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Sensitivity to Rupture Characteristics of Hybrid Broadband Ground-Motion Simulations for M_w8.7 Rupture Scenarios on the Hikurangi Subduction Zone

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ABSTRACT

The Hikurangi Subduction Zone in New Zealand can produce very large subduction interface earthquakes similar to the 2004 M_w9.2 Sumatra, 2010 M_w8.8 Maule, and 2011 M_w9.1 Tōhoku events. In this study, realistic ground motions for rupture scenarios along the Hikurangi Subduction Zone were developed using physics-based hybrid broadband ground-motion simulation. Simulations for 50 scenarios were conducted with parameter models validated using observed ground motions from small- and moderate-magnitude subduction interface earthquakes in New Zealand. The ground motions for the rupture scenarios exhibit significant sensitivity to the locations of strong ground motion generating subevents, rupture velocity, and stress parameter. The simulated ground motion intensities are generally lower than empirical ground motion model predictions at short periods, except around subevents, and slightly larger at long periods, especially within sedimentary basins.

Introduction

The Hikurangi subduction interface is a shallow dip reverse thrust fault under the North Island of New Zealand (NZ) which has formed between the Australian and Pacific plates [1]. Temporal correlation of geological evidence suggests that the Hikurangi Subduction Zone has experienced at least ten significant ruptures in the last 7000 years, with the most recent full-margin event occurring approximately 870–815 years ago [2]. In this study, we use hybrid broadband ground motion simulation to estimate likely ground motions from this event, which are particularly suitable: (i) given the large uncertainty in empirical ground-motion model-based predictions for such large events, (ii) for use in emergency management and scenario planning exercises; and (iii) as a large magnitude scenario testbed toward simulation-based seismic hazard analysis projects (e.g., Cybershake NZ).

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Interface Simulation Models and Rupture Kinematics

A kinematic source model with representations of slip, rake, and rise time was used within the Graves and Pitarka hybrid broadband simulation method [3,4]. The simulations utilized a 3D finite difference oriented to encapsulate the rupture extent and landmass of NZ. A grid spacing of 100 m was used with a minimum shear wave velocity of 500 m/s, which can resolve frequencies up to 1.0 Hz in the low-frequency component. Subduction-specific simulation models validated with small- and moderate-magnitude NZ subduction interface earthquake ground motions were implemented as median (i.e., archetype) rupture properties [5]. The simulations include explicit representation of strong-motion-generating subevents on the deeper portions of the rupture, consistent with observations of the 2010 M_w8.8 Maule and 2011 M_w9.1 Tōhoku events [6,7].

Sensitivity to Rupture Characteristics

To investigate ground-motion sensitivity to rupture characterization, 50 rupture scenarios were considered with perturbed source properties for: (i) hypocentre location; (ii) average rupture velocity; (ii) background stress parameter; (iv) subevent stress parameter; (v) subevent rise time; and (vi) subevent locations. Figure 1 illustrates sensitivity of simulated ground motion to variation of rupture characteristics between scenarios.

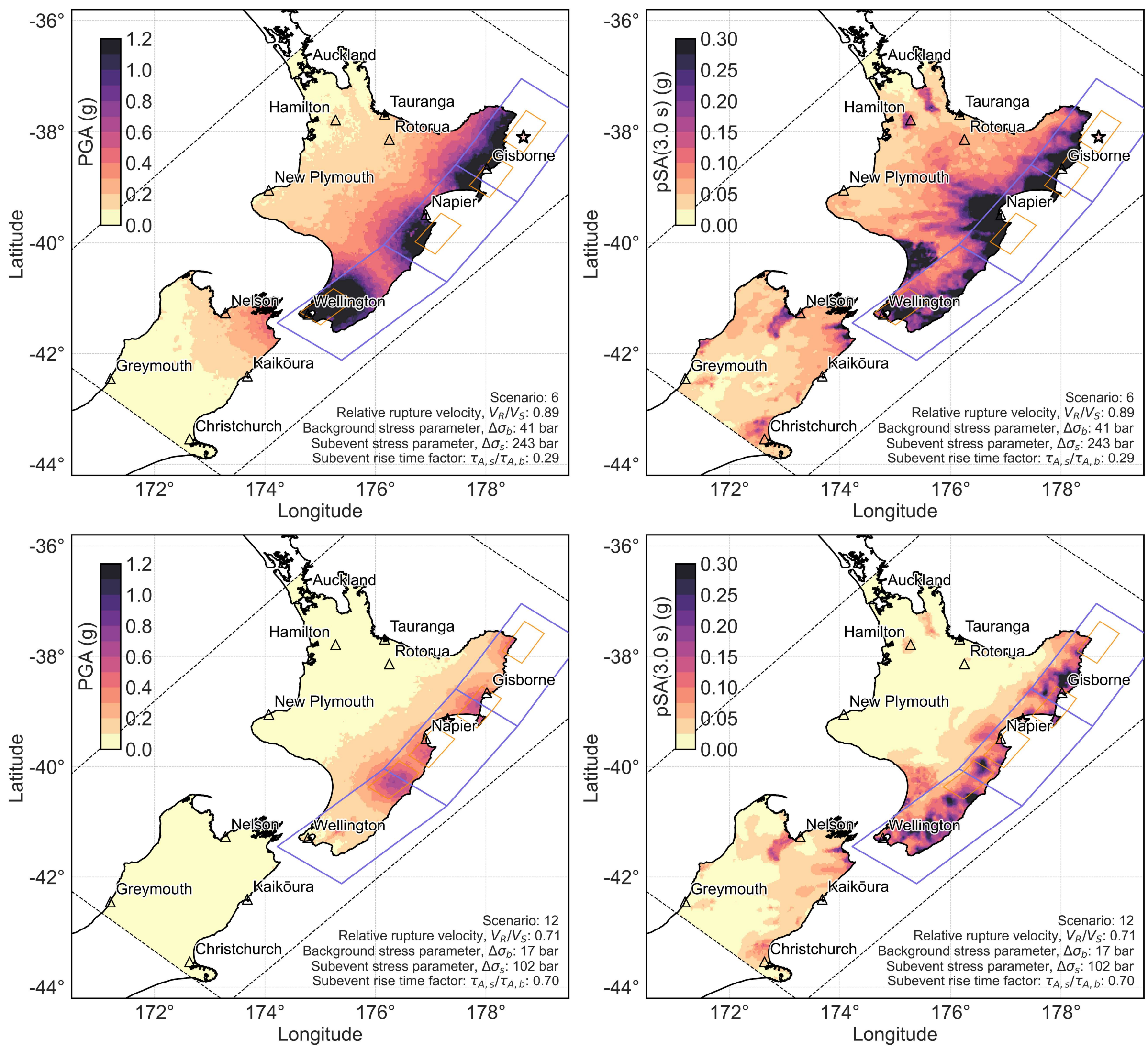

Figure 1. Peak ground acceleration (PGA) (left) and pseudo-spectral acceleration at T = 3 s, pSA(3 s), (right) for severe (top) and less intense (bottom) scenarios.

Rupture velocity, subevent stress parameter and rise time were observed to have a significant effect on ground motions, especially at short periods. Hypocentre location, both along-strike and down-dip, was found to have relatively little effect on the simulated ground motions. However, for certain scenarios rupture directivity combined with subevent positioning to produce very strong shaking in some locations. Scenarios with large rupture velocity and stress parameter, which also have short relative rise times on the subevents, tend to produce the largest ground motion intensities. In Wellington and Gisborne, as well as other population centres which are near the background rupture, there is very large sensitivity of the ground motion to subevent location.

Comparison with Empirical Predictions and Recorded Events

Figure 2 compares the simulations with ground-motion predictions from empirical ground motion models (GMMs) for subduction interface earthquakes for selected cities. As per the 2023 NZ National Seismic Hazard Model (NSHM) four GMMs for subduction interface earthquakes were considered [8]. These GMMs were combined using logic tree weights from the NZ NSHM [8] to develop composite empirical ground-motion predictions. Source, path, and site attributes were used as permitted by the empirical GMM functional forms; however, explicit treatment of subevent locations by the empirical GMMs was not practical.

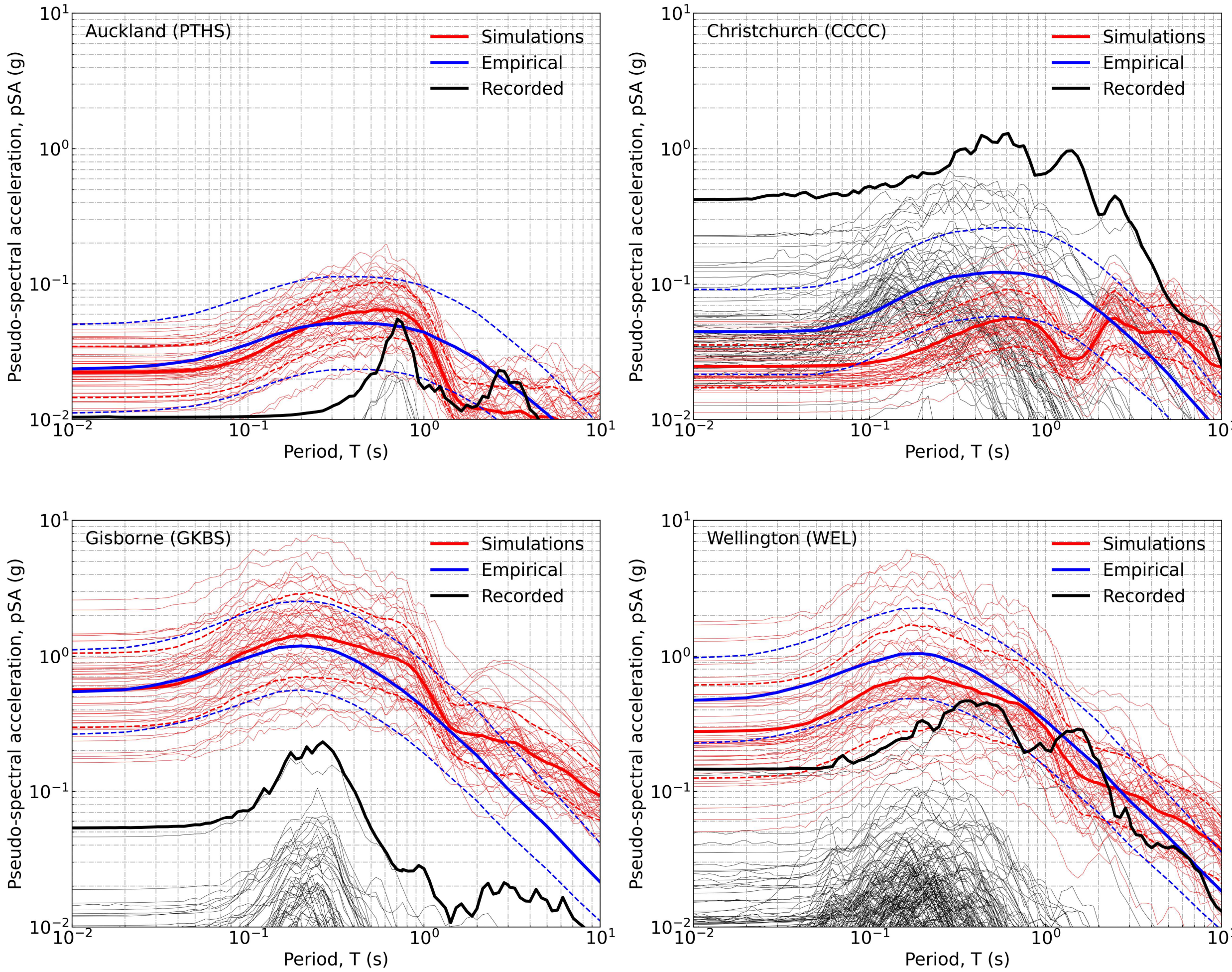

Figure 2. Simulation and empirical predictions for Auckland (top left), Christchurch (top right), Gisborne (bottom left), and Wellington (bottom right) with the mean (simulation) or median (empirical) predictions shown in bold and mean/median plus/minus one standard deviation shown with dashed lines. All previously recorded ground motions at each recording station are shown in black, with the envelope of all recorded historic shaking shown in bold.

At short periods, e.g., T = 0.2 s, the empirical predictions are moderately greater than the simulations (approximately twice the amplitude). At long periods, e.g., T = 3.0 s, the spectral accelerations predicted by the simulations and empirical GMM are generally similar. The simulations exhibit very large variability, especially at short periods, e.g., T = 0.2 s, and short rupture distances (e.g., Gisborne and Wellington). At long periods, e.g., T = 3.0 s, simulated ground motions exceed empirical predictions above the subevents and within sedimentary basins. For other regions, the empirical predictions for long periods are generally slightly greater than the simulations.

Figure 2 also compares the simulated response spectra from all scenarios with all previously recorded response spectra for selected cities. For most cities on the North Island (e.g., Auckland, Gisborne, and Wellington), the simulated spectral accelerations greatly exceed all previously recorded ground motions. On the South Island, the ground motions in Christchurch are significantly smaller than these previously experienced from past events, e.g., the 2010 M_w7.1 Darfield and 2011 M_w6.2 Christchurch earthquakes, except at very long periods, e.g., T = 10 s. Such a comparison is illustrative as it may indicate which cities may contain structures which have not experienced significant shaking and for which the Hikurangi Megathrust Scenario may produce locally unprecedented shaking intensities.

Conclusions

Sensitivity to rupture characteristics was examined across 50 rupture scenarios. The sensitivity of ground motions to variations in rupture characteristics is significant, especially at short rupture distances and for short period response. For some locations and response periods, spectral accelerations vary by over an order of magnitude between scenarios. The ground motions are especially sensitive to the locations of subevents, which are unknowable in advance of a rupture given our current level of scientific understanding. These findings highlight the inherent challenges in predicting ground motions for megathrust events but indicate such an event is likely to have significant impacts across NZ.

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