Insights from ground-motion simulation validation of New Zealand small magnitude subduction earthquakes

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1. Unique characteristics warrant special treatment

Physics-based ground-motion simulation can provide predictions of crustal earthquake ground-motion intensity metrics in New Zealand which are better than empirical ground-motion models. This study aims to extend this level of performance to subduction interface and slab earthquakes which have unique source rupture and travel path characteristics:

Interface earthquakes:

- Rupture interface at interplate boundary
- Effect of subducted sediment and seamounts
- Potential for very large ruptures (Figure 1–3)

Slab earthquakes:

- Deep ruptures within descending subducted slab
- Occur in high-stress/temperature environments
- Effect of volcanic arc on energy attenuation

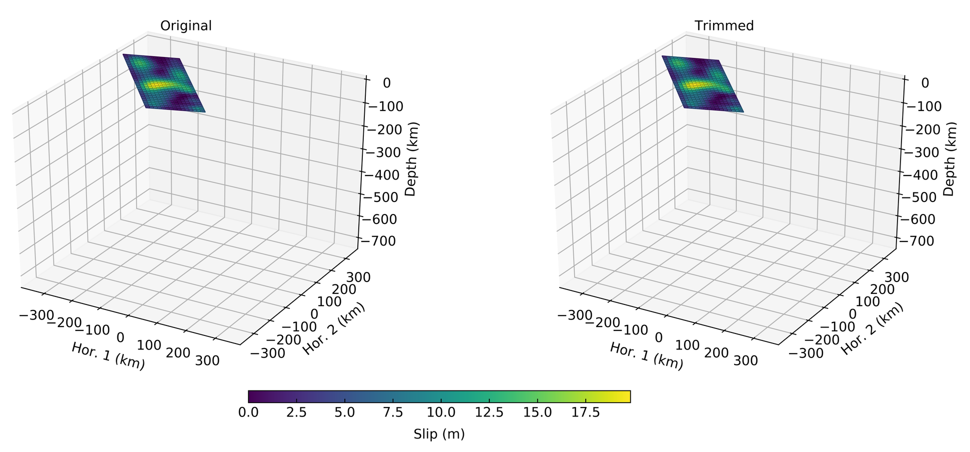

Figure 1: Rupture model for 2004 M_w9.2 Sumatra earthquake (Ji 2005)

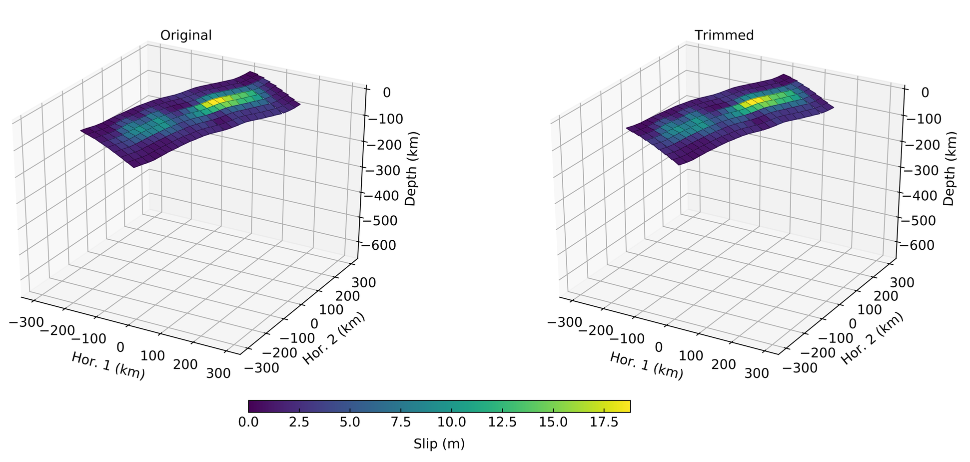

Figure 2: Rupture model for 2010 M_w8.8 Maule earthquake (Lorito et al. 2011)

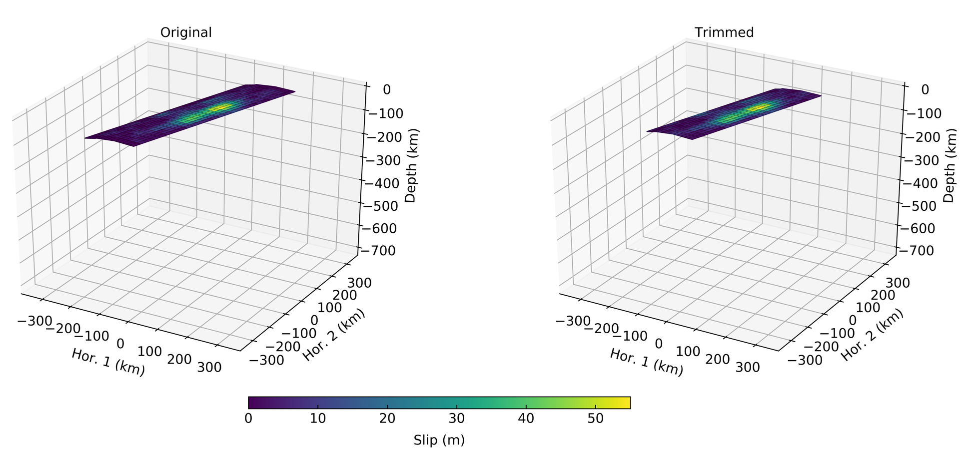

Figure 3: Rupture model for 2011 M_w9.0 Tohoku earthquake (Hayes 2013)

2. Methodology

A mixed-effects regression approach, in which residuals are partitioned based on causative effects was used in several portions of this study:

- Analysis of a catalogue of finite-fault models to inform models for subduction ruptures
- Analysis of empirical ground-motion model predictions to inform models for volcanic arc path effects
- Validation of simulation predictions for subduction earthquake ground-motions using the new models

The general form of the equation is:

$$\ln IM_{es} = f_{es} + a + \delta B_e + \delta W_{es} \tag{1}$$

where $\ln IM_{es}$ is the natural logarithm of the reference intensity metric (IM); f_{es} is the median of the predicted logarithmic IM for event, e, and site, s, either from a simulation or empirical GMM; a is the predictive model bias; δB_e is the between-event residual with zero mean and variance τ^2; and δW_{es} is the within-event residual with zero mean and variance ϕ^2.

3. Models for rupture characterstics

To gain insights on systematic differences between crustal, interface, and slab earthquake source ruptures, the models contained in SRCMOD (Mai et al. 2014), an online catalogue of finite-fault rupture models, were analysed. The variations of the between-event residuals with magnitude and hypocentre depth for these three tectonic classifications are shown in Figure 4–5. By comparing between-event residuals of risetime and relative rupture velocity and the dependence on hypocentre depth and magnitude, it was possible to infer systematic differences between crustal, interface, and slab ruptures.

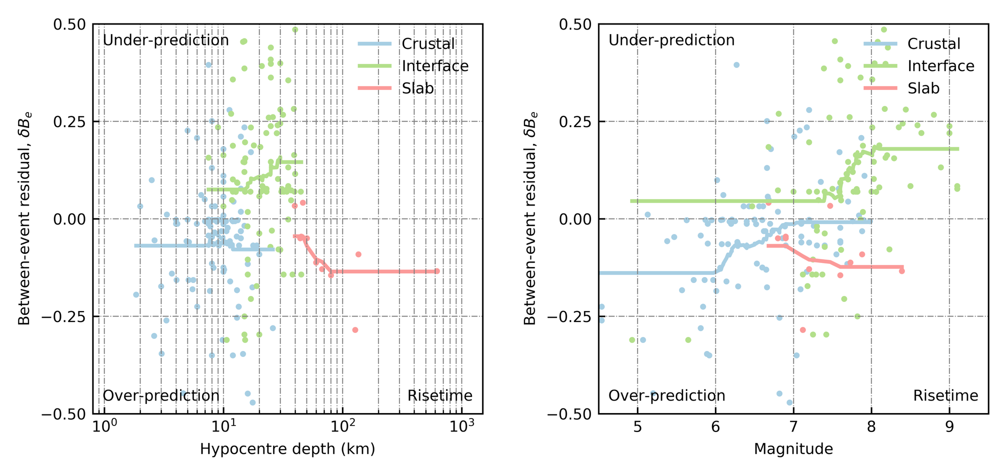

Figure 4: Between-event residuals, δB_e, for risetime

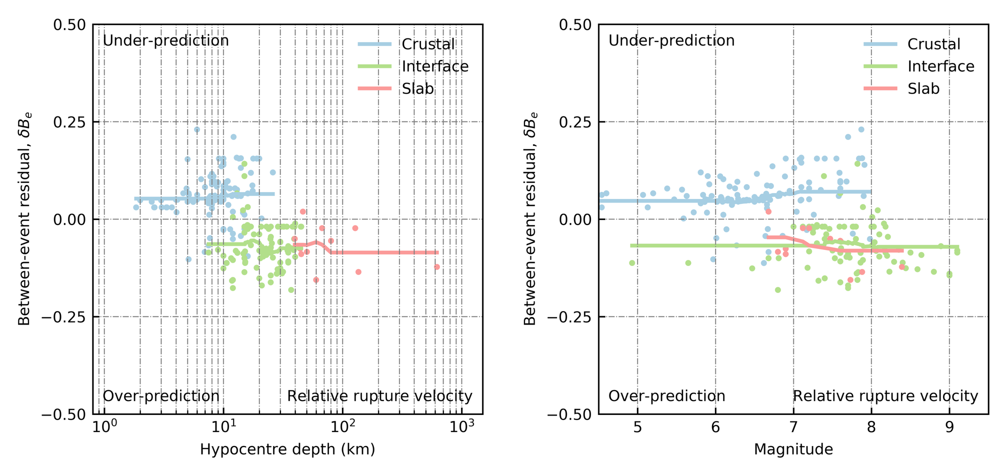

Figure 5: Between-event residuals, δB_e, for rupture velocity

New models for subduction earthquake ruptures were developed based on the observed trend for residuals of risetime and relative rupture velocity:

$$\Delta\sigma_{if} = 25 + 0.5 \times depth \tag{2}$$

$$\Delta\sigma_{slab} = 50 + 1.5 \times depth \tag{3}$$

$$Rup.velocity_{if} = 70\% \times \beta \tag{4}$$

$$Rup.velocity_{slab} = 90\% \times \beta \tag{5}$$

where β is the shear wave velocity at the source and $\Delta\sigma$ is stress parameter. ($Rup.velocity_{crstl} = 80\% \times \beta$, $\Delta\sigma_{crstl} = 50$ bar)

4. Models for path effects

To account for greater backarc anelastic attenuation determined from analysis of empirical ground-motion models, a record-specific adjustment factor, ϕ was computed based on the absolute value of the source-to-site azimuth from the backarc, θ, and a source-specific adjustment factor η was computed based on the source hypocentre depth, where:

$$\phi_{if,slab} = \begin{cases} -0.3, & \text{for } 0 \le \theta \le 80 \\ -0.3 + 0.03(\theta - 80), & \text{for } 80 \le \theta \le 100 \\ 0.3, & \text{for } 100 \le \theta \le 180 \end{cases} \tag{6}$$

$$\eta_{if,slab} = \begin{cases} 0, & \text{for } 0 \le depth \le 40 \\ (depth - 40)/60, & \text{for } 40 \le depth \le 100 \\ 1, & \text{for } 100 \le depth \end{cases} \tag{7}$$

These adjustment factors were used to modify the rock-quality factors Q_P and Q_S, which control anelastic attenuation in the HF simulation component:

$$Q_{if,slab} = Q \times (1 + \phi_{if,slab}\eta_{if,slab}) \tag{8}$$

5. Simulation validation

The new subduction models were implemented within the hybrid broadband ground-motion simulation approach developed by Graves and Pitarka 2010, 2015, 2016. Ground-motion predictions were validated using high-quality small magnitude subduction earthquake ground-motions in New Zealand. The geospatial distribution of earthquakes and stations used for validation are shown in Figure 6—only earthquakes and stations with atleast three associated high-quality observed ground-motion records were considered.

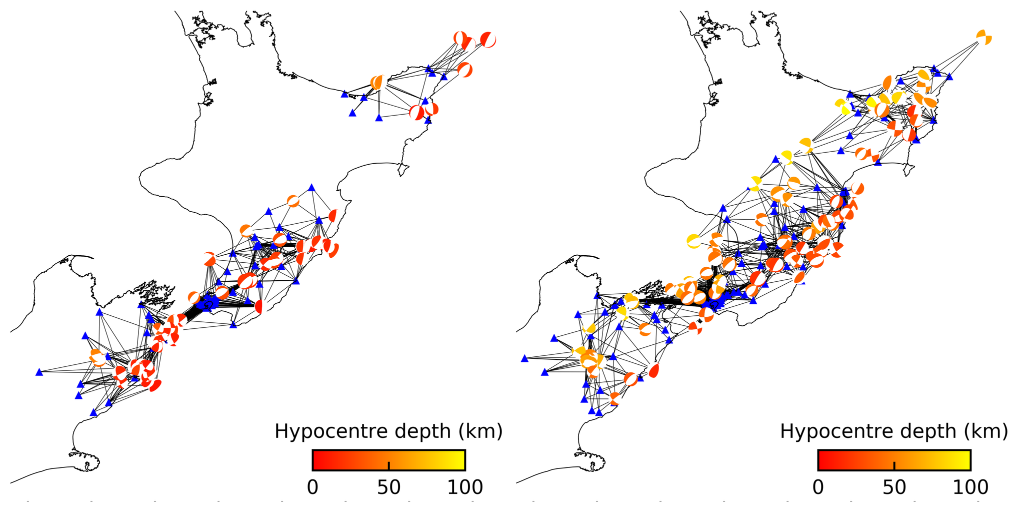

Figure 6: Validation data set; left: interface earthquakes; right: slab earthquakes

6. Results and next steps

The predictions for subduction earthquakes done with the new subduction simulation models show that the simulations are performing well for subduction earthquakes. The simulations are able to provide predictions for small magnitude subduction earthquakes in New Zealand which are more accurate than global empirical ground-motion models for subduction earthquakes. The simulations are now able to provide comparable levels of predictive accuracy for small magnitude subduction and crustal earthquakes in New Zealand.

Investigation of the spatial distribution of between-event and systematic site-to-site residuals indicates that some regional trends in prediction misfit persist (Figure 7 and 8). In particular, there appears to be over-prediction for sites located along the forearc and for deep slab events in the Taupō volcanic zone.

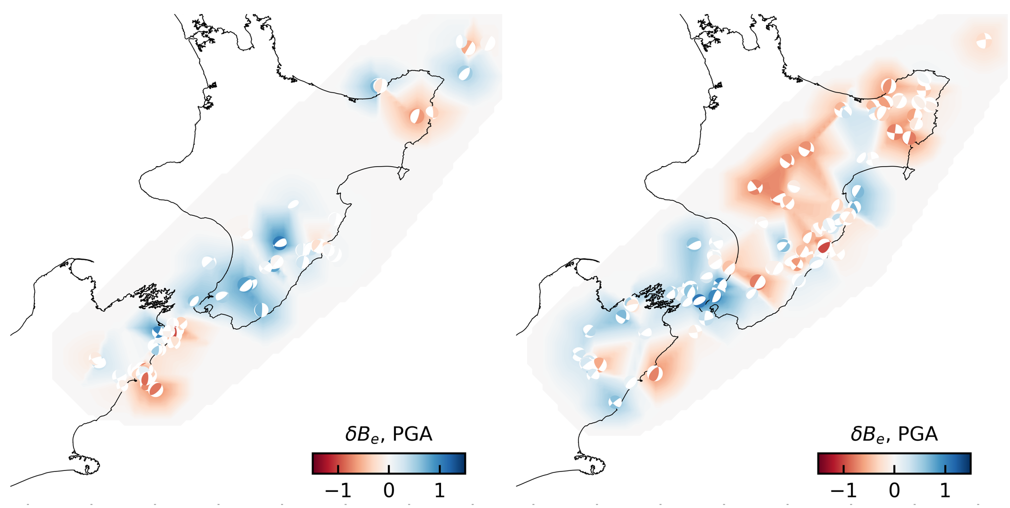

Figure 7: Between-event residuals, δB_e, for peak ground acceleration (PGA); left: interface ground-motions; right: slab ground-motions

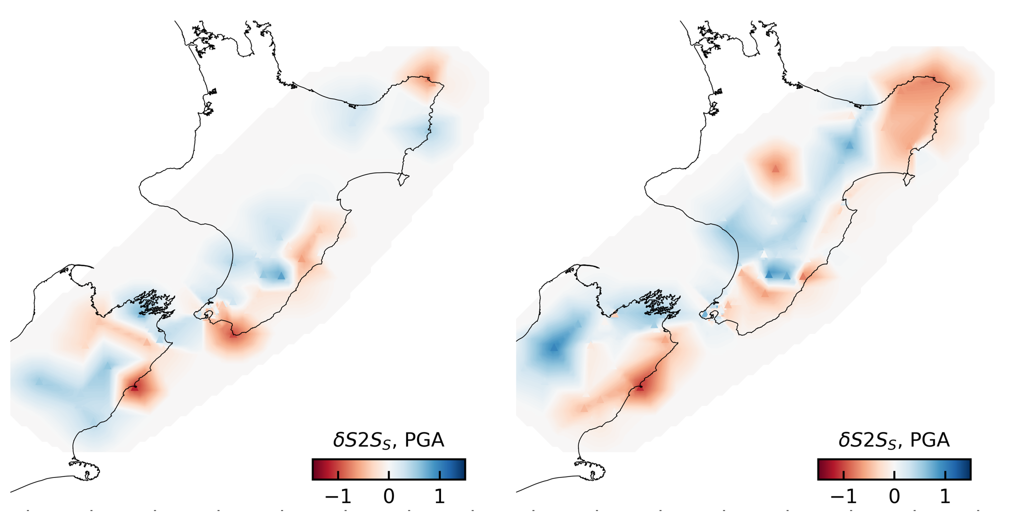

Figure 8: Systematic site-to-site residuals (the portion of δW_{es} ascribed to systematic site effects), $S2S_s$, for peak ground acceleration (PGA); left: interface ground-motions; right: slab ground-motions

Future work will focus on:

- Reduction of the observed regional residual trends with tuning of the volcanic arc-based modifications to the rock-quality factors Q_P and Q_S
- Extend the models validated on small magnitudes to large magnitude and megathrust scenario ruptures of subduction earthquakes