Ground motion simulation validation with explicit uncertainty incorporation for small magnitude earthquakes in the Canterbury region

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1. Motivation

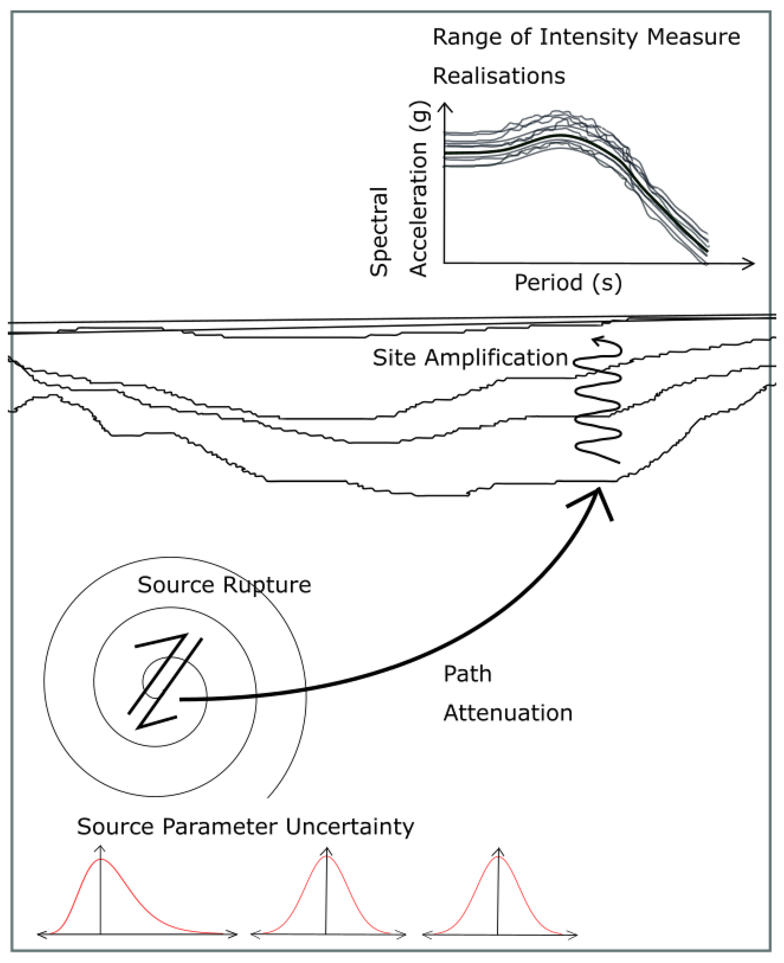

Figure 1: Ground motion simulation with explicit uncertainty incorporation, to produce intensity measure realisations.

Ground motion models are used to predict intensity measures from seismic events, and are part of the probabilistic seismic hazard framework used for earthquake engineering design. Over recent years there has been a trend towards developing site-specific physics-based ground motion simulation models, however, these models do not yet explicitly incorporate uncertainty, and are intrinsically deterministic.

Figure 1 demonstrates schematically how this study explicitly includes source uncertainty into physics-based ground motion simulations, in order to account for: inherent modelling restrictions, ground motion randomness and modelling errors. These uncertainties are propagated through the model to produce a range of realisations for a given intensity measure, site and event.

Once validated, these probabilistic distributions will provide a more reliable prediction of ground motions.

2. Earthquake Events and Simulation Method

This study provides an initial examination of source parameter uncertainty in a New Zealand ground motion simulation model, by simulating multiple event realisations with perturbed source parameters.

Small magnitude events in Canterbury have been selected for this study due to the small number of source input parameters, the wealth of recorded data, and the lack of appreciable off-fault non-linear effects. Which provides greater opportunity to identify systematic source, path and site effects, required to robustly investigate the causes of uncertainty.

Figure 2 illustrates the locations of the 148 small magnitude (Mw 3.5-5) point source events and 42 sites in Canterbury that were considered.

The hybrid broadband ground motion simulation method developed by Graves and Pitarka (2010, 2015, 2016) was adopted with modifications from Lee et al (2019).

Crustal seismic velocities were prescribed from the Canterbury Velocity Model (Lee et al 2017; Thomson et al 2019). An interim resolution of 0.4km was used for the velocity model. It is planned to decrease this to 0.1km.

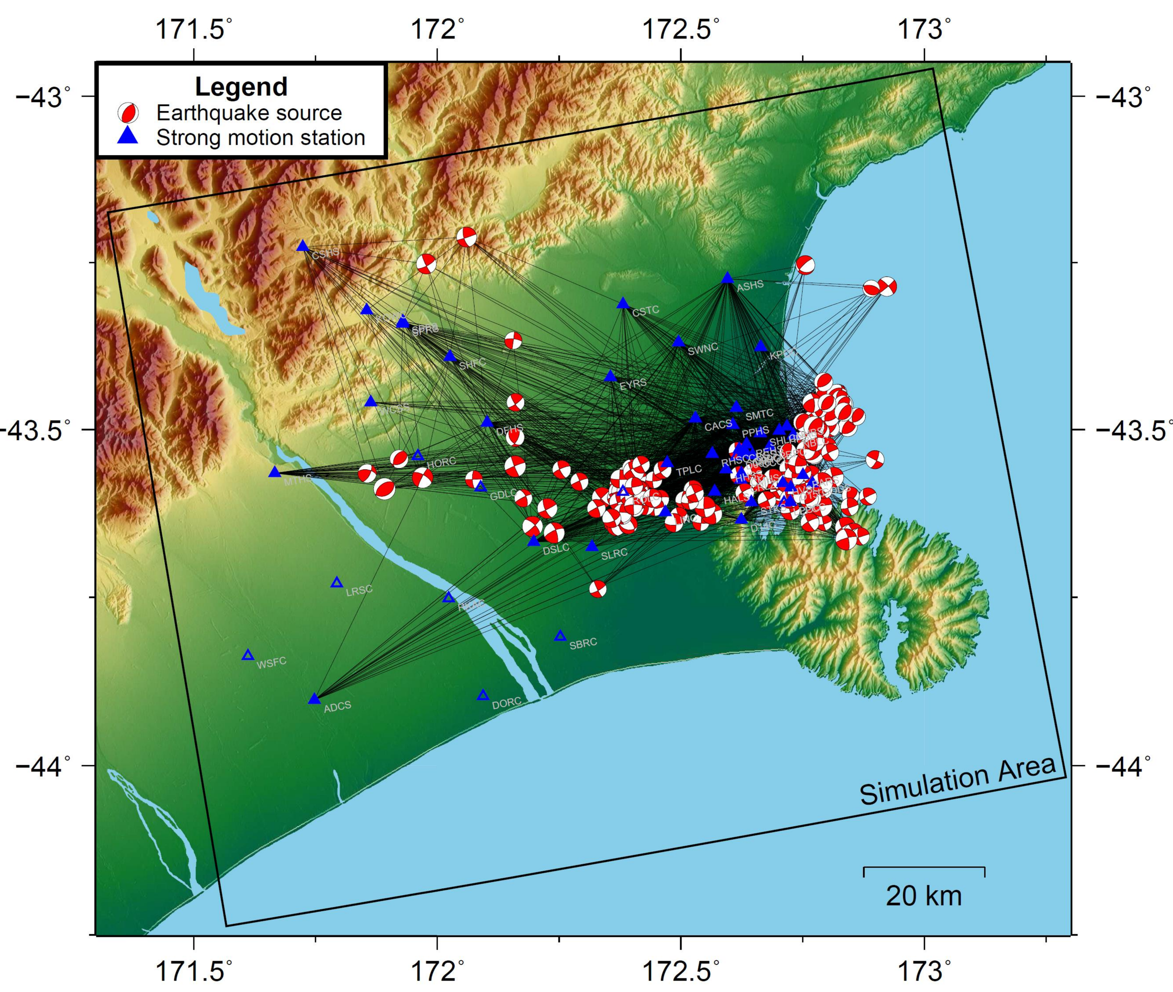

Figure 2: Map of the Canterbury region with the event and station locations considered in this study.

3. Uncertainties Considered

Figure 3 shows an example of the distributions that were used for the three source parameters selected to be perturbed for 20 monte-carlo realisations over each event for the purpose of this initial study. The selected source parameters were: magnitude, rupture velocity and the Brune stress parameter.

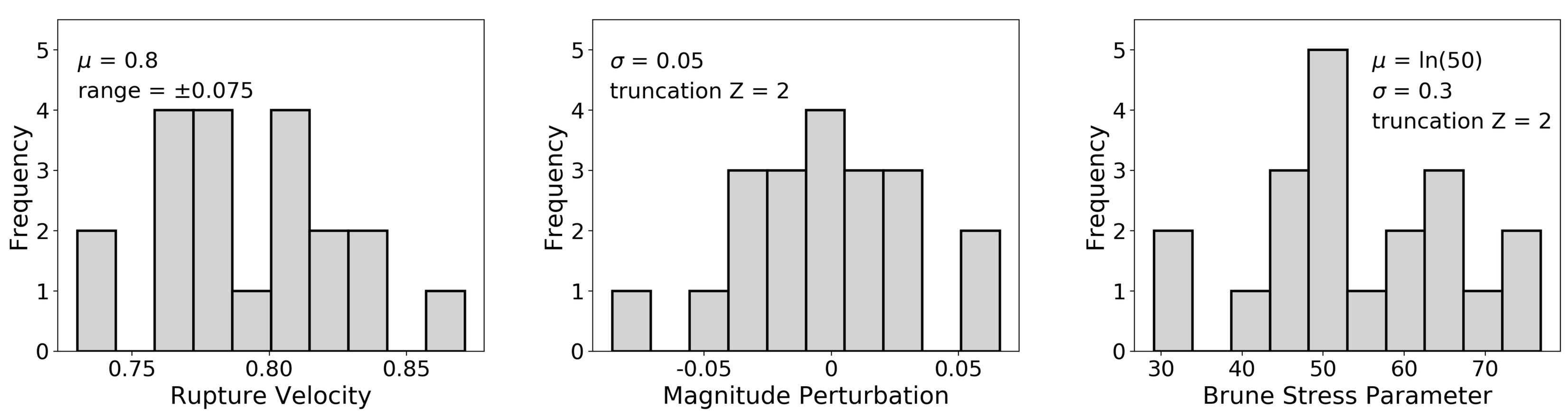

Figure 3: Prior distributions for an example event, used for source parameter perturbations. A uniform distribution was used for rupture velocity, a truncated normal distribution was used for magnitude, and truncated lognormal for the Brune stress parameter.

4. Illustration for One Event

Figure 4 presents response spectra from four selected stations for a selected event, Christchurch Port Hills, 22/02/2011, Mw 4.2. This is just a sample of the 1800 response spectra plots that were produced for this study (one for each different event-station combination).

Each response spectra plot has a distribution of simulations due to the 20 realisations made for each event. Where each realisation is a different combination of perturbed parameters.

- We found that the range of spectral ordinates from the ensemble of realisations does not encompass the observation across all events, stations and intensity measures. For example, Christchurch Cathedral College (Station CCCC) at T>0.3s, the observation is outside the range of simulation realisations. This qualitatively indicates that the total simulation uncertainty is not high enough.

- Key trends from Figure 4 show under-prediction in the long period range for sites located in central Christchurch (eg CCCC), for this particular event. Stations located at significant distance from the source, generally show lower residuals (ASHS and SLRC).

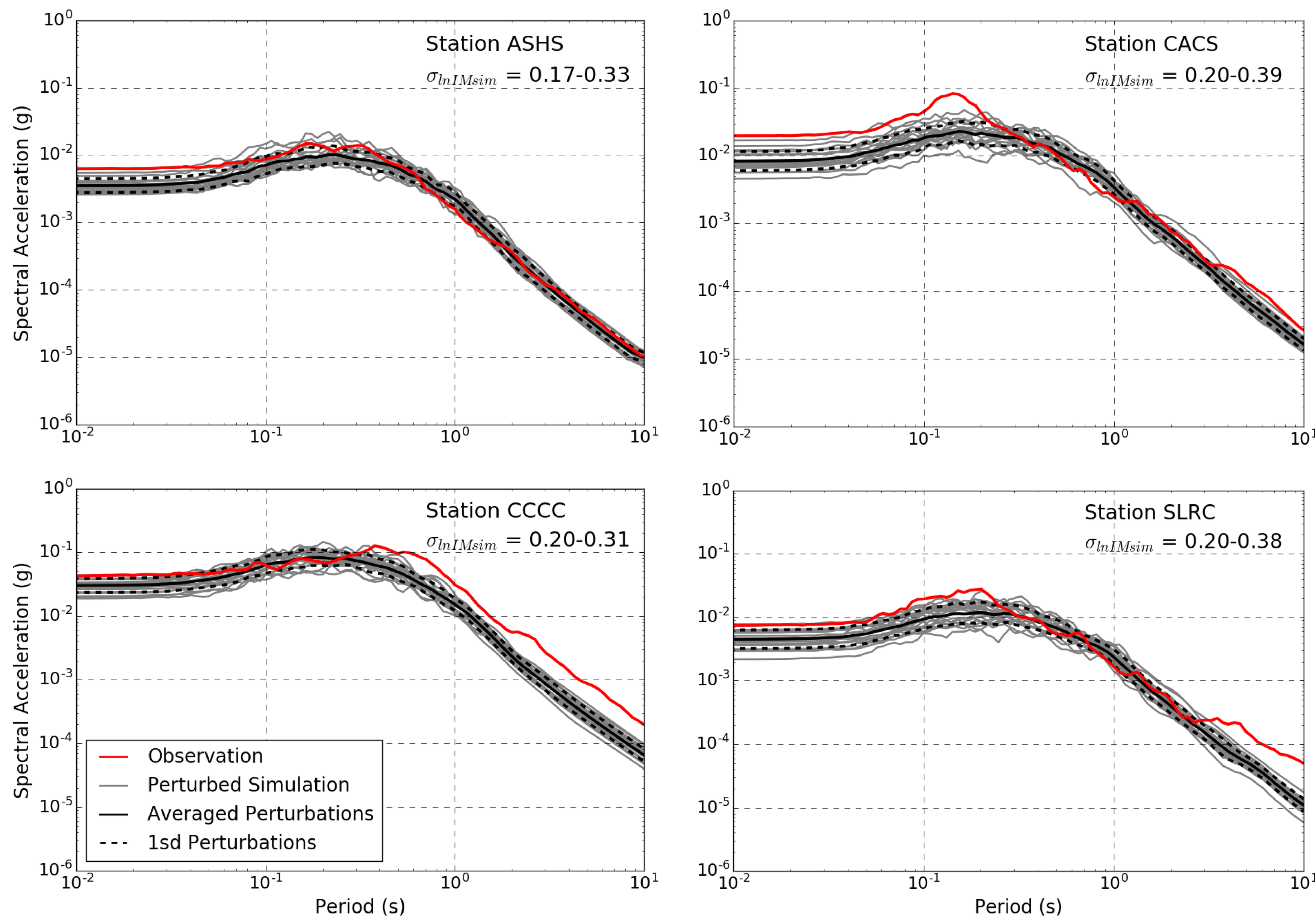

Figure 4: Response spectra for a single event (Mw 4.2, Christchurch, 22/02/2011), at four different sites in Canterbury. Each earthquake has 20 realisations, shown by the Perturbed Simulation lines on the plots. These perturbations provide an uncertainty range for the simulation.

5. Results for All Events

We computed the standard normalised residual (Z) between observations and simulations for each intensity measure, across all stations and all events (Equation 1). Mixed effects regression of Z was undertaken to partition the ground motion uncertainty, as per Equation 2. Where a is the model bias, δ_e is the between event effects component, δ_s is the systematic site-to-site effects component, and δ_{es} is the remaining within-event component. Figure 5 presents the standard deviation of each partitioned component that was calculated. The target total standard deviation is one, and the target Z mean is zero.

$$Z = \frac{\ln IM_{obs} - \mu_{\ln IM_{sim}}}{\sigma_{\ln IM_{sim}}} \quad (1)$$

$$Z = a + \delta_e + \delta_{es} + \delta_s \quad (2)$$

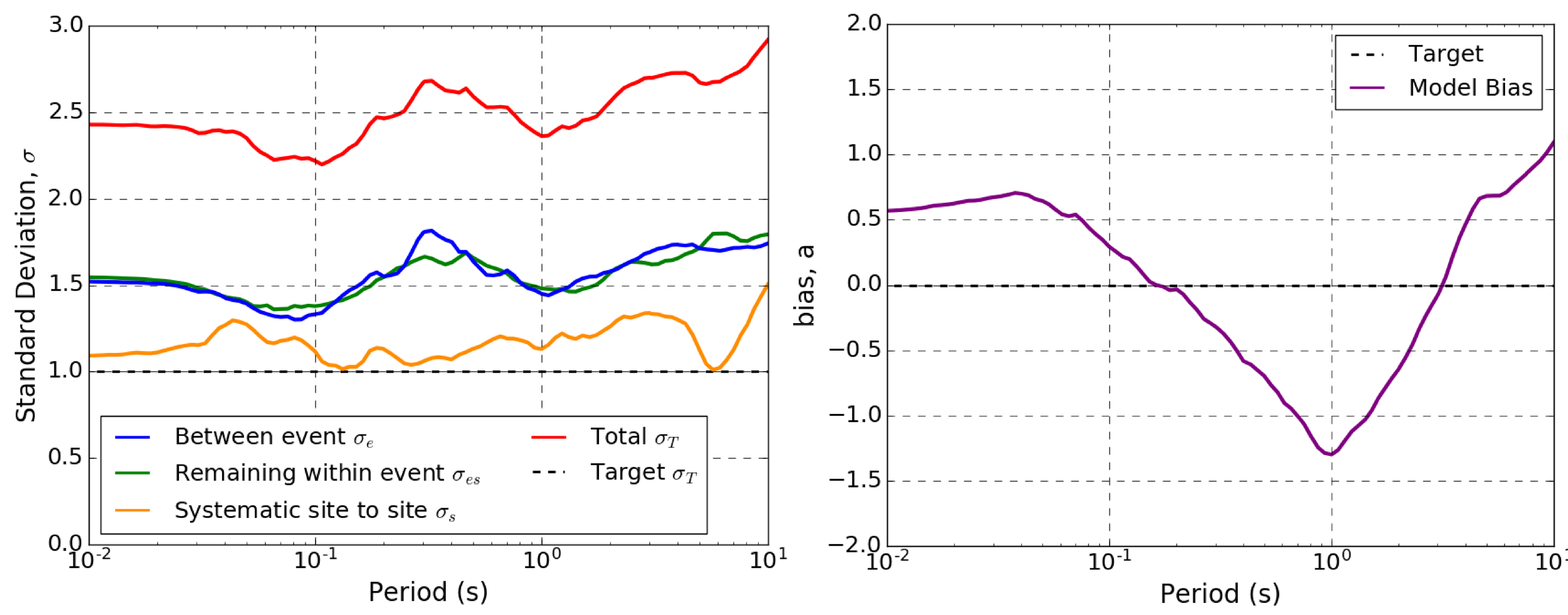

Figure 5: **(1)** The standard deviation contribution from each component of the partitioned standard normalised residual, across different intensity measures. **(2)** The model bias observed from a mixed-effects regression analysis.

- Key trends from Figure 5 show the total standard deviation in Z to be approximately 2.5 times larger than the target, which indicates that the standard deviation of the intensity measure realisations ($\sigma_{lnIMsim}$) is approximately 2.5 times too small.

- The highest contribution to uncertainty is due to the between-event (source) and remaining within-event (path) components of the standard normalised residual standard deviation. This is not surprising considering that no explicit site uncertainty was considered in the simulations performed so far. A degree of path uncertainty was included in the high frequency component of the simulation through its stochastic model.

- The model bias shows over-prediction in the approximate period range 0.2<T<3 sec, and under-prediction elsewhere. It is expected that the over-prediction is partially due to high site-amplification from the empirical model used. The size of the bias is exacerbated by $\sigma_{lnIMsim}$ being too small.

6. Conclusions

We undertook a preliminary assessment of ground motion simulations for small magnitude events in the Canterbury region, with explicit consideration of uncertainty. 20 realisations were made for each simulation, with perturbations of rupture velocity, magnitude and the Brune stress parameter, in order to include their uncertainty.

We found that the uncertainty considered is insufficient when compared with observational data. Further refinement of the utilised uncertainties is required, as well as the incorporation of additional uncertainties.

Inclusion of uncertainty in Vs30 and a higher velocity model resolution should provide a more accurate standard deviation of the systematic site to site component of Z.