Evaluating the Performance of 1D Site-Response Analysis in Physics-Based Earthquake Ground-Motion Simulations: Insights from Small-Magnitude Events

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1. Introduction

Local site effects are usually not explicitly included in physics-based earthquake ground-motion simulations. Instead, they are typically modelled through an empirical amplification factor based on the parameter V_{s30} (Figure 1a). Recent validation studies conducted in New Zealand [e.g., 1, 2] have suggested that the explicit modelling of local site effects using site-response analysis (Figure 1b) has the potential to improve predictions, especially at complex sites.

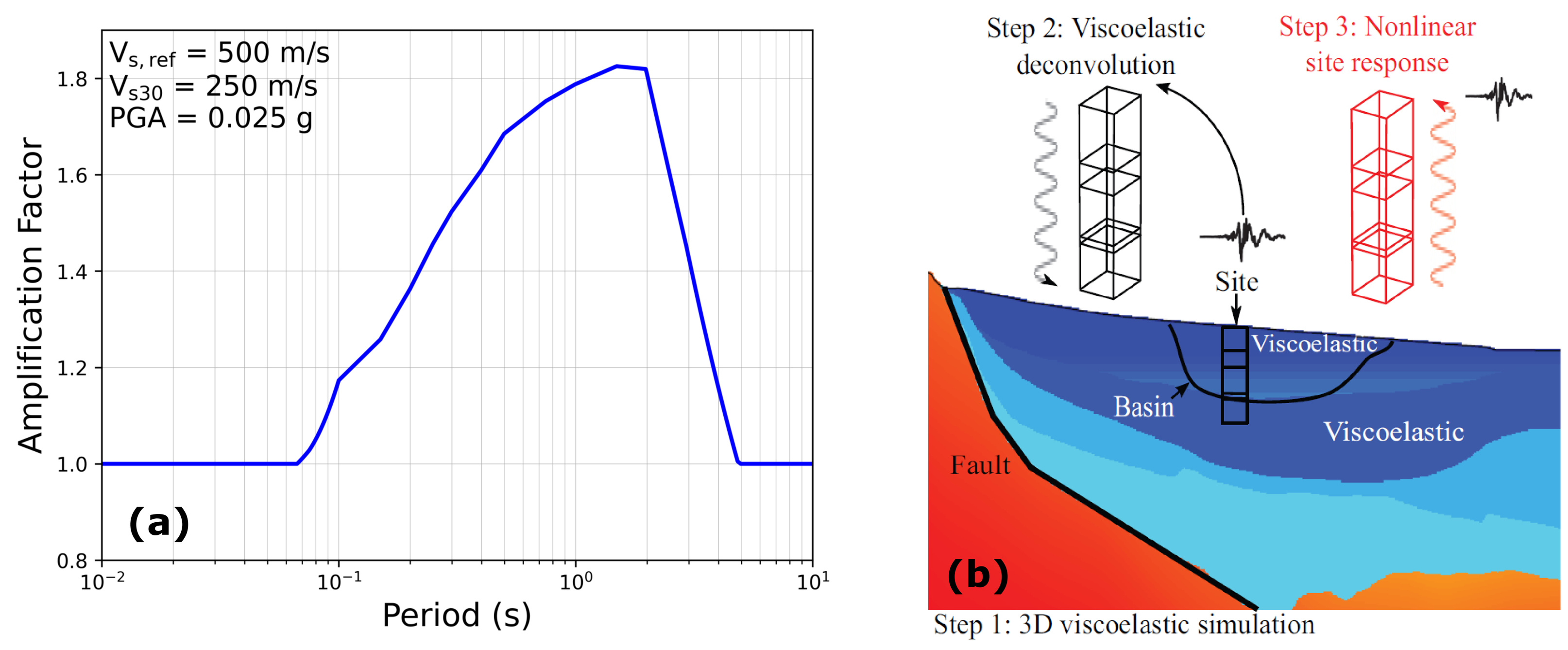

Figure 1: Two approaches for modelling local site effects in physics-based earthquake ground-motion simulations: (a) empirical amplification factor based on V_{s30}, and (b) site-response analysis.

Previously, de la Torre et al. [1] conducted a validation study of the 1D site-response analysis (see Table 1) considering 20 (strong-motion) stations and 11 events, associated with the 2010-2011 Canterbury Earthquake Sequence. However, modelling complexities related to those events limited the inferences regarding the performance of this approach.

This poster presents preliminary results of an ongoing research project that seeks to extend the validation study [1] using stations from all over the country and a wider range of earthquake magnitudes, increasing the amount of validation data by more than an order of magnitude (see Table 1). In particular, this poster is focused on small-magnitude events ($3.5 \leq M_w \leq 5.0$) recorded in Christchurch.

Table 1: Validation data used by de la Torre et al. [1], in this study, and the project goal, showing a significant increment in the data at every stage.

Study	N° Sites	N° Events	Magnitude Range	N° Ground Motions
de la Torre et al. [1]	20	11	4.7 – 7.1	200
This study	17	156	3.5 – 5.0	937
Research project goal	>55	>400	3.5 – 7.8	>2000

2. Methodology

The regional-scale simulations used in this study were generated by Lee et al. [2]. Figure 2a shows the 17 stations that were considered here, as adopted by [1]; but excluding HVSC, ROLC, and SMTC, for which not enough observational data was available for small-magnitude events. Figure 2b provides the magnitude-PGA distribution of the observed ground motions used and the approximate distribution that will be considered in the final stage of the project. Based on this distribution, nonlinear constitutive models were used to characterize the soil dynamic behaviour.

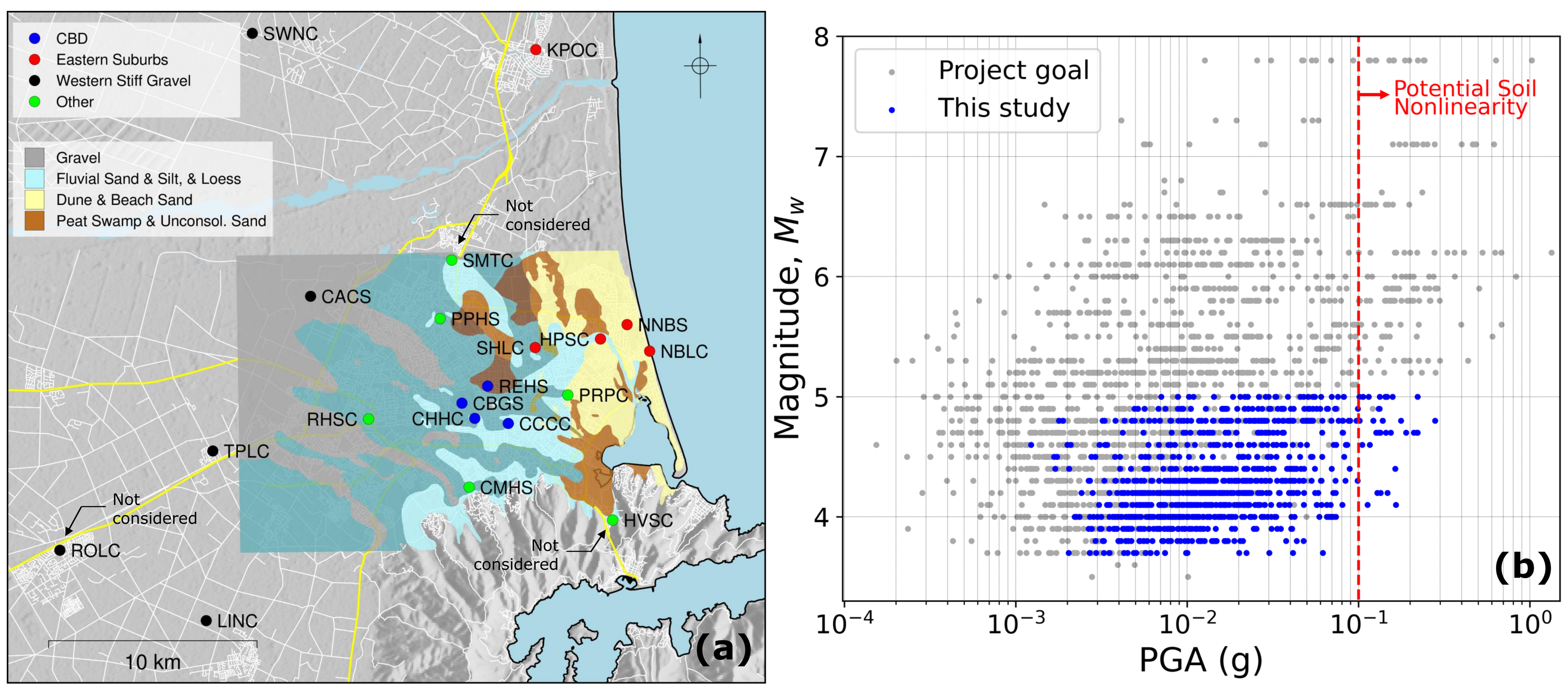

Figure 2: (a) Location of the 17 stations considered and variability in the surface geology of Christchurch; (b) Magnitude-PGA distribution of observed ground motions considered in this study and those that will be used in the final stage of the project. The red dashed line indicates the approximate value of PGA from which soil nonlinear behaviour can be expected and illustrates that some of the ground motions considered in this study can produce nonlinearity.

3. Illustrative result

Figure 3 presents an example comparison between the observed and predicted spectral accelerations (SAs). This comparison illustrates some of the main trends found, which are discussed in the next section.

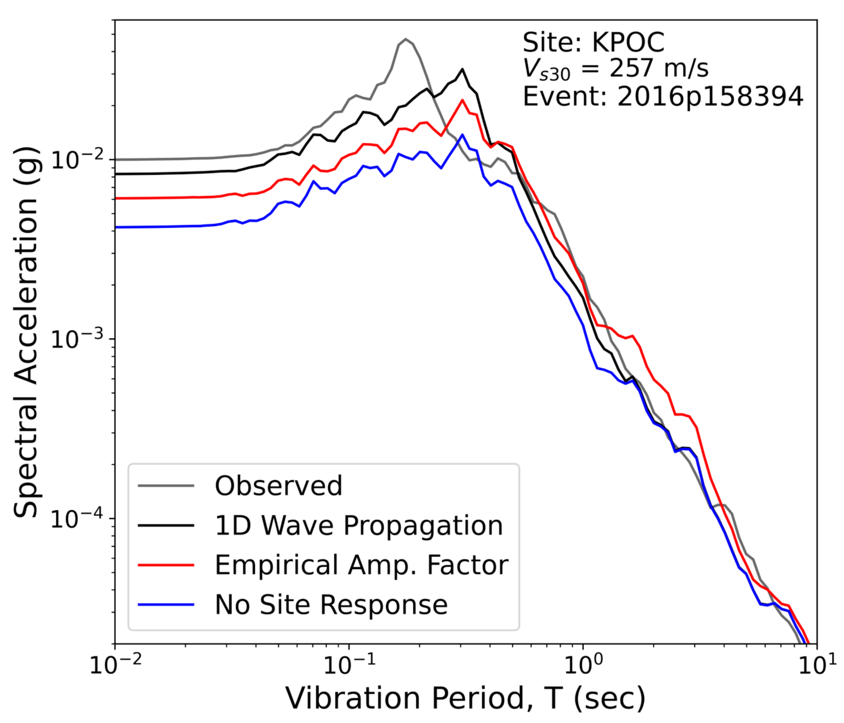

Figure 3: Comparison between the observed and simulated spectral accelerations for one ground motion.

4. Model bias and total uncertainty

In order to consider the entire dataset of ground motions in the evaluation, a residual analysis is performed. The prediction residual (Δ_{es}) for the event e and the site s is defined as the difference between the natural logarithm of the observed intensity measure (IM_{es}) and the predicted logarithmic intensity measure (f_{es}), and it can be partitioned into the different components of ground motion variability. Specifically,

$$\Delta_{es} = \ln IM_{es} - f_{es} = a + \delta B_e + \delta S2S_s + \delta W_{es}^0$$

where a is the model bias, δB_e is the between-event residual, $\delta S2S_s$ is the systematic site-to-site residual, and δW_{es}^0 is the "remaining" within-event residual.

Figure 4 provides the systematic model bias (a) for the alternative approaches and intensity measures (IMs) considered, and the corresponding total standard deviation (σ). The following main trends can be identified: **(1)** not considering site effects underpredicts SA across the entire vibration period range; **(2)** the empirical amplification factor underpredicts SA at short periods ($T < 0.35\ s$) and overpredicts it at longer periods; **(3)** 1D site-response analysis shows the lowest model bias for almost all the IMs considered; **(4)** both approaches for capturing site effects show comparable variability (σ) in their prediction.

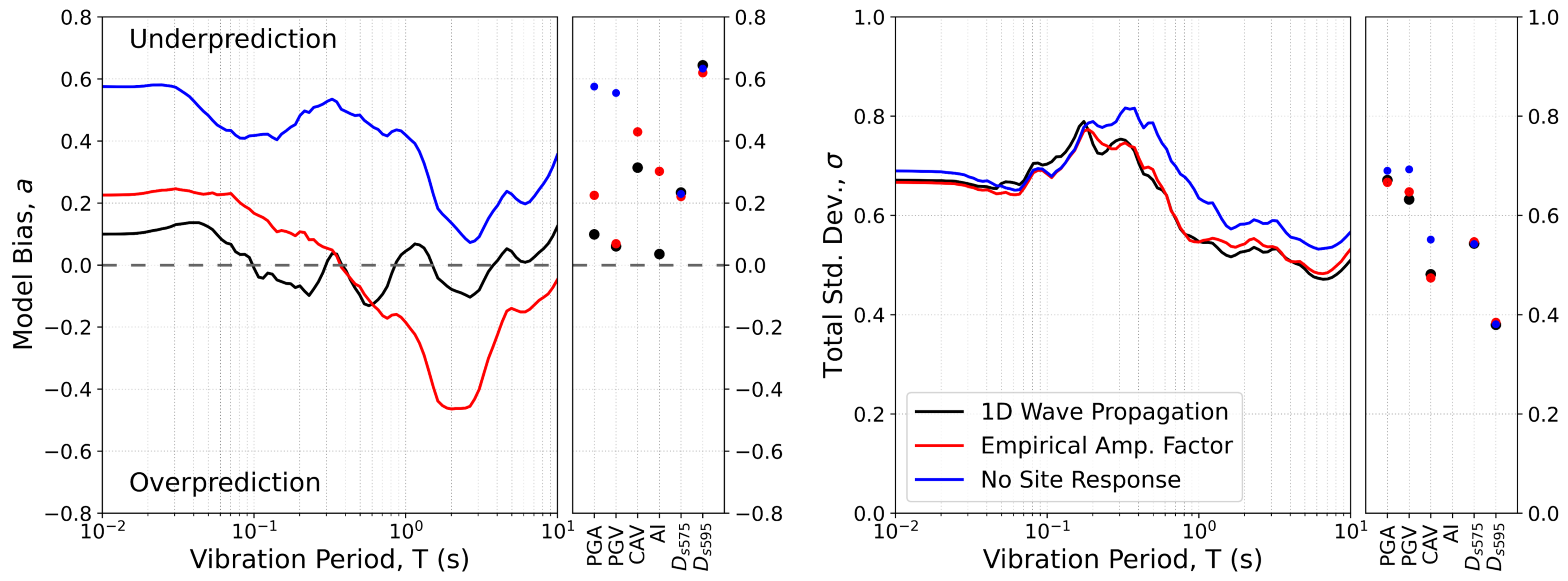

Figure 4: Model bias (left panel) and total standard deviation (right panel), showing that, in the aggregate, 1D site-response analysis performed better than the empirical approach for almost all the IMs considered.

5. Site-specific systematic effects

Figure 4 illustrated that, on average, 1D site-response analysis performed better than the empirical amplification factor. However, when the results are disaggregated by site, significant differences are found in the relative performance of both approaches. Figure 5 plots the systematic residual ($a + \delta S2S_s$) for the sites RHSC and SWNC, and shows that for RHSC the improvement achieved by explicitly modelling site effects is substantial, whereas for SWNC there are only small differences between both methods since site effects are negligible for this stiff site.

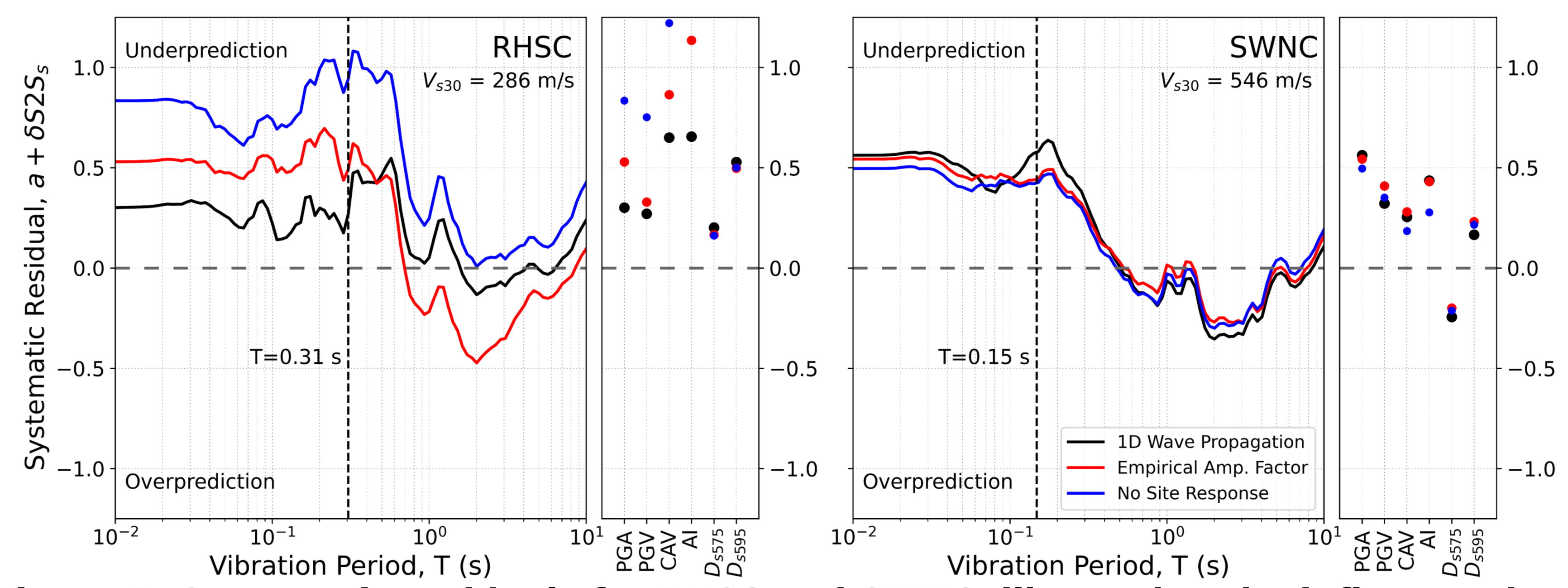

Figure 5: Systematic residuals for RHSC and SWNC, illustrating the influence that site-specific features have on the relative performance of each modelling approach.

Figure 6 further illustrates the influence that the soil stiffness has on the relative performance of each modelling approach, showing that for both PGA and CAV strong differences are found for sites with $V_{s30} < 300\ m/s$, being the 1D site-response analysis prediction less biased. The incorporation of additional sites into the analysis (see Table 1) will provide additional insights into the effect that the site complexity has on the ground motion prediction.

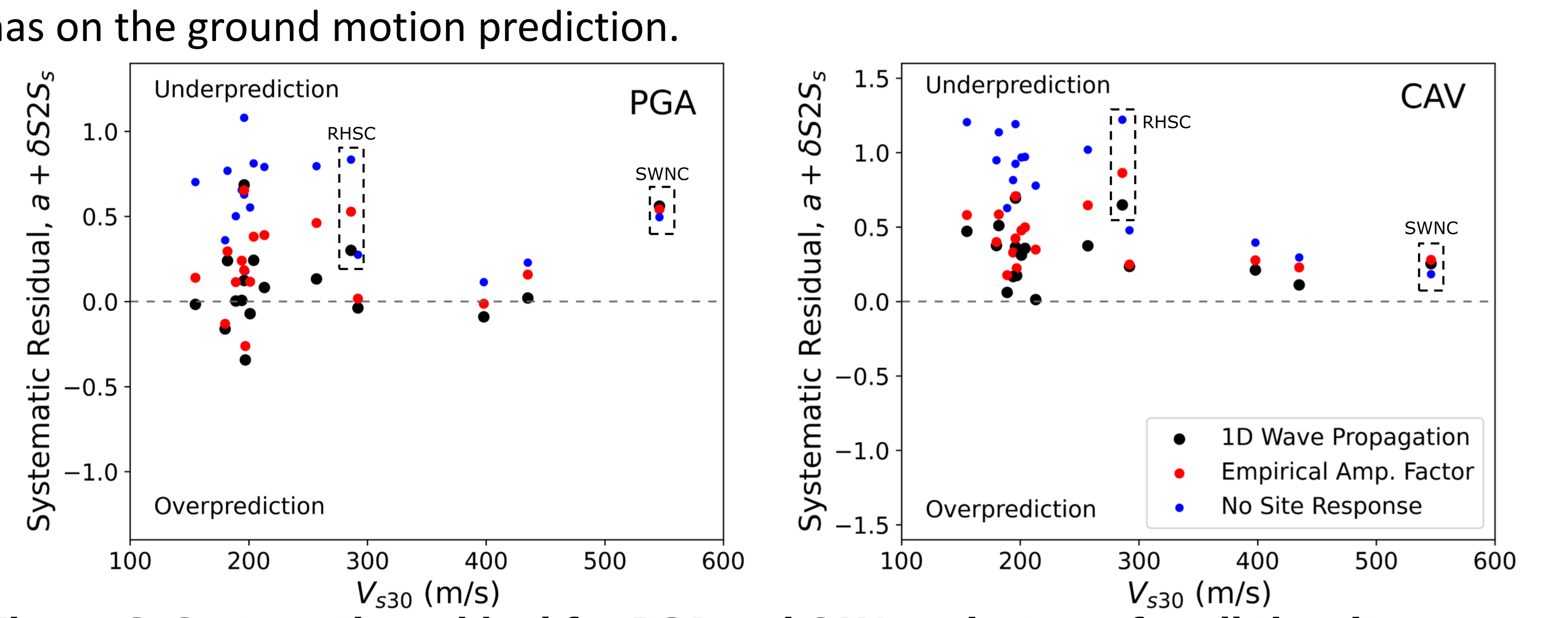

Figure 6: Systematic residual for PGA and CAV against V_{s30} for all the sites.

6. References

[1] de la Torre, C. A., Bradley, B. A., and Lee, R. L. (2020) Modeling nonlinear site effects in physics-based ground motion simulations of the 2010–2011 Canterbury earthquake sequence. *Earthquake Spectra*, 36(2), 856–879. https://doi.org/10.1177/8755293019891729.

[2] Lee, R. L., Bradley, B. A., Stafford, P. J., Graves, R. W., and Rodriguez-Marek, A. (2022) Hybrid broadband ground-motion simulation validation of small magnitude active shallow crustal earthquakes in New Zealand. *Earthquake Spectra*. https://doi.org/10.1177/87552930221109297.