Investigation of Systematic Ground Motion Effects through Ground Motion Simulation of Small-to-Moderate Magnitude Earthquakes

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ABSTRACT

This paper presents results of ground motion simulations of small-to-moderate magnitude ($3.5 \leq M_w \leq 5.0$) earthquake events in the Canterbury, New Zealand, region over the past decade, for which centroid moment tensor solutions are available, and an investigation of systematic source and site effects determined via non-ergodic analysis. The simulations are carried out using the Graves and Pitarka methodology with the recently developed 3D Canterbury velocity model. In this study, 144 earthquake ruptures, modelled as point sources, are considered with 1924 quality-assured ground motions recorded at 45 strong motion stations located throughout the Canterbury region. The simulated ground motions, and also empirical prediction equations, are compared with observed ground motions via various intensity measures where the residuals are separated into between-event and within-event components to determine systematic source and site effects. Lastly, the causes of the biases are identified leading to recommendations which could improve the predictive capabilities of the simulation methodology.

INTRODUCTION

The Canterbury, New Zealand region is a seismically active region where the 2010-2011 Canterbury earthquake sequence (CES) occurred. The most notable events from the sequence, the 4th September 2010 M_w 7.1 Darfield and 22nd February 2011 M_w 6.2 Christchurch earthquakes, have been thoroughly investigated as they had the greatest tendency to cause structural, infrastructural and geotechnical damage. However, large magnitude earthquakes (e.g. $M_w > 5.0$) occur relatively infrequently within one region thus limiting their applications in analyses involving repeatable, systematic effects. Comparatively, small-to-moderate magnitude (SMM) earthquakes (e.g. $3.5 \leq M_w \leq 5.0$) occur at a much higher frequency and can therefore provide more statistically robust analyses.

This paper presents a comprehensive investigation of systematic source and site effects in the Canterbury, New Zealand region occurring from hybrid broadband ground motion simulation of SMM earthquakes using the Graves and Pitarka (2010, 2015) methodology. Firstly, the earthquake sources and strong motion stations considered are presented, along with the ground motion processing details. Next, the ground motion modelling methodologies and input models are described. Lastly, the results of the validation are presented. The results of this study highlight numerous shortcomings of the Graves and Pitarka (2010, 2015) ground motion simulation methodology and potential modifications which could improve the predictive capabilities of the simulation methodology.

EARTHQUAKE SOURCES AND STRONG MOTION STATIONS CONSIDERED

The Canterbury region has a wealth of ground motion data from SMM earthquakes, primarily as a result of the recent 2010–2011 CES and dense array of strong motion recording instrumentation. Due to the inherent characteristics of SMM earthquakes and the resulting smaller-amplitude ground motions, a rational selection process of which earthquakes and observed ground motions to consider is imperative.

Event information: Earthquake source descriptions used in this study were obtained from the GeoNet New Zealand earthquake catalogue. Figure 1 presents the earthquake sources, strong motion recording stations and raypaths of ground motions (shown as black lines) considered. Earthquakes with $3.5 \leq M_w \leq 5.0$ were considered for this study to ensure: (i) good constraint on the earthquake source parameters; (ii) adequate signal-to-noise ratio (SNR); (iii) that the point source approximation is valid; and (iv) that there is no appreciable off-fault nonlinear behaviour. After enforcing a minimum requirement of 5 high-quality observed ground motions, 144 earthquakes remained in the final dataset. Figure 2a shows the M_w–R_{rup} distribution of the recordings while Figures 2b presents the distribution of M_w of the 144 earthquake sources. All sources are located in the shallow crustal region with the majority of centroid depths shallower than 10 km. For the simulations, the earthquake sources are modelled as double-couple point sources.

Station information: A total of 45 strong motion stations, whose locations are shown in Figure 1, recorded high-quality ground motions. V_{s30} values for the strong motion stations are taken from Wood et al. (2011), Van Houtte et al. (2014), and Wotherspoon et al. (2014, 2016) who collectively characterized the sites through various geotechnical and geophysical techniques. Figure 2c presents a histogram of the station V_{s30} values.

Processing of observed ground motions: Volume 1 ground motion records were obtained from the GeoNet file transfer protocol. All ground motions were baseline corrected, detrended and processed with a low-pass causal butterworth filter of 50 Hz and a high-pass frequency of 0.08 Hz to retain the Fourier amplitudes at 0.1 Hz. As ground motions from SMM events have relatively small amplitudes, they are often dominated by noise and therefore a minimum signal-to-noise ratio of 2.0 was enforced along with additional screening criteria which required a distinct and appropriate P-wave arrival, and ensured the ground motion records did not end prematurely. The ground motion records were subsequently manually screened to ensure the integrity of the resulting high-quality dataset, which contained 1924 ground motion recordings from an initial set of 4272.

GROUND MOTION MODELLING METHODOLOGIES AND INPUTS

Ground motion simulation methodology: This study adopts the hybrid broadband ground motion simulation methodology developed by Graves and Pitarka (2010, 2015). This method uses two different approaches for simulating the low- and high-frequency components (LF and HF, respectively) of the ground motion which are then combined in the time domain to produce a single broadband time series. A period-dependent V_{s30}-based site amplification factor (modified from Campbell and Bozorgnia 2014) is also applied up to a period of T=5s which is intended to account for site conditions which are not explicitly represented in the velocity models. Explicit site response (where nonlinear site effects can be considered) is outside the scope of this study but is an ongoing research effort (de la Torre et al., 2017).

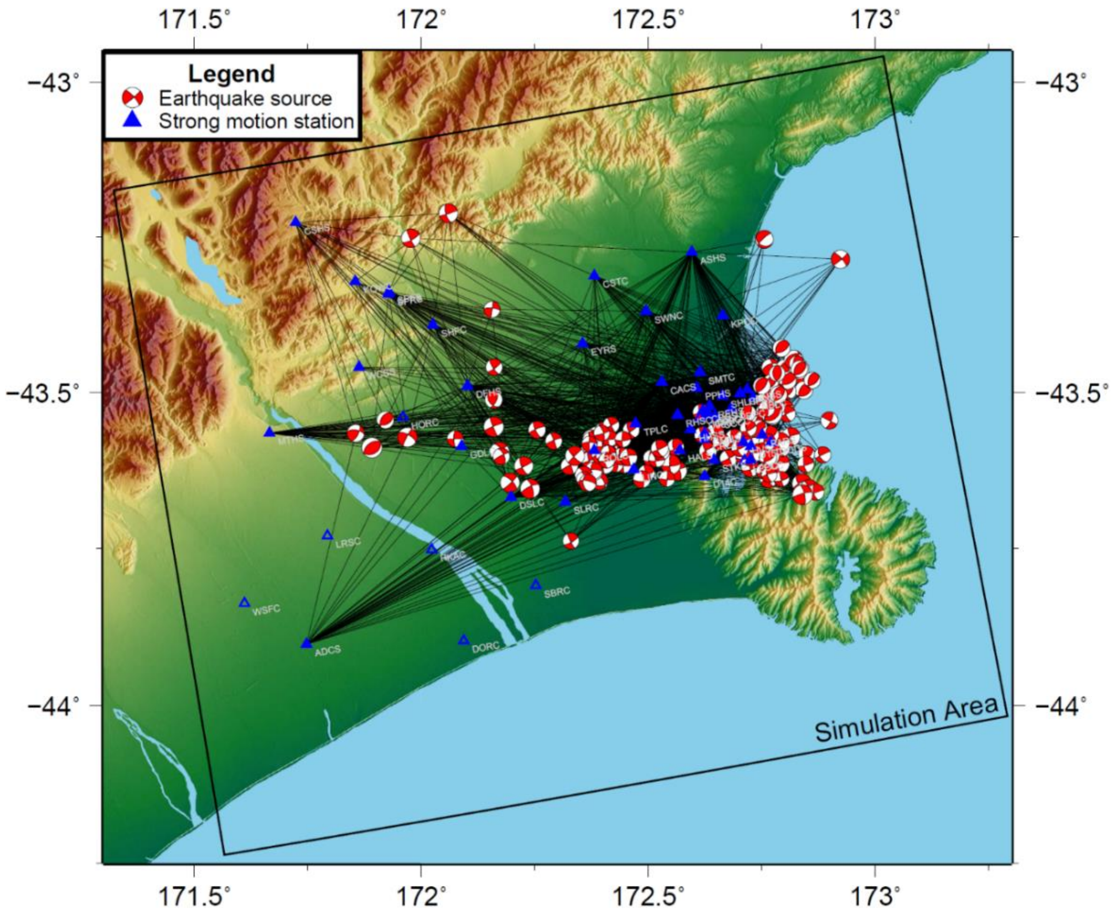

Figure 1. 144 Earthquake sources and 53 strong motion stations considered. 8 strong motion stations without any high-quality recordings are shown as unfilled markers.

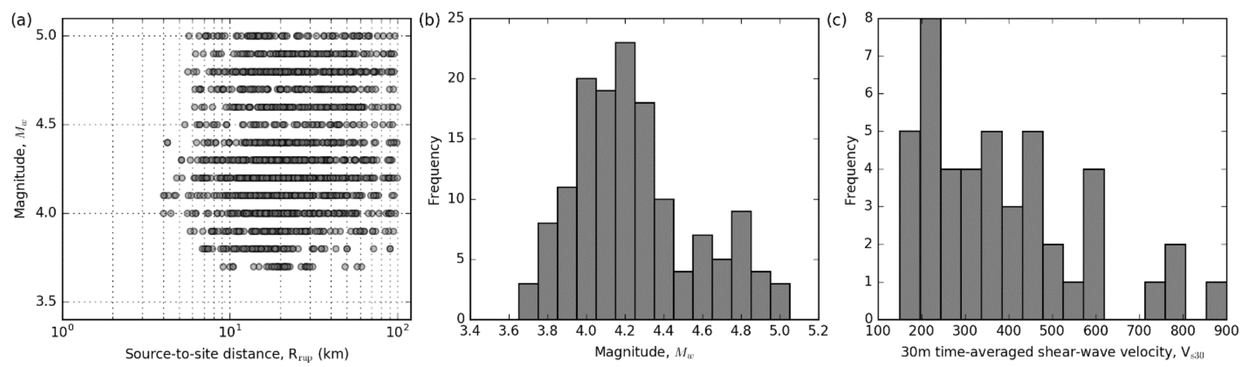

Figure 2. Earthquake source, ground motion and station distributions: (a) R_{rup} against M_w plot; (b) M_w distribution; and (c) station V_{s30} distribution.

The LF simulation component uses a comprehensive representation of source and wave propagation physics by solving the 3D viscoelastic wave equation using a staggered-grid finite difference scheme. To simulate LF ground motions, the 3D Canterbury Velocity Model

(CantVM; Lee et al. 2017), shown in Figure 3a, is used in this study to provide the P-wave and S-wave velocities, and density required.

The HF simulation component is computed using a simplified physics-based simulation which considers a stochastic source radiation pattern and simplified wave propagation through a simple 1D layered velocity model. A HF attenuation factor of κ=0.045 and mean Brune stress parameter of $\Delta\sigma$=5 MPa were used. These are typical values for active shallow crustal regions (Oth and Kaiser, 2014). A generic 1D velocity model, shown in Figure 3b, with a 5 km deep sedimentary basin is used in the HF simulations for all sites.

The LF simulations were performed within a computational domain of 140 km × 120 km × 46 km (whose surface projection is shown in Figure 1), with a finite difference grid spacing of 0.1 km and a minimum shear wave velocity of 500 m/s, yielding a maximum frequency of 1.0 Hz. A timestep of Δt=0.005 s was used.

Empirical ground motion intensity measure models: The results from the ground motion simulations of SMM earthquakes are investigated through a comprehensive comparison between observed and simulated ground motions, as well as empirical predictions of ground motion intensity measures (IMs). The empirical prediction models considered in this study are the Bradley (2013) New Zealand-specific ground motion model for PGA, pSA and PGV; Campbell and Bozorgnia (2012) for AI; and Afshari and Stewart (2016) for D_{s575} and D_{s595}. The aim of using empirical prediction models is to provide insight into the relative predictive capability of the simulations, and hence no attempt is made to utilize an exhaustive ensemble of empirical models.

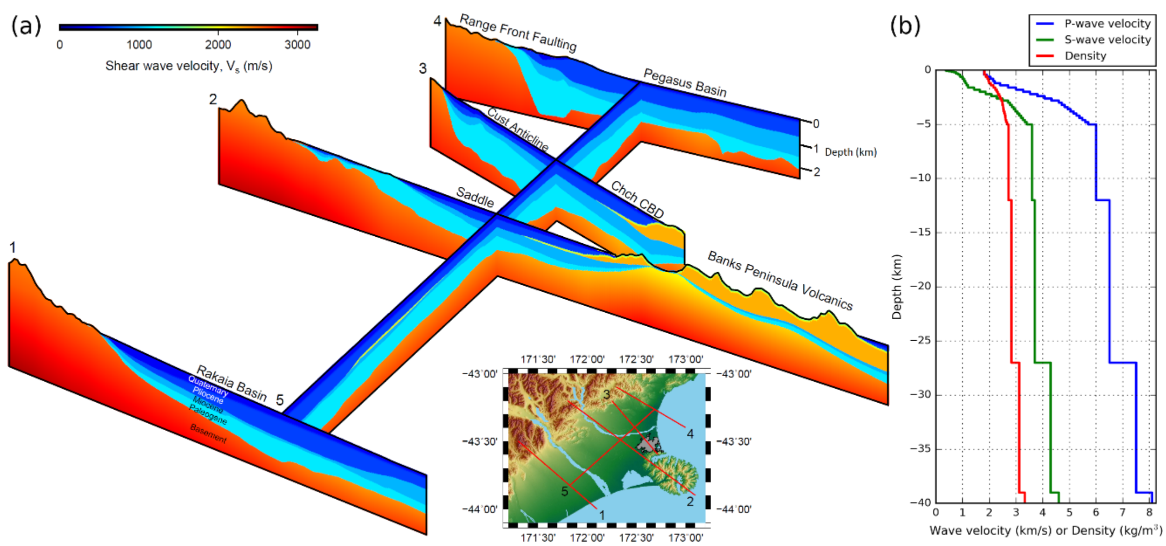

Figure 3. Velocity models used: (a) 3D CantVM for LF; and (b) 1D profiles for HF.

OBSERVED MODEL BIAS

Figure 4 presents the observed model bias between simulation and observation, and empirical prediction and observation. The bias in the simulation is negative for all pSA periods indicating the simulations are overpredicted while the Bradley (2013) empirical model overpredicts pSA at short periods (T=0.01-0.3s), is unbiased at moderate periods (T=0.03-3.0s) and underpredicts for long periods (T>3.0s). Both simulated significant durations are severely underpredicted with bias values of 1.53 and 1.87 natural log units for D_{s575} and D_{s595}, respectively, which were too large to be included in the plot. The Afshari and Stewart (2015) empirical model has effectively no bias for both Ds_{575} and Ds_{595}.

The negative dip in the simulation bias between T=1.0-5.0s is attributed to the V_{s30}-based site amplification which, at these longer periods, is often double counting for larger-scale site effects which are explicitly modelled in the simulations. The appropriate level of amplification depends on the regional geology, and the resolution and quality of the velocity models used.

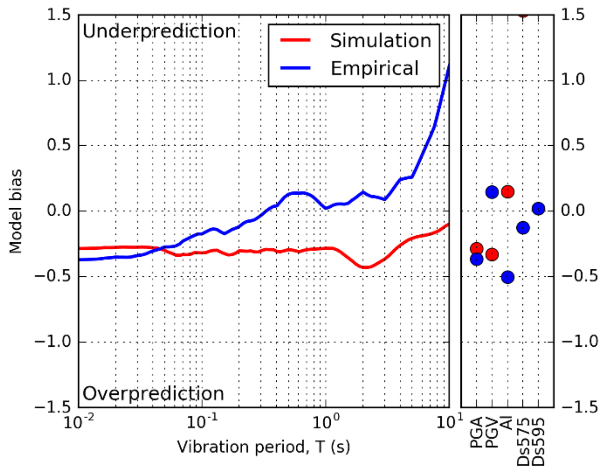

Figure 4. Observed model bias for simulation and empirical prediction.

OBSERVED BETWEEN-EVENT RESIDUALS ΔB$_E$

Figures 5a and 5b present the computed values for between-event residuals, δB_e, for the 144 events considered for simulated and empirical predictions, respectively. The ±1σ are also shown as the dashed lines in the pSA plots and horizontal bars in the plot of other IMs. The plots serve to highlight the variability which is attributed to source effects and the similarities between simulated and empirical predictions with the exception of significant durations.

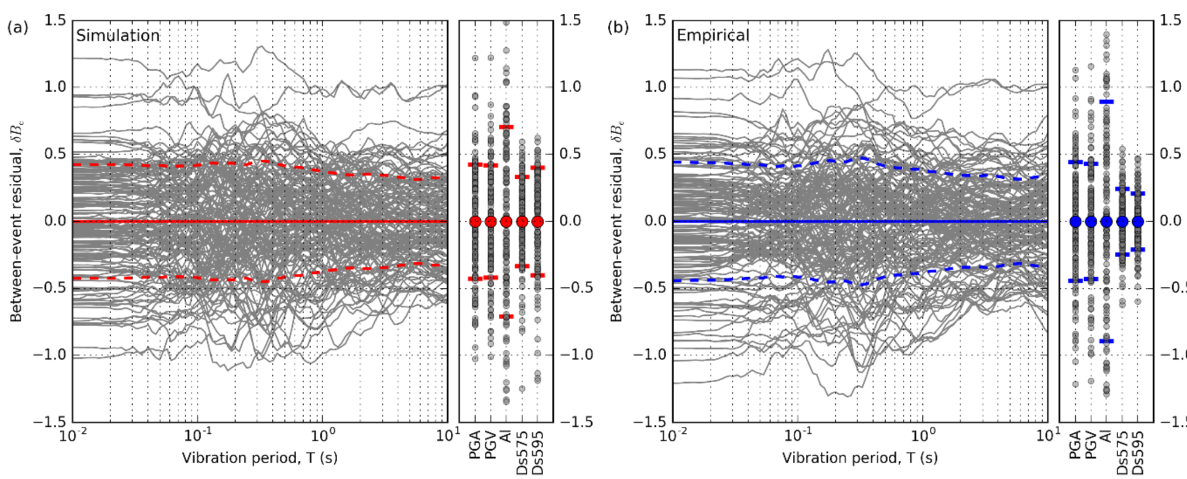

Figure 5. Between-event residuals (grey lines and points) for the 144 earthquakes and ±1σ for: (a) simulated vs observed; and (b) empirical vs observed.

Simulated δB_e for PGA and significant durations were found to be dependent on M_w, where the PGA has a positive trend, resulting in less overprediction with increasing M_w, and the significant durations have negative trends, resulting in less underprediction with increasing M_w.

These two trends are inherently linked by the HF path duration which is expected to be too short. With increasing magnitude, the source duration increases such that the path duration comprises an increasingly smaller percentage of the total duration. An increase in the total duration independently of the path duration, decreases the overprediction of PGA and underprediction of significant durations. Boore and Thompson (2014) also concluded that many path duration models being used in "stochastic" simulations were too short, and not properly accounting for all factors which increase duration with source-to-site distance.

OBSERVED WITHIN-EVENT RESIDUALS ΔW_{ES}

Figure 6 presents all systematic site-to-site residuals, $\delta S2S_s$, for the 45 strong motion stations for both simulated and empirical predictions, as well as their $\pm 1\sigma$. These plots serve to clearly illustrate that a significant amount of the variability between observation and prediction is the result of systematic site effects. The standard deviations are relatively similar between simulation and empirical prediction, likely because both consider site amplification through V_{s30}. The exception is between T=1.0-5.0s where three rock sites are severely underpredicted in the simulations.

Figure 7 presents a plot of the spatial variation of $\delta S2S_s$ for simulated PGA (developed using geostatistical Kriging). The Canterbury Plains immediately west of Christchurch City have positive $\delta S2S_s$ while areas near or on the Canterbury foothills, where the geologic Basement is shallow or outcropped, are negative. Negative $\delta S2S_s$ are also present for the rock sites located on Banks Peninsula or near the BPV outcrop. Additionally, at short periods where small-scale features are significant, the Christchurch City region can be roughly separated into two areas, the western side which is overpredicted and the eastern side which is underpredicted. This segregation is likely a result of the different surface geology where the Christchurch Formation, which mainly consists of marine sediments (lower V_{s30}), is prevalent in the east and the Springston Formation, which is predominantly gravel (higher V_{s30}), is prevalent in the west. The discrepancies between velocity models and reality, particularly near-surface, suggest that explicit site response is needed.

Figure 8 presents plots of location-specific δW_{es} for various sites throughout the Canterbury region along with their respective $\delta S2S_s$. It is noted that the simulation and empirical prediction results are very similar, as the spectral content of the HF simulations is calibrated using empirically determined parameters and both consider site effects through V_{s30} and are therefore jointly discussed. The D14C station (Figures 8a and 8b) is a volcanic rock site located on Banks Peninsula. The positive $\delta S2S_s$ at short periods, indicating underprediction, may be caused by various factors such as differences between the 1D velocity model used in the HF simulations and reality or topography effects. The DFHS station (Figures 8c and 8d) is located on the Canterbury Plains and has $\delta S2S_s$ values that are small at all vibration periods with only minor variations. The uniformity of the $\delta S2S_s$ is reflective of the subsurface geology being dominated by fluvial gravels at this location. The CBGS (Figures 8e and 8f) and REHS (Figures 8g and 8h) stations are located in Christchurch City and are underlain by interbedded marine-fine and gravel formations. The period-dependent variations between T=0.05-1.0s are caused by the site-specific wave propagation effects and small-scale near-surface heterogeneities which are not explicitly included in either simulation or empirical models. REHS has a significant positive $\delta S2S_s$ peak, indicating underprediction, at roughly T=0.5-0.6s which is consistent with the site period down to the Riccarton Gravel, the shallowest gravel formation (at roughly 20-30 m depth below Christchurch city). The variability manifests here as the Riccarton Gravel is not explicitly modelled in either prediction method and the soil overlying the Riccarton Gravel at this site was noted to be very soft (V_{s30}=154 m/s).

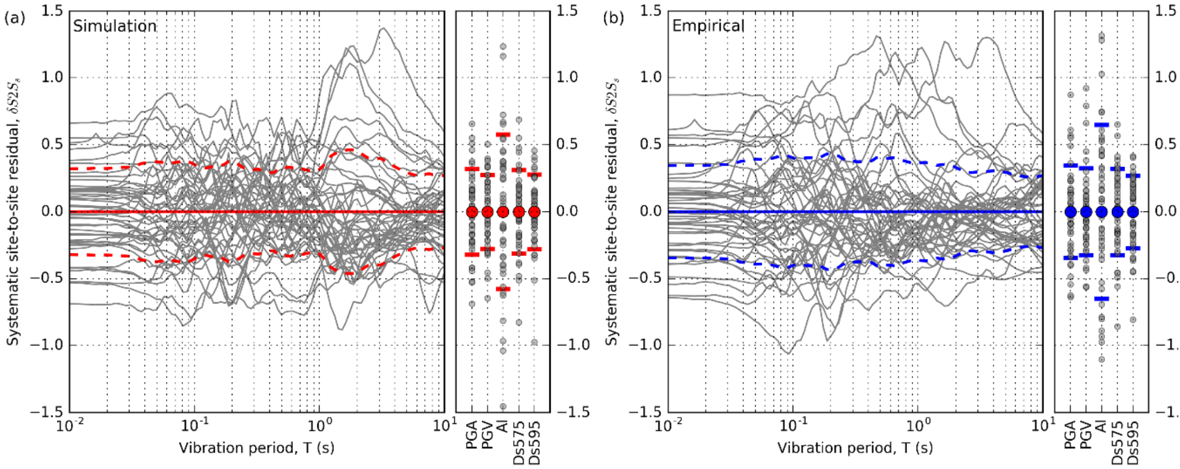

Figure 6. Systematic site-to-site residuals (grey lines and points) for the 45 stations and ±1σ for: (a) simulated vs observed; and (b) empirical vs observed.

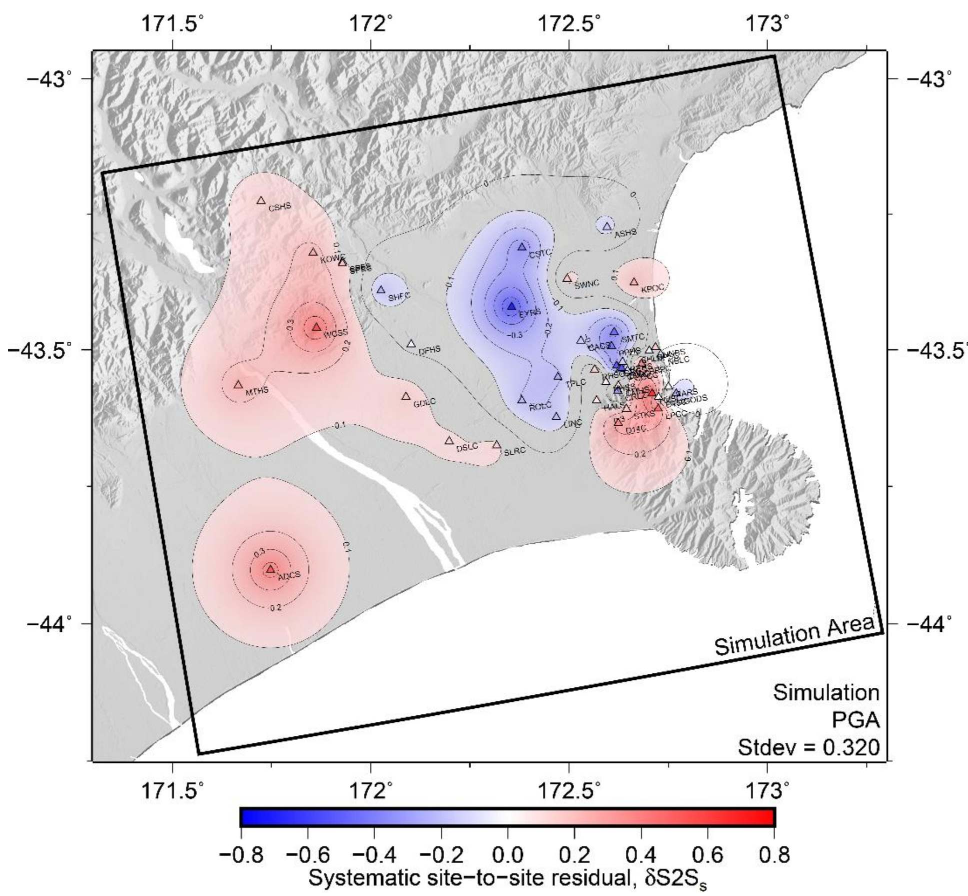

Figure 7. Spatial distribution of δS2S$_s$ for simulated PGA

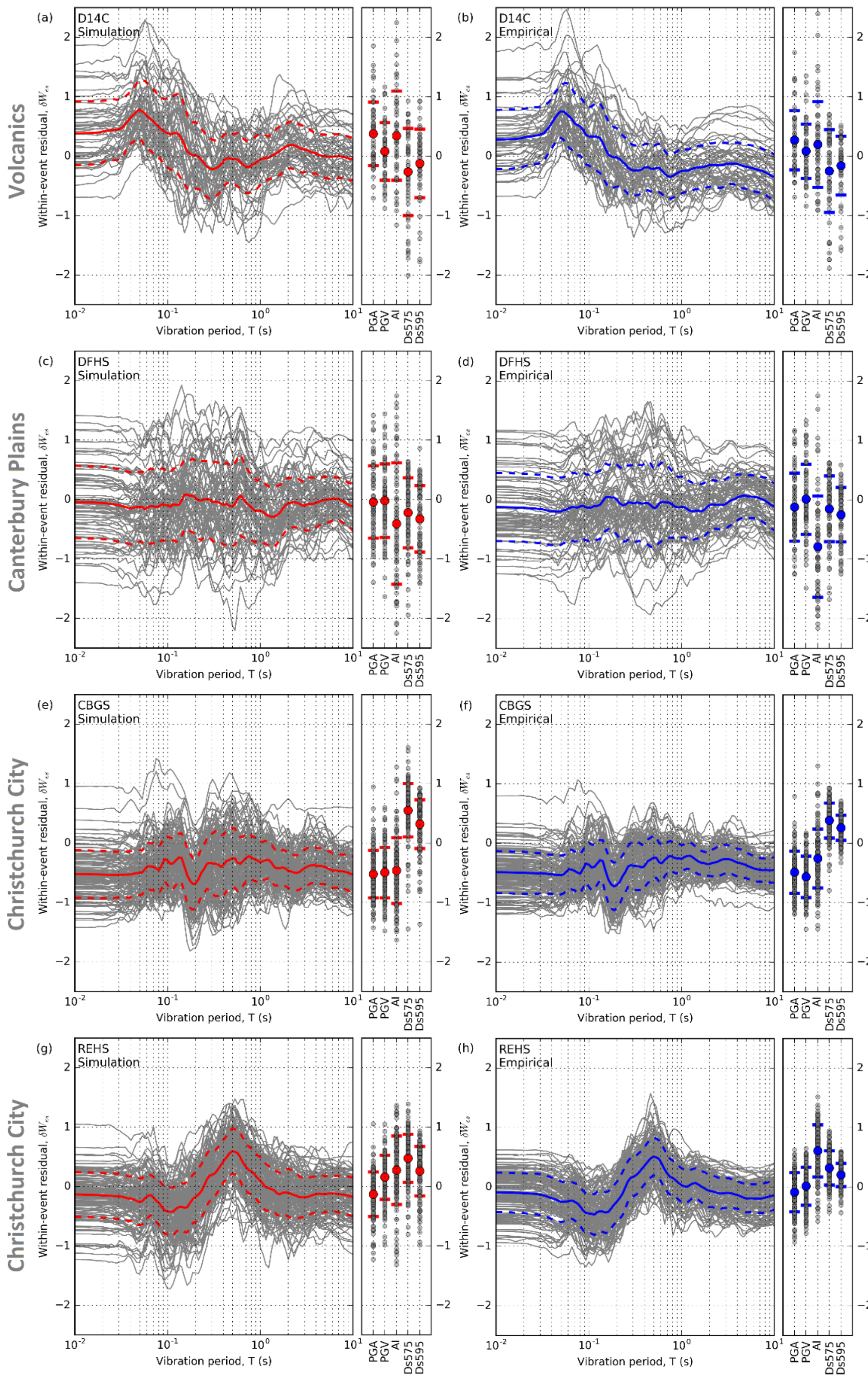

Figure 8. Computed within-event residuals for the: (a) simulated D14C; (b) empirical D14C; (c) simulated DFHS; (d) empirical DFHS; (e) simulated CBGS; (f) empirical CBGS; (g) simulated REHS; and (h) empirical REHS predictions.

DISCUSSION AND CONCLUSION

The results from this study highlighted several limitations in the simulations and suggest some modifications can be made to the ground motion simulation methodology utilized for the Canterbury region to improve its predictive capability, in particular: (i) underprediction of significant durations through an improved path duration model (e.g. Boore and Thompson 2014 active crustal region model); (ii) overprediction of HF ground motion IMs, again through an improved path duration model; and (iii) overprediction of LF ground motion IMs by reducing the maximum period which the V_{s30}-based site amplification is applied, hence reducing the double counting of long period site effects. Implementation of site-specific 1D velocity models and κ is also expected to improve the accuracy and precision of the simulations.

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