Validation of hybrid broadband ground-motion simulation for large magnitude earthquakes in New Zealand

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ABSTRACT

This study provides key insights from an extensive validation of ground-motion simulations for large-magnitude earthquakes in New Zealand, utilizing a dataset of over 548 recordings from 11 events (up to Mw 7.8) across 200+ stations nationwide. The simulation results are benchmarked against observational data and empirical ground-motion models to assess the agreement between simulated and recorded ground motions. The validation also examines the uncertainty in the estimated ground-motion intensities for various source geometries, ranging from single-plane finite faults (e.g. 7.8 Mw Dusky Sound earthquake) to complex multi-segment models (e.g. 7.1 Mw Darfield earthquake), and for different slip distributions across the fault. The results illustrate that the adopted finite-fault geometry has a primary impact on the simulation results; that the effect of different slip distributions is insignificant in the mean simulation bias; and that predictions from simulation exhibit a similar misfit to observations as that of empirical ground-motion models.

1 INTRODUCTION

Large-magnitude earthquakes are among the most devastating natural disasters worldwide, causing significant casualties, economic losses, and infrastructure damage. For example, the 2023 Kahramanmaraş earthquake sequence in Turkey and Syria resulted in over 50,000 deaths, displaced millions, and led to economic losses exceeding $51 billion (Goldberg et al., 2023; Dilsiz et al., 2023; World-Bank 2024). Similarly, past earthquakes in New Zealand (NZ), such as the 2010-2011 Canterbury sequence ($21 billion in losses, 182 fatalities) and the 2016 Mw 7.8 Kaikoura earthquake, have caused widespread destruction, including landslides, surface fault ruptures, and liquefaction (Delforge et al., 2023; Johnston et al., 2014; Massey et al., 2020; Van Dissen et al., 2018; Cubrinovski et al., 2017; Stringer et al., 2017). Therefore, accurate estimates of ground motions from large earthquakes is crucial for disaster preparedness. However, empirical ground-motion models (GMMs) face limitations due to the scarcity of observed data in both global and regional databases, and particularly for large magnitude events.

Hybrid broadband ground-motion simulations (hereafter referred as GM simulations) (e.g., Graves and Pitarka, 2010; 2015) offer an alternative for predicting ground motions by explicitly incorporating the physics of source rupture, wave propagation, and site response (Bradley et al. 2017). These simulations help model site- and region-specific effects, reducing reliance on ergodic assumptions.

Building on previous validation efforts for small- to moderate-magnitude earthquakes in NZ (Lee et al., 2022; 2021), this study expand the validation efforts for large-magnitude events. Earlier studies used point sources or single-plane finite fault models (FFMs), which were appropriate for smaller events due to their simpler rupture characteristics (Lee et al., 2022; 2021). However, for large-magnitude earthquakes, accurately modelling the rupture complexity is essential for reliable simulations. To ensure accurate source representation, this study validates only large-magnitude events with available finite fault models in NZ. For brevity, preliminary results and key insights from the validation efforts carried out for large magnitude earthquakes, focusing on the 7.8 Mw Dusky Sound and 7.1 Mw Darfield earthquakes, are presented herein.

2 EVENTS AND GROUND MOTION RECORDS SELECTED

This study selected NZ earthquakes that met the following criteria: (I) published finite fault inversions (e.g., Beavan et al., 2012; Hamling et al., 2014, 2017; Kubota et al., 2018); (II) finite fault models available in the global SRCMOD database (Mai and Thingbaijam, 2014); and (III) models estimated by geological agencies such as GNS Science or the USGS. Figure 1 depicts the geographic distribution of the events in the NZ GM database (Hutchinson et al., 2024) having available finite-fault models (FFMs). Most of these events are crustal earthquakes as their shallow depths and surface rupture traces allow for more straightforward fault geometry estimation, e.g., the Kaikoura earthquake (Hamling et al., 2017). Additionally, Figure 2 presents the available FFMs for the 7.8 Mw 2009 Dusky Sound earthquake. It is clear that despite their similarities, the strike, dip and dimensions of the rupture planes differs across the different models which will impact the simulation results.

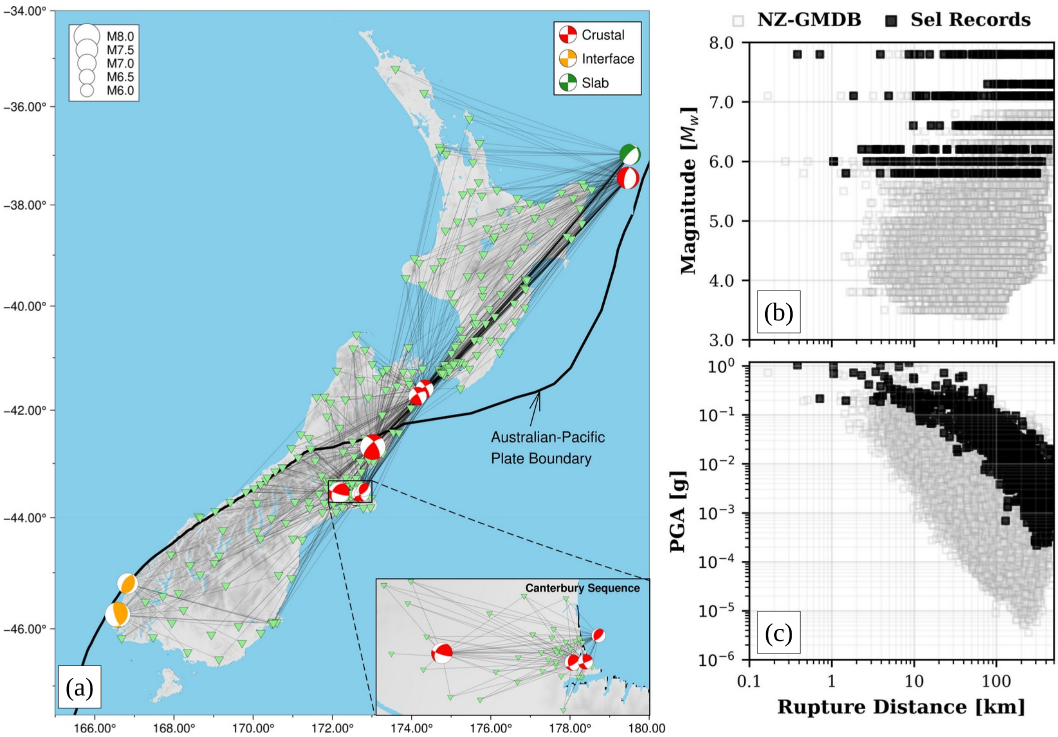

Figure 1: Events and records selected from the NZGMDB. (a) Geographical distribution of the epicenters; (b) Scenarios available (Magnitude vs Rupture distance); (c) PGA vs Rupture distance.

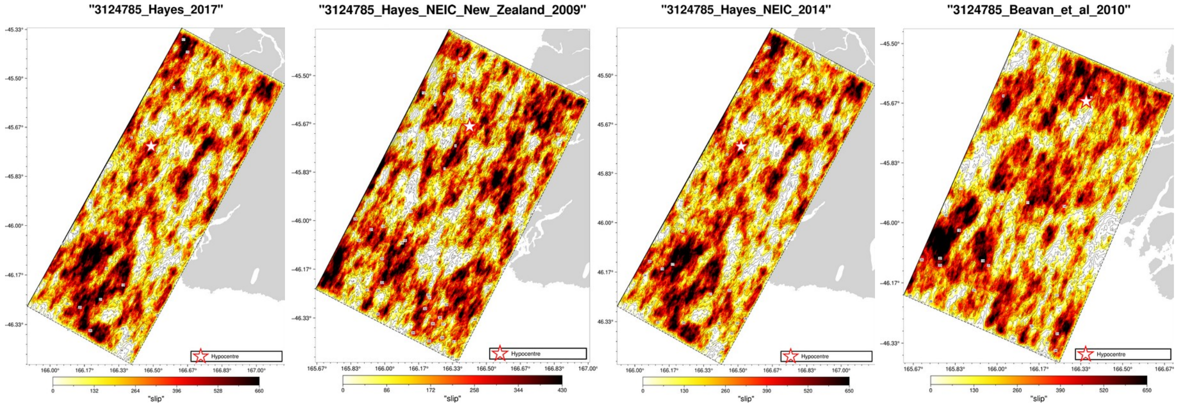

Figure 2: Finite Fault Models available for the 7.8 Mw 2009 Dusky Sound earthquake. (a – b - c) Developed by USGS; (d) Developed by Beavan et al. (2010)

A common approach in developing FFMs is specifying large rupture dimensions to capture slip over the entire fault. However, this often leads to overestimations of the rupture plane sizes (Somerville et al., 1999). To address this, we applied the trimming criterion from Somerville et al. (1999), which removes rows or columns where the average slip per fault element is less than 30% of the total fault's average slip. Figures 3 and 4 illustrates this process for the 7.8 Mw 2009 Dusky Sound solution of Beavan et al. (2010), and the 7.1 Mw 2010 Darfield solution of Beavan et al. (2012), respectively. Figures 3a and 4a present the original slip distribution, while Figures 3b and 4b present the trimmed versions ultimately used in the simulation. In the Dusky Sound case, the trimmed model is approximately one half the area of the original and lies in the lower bound of the mean +/- 2 standard deviations of the dimensions expected from the Skarlatoudis et al. (2016) magnitude-area scaling relationship for interface earthquakes. Meanwhile, both the original and trimmed models for the Darfield event match the expected fault dimensions from the Leonard (2014) scaling relationship for crustal earthquakes.

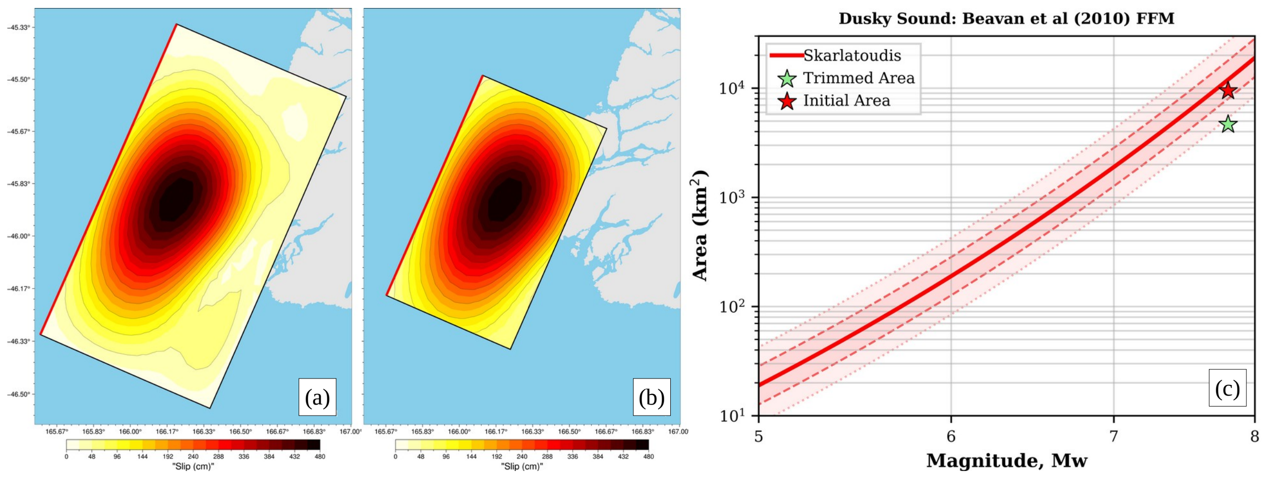

Figure 3: Example of the FFMs trimming procedure proposed by Somerville et al. (1999) for the Dusky Sound FFM developed by Beavan et al. (2010). (a) Original slip distribution; (b) Slip distribution in the trimmed FFM used in the simulation; (c) Comparison of the FFM's area respect to the Skarlatoudis et al. (2016).

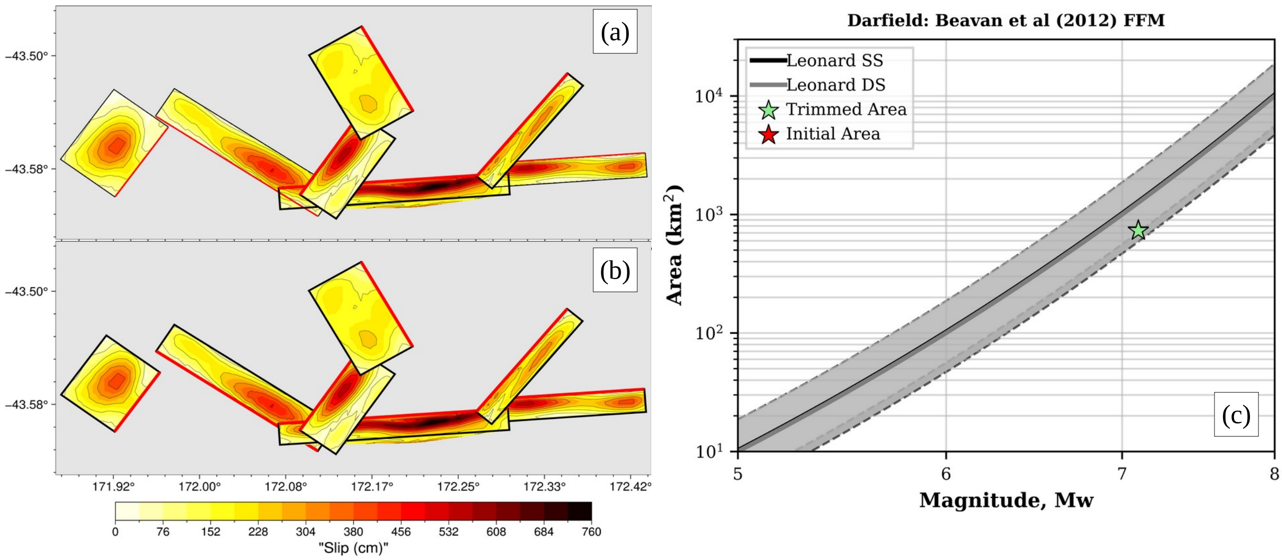

Figure 4: Example of the FFMs trimming procedure proposed by Somerville et al. (1999) for the Darfield FFM developed by Beavan et al. (2012). (a) Original slip distribution; (b) Slip distribution in the trimmed FFM used in the simulation; (c) Comparison of the FFM's area respect to the Leonard (2014).

3 GROUND MOTION SIMULATION AND VALIDATION METHODS

3.1 Hybrid broadband ground-motion simulation

We employ the hybrid broadband ground-motion simulation approach developed by Graves and Pitarka (2010; 2015). This method computes the low-frequency (LF) component using a 3D finite difference formulation to explicitly model wave propagation, and high frequency (HF) component a simplified physics-based method. The broadband waveform is then constructed by merging the LF and HF components in the time domain using a fourth-order Butterworth filter (Graves and Pitarka 2010). The LF-HF transition frequency is typically set around 1 Hz, corresponding to a 100 m grid spacing (see Graves 1996). In this preliminary study, we use a 200 m grid spacing, for computational expediency, resulting in a transition frequency of 0.5 Hz. Figures 5 and 6 compare simulated ground-motion intensities with observations for the Mw 7.8 Dusky Sound and Mw 7.1 Darfield earthquakes, respectively. For distance ranges with available records, the simulations show good agreement with observed ground-motion intensities.

3.2 Benchmark against empirical ground-motion models

The GM simulations are benchmarked against empirical GMMs, following validation approaches previously used in NZ (e.g., Lee et al., 2022) and internationally (e.g., Afshari and Stewart, 2016). We use the empirical GMMs adopted in the 2022 NZ National Seismic Hazard Model (Gerstenberger et al., 2024; Bradley et al., 2024) to estimate pseudo-spectral accelerations and PGA. For crustal events, selected models include NZ-specific GMMs (Bradley 2013; Stafford 2022; Atkinson 2024) and NGA-West2 models (Abrahamson, Silva, and Kamai 2014; Boore et al., 2014; Chiou and Youngs 2014; Campbell and Bozorgnia 2014). For subduction events, we use the local model by Atkinson et al. (2024) and NGA-Subduction models (Abrahamson and Gulerce 2022; Kuehn et al., 2023; Parker et al., 2022). Although Stafford et al. (2022) and Atkinson et al. (2024) developed their models using the NZ Ground Motion Database (NZ GMDB), the limited number of large-magnitude records in the database reduces the risk of bias in their predictions. For non-spectral intensity measures, we use Chiou and Youngs (2014) for PGV, Campbell et al. (2008) for

Cumulative Absolute Velocity (CAV), Bahrampouri et al. (2021) for Arias intensity and Afshari and Stewart (2016) for significant duration (Ds575 – Ds595). Figures 5 and 6 compares empirically predicted median and 16th/84th percentile ground-motion intensities against the observed data for the 7.8 Mw Dusky Sound and 7.1 Mw Darfield earthquakes. Most observations (black squares) fall within ±1 standard deviation of empirical model predictions.

3.3 Residual validation framework

We validate the simulated and empirical predictions using total residual analysis, computing residuals across all observations as per Equation (1). Note that total residuals are shown here, but they can be partitioned into between and within event components. This method helps assess systematic biases in simulations for different FFMs. Residual analysis is a standard approach in validating physics-based ground-motion simulations (Rezaeian et al. 2024) and has been previously applied in New Zealand (Lee et al. 2021; 2022).

$$\Delta_{Residual} = \ln(IM_{Observed}) - \ln(IM_{Predicted}) \quad (1)$$

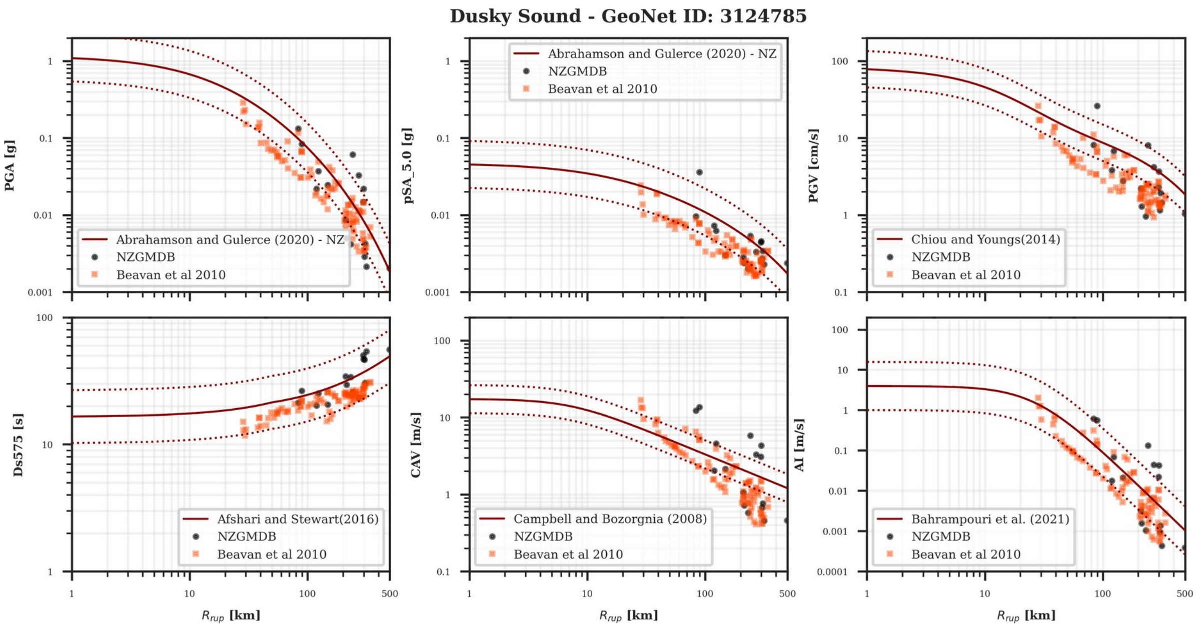

Figure 5: Observed, simulated, and empirically predicted ground-motion intensities as a function of rupture distance (Rrup) for the Dusky Sound earthquake. The median and 16th/84th percentiles of the empirical ground-motion are represented by solid and dashed lines.

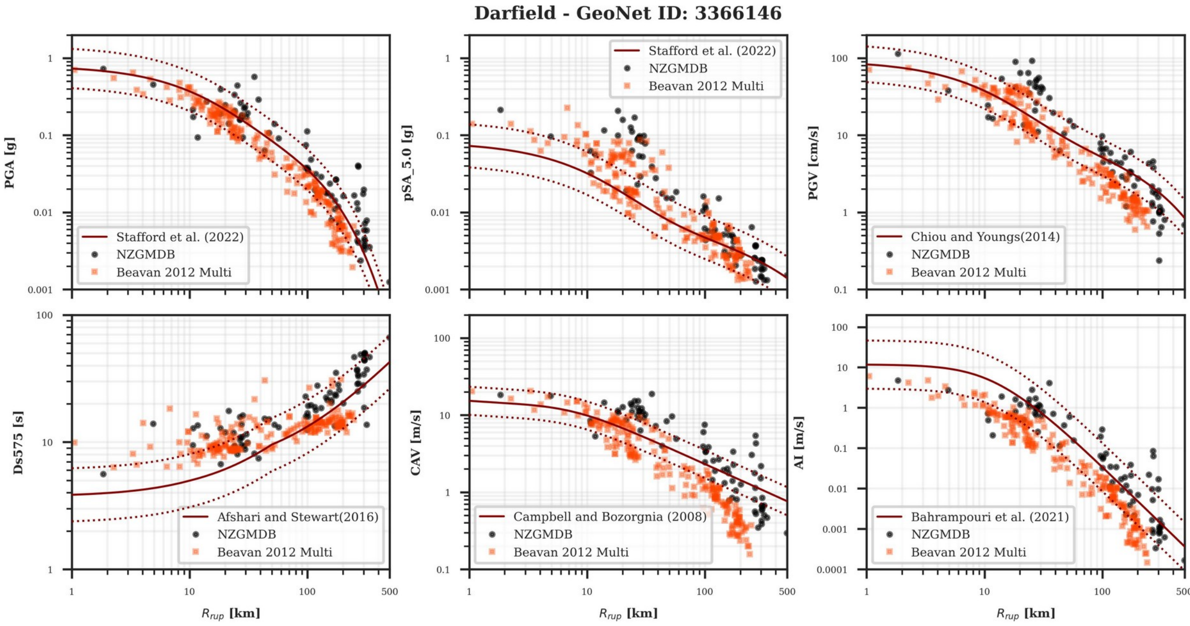

Figure 6: Observed, simulated, and empirically predicted ground-motion intensities as a function of rupture distance (Rrup) for the Darfield earthquake. The median and 16th/84th percentiles of the empirical ground-motion are represented by solid and dashed lines.

5 PRELIMINARY RESULTS AND KEY FINDINGS

5.1 Effect of the Finite Fault Geometry

The impact of the FFM geometry in the mean total residual across the selected intensity measures is depicted in Figure 7 for both Dusky Sound (Figure 7a) and Darfield (Figure 7b) earthquakes. For the Darfield case, it is clear that the model proposed by Beavan et al. (2012) presents a better agreement with the observed ground-motion intensities across all of the selected intensity measures. For the Dusky Sound case there is agreement between the different FFMs developed by the USGS at the high frequency IMs (e.g. spectral accelerations at periods shorter than 1 second, Arias Intensity, PGA) the main reason for this is due to their similar location since the stochastic method for high frequencies is less sensitive to the FFMs geometry given that it uses a downsampled 1D version of the slip distribution across the FFM plane. Conversely, for the low-frequency IMs (e.g. spectral accelerations at periods longer than 3 seconds, significant durations: Ds575 or Ds595), there are differences in the performance of the USGS FFMs since the simulations use a 2D slip distribution across the FFM plane. The FFM developed in 2009 exhibits a better agreement with the observed ground-motion intensities than the newer versions (2014, 2017). The reason behind these differences lies in the similarity between the geometries proposed for the newer FFMs, and the clear differences between their geometries and the one proposed for the older one (2009). On the other hand, the FFM proposed by Beavan et al. (2010) for the Dusky Sound exhibits the better overall performance for both low and high frequencies. These findings confirm the expected dependence of simulation results on FFM geometry. Additionally, they emphasize the importance of assessing ground motion simulation performance using intensity measures across a wide frequency range, as the accuracy of the simulations is influenced by the methodologies used in their calculation.

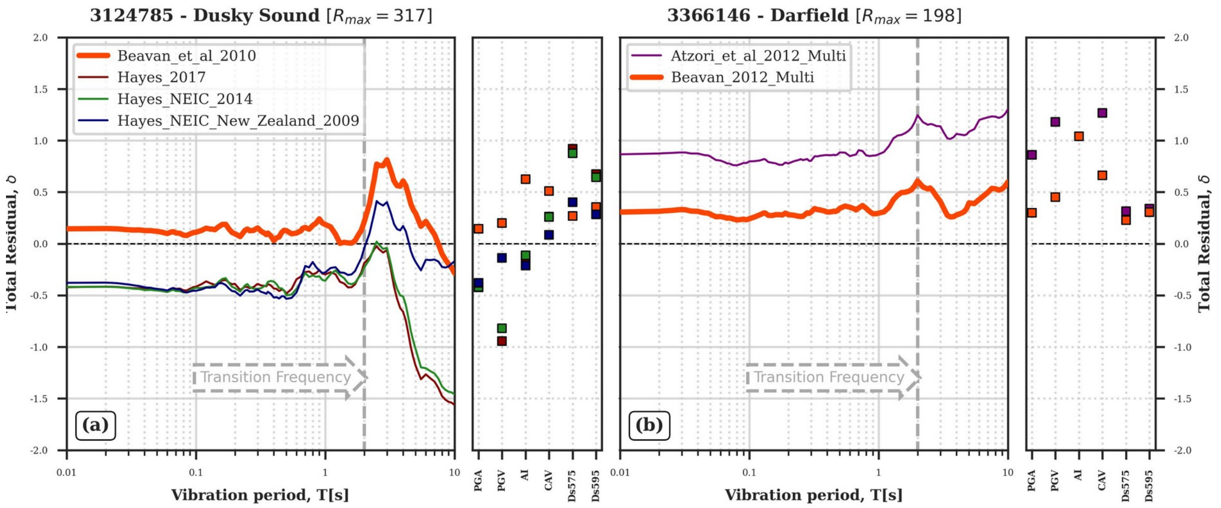

Figure 7: Variation of the average total residual for different FFM geometries. (a) 7.8 Mw 2009 Dusky Sound event; (b) 7.1 Mw 2010 Darfield event.

5.2 Effect of the Slip Distribution

We also examined the impact of slip distribution across the rupture planes on simulation performance. Figure 8 presents the 16th, 50th, and 84th percentiles (i.e., median ±1 standard deviation) of the mean total residual for the Beavan et al. (2010) Dusky Sound FFM using 11 different slip distributions. The variations in mean total residual due to slip distribution are smaller than those observed for FFM geometry (see Figure 7a). This suggests that using random slip variations, the standard approach for estimating future earthquakes, does not significantly affect simulation performance. Additionally, the impact of slip distribution appears to be consistent across both high- and low-frequency intensity measures.

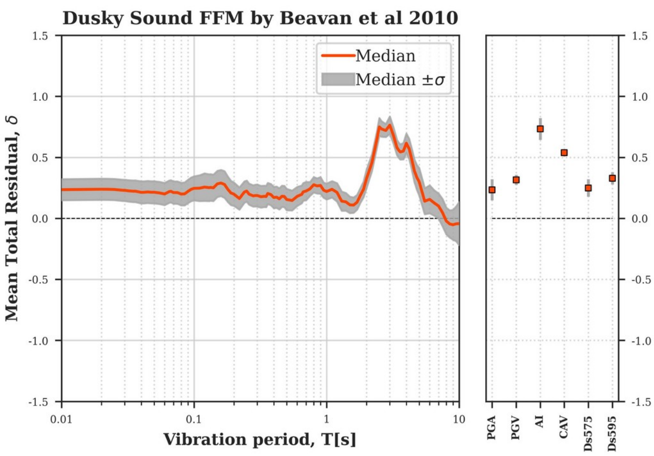

Figure 8: Variation of the mean total residual with slip distribution across the selected intensity measures for the Beavan et al. (2010) FFM for the 7.8 Mw Dusky Sound Earthquake.

6 CONCLUDING REMARKS

The preliminary results for both the Darfield and Dusky Sound events indicate good agreement between observed and simulated intensity measures across a wide frequency range. Additionally, the findings suggest that the finite fault geometry has a more significant impact on simulation performance than slip distribution. A broader analysis, including more large-magnitude events, is underway to further validate this hypothesis.

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