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# Preliminary examination of kinematic rupture parameter variability in simulated ground motions

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## ABSTRACT

This paper investigates the effects of variability in source rupture parameters on site-specific physics-based simulated ground motions, ascertained through the systematic analysis of ground motion intensity measures. As a preliminary study, we consider simulations of the 22 February 2011 Christchurch earthquake using the Graves and Pitarka (2015) methodology. The effects of source variability are considered via a sensitivity study in which parameters (hypocentre location, earthquake magnitude, average rupture velocity, fault geometry and the Brune stress parameter) are individually varied by one standard deviation. The sensitivity of simulated ground motion intensity measures are subsequently compared against observational data. The preliminary results from this study indicate that uncertainty in the stress parameter and the rupture velocity have the most significant effect on the high frequency amplitudes. Conversely, magnitude uncertainty was found to be most influential on the spectral acceleration amplitudes at low frequencies. Further work is required to extend this preliminary study to exhaustively consider more events and to include parameter covariance. The ultimate results of this research will assist in the validation of the overall simulation method's accuracy in capturing various rupture parameters, which is essential for the use of simulated ground motion models in probabilistic seismic hazard analysis.

## 1 INTRODUCTION

Ground motion prediction is increasingly adopting simulation methods alongside, or in lieu of, empirical methods (Bradley et al. 2017; Bradley 2018). However, while ground motion simulation models continue to develop, they have modelling uncertainty in their adopted input parameters, constitutive models, and governing equations. Unlike empirical models, these uncertainties are not naturally implicit in the models. In order to account for the uncertainty, multiple models for the same earthquake scenario can be used in conjunction with the individual uncertainty of each model and its constitutive parameters. Appropriate uncertainty consideration should be validated before simulation models can comprehensively generate future seismic events. The majority of previous simulation validation work has utilised median input parameters, when comparing simulated spectra against observed or empirical spectra, consequently excluding uncertainties (Graves and Pitarka 2010; Mai et al. 2010).

By compartmentalising the uncertainty by type, as shown in Table 1 (Bradley 2011), a degree of transparency is provided, and future adjustments can easily be made. The effect that a type of uncertainty has on an intensity measure (e.g. PGA, PGV, etc.) can be assessed against other types or within types, to establish focus areas for uncertainty reduction and model improvement. Uncertainty effects can also be grouped by model to establish where the greatest uncertainties occur.

*Table 1: Summary of types of uncertainties to consider*

| No. | Uncertainty Type | Explanatory Details |
|---|---|---|
| Type 1 | Measurement uncertainties | From a measured quantity e.g. Shear wave velocity of soil |
| Type 2 | Constitutive model parameter uncertainties | A parameter derived from an empirical correlation with data, e.g. moment magnitude |
| Type 3 | Constitutive model uncertainties | Due to simplifications in theoretical models or from empirical construction |
| Type 4 | Model methodology uncertainties | The computational model adopted |

A pilot sensitivity study for Type 2 uncertainty was previously undertaken for the February 22$^{nd}$ and September 4$^{th}$ Canterbury events (Razafindrakoto et al. 2018). This previous work forms a basis of the uncertainty validation process for large magnitude events described here. The research conveyed in this paper builds upon the initial pilot study of (Razafindrakoto et al. 2018), by incorporating a more rigorous selection of source parameters and their uncertainty distributions. Other additions include the assessment of perturbation effects at individual sites, assessment of effects with distance from the rupture, and the evaluation of more intensity measures.

## 2 CASE STUDY: 22 FEB 2011 CHRISTCHURCH EARTHQUAKE GM SIMULATION

The focus for this paper is the uncertainty in the source component of the simulation model, considered to be where the greatest unquantified uncertainty exists. In particular, Type 2 uncertainties (as defined in Table 1) from source parameters are assessed for a single earthquake. The aim of this study is to introduce uncertainty into ground motion simulations, so that they can provide a probabilistic estimation. A single event is used to provide an illustration of the effects of parameter uncertainty, and is not intended to be an exhaustive assessment of uncertainties.

### 2.1 Earthquake event details

The 22nd February 2011 Mw 6.2 Christchurch Earthquake was selected as a test case for this study. It was chosen due to its close proximity to the dense array of seismic recording stations across the Canterbury region, as well as the high level of ground motion shaking recorded (PGA >1g) and relatively high magnitude. Figure 1(a) shows the spatial locations of the 38 recording stations that were utilised to compare simulation results with observational data. A single fault plane with a rupture length of 16km and width 8km was used in the reference case, based on the work by Beavan et al. (2011). The fault model adopted by Razafindrakoto et al. (2018) was used as a 'median' reference case for this study.

## 2.2 Simulation methodology

This study adopted the hybrid broadband ground motion simulation methodology developed by Graves and Pitarka (2010, 2015, 2016), which simulates low-frequencies (LF; $f<1Hz$) using a comprehensive physics-based approach and high-frequencies (HF; $f>1Hz$) using a simplified physics-based approach. The two components are subsequently modified with empirical amplification factors to account for local site effects and then merged to produce a single broadband time series. Figure 1(b) illustrates a realisation of the source kinematic rupture representation, with slip distribution, rise time and rake angle for this reference case, produced by a stochastic slip generator.

The ground motion simulations were performed within a computational domain of 140km x 120km x 46km, of which the surface projection is shown in Figure 1(b). Crustal seismic velocities were prescribed from the Canterbury Velocity Model (Lee et al. 2017; Thomson et al. 2019). The velocity model has a resolution of 0.1 km and an enforced minimum shear wave velocity of 500 m/s, which yields a maximum frequency of 1.0 Hz in the LF component. A time-step of $\Delta t = 0.005$ s was used to ensure numerical stability.

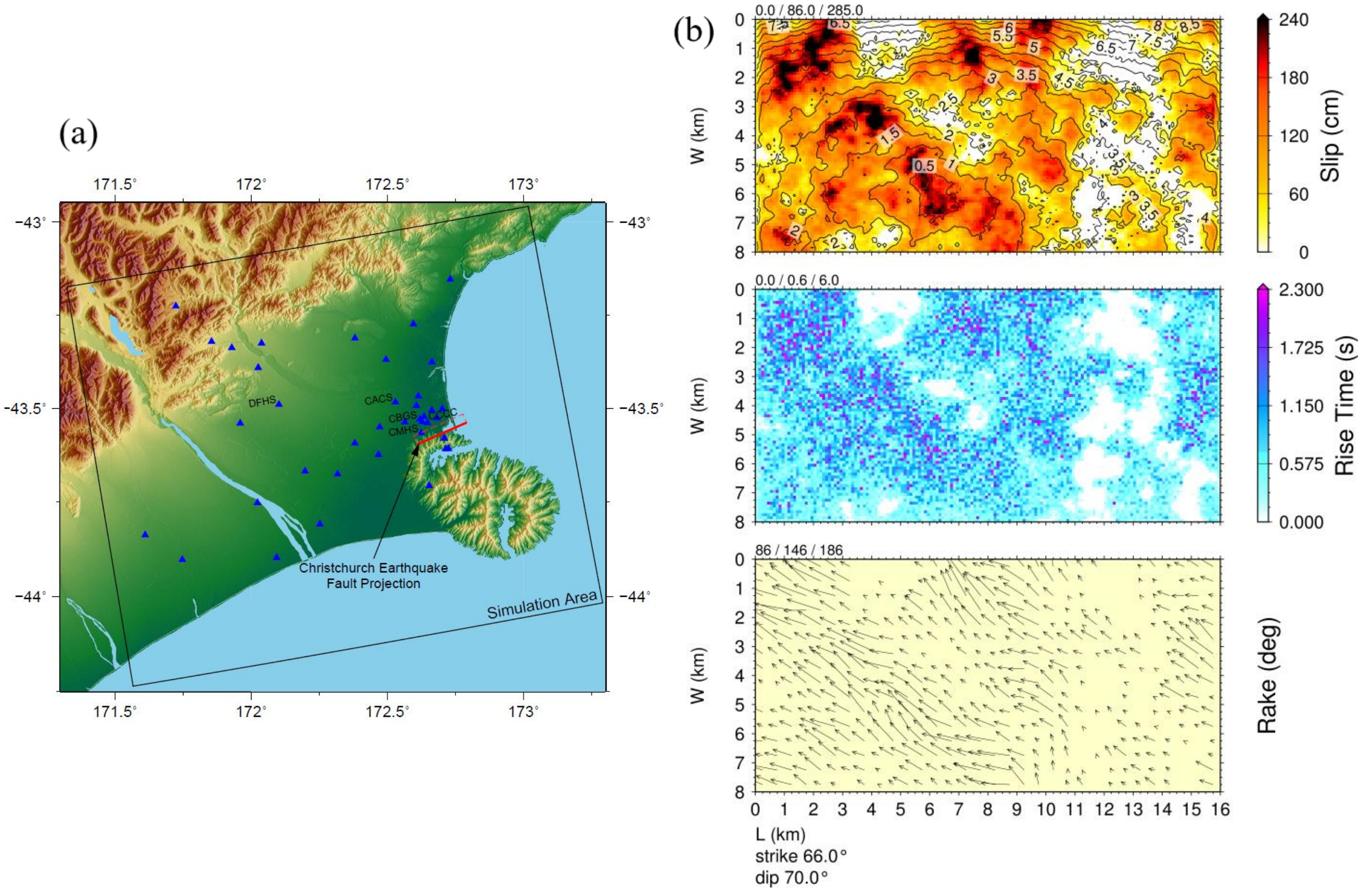


*Figure 1: (a) Map of the Canterbury region with the surface projection of the fault plane and station locations considered in this study. (b) Kinematic rupture model realisation of the 2011 Christchurch earthquake showing (top panel) the slip distribution with the rupture front contours superimposed at 1 s intervals. (middle panel) rise time distribution, and (bottom panel) rake angle distribution. Minimum, median, and maximum values are shown on the top right corner of reach panel.*

## 2.3 Selection of parameters

In order to assess the predominant uncertainties in the source component of the simulation model, five key source parameters were identified for assessment. The parameters, outlined in Table 2, have sensitivity values based on one standard deviation above and below the median, using an assumed distribution. The parameters selected form the preliminary assessment of source uncertainty, further uncertainties are intended to be assessed in future studies.

*Table 2: Summary of source parameter sensitivity study distributions*

| Source parameter | Reference case | Perturbation Range |
|---|---|---|
| Magnitude, $M_w$ | 6.2 | [6.15, 6.25] |
| Hypocentre (km), ($h_{strike}$, $h_{dip}$) | (-2, 6) | [(-1, 4), (-3, 8)] |
| Fault width (km), $F_w$ | 8 | [6.8, 9.2] |
| Rupture velocity, $V_{rup}$ | 0.8 $V_s$* | [0.725Vs, 0.875Vs] |
| Stress parameter (MPa), $\Delta\sigma$ | 5 | [4.207, 5.943] |

* $V_s$ is the local shear wave velocity of the fault plane.

***Magnitude:*** Previous work has shown that perturbations in magnitude have more effect on LF intensity measures (Razafindrakoto et al. 2018). Magnitude perturbations of ±0.05 have been based on Graves and Pitarka (2015) and derived from the seismic moment.

***Hypocentre location:*** contributes to directivity effects and the rupture time in the source model. The reference hypocentre location is 2km from the centre of the rupture along strike, and 6km down dip from the surface. The hypocentre perturbations used in this study of ±1 km along strike and ±2 km down dip are based on Mai et al. (2005).

***Fault width:*** has been selected as a proxy change to rupture area, as it has less effect on the site distance to rupture ($R_{rup}$) than fault length, and therefore allows area to be assessed independently of other parameters. Fault width also carries more uncertainty than fault length. Changing rupture area directly affects the average slip (to conserve seismic moment) and local slip to each subfault, as well as small changes to the shear wave velocity and rigidity at depth. The fault width perturbation in isolation is likely to have more significant effects on the HF spectrum, as the amount of work done is changed. Fault width perturbations of ±1.2 km have been selected based on Graves and Pitarka (2015).

***Rupture Velocity:*** is used in determining the rupture initiation time for each sub-fault within the fault plane of the comprehensive physics LF model. In the simplified physics (HF) model, rupture velocity is directly proportional to corner frequency. The rupture velocity is generally a mean function of the shear wave velocity based on Pitarka et al (2009) and Graves and Pitarka (2010). The reference rupture velocity is defined as per Graves and Pitarka (2015). The rupture velocity perturbations of ±0.075 Vs have been selected based on Graves and Pitarka (2015).

***Brune stress parameter:*** represents the compactness of the rupture in space or time. It is related to the ratio of moment magnitude and rupture area. The stress parameter is only utilised in the simplified physics component of the ground motion simulation, therefore it only affects HF ground motions. The stress parameter reference model assumes a stress parameter of 5 MPa based on Graves and Pitarka (2010). The perturbations of ×1.1886 are based on the Leonard (2010) moment scaling relationships and utilise the centre of circular rupture formulation from Anderson and Kanamori (1975).

## 2.4 Sensitivity analysis approach

A sensitivity study using tornado plots and residual analysis was chosen to make an initial assessment of the parameters selected in Section 2.3. This sensitivity study involved modifying each parameter in isolation by a chosen amount (Table 2). The purpose of this sensitivity study is to develop a degree of intuition for each parameter and how it affects the simulated ground motions and intensity measures. A further sensitivity analysis will be conducted following a Monte Carlo analysis.

# 3 UNCERTAINTY ANALYSIS RESULTS

Source parameter perturbations were applied to the simulation model in isolation as per the distributions provided in Table 2. The log ratio of the perturbed simulation to the reference simulation (the unperturbed simulation) were computed for each station across pseudo-spectral accelerations of 0.01 to 10 second periods (Equation 1). The log ratio of the station observations to the reference simulation were also similarly computed (Equation 2). These results are shown in Figure 2 for all stations, and for the acceleration intensity measures at all periods, with each subplot for a different perturbed parameter. The relative size of the residuals calculated in Equations 1 and 2, demonstrates whether the marginal uncertainty adopted captures the residual of the median simulation. If Δobs is between the maximum and minimum values of Δunc, this is achieved.

$$\Delta unc = log\left(\frac{IM_{sim,pert}}{IM_{sim,ref}}\right) \quad (1)$$

$$\Delta obs = log\left(\frac{IM_{obs}}{IM_{sim,ref}}\right) \quad (2)$$

## 3.1 Uncertainty in parameters considered

Through investigation of the residual between perturbed and reference scenarios in Figure 2, several trends were identified which quantify the effect of each parameter perturbation. The reference simulation is generally over predicted at long periods, this is shown by the average observation residual sitting below zero at periods above 1 second.

As show by Figure 2(a) changes to the magnitude are found to be more significant and consistent at long periods. At short periods (less than 1 second), increasing or decreasing the magnitude does not have a consistent effect, and is generally less significant. This is because the HF simulation model is generally more sensitive to changes in the stress parameter, rather than from the magnitude. It is also noted that at long periods, the effect on intensity measures from perturbations of magnitude are not station dependent, which is shown by the clustering of station residuals. This is also noted in tornado plot findings (Section 0). Clustering is due to the direct effect that the magnitude has on the average slip, when the rupture area and shear modulus of the crust are held constant, as illustrated by the formulation definition of moment magnitude.

Perturbations to the hypocentre produced randomised results, as shown in Figure 2(b). This was anticipated, as small changes to hypocentre location are not expected to have any general trends.

Acceleration intensity measures were found to be less sensitive to rupture velocity perturbations at long periods, as shown in Figure 2(c). At short periods, the changes to intensity measures are consistent across periods for each station, similarly, but not as pronounced, as was observed with the stress parameter. In the simplified physics model, rupture velocity directly effects the stress parameter and indirectly effects the path duration, through the corner frequency of the model (Graves and Pitarka 2010). It is through modification of the stress parameter that these period consistent results are realised.

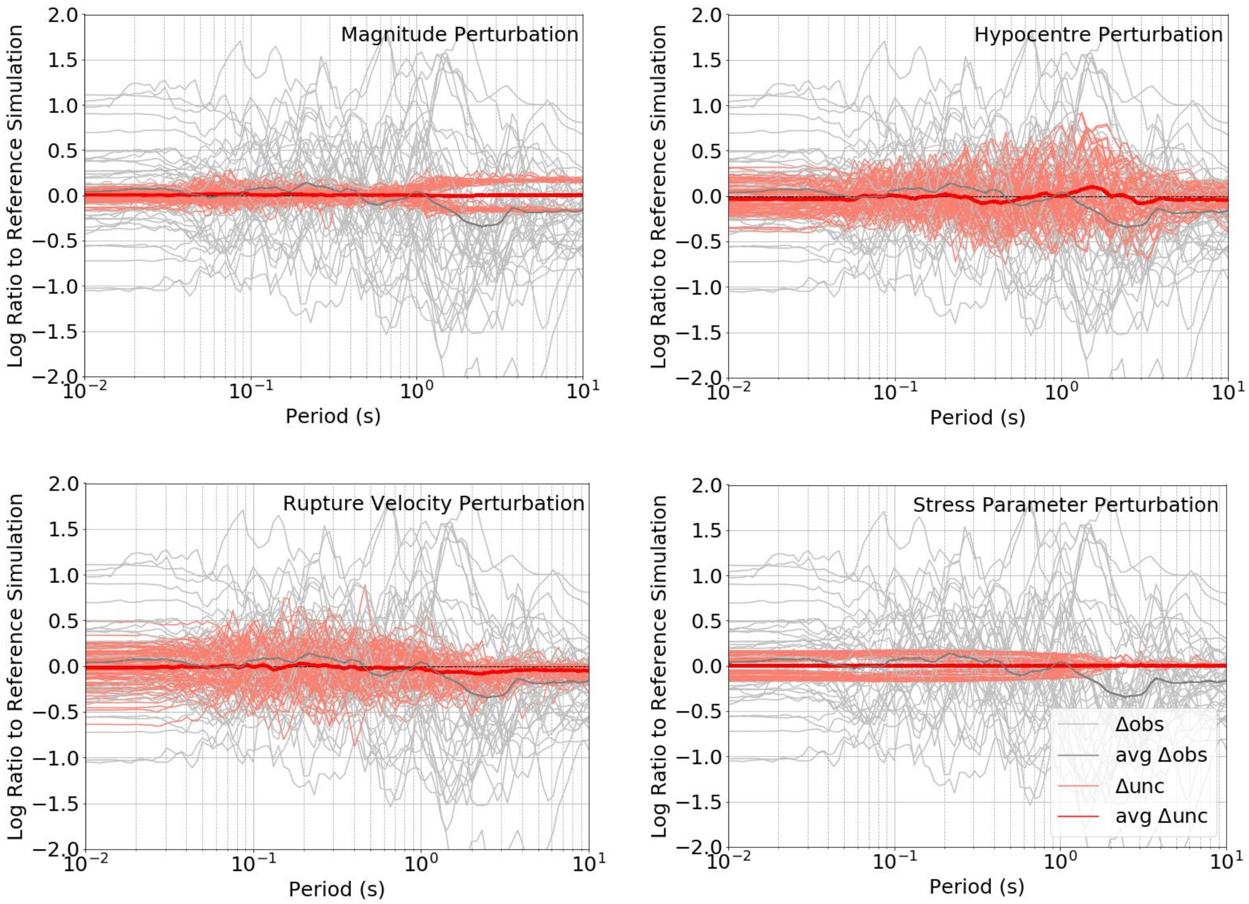


*Figure 2: Residuals for each station of observations and perturbed simulations with respect to the reference simulation.*

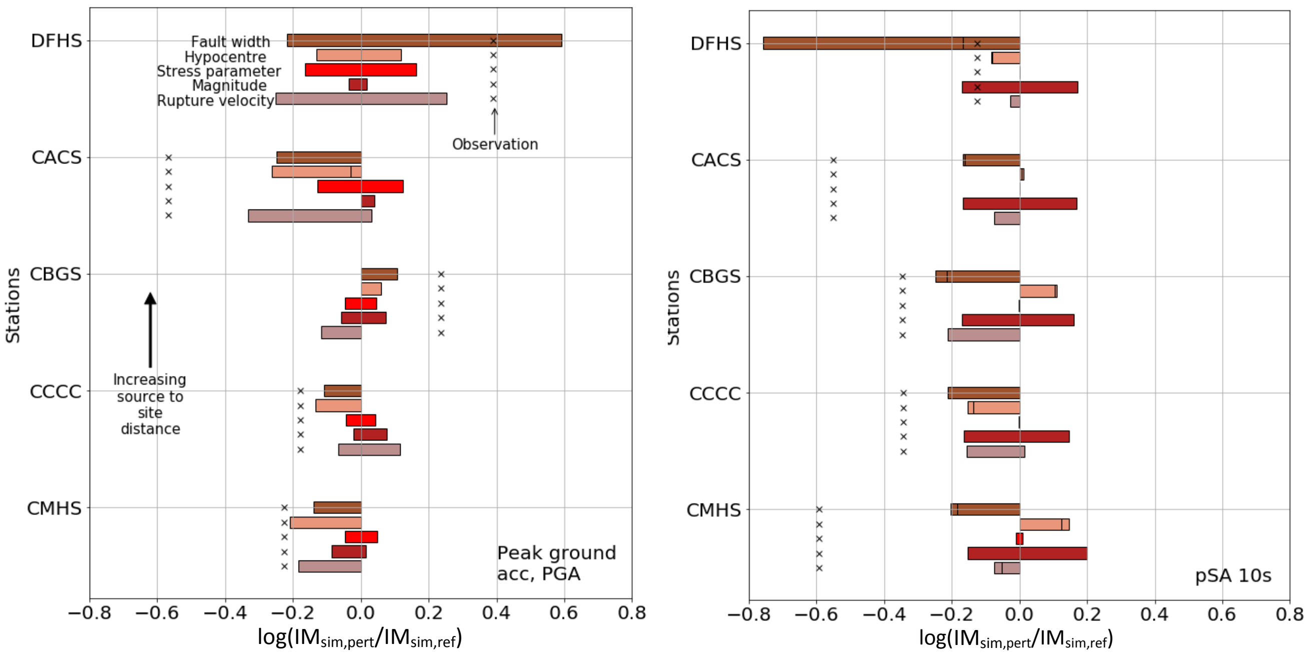


*Figure 3: Tornado plot for five stations with increasing distance to rupture, all parameter perturbations and for intensity measures PGA and pSA 10seconds. Results are normalised by the reference simulation.*

Changes in the stress parameter have minimal effect on the intensity measures at long periods (as the stress parameter is only utilised in the simplified physics formulation). Perturbations to the stress parameter were found to have very consistent affects across the short periods for each station (as shown in Figure 2(d)). This is consistent with the $\omega^2$ source model, which demonstrates that changing the stress parameter will have a consistent effect in the HF component of the spectrum (Boore et al. 2014).

### 3.2 Sensitivity analysis results

Figure 3(a) and 3(b) present tornado plots for peak ground acceleration (PGA) and pseudo spectral acceleration at 10 seconds, respectively. In order to assess the sensitivity effects with increasing distance to the rupture, the following five stations were selected (in order of decreasing $R_{rup}$): Darfield High School, Christchurch Canterbury Aero Club, Christchurch Botanic Gardens, Christchurch Cathedral College, and Christchurch Cashmere High School. Each station and intensity measure has a subplot with results from the five perturbed parameters (fault width, hypocentre, stress drop, magnitude, and rupture velocity respectively). The main advantage of the tornado plots is to see the significance of each perturbed source parameter in isolation relative to each other.

Generally, it was observed that variability in the intensity measures increase with increasing $R_{rup}$. In Figure 3(a) the fault width and rupture velocity are shown to be the most dominant parameters at distance, due to their direct effect on the average slip and the corner frequency. Secondly, hypocentre location and the stress parameter also have relatively large effects on the PGA at distance. However, at close proximity these parameters become saturated and have a similar effect on the PGA as the other parameters. Conversely, Figure 3(b) shows magnitude to have a consistently large effect on the spectral acceleration of 10 seconds intensity measure at all stations. This is consistent with the application of input magnitude in the comprehensive physics simulations, which directly determines the slip amplitude when no other parameters are perturbed.

The tornado plots (in Figure 2) display qualitative results that the observations are not captured by the variability in the simulation source parameters when varied in isolation, except in a few instances. A quantitative analysis was also undertaken using Equation 3. This showed on average that the variability due to the marginal uncertainties does not explain the average deviation of the observed ground motion from the median simulation. It was expected that this study would under-account for observation uncertainty, as each source parameter variability has been considered in isolation. Once randomness is applied to each parameter simultaneously (through the proposed Monte Carlo analysis) then these uncertainties should aggregate. Further studies on the size of the standard deviations adopted and their distributions will be undertaken as part of the Monte Carlo analysis, in order to verify these parameter hierarchal findings.

$$Sim\ variability\ vs.\ \Delta\ obs = \frac{log\left(\frac{IM_{sim,pert\ max}}{IM_{sim,pert\ min}}\right)}{2} - \left|log\left(\frac{IM_{obs}}{IM_{sim,ref}}\right)\right| \quad (3)$$

## 4 CONCLUSION

Ground motion models are used to produce an intensity measure spectrum for engineering design. Over recent years there has been a trend towards developing physics-based simulation models to replace the historically used empirical models. In order to use simulation models for engineering design, quantified uncertainty should be explicitly included. This paper outlined a preliminary examination of kinematic rupture parameter variability in a New Zealand ground motion simulation model, using the 22 February 2011 Christchurch earthquake. Five parameters were considered for Type 2 uncertainty in this study, stress parameter, magnitude, hypocentre location, rupture velocity and fault geometry. General trends found that uncertainty in the selected parameters all have a significant effect on the intensity measures. However, the stress parameter was found to only affect high frequencies, the rupture velocity was found to be less effective at low frequencies, and magnitude was found to have more effect at low frequencies. As expected, these marginal uncertainties in isolation underestimate the observation residuals. The purpose of using a single event for this assessment, was not to optimise or fit the uncertainty, but rather to understand the hierarchical results of the perturbation variations, and how these compare to ground motion observations. Refinement of parameter perturbation distributions is anticipated to occur as this study progresses. Further evaluations of uncertainties are planned to comprehensively consider source parameters, events, sites uncertainty types and parameter covariance.

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