Analysis of Observed Site Response in Wellington Sedimentary Basins using Empirical Ground Motion Models

C.A. de la Torre, B.A. Bradley, R.L. Lee, A. Tiwari
University of Canterbury, Christchurch, New Zealand.

L. Wotherspoon
University of Auckland, Auckland, New Zealand.

A. Kaiser
GNS Science, Lower Hutt, New Zealand.

ABSTRACT

Analysis of prediction-observation residuals from the empirical ground motion models (GMMs) used in the 2022 New Zealand National Seismic Hazard Model (NZ NSHM) update indicates a general underprediction of ground motions in the period range of 0.5-2 seconds for soft sedimentary basin sites in Wellington. This study uses residual analysis to quantify this underprediction, understand the spatial distribution of these residuals and the specific conditions that cause them, and investigate options for development of non-ergodic site response adjustments to the GMMs. All 15 GMMs used in the NZ NSHM were evaluated, and the variability in site-response residuals between different models and different tectonic types of earthquake sources quantified. Sites are regionalized based on different geomorphic features, such as individual basins and valleys. For example, average site terms are calculated for Te Aro, Thorndon, Miramar, Lower Hutt, Upper Hutt, and several smaller valleys. The period at which maximum underprediction occurs at these sedimentary basin and valley sites was found to correlate well with the fundamental site period of the soil profile (T_0), suggesting improvements can be made to regionalized GMMs by incorporating site period into the site-response prediction for sedimentary basin sites.

1 INTRODUCTION

The Wellington basin, in the capital city of New Zealand (NZ), has been observed to strongly amplify ground motions, especially in the vibration period range of T =0.5-2 seconds (Adams et al., 1999; Bradley et al., 2018; Kaiser et al., 2020; de la Torre et al., 2023). Studies from the 2022 NZ NSHM have demonstrated that empirical GMMs generally underpredict the observed site amplification in Wellington due to combined basin and site effects for soft sedimentary basin sites (de la Torre et al., 2023; Kaiser et al., 2022). Wellington has a high seismic hazard as it is underlain by the Wellington and Aotea faults, and is in close proximity to the Hikorangi subduction zone, making it critical to understand patterns of site amplification and the performance of GMMs in this region.

This paper focuses on quantifying the performance of empirical GMMs at predicting site-specific ground motions in the Wellington region of New Zealand. It is the first study that rigorously and systematically assesses residuals in the Wellington region. Unlike prior non-ergodic site response studies that have considered a single GMM (Atkinson et al., 2006; Bradley et a. 2015b, Sung and Abrahamson, 2022), this study evaluates all 15 GMMs used in the NZ NSHM logic tree for developing site and basin-specific regionalisations of site-response residuals for all the GMMs. Models from different tectonic types are compared and the variability between these models is assessed. Site terms are grouped geographically by specific basin or valley sub-regions in Wellington to understand small-scale fluctuations in basin and site effects. More details on this study can be found in de la Torre et al., 2024

2 GROUND-MOTIONS AND SITES CONSIDERED

2.1 Ground-motion database

We considered the dataset of Lee et al., 2024 which is based on a subset of the New Zealand ground-motion database (NZ GMDB) v1.0 Hutchinson et al., 2022. The remaining dataset, after application of the filtering criteria imposed by Lee et al., 2024, contains 17,691 ground motions across New Zealand, of which 4,710 records exist at sites in the Wellington Region, including the Lower Hutt and Upper Hutt valleys. Figure 1 shows the distributions of moment magnitude (M_W) and source-to-site distance (R_{rup}) for the NZ-wide dataset and the Wellington region subset. The Wellington subset of ground motions are coloured by tectonic type of the event corresponding to each ground motion, showing that the database has significantly more shallow crustal than subduction interface or slab ground motion records. As tabulated on the top right corner of Figure 1, the Wellington region subset contains 3,538 crustal, 506 interface, and 666 slab ground-motion records.

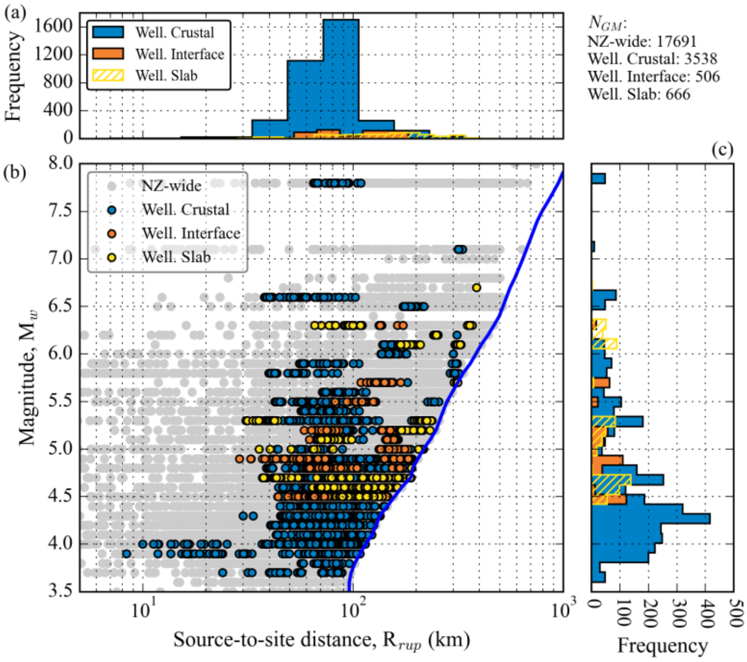

Figure 1: Earthquake source and ground-motion M_W and R_{rup} distributions for the NZ-wide and Wellington ground motion datasets.

2.2 Strong-motion stations (SMS) in the Wellington region

SMS sites in the greater Wellington region, including the surrounding hills and valleys, were subdivided based on location, geomorphic categorization, basin geometry, and site-response characteristics. The sub-regions considered generally correspond to specific sedimentary basins and valleys. These sub-regions include: Te Aro, Thorndon, Lower Hutt, Upper Hutt, Miramar, Karori, Porirua, and Wainuiomata. Figure 3 provides maps for the different sub-regions and identifies the station IDs for all SMS. The Wellington Central Business District (CBD) spans across the Te Aro and Thorndon areas. Sites were also divided into four geomorphic categories including basin, basin-edge, valley, and hill by Tiwari et al., 2023 using category definitions by Nweke et al., 2022.

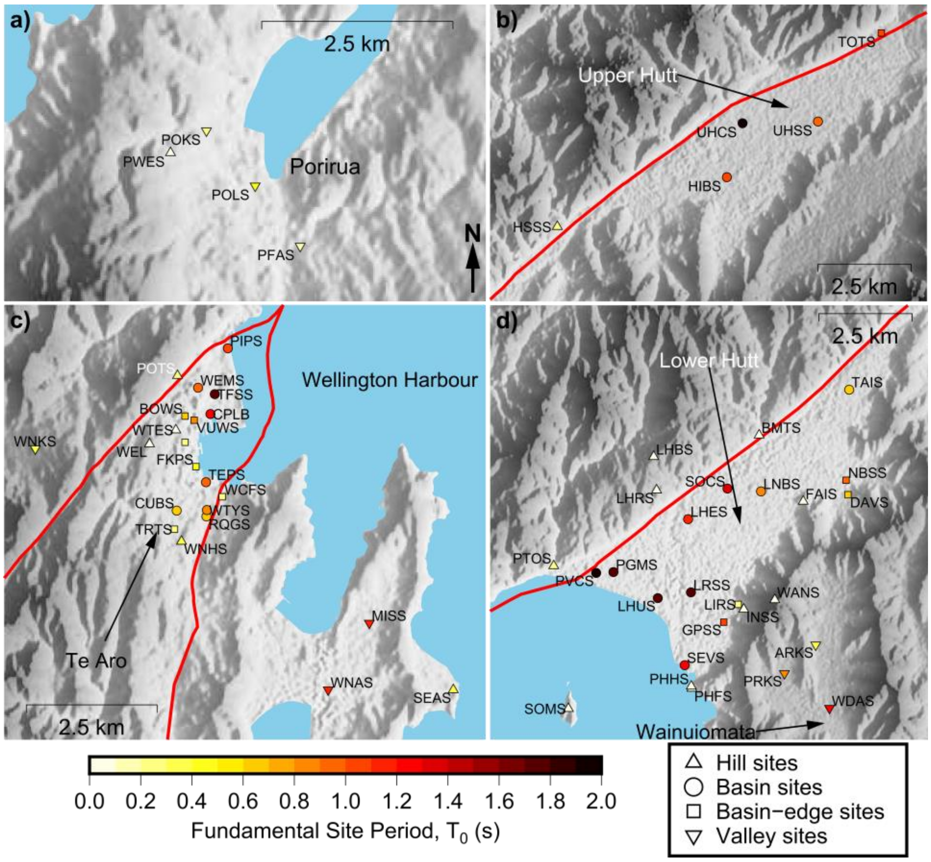

Figure 2: Maps identifying the station ID for all SMS considered in the Wellington region divided into regions as: a) Porirua, b) Upper Hutt, c) Wellington CBD, Karori and Miramar, and d) Lower Hutt and Wainuiomata. Site symbols are color-coded by T_0 and the symbol shape indicates the geomorphic category assigned to each site as indicated in the legend.

3 METHODOLOGY

3.1 Residual analysis

The performance of GMMs on a region-by-region and site-by-site basis is assessed using mixed-effects residual analysis to decompose the residual into its various components (Al Atik et al., 2010; Bradley et al., 2015b). The total prediction residual, Δ_{es}, for spectral acceleration at a given oscillator period, T, can be expressed as:

$$\Delta_{es} = \ln SA_{es}^{Obs} - \ln SA_{es}^{GMM} \tag{1}$$

where $\ln SA_{es}^{Obs}$ is the natural logarithm of the observed spectral acceleration at an oscillator period T, for earthquake e at site s; and $\ln SA_{es}^{GMM}$ is the natural logarithm of the respective spectral acceleration predicted by a GMM.

To identify systematic trends in prediction bias for a given ground motion model m, earthquake e, and site s, the prediction residual in Equation \ref{eq:residual1} is partitioned as:

$$\Delta_{es} = a^m + \delta B_e^m + \delta S2S_s^m + \delta W_{es}^{0,m}$$
(2)

where a is a constant representing overall model bias for all earthquakes and sites considered, δB_e^m is the between-event residual for earthquake e, $\delta S2S_s^m$ is the systematic site-to-site residual for site s, $\delta W_{es}^{0,m}$ is the ``remaining" within-event residual for earthquake e at site s, and the superscript m denotes the m^{th} considered GMM.

3.2 Ground-motion models investigated and weighting scheme

All 15 GMMs used in the 2022 NZ NSHM (Bradleyet al., 2024) are included in the subsequent analysis. In addition to model-specific mixed-effects residuals, we also sought to compute a resulting weighted average over all GMMs considered. The model-specific weight (w_T^m) is comprised of two parts:

$$w_T^m = w_{NSHM}^m \times w_{Ngm}^m \qquad (3)$$

where w_{NSHM}^m was the weight given to the model in the NSHM logic (Gerstenberger et al., 2023, Bradley et al., 2024) and w_{Ngm}^m is a function of the number of ground motions that were used in the mixed-effects residual analysis for each tectonic type.

4 RESIDUAL ANALYSIS RESULTS

4.1 Between-model variability in site-specific residuals

Figure 3 illustrates the site-to-site residuals, $\delta S2S_s^m$, for all GMMs at two example basin sites in the Wellington CBD. For both sites, all GMMs underpredict (positive residuals) in the period range corresponding to basin amplification in the Wellington basin (i.e., T = 0.5-2 s) and is most pronounced around the experimentally-measured fundamental site period, T_0. For TEPS, there is significant overpredictions for T < 0.3 s.

It is apparent from Figure 4 that the between-model variability is relatively low for both sites, especially between GMMs of the same tectonic type. Considering that $\delta S2S_s^m$ represents repeatable site effects at site s this illustrates that the variability in unexplained site response between the GMMs is low. This is likely because several of the GMMs use similar formulations for the site response, thus yielding similar site-response predictions.

Interestingly, the site terms between interface and slab events are different even though the predictions for these subduction ground motions use the same base GMMs (Bradley et al., 2024). For example, in Figure 3 the peak value of the site terms for interface events is approximately 50% lower than that from slab and crustal events. This illustrates, in our opinion, that source and path effects are being mapped into the systematic site term.

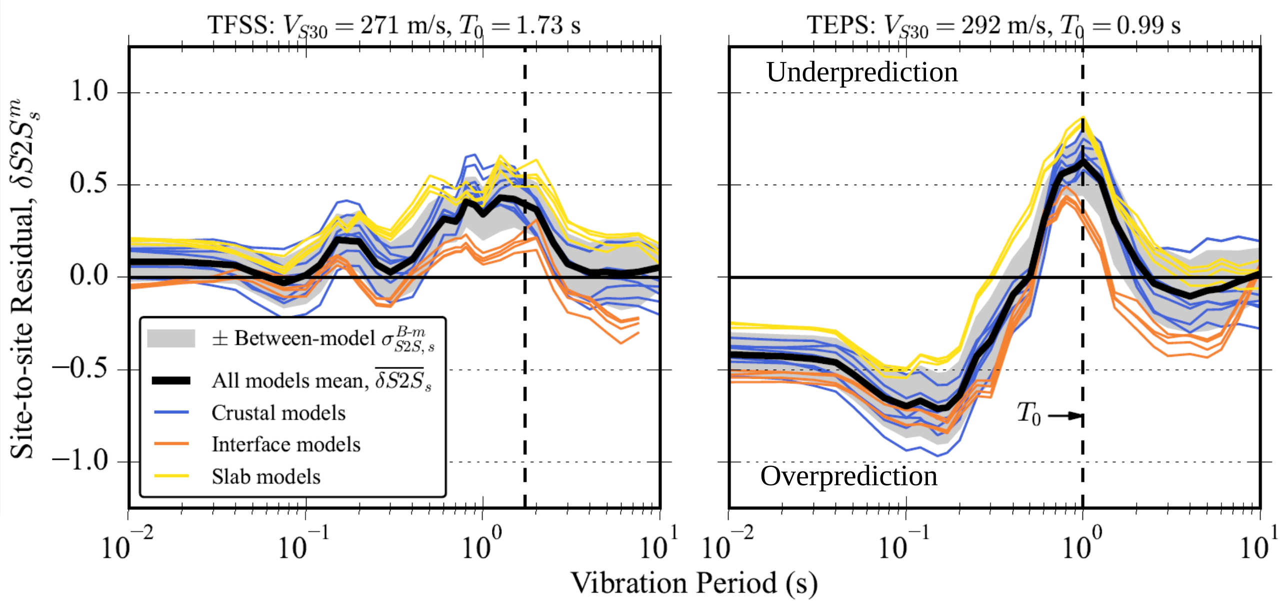

Figure 3: Site-to-site residuals, $\delta S2S_s^m$, as a function of period for two example basin sites in the Wellington region. For each site, $\delta S2S_s^m$ from individual GMMs are included as well as the weighted mean ($\overline{\delta S2S_s^m}$) and standard deviation ($\sigma_{S2S,s}^{B-m}$) of all GMMs. Lines for individual GMMs are color-coded by tectonic type (i.e., crustal, interface, and slab).

4.2 Regionalisation of site terms

The site-to-site residuals, $\delta S2S_s$, can be used in site-specific adjustments to GMMs, however, this study aims to understand site response trends more broadly across the region, given that most forward prediction applications are for cases where ground motions and site response have not been instrumentally measured. To understand such regional trends, the weighted means of $\delta S2S_s^m$ (i.e., $\overline{\delta S2S_s}$) are regionalized and presented in Figure 4 as a function of vibration period. Each column of Figure 4 includes the site terms for one of the three basin sub-regions of Te Aro, Thorndon, and Lower Hutt. The regional mean and standard deviation are also included in the respective panel for each region. The regional means generally show underprediction in the period range of T = 0.5-2 s for all regions, with peaks in the mean residuals of approximately 0.16-0.26 lognormal units. For T > 2.5 s all basin regions display some overprediction with fairly constant mean residual values of approximately -0.1 to -0.25. The Te Aro and Upper Hutt regions also display average overprediction for T < 0.3 s. The maximum error in these average residuals occurs in the Te Aro region at T ≈ 0.1 s with a value of -0.39, corresponding to overprediction.

The average underprediction for T = 0.5-2 s in all regions is not unexpected, given that this is the period range at which the Wellington basin has been observed to strongly amplify ground motions. The regional site-to-site standard deviations ($\phi_{S2S,R}$) reach high values of 0.3 to 0.5 at their peaks. Importantly, these peaks in $\phi_{S2S,R}$ generally occur at the period range of interest for basin effects in Wellington (i.e., close to T = 1 s). This suggests that sites within the same sub-basin experience amplification (or underprediction) at different periods, and different site parameters should be further investigated to identify any correlations between the shape of the site terms and site characteristics.

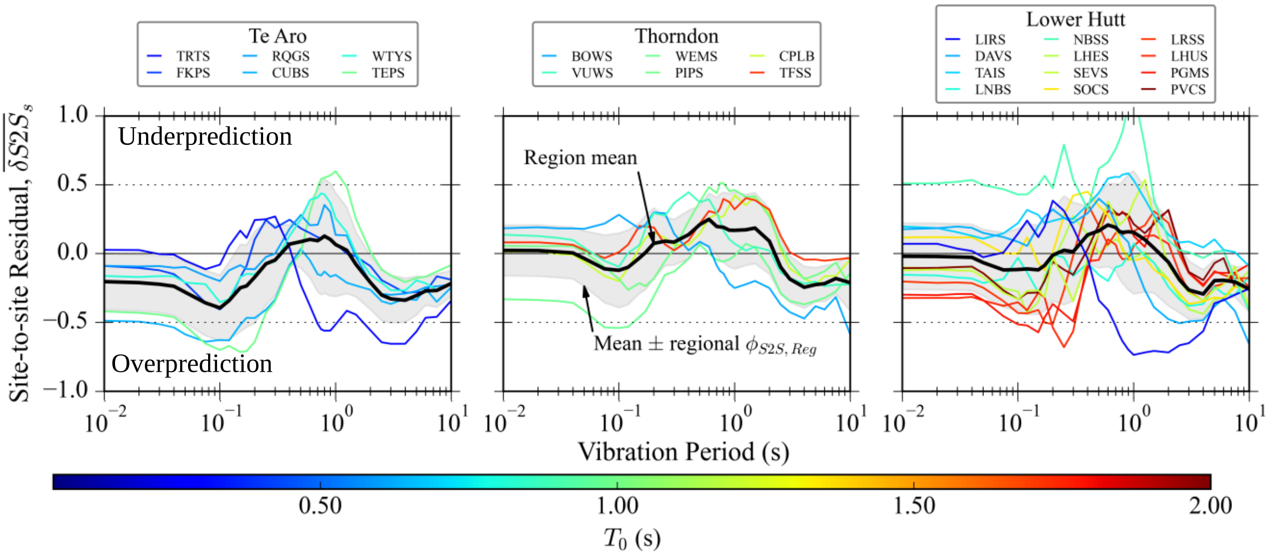

Figure 4: Site-to-site residuals and standard deviations for three basin sub-regions (Te Aro, Thorndon, and Lower Hutt) as a function of vibration period. For each site, the mean site-to-site residuals from all 15 GMMs is plotted. The regional mean and standard deviation for each region is also included. Individual site lines are color-coded by site period (T_0).

4.3 Normalisation of spectral period by site period

Previous work in Wellington has illustrated that patterns of basin/site amplification are consistent with patterns of site period estimates, and that site period may be a good predictor for site response (de la Torre et al., 2023; Kaiser et al., 2024). Other studies have leveraged off this dependence on site period and had success with incorporating site period into empirical site response models (Heloise et al., 2012; Hassani et al., 2018). To further elucidate this trend, vibration periods at which $\delta S2S_s$ was calculated were normalized by the site period of each site. Figure 5 plots the same regionally-segregated $\delta S2S_s$ plotted in Figure 4 above, albeit as a function of normalized period (T/T_0). T_0 estimates used in this study are taken directly from the NZ GMDB (Hutchinson et al., 2022) and are generally based on earthquake and microtremor horizontal-to-vertical spectral ratio (eHVSR and mHVSR, respectively; Wotherspoon2024)

For many sub-basins, there appears to be consistency between the various site $\overline{\delta S2S_s}$ when period is normalized. That is, most sites generally display underprediction at or near the site period. This is especially true for Te Aro and Lower Hutt basin sub-regions (Figure 5). The regionalized site terms are influenced by the following complexities: In Thorndon, site VUWS is a complicated site on the edge of a steep drop-off in bedrock at which the site response and/or site period estimate may be influenced by complex multidimensional site response. Both VUWS and BOWS are also closer to the basin edge compared to the other sites in Thorndon, and therefore may be influenced by other phenomena not captured by the GMMs or the site period estimate (e.g., basin-edge effects). Lower Hutt sites display strong site amplification not only at the fundamental site period but also at a shorter period peak, which is likely representative of a shallower impedance contrast. This ``double-peak" is visible in many individual site curves and, to a lesser extent, in the regional mean.

In general, normalization by site period results in a significant reduction in the regional between-site standard deviation. For most regions the maximum regional standard deviation drops from about 0.4 - 0.5 to 0.25 - 0.4 in natural log units. Again, the benefits of normalizing by site period at Te Aro are illustrated by the standard deviation which drops from a maximum of about 0.4 to about 0.25. This suggests that an adjustment factor to GMMs conditioned on site period could perform better than a model that is independent of site period (e.g., Figure 4).

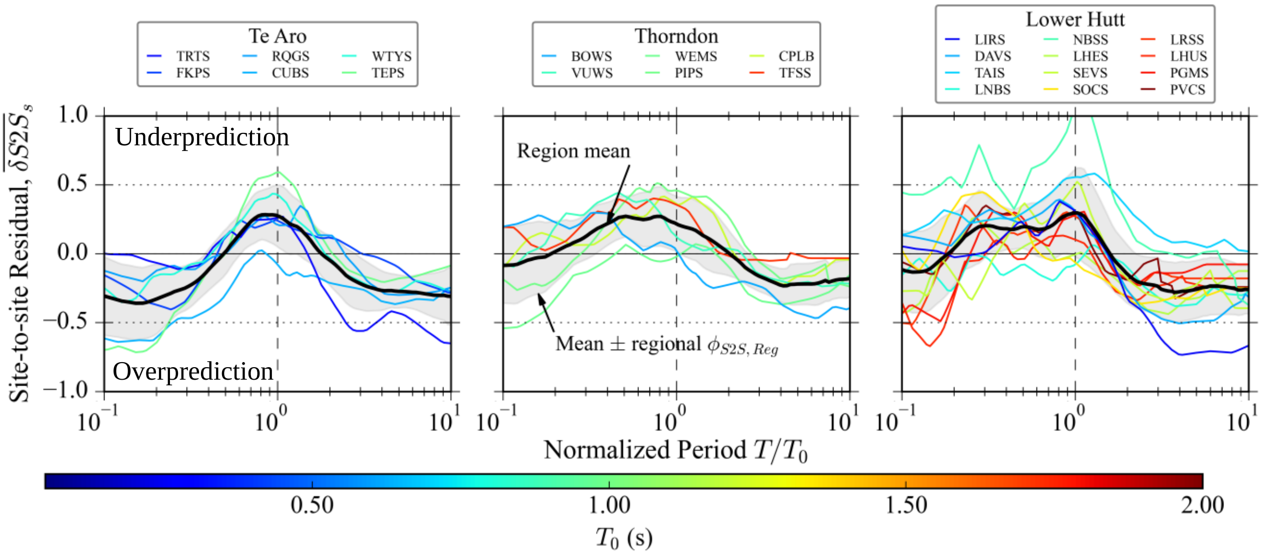

Figure 5: Site-to-site residuals for three basin regions (Te Aro, Thorndon, and Lower Hutt) as a function of normalized period (i.e., T/T_0). For each site, the mean site-to-site residuals, across all 15 GMMs, is plotted, as well as the regional mean and standard deviation (ϕ_{S2S}) for each region. Individual site lines are color-coded by site period (T_0).

5 CONCLUSIONS

This paper analysed ground-motion residuals for the Wellington region to assess the performance of empirical GMMs used in the 2022 New Zealand National Seismic Hazard Model (NZ NSHM) revision. Specifically, the site-to-site residuals ($\delta S2S_s$), or ``site terms", for sites in Wellington were closely inspected to judge the GMMs in their ability to predict site effects attributed to sedimentary basins. Site terms from all the GMMs considered in the NSHM were evaluated to quantify the between-model epistemic uncertainty. Then, site terms were grouped geographically by specific basin or valley sub-regions. The dependence of these site terms on various site characterization parameters and on tectonic type was also assessed.

When all sites from all geomorphic categories in the Wellington region are combined, no significant systematic bias is observed relative to the rest of the country. However, when segregated into different categories, a clear underprediction is observed for basin sites at periods of 0.5-2 s. This underprediction is attributed to the models' inability to capture strong resonance in site response of sedimentary basins in Wellington. Further separation into individual geomorphological features, such as separate basins and valleys, shows that different sub-regions can have unique site response characteristics. Most basin and valley regions demonstrate the maximum underprediction over a period range centred around the site period (T_0), suggesting that T_0 could be used to better constrain the site response of sedimentary basin sites.

This study identified basin-specific systematic trends in bias and imprecision, based on mean site-to-site residuals, for the following basins and valleys in the Wellington region: Te Aro, Thorndon, Lower Hutt, Porirua, Wainuiomata, Miramar, and Karori. These residual trends form the basis for development of adjustment factors to the mean site response model within GMMs, to create partially non-ergodic GMMs for use in PSHA. Further work is required to fully develop and test the framework for application of these adjustment factors to PSHA is the Wellington region.

6 REFERENCES

Al Atik, L., Abrahamson, N., Bommer, J. J., Scherbaum, F., Cotton, F., and Kuehn, N., 2010. The Variability of Ground-Motion PredictionModels and its Components. Seismological Research Letters 81, 794–801.

Atkinson, G. M., 2006. Single-Station Sigma. Bulletin of the Seismological Society of America 96, 446–455. doi:10.1785/0120050137.

Adams, B., Davis, R., Berrill, J., and Taber, J., 2012. Two-dimensional site effects in Wellington and the Hutt Valley similarities to Kobe. Tech. rep., Department of Civil Engineering, University of Canterbury Research Report.

Bradley, B. A., 2015. Systematic Ground Motion Observations in the Canterbury Earthquakes and Region-Specific Non-Ergodic Empirical Ground Motion Modeling. Earthquake Spectra 31, 1735–1761.

Bradley, B., Bora, S., Lee, R., Manea, E., Gerstenberger, M., Stafford, P., Atkinson, G., Weatherill, G., Hutchinson, J., de la Torre, C., Hulsey, A., Kaiser, A., and Van Dissen, R., 2024. Summary of the ground-motion characterization model for the 2022 New Zealand National Seismic Hazard Model. Bulletin of the Seismological Society of America.

de la Torre, C. A., Bradley, B. A., Kuncar, F., Lee, R. L., Wotherspoon, L. M., & Kaiser, A. E. (2024). Combining observed linear basin amplification factors with 1D nonlinear site-response analyses to predict site response for strong ground motions: Application to Wellington, New Zealand. Earthquake Spectra, 40(1), 143-173.

de la Torre, C.A., Bradley, B.A, Lee, R.L., Tiwari, A., Wotherspoon, L.M., Ridden, J., Kaiser, A. (2024) Analysis of Site-Response Residuals from Empirical Ground-Motion Models to Account for Observed Sedimentary Basin Effects in Wellington, New Zealand. Accepted in Earthquake Spectra

Hassani, B. and Atkinson, G. M., 2018. Site-Effects Model for Central and Eastern North America Based on Peak Frequency and Average Shear-Wave Velocity. Bulletin of the Seismological Society of America 108, 338–350. doi:10.1785/0120170061.

He´lo¨ıse, C., Bard, P.-Y., Duval, A.-M., and Bertrand, E., 2012. Site effect assessment using KiK-net data: part 2—site amplification prediction equation based on f0 and Vsz. Bulletin of Earthquake Engineering 10, 451–489. doi:10.1007/s10518-011-9298-7.

Hutchinson, J., Bradley, B., Lee, R., Wotherspoon, L., Dupuis, M., Schill, C., Motha, J., Kaiser, A., and Manea, E., 2022. 2021 New Zealand Strong Ground Motion Database. Tech. Rep. 2021/56, GNS Science.

Kaiser, A., Hill, M., de la Torre, C., Manea, E., Bora, S., Wotherspoon, L., Atkinson, G., Lee, R., Bradley, B., Hulsey, A., Stolte, A., and Gerstenberger, M., 2023. Overview of site effects and the application of the 2022 New Zealand NSHM in the Wellington Basin, New Zealand. Accepted in Bulletin of the Seismological Society of America.

Kaiser, A. E., Hill, M., McVerry, G., Bourguignon, S., Bruce, Z., Morgenstern, R., Giallini, S., and Wotherspoon, L., 2020. Wellington's sedimentary basin and it's role in amplifying earthquake ground motions: new CBD 3D model and maps. In New Zealand Society of Earthquake Engineering Conference. April 22-24, Wellington, New Zealand.

Nweke, C. C., Stewart, J. P.,Wang, P., and Brandenberg, S. J., 2022. Site response of sedimentary basins and other geomorphic provinces in southern California. Earthquake Spectra 38, 2341–2370.

Sung, C.-H., Abrahamson, 618 N. A., Kuehn, N. M., Traversa, P., and Zentner, I., 2023. A non-ergodic ground-motion model of Fourier amplitude spectra for France. Bulletin of Earthquake Engineering 21, 5293–5317. doi:10.1007/s10518-022-01403-1.

Tiwari, A., de la Torre, C., Bradley, B., Lee, R., and Kuncar, F., 2023. Trends in systematic site residuals with geomorphic categories for New Zealand ground-motion instrument sites. In 2023 New Zealand Society of Earthquake Engineering Conference. 19-21 April, 2023, Auckland, New Zealand.