Trends in systematic site residuals with geomorphic categories for New Zealand ground-motion instrument sites

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ABSTRACT

This paper provides a summary of initial research results investigating systematic site effects from the prediction residuals of empirical- and physics-based ground-motion models (GMMs) for small magnitude (i.e., $3.5 \leq M_W \leq 5$) active shallow crustal earthquakes in New Zealand (NZ). Advancing ground-motion predictability through physics-based GMMs is an iterative process and requires addressing fundamental questions like: Is there salient physics which has been overlooked? Which geographic regions have predictions that significantly deviate from observations and why? Which sites exhibit systematic prediction residuals and how can the attributes influencing them be identified? This preliminary study examines these questions by classifying 171 sites from the Canterbury and Wellington regions into four geomorphic categories: basin, basin-edge, hill, and valley, following the categorisation by Nweke et al. (2022). Trends in the site-to-site residuals for each geomorphic category indicate apparent differences between the four categories, with residuals for valley sites illustrating a clear dependence with the inferred fundamental site period. Computed residuals from both empirical- and physics-based GMMs also provided insight into the role of site-specific attributes vs. the different prediction methods, assisting to understand the salient causes of these residuals.

1 GEOMORPHIC CLASSIFICATION OF CONSIDERED SITES

Nweke et al. (2022) proposed a method, illustrated in Figure 1, for classifying the geomorphology of sedimentary basins to model site amplification for Southern California. In this study, we apply this classification in a New Zealand context, specifically to sites in Canterbury and Wellington, which have multiple observed strong-motion records and higher quality site classification. In summary, the classification resulted in 88 Basin, 20 Basin-edge, 49 Hill, and 14 Valley sites, as shown in Figure 2. This categorisation will be eventually extended to the entire country.

2 GROUND MOTIONS AND PREDICTION RESIDUALS

Residuals from the empirical- and physics-based GMM predictions from Lee et al. (2022) were then examined with respect to the site geomorphic categories. The ground-motion database includes 5,218 ground motions from 479 earthquakes and 212 strong motion stations. The site conditions are quantified using site metrics, such as 30-m time-averaged shear wave velocity, V_{S30}, and fundamental site period, T_0, from Wotherspoon et al. (2022).

Province	Description	Criteria	Province no.	No. of sites
Basin	Basin interior	Short direction width >3 km	3	429
Basin edge	Along basin margin	Within 300 m of basin edge[a]	2	72
Valley	"Small" sedimentary structure	Short direction width <3 km	1	172
Mountain/hill	Sites without significant sediments, generally having topographic relief	Generally identified on basis of appreciable gradients and/or irregular morphology	0	329

[a]Basin edge defined visually from break in slope (topographic features).

Figure 1: Proposed geomorphic classification (Nweke et al., 2022)

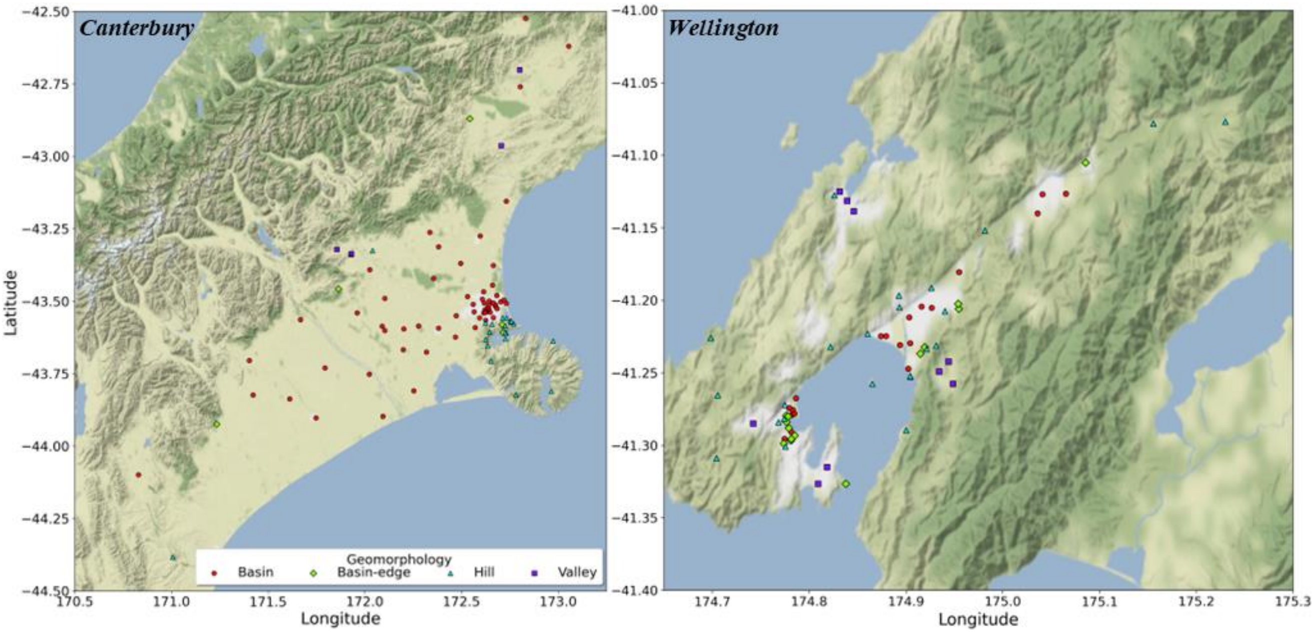

Figure 2: Categorisation of stations based on geomorphology in the Canterbury and Wellington regions

The hybrid broadband ground-motion simulation methodology adopted in Lee et al. (2022) was developed by Graves and Pitarka (2015) and uses two different approaches for simulating the low- and high-frequency components (LF and HF, respectively). A LF-HF transition frequency of 1.0 Hz and a minimum shear wave velocity of 500 m/s was adopted. For the LF component, the New Zealand Velocity Model, v2.02 (Thomson et al., 2020) was utilized, considering a finite difference grid spacing of 100 m. The Bradley (2013) NZ-specific GMM model is used for the empirical-based predictions in Lee et al. (2022). The prediction residuals were partitioned following the Al Atik et al. (2010) notation into various components associated with source, path, and site terms using mixed-effects regression. The total prediction residual, Δ between either of the GMMs and observed ground motion is given by Equation (1). This can be further decomposed into fixed and random effects:

$$\Delta = ln\, IM_{es} - f_{es} = a + \delta B_e + \delta S2S_s + \delta W_{es}^0 \quad (1)$$

where $ln\ IM_{es}$ is the natural logarithm of the observed intensity measure (IM) for earthquake e and site s, f_{es} is the mean of the predicted logarithmic IM (from either empirical- or physics-based GMM); a is the model bias, δB_e, $\delta S2S_s$, and δW_{es}^0 are the residuals with zero mean and variances τ^2, ϕ_{S2S}^2, and ϕ_{SS}^2 respectively. This work focuses on understanding the site-to-site residual, $\delta S2S_s$, and its standard deviation ϕ_{S2S}.

3 SITE RESIDUAL DEPENDENCE ON GEOMORPHIC CLASSIFICATIONS

3.1 Site-to-site residuals in the Wellington region

Figure 3 illustrates the site-to-site residuals from physics-based simulations in each proposed geomorphic category. The average $\delta S2S_s$ is generally unbiased for all categories, especially at long periods (i.e., T>1s). Basin sites, on average, are overpredicted at short vibration periods (T<0.2s) and underpredicted in the range of T=0.5-3s. These trends are consistent with prior observations of ground motions in Wellington, attributable to basin amplification at moderate periods (Bradley et al. 2018). The fact that they are present despite the use of a 3D ground-motion simulation prediction indicates that the 3D velocity models may not be refined enough to capture the full site amplification, and/or the adopted spatial resolution is too coarse.

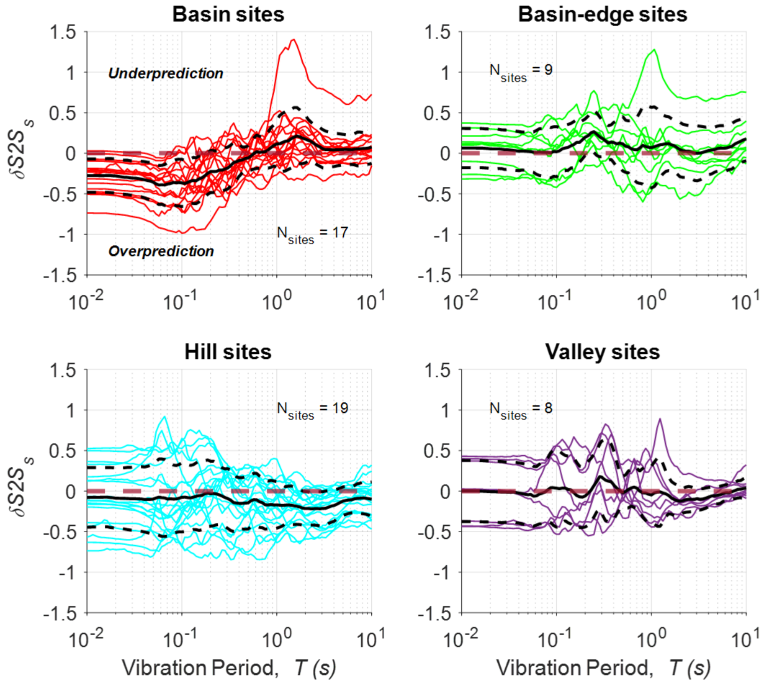

Figure 3: Site-to-site residuals as a function of vibration period from physics-based simulations for each geomorphic category in the Wellington region. The black solid and dashed lines are the mean and mean ±1 standard deviations respectively

The observed underprediction at moderate periods is better understood for basin and valley sites when the $\delta S2S_s$ residuals are interpreted in terms of normalised vibration periods (i.e., the x-axis is normalised with respect to individual site's T_0) as shown in Figure 4. $\delta S2S_s$ for valley sites peaks at their respective T_0's as seen in Figure 4, reducing between-site standard deviations at T_0, suggesting that it has a strong impact on site response for these sites.

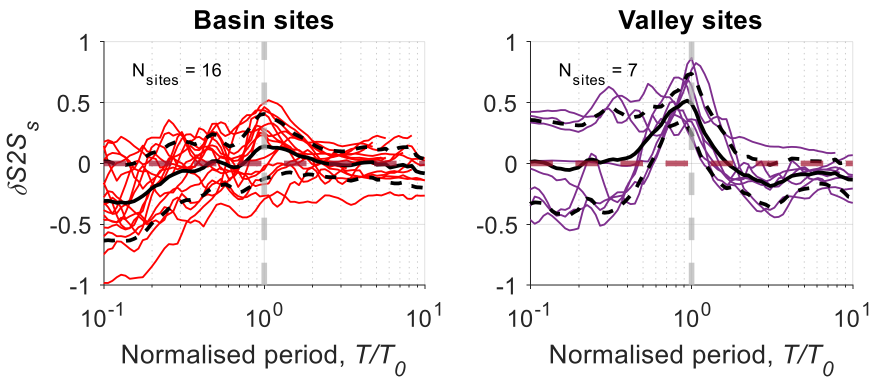

Figure 4: Site-to-site residuals as a function of normalised period (i.e., T/T_0) from physics-based simulations for all basin and valley sites in the Wellington region. Black solid and dashed lines are the mean and mean ±1 standard deviations respectively. T_0 ranges between 0.28 to 1.25s for the valley sites

Site-to-site residuals for basin sites also peak at their respective T_0's (Figure 4). However, it is more apparent for valley sites as the basin response is partly captured in physics-based simulations while valleys are much smaller in length scale and generally not appropriately represented in the 100m grid spacing of the low-frequency portion of the 3D simulations.

A comparison of $\delta S2S_s$ from empirical- and physics-based GMMs for these four geomorphic categories is shown in Figure 5. In general, mean residuals for each category are similar between the two different predictions. Average $\delta S2S_s$ primarily differs at long periods (T>1s) for all categories where comprehensive physics is used in the physics-based GMMs, as opposed to simplified physics at short periods (T<1s). The mean and standard deviation of $\delta S2S_s$ at short periods are similar for empirical- and physics-based GMMs. This similarity is reasonable given the empirical nature of the simplified physics HF method, and the fact that both empirical- and physics-based GMMs use a V_{S30}-based site response model to represent shallow site response. Standard deviation of basin sites is generally lower than other categories in physics-based GMMs (also seen in Figure 3), indicating basin sites are the best captured in simulations as compared to other geomorphic categories. Basin-edge and valley sites are overpredicting in empirical GMMs at longer periods (T>1s). Deeper investigation into the ground-motion records at these sites is needed to understand these causes.

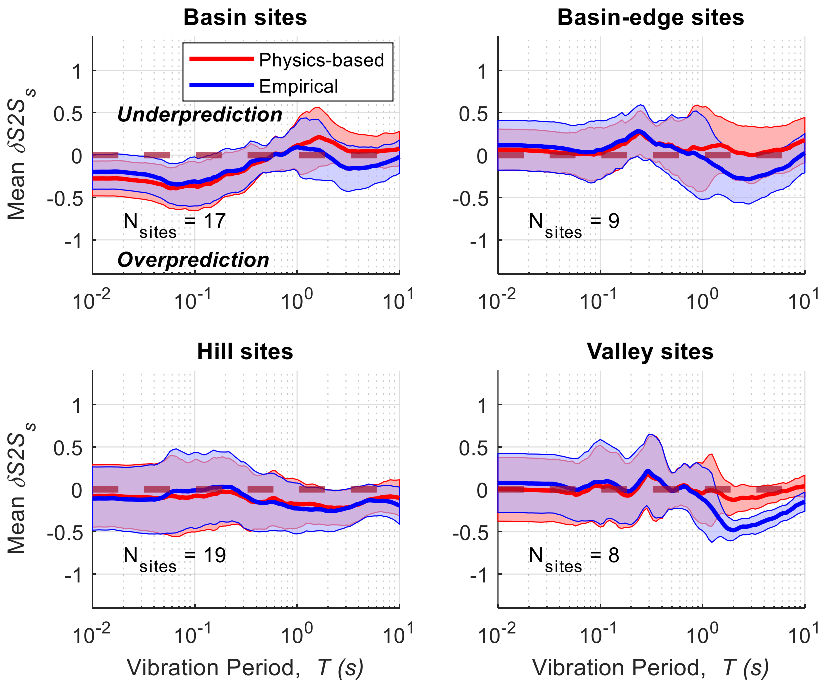

Figure 5: Means and the shaded standard deviations as a function of vibration period of the four geomorphic categories for empirical- and physics-based GMMs in the Wellington region

3.2 Site-to-site residuals in the Canterbury region

Figure 6 shows the corresponding site-to-site residuals for the four geomorphic categories in the Canterbury region. The average $\delta S2S_s$ is almost zero at all periods for basin sites in the Canterbury region, as compared to that observed for the Wellington sites, which is indicative of the high-resolution basin model used in these physics-based simulations and generally better site characterisation (Lee et al. 2022).

As seen in Figure 6 & Figure 7, most sites in the Canterbury region are basin and hill sites. The high-resolution velocity model produces good predictions for basin sites at all periods and hill sites at longer periods using physics-based GMMs. However, strong statistical inferences at a high level cannot currently be made for the basin-edge and valley sites categories as the number of sites associated with those categories are small. Similar to the observations in Wellington, there does appear to be a consistent underprediction of valley sites for T~0.5s, which is not explicitly accounted for in the simple V_{S30}-based site response models in both empirical- and physics-based prediction methods (for T<1s). In contrast to Wellington, there is a clear underprediction of short period amplifications for the Canterbury hill sites. Topographic effects are not currently modelled in physics-based simulations (or empirical GMM) but may be incorporated if found significant. Further work is needed to understand the extent to which some of these hill sites may be underlain by uncompacted sediments (often loess soils), and/or topographic effects are prevalent vs. those observed for the Wellington hill sites.

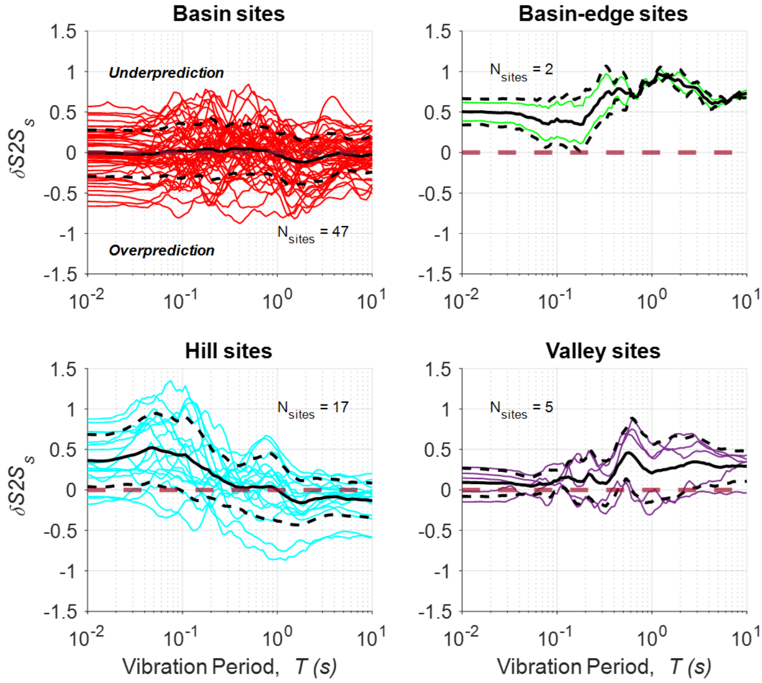

Figure 6: Site-to-site residuals as a function of vibration period from physics-based simulations for each geomorphic category in the Canterbury region. The black solid and dashed lines are the mean and mean ±1 standard deviations respectively

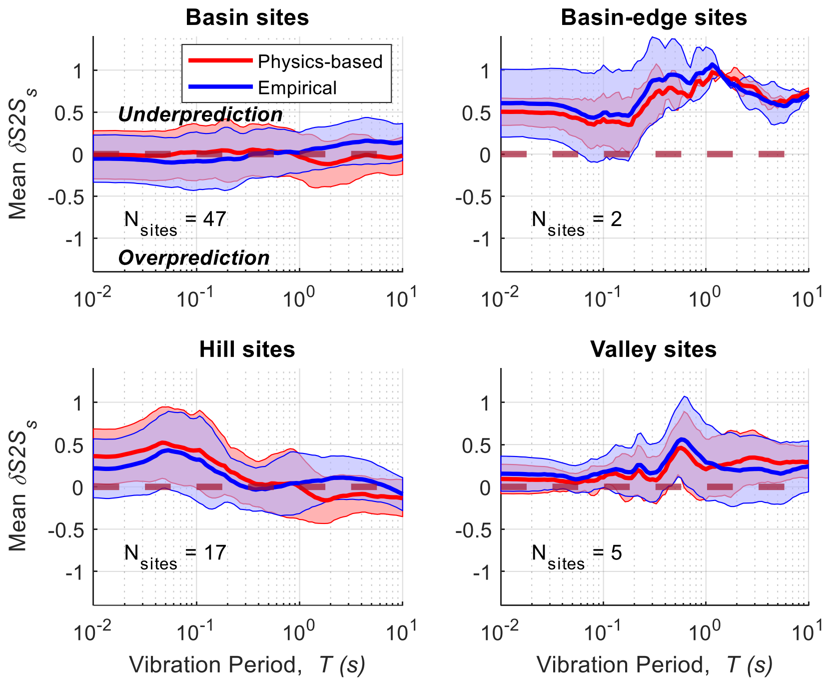

Figure 7: Means and the shaded standard deviations as a function of vibration period of the four geomorphic categories for empirical- and physics-based GMMs in the Canterbury region

4 SUMMARY

With the overarching goal of improving physics-based simulations, this study is aimed to understand systematic site effects in the Wellington and Canterbury regions based on their geomorphic classification, following Nweke et al. (2022). In general, similar trends were seen between Wellington and Canterbury regions, and between the use of empirical- and physics-based simulation predictions. The similarity between the two prediction methods was primarily at short periods (T<1s) since both approaches reflect site response via V_{S30}-based site amplification factors, whereas there were clear differences in predictions at long periods (T>1s). Trends were identified between the site residuals at valley sites in the Wellington region with their fundamental site period. Short period over-prediction at hill sites were present in the Canterbury region, but not in Wellington. Some of these observations illustrate that geomorphic classification can aid in understanding the reason for site-specific biases and imprecisions in ground-motion modelling. Further work will extend this analysis to all NZ sites, as well as additional interrogation of the resulting residuals with multiple predictor variables.

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