Source modelling considerations for ground motion simulation validation of moderate magnitude active shallow crustal earthquakes in New Zealand

R.L. Lee, B.A. Bradley & J. Paterson
University of Canterbury, Christchurch.

R.W. Graves
United States Geological Survey, Pasadena, CA, USA.

ABSTRACT

This paper summarises progress toward NZ-wide physics-based hybrid broadband ground motion simulation validation of moderate magnitude ($5.0 < M_w < 7.0$), active shallow crustal earthquake events through low spatial resolution prototype runs with an emphasis on source modelling methods. 62 earthquakes were considered with 1692 observed ground motion recorded across 200 sites. The simulations are carried out using the Graves and Pitarka (2016) hybrid broadband ground motion simulation methodology with various source models, and crustal velocities prescribed from the NZVM 2.0 (Thomson et al. 2020). The simulation results are compared with the recorded ground motions through multiple ground motion intensity measures. In terms of model prediction bias, the simulations perform well at short period spectral accelerations (T < 0.3s) and overpredict to varying extents at other periods. Finite faults sources have less bias than point sources at long periods (T > 4s) and have lower total standard deviation at short periods (T < 2s). Future work includes simulating high spatial resolution production runs, improving source and site characterisation, and additional analyses of simulation predictive capability.

1 INTRODUCTION

Ground motion simulation validation is the process by which simulated ground motions are compared to observed ground motions to quantify their predictive capability and identify where improvements can be made. Previous efforts in New Zealand (NZ) have been focussed on large magnitude earthquakes (Bradley et al. 2017, Razafindrakoto et al. 2018) due to their significance for engineering applications, and more recently small magnitude earthquakes (Lee et al. 2019, 2020) due to their relative simplicity and ubiquity which provided an opportunity to rigorously investigate repeated, systematic effects. To further validation efforts, naturally the next step is to systematically consider all available moderate magnitudes earthquakes ($5.0 < M_w < 7.0$) across NZ, which is the focus of this paper.

The simulation of general moderate magnitude earthquake events present additional nuances which are not apparent with the consideration of small magnitude events. Firstly, the point source approximation is most likely invalid and therefore finite fault models must be adopted, which includes additional complexity to represent in modelling. Secondly, the amplitudes of some ground motions may be large enough to generate nonlinear constitutive response in surficial soils, resulting in more complex site effects which may require more detailed site response modelling approaches. This paper presents results from initial prototype runs of ground motion simulation validation of moderate magnitude earthquakes across NZ considering different methods of source modelling. Subsequent steps are discussed at the end of the paper in light of the progress and results to date.

2 EVENTS AND STATIONS CONSIDERED

Earthquake source descriptions used in this study were obtained from the GeoNet centroid moment tensor catalogue (Ristau (2008), https://github.com/GeoNet/data/tree/master/moment-tensor). While the catalogue contains over 2000 earthquakes, the scope of this study is limited to moderate magnitude ($5.0 < M_w < 7.0$), active shallow crustal events (centroid depth less than 20km), as a companion to the $3.5 < M_w \leq 5.0$ range considered in Lee et al. (2019, 2020). A minimum of 3 high-quality records (discussed subsequently) per earthquake and per station was enforced to ensure robust statistical inferences. Following this screening, 62 earthquake sources remained. Figure 1 shows the spatial locations of the earthquakes considered as well as ground motion recording stations (both strong motion and broadband) and schematic source-to-site raypaths. The majority of earthquakes are located in Canterbury and the north-east coast of the South Island as a result of the 2010-2011 Canterbury and 2016 Kaikōura earthquake sequences, respectively. Several earthquakes are also located on the eastern side of the North Island and south-west side of the South Island.

Figure 2 illustrates the magnitude and source-to-site distance (R_{rup}) distributions of the considered events and recorded ground motions. Figure 2b shows the M_w-R_{rup} distribution of the recordings illustrating a paucity of ground motions at larger magnitudes and short distances (e.g. M_w 6.5, R_{rup} < 20km) but otherwise good coverage up to 200km. Figures 2a and 2c highlight that most events considered have $5.1 \leq M_w \leq 5.6$ and most records result from source-to-site distances in the range of $60\text{km} \leq R_{rup} \leq 130\text{km}$.

Figure 3a presents the distribution of earthquake source centroid depths and Figure 3b the distribution of site 30m time-averaged shear wave velocity (V_{s30}). Centroid depths of the events are distributed relatively uniformly within the range considered (4-20km). Most sites have V_{s30} between 175m/s and 400m/s indicating that most sites are soil, as opposed to rock.

Observed ground motion records were obtained from the GeoNet file transfer protocol (ftp://ftp.geonet.org.nz/strong/processed/Proc/) and were baseline corrected and bandpass filtered between frequencies of 0.05Hz and 50Hz. A total of 1692 records across 200 stations are included in this study. This subset of records, from a prospective set containing over 4500, are classified as high-quality records using a ground motion quality classification neural network (Bellagamba et al. 2019). The neural network determines a quality score for each ground motion based on various quality metrics such as signal-to-noise ratios, acceleration amplitude ratios and Fourier amplitude ratios. A quality score threshold of 0.5 was used.

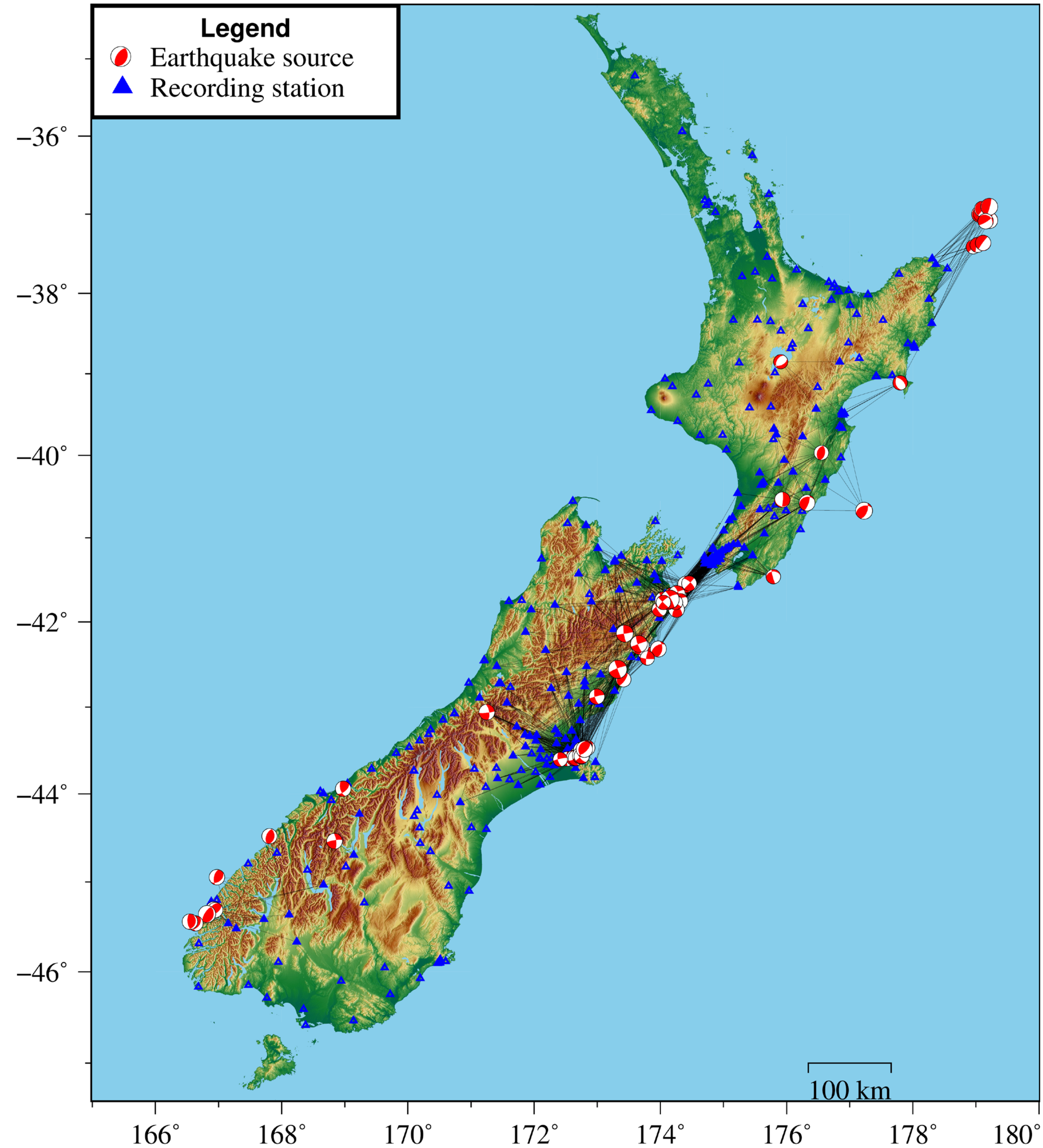

Figure 1. 62 Earthquake sources and 383 ground motion recording stations (200 of which have sufficient high-quality records, shown as filled triangles, and 183 which do not, shown as unfilled triangles) considered. Schematic ray paths of observed ground motions are also shown as black lines. A total of 1692 ground motions satisfy the quality criteria and are used for simulation validation.

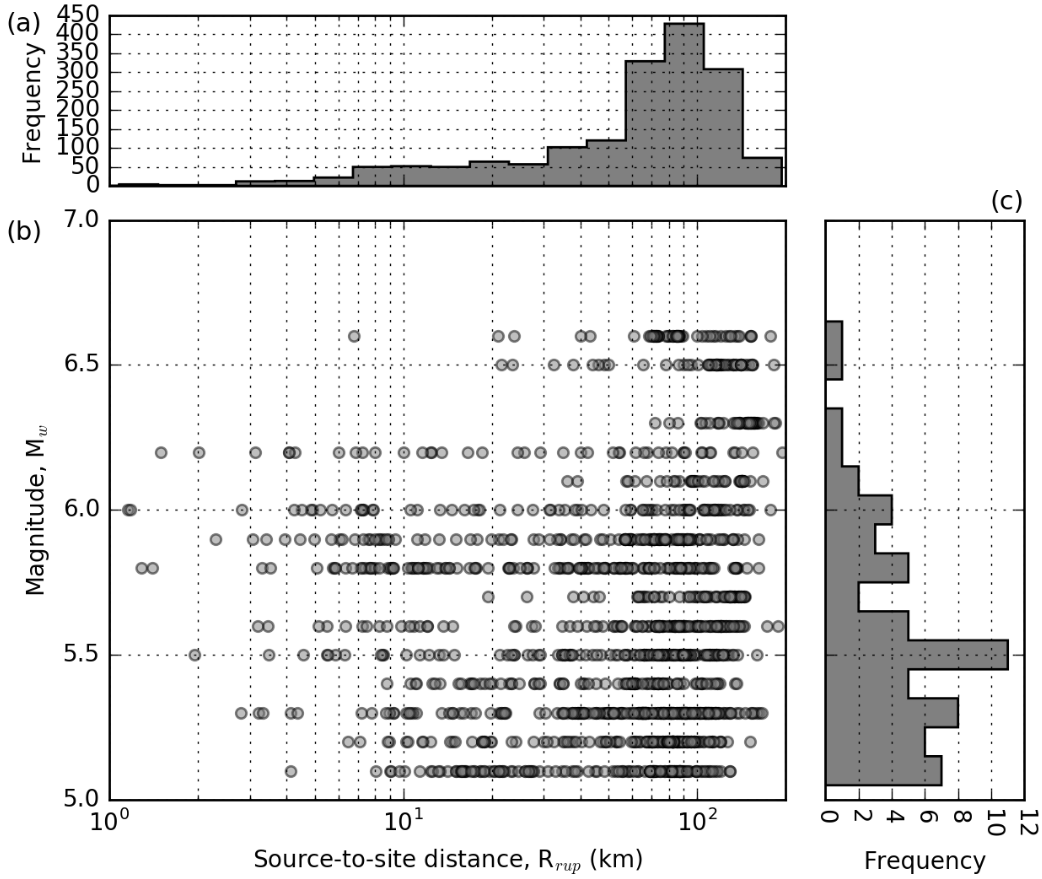

Figure 2. Earthquake source and ground motion distributions: (a) source-to-site distance histogram; (b) magnitude versus source-to-site distance plot; (c) magnitude histogram.

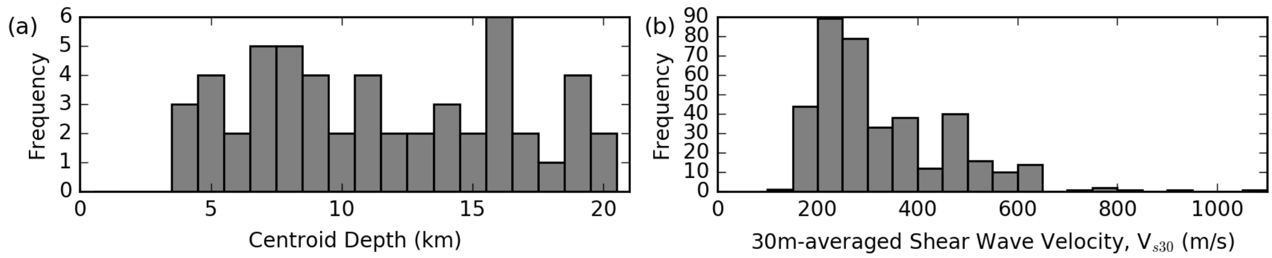

Figure 3. Histograms illustrating distributions of: (a) source centroid depth; (b) site 30m time-averaged shear wave velocity.

3 MODELLING ASPECTS

3.1 Simulation Methodology

This study adopts the commonly-used Graves and Pitarka (2010, 2015, 2016) hybrid broadband ground motion simulation methodology. The broadband time series are a product of two parts, a low-frequency (LF) component and a high-frequency (HF) component. The LF component is calculated using 3D finite difference wave propagation considering comprehensive physics while the HF component is calculated using simplified physics based on ray theory. The HF component is subsequently modified with empirical V_{s30}-based amplification factors to account for local site effects and then merged to produce a single broadband time series. The HF simulation adopts a constant HF attenuation factor of κ=0.045 and Brune stress parameter of $\Delta\sigma$=5MPa. Due to the computational configuration of the simulations, discussed subsequently, LF corresponds to $f < 0.25$Hz and HF corresponds to $f > 0.25$Hz.

3.2 Source Modelling

For moderate magnitude earthquakes, the choice of source modelling assumptions can have significant impact on predicted ground motions. For comparison purposes, this study considers both point source and finite fault source models. Although point sources are likely not appropriate for moderate magnitude earthquakes at this regional scale, it is still informative and provides a benchmark for comparisons. Three implementations of finite faults are considered which utilise the Leonard (2010) M_w-area scaling relationships, various versions of the Graves and Pitarka (2010, 2016) slip generator (which also produces spatially-variable rise times and rake angles), and different fault dimension aspect ratios. These are summarised in Table 1. Figure 4 provides an example of three finite fault models for a M_w 5.9 earthquake occurring on August 16 2013 in the Marlborough region (an aftershock of the 2013 M_w 6.6 Lake Grassmere earthquake) for each of the adopted finite fault modelling methods.

3.3 Velocity Modelling

The NZVM 2.0 (Thomson et al., 2020) is used to prescribe elastic crustal properties (via P- and S-wave velocities and density), for the LF finite difference wave propagation simulation. The extents of the simulation domains were optimised using the M_w-dependent algorithms specified in Tarbali et al. (2019) and Lee et al. (2019). A minimum shear wave velocity of 500m/s was enforced in the LF simulations which yields a maximum frequency of 0.25Hz in the LF simulation for the 400m spatial grid adopted in these prototype simulations (with a reduction to 100m planned in production calculations). Generic 1D profile models were used for P- and S-wave velocities, and density for the HF simulation.

Table 1. Point source and finite fault source model parameters.

Method	M_w-Area Scaling	Slip Generator	Aspect Ratio	Figure
Point Source	Leonard (2010) for slip determination	N/A	N/A	N/A
Finite Fault 1	Leonard (2010)	genslip v3.3 (Graves and Pitarka 2010)	1.0	Figure 5a
Finite Fault 2	Leonard (2010)	genslip v5.4.2 (Graves and Pitarka 2016)	1.0	Figure 5b
Finite Fault 3	Leonard (2010)	genslip v5.4.2 (Graves and Pitarka 2016)	Proportional to L/W (Leonard 2010)	Figure 5c

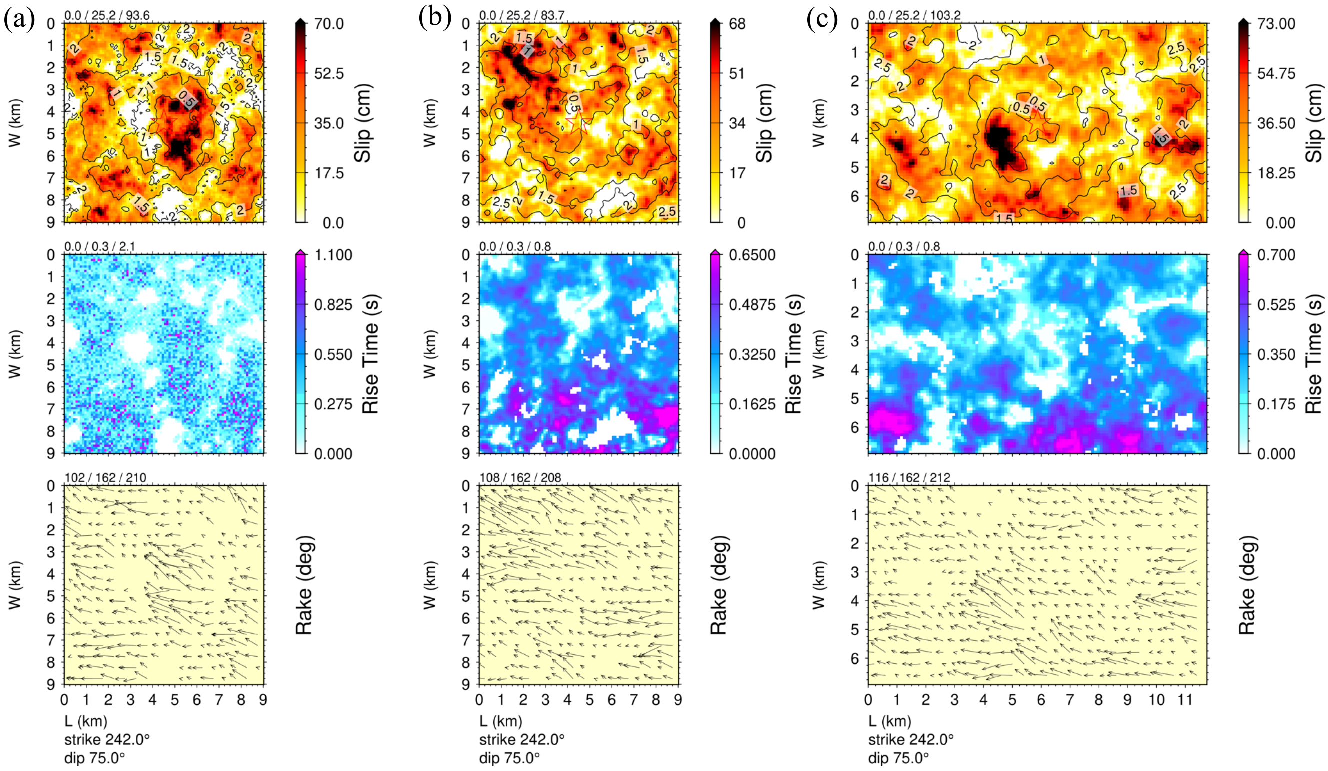

Figure 4. Example finite fault characteristics and distributions - slip, rise time, and rake angle - using: (a) genslip v3.3; (b) genslip v5.4.2; (c) genslip v5.4.2 with aspect ratio proportional to Leonard (2010) length and width relations.

4 RESULTS

To analyse the predictive performance of the simulations, they are compared against observed records via ground motion intensity measures (IMs). Natural log residuals are used to quantify the difference and subsequent mixed-effects regression is carried out to partition the residuals into various components of ground motion variability (see Lee et al. (2020) for further details). As the results are preliminary and the LF simulations are run at a coarse spatial resolution, only a subset of high-level results are presented here. Conventional empirical ground motion models are also considered for benchmarking purposes; Bradley (2013) for spectral acceleration (SA), PGA and PGV, Campbell and Bozorgnia (2010, 2012) for cumulative absolute velocity (CAV) and Arias intensity (AI), and Afshari and Stewart (2016) for significant durations (D_{s575} and D_{s595}). Figure 5a and 5b present the model prediction bias and total standard deviations from this analysis, respectively.

The SA model prediction biases for simulations are relatively small for all cases at very short periods, $T < 0.3s$, and tend to overpredict for periods between $0.3s < T < 4s$. This overprediction is partially attributed to low V_{s30} values from the NZ-wide V_{s30} map of Foster et al. (2019) at some old or stiff alluvial gravel sites which was identified in Lee et al. (2019) to affect the HF-portion of simulations. Current research efforts are looking to improve the map prescriptions for this geologic category. The point source simulations then continue to overpredict at a similar level, while the alternative finite fault simulations have relatively small biases, above $T > 4s$. All cases of finite fault simulations appear to have similar model prediction bias. To provide context to the simulation prediction performances, it is noted that the empirical modelling for SA tends to overpredict at all periods except at very long periods near $T = 10s$.

The total standard deviation of point source simulations is larger than the finite fault simulations at periods $T < 2s$ and similar for periods $T > 2s$. This difference manifests from the between-event standard deviation which suggests that finite faults are better at capturing ground motion variability corresponding to source effects. Empirical predictions for SA have similar total standard deviation to the finite fault simulations at all periods except between 1s < T < 4s, where the empirical values are smaller. Higher resolution LF simulations, which will be carried out in production runs, are expected to reduce the simulation standard deviations at these periods as the total standard deviations corresponding to the comprehensive physics LF simulations appear to be lower (i.e. T > 4s) than the periods corresponding to the simplified physics HF simulations (i.e. T < 4s).

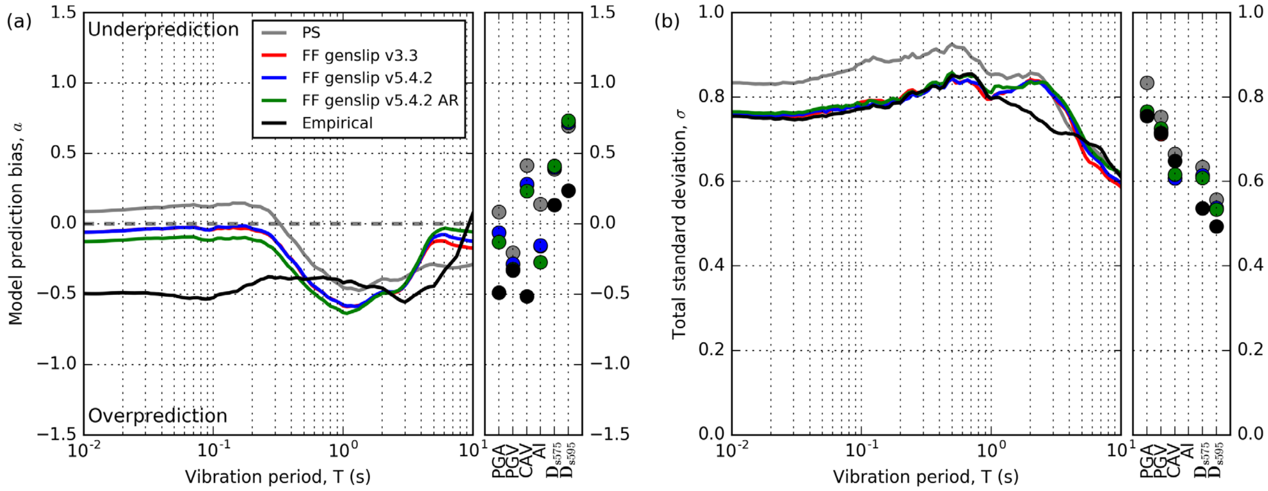

Figure 5. Ground motion model (simulation and empirical) predictive capability relative to observed ground motions for spectral acceleration as a function of vibration period, and six other IMs: (a) systematic model prediction bias, a; and (b) total standard deviation, σ.

5 CONCLUSIONS AND FUTURE WORK

This paper presented progress towards hybrid broadband ground motion simulation validation in New Zealand for moderate magnitude, active shallow crustal earthquakes. Computationally low-cost prototype runs were carried out to develop the computational workflow requirements beyond that previously utilised in small magnitude earthquake ground motion simulations, and also to investigate various source modelling options.

Ensuing work will seek to move from low resolution 400m grid LF simulations to higher resolution (i.e. 200m and 100m) runs. This will allow increasingly shorter periods to be based on the comprehensive physics LF simulation component. Improvements to HF stress parameter and site V_{s30} values inferred from previous validation studies will also be implemented. Additional analysis includes investigation into the dependence of prediction residuals on source, path, and site parameters, spatial variation of prediction residuals, the potential of different site response models, and comparisons between results from small and moderate magnitude ground motion simulation validations. In parallel, we also plan to commence simulation of subduction interface and slab earthquake sources, thus addressing all earthquakes and ground motions in historical databases.

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