Hybrid Broadband Ground Motion Simulation Validation of Small Magnitude Earthquakes in Canterbury, New Zealand

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Ground motion simulation validation is an important and necessary task towards establishing the efficacy of physics-based ground motion simulations for seismic hazard analysis and earthquake engineering applications. This paper presents a comprehensive validation of the commonly used Graves and Pitarka (2010, 2015) hybrid broadband ground motion simulation methodology with a recently developed 3D Canterbury Velocity Model. This is done through simulation of 148 small magnitude earthquake events in the Canterbury, New Zealand, region in order to supplement prior validation efforts directed at several larger magnitude events. Recent empirical ground motion models are also considered to benchmark the simulation predictive capability, which is examined by partitioning the prediction residuals into the various components of ground motion variability. Biases identified in source, path and site components suggest that improvements to the predictive capabilities of the simulation methodology can be made by using a longer high frequency path duration model, reducing empirical V_{s30}-based low frequency site amplification, and utilizing site-specific velocity models in the high frequency simulations.

INTRODUCTION

Interest in using physics-based ground motion simulations for seismic hazard analysis and earthquake engineering applications has increased significantly over the past decade (Porter et al., 2011; Graves et al., 2011; Bradley et al., 2017b). The underlying physics-based nature of simulations is attractive to explicitly model salient ground motion phenomena, e.g. fault rupture,

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wave propagation, and surficial site response. Other benefits of physics-based simulations are their ability to alleviate the paucity of large magnitude (M_w), short distance recordings by directly simulating such scenarios, and the direct provision of ground motion time series instead of intensity measures, as provided by empirical ground motion models. However, before physics-based simulations can be widely adopted in seismic hazard analysis and earthquake engineering applications, the simulation methodologies must first be robustly validated to ensure their predictive capability approximately matches or exceeds conventional empirical ground motion models.

In the past, there have been various approaches towards the validation of ground motion simulation methodologies. Validation is most commonly provided in publications alongside details of, or improvements to, their respective ground motion simulation method (e.g. Komatitsch et al. (2004), Mai et al. (2010), Graves and Pitarka (2010), and Taborda and Bielak (2013)). The above references illustrate that this type of validation is often limited to a single or few historical events. With a large focus of ground motion simulation advancements centered in Southern California, a few events are commonly considered for validation, such as the 1994 M_w 6.7 Northridge earthquake, although some other events have also taken preference in specific studies (e.g. 2008 M_w 5.4 Chino Hills earthquake (Taborda and Bielak, 2013)). The events which are usually considered are generally significant moderate-to-large magnitude events as these contribute more to hazard and have more engineering significance. However, moderate-to-large magnitude events exhibit complex phenomena, such as source rupture complexity and nonlinear site effects with larger amplitude shaking, often making it difficult to properly identify and decouple the causes of any bias. Hence the modelling of many smaller events, which do not exhibit the aforementioned complexities, can enable improved understanding of modelling for larger events under the assumption that the physical processes being represented in the simulation approach also scale appropriately to larger magnitude events. Previously, Taborda et al. (2016) simulated 30 earthquake events with $3.6 \leq M_w \leq 5.4$ in Southern California but had an emphasis on comparing the performance of various community velocity models as opposed to quantifying systematic biases and variability.

Several significant validation efforts have recently emerged in which the predictive capability of several ground motion simulation methods are tested (Hartzell et al., 2011; Dreger and Jordan, 2015; Maufroy et al., 2015). The Southern California Earthquake Center (SCEC) Broadband Platform (BBP) validation exercise rigorously evaluated four widely used simulation methods implemented on the SCEC BBP (Atkinson and Assatourians, 2015; Crempien and

Archuleta, 2015; Graves and Pitarka, 2015; Olsen and Takedatsu, 2015). This exercise focused on comparing median pseudo-spectral acceleration (pSA) predictions using a one-dimensional (1D) velocity model against both recorded ground motions from historical earthquakes in different geographic regions, as well as against empirical ground motion models for scenarios which are well constrained with an abundance of data (essentially testing the centering of the simulation methods) (Goulet et al., 2015). There were several exercise design decisions and imposed constraints to ensure the integrity of the validation exercise emphasizing transparency, consistency in model inputs, robustness of the validation and more. Generally, the simulation methods performed favourably although several shortcomings and improvements were identified (Dreger et al., 2015). The twelve events considered were all $M_w \geq 5.39$, with the exception of one central and eastern United States earthquake with $M_w = 4.60$.

Although the rationale for the events considered is justified and fit the purpose of the exercise, the same aforementioned limitation of omitting smaller magnitude events is present. Other limitations of this exercise include not considering non-pSA intensity measures (IMs), and not considering uncertainty in the prediction (also referred to as dispersion) although it is noted that these will be included in future validation exercises. Afshari and Stewart (2016b) presented a supplemental study which compared significant duration metrics from the four SCEC BBP simulation methods against the recently developed Afshari and Stewart (2016a) empirical ground motion model (GMM) but for only 5 events with $M_w = 6.0$–7.3. The results suggested there were shortcomings for the simulated durations.

Ground motion simulation validation efforts in New Zealand have been largely focused on the major events from the 2010–2011 Canterbury earthquake sequence, particularly the 4 September 2010 M_w 7.1 Darfield and 22 February 2011 M_w 6.2 Christchurch earthquakes (Razafindrakoto et al., 2018), and 14 November 2016 M_w 7.8 Kaikoura earthquake (Bradley et al., 2017c). However, moderate-to-large magnitude earthquakes occur relatively infrequently within a specific region. To build on previous validation efforts, small magnitude (SM) earthquakes ($3.5 \leq M_w \leq 5.0$) can be considered and due to their frequency of occurrence they can offer a wealth of information about systematic source, path and site effects as a substantial number of recordings can be made at the same locations. Systematic ground motion phenomena can be examined through a non-ergodic analysis framework, where the ergodic assumption, which assumes that the variability in ground motion at a single site-source pairing is the same as the variability across the global dataset, is relaxed. While this analysis framework is most commonly utilized in empirical ground motion prediction to reduce aleatory variability (Rodriguez-Marek

et al., 2011), it is also a powerful tool for evaluating the performance of any prediction method.

This paper presents a comprehensive validation of the Graves and Pitarka (2010, 2015) hybrid broadband ground motion simulation methodology. This methodology is one of the simulation methods considered in the SCEC BBP validation exercise (Goulet et al., 2015; Dreger et al., 2015)). Simultaneously, the Canterbury region-specific source and velocity model inputs will be validated through the ground motion simulation of SM earthquakes. The performance of selected empirical ground motion models are also considered to provide a benchmark for the evaluation of the simulations. Firstly, the earthquake sources and strong motion stations considered are presented. Next, the input models are detailed, followed by an outline of the ground motion simulation validation analysis methodology. Lastly, the results of the validation are presented including an investigation of systematic source, path and site effects.

EARTHQUAKE SOURCES AND STRONG MOTION STATIONS CONSIDERED

The Canterbury region has a wealth of ground motion data, primarily as a result of the recent 2010–2011 Canterbury earthquake sequence and the dense array of strong motion recording instrumentation. As SM earthquakes produce smaller-amplitude ground motions than large M_w earthquakes at similar distances, a rational selection process is imperative to balance quantity and quality of observational data. In this section, the selection criteria and details of the earthquake sources and strong motion stations considered are presented while details of recorded ground motions and associated signal processing are presented in Electronic Supplement D.

EVENT AND STATION INFORMATION

Earthquake source descriptions used in this study were obtained from the GeoNet New Zealand earthquake catalogue (Ristau (2008), see Data and resources). Figure 1 presents the earthquakes considered, highlighting their spatial distribution across the region. Also shown are the location of strong motion recording stations and raypaths of ground motions considered which provides a qualitative illustration of the spatial domain being robustly assessed in the simulations. The earthquakes are densely located around the Christchurch city, Rolleston and Darfield areas as most were aftershocks from the 4 September 2010 M_w 7.1 Darfield, and 22 February 2011 M_w 6.2, 13 June 2011 M_w 6.0, and 23 December 2011 M_w 5.9 Christchurch earthquakes (Bannister and Gledhill, 2012). Earthquakes with M_w = 3.5–5.0 were considered for this study. The minimum M_w 3.5 was chosen to ensure there is good constraint on the earthquake source param-

eters (specifically a centroid moment tensor solution) and adequate signal-to-noise ratio of the ground motion records. The maximum M_w 5.0 was chosen to ensure that the point source approximation is generally valid for the majority of recorded ground motions (which significantly simplifies the source modelling and consequent uncertainties) and that there is no appreciable off-fault nonlinear behaviour in order to reduce uncertainties associated with modelling nonlinear site response. A minimum requirement of five high-quality observed ground motion records per event was also enforced (for reasons discussed subsequently) resulting in 148 earthquakes in the final dataset. Larger magnitude events generally had more high-quality ground motions. Table A.1 in Electronic Supplement A provides details of the considered events.

Figure 2 illustrates the M_w, source-to-site distance ($\mathrm{R_{rup}}$), and centroid depth (CD) distributions of the considered events and recorded ground motions. Figure 2a shows the M_w–$\mathrm{R_{rup}}$ distribution of the recordings from which it is illustrated that the database of recorded ground motions provides an approximately uniform coverage of the magnitude-distance space of interest, although the density of low magnitude, large distance records is expectedly lower. Figures 2b and 2d present the distribution of M_w and CD of the 148 earthquake sources, respectively. The majority of sources are $M_w \geq 4.0$ and CD $\leq$ 10km. The observed distribution of M_w arises as regional centroid moment tensor solutions require sufficient energy at low frequencies to invert reliable solutions. Earthquakes with $M_w \geq 4.0$ are routinely generated while earthquakes with $M_w < 4.0$ often do not contain sufficient low frequency energy and are therefore more selectively calculated. Of the 148 earthquakes, the rake directions indicate that the rupture mechanisms are 107 strike slip, 23 reverse, 3 normal, 12 reverse-oblique and 3 normal-oblique. The distribution of $\mathrm{R_{rup}}$ for the ground motion recordings considered is shown in Figure 2c. Note that the majority of recordings have $\mathrm{R_{rup}} \leq$ 60km such that small errors in the assumed anelastic attenuation are not considered significant. No maximum $\mathrm{R_{rup}}$ is enforced; this could lead to some bias associated with instrument triggering. However, the largest $\mathrm{R_{rup}}$ considered in this study are generally much smaller than those considered in other empirical ground motion model studies that include SM earthquakes (over 200km, e.g. Chiou et al. (2010), Bradley (2013), Ancheta et al. (2014)), thus we do not expect that these biases would affect results. Overall, the annotated ray paths in Figure 1 provide relatively wide coverage of the Canterbury region and are significantly denser in the Christchurch city area such that some sites are better represented than others.

A total of 43 strong motion stations, whose locations are shown in Figure 1, recorded a sufficient quantity of high-quality ground motions from different events (at least five) and were

Figure 1. 148 Earthquake sources and 53 strong motion stations considered within the ground motion simulation domain. Schematic ray paths of observed ground motions are also shown as black lines. A total of 1896 ground motions satisfy the quality criteria and are used for simulation validation. 10 strong motion stations with insufficient high-quality recordings are shown as unfilled markers. Focal mechanisms are shown as lower hemisphere projections.

considered for the purpose of examining the predictive capabilities of ground motion simulations. Table C.1 in Electronic Supplement C provides the list of stations along with their geographic coordinates, 30m time-averaged shear-wave velocity (V_{s30}), and number of earthquakes observed (NE_s). V_{s30} values are taken from Wood et al. (2011), Van Houtte et al. (2014), and Wotherspoon et al. (2014, 2015, 2016) who collectively characterized the sites through various geotechnical and geophysical techniques. The Canterbury region has a complex geology which results in the strong motion stations being located on a diverse range of site conditions, ranging from rock conditions on Banks Peninsula and the Canterbury Foothills, to gravels and marine fines in the Christchurch City and Canterbury Plains (west of Christchurch City) areas. More context on the shallow site behaviour is provided with the interpretations of the analyses

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; and (d) centroid depth distribution.

results. Values of V_{s30} range from 154m/s (REHS) to 900m/s (CRLZ) and NE_s ranges from 6 (HVSC, LPCC and SMTC) to 136 (PPHS).

GROUND MOTION MODELLING METHODOLOGIES AND INPUTS

BROADBAND GROUND MOTION SIMULATION METHODOLOGY

This study adopts the hybrid broadband ground motion stimulation methodology developed by Graves and Pitarka (2010, 2015, 2016) (specifically the wave propagation component of the methodology as the earthquake ruptures are modelled as point sources in this study). 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 using a 4th order butterworth filter to produce a single broadband (BB) time series. A summary of the simulation methodology pertaining to this specific study is included in Electronic Supplement E while comprehensive details of the methodology can be found in the respective

papers (e.g. Graves and Pitarka (2010, 2015, 2016)).

The ground motion simulations were performed within a computational domain of 140km x 120km x 46km (whose surface projection is shown in Figure 1), with a finite difference grid spacing of 0.1km. As the maximum resolvable frequency in the LF simulations is dependent on the grid resolution and minimum shear wave velocity, a minimum shear wave velocity of 500m/s is enforced in the Canterbury basin to yield a maximum frequency of 1.0Hz based on 5 points per wavelength for a 4th order spatial finite difference method, which is subsequently the transition frequency where the LF and HF components are merged. This merging is performed using power spectra-based matching (as opposed to Fourier amplitude spectra-based matching, Graves and Pitarka (2016)). The simulation domain adopts the bulldozed topography approach as the Canterbury region is mostly a flat alluvial plain. A time increment of Δt = 0.005s was utilized, matching the timestep of observed strong motion station recordings, for 20,000 time steps to produce simulated ground motions of 100s duration for both LF and HF components.

SEISMIC VELOCITY MODELS OF THE REGION

To simulate LF ground motions, a recently developed 3D Canterbury Velocity Model (CantVM; Lee et al. (2017a), Thomson et al. (2019)) is used in this study to provide the P-wave and S-wave velocities, and density required (V_p, V_s and ρ, respectively). Figure 3a presents a fence diagram of five cross sections of the CantVM through the Canterbury region which highlights the dominant regional geologic features. The CantVM explicitly models the Canterbury sedimentary basin with high spatial resolution via five distinct geologic layers. Velocities of the shallowest layer, the Quaternary unit, are prescribed from a generic regional 1D velocity model, discussed subsequently, while the other three layers are prescribed constant characteristic velocities. The depth of the sedimentary basin (i.e. depth to geologic Basement) generally ranges from around 1500m to 2500m in the Canterbury Basin (Lee et al., 2017a). The Basement structure utilizes velocities from a regional-scale travel-time tomography-based seismic velocity model (Eberhart-Phillips et al., 2010) which varies smoothly with location and depth. Additionally, the high velocity Banks Peninsula volcanics, located beneath and adjacent to Christchurch city, is also explicitly modelled. The geologic features modelled have been noted in simulations of validated historical events (e.g. Bradley et al. (2017c), Razafindrakoto et al. (2018)), as well as future prospective events (e.g. Bradley et al. (2017a)), to strongly influence earthquake ground motions through phenomena such as basin wave-guide effects, basin-edge effects, and

Figure 3. Crustal velocity models for ground motion simulations: (a) Fence diagram of five shear wave velocity (V_s) cross sections through the 3D Canterbury Velocity Model across the Canterbury region (for LF simulations), highlighting the velocity variations and modelled geologic features; and (b) 1D velocity profiles (for HF simulations).

nonlinear soil response at frequencies of engineering interest.

For the HF component of the ground motion simulations, a regional 1D velocity model is used. Figure 3b presents the V_p, V_s and ρ profiles which comprise the 1D velocity model. The profiles have several low velocity and density layers in the top 3km, and moderate velocity and density layers between 3–5km, which effectively represents the sedimentary basin, while deeper layers represent geologic Basement rock. Only the top 40km of the model are shown here as the model takes on constant values below 38km.

EMPIRICAL GROUND MOTION INTENSITY MEASURE MODELS

In addition to the comparison between observed and simulated ground motions, the performance of selected empirical GMMs is also evaluated. The following IMs are considered: peak ground acceleration, PGA; pseudo-spectral accelerations, pSA; peak ground velocity, PGV; Arias intensity, AI; and 5-75% and 5-95% significant durations, $\mathrm{D_{s575}}$ and $\mathrm{D_{s595}}$, respectively. 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 (2016a) for $\mathrm{D_{s575}}$ and $\mathrm{D_{s595}}$. Justification of the choice of empirical models for the purpose of this study is presented in Electronic Supplement F.

VALIDATION ANALYSIS METHODOLOGY

Due to the large number of earthquake events considered, the analysis is primarily focused on results from considering the entire dataset of ground motions. To achieve this, the prediction residuals are partitioned into the various components of ground motion variability. A detailed comparison between observed and simulated ground motion waveforms and intensity measures from one event is presented in Electronic Supplement G to highlight ground motion features of the simulations.

The total prediction residual is partitioned into the various components associated with ground motion variability using a partially crossed linear mixed effects regression algorithm (Stafford, 2014; Bates et al., 2015). Following the notation of Al Atik et al. (2010), the general form of a GMM for an event, e, and station location, s, pairing can be written as:

$$\ln \mathrm{IM}_{es} = f_{es} + \Delta \tag{1}$$

where $\ln \mathrm{IM}_{es}$ is the natural logarithm of the observed intensity measure; f_{es} is the median of the predicted logarithmic intensity measure (given by either the ground motion simulation or an empirical GMM) which is a function of the earthquake rupture, e, and site location, s; and Δ is the total residual. The total residual can be further decomposed into fixed and random effects:

$$\ln \mathrm{IM}_{es} = f_{es} + a + \delta B_e + \delta W_{es} \tag{2}$$

where a is the 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. Comparison of Equations (1) and (2) illustrates that Δ has mean a and variance $\sigma^2 = \tau^2 + \phi^2$. δB_e represents the systematic misfit between observation and bias-corrected median prediction for a given earthquake, e. δW_{es} represents the difference between observation and the bias- and event-corrected median prediction for a ground motion record corresponding to a given earthquake, e, and site, s. Lastly, δW_{es} can be further broken down into a systematic effect and a remaining residual:

$$\ln \mathrm{IM}_{es} = f_{es} + a + \delta B_e + \delta S2S_s + \delta W^0_{es} \tag{3}$$

where $\delta S2S_s$ is the systematic site-to-site residual, and δW^0_{es} is the 'remaining' within-

event residual which represents factors which are not accounted for in the models. $\delta S2S_s$ is a zero mean random effect with variance ϕ^2_{S2S} and δW^0_{es} has residual variance ϕ^2_{ss}. When multiple source regions are considered, δB_e can also be decomposed into a systematic location-to-location residual and a 'remaining' between-event residual. However, only one source region (Canterbury as a whole) is considered in this study therefore such partitioning is not undertaken and variations in δB_e are spatially continuous.

OBSERVED SYSTEMATIC EFFECTS IN GROUND MOTION MODELLING

Comparisons between observations and predictions for a single event are commonly used to provide validation and insight on a method's predictive capability. However, earthquake ground motions are known to have large variability. In order to robustly validate the systematic performance of the ground motion simulations and empirical GMMs, they are compared against observations from 148 earthquakes. In this section, the various components of ground motion variability determined using the previously presented framework (in the Validation Analysis Methodology section) are presented and discussed.

MODEL BIAS, a

Model bias is the systematic difference between observation and prediction using a specific model. In this study, this refers to either ground motion simulations or the empirical GMM for the respective IM. Figure 4 presents the model bias and total standard deviation (σ) across all events and stations considered for these prediction methods. Figure 4a illustrates the model bias in the simulations is negative for all pSA periods indicating the simulations overpredict observed ground motions, while the Bradley (2013) empirical model also overpredicts pSA at short periods (T = 0.01–0.3s), is unbiased at moderate periods (T = 0.3–3.0s) and underpredicts for long periods (T $\geq$ 3.0s). Bradley (2015) investigated the bias of the Bradley (2013) model for large amplitude ground motions from 10 events in the 2010–2011 Canterbury earthquake sequence and found a similar trend was evident at moderate to long periods. The simulated AI bias is relatively small while the empirical Campbell and Bozorgnia (2014) AI is severely overpredicted, with a bias value of -1.67 (although this is plotted at -1.5 for the plot to be all-inclusive) which corresponds to a factor of 5.3. This is a result of the considered earthquakes being below the model's range of magnitude applicability. Both simulated significant durations are severely underpredicted with bias values of 1.53 (corresponding to a factor of 4.6) and 1.84

(corresponding to a factor of 6.3), for D_{s575} and D_{s595}, respectively (both have been plotted at 1.5 for the plot to be all-inclusive though). The Afshari and Stewart (2016a) empirical model has effectively no bias for both D_{s575} and D_{s595}.

The simulation bias for pSA in Figure 4a has a negative dip within a localized period band, between T = 1.0–4.0s, which is likely caused by the empirical V_{s30}-based site amplification for the LF ground motion (which is applied for frequencies f = 0.2–1.0Hz, affecting approximately T = 1.0–5.0s). The long period amplification, as recommended by Graves and Pitarka (2010), is intended to account for long period site effects when low resolution velocity models are used that are not able to explicitly model these effects (i.e. even though the spatial discretization in the numerical simulation allows for a maximum frequency of f_{max} = 1.0Hz, it is implied that the model may not adequately represent velocity variations at the corresponding spatial scales). Therefore, the appropriate level of amplification depends on the regional geology, and the resolution and quality of the specific velocity models used. As the CantVM is used in the LF simulations, which explicitly models the Canterbury basin in high resolution, some long period site effects are explicitly modelled and therefore it is inferred that the empirical amplification is effectively 'double counting' these long period site effects.

The total standard deviations, σ, of the simulation and Bradley (2013) model for pSA are similar at all vibration periods except between T = 1.0–4.0s where the simulation σ is slightly larger (by roughly 7%). The σ for empirical significant durations are also lower than their simulated counterparts. The σ of all IMs, simulated and empirical, are roughly between 0.6–0.8 with the exception of simulated and empirical AI, which have values of 1.21 and 1.27, respectively, and empirical D_{s595}, which is the most precise IM considered. The relatively large σ for AI is consistent with previous studies (Campbell and Bozorgnia, 2012).

BETWEEN-EVENT RESIDUAL, δB_E

The between-event residuals, δB_e, are inherently associated with the location and source characteristics of each event. The present stress field of the Canterbury region typically favours inland strike-slip faulting and reverse faulting in the coastal areas (Sibson et al., 2011), hence most sources considered in this study are strike-slip or reverse ruptures. In the ground motion simulations, the between-event variability can arise from the location of the earthquake source and kinematic source parameters which describe the fault's slip evolution. As the source models are simplified as point sources for this study, the primary factors which characterize the source

Figure 4. Simulated and empirical prediction for pSA as a function of vibration period, and five other IMs: (a) systematic model bias, a; and (b) total standard deviations, σ. Note that values which exceed the specified axis limits are plotted at the axis limits (1.5 or -1.5) for clarity and completeness, with specific values provided in the related text.

model are the magnitude, location in the Earth's crust, faulting mechanism (Ristau, 2008) and HF stress parameter (Oth and Kaiser, 2014). It should be noted here that the local V_s used for calculating source slip is obtained from the 1D velocity model (and depends on the hypocentral depth) which effectively models a sedimentary basin above 5km. The empirical GMMs considered in this study represent the source effects through magnitude scaling, depth-to-rupture measures (e.g. Z_{TOR}), and faulting mechanism modifications.

Comparison for entire dataset

Figure 5a and 5b present the $\delta\mathrm{B_e}$ as a function of the considered IMs for the 148 events considered for the simulated and empirical predictions, respectively. For plots of this style throughout this paper, the mean and ± 1 standard deviation (τ for the between-event residuals) values are shown as the solid and dashed lines, respectively, for pSA plots and the large points and horizontal lines, respectively, for discrete IM plots. The variability and range of δB_e are similar between simulation and empirical predictions for pSA across all vibration periods considered, PGA, and PGV but different for AI, $\mathrm{D_{s575}}$ and $\mathrm{D_{s595}}$, each of which exhibited large model bias.

Figure 6 explicitly presents the between-event standard deviations, τ, for the simulated and empirical predictions. For pSA, PGA and PGV, τ is practically equal between simulation and empirical prediction, with values between roughly 0.32–0.46, implying that the between-event variability is similar between the two methods. The larger values of τ occur at shorter periods while the smaller values occur at longer periods implying there is less variability between events

Figure 5. Computed between-event residuals for the 148 earthquakes (grey lines and points) for: (a) simulated IMs; and (b) empirical IMs.

Figure 6. Between-event standard deviation, τ, for simulated and empirical predictions.

at long periods. This may be a result of the spectral ordinates at the longer periods being driven by the Fourier amplitudes below the source corner frequency so variability in factors such as stress drop are not present (although a non-trivial contributor at these periods would be the uncertainty in the focal mechanism and its mapping into the radiation pattern). The empirical predictions for significant durations have the smallest τ, at roughly 0.2 while the simulated significant durations have slightly larger τ, between 0.3–0.4.

Dependence on source parameters

To determine the causes of the variability and identify any bias with $\delta\mathrm{B_e}$, the $\delta\mathrm{B_e}$ values are compared against several source parameters; M_w, CD and focal mechanism. Here, only a subset

of selected plots of simulated predictions are shown to highlight particular trends while an exhaustive set of plots is provided in Electronic Supplement I. In these plots, the average trend is also indicated qualitatively via local linear regression. Figures 7a and 7b provide comparisons between $\delta\mathrm{B_e}$ and M_w for PGA and $\mathrm{D_{s575}}$, respectively. The comparison for PGA highlights the trend of increasing $\delta\mathrm{B_e}$ with increasing M_w. As the simulation model bias for PGA was identified as negative (a_{PGA} = -0.25; Figure 4), larger M_w events with positive $\delta\mathrm{B_e}$ produce more accurate predictions of PGA in an overall sense. The comparison for $\mathrm{D_{s575}}$ highlights the opposite trend of decreasing $\delta\mathrm{B_e}$ with increasing M_w. However, as the simulation model bias was identified as positive ($a_{D_{s575}}$ = 1.53; Figure 4) for $\mathrm{D_{s575}}$, larger M_w events also result in more accurate predictions of $\mathrm{D_{s575}}$. While not shown here, $\mathrm{D_{s595}}$ also exhibits the same trend as $\mathrm{D_{s575}}$. The lower bias with larger magnitude is consistent with results from validation against past large magnitude events which showed relatively small bias (Graves and Pitarka, 2010; Bradley et al., 2017a; Razafindrakoto et al., 2018).

For the simulations of SM earthquakes, the two M_w-dependent trends noted above for PGA and significant durations are inherently linked by the HF simulation duration which comprises path and source duration components. With increasing magnitude, the source duration increases such that the path duration (which remains constant for a given source-to-site distance) comprises an increasingly smaller percentage of the total duration. An increase in the total duration in this manner decreases the underprediction of significant durations, and overprediction of PGA and short period pSA. Hence, the observed biases manifest from the HF simulation path duration being too short. Consistent with these observations, Boore and Thompson (2014, 2015) found that conventionally used path duration models used in 'stochastic' simulations don't appropriately account for all factors which increase duration with distance (e.g. different arrival times for waves of varying speed, scattering, reflected and basin waves). The significant durations of many simulated ground motions from SM earthquakes in this study are dominated by the HF acceleration amplitudes and hence demonstrate this underprediction, especially for $\mathrm{D_{s575}}$. However, ground motions which have significant LF acceleration amplitudes, such as those with significant basin-induced waves, actually produce significant durations which are broadly consistent with the observations. For larger magnitude earthquakes, the biases are smaller because the HF simulation duration becomes dominated by the source corner frequency and rupture propagation over the subfaults, and the LF simulation acceleration amplitudes become significant. It should also be noted that Afshari and Stewart (2016b) found Graves and Pitarka (2010, 2015) to have distance-scaling issues, despite having relatively small bias, which

Figure 7. Comparison of simulation between-event residual against M_w for: (a) PGA; and (b) $\mathrm{D_{s575}}$. The local linear regression trend lines are represented as the thick dashed lines while the associated model biases, a, are represented as the thin dashed line.

may be related to the biases identified in this study. The lack of site effect consideration for duration is another source of underestimation and is elaborated upon in later sections.

Comparisons between $\delta\mathrm{B_e}$ and CD were unreliable for identifying trends as there are few earthquakes with CD below 10km. However, it is acknowledged that the use of a constant stress parameter could cause bias with CD related to the source corner frequency and high frequency amplitudes. For pSA(3.0s) there appeared to be a strong tendency for 4km deep earthquakes to be overpredicted which is inferred to be caused by lower local shear wave velocities requiring larger slip values in the source models to achieve the target moments. Shallower earthquakes also naturally have shallower incidence angles upon the Canterbury sedimentary basin boundary which can result in greater critical reflections at the basin interface. A comparison between $\delta\mathrm{B_e}$ and focal mechanism for PGA identified that reverse faulting tended to produce lower $\delta\mathrm{B_e}$ than other focal mechanisms (likely partially attributed to the use of an azimuthal-constant radiation pattern and constant stress drop). However, it should be noted that reverse faults were also mostly shallow and located in the Pegasus Bay area, and therefore this trend may be caused by bias in those factors.

Spatial dependence

Figure 8 presents a plot of the spatial variation of $\delta\mathrm{B_e}$ for simulated PGA with the observed values and a Kriged surface. Spatial plots of $\delta\mathrm{B_e}$ for other simulated IMs and the empirical predictions are included in Electronic Supplement J. The surface projections of the 4 September 2010 M_w 7.1 Darfield and 22 February 2011 M_w 6.2 Christchurch earthquake ruptures are also plotted to help infer any influence of these events on the observed $\delta\mathrm{B_e}$. The cluster of

earthquakes on the easternmost segment of the Darfield earthquake rupture has primarily small or negative $\delta\mathrm{B_e}$ and is surrounded by earthquakes with positive $\delta\mathrm{B_e}$. The offshore earthquakes to the northeast of the Christchurch earthquake with negative $\delta\mathrm{B_e}$ were aftershocks related to the 23 December 2011 M_w 5.8 and 5.9 earthquakes. It should also be noted that these offshore earthquakes were generally on shallow and reverse faults, which were previously noted to have systematically overpredicted PGA and pSA amplitudes. Again, this may be attributed to the tendency for these types of faults to have lower local V_s and stress parameters values. The results presented here are generally consistent with Trugman and Shearer (2018) who investigated 5297 earthquakes in the San Francisco Bay area between M_w = 1-4 and identified strong correlation between PGA and stress parameter values. The spatial distribution of $\delta\mathrm{B_e}$ appears to be relatively consistent between vibration periods which further indicates source properties such as the Brune stress parameter could be considered regionally variable.

SITE-TO-SITE AND WITHIN-EVENT RESIDUALS, $\delta S2S_S$ AND δW_{ES}

The Canterbury region can be loosely categorized into four geographic regions with distinct geologic character; Banks Peninsula, Christchurch city, Canterbury Plains and Canterbury Foothills. Stations located on Banks Peninsula are generally volcanic rock sites with high velocity and stiffness (Van Houtte et al., 2012). Stations located in Christchurch city are generally underlain by a sequence of interbedded marine and gravel formations, as well as the Banks Peninsula volcanics at depth, all of which can lead to complex wave propagation (Wotherspoon et al., 2014, 2015; Lee et al., 2017b). Stations located on the Canterbury Plains are mostly characterized as deep soil sites corresponding to the sedimentary deposits of the Canterbury Basin. These sites generally have gravel layers near the surface (Wotherspoon et al., 2016). Stations located in the Canterbury Foothills area are located on Basement rock or relatively thin alluvial deposits overlying Basement rock. The analyses presented here will loosely evaluate each of these categories as well as investigate specific sites where salient features are observed.

As within-event residuals are inherently associated with wave propagation path and site effects, the components of the prediction which account for these effects are the cause of any bias present in these residuals. For simulated ground motions, the path effect is dependent on the wave propagation through the specific velocity model (3D CantVM for LF and 1D velocity model for HF, as shown in Figure 3a and 3b, respectively). However, azimuth-specific path effects are not investigated in this study, rather, path effects are simply considered with respect to $\mathrm{R_{rup}}$. Site effects are also dependent on the velocity model, however, the resolution

Figure 8. Spatial distribution of between-event residual, δB_e, for simulated PGA for all 148 earthquake events.

of the velocity models used are usually unable to accurately capture the near-surface site effects. Therefore site amplification is also applied via the V_{s30}-based shallow site response term developed by Campbell and Bozorgnia (2014). The Bradley (2013), Campbell and Bozorgnia (2012) and Afshari and Stewart (2016a) empirical GMMs all treat path effects through various source-to-site distance parameters, and site effects through V_{s30} and depth-to-rock parameters (e.g. $Z_{1.0}$ and $Z_{2.5}$, although these values have been calculated using the Abrahamson and Silva (2008) correlations with V_{s30} for this study).

Figure 9. Computed δS2S$_s$ for all 43 stations considered for: (a) simulated IMs; and (b) empirical IMs.

Systematic site-to-site residuals for all stations

Figure 9a and 9b presents all δS2S$_s$ for the 43 strong motion stations considered for simulated and empirical predictions, respectively. The variability and range of $\delta S2S_s$ are similar between simulation and empirical predictions for pSA across all periods considered. For simulated predictions, three stations appear to have significant long period underprediction. These sites are CSHS, MTHS and WCSS, which are all located in the Canterbury foothill region. Although MTHS is not rock at the surface, it exhibits similar systematic site residuals to CSHS and WCSS, which are rock at the surface. There may be several factors causing this underprediction. Firstly, the V_s of Basement rock in the CantVM, used in the LF simulations, corresponds to unweathered rock and is relatively high (e.g. V_s = 2500m/s). In reality, the near-surface rock would be weathered and be lower velocity which would result in larger simulated amplitudes. Secondly, the three stations in question are located in the North-West of the simulation domain and only record earthquakes from a limited range of azimuths. Therefore it is possible that systematic paths effects could be included in the δS2S$_s$ for these sites. The corresponding empirical δS2S$_s$ for these three sites also exhibit large peaks but at different periods. As the features of the Canterbury Foothills sites have been discussed here, they are not included in the subsequent location-specific section.

Figure 10a and 10b explicitly presents the within-event standard deviations, ϕ_{S2S} and ϕ_{ss}, respectively, for the simulated and empirical predictions which the former clearly illustrates that a significant amount of the variability between observation and prediction is the result of systematic site effects. For all IMs considered, ϕ_{S2S} are similar between simulation and empirical

Figure 10. Within-event standard deviations: (a) systematic site-to-site uncertainty; and (b) single-station within-event variability.

prediction, with values between roughly 0.30–0.45, except for pSA between T = 1.0–4.0s. The larger values of ϕ_{S2S} in this range are caused by the sites at the Canterbury Foothills having significantly larger $\delta\mathrm{S2S_s}$ than all other sites. This difference between simulated and empirical prediction ϕ_{S2S} is the primary cause of the difference in σ identified in this same period range (Figure 4). The size of ϕ_{S2S}, relative to σ, indicates that significant improvements in ground motion prediction are possible through being able to capture this systematic phenomena (Rodriguez-Marek et al., 2011). ϕ_{ss} from simulations is slightly larger than the ϕ_{ss} for empirical prediction for all IMs considered suggesting that the empirical GMMs have less unexplained variability than the ground motion simulations. It is also important to note that τ (Figure 6), ϕ_{S2S} and ϕ_{ss} are all of similar size implying that the variability in δB_e, $\delta S2S_s$ and δW_{es}^0 are similar.

Dependence on path and site parameters

In order to evaluate the variability and biases resulting from site and path effects, the systematic site-to-site residuals, $\delta\mathrm{S2S_s}$, are compared against $\mathrm{V_{s30}}$ and the 'remaining' within-event residuals, $\delta\mathrm{W_{es}^0}$, are compared against source-to-site distance, $\mathrm{R_{rup}}$. As with $\delta\mathrm{B_e}$, only a subset of comparisons for simulation residuals are presented here while an exhaustive set of plots for both simulation and empirical prediction are included in Electronic Supplement I.

Figure 11a and 11b present the comparisons of $\delta\mathrm{S2S_s}$ against $\mathrm{V_{s30}}$ for PGA and $\mathrm{D_{s575}}$, respectively. The comparison with $\mathrm{V_{s30}}$ for PGA shows no significant trend while the comparison with $\mathrm{V_{s30}}$ for $\mathrm{D_{s575}}$ shows a negative trend where values are more underpredicted at low

Figure 11. Comparison of simulation systematic site-to-site residual against $\mathrm{V_{s30}}$ for: (a) PGA; and (b) $\mathrm{D_{s575}}$.

$\mathrm{V_{s30}}$ sites. Despite PGA and $\mathrm{D_{s575}}$ being strongly linked for the simulations, there is a lack of opposing trends here. This is attributed to the fact that the PGA has been modified by the period-dependent $\mathrm{V_{s30}}$-based site amplification while $\mathrm{D_{s575}}$ has had no modification (the site effect is applied to the FAS amplitudes). Overall, the lack of site effect contributions to significant duration leads to underestimation, and is more significant for softer sites. A comparison of $\delta\mathrm{S2S_s}$ with $\mathrm{V_{s30}}$ for pSA(3.0s), not shown here, identified a positive trend where low $\mathrm{V_{s30}}$ sites are more overpredicted. This is likely caused by overamplification via the period-dependent $\mathrm{V_{s30}}$-based site amplification as the long period amplification is larger for softer sites.

Figure 12a and 12b illustrate the comparisons of $\delta\mathrm{W^0_{es}}$ against $\mathrm{R_{rup}}$ for PGA and $\mathrm{D_{s575}}$, respectively. For PGA, the local regression suggests that $\delta\mathrm{W^0_{es}}$ values are slightly positive at distances beyond roughly 40km. This feature is also apparent in pSA for all periods considered. As this bias only occurs at greater than 40km, the most likely cause would be wave propagation effects. The comparison for $\mathrm{D_{s575}}$, which is less sensitive to attenuation, shows no trend.

Spatial dependence of site-to-site and within-event residuals

Figure 13 presents a plot of the spatial variation of $\delta\mathrm{S2S_s}$ for simulated PGA with the observed values and a Kriged surface. Spatial plots of $\delta\mathrm{S2S_s}$ for other simulated IMs and the empirical predictions are included in Electronic Supplement J. There are many trends which are common between the PGA and pSA maps. The Canterbury Plains immediately west of Christchurch City has positive $\delta\mathrm{S2S_s}$ while areas near or on the Canterbury foothills, where the geologic Basement is shallow or outcrops, are negative. Negative $\delta\mathrm{S2S_s}$ are also present for the rock sites located on Banks Peninsula or near the Banks Peninsula volcanics outcrop. Additionally, at short pe-

Figure 12. Comparison of simulation 'remaining' within-event residual against $\mathrm{R_{rup}}$ for: (a) PGA; and (b) $\mathrm{D_{s575}}$.

riods 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 mostly a result of the different surface geology where the Christchurch Formation, which mainly consists of marine sediments, is prevalent in the east and the Springston Formation, which is predominantly gravel, is prevalent in the west (Brown and Weeber, 1992). The discrepancies between velocity models and reality, particularly near-surface, suggest that explicit site response is needed although several improvements can also be made to the HF simulations to better consider site-specific characteristics (e.g. site-specific 1D velocity models and κ_0). Figure J.3b in Electronic Supplement J presents the spatial plot of $\delta\mathrm{S2S_s}$ for pSA(3.0s) which illustrates overprediction of long period spectral accelerations at sites located within the Canterbury Basin.

Banks Peninsula volcanic sites

Rock sites are often used as references for site response investigations as they are unlikely to be affected by nonlinear effects during large amplitude ground shaking. Figure 14a and 14b present the within-event residuals (i.e. $\delta\mathrm{S2S_s} + \delta W^0_{es}$) for the simulated predictions at the GODS and HVSC sites which have a modelled $\mathrm{V_{s30}}$ of 500 and 350m/s, respectively. In the remainder of this section, only the simulated results are discussed while the empirical results are included in Electronic Supplement K. It is noted that the empirical predictions are generally similar to the simulated results. This similarity clearly shows systematic site effects not considered via either approach, and highlights the opportunity for improved near surface site response modelling.

The GODS prediction exhibits a broad peak in $\delta\mathrm{S2S_s}$ at roughly 1.0Hz. Van Houtte et al. (2014) determined that the fundamental frequency of the GODS station was around 1Hz through

Figure 13. Spatial distribution of δS2S$_s$ for simulated PGA for all 43 strong motion stations.

horizontal to vertical spectral ratios. Although the fundamental period is long for a rock site, Kaiser et al. (2014) investigated the site and attributed this feature to topographic effects from being located on the crest of a basaltic lava flow ridge. As the simulations and empirical models have not considered such complex topographic effects, the bias is may be attributed to this effect.

The HVSC predictions show large positive δS2S$_s$ at short periods (T $<$ 0.6s) and some negative values at long periods. The results found here are consistent with the findings of Razafindrakoto et al. (2016) (for simulations) and Bradley (2015) (for empirical model) in their comparisons against 10 moderate-to-large M_w events in the 2010–2011 Canterbury earthquake sequence. The observed ground motions were particularly strong at short periods due to the local geology where a thin soil layer overlying the Banks Peninsula volcanics rock results in a strong

shallow impedance contrast, as well as surface waves generated at the inclined soil-rock interface (Bradley and Cubrinovski, 2011). The positive $\delta S2S_s$ at short periods manifests as neither of these features are explicitly modelled in the HF simulation or the empirical prediction. The long period overprediction is attributed to the deamplification caused by topographic effects as investigated by Jeong and Bradley (2017).

Christchurch city sites

Figure 14c and 14d presents the within-event residuals for the simulated ground motion predictions at the CBGS and REHS sites which have modelled V_{s30} of 197 and 154, respectively. The two sites are located in the Christchurch central business district (CBD) where the surficial Christchurch Formation, consisting of marine sediments, is present resulting in low V_{s30} values. Interbedded marine and gravel formations are also expected at both sites.

At the CBGS site, many narrow-band period-dependent variations of $\delta S2S_s$ between periods of T = 0.05–1.0s are present. These variations are caused by the complex observed site-specific wave propagation effects resulting from the interbedded terrestrial gravel and fine-grained marine formations, and small-scale near-surface heterogeneities, which are not modelled in the simulations or empirical model. Both also adopt a V_{s30}-based site amplification model which cannot capture these complexities and does not consider site characteristics below 30m.

REHS has a significant positive peak at roughly T = 0.5–0.6s which is consistent with the site period down to the Riccarton Gravel, located just over 20m below the ground surface, determined from numerous studies (Wood et al., 2011; Wotherspoon et al., 2014, 2015). The underprediction manifests here as the Riccarton Gravel is not explicitly modelled in either prediction method. The amplification at this period is particularly strong as very soft surface deposits (a mix of sands, silts, clayey silts and organic material) overlie the Riccarton Gravel at this site (Wotherspoon et al., 2014).

Canterbury Plains sites

Figure 14e and 14f presents the within-event residuals for the simulated ground motion predictions at the DFHS and DSLC sites located in the Canterbury Plains with modelled V_{s30} of 515m/s and 350m/s, respectively. The DFHS site has small $\delta S2S_s$ for all periods considered. The degree of empirical site amplification at this site is small so there is no significant overamplification at long periods. The DSLC site has negative $\delta S2S_s$ at long periods which is likely caused by overly strong basin waves in the simulation caused by constant velocities in the basin

Figure 14. Computed within-event residuals, δW_{es}, for simulation prediction at sites: (a) GODS; (b) HVSC; (c) CBGS; (d) REHS; (e) DFHS; and (d) DSLC.

layers (Imperatori and Gallovič, 2017). Better characterization of velocities within the basin, such as including depth-dependence, could improve this prediction.

DISCUSSION AND CONCLUSIONS

Through extensive validation using 1896 ground motions from 148 SM earthquake events recorded at 43 sites, the results from this study highlighted several limitations in the simulations and suggest some recommendations can be made to the ground motion simulation methodology utilized for the Canterbury region to improve its predictive capability, as well as other regions in general. In particular: (i) underprediction of significant durations; (ii) overprediction of HF ground motion IMs; (iii) overprediction of LF ground motion IMs; and (iv) significant systematic regional variability.

Firstly, the significant durations of the simulated ground motions were severely underpredicted. The underprediction was seen to reduce with increasing magnitude, over the M_w 3.5–5.0 range considered. Such large biases in $\mathrm{D_{s595}}$ have not been observed in past simulations using the Graves and Pitarka (2010, 2015) method for validation over the M_w 6.0–7.5 range (Razafindrakoto et al., 2018; Afshari and Stewart, 2016a). These trends indicate that the issue lies with the path duration of the HF simulations, because for larger events the ground motion duration is dominated by the source corner frequency and rupture propagation over the subfaults. Figure 15a–c illustrates this by presenting the Husid plots of the observed and simulated CMHS 000 (north-south) ground motions from the 23 December 2011 M_w 4.9 event (examined in the illustrative example simulation in Electronic Supplement G) for LF, HF and BB components, respectively. The simulated and observed LF ground motions have relatively similar shape resulting in similar $\mathrm{D_{s575}}$ and $\mathrm{D_{s595}}$. Conversely, the simulated HF component has a much steeper slope than the observed HF ground motion such that the simulated $\mathrm{D_{s575}}$ and $\mathrm{D_{s595}}$ are significantly shorter than the observed. The last Husid plot illustrates that the evolution of AI in the simulated BB ground motion is dominated by the HF component, as they have similar shapes, which results in simulated $\mathrm{D_{s575}}$ and $\mathrm{D_{s595}}$ that are significantly shorter than the observed. Figure 15d presents the $\mathrm{D_{s575}}$ and $\mathrm{D_{s595}}$ bias for the BB, HF and LF component ground motions across the entire dataset. The BB and HF values are significantly underpredicted while the LF values are only slightly underpredicted. The slight underprediction is likely caused by the constant velocities prescribed to each sedimentary layer in the 3D CantVM, which would not adequately model the scattering of waves. Alternative formulations for the HF path duration from that in Graves and Pitarka (2010, 2015) are easily usable. For example, Boore and Thompson (2014, 2015) highlighted this problem and developed a new path duration model for active crustal regions based on the NGA-West2 database which more appropriately represents

Figure 15. Husid plots for observed and simulated CMHS 000 ground motions from the 23 December M_w 4.9 event: (a) low-frequency; (b) high-frequency; (c) broadband; and (d) $\mathrm{D_{s575}}$ and $\mathrm{D_{s595}}$ model bias for each component.

factors which increase path duration with distance. Implementation of such a model would likely reduce the bias observed in significant durations. The empirical model of Afshari and Stewart (2016a) used in this paper was seen to be consistent with observations, and hence the 'path' component of that empirical model could also be used. Additionally, the consideration of site contributions through an explicit site effect factor (such as that of Afshari and Stewart (2016a)) or a proxy such as a minimum source duration (as source durations practically saturate at the low magnitudes considered) could also reduce the underprediction. These sentiments also apply to other regions, although the extent of underprediction in significant duration may vary.

The overprediction of HF amplitudes (e.g. pSA(T $<$ 1.0s), Figure 4) can also be partly attributed to the HF path duration being too short because the HF simulation is based on the definition of the FAS, and it is well acknowledged that power spectral amplitudes (and consequently pseudo-spectral ordinates) will decrease as duration increases for a constant FAS (Boore, 2003). Other factors that may also affect HF simulation bias include the assumed stress parameter $\Delta\sigma$, near-surface attenuation κ_0 and anelastic attenuation.

The overprediction of LF amplitudes (e.g. pSA(T $>$ 1.0s) can be partly attributed to the $\mathrm{V_{s30}}$-based site amplification model applied at low frequencies. de la Torre et al. (2019) has recently shown, by comparing simulations using the same $\mathrm{V_{s30}}$-based empirical site response factors or using comprehensive 1D site response wave propagation analyses, that the $\mathrm{V_{s30}}$-based amplification suggested in Graves and Pitarka (2010, 2015) tends to over-amplify the

long period ground motions (at least for application in the Canterbury region in conjunction with the high resolution velocity model of Lee et al. (2017a)). The overamplification demonstrated by de la Torre et al. (2019) was most significant over the T = 2.0–5.0s range, which is also the range of largest overprediction in the simulations in this study. Reduction of the amplification at long periods, since the Canterbury Basin is explicitly modelled at relatively high resolution in the 3D CantVM, would reduce this bias. This 'double counting' of site amplification is a potential problem for all regions of application and depends on how well the adopted velocity model represents the crustal structure up to the maximum resolvable frequency of the LF component. Specifically, just because the simulation is set up to achieve a certain frequency numerically doesn't mean that the velocity model is realistic to these frequencies - this is region specific, and hence underscores the importance of region-specific validation such as that performed in this study. Additionally, the adopted 3D velocity model, has constant velocities within discrete sedimentary layers (Lee et al., 2017a) and, as a result, larger impedance contrasts may also contribute to overamplification. Using the $\mathrm{V_s}$ value from the top surface of the finite difference grid for the LF simulation reference $\mathrm{V_{s30}}$ in the site amplification factor can also contribute to the overprediction as this V_s value occurs at 50m depth (for a 100m-spaced grid) and would be larger than a representative LF simulation $\mathrm{V_{s30}}$.

The significant systematic regional variability in $\delta\mathrm{S2S_s}$ can mostly be attributed to the assumptions and simplifications in the crustal velocity modelling. The generic 1D velocity model, anelastic attenuation and constant κ_0 utilized in the HF simulations are all simplifications which are regionally calibrated but don't necessarily model specific sites well. The 3D velocity model used in the LF simulations, although comprehensive and high resolution, prescribes only constant velocities within most layers in the Canterbury basin. The empirical site amplification is based on $\mathrm{V_{s30}}$, which itself is only a proxy parameter for site conditions. Better velocity characterization through more realistic models and more rigorous approaches should reduce this variability. The most readily implementable changes would be the use of site-specific 1D velocity profiles and κ_0 in HF simulations. The variability in $\delta\mathrm{S2S_s}$ is expected to be similarly present in other regions, and, as examined by (de la Torre et al., 2019), 'geotechnical' approaches that include significantly more information on the shallow soil profile are likely necessary to significantly improve simulation prediction at HF.

The above four factors are likely to result in appreciable improvements to the simulations, all of which can be justified physically. Although the improvements were identified by investigating SM earthquakes, they will also lead to more robust predictions for large magnitude

earthquakes due to the physics-based nature of the simulations. Following this, additional, less obvious, modifications may further improve the simulation predictions. With the large number of events and stations considered, the standard deviations of the components of ground motion variability were also examined to demonstrate simulation precision. The simulation and empirical prediction standard deviations were found to be similar showing that a single simulation currently gives an 'average' estimate that is similar to the 'average' median empirical model. This implies that the standard deviations are dominated by the underlying variability in the observations. As the improvements aim to represent the underlying physics better, they are also expected to improve simulation precision. Initial results with the modifications to the HF path duration model and reduction of long period site amplification show promise and will be more extensively detailed in future publications.

DATA AND RESOURCES

Earthquake source descriptions used in this study were obtained from the GeoNet New Zealand earthquake catalogue (`https://github.com/GeoNet/data/tree/master/moment-tensor`, recorded ground motions were obtained from the GeoNet file transfer protocol (`ftp://ftp.geonet.org.nz/strong/`), the 3D Canterbury Velocity Model was created using the NZVM code (`https://github.com/ucgmsim/Velocity-Model`) and V_{s30} values were provided by Dr Liam Wotherspoon.

The ground motion simulations were computed on NeSI high performance computing resources using the workflow developed by the QuakeCoRE ground motion simulation team (`https://github.com/ucgmsim/slurm_gm_workflow`). Linear mixed effects regression was carried out using the lme4 package on RStudio.

Figures were prepared using Generic Mapping Tools (`http://gmt.soest.hawaii.edu/`), Python (`https://www.python.org/`) and Matplotlib (`https://matplotlib.org/`).

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Appendices

ELECTRONIC SUPPLEMENT A: EVENT INFORMATION

Tables A.1 provides details and metadata of the 148 earthquake events including public event ID, date, geographic location, source characteristics and number of sites which recorded the event.

Table A.1. Earthquake event date, location and source characteristics.

Event ID	**Date**	**Time (UTC)**	**Longitude (°)**	**Latitude (°)**	M_w	**CD (km)**	**Strike (°)**	**Dip (°)**	**Rake (°)**	$\mathrm{NS_e}$
2122842	29/09/2003	18/22/32	172.9231	-43.2859	4.5	20	49	85	12	8
2128373	14/10/2003	01/44/01	172.8909	-43.2889	3.9	18	283	60	80	5
2290108	05/09/2004	09/12/50	172.7555	-43.2538	4.4	27	227	78	-115	7
3366213	03/09/2010	19/07/01	172.2259	-43.6177	4.6	16	64	85	161	11
3366241	03/09/2010	20/15/05	172.3911	-43.5859	4.4	4	152	74	-26	7
3366376	04/09/2010	01/52/21	172.3335	-43.5973	4.1	4	102	87	154	6
3366452	04/09/2010	04/55/56	171.9697	-43.5716	4.8	8	207	84	-22	12
3366499	04/09/2010	06/54/11	172.3747	-43.6024	4	10	176	69	27	6
3366503	04/09/2010	07/03/14	172.3684	-43.6021	4.3	6	351	89	21	6
3366504	04/09/2010	07/07/07	172.3716	-43.5923	4.4	6	160	90	-12	7
3366544	04/09/2010	08/54/27	171.8559	-43.5653	4.3	6	27	66	36	7
3366585	04/09/2010	10/34/52	172.3811	-43.6228	4	6	69	87	-173	6
3366586	04/09/2010	10/38/01	171.9773	-43.252	4.6	8	154	83	16	7
3366751	04/09/2010	17/20/31	172.1725	-43.5949	4.7	6	232	88	154	6
3366858	04/09/2010	21/46/09	172.4109	-43.5709	4	8	352	88	-9	5
3366933	05/09/2010	01/04/56	172.382	-43.6309	4.5	4	299	70	-91	9
3367476	06/09/2010	00/35/04	172.2918	-43.5777	4.1	16	339	86	7	8
3367535	06/09/2010	03/07/42	172.3763	-43.592	4.1	10	255	84	170	6
3367608	06/09/2010	06/01/52	172.3264	-43.6179	4.2	8	244	83	166	8
3367742	06/09/2010	11/24/01	172.3878	-43.5699	4.8	6	350	85	23	15
3367749	06/09/2010	11/40/50	171.8914	-43.5885	5	6	232	51	84	14
3367832	06/09/2010	15/24/44	172.2399	-43.654	4.8	12	245	73	160	18
3368287	07/09/2010	12/41/09	172.4162	-43.5901	4.3	6	265	84	-172	8
3368361	07/09/2010	15/59/14	172.1597	-43.5115	4.3	8	24	64	127	8
3368445	07/09/2010	19/49/57	172.69	-43.574	4.7	4	161	67	27	18
3368471	07/09/2010	21/01/37	172.3975	-43.5573	4	4	257	87	156	5
3369682	09/09/2010	19/10/20	172.3802	-43.6057	4.2	8	324	88	8	10

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Event ID	**Date**	**Time (UTC)**	**Longitude (°)**	**Latitude (°)**	M_w	**CD (km)**	**Strike (°)**	**Dip (°)**	**Rake (°)**	$\mathrm{NS_e}$
3370677	11/09/2010	18/03/22	172.3923	-43.642	4.2	6	321	54	-63	8
3370916	12/09/2010	05/27/02	172.3878	-43.5907	4.2	4	165	78	-13	8
3372087	14/09/2010	12/36/06	172.3762	-43.627	4	4	346	73	18	8
3372561	15/09/2010	10/42/41	172.5067	-43.605	4	10	179	68	33	8
3372661	15/09/2010	15/13/51	172.4958	-43.6288	4	4	162	87	28	6
3373091	16/09/2010	10/58/14	172.4624	-43.6396	4.2	4	261	83	-157	8
3373723	17/09/2010	13/37/38	172.1606	-43.4593	4.1	6	147	78	13	6
3373925	17/09/2010	22/03/47	172.4465	-43.6151	4.2	10	180	83	16	8
3374803	19/09/2010	12/30/03	172.3743	-43.5735	4.2	8	182	88	6	8
3376639	22/09/2010	18/22/26	172.4623	-43.5602	4.1	6	57	81	154	8
3377148	23/09/2010	15/40/17	172.3722	-43.6082	4.2	8	69	86	168	8
3377880	24/09/2010	21/22/22	172.4274	-43.6145	4	10	261	78	151	6
3380440	29/09/2010	20/39/19	172.3806	-43.6278	4.1	6	173	72	21	7
3382676	04/10/2010	09/21/50	172.4031	-43.5627	4.8	4	149	76	-25	17
3384315	07/10/2010	17/17/09	172.3297	-43.7377	4	6	153	85	13	8
3388384	13/10/2010	03/42/30	172.4131	-43.5899	4.3	6	67	84	169	11
3389582	15/10/2010	09/31/40	172.4859	-43.639	4.3	6	352	75	-21	12
3390805	17/10/2010	20/28/22	172.4058	-43.6166	4.1	8	188	70	26	9
3391440	18/10/2010	22/32/15	172.5636	-43.6256	4.8	4	246	84	159	19
3392462	19/10/2010	20/17/55	172.4087	-43.5933	4.1	8	80	90	167	8
3394581	24/10/2010	02/13/29	172.7694	-43.4601	4.4	4	353	69	36	13
3400620	01/11/2010	06/19/55	172.3797	-43.6248	4.2	4	273	81	-154	8
3403219	06/11/2010	13/52/03	172.06	-43.2118	4.6	6	72	87	157	12
3406713	13/11/2010	12/34/06	172.3953	-43.6002	4.4	6	155	77	-18	11
3407078	14/11/2010	06/21/05	172.4131	-43.5989	4.4	6	157	87	-17	11
3437366	26/12/2010	11/10/49	172.616	-43.5316	4	4	72	87	166	9
3439993	01/01/2011	01/05/44	172.4183	-43.5522	4	4	153	87	5	8
3450113	19/01/2011	17/03/20	172.5497	-43.6153	4.8	8	177	80	15	16

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Event ID	**Date**	**Time (UTC)**	**Longitude (°)**	**Latitude (°)**	M_w	**CD (km)**	**Strike (°)**	**Dip (°)**	**Rake (°)**	$\mathrm{NS_e}$
3450491	20/01/2011	13/12/22	172.5186	-43.6066	4	8	178	74	21	8
3460014	04/02/2011	04/56/28	172.3579	-43.6323	4.3	4	329	79	-29	10
3468672	22/02/2011	03/04/09	172.647	-43.5652	4.5	4	342	89	-5	10
3468746	22/02/2011	05/59/36	172.765	-43.6386	4.3	6	149	79	-14	6
3468765	22/02/2011	06/43/32	172.7248	-43.6207	4.4	4	166	86	17	9
3468931	22/02/2011	14/30/15	172.6766	-43.6055	4.2	4	64	88	-173	8
3468980	22/02/2011	17/00/20	172.7227	-43.6036	4.3	4	246	83	-163	7
3469360	23/02/2011	11/12/56	172.7511	-43.5648	3.8	6	71	77	157	5
3470222	25/02/2011	04/40/11	172.6606	-43.5791	4.2	4	47	88	169	7
3471449	27/02/2011	21/35/43	172.8483	-43.5985	4	6	174	56	47	7
3471884	28/02/2011	20/10/13	172.8466	-43.6151	4.1	6	75	82	162	8
3474093	05/03/2011	06/34/02	172.7337	-43.5686	4.6	6	82	71	155	16
3476510	10/03/2011	07/07/11	172.7394	-43.5518	4.3	6	92	74	161	7
3478149	13/03/2011	16/14/14	172.8986	-43.5449	4.2	14	117	89	17	6
3495817	22/02/2011	01/15/54	172.6312	-43.5941	4.3	4	239	75	-163	6
3497857	16/04/2011	05/49/22	172.7886	-43.6134	5	4	83	89	165	32
3509905	09/05/2011	15/04/23	172.4068	-43.5994	4.9	6	149	79	-14	30
3525417	06/06/2011	05/04/19	172.4039	-43.5846	4.1	4	81	83	157	13
3528800	13/06/2011	00/29/44	172.1559	-43.3668	4	4	7	89	16	6
3529125	13/06/2011	14/48/08	172.7382	-43.5959	4.2	6	88	86	145	19
3529702	14/06/2011	18/27/24	172.8382	-43.6461	4.8	4	241	76	-154	20
3529858	15/06/2011	01/03/42	172.8547	-43.6546	4.6	3	330	87	26	19
3529888	15/06/2011	02/27/08	172.8695	-43.6594	4	5	74	88	154	10
3530742	16/06/2011	18/37/27	172.7932	-43.5897	4.1	8	69	86	164	14
3530917	17/06/2011	02/39/11	172.7566	-43.5306	4.3	4	273	80	-157	18
3530953	17/06/2011	04/21/57	172.7694	-43.6019	4.2	6	247	83	-160	15
3531220	17/06/2011	18/50/50	172.7998	-43.5727	4.1	4	276	90	-156	15
3533219	21/06/2011	15/28/08	172.5286	-43.5948	4.1	6	336	89	-2	14

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Event ID	**Date**	**Time (UTC)**	**Longitude (°)**	**Latitude (°)**	M_w	**CD (km)**	**Strike (°)**	**Dip (°)**	**Rake (°)**	$\mathrm{NS_e}$
3550173	21/07/2011	17/39/32	172.1954	-43.6445	4.7	6	47	83	-158	22
3556574	03/08/2011	15/08/36	172.8842	-43.5999	4	6	244	87	-144	14
3566526	22/08/2011	08/36/34	172.0749	-43.5742	4	8	88	89	166	11
3571192	31/08/2011	01/30/51	172.4415	-43.6022	4.3	6	267	74	-157	20
3572067	01/09/2011	15/29/51	172.8137	-43.5711	4.6	6	161	84	-8	23
3577039	10/09/2011	23/19/09	172.7635	-43.6039	4.3	8	62	60	132	17
3590805	21/06/2011	10/38/05	172.5309	-43.5971	4.3	4	172	84	-17	7
3591999	09/10/2011	07/34/41	172.7899	-43.5799	4.9	6	250	86	-160	30
3631369	23/12/2011	01/30/27	172.8002	-43.5258	4.4	4	248	79	-141	22
3631409	23/12/2011	03/14/35	172.8345	-43.4734	4.2	6	215	65	87	19
3631432	23/12/2011	03/50/14	172.7734	-43.4955	4.7	4	210	56	77	24
3631755	23/12/2011	17/37/31	172.8397	-43.6638	4.9	4	254	80	163	33
3634529	29/12/2011	09/48/51	172.8066	-43.5341	4	6	245	86	-159	19
3634645	29/12/2011	15/45/17	172.8	-43.4604	4.1	4	213	50	82	14
3635309	31/12/2011	00/44/47	172.7754	-43.5173	4.5	4	357	67	28	25
3791909	03/09/2010	22/17/26	172.4025	-43.6138	4.1	4	357	90	11	6
3792018	03/09/2010	23/12/45	172.1597	-43.5549	4.9	6	248	86	-175	11
2012p001403	01/01/2012	12/27/57	172.8325	-43.4625	4.8	4	222	53	101	25
2012p001410	01/01/2012	12/31/26	172.8235	-43.4451	4	4	214	61	89	6
2012p002254	01/01/2012	20/01/12	172.7935	-43.4407	3.8	4	242	60	124	5
2012p003376	02/01/2012	05/59/14	172.8201	-43.4473	4.6	4	24	55	64	26
2012p010301	04/01/2012	19/28/54	172.8426	-43.4962	4.4	6	212	54	73	24
2012p014309	06/01/2012	07/04/16	172.7442	-43.5582	4.2	6	209	51	87	16
2012p014905	06/01/2012	12/21/37	172.7727	-43.5363	4.8	4	76	67	129	32
2012p023269	09/01/2012	14/38/15	172.8088	-43.4983	3.8	6	41	63	134	14
2012p030624	12/01/2012	07/56/56	172.7932	-43.4288	4.3	4	61	57	111	17
2012p043955	17/01/2012	06/19/45	172.7936	-43.6387	3.7	6	166	84	15	14
2012p052719	20/01/2012	12/08/54	172.4151	-43.5736	3.9	8	87	78	165	14

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Event ID	**Date**	**Time (UTC)**	**Longitude (°)**	**Latitude (°)**	M_w	**CD (km)**	**Strike (°)**	**Dip (°)**	**Rake (°)**	$\mathrm{NS_e}$
2012p053801	20/01/2012	21/45/22	172.4124	-43.5969	3.7	8	88	89	-170	13
2012p058758	22/01/2012	17/46/18	172.7809	-43.5213	4.2	4	60	59	114	19
2012p071137	27/01/2012	07/42/01	172.2553	-43.5597	4.2	6	247	79	-163	19
2012p073274	28/01/2012	02/40/33	172.8277	-43.4539	3.9	6	56	59	133	11
2012p104038	08/02/2012	11/51/36	172.7662	-43.6317	3.8	4	252	81	-159	12
2012p123336	15/02/2012	15/13/54	172.782	-43.5196	3.8	4	11	55	90	17
2012p142382	22/02/2012	16/21/27	172.7702	-43.483	3.8	8	40	47	83	6
2012p149826	25/02/2012	10/27/20	172.8326	-43.4624	4.1	6	49	47	103	17
2012p161604	29/02/2012	19/02/37	172.3726	-43.5754	3.7	6	77	85	171	13
2012p206748	17/03/2012	11/55/25	172.7099	-43.6029	3.9	8	185	74	28	18
2012p260761	06/04/2012	11/33/37	172.3705	-43.5824	3.8	8	179	87	-18	16
2012p275677	12/04/2012	00/00/51	172.757	-43.5129	4.2	8	74	87	175	21
2012p303845	22/04/2012	10/08/53	172.7836	-43.5243	3.8	4	231	62	116	14
2012p365028	15/05/2012	01/27/17	172.75	-43.4893	4.2	4	41	63	100	19
2012p378107	19/05/2012	21/35/34	172.4087	-43.6085	3.9	20	81	82	157	9
2012p378954	20/05/2012	05/06/57	172.7679	-43.5678	4.4	4	56	61	134	23
2012p392201	25/05/2012	02/44/50	172.7723	-43.534	5	6	222	48	83	26
2012p399212	27/05/2012	17/00/29	172.7865	-43.5033	4.3	6	46	52	107	13
2012p413162	01/06/2012	20/52/50	172.7619	-43.5794	4.1	4	260	86	-152	17
2012p416981	03/06/2012	06/47/29	172.72	-43.5331	3.9	4	23	66	104	12
2012p505798	06/07/2012	03/29/30	172.3383	-43.6015	4.7	8	226	89	-168	28
2012p517515	10/07/2012	11/32/17	172.5411	-43.6382	3.9	4	4	87	-9	18
2012p713691	21/09/2012	01/35/03	172.8071	-43.4807	4.2	6	67	58	118	16
2012p764736	09/10/2012	22/51/19	172.7837	-43.4692	3.9	6	11	46	101	12
2012p801609	23/10/2012	14/17/46	172.8612	-43.4806	4	6	55	50	119	12
2013p049577	19/01/2013	08/15/08	172.4568	-43.6038	4.3	4	168	89	-15	14
2013p368016	17/05/2013	03/59/07	172.3592	-43.6393	3.9	4	341	76	-22	6
2013p653606	30/08/2013	20/01/53	172.1765	-43.6023	4.1	9	243	83	152	7

Continued on next page

Table A.1 continued from previous page

Event ID	**Date**	**Time (UTC)**	**Longitude** (°)	**Latitude** (°)	M_w	**CD (km)**	**Strike** (°)	**Dip** (°)	**Rake** (°)	$\mathrm{NS_e}$
2013p708602	20/09/2013	04/23/27	172.4443	-43.5749	3.9	7	180	78	15	11
2013p817946	30/10/2013	15/21/54	172.3975	-43.565	3.9	8	73	81	-161	9
2013p868761	18/11/2013	10/36/21	172.5252	-43.5897	4.3	7	67	85	156	10
2014p237547	29/03/2014	21/25/25	172.7088	-43.5733	3.8	6	188	68	30	9
2014p933966	12/12/2014	13/37/04	172.367	-43.6447	4.2	4	284	70	-129	13
2014p965622	24/12/2014	06/43/44	172.7204	-43.5575	4	9	66	71	155	12
2016p119534	14/02/2016	05/27/50	172.7607	-43.5257	4	4	87	85	-166	16
2016p158394	28/02/2016	14/32/40	172.6198	-43.568	4.1	4	156	80	12	12
2016p355041	11/05/2016	08/45/53	172.702	-43.5891	4.2	7	69	86	154	19

Figure B.1. Number of ground motion records for each earthquake: (a) histogram; and (b) as a function of source magnitude, illustrating the increase in $\mathrm{NS_e}$ with magnitude.

ELECTRONIC SUPPLEMENT B: GROUND MOTION RECORDS PER EVENT

Figure B.1a shows the distribution of the number of sites ($\mathrm{NS_e}$) which have recorded high-quality ground motions for each earthquake e. Figure B.1b illustrates the dependence of $\mathrm{NS_e}$ on the event M_w, evidently showing a positive correlation between the two, as expected. As M_w has been determined in intervals of 0.1 (Ristau, 2008), leading to overlapping data points, a darker shade implies more points at that coordinate.

ELECTRONIC SUPPLEMENT C: STATION INFORMATION

Figure C.1 shows the locations of strong motion stations in Canterbury and Table C.1 provides details of the 43 strong motion stations with sufficient high-quality recordings considered including the strong motion station code, geographic location, modelled $\mathrm{V_{s30}}$ and number of earthquakes observed NS_e.

Figure C.1. 53 strong motion stations considered within the ground motion simulation domain: (a) in the wider Canterbury region; and (b) in the Christchurch city region. 43 strong motion stations have sufficient high-quality recordings, shown by filled makers, while 10 strong motion stations have insufficient high-quality recordings and are shown as unfilled markers. Stations which are discussed in the within-event residual analysis are coloured in red.

Table C.1. Geographic location, V_{s30} and NE_s of strong motion stations considered.

Site	**Longitude (°)**	**Latitude (°)**	V_{s30} **(m/s)**	NE_s
ADCS	171.7476	-43.9024	300	16
ASHS	172.5959	-43.2744	300	79
CACS	172.53	-43.4832	435	120
CBGS	172.6199	-43.5293	197	115
CCCC	172.6474	-43.5381	177	11
CHHC	172.6275	-43.5359	206	19
CMHS	172.6242	-43.5656	205	133
CRLZ	172.6232	-43.5747	900	74
CSHS	171.7236	-43.2265	800	21
CSTC	172.3813	-43.3123	350	36
D09C	172.6325	-43.5339	200	22
D14C	172.6244	-43.6342	733	59
D15C	172.7256	-43.5864	600	44
DFHS	172.1022	-43.4897	515	73
DSLC	172.1979	-43.6675	350	67
EYRS	172.3554	-43.4214	400	43
GODS	172.7703	-43.58	586	58
HALS	172.5694	-43.5925	250	31
HHSS	172.5928	-43.5592	250	38
HPSC	172.7022	-43.5016	207	17
HVSC	172.7094	-43.5798	352	7
KOWC	171.8549	-43.3215	350	10
KPOC	172.6638	-43.3765	257	23
LINC	172.468	-43.6232	293	15
LPCC	172.7248	-43.6078	792	6
MTHS	171.6661	-43.565	600	37
NBLC	172.7311	-43.5086	190	9
NNBS	172.718	-43.4954	212	120
PARS	172.7507	-43.5679	500	65
PPHS	172.6069	-43.4928	187	135
PRPC	172.6828	-43.5258	196	22
REHS	172.6351	-43.5219	154	123
RHSC	172.5644	-43.5362	286	18
SHFC	172.0258	-43.3912	350	16
SHLC	172.6634	-43.5053	210	17
SLRC	172.3175	-43.6751	323	12
SMTC	172.6139	-43.4675	226	6
SPFS	171.9289	-43.338	450	30
SPRS	171.9286	-43.3414	400	27
STKS	172.6447	-43.6083	600	44
SWNC	172.4954	-43.3694	545	44
TPLC	172.472	-43.55	391	24
WCSS	171.8633	-43.4594	450	10

ELECTRONIC SUPPLEMENT D: PROCESSING OF OBSERVED GROUND MOTIONS

Volume 1 (unprocessed) ground motion records were obtained from the GeoNet file transfer protocol (see Data and resources). All ground motions were baseline corrected, detrended and processed with a 4th order butterworth filter with a low-pass frequency of 50Hz and a high-pass frequency of 0.08Hz (Boore and Bommer, 2005) to retain the Fourier amplitudes at 0.1Hz (Ancheta et al., 2014). As ground motions from SM events have relatively small amplitudes, they can be dominated by noise such that the ground motion signal cannot be adequately resolved from the recording. In the suite of ground motions corresponding to the earthquake sources considered, a large percentage of records were considered low-quality as a result of low signal-to-noise ratio (SNR) or other factors (e.g. premature ending of records). In order to produce a database of high-quality ground motion recordings, the records were passed through a screening process to evaluate their usability. Figure D.1 illustrates the percentage of records with SNR which exceed a minimum ratio for each frequency. For all records, their respective frequency-dependent SNR were determined by dividing the Fourier amplitude spectra (FAS) of the signal (windowed with a Hanning Taper in the time domain) by the FAS of the pre-event trace for each discrete frequency, and then taking the geometric mean of the horizontal components. That is, the Fourier amplitude of the signal at frequency f_i is divided by the Fourier amplitude of the pre-event trace at frequency f_i, resulting in a spectrum of SNR. The pre-event trace was determined using the 'ar_pick' software from the ObsPy python toolbox (Beyreuther et al., May/June 2010), which calculates the P-wave arrival time based on short-term average to long-term average ratios (STA/LTA). The FAS were smoothed using the Konno-Ohmachi windowing function (Konno and Ohmachi, 1998) with b = 20, as stronger smoothing was required for the small amplitude ground motions (as opposed to the conventionally used b = 40). Based on the percentage of usable records shown, a minimum SNR of 2.0 was chosen which retains roughly 40% of records above 0.1Hz. Additional semi-automated screening criteria required: (1) the average absolute acceleration of the tail end of the record (defined as the greater of the last 5 seconds or 10% of the record duration) to be less than 5% of the record's peak ground acceleration—to remove ground motions which ended prematurely, (2) the P-wave arrival must not occur before 0.5 seconds to remove records with poor P-wave picks and records without a sufficiently long pre-event trace, and (3) the P-wave arrival must occur before 5% of the cumulative Arias intensity is reached. The values used in these criteria were determined from preliminary analysis of the ground motion dataset. The ground motion records were subse-

Figure D.1. Percentage of usable ground motions at each frequency for a given minimum signal-to-noise ratio. A minimum signal-to-noise ratio of 2.0 was selected for use in subsequent simulation validation.

quently manually screened to ensure the integrity of the resultant high-quality dataset. The final ground motion dataset considered consists of 1896 ground motion recordings, corresponding to the 148 earthquakes, from an initial set of 3988, i.e. 52.5% of records were rejected.

ELECTRONIC SUPPLEMENT E: GROUND MOTION SIMULATION METHODOLOGY SUMMARY

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 with fourth-order spatial and second-order temporal accuracies. For the SM earthquake events considered, the earthquake source is modelled as a double-couple point source with location, magnitude and focal mechanism obtained from centroid moment tensor solutions. A constant rise time of 0.5s is used. Anelastic attenuation is incorporated with quality factors given by the relations $Q_s = 50V_s$ and $Q_p = 2Q_s$, where V_s is in units of km/s. Lee and Bradley (2016) compared the relations with regional travel-time tomography and Q_p models in the Canterbury region developed by Eberhart-Phillips et al. (2010, 2015) and found the relations match the data well down to 12km below mean sea level.

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 (Boore, 2003). Attenuation is incorporated using a travel-time weighted average of the Q values for each of the 1D velocity model layers and a HF attenuation factor of $\kappa_0 = 0.045$ to account for the attenuation due to site effects. A constant Brune stress parameter of $\Delta\sigma$ = 5MPa was also used. These are typical values for active shallow crustal regions (Graves and Pitarka, 2010) and the suitability of the values were also independently demonstrated by source-specific studies of the Canterbury earthquake sequence (Oth and Kaiser, 2014), and other ground motion simulations of the Canterbury earthquakes (Razafindrakoto et al., 2018). A spatially averaged radiation pattern coefficient of 0.55 is used.

As the modelled near-surface velocity structure is a simplified and coarse representation of the real site conditions due to the velocity model discretization, enforced minimum velocities, and lack of sufficient knowledge regarding the detailed near-surface structure, empirical site-specific amplification factors are applied. Graves and Pitarka (2010) utilizes the period-dependent $\mathrm{V_{s30}}$-based site-specific amplification factor of Campbell and Bozorgnia (2008). However, Razafindrakoto et al. (2018) demonstrates several empirical models all give similar results, hence this study adopts the site-specific amplification factor of the more recent Campbell and Bozorgnia (2014) empirical model. The amplification is directly applied up to a period of T = 1.0s to account for the aforementioned small-scale limitations and potential nonlinear site response (if the shaking intensity is large enough), but modified for T $>$ 1.0s as some longer period site effects are already explicitly accounted for in the LF simulations via the 3D crustal model velocity variations. Specifically, the amplification linearly tapers to unity in logarithmic space between T = 2.0–5.0s. Figure E.1 presents an example of an amplification factor function. The amplification factors are applied to both LF and HF components before they are merged to form the BB ground motions. Explicit site response is outside the scope of this study but is an ongoing research effort (de la Torre et al., 2019), however, insights are drawn from such analyses when interpreting prediction residuals.

Figure E.1. An example of the Campbell and Bozorgnia (2014) site amplification factor for a simulation reference velocity $\mathrm{V_{s,ref}}$ = 500m/s, $\mathrm{V_{s30}}$ = 250m/s, and PGA = 0.025g.

ELECTRONIC SUPPLEMENT F: JUSTIFICATION OF EMPIRICAL MODELS CONSIDERED

The aim of using empirical prediction models is to provide insight into the relative predictive capability (both accuracy and precision) of the simulations, and hence no attempt is made to utilise an exhaustive ensemble of empirical models. Despite this, the basic rationale for the considered models are as follows. The Bradley (2013) PGA/pSA/PGV model was developed from a robust database of New Zealand recordings through modifications of the Chiou et al. (2010) model, in particular, with attention to the explicit consideration of SM earthquakes. The Campbell and Bozorgnia (2012) AI model was developed using the NGA-West dataset and utilizes a functional form identical to many other accepted empirical ground motion models (e.g. Campbell and Bozorgnia (2010)). Although the model is only valid for shallow crustal earthquakes in active tectonic regions between M_w 5.0 and 7.5–8.5 (depending on the fault mechanism), it is still used as there is currently no AI model that has been extensively validated for the magnitude range considered in this study. The Afshari and Stewart (2016a) model was considered the most appropriate model for significant duration prediction, being developed from the NGA-West2 dataset for active crustal regions with explicit consideration for earthquakes with M_w between 3.0 and 7.9, as opposed to other significant duration models which are not developed for such small magnitude events (e.g. Kempton and Stewart (2006)). Note that while neither Campbell and Bozorgnia (2012) and Afshari and Stewart (2016a) are New Zealand-specific empirical models (although Afshari and Stewart (2016a) does use data from New Zealand), the consistency of the Chiou et al. (2010) model with New Zealand ground

motion observations (Bradley, 2013) implies that there are not any obviously superior alternatives, and the validation examined in the main text will provide an absolute assessment of their validity as well as a relative measure of the simulation validity.

ELECTRONIC SUPPLEMENT G: ILLUSTRATIVE EXAMPLE SIMULATION: 23RD DECEMBER 2011 M_W 4.9

As an example, simulation results from the 23rd December 2011 M_w 4.9 earthquake located at CD = 4km, under Banks Peninsula, are presented to provide insight on the salient attributes of the ground motion simulations. The focal mechanism of the event was associated with a right lateral strike slip fault (strike ϕ = 254°, dip δ = 80°, rake λ = 163°). This event had the most high-quality recordings of the events considered with $\mathrm{NS_e}$ = 34.

Figure G.1 provides a comparison of the observed and simulated velocity time series at 10 stations of interest chosen because of their location, and quantity and quality of recordings across multiple earthquakes. D14C and PARS are rock sites located on the Banks Peninsula volcanics outcrop, the CACS, CBGS, NNBS and REHS sites are located on sedimentary deposits underlain by the sloped Banks Peninsula volcanics edifice in the Christchurch city area, the ASHS, DSLC and SWNC sites are located in the wider Canterbury Plains region where the stratigraphy is predominantly gravels, and the WCSS site is located on rock in the Canterbury Foothills area (Van Houtte et al., 2012; Lee et al., 2017a). Figure G.1 illustrates that arrival times are relatively consistent between simulated and observed ground motions while there is more variability in amplitudes. As expected, the sites located in the Canterbury Foothills and Canterbury Plains have the smallest PGV (shown to the right of each ground motion) due to their large $\mathrm{R_{rup}}$, while the sites located in the Christchurch city and atop the Banks Peninsula volcanics have comparable peak values. The rock site records are dominated by HF motion while the Christchurch city and Canterbury Plains sites also have noticeable LF amplitudes. The Canterbury Plains sites also have significant late-arriving basin-guided waveforms. The duration of simulated ground motions appear to match the observed ground motions relatively well for many of the records shown, although in general this is not the case (as elaborated upon in the main text).

Figure G.2 illustrates several ground-motion IMs as a function of $\mathrm{R_{rup}}$ for the 34 observed and simulated motions. The median and ± 1 standard deviation of the relevant empirical prediction model is shown in these figures as the solid and dashed lines, respectively. Note that to

Figure G.1. Comparison of observed (black) and simulated (red) broadband velocity time series at ten strong-motion stations of interest for the 23rd December 2011 M_w 4.9 event. Maximum observed PGV values are provided to the right of each waveform in cm/s. The three columns represent the 000 (north-south), 090 (east-west), and vertical components.

show the empirical model as a single line with $\mathrm{R_{rup}}$ on Figure G.2 a reference $\mathrm{V_{s30}}$ of 250m/s is used, corresponding to an NZS1170.5 (New Zealand Standards, 2004) site class of D which the majority of strong motion stations in Canterbury are classified as (while site-specific prediction bias comparisons use the value of each individual station). Both simulation and empirical models provide a generally good comparison with observed PGA amplitudes. In contrast, the simulation overpredicts pSA(3.0s) at $\mathrm{R_{rup}}$ between 20 and 50km, while the empirical model underpredicts in this range. The simulated PGV values are also slightly overpredicted at this distance range. The simulated AI values compare relatively well against observations up to

Figure G.2. Observed, simulated and empirically predicted geometric mean ground-motion intensity measures as a function of source-to-site distance, $\mathrm{R_{rup}}$, for the 23rd December 2011 M_w 4.9 event: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) $\mathrm{D_{s575}}$; and (f) $\mathrm{D_{s595}}$.

60km, beyond which they are underpredicted, while the empirical model overpredicts AI. For the significant durations, the empirical models provide values which are largely consistent with the observations while the simulated values are often considerably lower than their observed counterparts. The $\mathrm{D_{s595}}$ values that are relatively similar to observed values at moderate $\mathrm{R_{rup}}$ correspond to the same ground motions that have overpredicted pSA(3.0s). These ground motions are the Canterbury Plains sites which have significant LF acceleration amplitudes, such as those with significant basin-induced waves.

Figure G.3 provides a summary of the bias and variability (as the mean and standard devi-

Figure G.3. Total residuals between observed and predicted (simulated or empirical) IMs for all stations with ground motion recordings from the 23rd December 2011 M_w 4.9 event. Solid lines and points indicate the mean residual and the shaded regions and horizontal lines indicate plus or minus one standard deviation.

ation, respectively) of the total residuals for this event for the IMs considered. Both empirical and simulated predictions have no practical bias at vibration periods T $<$ 0.3s. However, the empirical prediction then steadily increases to over 1 natural log unit at a period of T = 10s implying that the model is increasingly underpredicting with longer periods. On the other hand, the simulated results show relatively small residuals with the largest mean residual, -0.5 natural log units (corresponding to simulated values which are roughly 0.6 of the observed values), occurring at roughly T = 2.0 seconds but having practically no bias at periods T $>$ 4.0s. Overall, the empirical model appears to predict well at short periods, up to roughly T = 0.6s while the simulation predicts well across the periods investigated, albeit slightly poorer at around T = 2.0s. Simulated significant durations are underpredicted while the empirical AI is overpredicted.

ELECTRONIC SUPPLEMENT H: CORRELATION OF SIMULATION AND EMPIRICAL δB_E AND $\delta S2S_S$

The correlation between residuals of simulated and empirically predicted IMs are calculated to further highlight the differences and similarities in the two prediction methods. Figure H.1 summarizes correlation coefficients between simulated and empirical $\delta \mathrm{B_e}$ across all events for the IMs considered. The correlation coefficients are larger for short period IMs (e.g. pSA(T $<$ 1.0s) and PGA) as they are primarily influenced by the HF simulation component which uses a simplified physics-based methodology similar to that used in empirical models (with the exception that the HF simulation is via FAS, while the empirical model predicts response spectra directly).

Figure H.1. Correlation coefficients between simulated and empirical $\delta\mathrm{B_e}$.

The smaller correlation coefficients for long period IMs (e.g pSA(T $>$ 1.0s)) are likely the result of the comprehensive physics-based nature of the LF component of the simulation, which differs appreciably from the nature of the empirical models.

Figure H.2 summarizes correlation coefficients between simulated and empirical $\delta\mathrm{S2S_s}$ across all of the sites for the considered IMs. The correlation coefficients are large for short period pSA and PGA, as they are short period ground motion IMs influenced most by the simplified physics-based HF simulations which are similar to empirical ground motion models (as with the correlation coefficients for $\delta\mathrm{B_e}$). Both simulation and empirical prediction also use a similar $\mathrm{V_{s30}}$-based site amplification. For HF simulations, small-scale site effects are not explicitly accounted for so the use of this amplification is appropriate and consistent with the empirical GMMs. It is important to note that both the HF simulations and empirical GMM (in their current implementation) do not explicitly model strong impedance contrasts near surface which further contributes towards large correlation coefficients. As vibration period increases, Figure H.2 illustrates that long period pSA has weaker correlation as a result of the 3D wave propagation effects in the LF simulation, which depart from the considerations in empirical modelling.

The weaker correlation for $\mathrm{D_{s595}}$ arises due to there being two ground motion features which generally govern the $\mathrm{D_{s595}}$ in simulations. $\mathrm{D_{s595}}$ for simulations are either determined by the (duration of the) HF acceleration amplitudes alone or by the LF acceleration amplitudes which occur after HF accelerations amplitudes have ceased. The former is more common across the sites considered while the latter is observed at stations which are far from most earthquake

Figure H.2. Correlation coefficients between simulated and empirical $\delta S2S_s$.

sources (where HF acceleration amplitudes have attenuated considerably) or have significant basin waves. The difference in D_{s595} governed by these two methods can be significantly different as the contribution of LF acceleration amplitudes to AI is small compared to HF acceleration amplitudes for SM earthquakes. The empirical prediction provides D_{s595} which do not strongly depend on two distinctly different mechanisms like the simulated D_{s595} does. D_{s575} has a large correlation coefficient as the majority of simulated values are usually determined from the duration of the HF acceleration amplitudes alone.

ELECTRONIC SUPPLEMENT I: COMPARISON OF INTENSITY MEASURES AGAINST SOURCE, PATH AND SITE PARAMETERS

Figures I.1 to I.10 provide a complete set of plots illustrating the dependence of between-event, systematic site-to-site, and 'remaining' within-event residuals on source, path and site parameters, including plots which were included in the main paper, for completeness. The salient trends and features of the dependencies were elaborated upon in the main text and therefore no further discussion is presented here.

Figure I.1. Comparison of simulated prediction between-event residual against M_w for: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595}.

Figure I.2. Comparison of empirical prediction between-event residual against M_w for: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595}.

Figure I.3. Comparison of simulated prediction between-event residual against centroid depth for: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595}.

Figure I.4. Comparison of empirical prediction between-event residual against centroid depth for: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595}.

Figure I.5. Comparison of simulated prediction between-event residual against focal mechanism for: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595}.

Figure I.6. Comparison of empirical prediction between-event residual against focal mechanism for: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595}.

Figure I.7. Comparison of simulated prediction systematic site-to-site residual against V_{s30} for: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595}.

Figure I.8. Comparison of empirical prediction systematic site-to-site residual against V_{s30} for: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595}.

Figure I.9. Comparison of simulated prediction 'remaining' within-event residual against R_{rup} for: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595}.

Figure I.10. Comparison of empirical prediction 'remaining' within-event residual against R_{rup} for: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595}.

ELECTRONIC SUPPLEMENT J: SPATIAL MAPS OF δB_E AND $\delta S2S_S$

Figures J.1 to J.4 provide a complete set of plots illustrating the spatial variation in between-event and site-to-site residuals for simulation and empirical prediction.

Figure J.1. Spatial distribution of between-event residuals, δB_e, for simulated prediction: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595} for all 148 earthquake events.

Figure J.2. Spatial distribution of between-event residuals, δB_e, for empirical prediction: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595} for all 148 earthquake events.

Figure J.3. Spatial distribution of systematic site-to-site residuals, $\delta S2S_s$, for simulated prediction: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595} for all 43 strong motion stations.

Figure J.4. Spatial distribution of systematic site-to-site residuals, $\delta S2S_s$, for empirical prediction: (a) PGA; (b) pSA(3.0s); (c) PGV; (d) AI; (e) D_{s575}; and (f) D_{s595} for all 43 strong motion stations.

ELECTRONIC SUPPLEMENT K: STATION PLOTS OF δW_{ES}

Figures K.1 to K.11 provide a complete set of within-event residual plots for each of the strong motion stations considered for both simulated and empirical prediction. Stations which were included in the main text are also included here for completeness. The additional stations shown here, which were not presented in the main text, generally follow trends and features identified by the stations in the main text based on their geographical region. Hence, there is no further elaboration is made on the figures presented.

Figure K.1. Computed within-event residuals for the: (a) simulated ADCS; (b) empirical ADCS; (c) simulated ASHS; (d) empirical ASHS; (e) simulated CACS; (f) empirical CACS; (g) simulated CBGS; and (h) empirical CBGS predictions.

Figure K.2. Computed within-event residuals for the: (a) simulated CCCC; (b) empirical CCCC; (c) simulated CHHC; (d) empirical CHHC; (e) simulated CMHS; (f) empirical CMHS; (g) simulated CRLZ; and (h) empirical CRLZ predictions.

Figure K.3. Computed within-event residuals for the: (a) simulated CSHS; (b) empirical CSHS; (c) simulated CSTC; (d) empirical CSTC; (e) simulated D09C; (f) empirical D09C; (g) simulated D14C; and (h) empirical D14C predictions.

Figure K.4. Computed within-event residuals for the: (a) simulated D15C; (b) empirical D15C; (c) simulated DFHS; (d) empirical DFHS; (e) simulated DSLC; (f) empirical DSLC; (g) simulated EYRS; and (h) empirical EYRS predictions.

Figure K.5. Computed within-event residuals for the: (a) simulated GODS; (b) empirical GODS; (c) simulated HALS; (d) empirical HALS; (e) simulated HHSS; (f) empirical HHSS; (g) simulated HPSC; and (h) empirical HPSC predictions.

Figure K.6. Computed within-event residuals for the: (a) simulated HVSC; (b) empirical HVSC; (c) simulated KOWC; (d) empirical KOWC; (e) simulated KPOC; (f) empirical KPOC; (g) simulated LINC; and (h) empirical LINC predictions.

Figure K.7. Computed within-event residuals for the: (a) simulated LPCC; (b) empirical LPCC; (c) simulated MTHS; (d) empirical MTHS; (e) simulated NBLC; (f) empirical NBLC; (g) simulated NNBS; and (h) empirical NNBS predictions.

Figure K.8. Computed within-event residuals for the: (a) simulated PARS; (b) empirical PARS; (c) simulated PPHS; (d) empirical PPHS; (e) simulated PRPC; (f) empirical PRPC; (g) simulated REHS; and (h) empirical REHS predictions.

Figure K.9. Computed within-event residuals for the: (a) simulated RHSC; (b) empirical RHSC; (c) simulated SHFC; (d) empirical SHFC; (e) simulated SHLC; (f) empirical SHLC; (g) simulated SLRC; and (h) empirical SLRC predictions.

Figure K.10. Computed within-event residuals for the: (a) simulated SMTC; (b) empirical SMTC; (c) simulated SPFS; (d) empirical SPFS; (e) simulated SPRS; (f) empirical SPRS; (g) simulated STKS; and (h) empirical STKS predictions.

Figure K.11. Computed within-event residuals for the: (a) simulated SWNC; (b) empirical SWNC; (c) simulated TPLC; (d) empirical TPLC; (e) simulated WCSS; and (f) empirical WCSS predictions.