1. Information about the project

Name of the project: A new near-field earthquake strong motion model for pseudo spectral accelerations using Bayesian statistics

Grant number: 1800-973

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2. Participants and their role in the project

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

Benedikt Halldorsson, Research 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.*

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.*

3. Objectives and work packages of the project

The *long-term goal* of the project (measurable a few years after the project has finished) is to mitigate the destructive impacts of future earthquakes in Iceland through the comprehensive implementation of the first physics-based approach to near-fault PSHA. To that end, the *short-term* objective of the project i.e., the direct and immediate effects that are measurable at the end of the project, is to deliver a new GMM that captures the characteristics of near-fault velocity pulses, that the details are reflected in the milestones defined in the proposal:

Milestones 1: Processing, analysis, classification, and parametrization of the synthetic near-fault ground motion dataset of time histories.

Milestones 2: Calibration of the near-fault velocity pulse model to the synthetic dataset of velocity pulses using the Bayesian Hierarchical Model.

Milestones 3: Testing the predictive capabilities of the new velocity pulse model in the near-fault region, augmenting existing GMMs with the new near-fault model, and quantifying their relative differences, which reveals the potential effects of this improvement on PSHA in the near-fault region.

There are no foreseeable changes in the work plan, management and/or participation, and no major deviation relative to the original application.

4. Progress of the project and the main results

Iceland is the most seismically active region in Northern Europe (Einarsson 2014). Probabilistic seismic hazard assessment (PSHA) is the international standard practice on which optimized seismic risk management is based e.g., through the earthquake resistant design of structures (Standards Council of Iceland / Staðlaráð Íslands (SI) and Halldorsson 2010). In turn, PSHA relies on three key inputs, the location of the earthquake fault system, the seismic activity of the system, and seismic ground motion models i.e., how far away from the earthquake source the strong shaking reaches (McGuire 2004). The strongest earthquakes in Iceland take place in the two transform zones of the country, one of which is the densely populated South Iceland Seismic Zone (SISZ), characterized by its unique North-South aligned bookshelf strike-slip faults that are responsible for the long-term release of tectonic strain across the tectonic plate margin (Sigmundsson et al. 1995; Sigmundsson 2006). Recently, the bookshelf fault system has been shown to be continuous along the margin towards West, all along the Reykjanes Peninsula Oblique Rift zone (RPOR) (Einarsson 2014; Steigerwald et al. 2018), bringing it in close proximity to the capital region of Reykjavík, where 2/3 of the population reside (Figure 1).

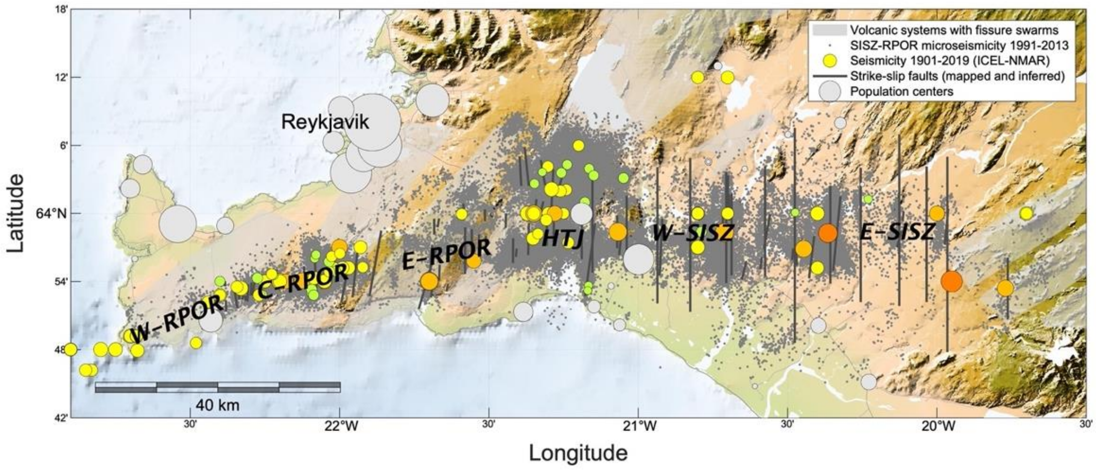

Figure 1. The transform zone of Southwest Iceland indicating the Western, Central and Eastern RPOR as continuation of the Western and Eastern SISZ bookshelf fault system. The epicentral distribution of instrumental seismicity (colored circles indicate mainshocks 1901-2019, and grey dots microseismicity 1991-2013) relative to the main population centers in the region (gray circles). The gray solid lines represent either surface mappings of North-South aligned strike-slip faults, vertical projections of relocated seismicity on such faults, and provisional fault plane projections of historical earthquakes.

It is well known both from observations as well as physics-based modeling of earthquake rupture and near-fault ground motion simulations, that the most damaging part of near-fault seismic motion is the velocity pulse, the large-amplitude and long-period pulse-like ground motions found along the fault and away from the ends of strike-slip faults, as shown in Figure 2 (Somerville 2003; Mavroeidis and Papageorgiou 2003, 2010; Dalguer and Mai 2011; Cork et al. 2016). With relatively large North-South striking earthquake faults being mapped directly South of the evermore expanding Capital region, this becomes a cause for great concern. In particular, since such effects have not been taken into account in any PSHA nor incorporated into modern building standards such as Eurocode 8. The key reason has been the lack of data in the near-fault region from strong earthquakes, and the subjective nature of selecting input parameters for complex models of earthquake rupture and ground motion simulations (Mavroeidis and Papageorgiou 2010; Dalguer and Mai 2011).

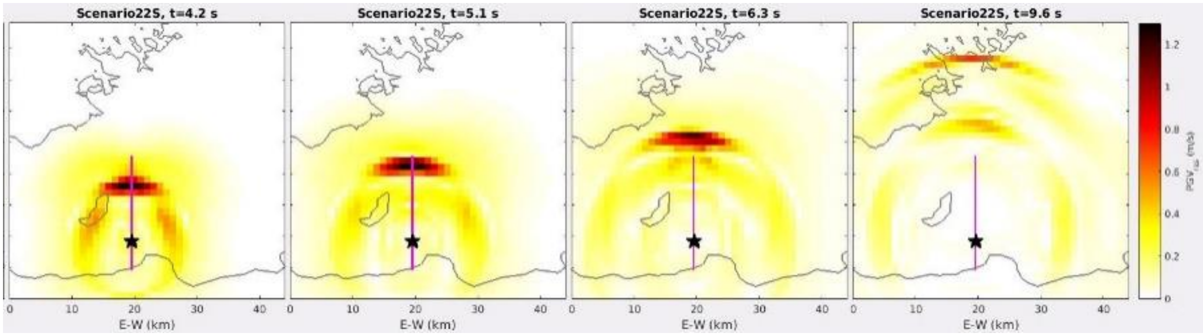

Figure 2. The total horizontal ground velocity amplitudes at various time intervals from the kinematic rupture modeling of a hypothetical $\boldsymbol{M_w}$6.5 vertical strike-slip earthquake (star marks the epicenter, located South of the Capital region, between C-RPOR and E-RPOR). The dark red colors indicate large amplitude and long period velocity pulses that propagate towards the Capital region as a result of earthquake rupture directivity effects.

Fortunately, however, three major developments have recently been made that now allow us to comprehensively address both of these issues for Southwest Iceland. (a) In the SENSHAZ project (2019-2022, Rannís No. 196089), a new 3D physics-based fault system model of the bookshelf strike-slip faults in the SISZ-RPOR has been developed that not only quantifies the location of the earthquake fault system but captures the long-term seismic activity of the region, thus effectively explaining the historical earthquake catalogue (Bayat et al. 2022, 2023). (b) In the ChEESE (2018-2021, H2020, No. SEP-210491613) project, this model has been formally incorporated into CyberShake, the physics-based earthquake rupture modeling and ground motion simulator developed by Southern California Earthquake Center and the foundation of physics-based PSHA (PB-PSHA) for California (Graves et al. 2011; Rojas et al. 2021). Moreover, the earthquake source rupture scaling laws in CyberShake have been adjusted to accurately represent the unique earthquake source scaling in South Iceland, a result of a collaboration between ChEESE and SENSHAZ (Halldorsson et al. 2022; Li et al. 2022). As a result, the simulator captures all salient features of near-fault velocity pulses from strong Icelandic earthquakes (Halldórsson et al. 2007). (c) A synthetic finite-fault catalogue of 223 earthquakes larger than M_{w}5 consistent with the new 3D fault system model has been generated, equivalent to a duration of 500 years seismic activity in the SISZ-RPOR (Figure 3, stars) (Kowsari et al. 2022). Then, CyberShake has been applied in the simulation of multiple earthquake rupture scenarios for each event capturing the variability in the hypocentral locations, and the corresponding three-component synthetic ground motion time histories simulated at every station of a dense grid of 145 hypothetical stations in Southwest Iceland (Figure 3, triangles). As a result, the largest synthetic dataset of physically realistic seismic ground motion time histories has been produced for the SISZ-RPOR which consists of ~350.000 event-station pairs i.e., sets of three-component synthetic ground motion time histories.

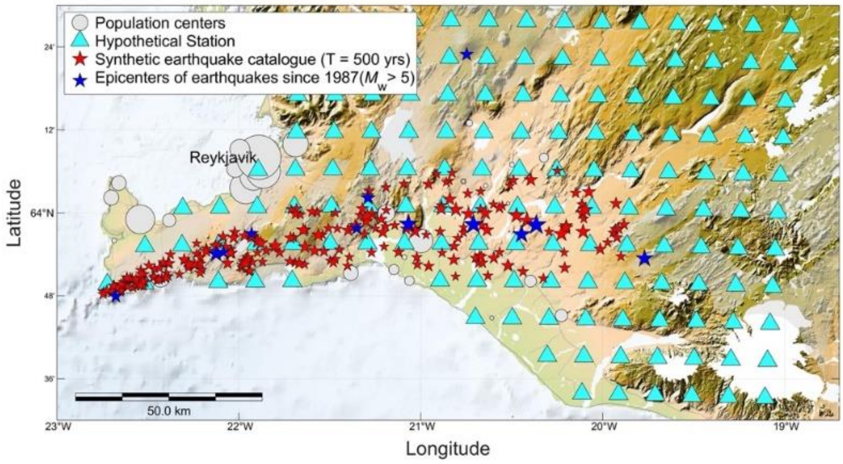

Figure 3. The region of Southwest Iceland along a 10x10 km grid of hypothetical stations for which the ground motions are simulated for each hypothetical earthquake in the 500 year-long finite-fault synthetic earthquake catalogue (red stars indicating the epicenter). The gray circles schematically indicate the locations and relative population differences of the main population centers in the region.

Further compounding the issue, the actual dataset only has M_w6.5 as the maximum recorded earthquake magnitude (Sigbjörnsson et al. 2014) with the Easternmost SISZ believed to be capable of producing M_w7-7.2 earthquake (Einarsson 2014; Jónasson et al. 2021). For comparison, the entire dataset of strong-motion time histories from tectonic earthquakes in Southwest Iceland that have been recorded on the relatively sparse Icelandic strong-motion network in the region are merely 83 event-station pairs (Ambraseys et al. 2004). Figure 4 shows the parametrization of the synthetic ground motions (in terms of horizontal pseudo spectral acceleration at 1 s period of oscillation) as black dots, each representing one event-station pair. In contrast, the red dots represent actual data. Both are plotted relative to the new suite of Bayesian ground motion models (GMMs) which importantly, confirms the validity of the synthetic dataset where we have data, and highlights the need for revised calibration at the largest magnitudes where no real data exists. In addition, due to the lack of actual near-fault data, the GMMs themselves are blind to any near-fault effects pulses in the data.

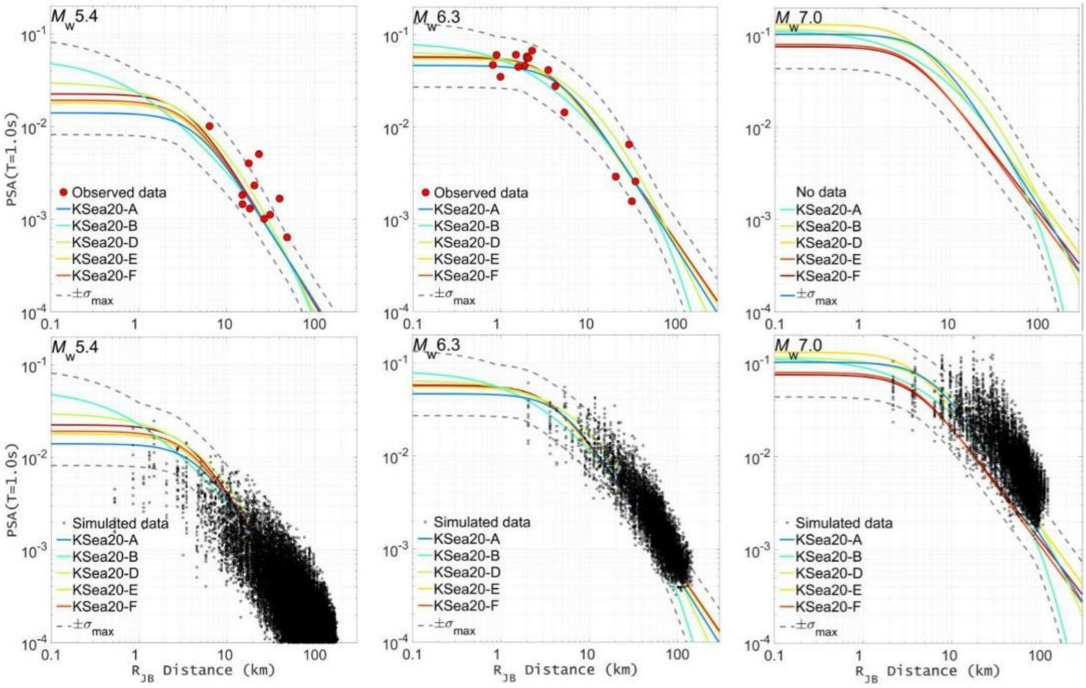

Figure 4. The attenuation with distance of pseudo spectral acceleration (PSA) at 1 s period (on rock site condition) as predicted by the new suite of Icelandic Bayesian ground motion models (solid lines) along with the envelope of their standard deviations (dashed lines), for three different magnitudes (left to right): $\boldsymbol{M_w}$5.4, 6.3 and 7.0. At top, the red circles show the extent of the actual data from earthquake mainshocks of those magnitudes that were recorded in Southwest Iceland from 1987-2008. Note that no data exists for magnitude 7. At bottom, the corresponding parametrization of the synthetic dataset is shown as a black dot, representing each event-station pair of given rupture scenario for each star and each hypothetical station in Figure 3.

The synthetic dataset now contains near all possible permutations of near-fault effects i.e., the damaging near-fault velocity pulses from the most realistic, and physics-based finite-fault earthquake rupture modeling that has been carried out for the SISZ-RPOR fault system. This is an exceedingly important issue, as a preliminary PSHA based on empirical GMMs for peak ground acceleration for the same catalogue shows that the high hazard levels that have been reserved for the SISZ are now seen to encroach on the capital region of Reykjavík. This is a cause for great concern because the current PSHA i.e., the National annex for Iceland for Eurocode 8, has not been revised for 20 years, was never peer-reviewed, and was based on a crude approach to PSHA with earthquakes modeled as point sources, used simplistic GMMs, and seismicity rates derived from a rudimentary statistical analysis of the limited earthquake catalogue of the region (European Committee for Standardization 2003; Standards Council of Iceland / Staðlaráð Íslands (SI) and Halldorsson 2010; Kowsari et al. 2019, 2020; Sonnemann et al. 2020; Kowsari et al. 2021).

In this study therefore, we develop a near-fault GMM using a Bayesian Hierarchical Model (BHM) that offers a flexible probabilistic framework for multilevel modeling of earthquake ground motion parameters. It also describes the relative contribution of source, path, and site effects to the overall GMM uncertainty, through its event, event-site, and site-terms, respectively, along with their associated uncertainties (Rahpeyma et al. 2021). The advantages of the BHM approach have been demonstrated through several studies in Iceland (Ordaz et al. 1994; Wang and Takada 2009; Arroyo and Ordaz 2010; Kuehn and Scherbaum 2015, 2016; Rahpeyma et al. 2018, 2021; Kowsari et al. 2019, 2020). For this purpose, we use the GMM's functional forms that satisfy the minimum requirements of GMMs used in PSHA (Cotton et al. 2006; Bommer et al. 2010). The functional forms include self-similar magnitude scaling and magnitude-distance dependent saturation terms, that introduce a controlled saturation of large magnitude ground motions. Then we add a near-fault term and recalibrate the regression coefficients of the selected GMMs to the simulated data using a BHM.

In the context of Bayesian statistics, the posterior distribution $\pi(\boldsymbol{\theta}|\boldsymbol{y})$ is proportional to the product of the prior density of the parameters, $P(\boldsymbol{\theta})$, and the likelihood function, $L(\boldsymbol{y}|\boldsymbol{\theta})$, where $\boldsymbol{y}$ is a ground motion intensity measure (here, PGA and PSA at different periods) and $\boldsymbol{\theta}$ regression coefficients of a GMM that is going to be recalibrated. The data covariance matrix to be used in the likelihood function is from the synthetic data because higher-order terms of the GMMs cannot be determined with confidence from the observed Icelandic dataset alone (due to the lack of data). For the prior distribution, we apply informative priors for selected model coefficients based on the original publications, allowing for incorporating a certain degree of knowledge about the values of the parameters that will affect the posterior distribution of model parameter and improve the overall fit. Therefore, we first estimate the posterior distribution by combining the informative priors of the model coefficients as prior distribution and synthetic data in a likelihood function i.e., $\pi_1(\boldsymbol{\theta}|\boldsymbol{y}) \propto P(\boldsymbol{\theta})L_{\mathrm{syn}}(\boldsymbol{y}|\boldsymbol{\theta})$. Then, we try another assumption where the prior distribution is the obtained posterior distribution and now the likelihood function is the Icelandic observations i.e., $\pi_2(\boldsymbol{\theta}|\boldsymbol{y}) \propto \pi_1(\boldsymbol{\theta}|\boldsymbol{y})L_{\mathrm{obs}}(\boldsymbol{y}|\boldsymbol{\theta})$.

Different methods for incorporating directivity effects into PSHA have been proposed in the literature (Shahi and Baker 2011). Indeed, one possible strategy is to introduce empirical adjustments into the GMMs and then recalibrate their model parameters using a set of near-fault datasets. The response amplifications due to directivity are investigated more in the two following projects of the NGA-West1 (Power et al. 2008), and NGA-West2 (Bozorgnia et al. 2014). The directivity modelers in NGA-West1, proposed post hoc "corrections factor" for the median of NGA GMMs by fitting their directivity functional forms to the residuals of that GMM. The implementation of these directivity models, however, experienced some conceptual difficulties. To overcome the shortcomings described in NGA-West1 models, the NGA-West2 directivity modelers developed four distinct directivity models for the ab-initio inclusion in the NGA-West2 GMMs with their coefficients determined simultaneously with the other GMM coefficients. Of these models, only the Chiou and Spudich (Spudich and Chiou 2013) is adopted by one of the NGA-West2's GMM (CY14) (Chiou and Youngs 2014). The Chiou and Spudich (Spudich and Chiou 2013) model has several advantages, including its attempt to keep directivity predictors as simple and computationally rapid as possible. It clarifies the various factors contributing to the azimuthal distribution of shaking around a fault and develops directivity models with empirically determined model parameters (Donahue et al. 2019). These parameters can be used to calculate a "directivity" correction for the seismic wavefield. Moreover, a new directivity predictor called the direct point parameter was introduced which was associated with three main factors: a measure of isochrone velocity (a quantity closely related to rupture velocity- high isochrone velocity is an indication of strong directivity effect); a measure of rupture propagation distance; and a radiation pattern term (Bernard and Madariaga 1984; Spudich and Frazer 1984, 1987). Figure 5 illustrates the spatial distribution of PSA (T=2s) in accordance with CY14. Two distinct rupture scenarios are considered (unilateral, and bilateral): the spatial distribution of PSA with its original model parameters in CY14 (a) and alterations in the spatial pattern of PSA at T=2s in CY14 due to a shift in the β_7 from its original 0.2 to 0.6 (b). (c) for a comparative perspective, the spatial pattern of the synthetic PSA (T=2s) is also presented.

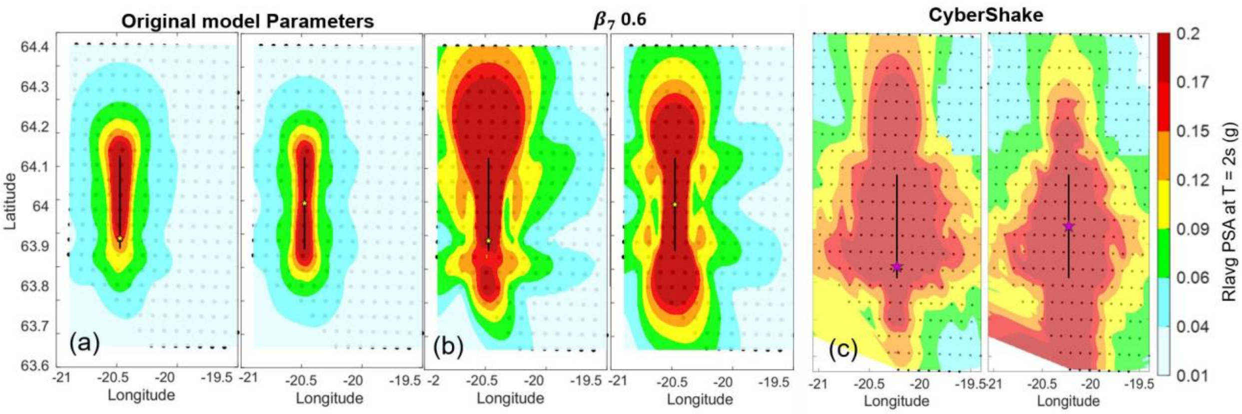

Figure 5. Comparison of the (a) spatial distribution of PSA at T=2s based on the CY14 with its original model parameters, (b) with the adjusted β_7 at 0.6, and (c) the CyberShake simulation.

The non-directive GMM of Kea20 predicts a symmetrical wavefield of RIavg PSA at different oscillation periods around the finite-fault plane, essentially providing a good overall approximation of the wavefield in both the near- and far-fault regions. This symmetry arises because there is uncertainty regarding the hypocentral location of the earthquake along the fault plane – whether it's at one end of the fault, the other, or at the center. Consequently, Kea20 GMM predicts an envelope at iso-distance from the fault, considering all different rupture variations. In this study, our interest primarily lies in a similar concept but is specifically focused on the near-fault directivity effects due to the finite-fault rupture extent, knowing the approximation of the hypocentral location. That is, we aim to add a directivity term that extends the iso-distance curve somewhat away from the fault ends to mimic the strong motions due to the directivity effect. This adjustment would then represent the corresponding approximation of the wavefield in the near-fault region.

The new Bayesian near-fault GMM has then been updated through BHM shown in Figure 6. This figure compares the predictions of the new updated near-fault GMM, the parameters of which are derived from the corresponding posterior distribution that results from the MCMC algorithm. The existing GMM appears to fit the data really well, as expected, but slightly overpredicts the synthetics at large magnitudes. On the other hand, the updated model underpredicts the synthetic near-fault motions. That is due to trade-offs between weakly constrained parameters and the mode of presentation. Namely, only one parameter of the near-fault term was being allowed a weak prior, instead of allowing all of them while at the same time applying strict priors on all parameters of the existing GMM.

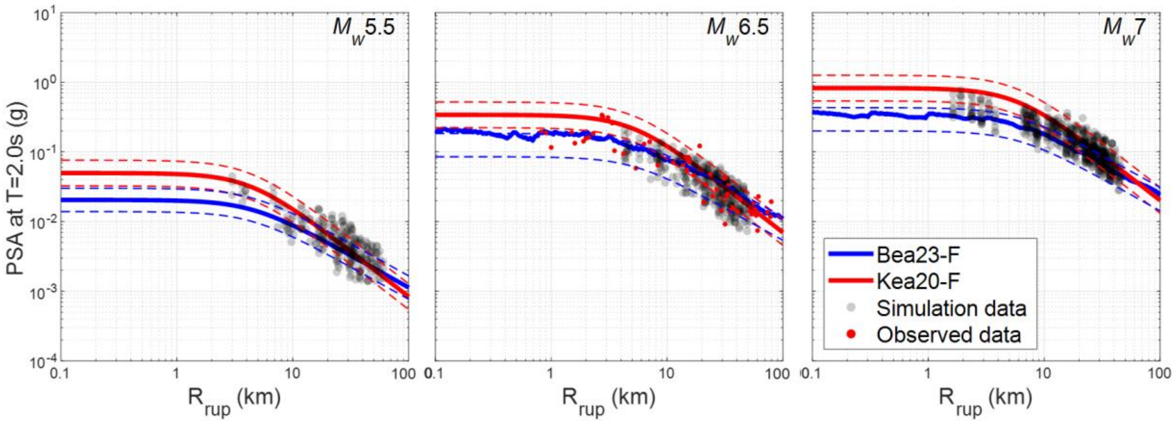

Figure 6. The attenuation of the Kea20 for PSA at T = 2s (red curves) vs. Bea23 (blue curves). The red circles show the observed datasets in Southwest Iceland.

From the results, we notice that a directivity model to be added to the GMM should be “centered,” in other words, it needs to be constructed so that if the directivity term calculated for a rupture were averaged over all potential hypocenters and racetracks having constant rupture distances, the resulting average should be zero so that the magnitude and distance scaling of the GMM will not be modified and result in a smooth decline of the GMM curve vs. the distance. For such a directivity predictor, the act of centering involves modifying the directivity adjustment so that, for a given distance from a fault, the average correction over all azimuths is zero. The near-fault GMM of this study provides an updated and state-of-the-art model that can capture the salient characteristic of the near-fault ground motions and can be used with confidence in a physics-based PSHA of the SISZ-RPOR.

5. Impacts

The near-fault GMM of this study will provide an updated state-of-the-art model that can capture the salient characteristic of the near-fault ground motions in Iceland and can be used with confidence in a physics-based PSHA as the basis for earthquake resistant design of large important structures and lifelines of the modern society. Therefore, the key impacts of the project will be a set of new physics-based near-fault GMMs, the first of their kind for Iceland. The results of this project will find 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 a 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.

6. Publications

The results of this project are published in international scientific journals and conferences where the support and funding provided by Vegagerðin are gratefully acknowledged. The following are the publications in the ISI-accredited journals:

1. **Kowsari M**, Eftekhari N and Yousefi Dadras E (2024) Uncertainty and Sensitivity Assessments on the Inputs of Probabilistic Seismic Hazard Assessment: A Case Study of the North Tehran, *Soil Dynamic and Earthquake Engineering*, 179, https://doi.org/10.1016/j.soildyn.2024.108558
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) A simplified seismicity model of the bookshelf fault system of the Southwest Iceland transform zone, accepted in *Bulletin of Earthquake Engineering*
4. 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:

5. **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.
6. Bayet 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.
7. 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 Iceland, the strongest earthquakes occur in two large transform zones, the Tjörnes fracture zone in the north, and the South Iceland seismic zone (SISZ) and Reykjanes Peninsula oblique rift (RPOR) in the southwest. Therefore, in these regions, the seismic hazard is highest and performing a probabilistic seismic hazard assessment (PSHA) is vital as the foundation of earthquake resistant building design and seismic risk mitigation. A reliable PSHA requires the state-of-the-art specification of its three key elements: (1) earthquake fault locations and sizes, their (2) seismic activity, and (3) the ground motion models (GMMs) that describe the ground shaking at any given location. However, the GMMs used in previous PSHA studies in Iceland have been calibrated to far-field motions, primarily high-frequency motions, and do not account for near-fault effects which are most prominent at low-frequencies. Namely, it is well known both from observations as well as physics-based modeling of earthquake rupture and near-fault ground motion simulations, that the most damaging part of near-fault seismic motion is the velocity pulse, the large-amplitude and long-period pulse-like ground motions found along the fault and away from the ends of strike-slip faults. As a result, conventional PSHA does not include key features of these near-fault velocity pulses. In this project therefore, we developed a new near-fault velocity pulse model using a Bayesian Hierarchical Model (BHM) that offers a flexible probabilistic framework for multilevel modeling of earthquake ground motion parameters. It also describes the relative contribution of source, path, and site effects to the overall GMM uncertainty, through its event, event-site, and site-terms, respectively, along with their associated uncertainties.

The results of this study show that the near-fault GMM fit the data really well, but slightly underpredicts the synthetic near-fault motions due to trade-offs between weakly constrained parameters and the mode of presentation. Namely, only one parameter of the near-fault term was being allowed a weak prior, instead of allowing all of them while at the same time applying strict priors on all parameters of the existing GMM. Moreover, we noticed that the directivity model should needs to be constructed so that if the directivity term calculated for a rupture were averaged over all potential hypocenters and racetracks having constant rupture distances, the resulting average should be zero so that the magnitude and distance scaling of the GMM will not be modified and result in a smooth decline of the GMM curve vs. the distance. For such a directivity predictor, the act of centering involves modifying the directivity adjustment so that, for a given distance from a fault, the average correction over all azimuths is zero. The near-fault GMM of this study provides an updated and state-of-the-art model that can capture the salient characteristic of the near-fault ground motions and can be used with confidence in a physics-based PSHA of the SISZ-RPOR.

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.

Undirskrift

Reykjavik 27.03.2024

Staður **Dagsetning**

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