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Progress toward New Zealand-wide hybrid broadband ground motion simulation validation

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ABSTRACT

This paper presents progress toward NZ-wide physics-based ground motion simulation validation of small magnitude ($3.5 \leq M_w \leq 5.0$) earthquake events. The computational demands for a nation-wide application of ground motion simulations can be expensive, hence several optimisations are adopted to make the cost manageable. The results of a low spatial resolution prototype run are compared against recorded ground motions to gain insights on the predictive capability of the simulations and are compared against results when considering only the Canterbury region. The predictive capability of empirical ground motion models are also quantified to benchmark against the simulations. Future work includes a production run at higher spatial resolution, and implementation and validation of improvements to the simulation methodology.

1 INTRODUCTION

The validation of ground motion modelling techniques is paramount as ground motion prediction, and its corresponding uncertainty, underpin seismic design philosophy via probabilistic seismic hazard analysis. Historically, empirical ground motion models have been used for this purpose and have relatively small computational demands compared to physics-based numerical prediction. However, recent scientific and computational advances have made routine large-scale physics-based ground motion simulation applications possible.

Previous ground motion simulation efforts have mostly focussed on applications at a regional scale. In particular, NZ applications have been centred on the Canterbury region (e.g. Razafindrakoto et al. 2018, Lee et al. 2019). Several recent studies have begun applying ground motion simulations at a larger scale, both internationally and within NZ, such as the Cybershake (US) (Graves et al. 2011) and Cybershake NZ

Paper 205

(Tarbali et al. 2018) projects which develop physics-based probabilistic seismic hazard analysis for California and NZ, respectively.

This paper presents progress toward validating ground motion simulations at a NZ-wide scale by comparing simulations of small magnitude earthquakes against recorded data. The optimisations required to move from a regional scale to a nation-wide scale are detailed and preliminary results of the validation are presented with a comparison against empirical prediction when considering the entire country, and also when applied to Canterbury only.

2 EVENTS AND STATIONS CONSIDERED

As a tectonically active country, New Zealand has an abundance of earthquakes occurring across the country. While earthquake ground motions have been recorded for many decades, recent deployments and upgrades in the past two decades have vastly improved the ability to characterise earthquake source mechanisms and provided sufficient records for validation of ground motion modelling methods.

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 small magnitude events (M_w between 3.5-5.0) and active shallow crustal events (centroid depth between 3-20km). Earthquakes located far offshore were also excluded. Following this screening, 609 earthquake sources remained. Figure 1 shows the location of the earthquakes considered as well as ground motion recording stations (both strong motion and broadband stations) and schematic raypaths of ground motion records. The majority of earthquakes are located in the vicinity of the tectonic plate boundary with a large cluster also in the Canterbury region.

Figure 2 illustrates the M_w, source-to-site distance (R_{rup}), and centroid depth (CD) distributions of the considered events and recorded ground motions. Figure 2a shows the M_w-R_{rup} distribution of the recordings illustrating that relatively larger magnitudes generally have records at larger R_{rup}. Figures 2b and 2c highlight that most events considered have $M_w \geq 4.0$ and most records have R_{rup}<80km. Figure 2d shows that a broad range of CD are considered although there are slightly more at CD≤10km.

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 0.08Hz and 50Hz. A total of 5472 records across 296 stations are included in this study. This subset of records, from a prospective set containing over 20000, 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.

3 SIMULATION METHODOLOGY

3.1 Modelling Aspects

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 wave propagation considering comprehensive physics while the HF component is calculated using simplified physics based on ray tracing. Each 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<0.25Hz and HF corresponds to f>0.25Hz. Therefore, the simulated ground motions are generally dominated by the HF component in the period range of engineering interest.

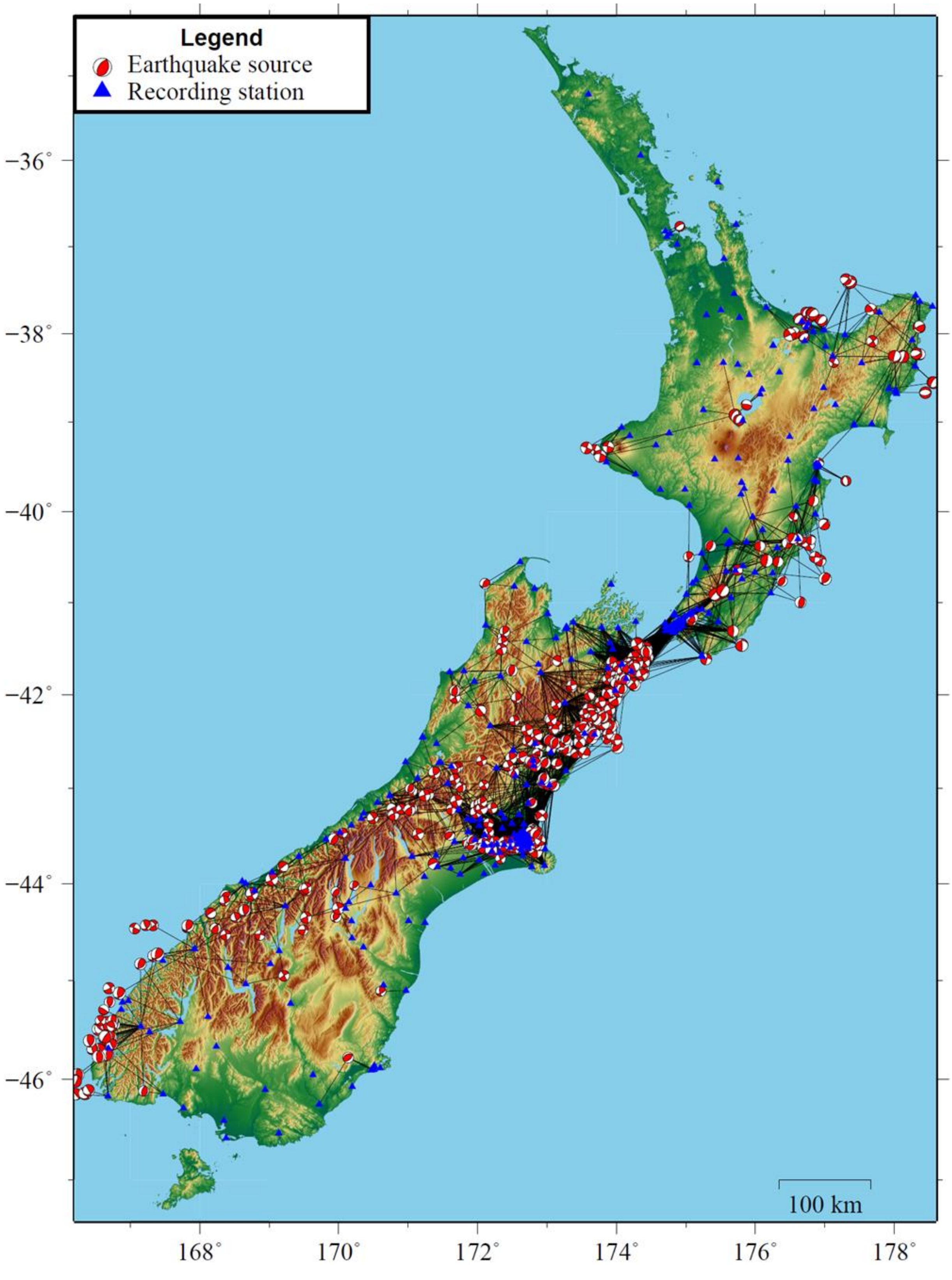

Figure 1: 609 Earthquake sources and 383 strong motion stations (87 of which do not have high quality records) considered. Schematic ray paths of observed ground motions are also shown as black lines. A total of 5472 ground motions satisfy the quality criteria and are used for simulation validation.

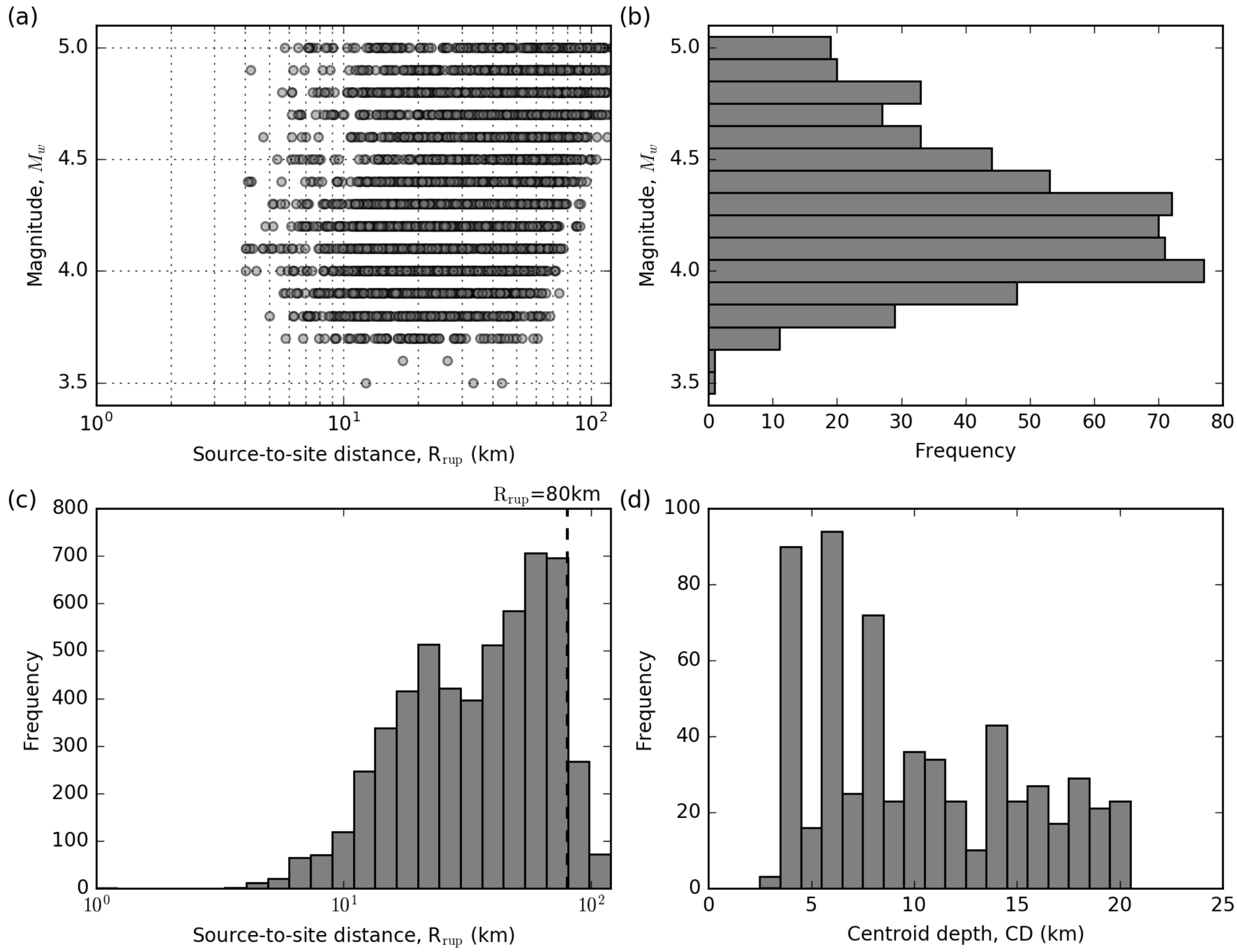

Figure 2: Earthquake source and ground motion distributions: (a) source-to-site distance versus magnitude plot; (b) magnitude distribution; (c) source-to-site distance distribution; (d) centroid depth distribution.

3.2 Computational Aspects

As the extension from a regional (e.g. Canterbury) ground motion simulation validation effort to a nationwide effort leads to drastic increases in computational resource requirements, several optimisations are necessary to ensure that the demands are realistic. The number of computations are strongly dependent on the number of finite difference gridpoints in the LF simulation, hence optimisation efforts were largely focused on determining the size of the simulation domain.

To estimate an initial simulation domain that is appropriate for a given earthquake (with smaller domains for smaller magnitude earthquakes and vice versa for larger magnitude earthquakes), the extents were obtained by calculating the R_{rup} at which a specified PGV would occur based on a given empirical ground motion model (Bradley, 2013). The lateral extents were taken to be twice the calculated R_{rup} and the domain was centred on the source epicentre. However, it was found that a constant PGV threshold did not scale well across the magnitudes considered, giving simulation domains that were too small at smaller magnitudes. Therefore, a variable PGV threshold was developed as a function of magnitude. Figure 3a presents the adopted function for this study and Figure 3b presents the corresponding lateral extents.

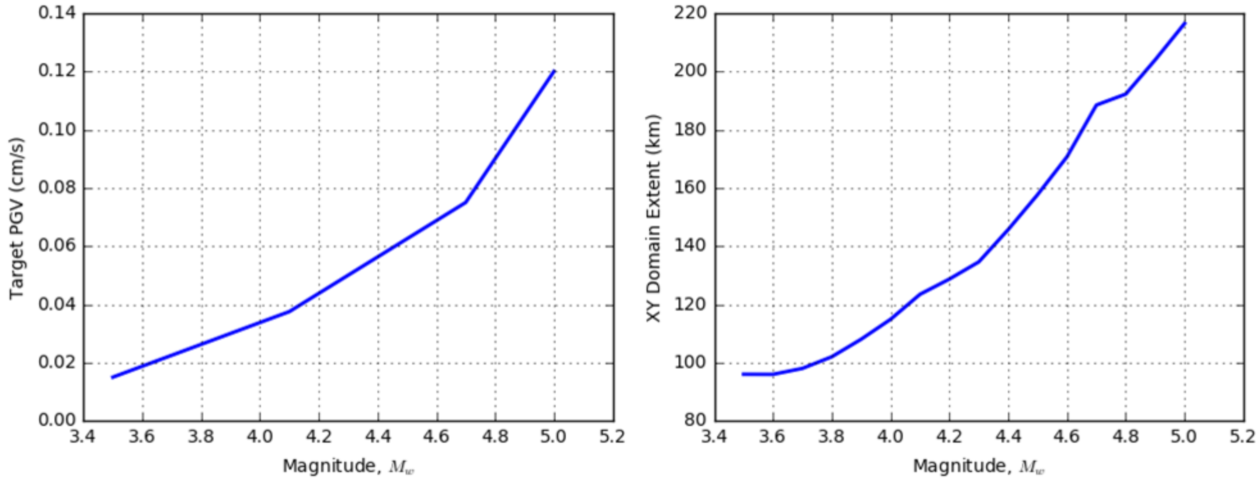

Figure 3: Simulation computational domain size determination: (a) adopted variable PGV threshold as a function of magnitude; and (b) corresponding XY-extents.

The simulation domains were further optimised by rotating and resizing the domains to reduce compute demands. Figure 4 presents a map plot of the simulation domains used in this study. In general, the algorithm rotates the domain to be parallel to the country's centreline and then resizes the lateral extents by trimming the offshore area out of the domain. The source epicentre is often not located in the centre of the domain. This optimisation algorithm was initially developed for the Cybershake NZ project (Tarbali et al. 2018).

The simulation domains have a finite difference grid spacing of 0.4km and are prescribed crustal seismic velocities from the New Zealand Velocity Model (NZVM, Lee et al. (2018) and Thomson et al. (2019)). A minimum shear wave velocity of 500m/s was enforced which yields a maximum frequency of 0.25Hz. For the HF simulations, a 1D generic sedimentary basin model is used. A time-step of Δt = 0.005s was used to ensure numerical stability. It is important to note that this coarse spatial resolution run carried out here is considered a prototype run and a production run will be carried out in the future with finite difference grid spacing of 0.1km and a maximum frequency of 1Hz.

4 RESULTS

To analyse the predictive performance of the simulations, they are compared against observed records via ground motion intensity measures. Natural log residuals are used to quantify the difference and subsequent mixed-effects regression is carried out to partition the residuals into the various components of ground motion variability. As the results are preliminary and the simulations are run at a coarse resolution, only a subset of the results are presented here. The predictive performance of commonly-used empirical ground motion models are also examined to provide a benchmark for the ground motion simulation results. Empirical ground motion models used are Bradley (2013) for PGA, PGV and spectral acceleration, Campbell and Bozorgnia (2012) for Arias intensity, and Afshari and Stewart (2016) for D_{s575} and D_{s595}.

Figure 5a and 5b present the model bias and total standard deviations from simulations and empirical prediction for both a nation-wide application and a regional application considering only earthquake events in Canterbury (a subset of 178 earthquakes from the 609 nation-wide).

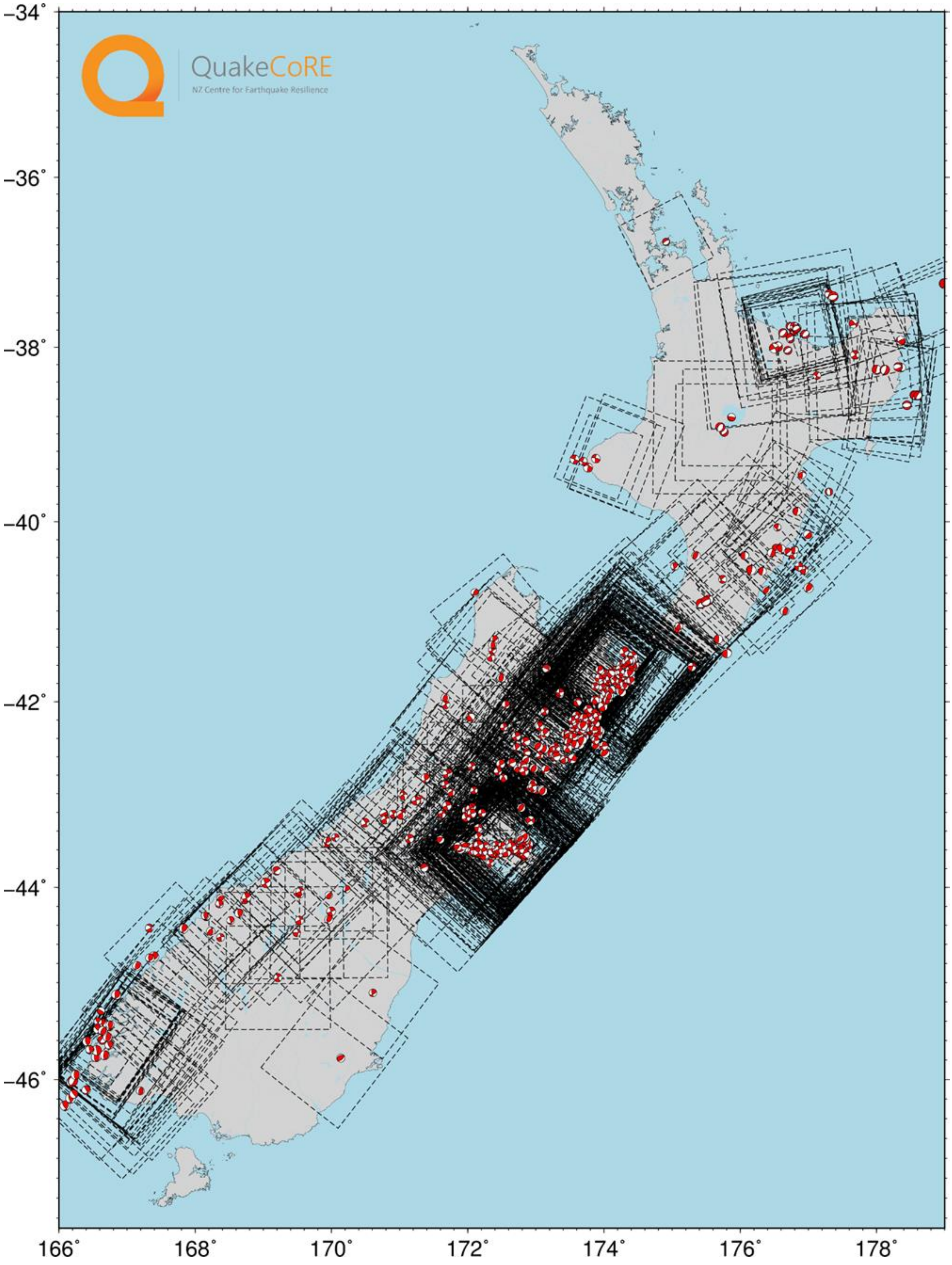

Figure 4: Optimised simulation computational domains for the 609 earthquake events considered.

The model bias from the simulations appear to be overpredicted at all vibration periods while the empirical prediction is generally overpredicted at short periods, T<0.2s, and overpredicted at long periods, T>5s. The model bias of simulated significant durations are in excess of the y-axis limit with natural log residuals of 1.67 and 2.00 for D_{s575} and D_{s595}, respectively, indicating significant underprediction. The results provided are broadly consistent with the comprehensive Canterbury-specific validation study by Lee et al (2019) which carried out simulations with finer spatial resolution (i.e. 0.1km finite difference grid spacing).

When comparing between the NZ-wide and Canterbury-only results, the model bias for both simulation and empirical prediction appear to overestimate less and underestimate more. Additionally, the total standard deviations are generally larger in the NZ-wide applications. The results presented here suggest that both prediction methods are more accurate and precise for Canterbury relative to the rest of NZ. Subsequent analysis, not included here, identifies the difference to be primarily caused by the systematic site-to-site residuals. As the majority of Canterbury stations are sedimentary basin sites, the generic 1D profile used in the HF component is relatively appropriate while site conditions which deviate from the generic 1D profile, such as rock sites, would increase the prediction variability. Hence, the superior predictive performance in the Canterbury region is an expected result.

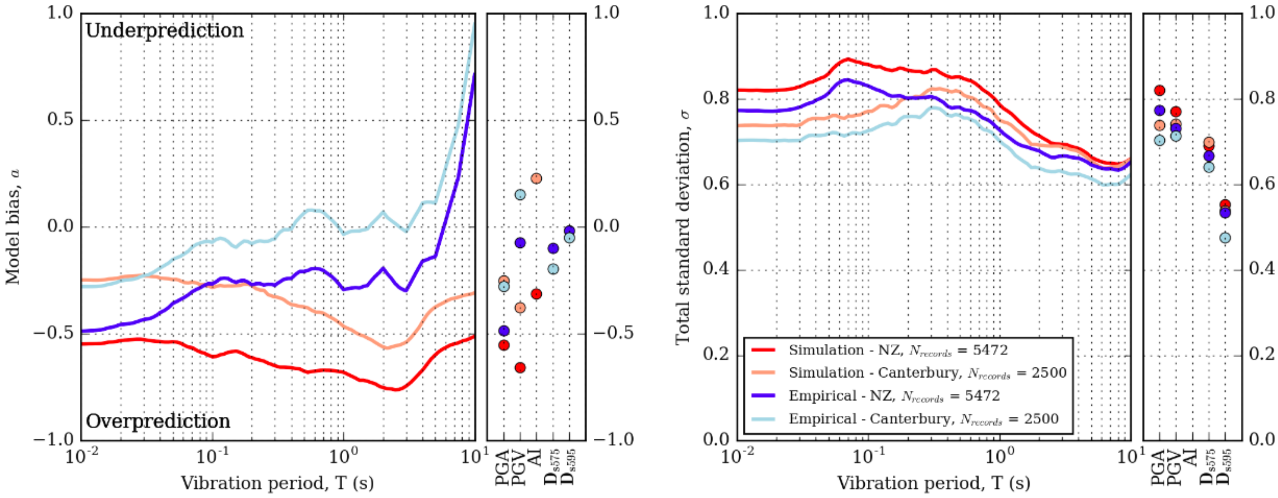

Figure 5: Simulated and empirical prediction for SA as a function of vibration period, and five other IMs: (a) systematic model bias, a; and (b) total standard deviations, σ.

5 CONCLUSIONS AND FUTURE WORK

This paper has presented progress towards NZ-wide ground motion simulation validation through increased data procurement, advances in computational optimisation, and a relatively low cost prototype run. Although the results are preliminary due to the coarse spatial resolution of the prototype simulations, insights into the predictive capability of ground motion simulations in NZ can already be gained.

There are several avenues of future work building on the results from this study. One of the next steps is to increase the spatial resolution of the simulations to increase the period range which is governed by the comprehensive physics as opposed to the simplified physics in what would be considered a production run. From the insights gained from a production run, and from previous work by Lee et al (2019), improvements can be made to the simulation methodology which can subsequently be validated by quantifying its predictive capability. Due to the physics-based nature of the simulations, the potential for improvement is substantial.

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