UNIVERSITY OF ICELAND
Icelandic Met Office

A new Near-Fault Earthquake Ground Motion Model for Iceland from Bayesian Hierarchical Modelling of Big Data

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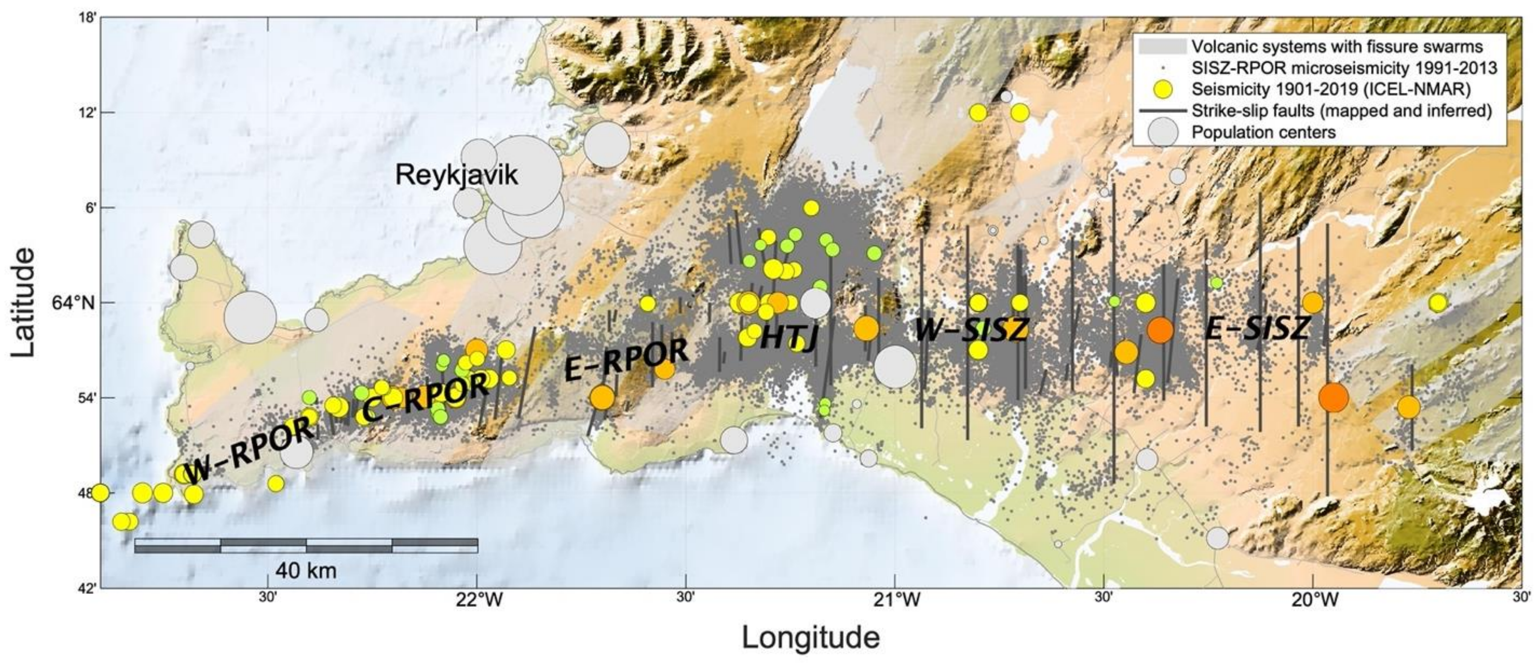
ABSTRACT

The South Iceland Seismic Zone (SISZ) and Reykjanes Peninsula Oblique Rift (RPOR) in Southwest Iceland together form one of the two major transform zones in the country that have the greatest capacity for the occurrence of destructive earthquakes. The SISZ is collocated with the South Iceland Lowland, a relatively flat and populated agricultural region with all critical infrastructures and lifelines of a modern society such as hydroelectric and geothermal power plants, dams, above-ground pipelines and electrical transmission lines. As a result, the earthquake hazard is the highest in this region and the investigation of earthquake strong-motion and its effects on manmade environment is of particular interest and vital for seismic risk assessment and its mitigation. In this regard, performing probabilistic seismic hazard analysis (PSHA) is the most acceptable way to quantify earthquake hazard for the systematic mitigation of seismic risk. In Iceland, velocity pulses as the most damaging part of near-fault motion, have been observed in all strong-motion recordings close to the causative faults of the last three large earthquakes. These velocity pulses have greatest effects on large structures such as bridges and tall/wide structures. However, conventional PSHA does not take into account such destructive effects. In this study, therefore we develop a new ground motion models (GMMs) that include near-fault velocity pulse model using a Bayesian Hierarchical Model (BHM). The BHM 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. By augmenting new GMMs with the new velocity pulse model, the new near-fault GMM will provide an updated and state-of-the-art model that can capture the salient characteristic of the near-fault ground motions and will enable the first physics-based near-fault seismic hazard estimation for Iceland.

INTRODUCTION

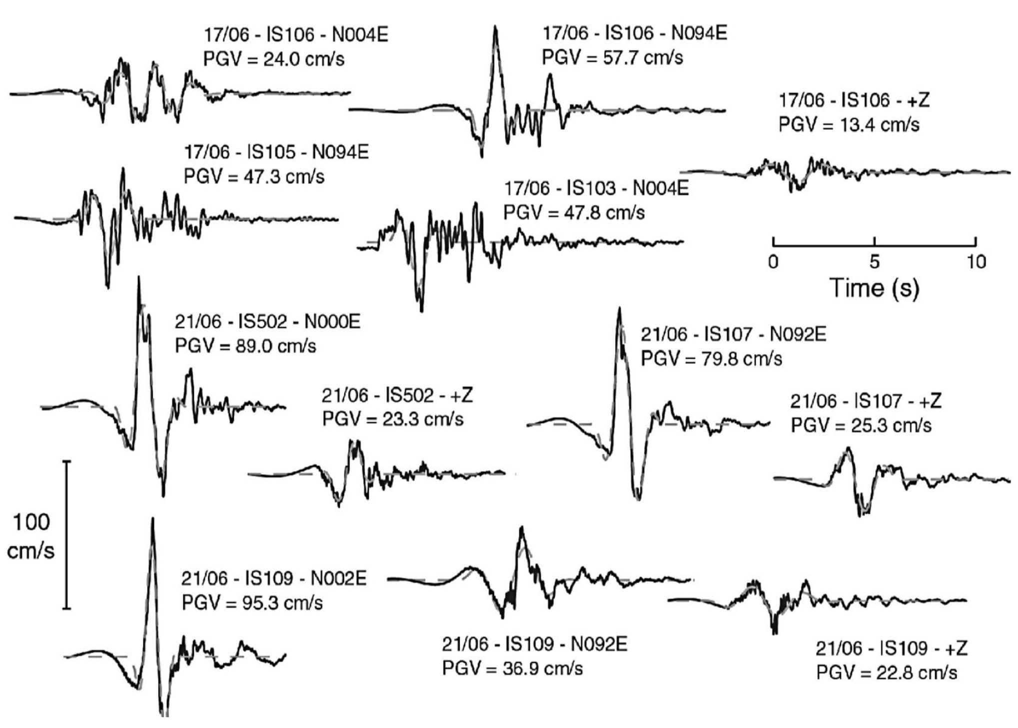
- The strongest earthquakes in Iceland take place on the densely populated South Iceland Seismic Zone (SISZ), and the Reykjanes Peninsula oblique rift, where 2/3 of the Icelandic population reside.
- A large number of N-S near-vertical dextral strike-slip faults perpendicular to the SISZ-RPOR has responsible for destructive earthquakes throughout history in Southern Iceland.



- As a result, the seismic hazard is highest in Southwest Iceland and performing the probabilistic seismic hazard assessment (PSHA) is needed.
- PSHA relies on three key elements: (1) the location of the earthquake fault system, (2) the seismic activity of the system, and the ground motion models (GMMs) i.e., how far away from the earthquake source the strong shaking reaches.
- The Icelandic Bayesian GMMs (Kowsari et al 2020) capture the high near-fault amplitudes along with the rapid ground motion attenuation with distance **but without inclusion of complex near-fault effects.**

NEAR-FAULT PULSES

- When the earthquake rupture propagates toward a near-fault site with a velocity almost equal to the shear-wave velocity, the ground motions may be characterized by intense **high-frequency** motions of **short duration**, but also **large amplitude** and **long-period** velocity pulses.
- In Iceland, such velocity pulses have been observed in all strong-motion recordings close to the causative faults of the last three large earthquakes (M_w 6.3-6.5).



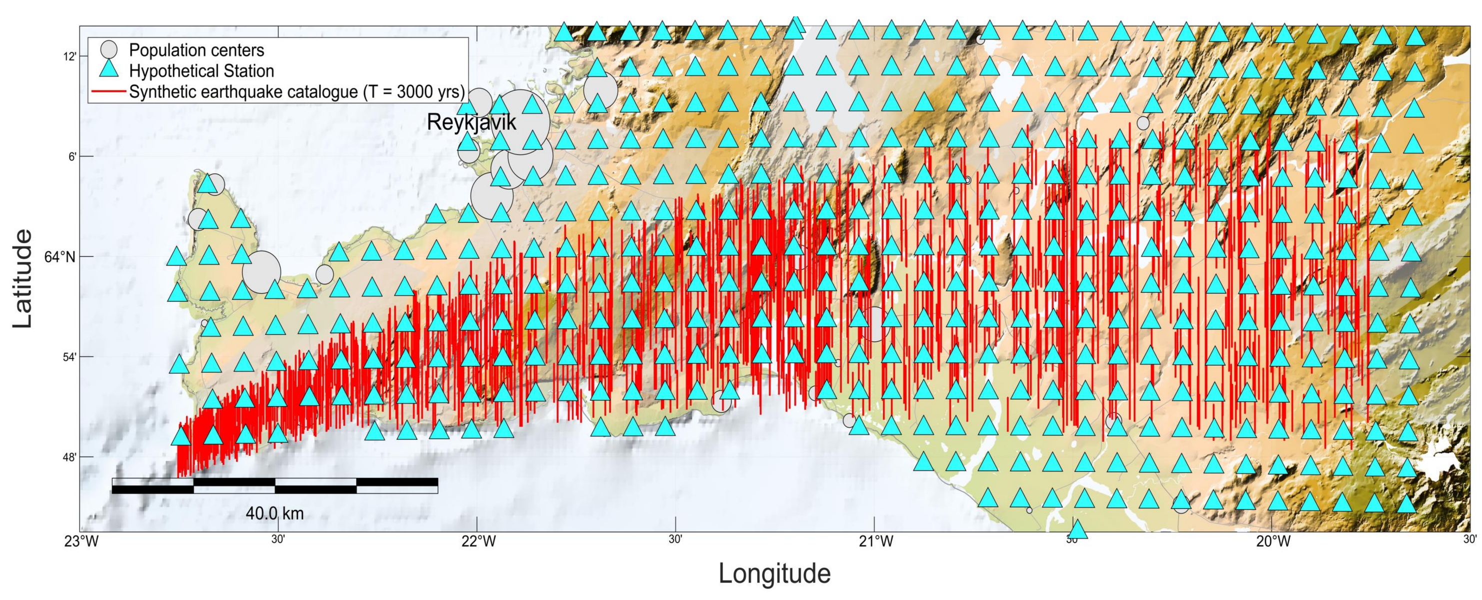
PHYSICS-BASED SIMULATION

Despite having all the strong-motion recordings from these earthquakes in southwest Iceland, the near-fault data is still too limited to enable the reliable calibration of a physically realistic, yet parsimonious, near-fault model that incorporate such effects into empirical GMMs. Such limitations are:

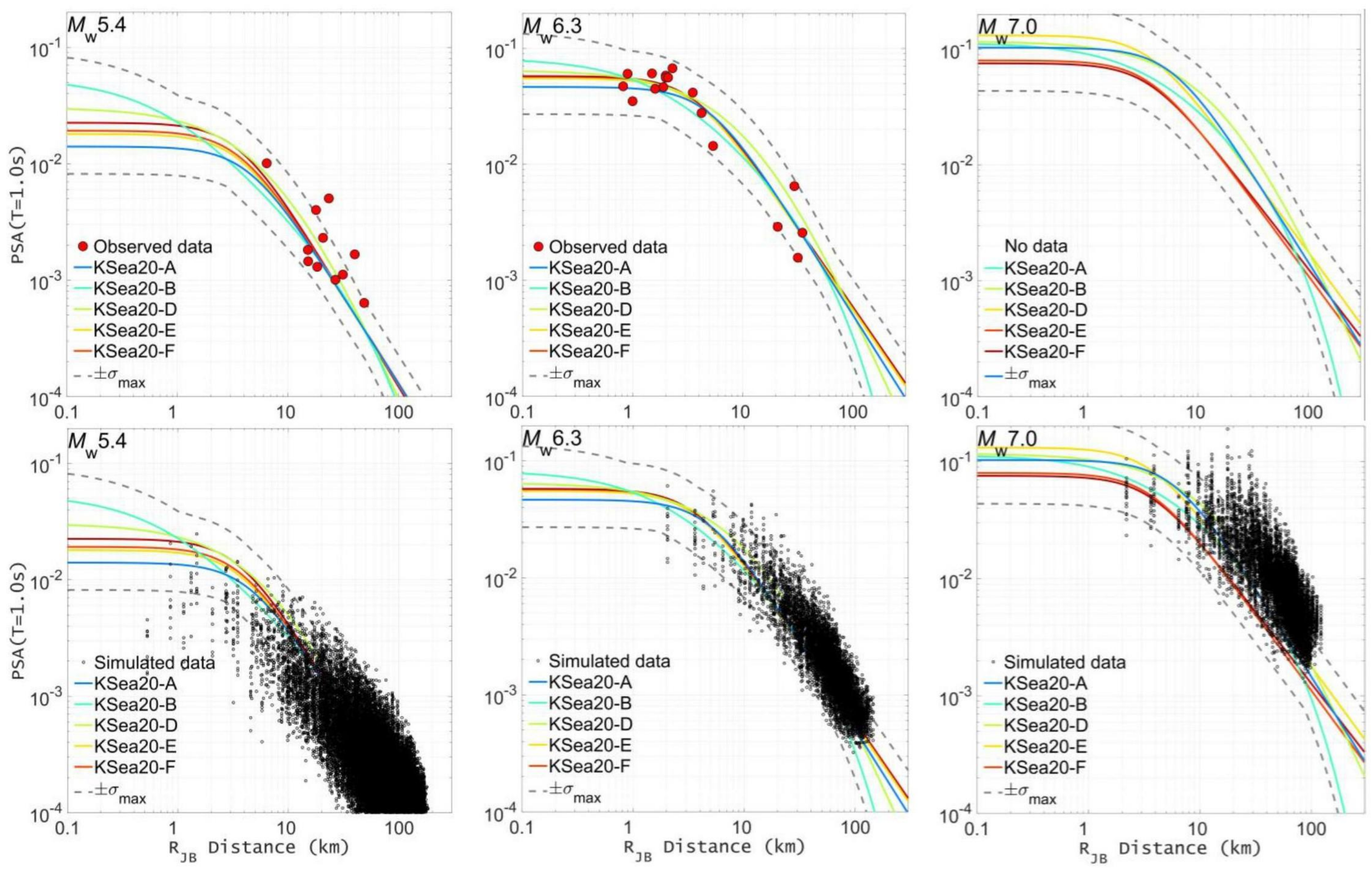
- Narrow magnitude range M 6.3-6.5
- Lack of data for earthquakes M > 6.5
- Only 40 records
- Not all stations have good data at long periods

To overcome this problem therefore, in collaboration with the European ChEESE project (Center of Excellence in Exascale Solid Earth, 2018-2022, H2020), we have generated a vast synthetic near-fault ground motion time histories using high-performance computing systems of the Barcelona Supercomputing Centre in Spain.

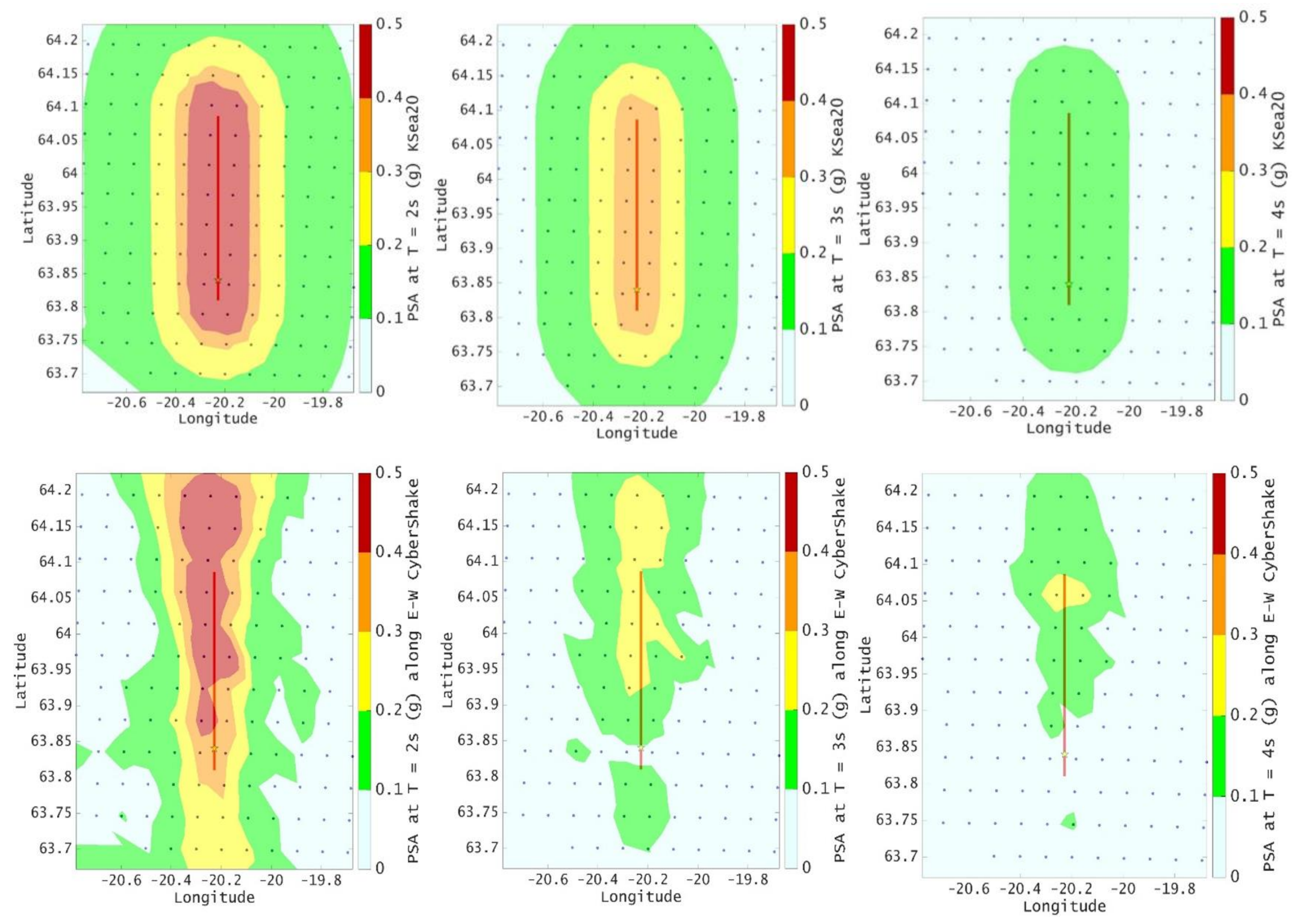
- The simulation has been carried out:
  - On a dense grid of 594 near-fault stations (triangles)
  - Using the CyberShake platform, a physics-based earthquake simulator that has been adapted to the characteristics of the SISZ-RPOR earthquakes.



The hypocentral locations and slip distributions on each synthetic fault have been varied, resulting in approximately 1 million earthquake-station-specific pairs of synthetic low frequency and high-amplitude near-fault ground motion time histories (black dots).



- The first and preliminary look at the parametrization of the synthetic ground motions time histories (in terms of horizontal PSA at 1s period of oscillation) is presented in above as black dots, each representing one event-station pair.
- In contrast, the red dots represent recorded strong motion data in Iceland. Both are plotted relative to the new suite of Bayesian GMMs of Kowsari et al (2020) that importantly, confirms the validity of the synthetic dataset, and highlights the need for revised calibration at the large magnitude earthquakes, i.e., M_w 7, where no real data exists.



The spatial distribution of PSA at three different period of oscillations predicted by Kowsari et al (2020)'s GMM (top figure) and from CyberShake (bottom figure) for the fault with M_w 7

BAYESIAN HIERARCHICAL MODLING

- We augment the far-field GMMs proposed by Kowsari et al (2020) with the near-fault directivity term and recalibrate the regression coefficients (i.e., $C_1 - C_{10}$) using the Bayesian Hierarchical Modeling (BHM) to the big synthetic dataset of CyberShake that contain near all possible permutations of near-fault effects.

$$\log Y = C_1 + C_2 M_w + C_3 \log_{10}\sqrt{R_{rup}^2 + Z(M_e)^2} + C_7 S + C_8 F_M F_R \exp(-C_9 (M_w - C_{10})^2) \cdot \ln\left(\frac{1}{\left(\frac{1}{0.8} - \frac{R_{Hyp} - R_D}{R_E}\right)} \cdot \max(E, 0.1f) \cdot \max(\overline{FS}, 0.2)\right)$$

$$Z(M_e) = C_4 + C_5 (M_w - C_6)^2 H(M_w - C_6)$$

- The BHM offers a flexible probabilistic framework for multilevel modeling of earthquake ground motion parameters and the quantifies the probability distribution of each coefficient along with the relative contributions of source and path effects to their overall uncertainties in near-fault region.

CONCLUSIONS

- The damaging near-fault velocity pulses, known as the directivity effect, have not been considered in previous PSHA studies due to a lack of seismic ground motion data in Southwest Iceland.
- The GMMs in Iceland are not calibrated to constrain the complex near-fault effects (e.g., directivity effect).
- To overcome this problem, we augment the far-field GMMs with a physics-based near-fault directivity terms and recalibrate the regression coefficients of the GMM using the BHM technique to:
  - A big dataset that includes merely ~1 million event-station pair of recorded strong motion in southern Iceland.
- The new near-fault GMMs of this study will thus capture the salient characteristic of the near-fault ground motions and will provide a fundamentally new and state-of-the-art approach to reassess the PSHA in Southwest Iceland where uncertainties will be incorporated in a novel manner and ultimately resolve the reliability and spatial resolution of the near-fault physics-based PSHA.
- The results will facilitate the incorporation of the near-fault effects into new near-fault and far-field GMMs, that are a key element of conventional PSHA.
- This will both enable the near-fault PB-PSHA along with the comparison of PSHA from the synthetic dataset vs. the GMMs.

ACKNOWLEDGEMENTS

This study was partially funded by the Icelandic Road and Coastal Administration Research Fund (No. 1800-973).

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