Low Frequency Non-Ergodic Synthetic Modeling of Earthquake Basin Effects in Wellington, New Zealand

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Abstract

The 2016 7.8 magnitude Kaikōura earthquake in the South Island of New Zealand consisted of a complex sequence of ruptures, lasting approximately two minutes. During the earthquake, the Wellington capital region experienced unexpected localized zones of damage due to focused seismic energy within its sedimentary basin. Some modern buildings adjacent to Wellington Harbour sustained devastating damage, while historical districts of low-rise unreinforced masonry sustained little to no damage. As seismic waves travel through soft sediments in basins like those underlying Wellington, energy moves at slower velocities and produces elevated shaking amplitudes. These effects accompany prolonged duration of ground shaking and are factors in the Kaikōura damage and the increased risk of damage and injury citywide. In order to understand how waves propagate through the basins of the Wellington region, we computed 27 low frequency (<0.6 Hz) 3D shaking models using SW4 software from Geodynamics.org. Three 3D velocity models were tested, one which contrasts an older geologically-based GNS Science basin model having a maximum sediment thickness under the city of 250 m, a second that included newly developed gravity-based model by Stronach and Stern with a maximum thickness of 540 m under the city, and a 1D model with no basins at all. Each scenario run took about 3 hours on an Intel MacBook. Our research aims to determine if the adjustments of sedimentary basin thickness under the city made by Stronach and Stern produce a substantial difference in how seismic waves travel. Not only will these results help us to understand focused seismic energy within sedimentary basins, it will also help inform hazard planning and preparation for expected seismic events.

Introduction and Methodology

SW4, developed at Lawrence Livermore National Laboratory (LLNL), is an open source software program used for simulating seismic wave propagation (Petersson and Sjögreen, 2017). Using SW4 software, three sets of nine M3.3 scenarios were built with epicenters in different locations. Nine models were built for the integrated Stronach and Stern and GNS basin models, nine models using only the GNS basin model, and nine models without basin data. 27 total earthquakes were built of the same size and mechanism in a compass rose near the edges of the GNS basin model. This process explored a variety of basin responses to events in every different direction, making each basin scenario non-ergodic.

	E1	E2	E3	E4	E5	E6	E7	E8	E9
Location	NW	N	NE	E	SE	S	SW	W	Basin Center
Longitude	174.7756	174.84416	174.90338	174.90198	174.90239	174.83946	174.77424	174.77448	174.84121
Latitude	-41.23952	-41.23997	-41.24028	-41.27601	-41.31496	-41.31455	-41.31258	-41.27393	-41.27553

Table 1: Earthquake 1-9 locations used in simulation.

Depth, m	Strike	Dip	Rake	Magnitude	Frequency	Minimum Velocity
10,000 m	44°	80°	-180°	3.3	0.3 Hz	350 m/s

Table 2: Earthquake 1-9 constant parameters used in simulation.

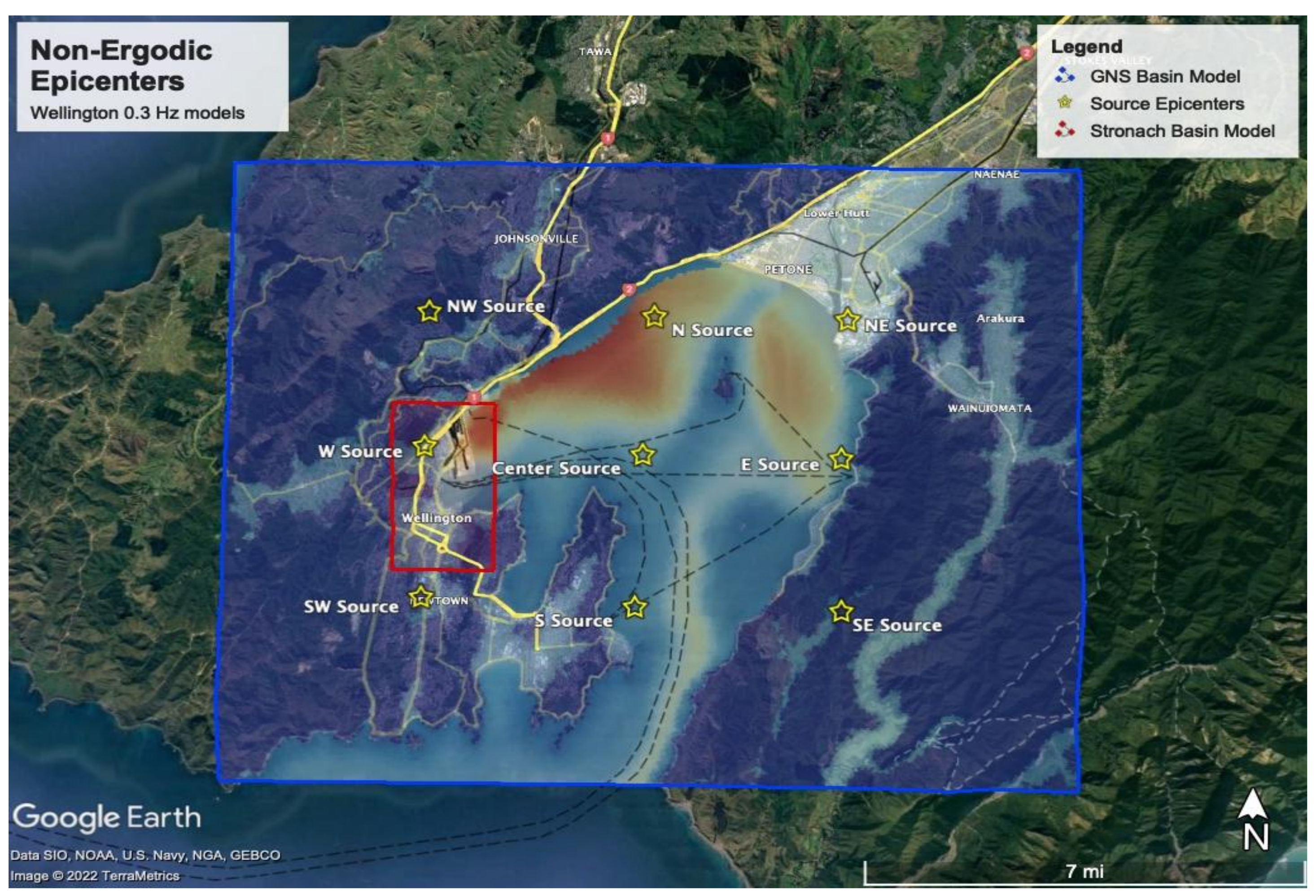


Figure 1: Map of the Wellington, New Zealand region. Epicenter locations within the Stronach (red rectangle area) and GNS Science (blue rectangle area, of Fig. 2) basin models. Sedimentary basin thicknesses are dark blue at zero and dark red at the 580 m maximum (Benites et al., 2005).

Basin Thickness Models

GNS Science Model

The older GNS basin model, derived using geological and geophysical data, has a maximum sediment thickness under the city of 250 m (Benites et al., 2005).

Stronach Model

The newly developed Stronach and Stern basin model derived by gravity surveying is two times greater in basin thickness than previous geologically-based estimates. The model measures a maximum basin thickness of 540 m under the city (Stronach et al., 2021), and spans a limited area of only 10 square km within Wellington's Central Business District (CBD).

Peak Ground Velocity (PGV) Maps

Data produced from our simulations allowed us to analyze predicted ground motions and wave velocity between diverse rock types throughout the Wellington region.

Basin Amplification PGV Maps, Stronach divided by No Basin

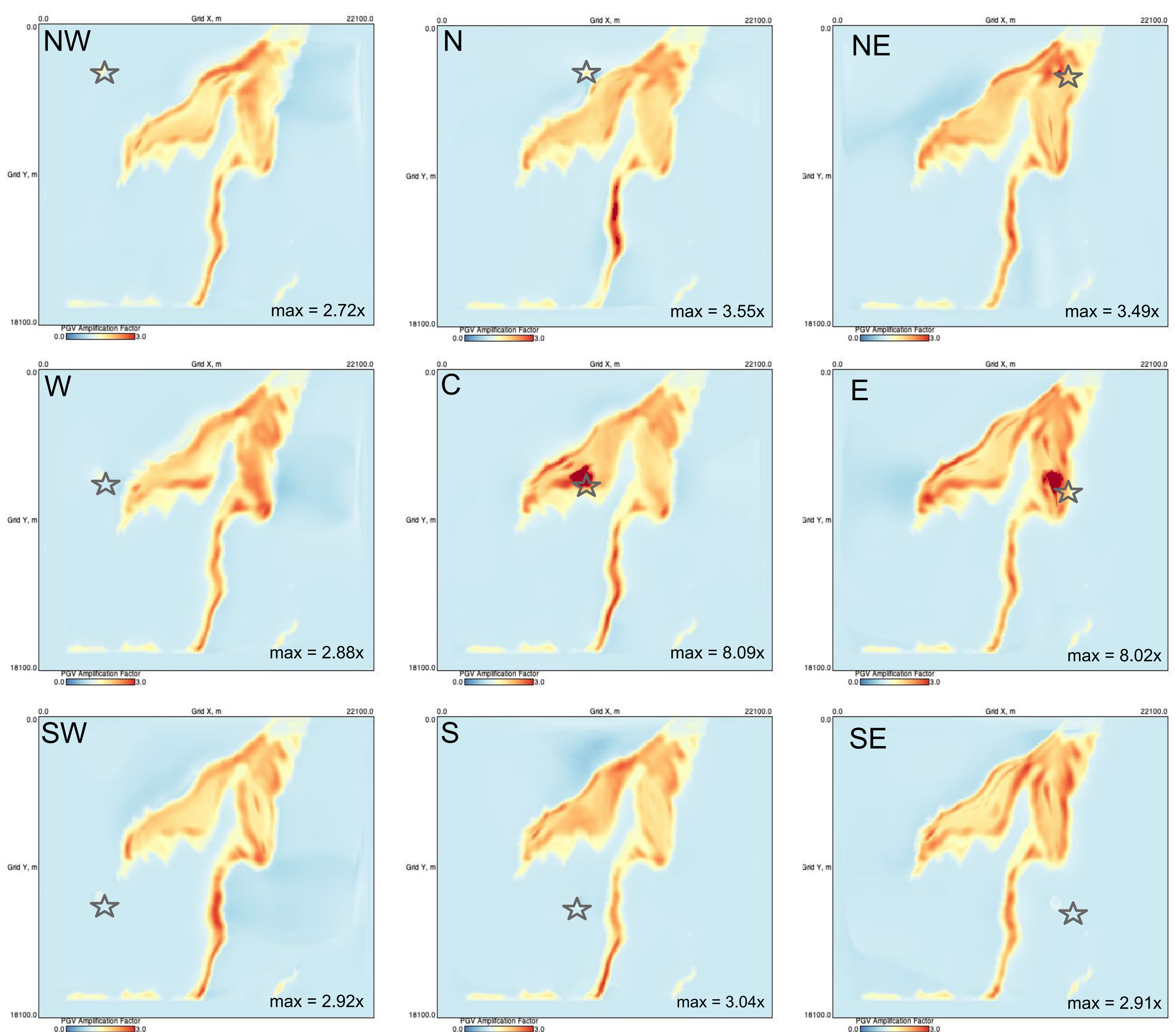


Figure 2: PGV-ratio basin-amplification maps of the blue rectangle area of Fig. 1, computed to 0.6 Hz for earthquakes 1-9, clipped at a max amplification of 3. Earthquake epicenter locations are marked by a star. Basin de-amplification is blue; an amplification of 1x is white; 3x is dark red.

Non-Ergodic Basin Amplification Average PGV Ratio Maps

Figure 3: Stronach / GNS Only

A. Non-Ergodic Average Map
Minimum Deamplification (blue) 76%
Maximum Amplification (orange) 170%

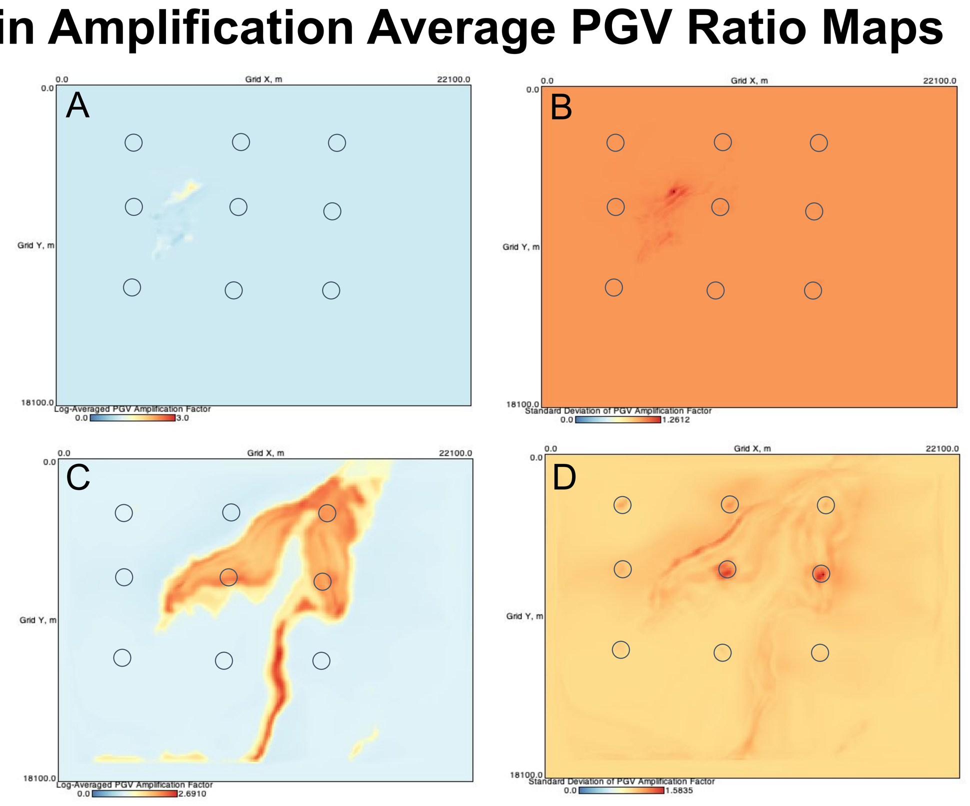
B. Amplification Standard Deviation Map
Min. Standard Deviation (orange) 0%
Max. Standard Deviation (red) 26%

Figure 4: Stronach / No Basin

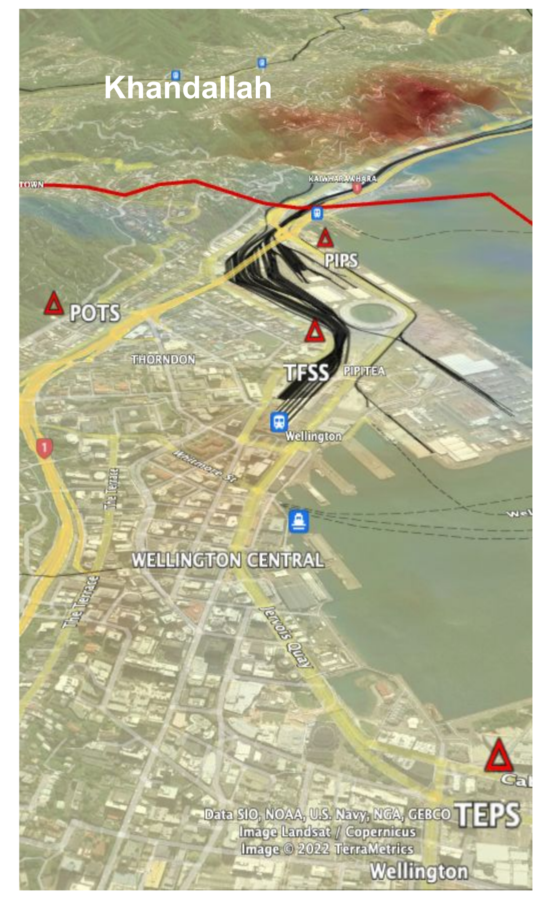
C. Non-Ergodic Average Map
Minimum Deamplification (blue) 91%
Maximum Amplification (red) 269%

D. Amplification Standard Deviation Map
Min. Standard Deviation (yellow) 0.2%
Max. Standard Deviation (red) 58%

*Note: Black circles show the 9 source locations above which the No Basin model produces unphysically small shaking.



Synthetic Seismograms



Using Seismic Analysis Code for all 27 models, we built x-component synthetic seismograms for 4 seismic stations located within the Stronach and Stern basin model. We chose these stations to observe basin effects in Wellington CBD.

- PGV Analysis (Figure 3) showed substantial amplification and deamplification within as well as outside the Stronach model area.
- Both synthetic seismograms and PGV maps show basin amplifications of 2-3x.
- The seismograms show basin trapped waves that extend the duration of shaking by at least 5 seconds.
- From Eckert et al. (2022), we would expect amplifications to be even greater at higher frequencies.

Figure 5: Oblique view of Stronach / GNS Only Amplification Map
Though outside the Stronach area, the Khandallah hills north of Wellington CBD experience additional amplification (red color).

- PIPS (Aotea Quay Pipitea Station) - strong motion sensor
- POTS (Wellington Pottery Assoc. Station) - accelerometer sensor
- TEPS (Wellington Te Papa Museum Station) - accelerometer sensor
- TFSS (Wellington Thorndon Fire Station) - strong motion sensor

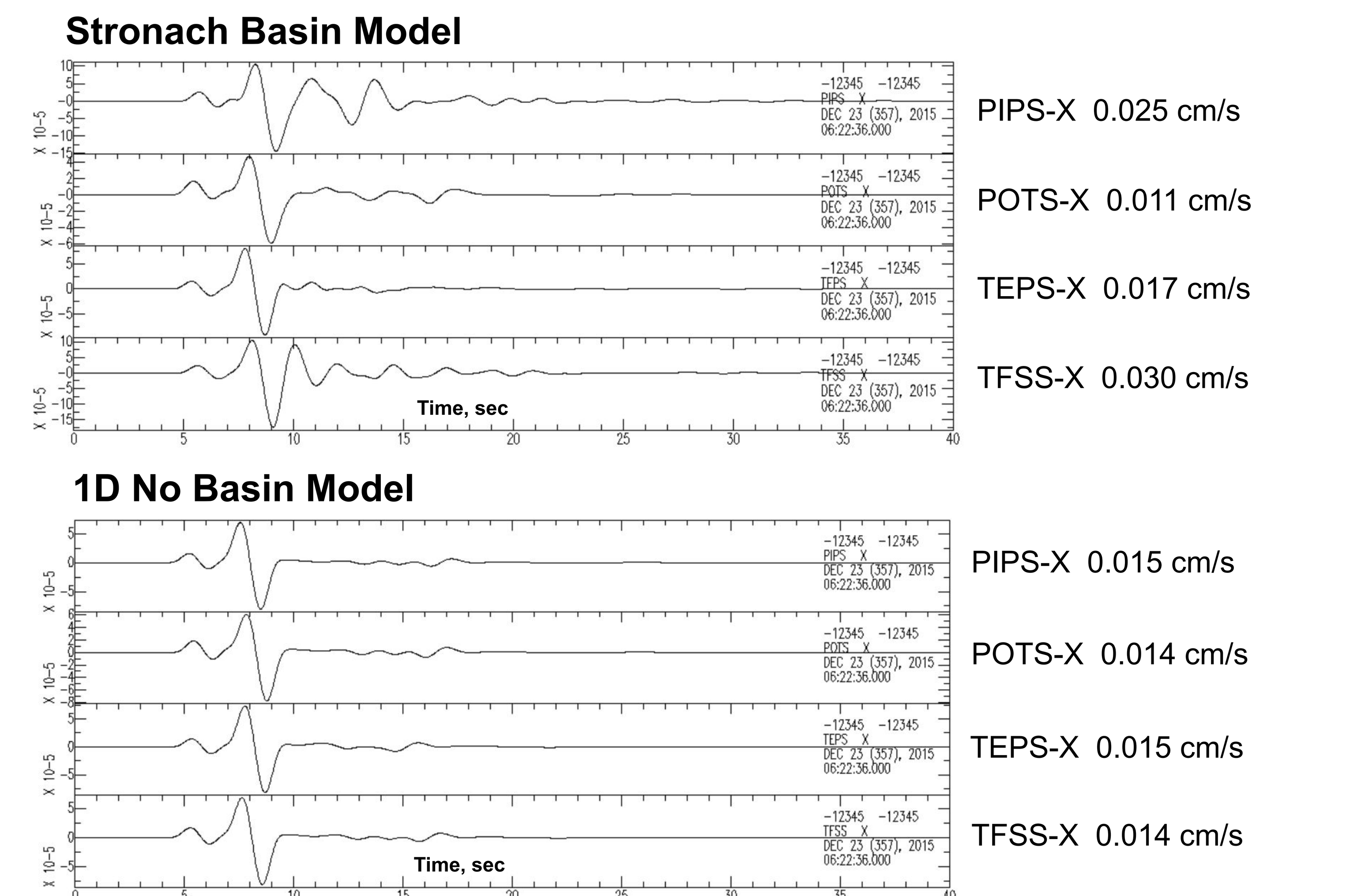


Figure 6: Synthetic seismogram x-component comparisons for seismic stations PIPS, POTS, TEPS and TFSS (located by Fig. 5) up to 0.6 Hz show differences between Stronach (upper) / No Basin (lower) models.

Conclusion

Non-ergodic PGV maps from nine distributed M3.3 virtual quakes indicate that the adjustments of sedimentary basin thickness under the city of Wellington made by Stronach and Stern produce a substantial difference in how seismic waves travel compared to the older GNS Science model. Even at low frequencies of <0.6 Hz, the Stronach model suggests further ground motion amplification of 155% above the amplification of the GNS Science basin model. The further amplification peaks outside the area of the Stronach model near the neighborhood of Khandallah, just above State Highway 1 and the main rail line.

Due to hardware limitations, simulations were built with an increased minimum shear-wave velocity paired with lower frequencies. We expect to overcome this restriction by using remote computer access for future simulations. Ongoing research will compare models with recorded earthquake data over the same frequency to validate results.

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