Modeling site effects in hybrid broadband ground-motion simulation: insights from validation studies in New Zealand

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ABSTRACT
One of the ongoing challenges in broadband ground-motion simulation is to improve the modeling of local site effects. This paper examines various methods for adjusting simulations to account for these effects using site-characterization data typically available in practice. We present key insights from two validation studies in New Zealand based on observations from multiple small-magnitude earthquakes (Mw=3.5-5.0) recorded at a wide range of soil conditions. The first validation study focuses on methods that use a shear-wave velocity (V_S) profile. The study considers 1,446 ground motions from 213 earthquakes recorded at 38 sites. Results show that the overall prediction improvement achieved with V_S-profile-based methods is comparable to that of simpler V_{S30}-based site adjustments commonly applied in regional simulations. However, specific site conditions are identified where the more advanced approach provides significant benefits. These conditions include sites that exhibit considerable resonance effects. The second validation study focuses on the evaluation of alternative V_{S30}-based site adjustments, using 5,218 ground motions from 479 earthquakes recorded at 212 sites. Based on residual examination, a simple protocol for applying the site factor to the low-frequency simulation component is proposed. This protocol is based on a basin-type and geomorphic site categorization, and it reduces the site-to-site variability in Fourier amplitude spectra prediction by up to 0.1 natural log units.

1 INTRODUCTION

Hybrid broadband ground-motion simulation (e.g., Graves and Pitarka, 2010) requires the modeling of source, path, and site effects. These simulations are generally performed adopting domain lengths of tens or hundreds of kilometers, which are needed to capture source and path effects. However, shallow site effects occur on a scale of meters, requiring a finer spatial resolution in the material modeling than that typically considered. This has led to the application of posterior adjustments to account for unmodeled site effects in ground-motion simulations (e.g., Graves and Pitarka, 2010, de la Torre et al., 2020).

Figure 1 illustrates the five methods presented in Kuncar et al. (2025a) for adjusting hybrid broadband ground-motion simulations to account for site effects. These methods utilize different site-response approaches and require different amounts of site-characterization data. Methods 1 and 2 use the 30 m time-averaged shear-wave velocity, V_{S30}, with Method 1 relying solely on proposed site-response scaling factors in existing semi-empirical ground-motion models, and Method 2 incorporating a host-to-target velocity-profile adjustment. Methods 3 and 4 utilize a V_s profile. Method 3 uses the square-root-impedance method (Boore, 2013), and Method 4 uses the theoretical 1D (SH1D) transfer function (Kramer and Stewart, 2024), to model the linear site-response component; in both cases, the nonlinear component of Method 1 is used. Method 5 is based on 1D time-domain nonlinear site-response analysis (Kramer and Stewart, 2024) and requires a V_s profile and additional data to constrain nonlinear constitutive-model input parameters.

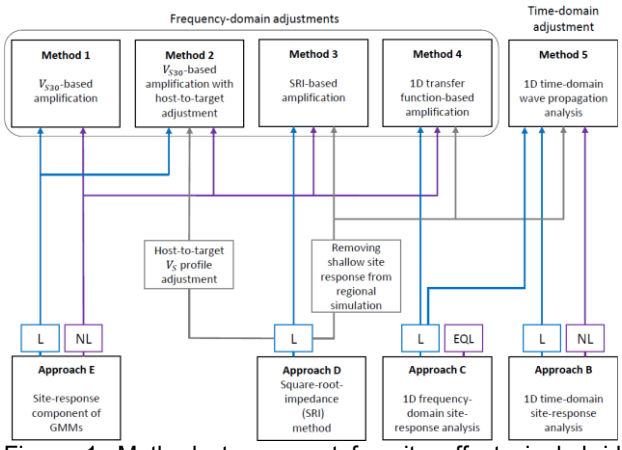


Figure 1. Methods to account for site effects in hybrid broadband ground-motion simulations (from Kuncar et al., 2025a).

Given that all these methods rely on some assumptions and simplifications for the representation of site conditions and seismic wave propagation, systematic validation against observations is needed to assess their relative

performance under different conditions. This paper synthesizes the main findings from two validation studies conducted in New Zealand (Kuncar et al., 2025b, 2026a), in which we evaluated several of the methods outlined in Figure 1 using a large dataset of observations from small-magnitude (Mw=3.5-5.0) earthquakes. The paper also outlines directions for future research needed to further extend this investigation.

2 METHODS

2.1 Simulation method

Simulations were performed by Lee et al. (2022) using the Graves and Pitarka (2010, 2015, 2016) hybrid broadband ground-motion simulation method. This simulation approach combines a comprehensive physics-based method to simulate the low-frequency (LF) ground motion and a simplified physics-based method to simulate the high-frequency (HF) ground motion. The New Zealand Velocity Model (NZVM) v2.02 (Thomson et al., 2020) was used for the LF simulation component, with a grid spacing of 100 m and a minimum V_S=500 m/s, which allows consideration of an LF-HF transition frequency of 1 Hz. Site adjustments are applied separately for the LF and HF simulation components before merging them to obtain the broadband (BB) simulated ground motion.

2.2 Site-adjustment methods

Given that the validation studies utilize small-magnitude events, soil nonlinearity is expected to be minor. Hence, Method 5 (Figure 1), which considers a comprehensive modeling of soil nonlinearity, was excluded from these studies. For brevity, results obtained with Method 2 (which corresponds to a modification of Method 1) in the second validation study are also excluded from this paper.

2.3 Residual analysis

Prediction performance is evaluated through residual analysis, considering multiple intensity measures (IMs). The prediction residual, Δ_{es}, is computed as

$$\Delta_{es} = \ln(IM_{obs})_{es} - \ln(IM_{sim})_{es} \quad [1]$$

where $\ln(IM_{obs})_{es}$ and $\ln(IM_{sim})_{es}$ are the natural logarithms of the observed and simulated IMs, respectively, for the event e and site s. Using mixed-effects regression, Δ_{es} can be partitioned into the different components of ground-motion variability:

$$\Delta_{es} = a + \delta S2S_s + \delta B_e + \delta W_{es}^0 \quad [2]$$

where a is the (global) model bias; $\delta S2S_s$ is the site-to-site residual for the site s; δB_e is the between-event residual for the event e; and δW_{es}^0 is the remaining within-event residual. Assuming that $\delta S2S_s$, δB_e, and δW_{es}^0 are independent and normally distributed random variables, with zero mean and variances of ϕ_{S2S}^2, τ^2, and ϕ_{ss}^2, respectively, the total variance, σ^2, can be expressed as

$$\sigma^2 = \phi_{S2S}^2 + \tau^2 + \phi_{ss}^2 \quad [3]$$

In the first validation study, the ground motions are grouped into two geographic clusters (see Figure 2). In this case, equation 2 can be written as

$$\Delta_{es} = a + \delta C2C_c + \delta S2S_s^0 + \delta B_e^0 + \delta W_{es}^0 \quad [4]$$

where $\delta C2C_c$ is the systematic cluster-to-cluster residual for the cluster c, and $\delta S2S_s^0$ and δB_e^0 are the remaining site-to-site and between-event residuals, respectively, after removing the cluster-to-cluster systematic effects. In this case, the total variance can be expressed as

$$\sigma^2 = \phi_{C2C}^2 + \phi_{S2S_0}^2 + \tau_0^2 + \phi_{ss}^2 \quad [5]$$

3 VALIDATION STUDY 1: V_S-PROFILE-BASED METHODS

3.1 Site-adjustment methods and dataset considered

The first validation study focuses on V_S-profile-based Methods 3 and 4, and it uses V_{S30}-based Method 1 as a benchmark to assess to what extent the more sophisticated methods allow for prediction improvements.
The study considers 1,446 ground motions from 213 small-magnitude events recorded at 38 sites with high-quality measured V_S profiles (e.g., Cox and Vantassel, 2018). The spatial distribution of the earthquake sources and sites is illustrated in Figure 2, which indicates that the dataset is grouped into two clusters: Canterbury and Wellington.

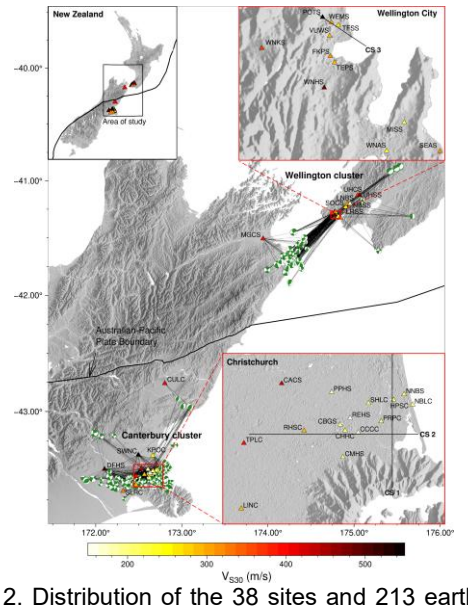


Figure 2. Distribution of the 38 sites and 213 earthquake sources considered in Validation Study 1 (from Kuncar et al., 2025b).

3.2 Results

Figure 3 shows the overall prediction performance of all methods considered, in terms of accuracy (model bias) and precision (site-to-site standard deviation). Figure 3a shows that, on average, the simulation without site adjustment underpredicts the response for all IMs considered. The application of site adjustments reduces this underprediction, although in some cases it produces significant overprediction. Figure 3b shows that all site-adjustment methods investigated considerably improve simulation precision for several IMs, particularly for response spectra at T = 0.4 – 1.0 s and for Arias Intensity (AI). This improvement is comparable across methods.

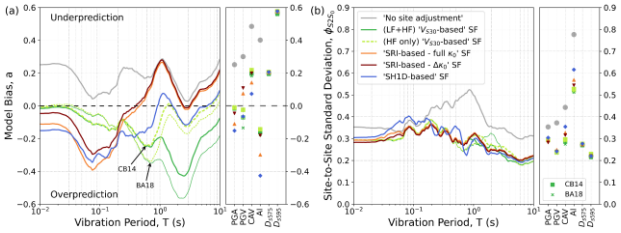


Figure 3. (a) Model bias and (b) site-to-site standard deviation, for the entire dataset considered, for SA, PGA, PGV, CAV, AI, D_{s575}, and D_{s595}. 'No site adjustment' corresponds to the simulation without any adjustment for site effects; 'Vs30-based' SF corresponds to the Method 1 site factor; 'SRI-based – full kappa0' SF and 'SRI-based – delta kappa0' SF are two variations of Method 3; and 'SH1D-based' SF corresponds to Method 4 (from Kuncar et al., 2025b).

To further investigate the overall results in Figure 3, Figure 4 presents the model bias disaggregated by cluster, illustrating significant inter-cluster differences. Figure 4a shows that Method 4 ('SH1D-based' SF) produces the lowest systematic residual for most of the IMs considered. Figure 4b shows that the simulation without any site adjustment already exhibits a near-zero or negative bias for short-period response spectra in Wellington, which produces significant overprediction once the site adjustments are applied. This suggests that inaccuracies exist in the modeling of source and path effects for the Wellington cluster, which requires improvement of the simulation input parameters for this region.

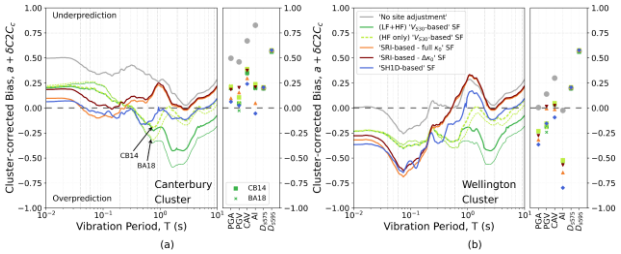


Figure 4. Cluster-corrected bias (a + $\delta C2C_c$) for the (a) Canterbury and (b) Wellington clusters (from Kuncar et al., 2025b).

To examine the residuals further, Figure 5 shows the systematic residual obtained at two representative sites in the Canterbury cluster, where Method 4 ('SH1D-based' SF) results in significant prediction improvement relative to Method 1 ('V_{S30}-based' SF). REHS (Figure 5a) is a relatively soft site that exhibits a very strong 1D transfer function (SH1D) resonance in the intermediate frequency range (~1.8 Hz). In this case, Method 4 results in a significant improvement (relative to Method 1) in the systematic response spectra residual in the vicinity of the vibration period associated with the site resonance. KPOC (Figure 5b) is a relatively stiff site that exhibits strong SH1D resonances at frequencies higher than 3.5 Hz. In this case, Method 4 results in a significant improvement of systematic residuals for PGA, PGV, CAV, AI, and response spectra at short vibration periods. Similar improvements are observed at several other sites with similar site conditions (Kuncar et al., 2025b).

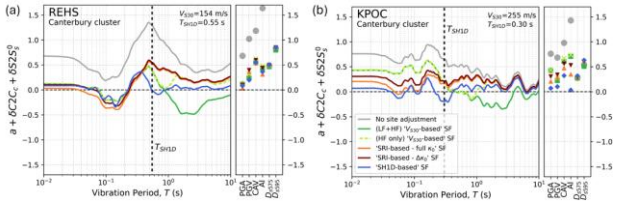


Figure 5. Systematic residuals for the different methods, for the sites (a) REHS and (b) KPOC (modified from Kuncar et al., 2025b).

Since site-adjustment evaluation through residual analysis was shown to be challenging in the Wellington cluster, validation is performed in terms of the relative response between a target and a reference site. Figure 6 shows the results of this evaluation for the target sites FKPS, TEPS, WEMS, TFSS, and VUWS, with the rock site POTS used as the reference. The relatively short distances between the five target sites and POTS with respect to the large source-to-site distances (see Figure 2) minimize the influence of source and path effects in the site-response ratios (AFs), which is optimal for the evaluation of site effect modeling. Figure 6 indicates that the regional simulation (without site adjustment) is unable to capture 3D effects in the relatively shallow Wellington basin, which is mainly due to the grid spacing (100 m) and minimum V_S (500 m/s) considered. The figure shows that Method 4 ('SH1D-based' SF) allows for better prediction of the observed site amplification at the site period than other methods, which underpredict it. However, site response is significantly underpredicted at other vibration periods, which suggests that methods based on 3D site-response analysis are required in this basin, where basin-edge effects are known to develop during earthquakes (e.g., Bradley et al., 2018).

4 VALIDATION STUDY 2: V_{S30}-BASED METHODS

4.1 Site-adjustment methods and dataset considered

The second validation study focuses on alternative V_{S30}-based Method 1 (and Method 2) implementations. The study considers 5,218 ground motions from 479 small-magnitude events recorded at 212 sites. The spatial distribution of the earthquake sources and sites is illustrated in Figure 7. V_{S30} values are obtained from Wotherspoon et al. (2024).

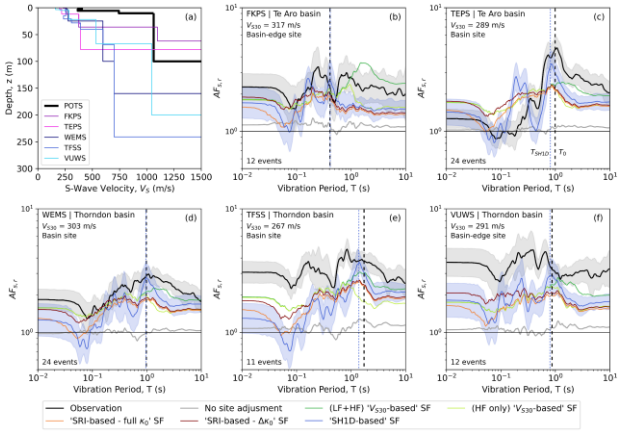


Figure 6. (a) V_S profiles and relative site response between the (b) FKPS, (c) TEPS, (d) WEMS, (e) TFSS, and (f) VUWS sites and POTS in Wellington (from Kuncar et al., 2025b).

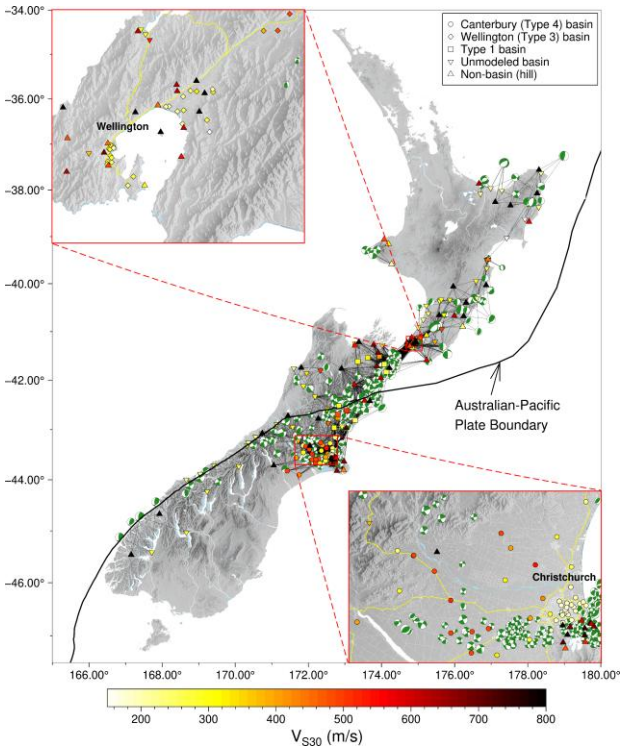


Figure 7. Distribution of the 212 sites and 479 earthquake sources considered in Validation Study 2 (from Kuncar et al., 2026a).

4.2 Results

Figure 8 shows the overall prediction performance for all implementations considered in terms of accuracy (model bias) and precision (site-to-site standard deviation). In addition to the IMs considered in Validation Study 1, we also consider (Fourier) effective amplitude spectra (EAS), which allows for a direct assessment of the LF and HF simulation components.

Empirical models for response spectra, such as the CB14 (Campbell and Bozorgnia, 2014) model have been used in several previous validation studies (e.g., de la Torre et al., 2020, Lee et al., 2022) to derive site adjustment factors. However, more recently developed empirical models for EAS, such as the BA18 (Bayless and Abrahamson, 2019) model, are more appropriate, as the site adjustment is applied in the Fourier spectral domain. In this study, we evaluate four alternative models (two for response spectra and two for EAS). Figure 8 shows that comparable results are obtained for the four models, with the BA18 model slightly improving model bias for EAS at very high frequencies, due to its treatment of high-frequency attenuation effects.

Figures 8b and 8d show that a significant improvement in precision is obtained for most of the IMs considered when site effects are included with any of the considered models.

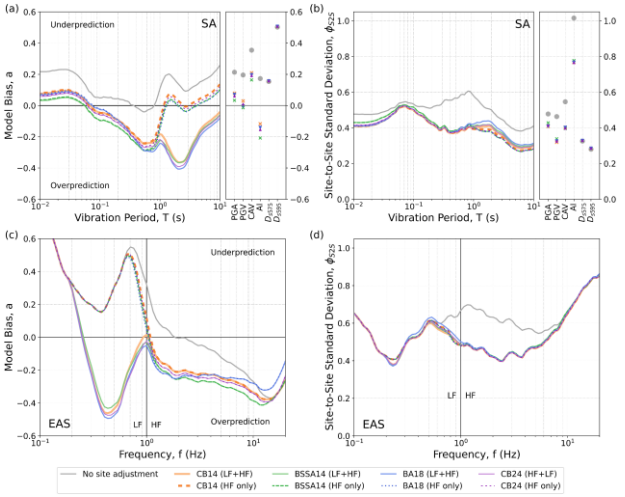


Figure 8. Model bias and site-to-site standard deviation for alternative ground motion models and site-factor application frequency ranges. IMs considered are SA, PGA, PGV, CAV, AI, D_{s575}, and D_{s595} (a, b) and EAS (c, d) (from Kuncar et al., 2026a).

One question raised in previous studies (e.g., Lee et al., 2022, Kuncar et al., 2025a) is whether the site amplification factor should be applied to the LF simulation component. Because the LF simulation approach explicitly models 3D wave-propagation effects, applying an empirical site factor may double-count these effects (e.g., as basin effects are implicit in these empirical models), potentially leading to low-frequency overprediction. Figure 8c shows that applying the site factor to the HF simulation component only ("HF only") produces significant underprediction in the

LF range. On the other hand, applying the site factor to both the LF and HF components ("LF+HF") generates considerable overprediction. Furthermore, Figure 8d shows that no material improvement in precision is obtained for frequencies lower than 0.6 Hz, regardless of the site factor application protocol ("HF only" or "LF+HF").

To further examine this issue, sites can be classified in relation to the quality of the basin model in the NZVM (Thomson et al., 2020) and distinct geomorphic categories (Nweke et al., 2022, Tiwari et al., 2024). Thomson et al. (2020) classified explicitly modeled basins in the NZVM into four Types (from Type 1 to 4), indicating increasing levels of site-characterization data used to develop the basin models. Several basins are not explicitly modeled in the NZVM, for which a simple V_{S30}-based geotechnical layer is considered. The geomorphic categories defined by Nweke et al. (2022) and used by Tiwari et al. (2024) to classify all stations in New Zealand are 'Basin', 'Basin-edge', 'Valley', and 'Hill'. Figure 7 indicates with different symbols the basin-type classification of the sites considered in this study, separating "Hill" sites from the non-hill sites, which are classified into the different NZVM types.

Through examination of residuals, we propose the following site-factor application protocol for the LF simulation component: the site adjustment is applied to the LF simulation component only if the site pertains to the geomorphic category "Basin" and simultaneously belongs to the NZVM categories "Unmodeled" (i.e., basin not explicitly modeled), "Type 1", or "Type 3". In this way, the LF site factor is only considered for sites that are in the interior of a relatively large sedimentary basin structure (i.e., "Basin" sites) for which the 3D basin model in the NZVM presents some limitations. This represents 24% of the sites considered.

Figure 9 presents the resulting model bias and site-to-site standard deviation for this "hybrid" application protocol and compares them with the "HF only" and "LF+HF" protocols. As observed, the "hybrid" application protocol results in a significant reduction of the EAS model bias and site-to-site variability in the frequency range 0.3-0.8 Hz. The reduction in standard deviation is up to 0.1 natural log units around f=0.5 Hz.

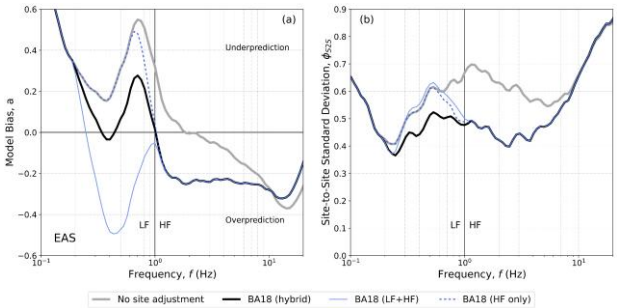


Figure 9. (a) Model bias and (b) site-to-site standard deviation for EAS, considering the "hybrid" site-adjustment application approach proposed in this study.

5 CONCLUSIONS

This paper presented the main findings obtained from two validation studies (Kuncar et al., 2025b, 2026a) conducted in New Zealand to evaluate alternative methods to account for site effects in hybrid broadband ground-motion simulation (Kuncar et al., 2025a). These studies utilized multiple small-magnitude earthquakes recorded across the country over a wide range of soil conditions.

Methods based on a V_S profile resulted in similar overall performance to those based on V_{S30} when the entire dataset was considered. However, they provided significant additional improvement in simulation accuracy for specific site conditions, including relatively soft sites that display strong resonances in the intermediate frequency range and relatively stiff sites that display considerable resonances at high frequencies.

V_{S30}-based empirical models developed for Fourier amplitude spectra provided similar or slightly better performance than models developed for response spectra, previously adopted in several validation studies. The former are more appropriate for simulations as the site factors are applied in the Fourier domain.

A protocol for the application of the V_{S30}-based site adjustment to the low-frequency simulation component was proposed, which is based on the geomorphic characterization of the site and the quality of the basin model. This protocol led to an improvement in simulation accuracy and precision at low frequencies, achieving a reduction in site-to-site standard deviation of up to 0.1 natural log units.

These studies utilized small-magnitude crustal events, which limited site response to the predominantly linear regime. Further insights will be obtained from utilizing a unified database of ground-motion simulations for ~1,600 Mw 3.5-7.8 crustal and subduction earthquakes in New Zealand (Kuncar et al., 2026b). Also, the V_S-profile-based methods considered assumed a 1D representation of the site, which limited the prediction improvement in sedimentary basins where site response is dominated by 3D effects. In future studies, we plan to consider adjustment methods based on 3D site-response analysis via the Domain Reduction Method (Bielak et al., 2003).

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