Physics-based earthquake ground-motion simulations in South Iceland

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Reliable estimates of earthquake ground motion are essential for the seismic design and assessment of buildings and infrastructure. Traditionally, these estimates rely on empirical ground-motion models (GMMs) developed from recordings of past earthquakes. However, their applicability can be limited in regions where strong-motion recordings are scarce, particularly for large earthquakes that have not occurred during the instrumental period. South Iceland provides a representative example of this challenge. The largest earthquake recorded by the Icelandic strong-motion network has a moment magnitude of approximately M_W 6.5, whereas historical and seismotectonic evidence suggests that earthquakes approaching M_W 7.0–7.2 may occur in the South Iceland Seismic Zone (SISZ). Consequently, estimating ground motions from such events requires extrapolation beyond the available observations, introducing considerable uncertainty into seismic hazard assessments. Furthermore, Icelandic earthquakes exhibit distinctive ground-motion characteristics, including high near-fault ground motion and rapid attenuation with distance, which are not always adequately represented by GMMs developed for other tectonic regions.

Physics-based ground-motion simulations (PBS) offer a complementary approach to addressing these limitations. Rather than predicting ground-motion intensity exclusively from statistical relationships derived from past earthquakes, PBS explicitly simulate the physical processes responsible for earthquake shaking: fault rupture, seismic-wave propagation through the Earth's crust, and the influence of local geological conditions. By combining numerical models of the geological structure with physically plausible earthquake sources, PBS can generate spatially distributed ground motions for both historical and hypothetical earthquakes. An important advantage is their ability to represent effects such as rupture directivity, wave propagation and local geological amplification, while allowing the investigation of earthquakes and rupture configurations for which no recordings are available.

This contribution presents recent developments in physics-based simulations for South Iceland, focusing on their potential applications in earthquake engineering. The simulations are performed using a large-scale three-dimensional numerical model of the region and the spectral-element code SPEED. The model incorporates the regional crustal structure and seismic attenuation and resolves seismic-wave propagation up to approximately 1.9 Hz. A recently developed kinematic rupture generator is employed to construct realistic earthquake sources characterized by heterogeneous correlated distributions of fault slip, rupture velocity and peak slip velocity. The generator enables the production of multiple physically plausible rupture realizations, providing a systematic way to investigate how uncertainty in earthquake rupture

A practical limitation of PBS is their restricted frequency range, as the computational cost increases substantially when higher frequencies are resolved. Since many engineering structures are sensitive to shorter-period ground motions, an additional procedure is required to obtain broadband predictions. For this purpose, the PBS are combined with a recently developed hybrid method, ANN2BB (Artificial Neural Network to BroadBand). The method uses an artificial neural

network to estimate short-period spectral accelerations from the long-period response of the simulated motions, together with source-site parameters, while a stochastic correlation model represents the ground-motion variability across locations, vibration periods and components.

The methodology is illustrated through simulations of the two major South Iceland earthquakes of 17 and 21 June 2000, with magnitudes M_W 6.5 and 6.4, respectively. These events provide an important validation opportunity because strong-motion recordings are available at several stations, including locations close to the causative faults. Comparisons between recorded and simulated ground motions demonstrate good agreement in waveforms, response spectra and relevant engineering intensity measures. These results provide confidence in the ability of the numerical framework to reproduce important features of observed earthquakes and constitute a basis for investigating future earthquake scenarios.

Beyond reproducing historical earthquakes, the framework can be used to investigate hypothetical events with different magnitudes, fault geometries and rupture characteristics. Ensembles of M_W 6.2 to M_W 7.0 scenarios have been generated to examine the distribution and variability of ground-motion intensity. Comparisons with empirical GMMs show generally consistent predictions within the magnitude range covered by Icelandic recordings, but also highlight potentially important differences for larger earthquakes. These findings illustrate the uncertainty associated with extrapolating empirical models beyond their calibration range and the potential contribution of physics-based simulations to evaluating ground motions from future large earthquakes.

From an engineering perspective, several practical applications can be envisaged. First, earthquake damage scenarios can be developed by combining spatially distributed simulated ground-motion intensities with structural vulnerability or fragility models. Such analyses can estimate the potential distribution of damage to buildings, bridges and critical infrastructure for selected earthquake scenarios, supporting emergency planning and seismic risk mitigation. Second, site-specific seismic hazard assessments can benefit from the explicit representation of source-to-site wave propagation, local geological conditions and rupture variability, particularly for important facilities located close to active faults. Third, physics-based simulations can support the development of hybrid ground-motion models, in which simulated scenarios complement the limited recordings available in Iceland. By combining simulation-based information with empirical observations, such models could provide improved constraints on magnitude scaling, distance attenuation and ground-motion variability, particularly for large earthquakes outside the range of the recorded database.

Overall, the results demonstrate that physics-based simulations, combined with efficient broadband modelling techniques, provide a promising complement to conventional approaches for seismic hazard and risk assessment. Although uncertainties associated with earthquake rupture, geological structure and numerical modelling remain important, the framework offers an opportunity to move beyond the limitations of the historical earthquake catalogue and investigate the potential consequences of future earthquakes in South Iceland. Its principal value for engineering practice lies in generating realistic, spatially distributed earthquake scenarios that can inform seismic design, infrastructure assessment and risk-reduction strategies.