# Exploring Basin Amplification Within the Reno, Nevada and Wellington, New Zealand Metropolitan Areas with Non-Ergodic Physics-Based 3D Scenarios

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## Introduction and Methodology

The effects of sedimentary basins on ground motion can increase seismic hazard through three primary processes: the focusing of S waves at the basin edge or at changes in basin depth, the conversion of S waves into surface waves with greater amplitudes, and the amplification of S and surface waves as they pass boundaries between rock and soft sediment (Thompson et al., 2020).

SW4, developed at Lawrence Livermore National Laboratory (LLNL), is open-source software useful for simulating seismic wave propagation in urban basins (Petersson and Sjögreen, 2017; Eckert et al., 2022). Using SW4 software, in Reno, Nevada, USA we modeled basin amplification of shaking from six M3+ events in and out of the Reno-area basin. For Wellington, New Zealand we modeled three sets of nine M3.3 scenarios with fictitious epicenters in nine 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.

This research explored a variety of basin responses to ergodic events in different directions, combining results from multiple events to produce non-ergodic views of potential basin amplification for each city at <1 Hz.

## Basin Thickness and Velocity Models

Eckert et al. (2022) combined basin thicknesses based on gravity analyses (Abbott & Louie, 2000) and deep refraction microtremor surveys (Pancha et al., 2017) with geotechnical measurements from Louie (2020) and Louie & Simpson (2020) into a comprehensive Reno CVM we use here. The older GNS basin model, derived using geological and geophysical data, has a maximum sediment thickness under Wellington's CBD of 250 m (Benites et al., 2005). The newly developed Stronach and Stern basin model derived from gravity surveying has a maximum basin thickness of 540 m under the city (Stronach et al., 2021). The Vs(z) database of Louie (2020) contributed >30 shear-wave velocity measurements to <100 m depth to the Wellington CVM used here.

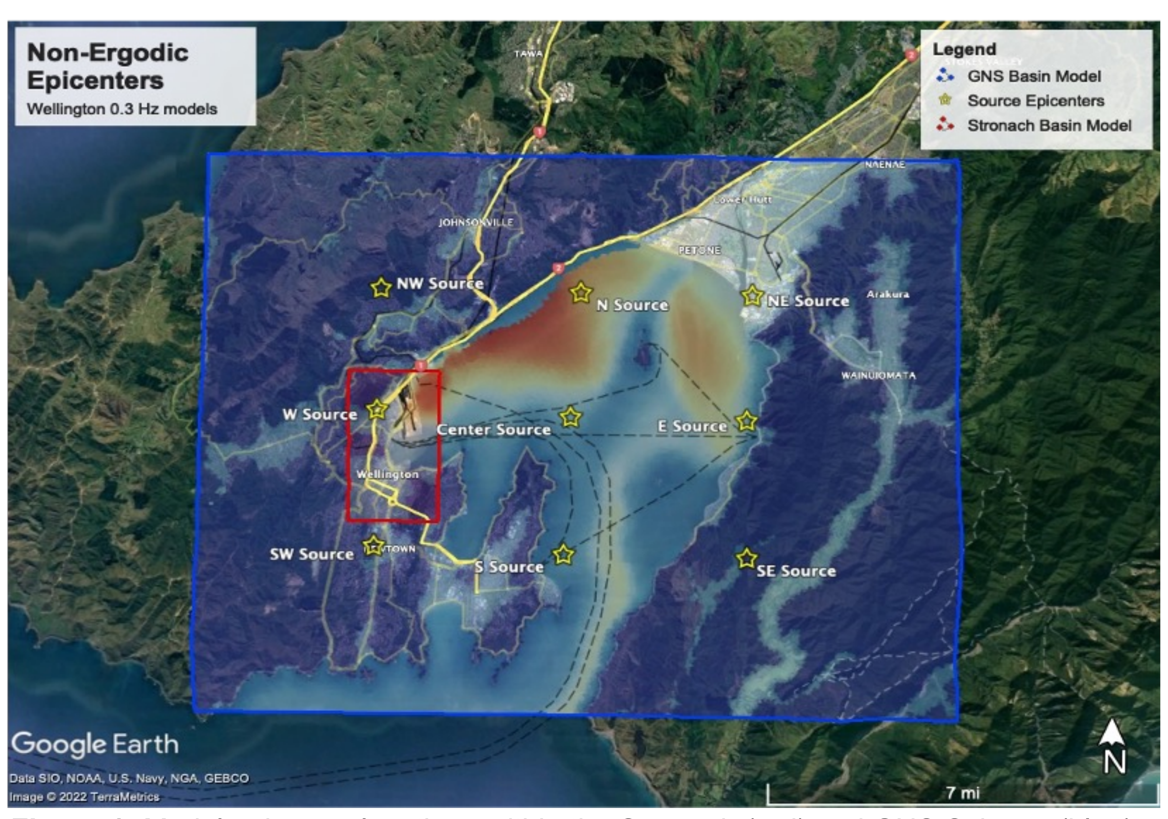



**Figure 1:** Model epicenter locations within the Stronach (red) and GNS Science (blue) basin models for Wellington, New Zealand.

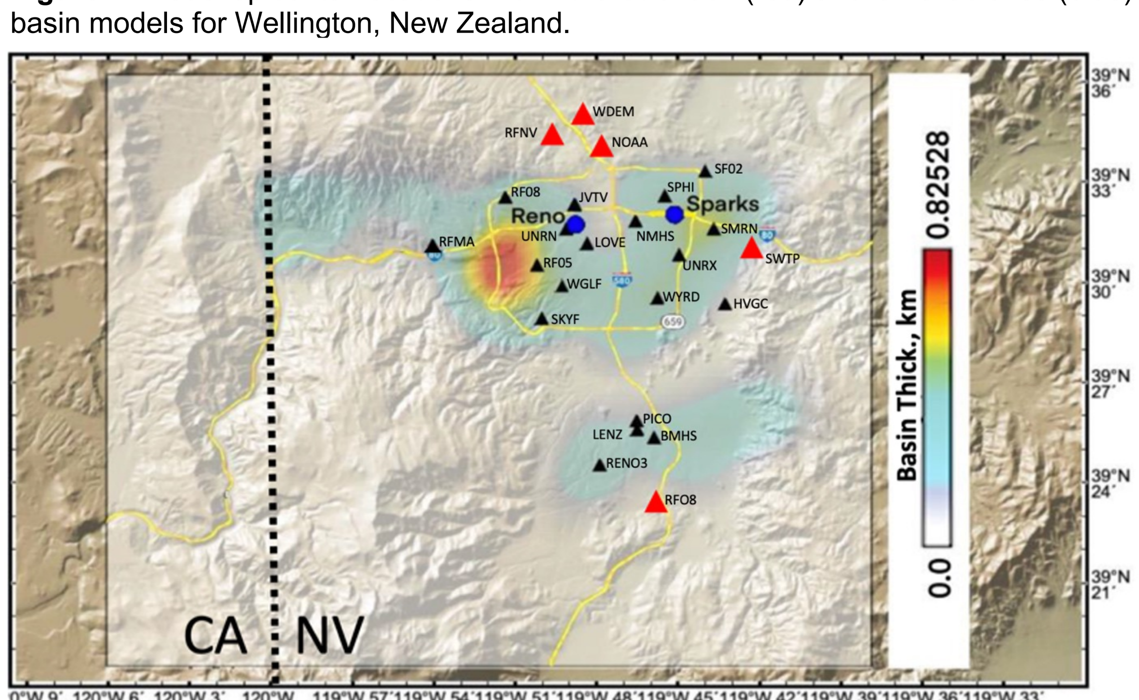



**Figure 2:** Thickness of Truckee Meadows basin from Abbott & Louie (2000). The location of basin stations and bedrock stations are represented by black and red triangles, respectively. Basin thickness is less than 0.5 km in most of the Truckee Meadows, reaching a maximum of 0.9 km in the west Reno sub-basin.

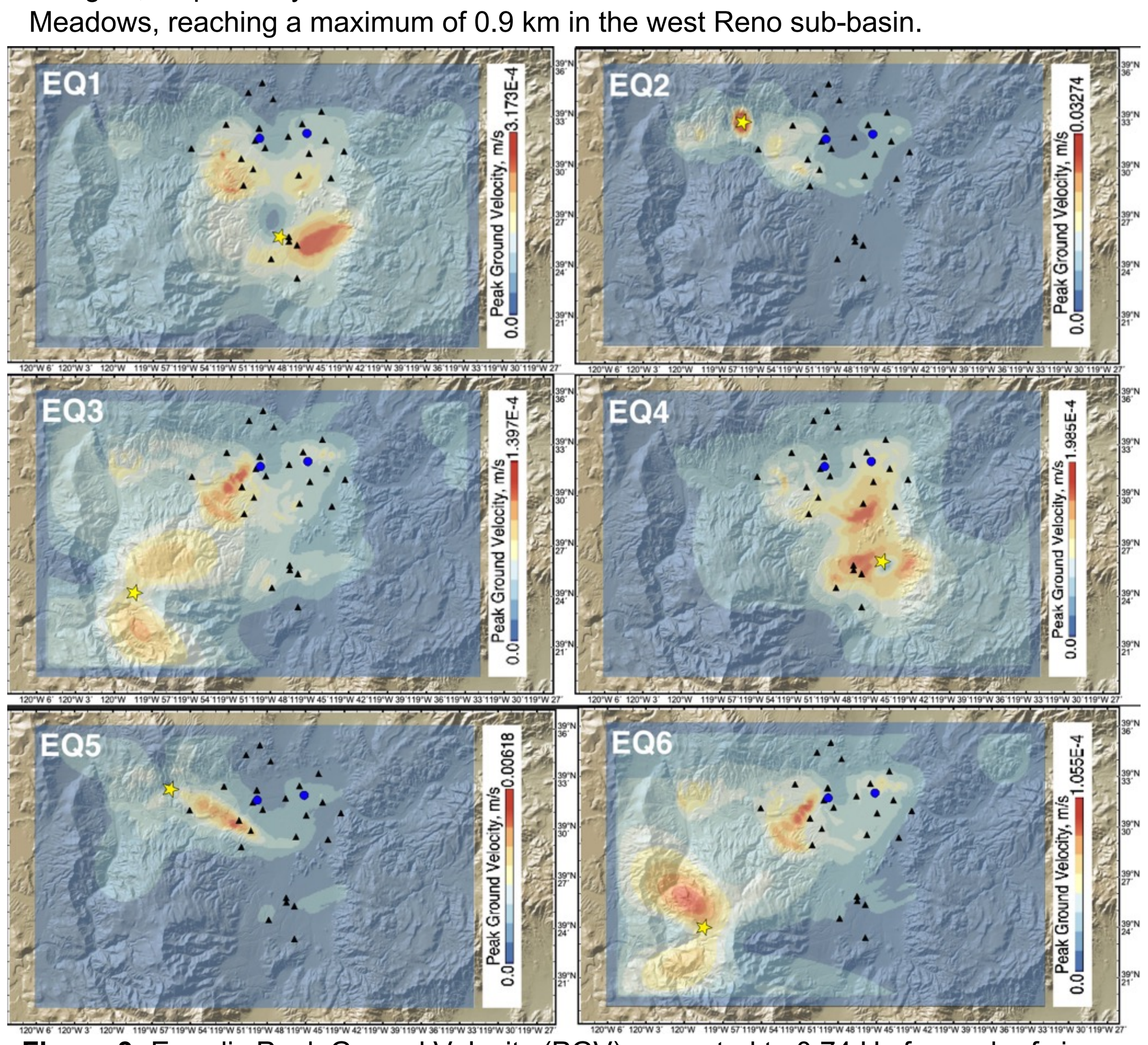



**Figure 3:** Ergodic Peak Ground Velocity (PGV) computed to 0.74 Hz for each of six minor earthquakes in the Reno area. Station locations are marked by black triangles; yellow stars indicate quake epicenters; blue circles mark the locations of Reno and Sparks, Nevada. Each quake has different color scaling, with basin amplifications of 3x relative to nearby bedrock areas in highly varying distributions.

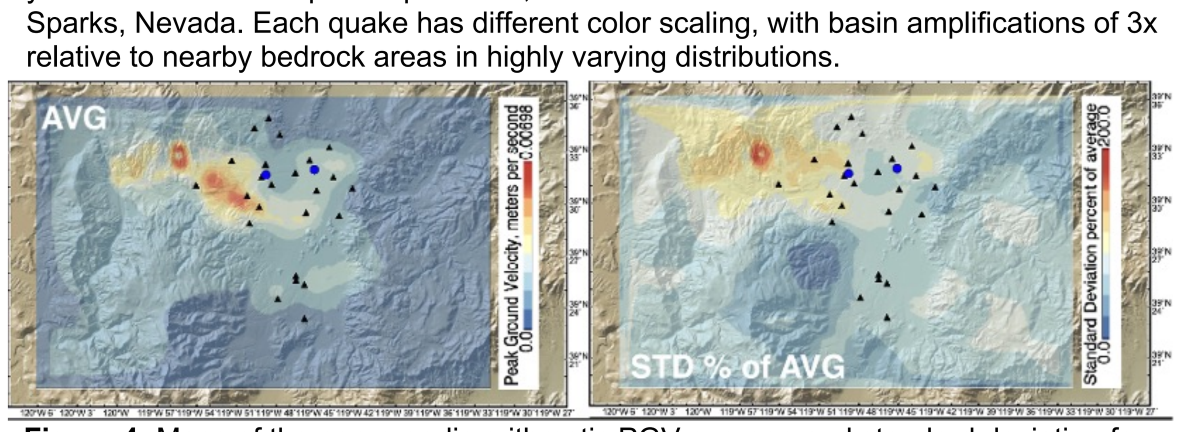



**Figure 4:** Maps of the non-ergodic arithmetic PGV average and standard deviation for six earthquakes after normalizing each to M3.9. Basin amplifications remain strong but appear more predictable, and related to basin thickness. The stdev of the non-ergodic average PGV appears related to basin edges and shallow events.

## Wellington 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.

### Single-Event Ergodic Basin Amplification PGV Maps, Stronach-GNS divided by No Basin CVMs

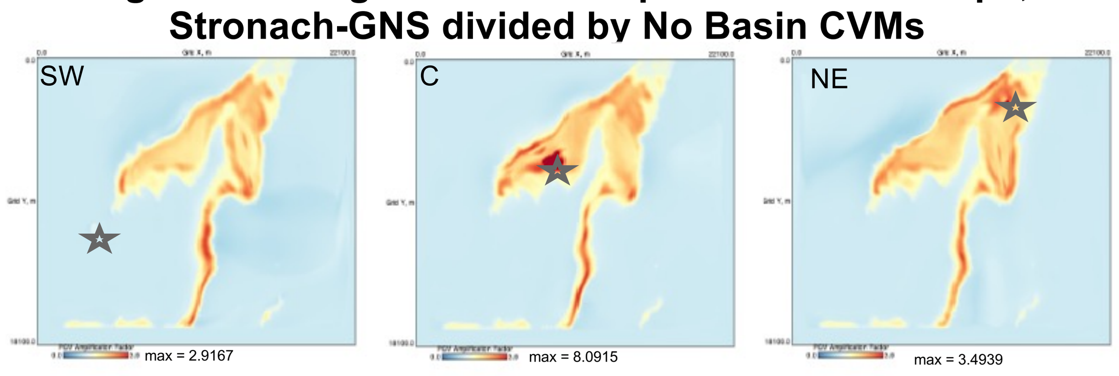



**Figure 5:** Peak Ground Velocity computed to 0.6 Hz for 3 of the 9 earthquakes modeled, clipped at a maximum basin amplification factor of 3. Model earthquake epicenter locations have a star. Ergodic single-event areas of high basin amplification appear at **seemingly random places** near the basin edges. No correlation to basin thickness is evident.

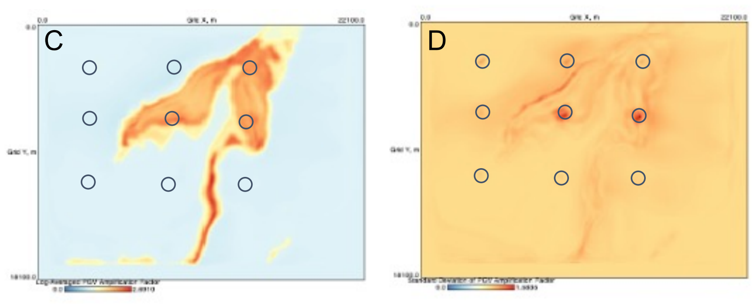
### Non-Ergodic 9-Event Basin Amplification Average PGV Ratio Maps

**Stronach-GNS Over No Basin**

**Figure 6:**
C. Non-Ergodic Average Map
Minimum Deamplification 0.91x
Maximum Amplification 2.69x

D. Amplification Standard Deviation Map
Maximum Standard Deviation 58%

*Note: Black circles show the 9 source locations




## Synthetic Wellington Basin Amplifications at 0.6 Hz

Using LLNL's SAC for all 27 models, we built x-component synthetic seismograms for 4 seismic stations located within the Stronach & Stern basin model.

- PGV Analysis (Figure 5) showed substantial amplification and deamplification within as well as outside the Stronach model area.
- 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.

## Non-Ergodic Basin Amplification Spectra for Reno

Seismic hazard in the city of Reno, Nevada is significantly increased due to its location within the subbasins of the Truckee Meadows, despite the relatively small thicknesses of the low-velocity basins, <1.2 km. In the Reno Shakeout Scenario, Eckert et al. (2021) used SW4 to quantify ergodic ground shaking in the Reno metropolitan area caused by a scenario M6.3 earthquake within the Truckee Meadows. Their computation to a maximum frequency of 3.125 Hz showed that a quake of this magnitude could produce severe shaking with PGV greater than 30 cm/sec over a wide swath of urban area, and extreme shaking (PGV > 150 cm/sec) in very limited areas, with great variations in shaking intensity across distances less than 0.1 km. While their simulation highlights likely responses of the basin to shaking from a single, specific earthquake scenario, further modeling and data collection are necessary to form a non-ergodic view of basin amplification.

To express computed amplification in the Truckee Meadows basin as Fourier spectral ratios, we calculated the Fourier amplitude spectral averages of the x- and y-components of synthetic seismograms at each seismic station for each of the six earthquakes. At each basin station, these spectral amplitudes were then divided by those of each of the five bedrock stations, overall producing 30 ergodic estimates of the basin amplification spectra for each basin station. Averaging the logs of the ergodic spectra produced a non-ergodic log simplification spectrum for each basin station.

The frequency corresponding to the non-ergodic peak average amplification for each station was used to calculate a quarter-wavelength basin thickness estimate according to: $\lambda/4 = V/4f_{peak}$. The estimates used an average basin shear-wave velocity V of 0.8 km/s (Pancha et al., 2017; Louie, 2020; Eckert et al., 2021). These thickness estimates for every station were plotted against the gravimetry-derived basin thickness estimates of Abbott and Louie (2000; Figure 10).

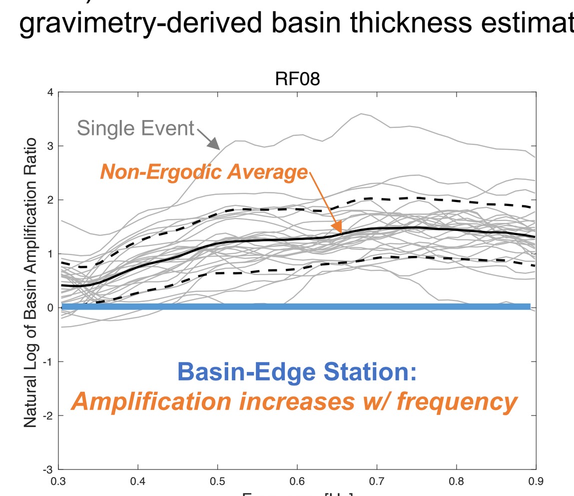



**Figure 7:** Example computed spectral amplification ratio summary plot for station RF08. Gray lines indicate the horizontal average synthetic spectral amplitude of the synthetic seismograms for each of the 6 synthetic quakes at RF08 over each of the 5 bedrock stations. The average and standard deviation are shown by the solid black line and dashed black lines, respectively. RF08 is located near the **basin's northern edge**.

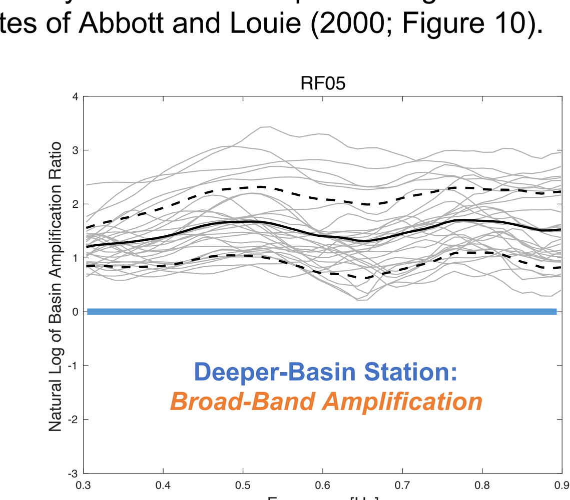



**Figure 8:** Example computed spectral amplification ratio summary plot for station RF05. Gray lines indicate the horizontal average spectral amplitude of the synthetic seismograms for each of the 6 synthetic quakes at RF05 over each of the 5 bedrock stations. The average and standard deviation are shown by the solid black line and dashed black lines, respectively. RF05 is located near the **deepest part of the basin** (Figure 2).

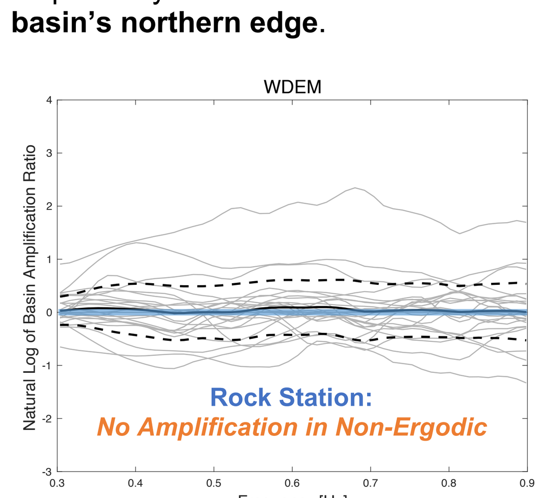



**Figure 9:** Example computed spectral amplification ratio summary plot for station WDEM. Gray lines indicate the horizontal average spectral amplitude of the synthetic seismograms for each of the 6 synthetic quakes at WDEM over each of the 5 bedrock stations. The average and standard deviation are shown by the solid black line and dashed black lines, respectively. WDEM is a **rock station** located north of the basin (Figure 2).

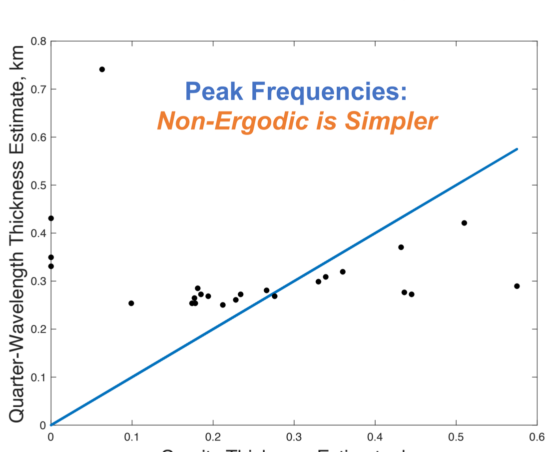


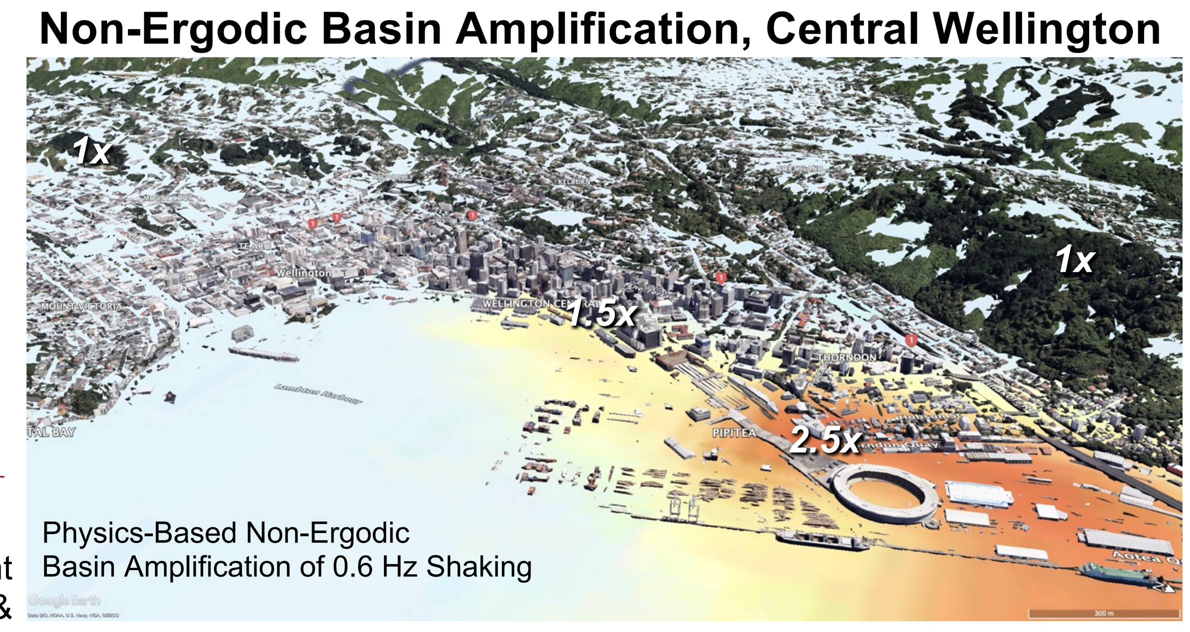

**Figure 10:** The **quarter-wavelength** thickness estimate is a simple one-dimensional function (blue line) that relates basin thickness to the frequency at which the peak average amplification occurs (points from the 25 basin stations). It may predict a few points in this non-ergodic view. Another possibility is that some other basin geometric property may predict a constant 0.3 Hz peak frequency at nearly all basin stations.

## Conclusions

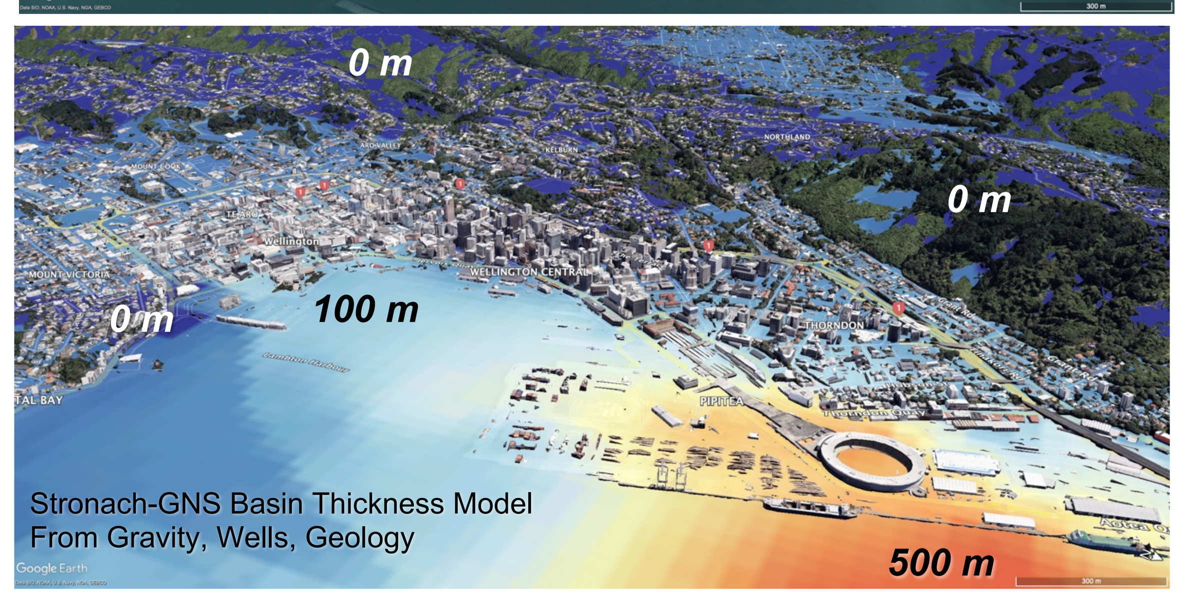
The relatively few earthquakes recorded in Reno, as well as single-scenario ergodic synthetics such as in Eckert et al. (2022) show wildly varying ground motions and basin amplifications around the city. The non-ergodic assessment of multiple synthetic events at a variety of locations presents a simpler and more predictable picture of basin amplification, with at least slight evidence of the expected correlation of spectral amplification peak frequencies to basin thickness.

Non-ergodic PGV maps from 9 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 prior models. Even at low frequencies of <0.6 Hz, the new, non-ergodic model suggests basin amplification ground motions at factors of 1.5x – 2.5x along Waterloo and Thorndon Quays on the northern end of the Wellington CBD.

## Non-Ergodic Basin Amplification, Central Wellington

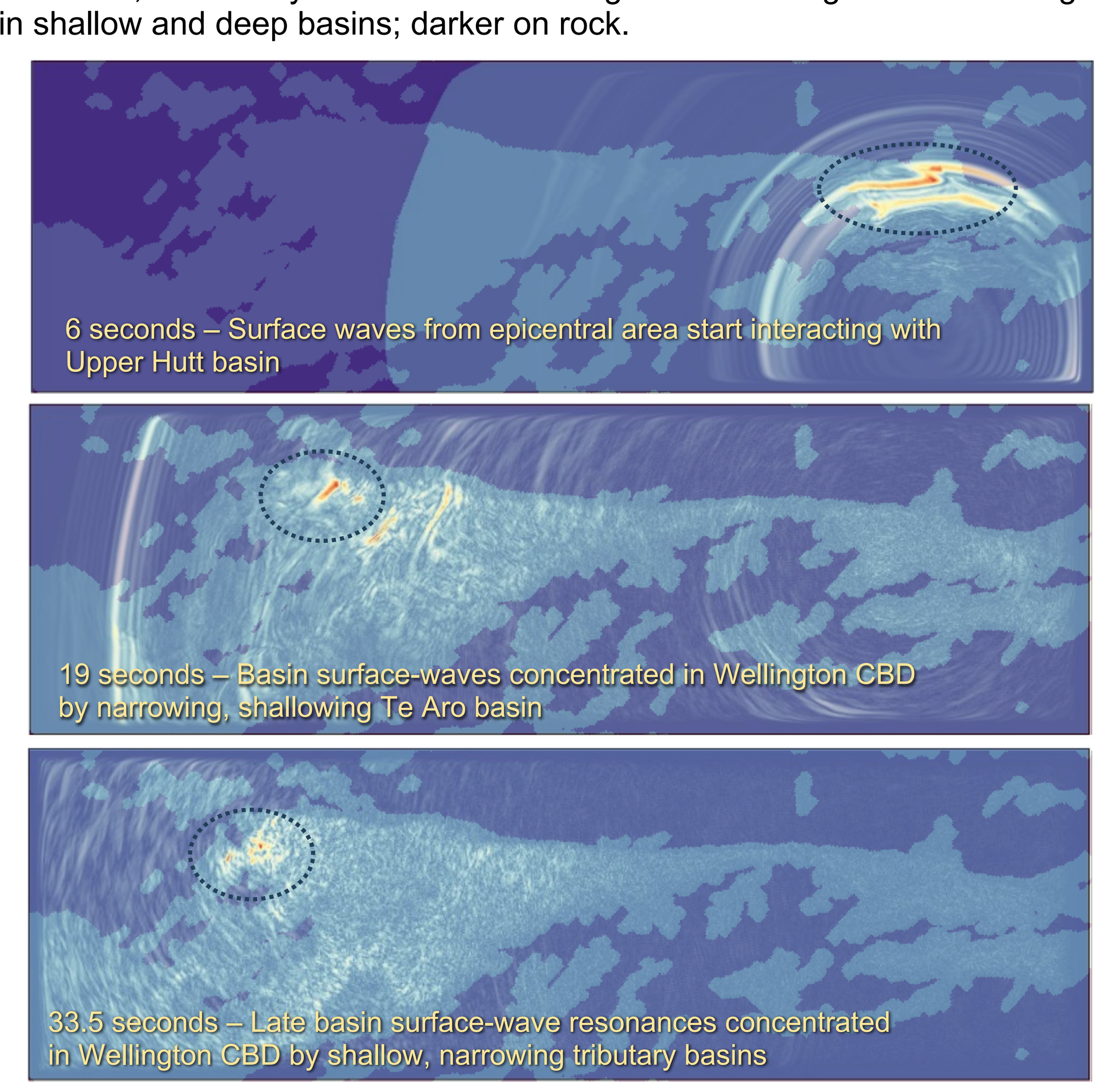







## Higher-Frequency Synthetics for Wellington Basin

Aurecon research is improving the availability of higher-frequency synthetic time histories for engineering design and hazard assessment in Wellington. The time-slice shaking maps below show example computations at 1.2-2.0 Hz through our updated CVM, matching a recorded event in Upper Hutt. Higher frequencies are showing even larger basin amplifications and longer shaking durations, with many features matched against recordings. Colors are lighter in shallow and deep basins; darker on rock.




## References

Abbott, Robert E., John N. Louie (2000). Depth to bedrock using gravimetry in the Reno and Carson City, Nevada area basins: *Geophysics*, **65**, 340-350.

Benites, Rafael, Kim B. Olsen (2005). Modeling Strong Ground Motion in the Wellington Metropolitan Area, New Zealand. *Bulletin of the Seismological Society of America*; **95** (6): 2180–2196. doi: https://doi.org/10.1785/0120040223

Eckert, Eric, Michelle Scalise, John N. Louie, Kenneth D. Smith (2022). Exploring basin amplification within the Reno metropolitan area in Northern Nevada using a magnitude 6.3 ShakeOut scenario: *Bulletin of the Seismological Society of America*, **112**(1), 457-473, doi: 10.1785/0120200309

Louie, John N. (2020). *Refraction Microtremor Vs(z) Profile Archive* (Version 2.0.0) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.3951865

Simpson, Alexander R., John N. Louie (2020). *Measurements and Predictions of Vs30, Z1.0, and Z2.5 in Nevada* (Version 2.0), peer-reviewed publication of the Nevada Seismological Lab., Zenodo, December 31, 28 pp. plus data and maps, http://doi.org/10.5281/zenodo.4408557, open access

Pancha, Aasha, S. Pullammanappallil, J. N. Louie, P. H. Cashman, J. H. Trexler (2017). Determination of 3D basin shear-wave velocity structure using ambient noise in an urban environment: A case study from Reno, Nevada: *Bulletin of the Seismological Society of America*, 107(6), 3004-3022, https://doi.org/10.1785/0120170136

Petersson, N. A., Sjögreen, B. (2017). *SW4, version 2.01* [software], Computational Infrastructure of Geodynamics, doi: 10.5281/zenodo.1063644, url: https://doi.org/10.5281/zenodo.1063644

Stronach, Alistair, Tim Stern (2021). A new basin depth map of the fault-bound Wellington CBD based on residual gravity anomalies, *New Zealand Journal of Geology and Geophysics*, doi: 10.1080/00288306.2021.2000438

Thompson, M., E. A.Wirth, A. D. Frankel, J. R. Hartog, and J. E. Vidale (2020). Basin amplification effects in the Puget Lowland, Washington, from strong-motion recordings and 3D simulations, *Bulletin of the Seismological Society of America,* **110(**2), 534–555, doi: 10.1785/0120190211

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