Assessing the Importance and Variability of kappa0, κ_0, in Ground-Motion Simulations: A Work in Progress

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ABSTRACT

This preliminary study examines the variability of the high-frequency site attenuation parameter, κ_0, and its effect on hybrid broadband ground-motion simulations for small-magnitude earthquakes ($3.5 \leq Mw \leq 5.0$). The study computes κ_0 values from these simulations and compares them to observed values using a New Zealand ground-motion database. Results show that while the adopted generic κ_0 value in the simulations is a reasonable average, high-frequency attenuation can be significantly over - or under-estimated in some regions. This analysis highlights the need for a spatially varying map of κ_0 in New Zealand to better represent site-attenuation characteristics at different locations. The study also underscores the importance of the number of records used to compute κ_0, recommending a minimum of 15 records for suitable statistical accuracy.

1 INTRODUCTION

The attenuation of high-frequency seismic waves is a critical factor in understanding and predicting ground motion during earthquakes. The high-frequency site attenuation parameter, κ_0, is an essential component of empirical ground-motion models, ground-motion simulations, and site-response analysis, among others. It accounts for the loss of energy in seismic waves within a frequency range that can significantly affect many low- to mir-rise buildings.

In recent years, hybrid broadband ground-motion simulations have become an integral tool in seismic hazard assessment, particularly in regions like New Zealand (NZ) (e.g., Graves and Pitarka, 2010). Nonetheless, recent hybrid broadband ground motion simulations in NZ (e.g., Lee et al., 2020, 2022; Bradley et al., 2017; Razafindrakoto et al., 2018) have adopted a fixed value of $\kappa_0 = 0.045\ s$, based on general assumptions about the site's attenuation properties. Such a constant value conflicts with the recognition that κ_0 is known to vary spatially (e.g., Van Houtte et al., 2014, 2018) leading to inaccurate ground-motion predictions.

This preliminary study aims to address these concerns by examining the variability of κ_0 and subsequently evaluating its impact on hybrid broadband ground-motion simulations, focusing on small-magnitude earthquakes in NZ ($3.5 \leq M_w \leq 5.0$). By comparing computed κ_0 values from simulations with observed data, this article identifies discrepancies in high-frequency attenuation across different regions of NZ. The findings suggest the need for a more refined, spatially varying approach to κ_0, which would improve the accuracy of ground-motion predictions.

2 HYBRID BROADBAND GOUND-MOTION SIMULATIONS

2.1 Overview

Hybrid broadband ground-motion simulations combine the rigor of comprehensive physics-based methods at low frequencies and a simplified physics-based approach at high frequencies (e.g., Baker et al., 2021, Chapter 5; Graves and Pitarka, 2010).

As hybrid broadband ground-motion simulations adopt physics-based methods, they require several input parameters that describe the earthquake rupture and wave propagation characteristics. For the high-frequency component of the simulation, κ_0 is one of the primary site parameters of interest, and is the main topic of this paper.

2.2 Hybrid broadband ground-motion simulations in New Zealand

Many historical earthquakes have been simulated through the hybrid broadband ground-motion approach in NZ. For large magnitude earthquakes, Razafindrakoto et al. (2018) used the hybrid simulation approach to model the $2010 - 2011$ Mw $4.7 - 7.1$ Canterbury earthquake sequence, while Bradley et al. (2017) modelled the 2016 Mw 7.8 Kaikoura earthquake.

However, the most comprehensive effort so far for implementing and validating the hybrid simulation approach worldwide has been carried out in NZ by Lee et al. (2020, 2022). Lee et al. (2020) used the hybrid simulation approach to model 148 small-M_w earthquakes in the Canterbury region, NZ; these simulations led to 1896 ground-motion records at 43 stations that were validated against observations and empirical GMMs. Lee et al. (2022) extended the work of Lee et al. (2020) by considering 5218 ground motions recorded at 212 sites from 479 active shallow crustal earthquakes across all of NZ. In their studies, Lee et al. (2020, 2022) adopted a fixed value of $\kappa_0 = 0.045\ s$ based on an analogue with values used in California by Graves and Pitarka (2010).

3 HIGH-FREQUENCY SITE ATTENUATION PARAMETER

3.1 Definition

The concept of the spectral decay factor κ (“kappa”) was introduced by Anderson and Hough (1984) to model the exponential decay of the acceleration spectrum at high frequencies in a log-linear space, for frequencies higher than a threshold frequency, f_1, above which the general shape of the spectrum begins to decay, as follows:

$$A(f) = A_0\, exp(-\pi\kappa f), \qquad f > f_1 \tag{1}$$

where $\pi\kappa$ is the slope of the decay of the FAS in a log $(A)-f$ space, as shown in Figure 1a.

Anderson and Hough (1984) also noticed a linear relation between κ values and epicentral distances, R_e, from different earthquakes, as shown in Figure 1b, and modelled it through a least-square regression of the form:

$$\kappa = \bar{\kappa} R_e + \kappa_0 \tag{2}$$

where the slope, $\bar{\kappa}$, is related to the regional attenuation due to (predominantly) the horizontal propagation of S-waves through the crust, and the zero-distance intercept, κ_0, represents site attenuation of the materials within the top few kilometres beneath the surface.

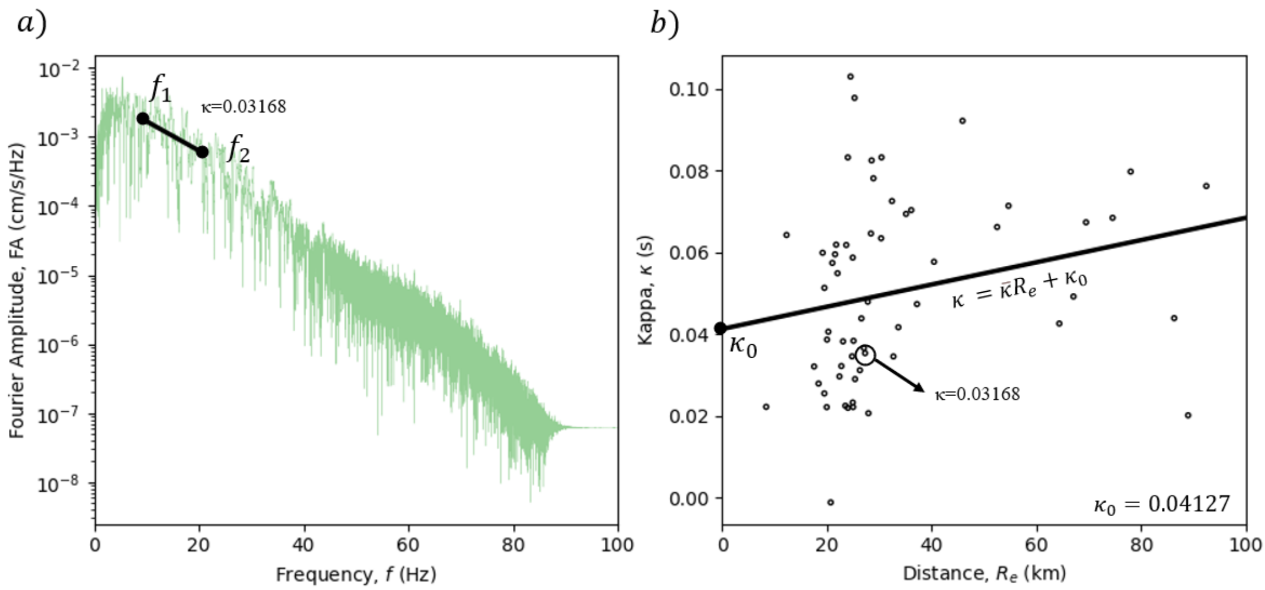

Figure 1: a) FAS of 000 component acceleration signal from the 2016 M_w4.7 2016p883896 earthquake recorded at the station SEDS, with bounds $f_1 = 10$ Hz and $f_2 = 20$ Hz indicated. b) Values of κ from different ground motion records recorded at the station SEDS, with linear regression and κ_0 indicated.

The absolute value of κ itself is not of primary interest, as path attenuation is typically modelled using Q (i.e., quality factors) and seismic wave velocity (Baker et al., 2021, Chapter 5). However, κ_0 is widely used for modelling near-surface attenuation in empirical GMMs adjustments, physics-based ground-motion simulations, and site-specific response analysis.

The computation of κ_0 at a seismic station, following the procedure of Anderson and Hough (1984), involves determining κ for each record and subsequently performing a linear regression between all the κ values and source-to-site distances of ground motions recorded at the site. In this procedure, κ_0 is defined as the y-intercept of the straight line or, in other words, the value of κ at zero distance.

3.2 Influence of κ_0 on the Fourier Amplitude Spectrum

To illustrate the influence and importance of κ_0 in hybrid broadband ground-motion simulations, a basic sensitivity analysis was undertaken. κ_0 values of $0.01, 0.025, 0.045, 0.075$, and $0.1\ s$ were considered, while the rest of the parameters of the simulation remain constant. Among all the input parameters, this analysis considers a $M_w = 4.5$, $\Delta\sigma = 50$ bars, $V_{s,src} = 3.5$ km/s, $\rho_{s,src} = 2000$ g/cm^3, and $R_e = 20$ km. The simplified approach used in this analysis follows the SMSIM procedure described and implemented by Boore (2003), since this represents the typical approach considered in hybrid broadband ground-motion simulations (e.g., Graves and Pitarka, 2010).

Figure 2 presents the different theoretical Fourier Amplitude Spectra obtained from the different κ_0 values. Most notably, Figure 2 illustrates that κ_0 values have a great influence on the shape and attenuation of the spectrum at high frequencies; the higher the κ_0 value, the higher the attenuation of the high-frequency waves. Conversely, the different spectra obtained in this analysis show no influence of κ_0 in the shape of the spectrum at low frequencies.

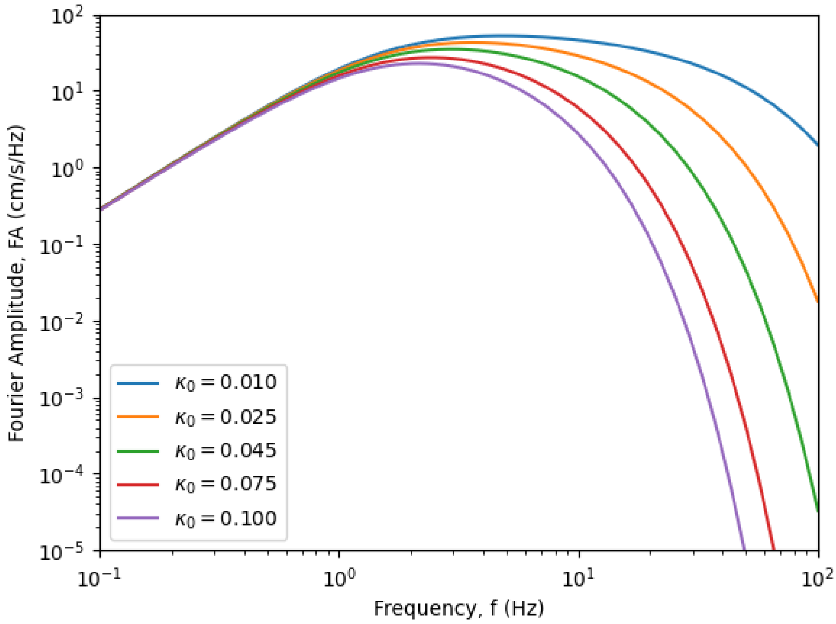

Figure 2: Sensitivity of the Fourier Amplitude Spectrum to different values of κ_0

4 COMPARISON OF κ_0 VALUES OBTAINED FROM OBSERVATIONS AND HYBRID SIMULATIONS IN NEW ZEALAND

4.1 Methodology

κ_0 values for both simulated and observed records presented by Lee et al. (2022) were determined. This database was selected for two main reasons: First, it represents the most comprehensive effort worldwide for implementing and validating hybrid broadband ground-motion simulations, providing a large number of records for κ_0 computation from both observations and simulations. Second, the database is composed of small-magnitude earthquakes (3.5 ≤ Mw ≤ 5.0), which allows for neglecting nonlinear site-response effects when computing κ_0.

The method of Anderson and Hough (1984) was used for computing κ_0. Specifically, κ values are obtained for all records in the database, assuming a frequency bandwidth of $f_1 = 10$ Hz to $f_2 = 20$ Hz (e.g., Figure 1a). This bandwidth was chosen conservatively to ensure that f_1 is above the corner frequency and f_2 is below f_{max} for all records A linear regression is then performed between the κ values and the source-to-site distances for each station (e.g., Figure 1b). The κ_0 values are defined as the intercept of the linear regression with the y-axis. This procedure is followed for all the stations in Lee et al. (2022), and κ_0 values are computed from both observed and simulated ground-motion records.

4.2 Results

Figure 3 compares the κ_0 values for all the 212 stations in the database of Lee et al. (2022). Ratios $ln(\kappa_{0,obs}/\kappa_{0,sim})$ are presented to facilitate the comparison between the κ_0 values obtained from simulations and observations.

In general, the comparison illustrates that most of the $ln(\kappa_{0,obs}/\kappa_{0,sim})$ ratios are close to 0, indicating a good overall agreement between the κ_0 values obtained from simulations and observations. Lee et al. (2020, 2022) used a $\kappa_0 = 0.045\ s$ for all the simulations, and Figure 3 suggests that this is a reasonable assumption, as the mean value of $ln(\kappa_{0,obs}/\kappa_{0,sim})$ is close to zero (specifically, $\mu_{ln(\kappa_{0,obs}/\kappa_{0,sim})}$=$-0.1087$. This indicates that the assumptions made by Lee et al. (2022) were broadly valid on a general scale for most of the stations.

However, while the mean ratio is close to zero, the data show a standard deviation of $\sigma_{ln(\kappa_{0,obs}/\kappa_{0,sim})} = 0.803$, highlighting a considerable amount of variability. This large variability clearly illustrates that there is significant variation in the $\kappa_{0,obs}$ values determined, and hence that the definition of κ_0 in for ground-motion simulation in NZ is an obvious area for improvement.

The variance observed in the data is important for further understanding seismic attenuation in NZ. For some stations, the κ_0 value can be as much as four times higher than initially assumed in the simulation. This variability could be attributed to several factors, including local geological conditions, soil composition, station-specific calibration, or even regional variations in seismic wave propagation characteristics.

The results in Figure 3 support the need for a spatially-varying κ_0 model in NZ Spatially varying κ_0 values would allow for better capturing the characteristics of earthquake-induced high-frequency wave attenuation at each station or location. Van Houtte et al. (2018) made some progress in this regard by computing κ_0 values for stations over rock and proposing a spatially varying map of κ_0. Nonetheless, the work done by Van Houtte et al. (2018) is limited to rock stations and must therefore be complemented with data from soil stations.

5 ANALYSIS OF THE APPARENT ALEATORY VARIABILITY IN κ_0

Another important topic is the sensitivity and statistical accuracy when computing κ_0. To this end, the simplified physics-based approach (see Section 2) is used in conjunction with Monte Carlo (MC) simulation to evaluate how sensitive is the computation of κ_0 in the light of the number of samples.

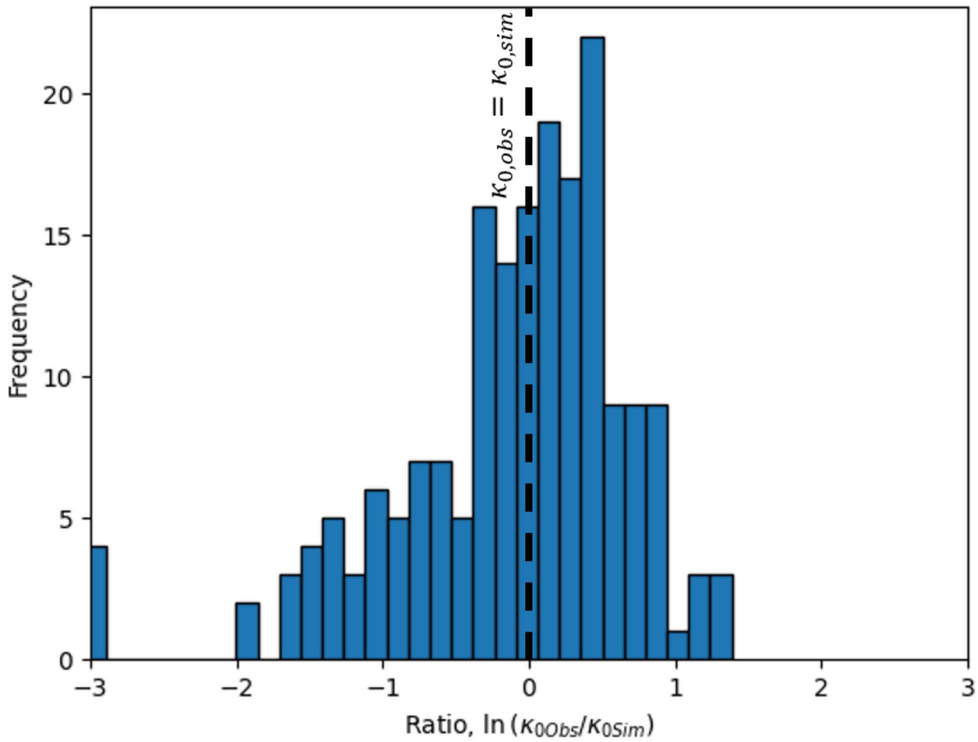

Figure 3: Histogram of $\kappa_{0,obs}/\kappa_{0,sim}$ for the stations in Lee et al. (2022)

For each MC simulation, the simplified physics-based approach is used to generate ground motion records. The value of κ_0 in the simulations is adopted as a fixed value of $\kappa_0 = 0.045\ s$, meaning that the true value of κ_0 is known. In order to reflect a range of ground motion conditions, moment magnitude and source-to-site distance uniformly vary between $3.5 \leq M_w \leq 5.0$ and $10 \leq R_{rup} \leq 150$km. The rest of the parameters of the simulation are fixed and do not change between simulations; these parameters include $\Delta\sigma = 50\ bars$, $V_{s,src} = 3.6$ km/s, $\rho_{s,src} = 2800$ g/cm^3. Frequency bounds of $f_1 = 10$ Hz and $f_2 = 20$ Hz were assumed for the computation of κ for all samples. For each number of samples considered (between 5 and 100), 100 MC simulations are performed, from which the average and standard deviation of κ_0 are then calculated.

Figure 4 presents the results from this analysis and plots the curves for the mean and plus/minus one standard deviation of κ_0. As seen in Figure 4, the standard deviation reduces as the number of samples increase. Figure 4 also shows that the mean value of κ_0 remains approximately constant, although slightly below the true value of $\kappa_0 = 0.045\ s$. This fact may be an indication that path attenuation can influence the calculated value of κ_0, and further research is required in this regard.

A useful measure to evaluate the variability of the κ_0 estimation is the coefficient of variation (CV), which is the ratio of the standard deviation to the mean. According to our analysis, to achieve a $CV \leq 7.5$, at least 15 records are needed.

6 FURTHER WORK PLANNED

Building on the findings of this preliminary study, several directions for future work are planned to further refine and expand the analysis of κ_0 and its impact on hybrid broadband ground-motion simulations. The next immediate step involves refining the frequency bandwidth used for the computation of κ_0. In this study, a frequency range of 10-20 Hz was adopted, but this bandwidth should be further examined and optimized to ensure more accurate and regionally representative κ_0 values.

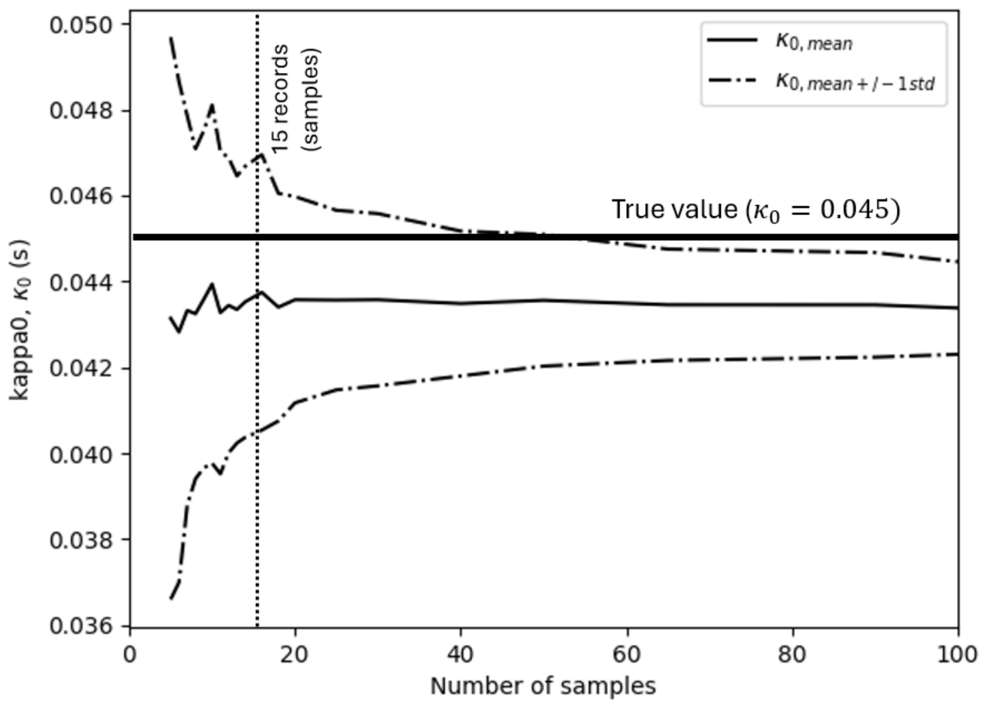

Figure 4: Mean and standard deviation of the κ_0 values as a function of the number of samples. Results obtained using a simplified physics-based simulation and a Monte Carlo Simulation technique.

In addition, we aim to explore potential correlations between κ_0 and various site-specific parameters, such as V_{s30} (average shear-wave velocity in the top 30 meters) and $Z_{1.0}$ (depth to the 1.0 km/s shear-wave velocity profile). We are also considering evaluating the dependence on different basins and geomorphic categories to determine if the variability in the correlations can be reduced. Investigating these relationships may provide deeper insights into how local site conditions influence high-frequency attenuation and improve the precision of κ_0 predictions.

Another important step will be extending the analysis to a larger and more diverse database, such as the NZ Ground Motion Database (Hutchinson et al., 2024). This would also allow for this study to extend beyond shallow crustal earthquakes and consider other tectonic types such as subduction interface and slab earthquakes. Incorporating a broader range of ground-motion records will enable a more comprehensive assessment of κ_0 variability across different regions and help refine the statistical accuracy of the results.

Finally, the ultimate goal is to develop spatially varying κ_0 maps for NZ, considering both soil and rock sites, in a manner that can be directly used in hybrid broadband ground-motion simulations in NZ. This effort builds on the work of Van Houtte et al. (2018), who developed a κ_0 map for rock sites only. These spatially varying maps would allow for more accurate ground-motion simulations and improve seismic hazard assessments.

7 CONCLUSIONS

This preliminary study evaluated the importance and variability of κ_0 values in hybrid broadband ground-motion simulations in NZ, using the database of Lee et al. (2022), and several conclusions can be drawn from the progress of this work to date. First, the results show that the high-frequency site attenuation parameter, κ_0, can vary significantly across different sites, leading to inconsistencies in high-frequency attenuation predictions for ground-motion simulations that adopt a constant value for all locations. The fixed value of $\kappa_0 = 0.045\ s$ may not accurately represent local site conditions, resulting in both overestimations and underestimations of high-frequency attenuation, particularly in regions with differing site characteristics.

There is also a growing need for spatially varying κ_0 maps in NZ that account for both soil and rock sites. Van Houtte et al. (2018) made a pioneering contribution in this area, focusing specifically on rock sites. Findings underscore the importance of developing κ_0 maps to enhance the accuracy of hybrid broadband ground-motion simulations and better represent site-attenuation effects in seismic hazard assessments. Additionally, this study highlights the necessity of using an adequate number of ground-motion records when calculating κ_0, recommending a minimum of 15 records to ensure reliable statistical accuracy in the results.

REFERENCES

Anderson JG and Hough, SE (1984). “A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies”. *Bulletin of the Seismological Society of America*, **74**(5): 1969-1993. https://doi.org/10.1785/BSSA0740051969

Baker JW, Bradley BB and Stafford PJ (2021). “*Seismic Hazard and Risk Analysis*”. Cambridge University Press.

Boore DM (2003). “Simulation of ground motion using the stochastic method”. *Pure and applied geophysics*, **160**: 635-676. https://doi.org/10.1007/PL00012553

Bradley BA, Razafindrakoto HN and Polak V (2017). “Ground-motion observations from the 14 November 2016 M w 7.8 Kaikoura, New Zealand, earthquake and insights from broadband simulations”. *Seismological Research Letters*, ***88***(3): 740-756. https://doi.org/10.1785/0220160225

Graves RW, and Pitarka A (2010). “Broadband ground-motion simulation using a hybrid approach”. *Bulletin of the Seismological Society of America*, **100**(5A): 2095-2123. https://doi.org/10.1785/0120100057

Hutchinson JA, Zhu C, Bradley BA, Lee RL, Wotherspoon LM, Dupuis M, Schill C, Motha J, Manea EF and Kaiser AE (2024). “The 2023 New Zealand ground-motion database. Bulletin of the Seismological Society of America”, **114**(1): 291-310. https://doi.org/10.1785/0120230184

Lee RL, Bradley BA, Stafford PJ, Graves RW and Rodriguez-Marek A (2020). “Hybrid broadband ground motion simulation validation of small magnitude earthquakes in Canterbury, New Zealand”. *Earthquake Spectra*, ***36***(2): 673-699. https://doi.org/10.1177/8755293019891718

Lee RL, Bradley BA, Stafford PJ, Graves RW and Rodriguez-Marek A (2022). “Hybrid broadband ground-motion simulation validation of small magnitude active shallow crustal earthquakes in New Zealand”. *Earthquake Spectra*, ***38***(4): 2548-2579. https://doi.org/10.1177/87552930221109297

Razafindrakoto HNT, Bradley BA, Graves RW (2018). “Broadband Ground-Motion Simulation of the 2011 6.2 Christchurch, New Zealand, Earthquake”. *Bulletin of the Seismological Society of America*, **108** (4): 2130–2147. https://doi.org/10.1785/0120170388

Van-Houtte C, Ktenidou OJ, Larkin T and Holden C (2014). “Hard-site κ0 (kappa) calculations for Christchurch, New Zealand, and comparison with local ground-motion prediction models”. *Bulletin of the Seismological Society of America*, **104**(4): 1899-1913. https://doi.org/10.1785/0120130271

Van-Houtte C, Ktenidou OJ, Larkin T and Holden C (2018). “A continuous map of near-surface S-wave attenuation in New Zealand”. *Geophysical Journal International*, **213**(1): 408-425. https://doi.org/10.1093/gji/ggx559