of the previous studies had been developed using data from other seismic regions and have been shown to be severely biased against Icelandic strong-motion data, while the other GMMs had functional forms that violated the international standard practice requirements for GMMs for use in PSHA.

Fortunately, however, intense research efforts over the last few years have addressed all of the above limitations. Most relevantly, new physics-based earthquake fault models have been developed for the transform zones of southwest Iceland that not only specify where the earthquake faults are, but predict long-term seismicity rates that are fully consistent with the latest and most reliable revision of the Icelandic historical catalogue, the ICEL-NMAR earthquake catalogue of all significant events since 1900. Also, new area seismic source zones for the volcanic regions of Iceland have been proposed, several new state-of-the-art Bayesian hybrid GMMs have been developed for Iceland, including a GMM that models ground motions by key geological types of Iceland (hard/old rock, rock, lava, soft soil), all of the new GMMs are consistent with the requirements of PSHA standard practice, and a new backbone approach to PSHA has been developed that treats uncertainties more comprehensively. In addition, the European Union's H2020 project (ChEESE) and the Rannís project (SENSHAZ), have produced huge datasets of synthetic physics-based earthquake ground motions from earthquakes in the transform zones. All of the above lays the foundation for the first comprehensive and state-of-the-art physics-based PSHA to be carried out for Iceland, with high resolution in the near-fault hazard in Southwest Iceland in particular. This project will revise the PSHA of Iceland and produce hazard maps that will serve as the new Icelandic National Annexes for Eurocode 8.

8. Declaration

The authors of the report are responsible for its content. Its results should not be interpreted as the stated policy of the Road Administration or the opinion of the institutions or companies the authors work for.

Benedikt Halldórsson

Undirskrift	Reykjavík	26.3.2024
	Staður	**Dagsetning**

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