
Assessing Basin Amplification and Rupture Directivity Effects Using Physics-Based Ground Motion Simulations in Wellington

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ABSTRACT

Near-surface velocity structure plays a crucial role in modulating ground motions, and in turn, contributes to seismic risk. However, a complete understanding of the basin effect is limited, owing to the paucity of detailed shallow basin structure, geological structures and near-field seismic sources. In this study, we perform physics-based simulations of ground motions incorporating the sedimentary low-shear velocity layers in the Wellington basin to evaluate the fundamental characteristics of regional seismic responses. We simulate ground motions of frequency up to ~ 2 Hz for intermediate-size earthquakes around Wellington then validate acceleration time series and spectral amplitude ratio against GeoNet strong motion records. After that, we simulate potential dynamic ruptures of $M_w \geq 7$ earthquakes on the Wellington Fault, investigating the impact of rupture directivity effects on basin amplification. Our models demonstrate distinct ground intensity patterns arising from dynamic fault ruptures, rather than from distant seismic point sources, revealing significant spatial variation in basin amplification.

1 Introduction

In New Zealand (NZ), sedimentary basins play a crucial role in amplifying surface ground shaking during upper plate earthquakes such as the 2017 M_w 7.8 Kaikoura earthquake (Kaiser et al. 2017; Bradley et al. 2018) and the 2011 M_w 6.2 Christchurch earthquake (Bradley and Cubrinovski 2011; Kaiser et al. 2012). Wellington, the capital city, is prone to high seismic hazard (Gerstenberger et al. 2024), as well as well-documented basin amplification effects arising from the extensive Quaternary sedimentary deposits that directly overlie shallow basement (Kaiser et al. 2019, 2024, Hill et al. 2022). Several previous modelling studies have highlighted aspects of the complex 3D basin amplification effects in Wellington. Adams et al. (2003) reported that the effect of the steep basin edge on amplified ground motion is pronounced in Lower Hutt and might impact

hazard assessment and resilience planning. Benites and Olsen (2005) used 3D physics-based simulations to investigate the impact of the Wellington - Hutt Valley basin on ground motion, using kinematic rupture scenarios mapped onto the Wellington Fault. More recently, Lee et al. (2022;2024) conducted 3D ground motion simulations of regional moderate-sized earthquakes for different basin geometries, seeking to reproduce basin amplification effects in higher spatial resolution, and validating results against local strong motion observations. However, the detailed near-source basin response from significant local earthquakes that dominate the hazard remains unknown, providing the motivation for this study. Using physics-based ground-motion simulations that incorporate fine-scale 3D basin geometry as well as realistic large fault rupture configurations offers a pathway to assess basin effects with realistic geophysical complexities (Wirth et al. 2018).

In this study, we develop 3D physics-based ground motion models for Wellington City, focusing on basin amplification during local earthquakes. A key feature of this study is the incorporation of physics-based spontaneous dynamic-rupture modelling into regional-scale ground-motion simulations, enabling us to capture realistic source complexity and source–path–site interactions that are typically oversimplified in conventional approaches. We integrate the up-to-date shear-wave velocity structure in Wellington basin (Hill et al. 2022) into a national-scale velocity model, ensuring adaptive spatial resolution for complex media in the target domain. We first simulate surface ground motions using local moderate-size seismic sources (M_w 3.7-5.3), validating the simulation approach and basin model against GeoNet acceleration records. Then we model ground motion from spontaneous dynamic rupture scenarios on the Wellington Fault. The dynamic scenarios have fault slip and moment magnitude comparable with paleoseismic records of surface ruptures. We explore the impact of dynamic rupture initiating from both onshore and offshore hypocenters on the Wellington basin.

2. Methods

2.1 Shear-wave velocity model of the Wellington Basin

The most recent geological model of the Wellington Basin integrates geological mapping, borehole records, and geophysical data (Hill et al. 2022). Low shear-wave velocities of the sedimentary layers are represented by 19 geological units with a minimum shear-wave velocity of 160 m/s. We assume a constant P-wave (V_p) to S-wave (V_s) velocity ratio ($V_p/V_s = 1.732$) throughout the basin, although spatial variation might be expected. The basin-scale seismic properties (including V_p , V_s , and density ρ) are merged with the *New Zealand Wide Model 2.2* seismic velocity model (Eberhart-Phillips et al. 2020) to represent the regional crustal structure outside the basin (Figure 1).

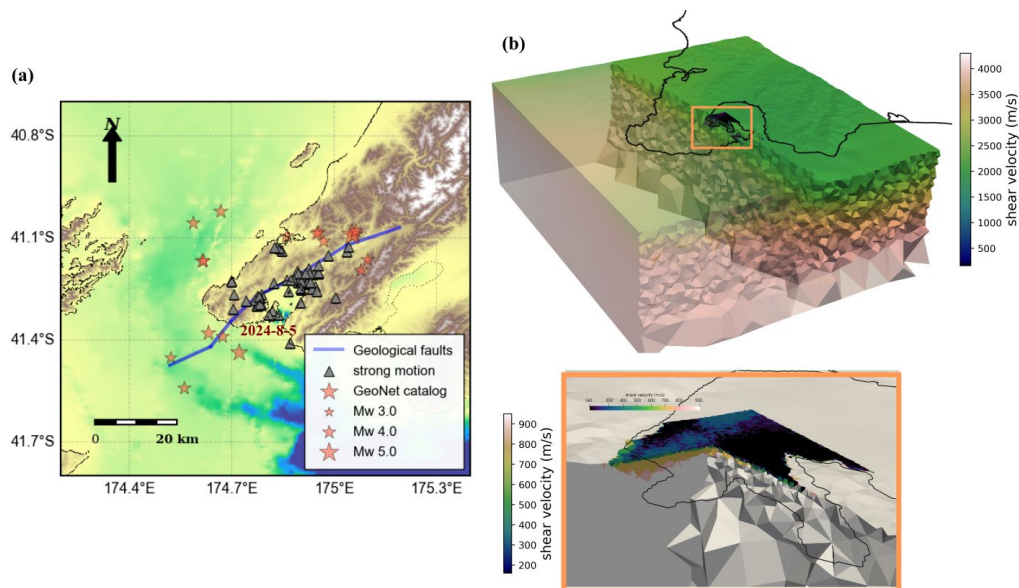


Figure 1: (a) Topographic map of the research domain with selected GeoNet earthquakes and strong motion sites indicated by stars and triangles, respectively. The event on August 5th, 2024 is labelled for the

following analysis. Blue line indicates the surface expression of the Wellington Fault rupture used in the dynamic rupture simulation. Black lines indicate the coastline. (b) Computational domain and 3D velocity model. (c) clipped basin structure with spatially-adaptive mesh size proportional to shear velocity.

2.2 Numerical methods

Figure 1 illustrates the resulting unstructured mesh and shear-wave velocity in the numerical domain. Adaptive mesh refinement clearly outlines the basin geometry, particularly the sharp basin-bedrock interface. The tetrahedral elements have a minimum edge length of approximately 110 m in the basin. The mesh is generated using open-source software GMSH (Geuzaine et al. 2009). The dimension of the computational domain is 100 x 100 x 50 km in *New Zealand Transverse Mercator 2000* (NZTM2000) coordinates, effectively suppressing boundary reflections from contaminating the wavefield. We use the open-source software *SeisSol* (<https://github.com/SeisSol/SeisSol>) to simulate the seismic wave propagation associated with either point sources or dynamic ruptures. *SeisSol* is based on the *Arbitrary high-order DERivative Discontinuous Galerkin* method (ADER-DG) (Dumbser and Käser 2006; Käser and Dumbser 2006) and employs fully adaptive, unstructured tetrahedral meshes to combine geometrically complex 3D geological structures and high-order accurate propagation of seismic waves (Pelties et al. 2014; Uphoff et al. 2017; Taufiqurrahman et al. 2023).

In this numerical framework, we consider two types of seismic sources: (1) point sources described with GeoNet focal mechanisms solutions (Ristau et al. 2013) and empirical source time functions (Section 2.3); (2) spontaneous dynamic rupture scenarios on Wellington Fault constrained by paleoearthquake records (Section 2.4). In both cases, the seismic properties of the 3D medium are interpolated into adaptive unstructured tetrahedrons (Section 2.1). Spontaneous dynamic rupture modeling requires slip weakening conditions on the fault interface, and thus explicitly additional physical variables on an internal surface (Pelties et al. 2014).

2.3 Regional earthquake catalog and seismic source characteristics

From the GeoNet moment tensor catalogue, we select a total of 18 earthquakes located within a radius of 0.3 arc-degree from the center of the Wellington basin (Figure 1a). These events occurred between 2009 and 2025 and have moment magnitudes ranging from 3.7 to 5.3. The event located closest to the center of the Wellington basin occurred on August 5th, 2024 with a moment magnitude of 4.3 (Figure 1a). We created the source time functions (STF) following the method of Liu et al. (2016), which is suitable for crustal moderate-size earthquakes. The STF is normalized so that its time integral is 1.0. The rise time of STF is set to be 1.5 s, although seismological studies might indicate magnitude-dependent scaling duration for intermediate-size earthquakes (Mai and Beroza 2000). Considering the source-to-site distance of the selected events, the constant duration is reasonable for simulating seismic waves.

2.4 Spontaneous dynamic rupture scenarios in Wellington-Hutt Valley fault

We simulate spontaneous three-dimensional (3D) dynamic rupture scenarios (Figure 4a) corresponding to $M_w \geq 7.0$ earthquakes inferred from paleoearthquake measurements in the Wellington region (Van Dissen and Berryman 1996). In the dynamic rupture models, the stresses are time-dependent and freely allowed to vary after the forced nucleation (Harris et al. 2018). We assume an initial stress tensor consistent with an Andersonian regime that promotes right-lateral strike slip on the Wellington Fault. The horizontal compression is controlled by SH_{max} which is set to be $N80^\circ$, consistent with the seismic focal mechanism inversion in central New Zealand (Townend et al. 2012). The relative stress amplitude in the initial setup is characterized by a seismic ratio S , defined as $\frac{\sigma\mu_s - \tau_0}{\sigma\mu_s - \sigma\mu_d}$, where σ is the normal stress, μ_s and μ_d are the static and dynamic friction coefficients, and τ_0 is the initial shear stress (Andrews 1985; Harris et al. 2018). Figure 4b shows this S ratio which reflects the closeness to rock failure defined by Mohr-Coulomb yield criterion is widely used in earthquake rupture simulations (Andrews 1985; Harris et al. 2018). To suppress fault slide below seismogenic zone, we assign a seismogenic depth of 11 km and a transitional band in depth between 11 and 12 km. Below 12 km deviatoric stress is tapering to zero and off-diagonal stresses are zero.

Two positions are selected to nucleate the earthquake: 1) off-shore in the southern segment or 2) on-shore in the northern segment (Figure 4c). After the fault is forced to slide within the nucleation radius, the fault slip

spontaneously extends due to the coupled evolution between dynamic stress in the volumetric domain and the friction weakening on the fault. The selected nucleation locations will affect the entire dynamic rupture process given the finite length of fault, heterogeneous stresses and complex material settings (e.g. Harris et al. 2021; Li et al. 2025). Here we limit our discussion to these two options, noting other hypocenter locations are possible within the uncertainties from geological studies in Wellington (Van Dissen and Berryman, 1996). The complete simulation for dynamic rupture and seismic wave requires approximately 1,000 CPU-hours on 128 AMD Genoa 9634 CPUs on the New Zealand eScience Infrastructure (NeSI). Simulating 40 seconds of dynamic rupture and wave propagation took about 3 hours wall clock time for each scenario.

3.RESULTS

3.1 Validation of seismic waves and Fourier amplitude spectra (FAS)

While the dynamic rupture simulations are designed to investigate the influence of near-source fault source dynamics on ground motions, the point-source models are primarily used to validate the 3D velocity model and basin structures against local strong motion records. We first examine the simulated wave field for one selected event on August 5th, 2024 (Public ID: 2024p587797). Figure 2a compares simulated and recorded acceleration Fourier amplitude spectra at selected stations. All seismic waveforms are bandpass filtered between 0.02–2.0 Hz. In order to reduce the influence of uncertainties in earthquake location, specifically in seismic crustal velocity models, event magnitude, and source depth due to limited inland stations, the simulated waveforms are normalized by a constant scaling factor C_i . We defined $C_i = \frac{A_{i,max}^{mod}}{A_{i,max}^{data}}$ for an event i , where $A_{i,max}^{mod}$ and $A_{i,max}^{data}$ denote the modelled and recorded maximum horizontal amplitude recorded at broadband site SNZO, respectively. This normalization is performed directly in time domain without any manipulation of Fourier spectra.

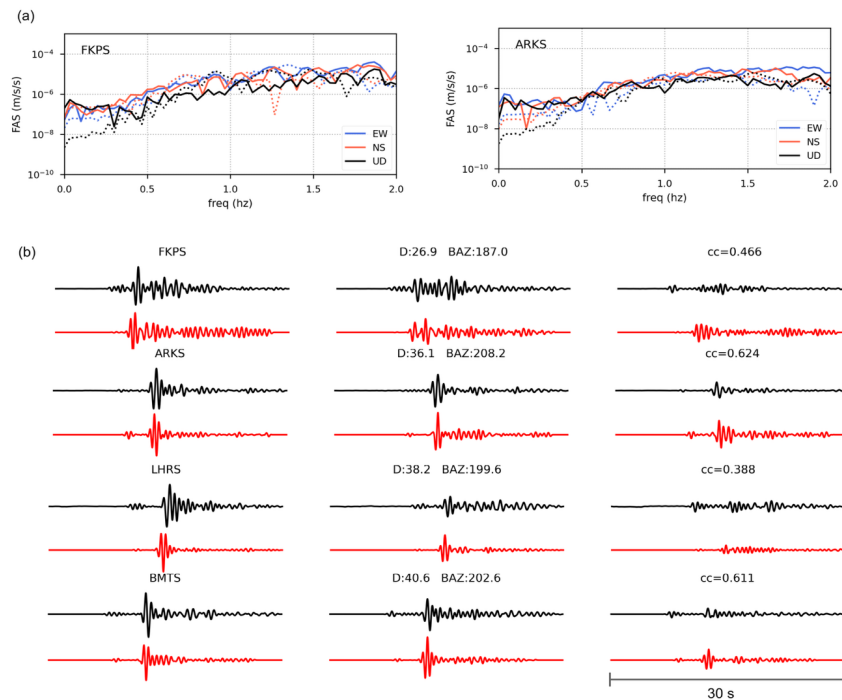


Figure 2: a) Comparison of observed (solid) and scaled simulated (dashed) acceleration Fourier amplitude spectra at FKPS and ARKS. (b) Comparison of observed waveforms at selected local strong motion stations (black lines) and simulations (red) ordered by epicentral distances. Three columns are components EW, NZ, and UD, respectively. The amplitudes are normalized by the maximum horizontal components. The station code, epicentral distance (D) in km, back azimuth (BAZ), and cross-correlation coefficient are labelled for each event.

The agreement of filtered waveforms at four sites are shown in Figure 2b, labelled by epicentral distance and azimuthal angle. To evaluate overall waveform agreement, we compute cross-correlation coefficients for all waveform pairs shown in the histogram in Figure 3b. Figure 3b shows the two-dimensional histogram as a function of arrival time shift between simulated and recorded waveform. Most waveform pairs have time shifts within 0–2 s and cross-correlation coefficients above 0.5, indicating a reasonably good agreement between simulations and observations.

Figure 3a summarizes the bias of FAS, defined as the logarithmic difference between the simulated and the recorded acceleration waveforms averaged on all catalogue events, at four sites in Wellington basin. The overall fit is good especially for frequency of 0.02–2.0 Hz. The mean trends to zero, reflecting the overall good fit of the simulated ground motion. The larger misfits between 0.02 and 0.3 Hz might reflect the uncertainties in source parameters, including epicentral location, focal depth and magnitude.

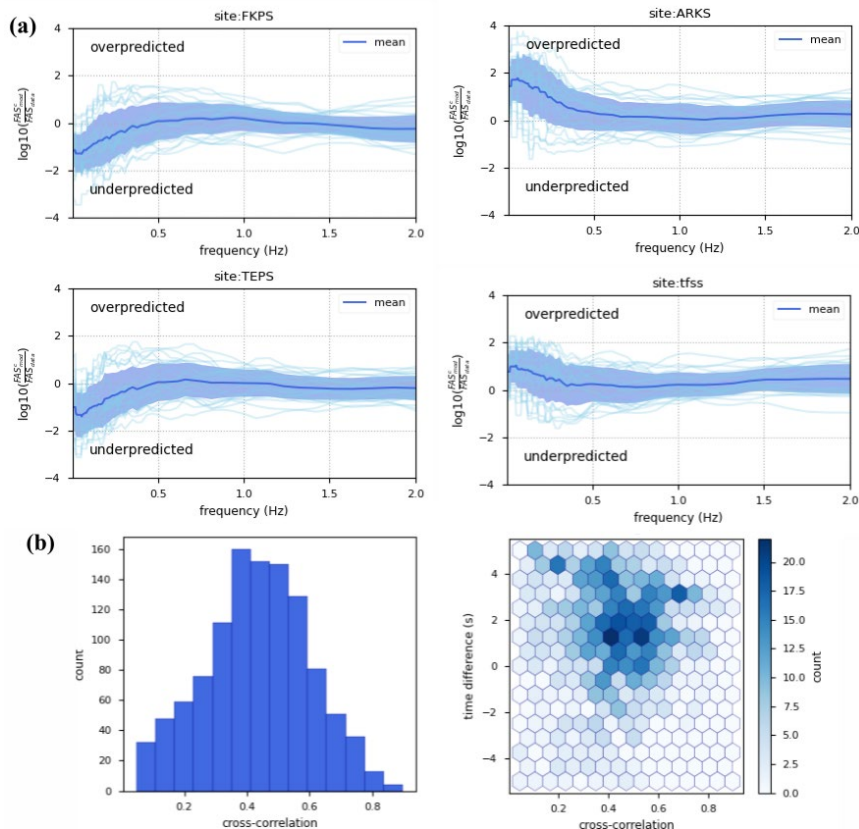


Figure 3: a) Bias of scaled Fourier acceleration spectra at selected stations (FKPS, TEPS, ARKS and TFSS) averaged over all recorded seismic events. b) Histogram of cross-correlation of two horizontal components of each station-source pair and 2D histogram of cross-correlation and time shift of the maximum cross-correlation value for all events.

3.2 Dynamic rupture scenarios of the Wellington fault

The dynamic rupture simulation provides detailed insights into the time-dependent stress transfer and slip evolution in the seismic sources. Since no instrumentally derived model of Wellington Fault slip is available, we select two preferred rupture models that produce moment magnitudes consistent with paleoseismic estimates (Van Dissen and Berryman, 1996). For a 75 km long rupture of the Wellington Fault, paleoseismic studies suggest moment magnitudes M_w 7.0–7.8 and average surface slip of approximately ~3.7 m (Berryman, 1990). The estimated magnitude and fault slip is consistent with empirical source scaling relations for upper-plate earthquakes (Thingbaijam et al., 2017). Higher magnitudes in numerical simulation are feasible in rupture simulations by assuming heterogeneously higher initial stress excess (i.e. lower S ratio) or a wider seismogenic zone.

Both rupture scenarios propagate along the entire Wellington Fault after the nucleation, in both the onshore (Scenario A) and offshore (Scenario B) scenarios (Figure 4c). In Scenario A, fault rupture initiates from the northern fault segment and continuously propagates southward, terminating after approximately 20 s. The entire rupture is about 75 km long, producing a moment magnitude of Mw 7.1. In Scenario B, the earthquake is nucleated in the southern offshore segment and propagates northward at a rupture velocity of 3 km/s, terminating at approximately 20 s. Although the total moment magnitude and slip distribution are similar between the two scenarios, the rupture pathways are substantially different. These differences lead to different ground motion intensity patterns, as shown in Figure 4d.

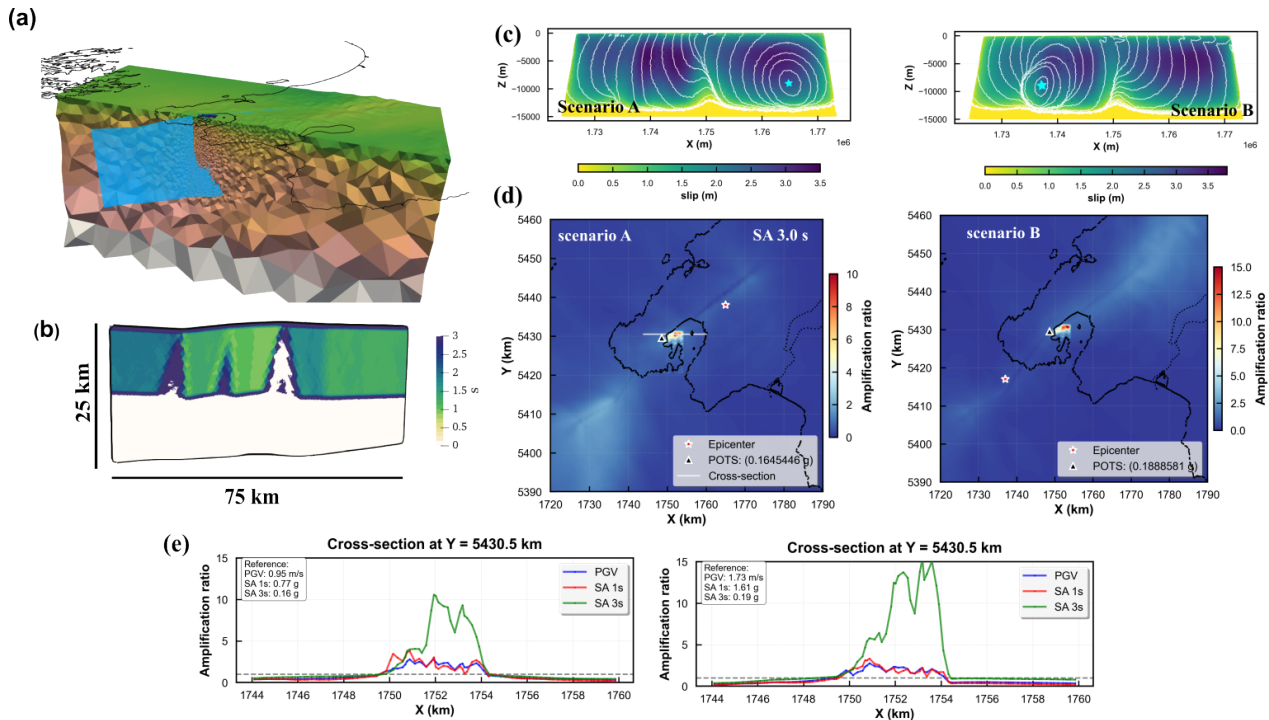


Figure 4: a) Cross-sections of unstructured tetrahedral computational mesh showing representative near-fault refinement. 3D S-wave velocity is coloured in the same scale as Figure 1b. Fault interface is coloured in blue. Black lines outline NZ coast. b) Seismic ratio S on the fault plane. c) Simulated dynamic rupture scenario A and B on segments of the Wellington Fault (cut off below 15 km). Surface projections of the nucleation is labelled with stars. The moment magnitude (M_w) of the two scenarios are 7.10 and 7.11, respectively. White lines represent contours of rupture front at every 0.5 s. Maximum fault slip is 3.5 and 3.8 m for scenarios A and scenario B, respectively. d) Map view of amplification ratio computed as amplitude to reference site (POTS) for SA 3.0 s. Reference site is indicated by triangle. e) Section showing amplification ratio of PGV (blue), SA 1.0 s (red), and SA 3.0 s (green). The ground intensities at POTS are labelled in upper-left corner. The position indicated by white line in (d).

3.3 Basin amplification from point-source models and dynamic rupture scenarios

Amplification within the Wellington basin has been investigated using both local moderate-size earthquakes and two dynamic rupture scenarios. We compute the amplification ratios for all surface elements relative to the reference bedrock site POTS. The point source for the 2024 August 5th event is offshore, and for this event peak ground motion at reference site POTS is quite small due to the long distance (Figure 5a). However, the amplification ratio of SA 1.0 s is significantly increasing up to 8 at the basin edge. The amplification ratio in the center of the basin is also enhanced, suggesting strong spatial variation as seen in other studies (Kaiser et al. 2024). In this event, amplification ratios are much higher for spectral acceleration (SA) at 1.0 s than 3.0 s, an observation which is compatible with the intermediate period amplification (1 - 2.5s) observed in Wellington – Lower Hutt. Simulated ground motion intensities compare well with observations from the *New Zealand Ground Motion Database* (NZGMDB) and align with empirical ground motion model of New Zealand (Atkinson 2023), indicating enough numerical resolution and structural configuration (Figure 5b).

The amplification ratio maps of the two dynamic rupture simulations are quite distinct from regional events as shown in Figure 4. Both scenarios created significant basin amplification in the Wellington basin for PGV intensities. However, the ground motion patterns are significantly different near the fault ends, illustrating the impact of near-source directivity effects arising from the extended fault ruptures. Different peak values of basin amplification are found in the two scenarios, highlighting that amplification is sensitive to the source scenario. Comparing Figure 4d and 4e, the basin amplification ratio is higher in Scenario B when rupture propagates offshore to onshore. The basin response is also seen in all intensity measures (PSA1.0 s, 3.0s, PGV) at somewhat lower amplitude in Scenario A. The amplification ratios of SA 1.0 s are lower overall when rupture propagates offshore, even compared to the 2024 August 5th event where the epicentral distance is larger. However, obvious difference arises in SA 3.0 s as scenario B yields a 1.5 times higher peak in the basin compared to scenario A. This distinction aligns with the reported amplifications in Seattle basin from offshore events by Wirth et al. (2018), although their focus is subduction reverse-slip events. This example further demonstrates the combined influence of rupture directivity and basin structure.

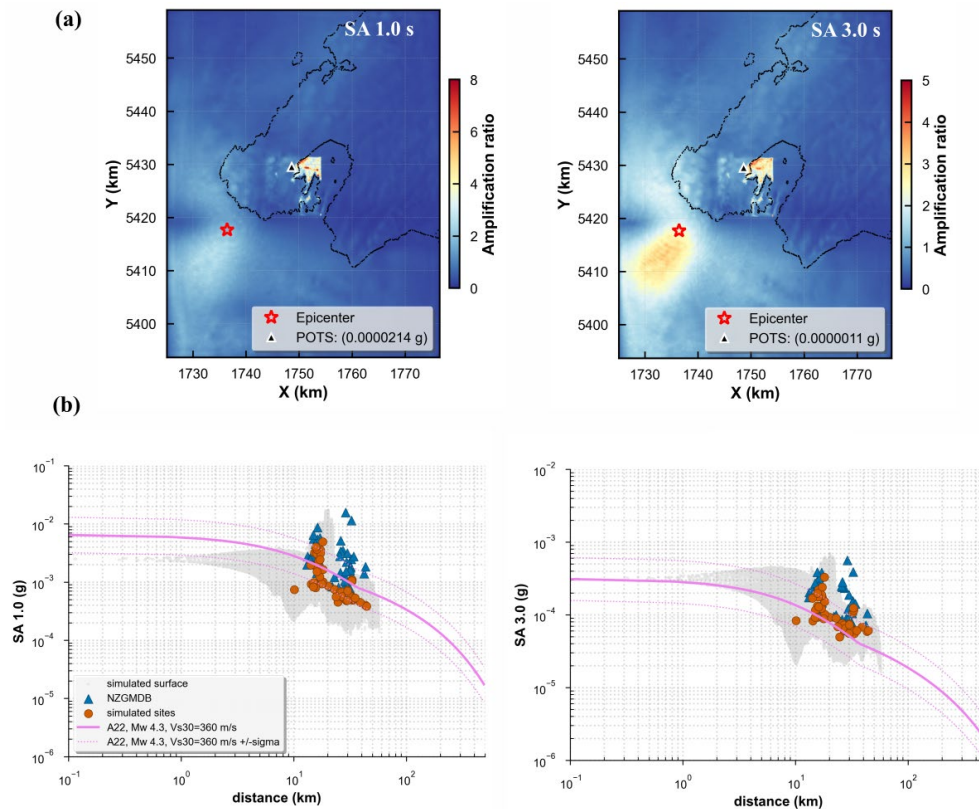


Figure 5: a) Amplification ratio of SA 1.0 s and SA 3.0 s for the simulated event. The reference strong motion station is POTS (triangle). b) Comparison of the observed (blue) and simulated (orange) ground motion intensity at 42 GeoNet strong motion stations for SA 1.0 s and SA 3.0 s; observed intensities sourced from New Zealand Ground Motion Database (NZGMDB; Hutchinson et al. 2023). Empirically predicted ground motions (SA 1.0 s and SA 3.0 s with R_{jb} distance are computed following Atkinson (2023), assuming $M_w=4.3$ and $V_{s30} = 360$ m/s. Dashed line are standard deviation in logarithmic scale (i.e. 1.25 in linear scale). No amplitude is normalized in this plot.

4. DISCUSSION AND CONCLUSIONS

The Wellington basin is shallow and infilled with Quaternary sedimentary layers and is therefore prone to strong seismic amplification, as observed in the latest large earthquakes such as the 2016 Mw 7.8 Kaikōura event (Kaiser et al. 2017; Bradley et al. 2018) and the 2013 Mw 6.6 Cook Strait event (Holden et al. 2013). Previously, Benites and Olsen (2005) reported significant amplified ground shaking at longer periods (>1.0 s) from kinematic ruptures, with different patterns associated with north-to-south and south-to-north propagation

along the Wellington-Hutt Valley segment of the Wellington Fault. This rupture directivity effect is consistent with findings from the Seattle Basin where offshore ruptures were shown to generate stronger basin amplification (Wirth et al. 2018). In the present study, using dynamic rupture simulations, we observed an increase in amplification factors of up to 3 times when the rupture initiates on the offshore segment of the Wellington Fault and propagates towards Wellington. Further validation and investigation of a wider range of realistic rupture scenarios on the Wellington Fault and other sources contributed to seismic hazard in Wellington, would aid in robustly quantifying the variability of expected amplification. In addition, consideration of the impact of non-linear effects on amplification is also desired, given that these are expected to impact high and intermediate frequency ground motions in Wellington (de la Torre et al. 2023).

Overall, our study is consistent with previous conclusions, that strong 3D basin amplification effects in the 1-3 s period range occur in Wellington and are variable according to the source rupture scenario (i.e. near-source directivity effects). While basin amplification effects are commonly observed in sedimentary basins, these Wellington amplification effects are of particular interest as they coincide with the fundamental period of resonance of mid-rise buildings in the populated central business district (Kaiser et al. 2017). Evaluation of observed (linear) amplification in central Wellington with respect to 2022 NSHM ground motion models (Kaiser et al. 2024; de la Torre et al. 2024) showed that some sites exhibit amplifications close to mean predictions, while many sites (particularly in the deeper/softer parts of the basin) exhibit higher and more strongly peaked amplification effects; while this amplification might deviate from the mean, it is expected to be captured within the uncertainties of the ground motion models considered in the NSHM 2022. Given the substantial seismic risk from nearby active faults, capturing these complex basin effects with consideration of source-basin interactions (as highlighted in this study) and nonlinear effects (e.g. de la Torre et al. 2023) is important for accurate ground-motion prediction.

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