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PGA adjustment factors for TS1170.5 to account for nonlinear site response on soft soils

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ABSTRACT

This paper summarises the development and implementation of an adjustment factor for PGA from the 2022 update of the New Zealand (NZ) National Seismic Hazard Model (NSHM2022) for adoption into the NZ technical specifications TS1170.5:2024 (TS1170). The study focuses on soft soil sites within TS1170 Site Classes IV, V, and VI (i.e., with $V_{S30} \leq 300$ m/s). The adjustment factor is based on nonlinear site-response analyses of NZ characteristic soft soil sites and an examination of observations from extensive national and global ground-motion databases. These simulations treat soil nonlinearity more rigorously than the approximations used in the empirical ground-motion models employed in NSHM2022. The scientific background and details of the analyses used to develop the PGA adjustment factors are documented in de la Torre et al. (2025a), and the parametrisation of the proposed adjustment factor for implementation into TS1170 is described in de la Torre et al. (2025b). We compare the adjusted PGAs to the PGAs from NSHM2022, and the PGAs from the 2004 NZ seismic loading standard NZS1170.5:2004. The adjustment factors reduce the PGA for all three site classes, and the amount of reduction increases as the PGA hazard increases. For example, the reductions for 500-year and 2500-year hazard levels for the highest hazard cities of New Zealand are approximately 10-20 % and 15-30 %, respectively. Despite this adjustment, compared with NZS1170.5:2004, the adjusted PGAs in these high-hazard regions are still 40-50 % higher for the 500-year return-period ground motion.

1 INTRODUCTION

The 2022 update of the New Zealand (NZ) National Seismic Hazard Model (NZSHM2022; Gerstenberger et al. 2024a) presented a major update since the previous 2010 update (Stirling et al. 2012), including a completely new set of ground-motion models (GMMs; Bradley et al. 2024) and a significantly improved source model (Gerstenberger et al. 2024b). The NSHM2022 results in peak ground accelerations (PGAs) that are approximately 1.5-2 times higher than the PGAs from the 2004 NZ seismic loading standard NZS1170.5:2004, for many cities in the highest seismic hazard regions of NZ (e.g., Wellington), depending on the site class considered (Kaiser et al. 2024, Bora et al. 2024). This increase in the PGA produced PGAs > 1.0 g for high hazard regions, even on soft soil sites, which triggered the need to scrutinise this particular output of NSHM2022.

The objective of de la Torre et al. (2025a, 2025b), which are summarised in this paper, was to carefully scrutinise the very high PGAs output by NSHM2022 for soft soil sites with V_{S30} < 300 m/s. The scrutiny involved comparison with historical observations from existing ground-motion databases, evaluation of the treatment of soil nonlinearity in GMMs, and quantification of the effects of this modelling aspect on the resulting PGA hazard. In the subsequent step, the nonlinear functions used in the GMMs were compared with equivalent relationships derived from more rigorous nonlinear site-response analyses, as well as with observations of soil nonlinearity from the records of 2010-2011 Canterbury Earthquake Sequence. This investigation revealed that the PGA for soft soil sites directly resulting from NSHM2022 is likely overpredicted due to the approximate treatment of the nonlinear site response in GMMs for high-intensity ground motions (i.e., PGA > 0.5 g). The interested reader should refer directly to de la Torre et al. (2025a, 2025b).

2 TREATMENT OF NONLINEAR SITE RESPONSE IN NSHM2022 GMMS

Nonlinear site-response effects in global GMMs are modelled as a simple reduction factor that is generally a function of V_{S30} and PGA on a reference condition (PGA^r), which is typically representative of rock conditions with V_{S30} = 760 – 1100 m/s. For weak shaking, the nonlinear site response models have no effect (i.e., the multiplicative factor is ~1). However, as the intensity of ground motion on rock (i.e. PGA^r) increases, more soil nonlinearity is expected in soft soils, which generally results in additional deamplification of the ground motion due to damping effects (primarily at short-to-moderate periods and PGA). This is illustrated in Figure 1, which shows the nonlinear site response models for PGA and V_{S30} = 225 m/s from all the GMMs adopted in the NSHM2022. Figure 1 shows that most of the GMMs produce similar levels of nonlinear deamplification for the V_{S30} values considered here. As explained in de la Torre et al. (2025a), many of the GMMs actually adopt the same nonlinear functions, or use the same or similar data to constrain the nonlinear function.

Given the scarcity of historical ground motion observations of very high intensities (i.e. PGA >> 0.3 g), the semi-empirical nonlinear site-response models adopted in GMMs utilise site response analyses to constrain the models at large intensities. For example, equivalent-linear site-response analyses by Walling et al (2008) and Kamai et al. (2014) have been used to partially or fully constrain the nonlinear models of most of the NSHM2022 GMMs. The equivalent-linear method approximates the nonlinear behaviour of soils by iterating to find a single value of shear modulus and damping, for each soil layer, that is representative of the expected level of strain (Idriss and Seed, 1968). These values of effective shear modulus and damping are then adopted for the entire duration of the ground motion. While this approximation is reasonable for weak-to-moderate levels of shaking, it is not appropriate for severe shaking where the behaviour of soil is strongly nonlinear and changes drastically throughout a ground motion (Kramer and Paulsen, 2004). For this reason, we compare results from equivalent-linear analyses and nonlinear analyses, and evaluate the sensitivity of the predicted PGA hazard to the method adopted for constraining nonlinear site-response models of GMMs.

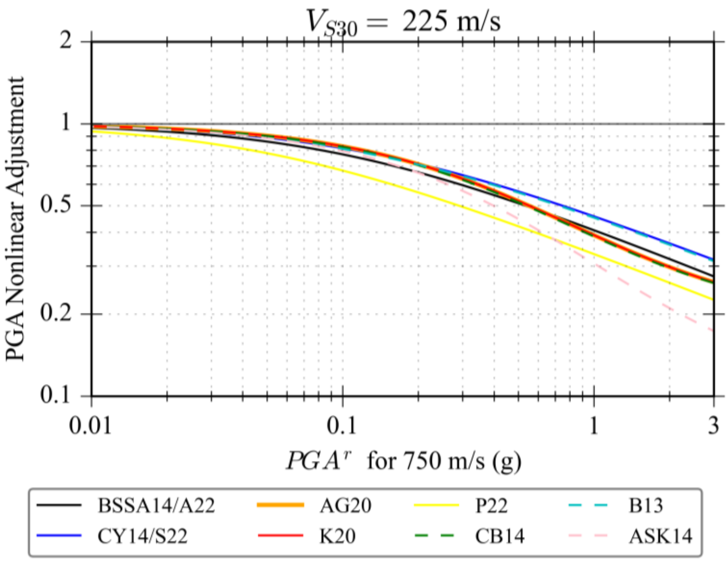

Figure 1: Nonlinear models adopted by the GMMs used in the NSHM2022 for PGA and V_{S30} = 225 m/s.

3 OVERVIEW OF NZ-SPECIFIC NONLINEAR SIMULATIONS

We used results from existing nonlinear simulations of New Zealand soft soil sites to evaluate the sensitivity of the PGA hazard from soil nonlinearity. The simulations used are those by de la Torre et al. (2024) and Cubrinovski and Ntritsos (2023), who performed nonlinear analyses for nine sites in Wellington, and thirteen sites in Christchurch, respectively. de la Torre et al. (2024) performed the nonlinear (NL) analyses in OpenSees and DEEPSOIL, and also performed equivalent linear analyses (EL) in DEEPSOIL. Cubrinovski and Ntritsos (2023) performed nonlinear total stress (TSA) and effective stress analyses (ESA) with the stress-density constitutive model (Cubrinovski and Ishihara, 1998) in the finite element code DianaJ. Both studies applied input motions with increasing intensity to evaluate the effect on the site response as intensity increases, which made their results easily adaptable for this application. For each site, we compute a moving average of nonlinear site amplification as a function of PGAr, as illustrated for two example sites in Figure 2. We then grouped sites by V_{S30} ranges of < 200 m/s, 200-250 m/s and 250-300 m/s, representative of Site Classes VI, V, and IV, respectively. We used these aggregated results to modify the nonlinear function of GMMs as summarised in the next section (Section 4).

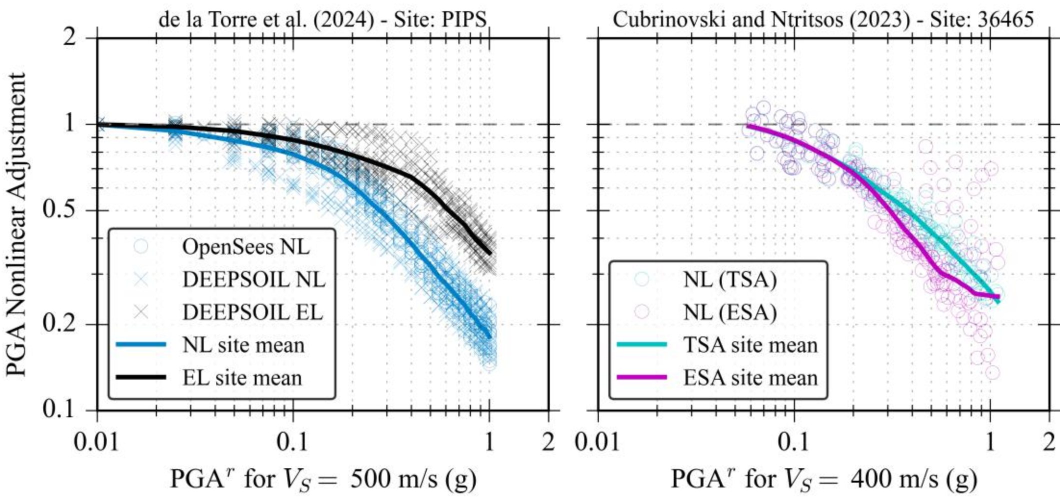

Figure 2: An example of the calculation of nonlinear site response from existing nonlinear simulations by de la Torre (2024) and Cubrinovski and Ntritsos (2023) for two sites. Each point represents the result for an individual ground motion and the solid lines are the moving average.

4 ADJUSTED NONLINEAR SITE RESPONSE FUNCTIONS CONTRAINED ON NZ-SPECIFIC SIMULATIONS

In order to use the results of NZ-specific nonlinear site response analyses, we recalibrated the nonlinear functions used in GMMs to match these results. For each site class (i.e. Site Classes IV, I, and VI, with representative V_{S30} values of 275, 225, and 175), we calibrated three models to capture the range of results observed from different simulation approaches and different sites. The three models for each V_{S30} are qualitatively labelled ‘Mild’, ‘Moderate’, and ‘Aggressive’, to reflect increasing levels of nonlinearity and increasing departures from the default nonlinear models. Figure 3 shows the background data from simulations, and the proposed adjusted models that were fit to the simulation results for V_{S30} = 175 and 225 m/s. The left side of Figure 3 includes the nonlinear models themselves, in the same format as Figure 1, while the right side shows the surface PGA implied by the nonlinear models, given a reference condition PGA^r . As shown on the left side of Figure 3, the nonlinear simulation results imply a steeper gradient to the nonlinear functions (i.e., more deamplification) than the model by Seyhan and Stewart (2014) [SS14], which is the default model adopted by some of the GMMs. The adjusted models therefore reflect this stronger level of nonlinearity, which manifests as lower surface PGAs for all cases (right side of Figure 3).

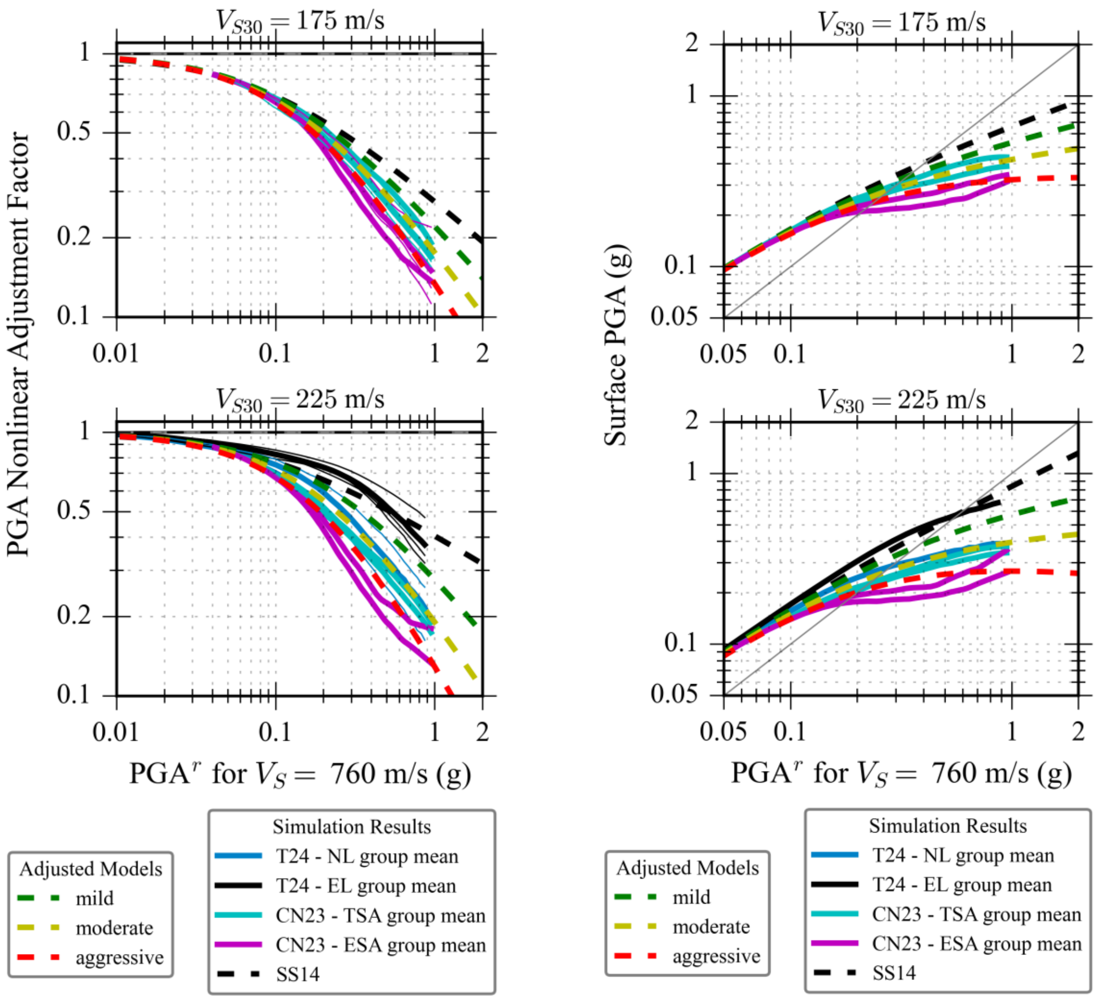

Figure 3: Left side: Adjusted nonlinear site-response models for PGA, as a function of PGA^r for a reference condition of V_{S30} = 760 m/s, based on site-response simulations results from de la Torre et al. (2024) [T24] and Cubrinovski and Ntritsos (2023) [CN23]. Results and modelling approximations are shown for two V_{S30} groups (i.e., site classes) in the different panels. For comparison the SS14 model, adopted by some GMMs, is also included. Right side: surface PGA as a function of PGA^r implied by the adjusted and default nonlinear site response models

5 INFLUENCE OF ADJUSTED MODELS ON THE OVERALL PGA HAZARD

The adjusted nonlinear functions shown above in Section 4 and Figure 3 were implemented into two GMMs used in the NSHM2022, and the hazard analysis was re-run with these new models to quantify the influence on the overall hazard. The full earthquake source model was used for this calculation. The hazard was calculated for six cities (Gisborne, Napier, Wellington, Blenheim, Christchurch, and Otira). Figure 4 shows the resulting PGA hazard curves for the city of Wellington for the 'Mild', 'Moderate' and 'Aggressive' adjusted nonlinear models, and the 'default' model for the V_{S30} = 175 and 225 m/s cases. The percent reduction in the PGA hazard (calculated from the hazard curves), relative to the default model, is also shown in Figure 4 for all six cities. The hazard curves in Figure 4 show a clear reduction in the PGA hazard for a given probability of exceedance, and this reduction is most pronounced for the 'Aggressive' case, as expected. It also evident from the hazard curves, that the reduction increases as the probability of exceedance decreases (i.e. as the return period and the hazard increases), which was also expected based on the adjusted models shown in Figure 3, which diverge from the default model as PGA^r increases. These trends are also visible in the plots of percent reduction to the PGA hazard in the right side of Figure 4. A weighted-average reduction in the PGA hazard was calculated by assigning degree-of-belief weights of 0.1, 0.4, 0.4 and 0.1 to the default (i.e., 0 % reduction), mild, moderate, and aggressive models, respectively. The weighted average percent reduction is included in Figure 4.

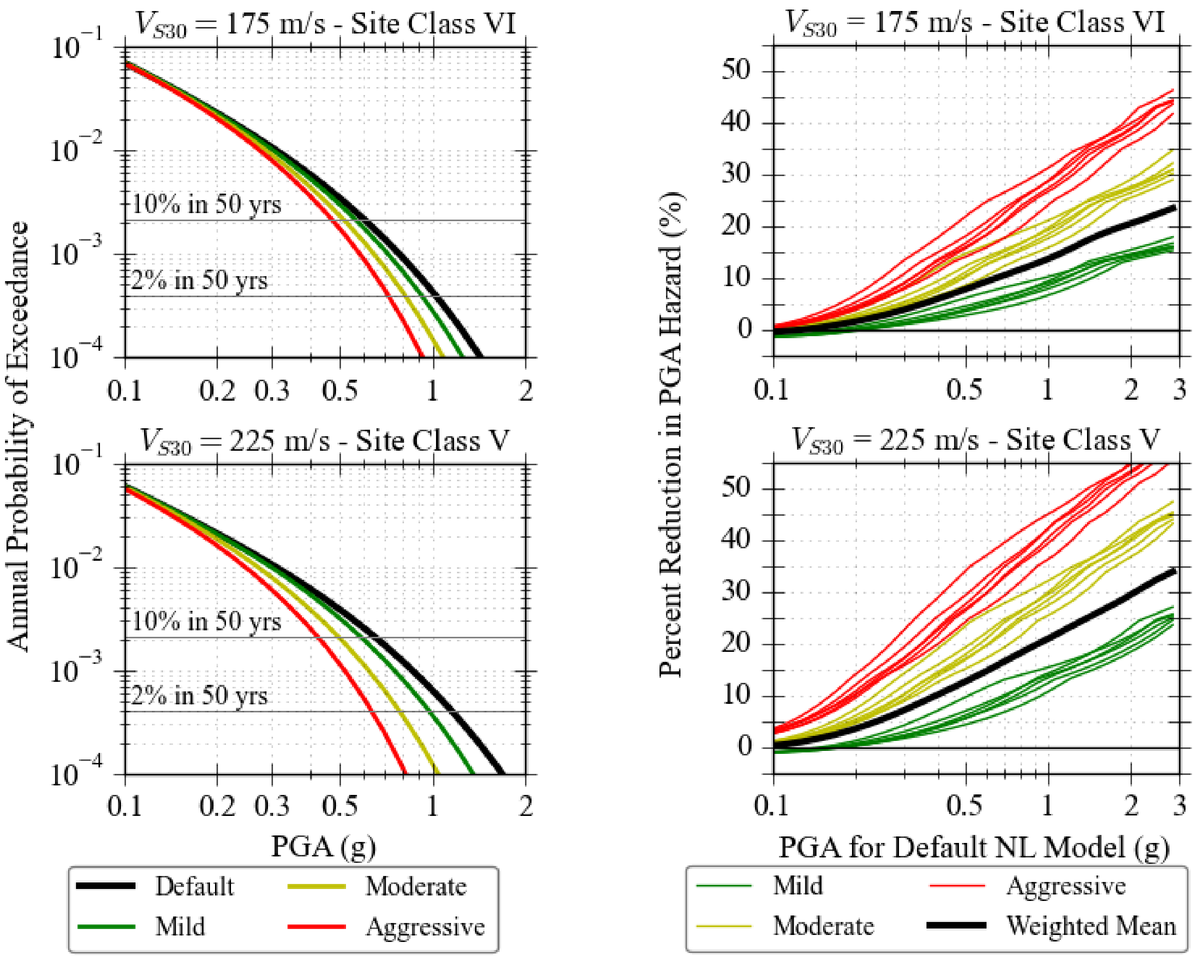

Figure 3: Left side: PGA hazard curves for Wellington using the Atkinson (2022) [A22] GMM with the default and three adjusted nonlinear site response models (shown in Figure 3) for VS30 = 175 m/s (top) and 225 m/s (bottom). Right side: percent reduction in PGA hazard as a function of PGA for the default nonlinear model, for all six cities and the three adjusted models.

6 PARAMETRIC MODEL FOR THE PGA ADJUSTMENT FACTOR

The weighted average percent reduction models (i.e. right side of Figure 4) were parametrised into a simple linear adjustment factor model, for adoption into TS1170.5. The adjusted PGA ($PGA_{Adjusted}$) can be calculated using Equation 1:

$$PGA_{Adjusted} = PGA_{NSHM2022} \times (1 - R_{PGA}) \quad (1)$$

where $PGA_{NSHM2022}$ is the PGA obtained directly from NSHM2022 and R_{PGA} is the PGA adjustment factor which is calculated with Equation 2:

$$R_{PGA} = \begin{cases} A_0 \times \ln(PGA_{NSHM2022}) + A_1, & for\ PGA_{NSHM2022} \geq PGA_{thresh} \\ 0, & otherwise \end{cases} \quad (2)$$

where A_0 and A_1 are coefficients for the linear models as defined in Table 1, and PGA_{thresh} is the threshold PGA, below which no adjustment to PGA is required. The parameterised linear models for all three site classes, along with the background data used to constrain the models (i.e. the weighted means), are shown in Figure 5. This adjustment factor was then applied to all locations across New Zealand for Site Classes IV, V, and VI.

Table 1: Coefficients for the proposed linear models to calculate the PGA reduction factor using Equation 2.

Site Class	A_0	A_1	PGA_{thresh} (g)
IV	0.076	0.123	0.198
V	0.114	0.227	0.137
VI	0.085	0.171	0.133

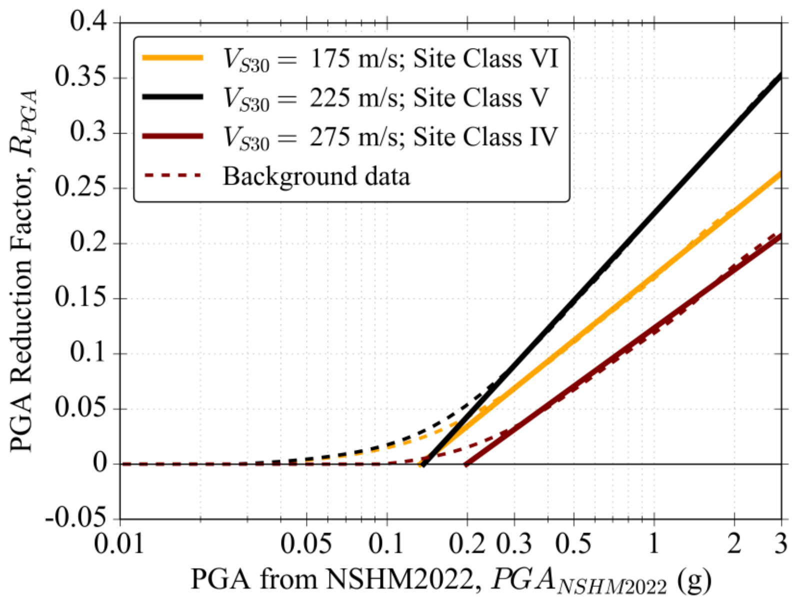

Figure 5: Recommended weighted mean percent reduction in the PGA hazard as a function of the NSHM2022 PGA values for V_{S30} = 175, 225, and 275 m/s, including the proposed simplified linear models given by Equation 2 and Table 1.

7 COMPARISON OF ADJUSTED PGA WITH NSHM2022 AND NZS1170.5

The adjustment factors (i.e. the percent reduction in PGA) in Figure 5 were applied to all locations listed in TS1170 for Site Classes IV, V, and VI using Equations 1 and 2. The ratios of the adjusted PGA ($PGA_{adjusted}$) to the NSHM2022 output ($PGA_{NSHM2022}$), and the values of $PGA_{adjusted}$ themselves, for the 500-year return period are plotted in Figure 6 for all locations. As the percent reduction increases with increasing PGA value (Figure 5), the highest hazard cities in NZ have the lowest ratios in Figure 6, with reductions in PGA of approximately 12% for Site Class IV, 15% for Site Class V, and 22% for Site Class VI. The greatest reductions occur for Site Class IV, as previously observed in Figure 5. This is because, for Site Class IV, the adjusted nonlinear site-response models deviate furthest from the default nonlinear models (e.g. SS14), as illustrated in Figure 3. In other words, the trends of percent reduction for the different site classes do not solely reflect the amount of nonlinearity expected for each representative V_{S30}, but they represent the difference between the adjusted model and the default model for a given V_{S30}.

The actual values of $PGA_{adjusted}$ for all locations are plotted in bottom half of Figure 6. As before, the PGAs for Site Class IV (i.e., the stiffest of the three considered) are the highest. The Site Class V PGAs are still higher than the Site Class VI PGAs, although they are much more similar after applying the adjustment factor. This is because the nonlinear simulation results for the V_{S30} = 175 and 225 m/s bins were not significantly different, resulting in similar nonlinear site-response models for both site classes. The abrupt changes in PGA ratios and PGA between nearby points in Figure 6 are caused by cities with similar latitude being distributed between the east coast and the west coast.

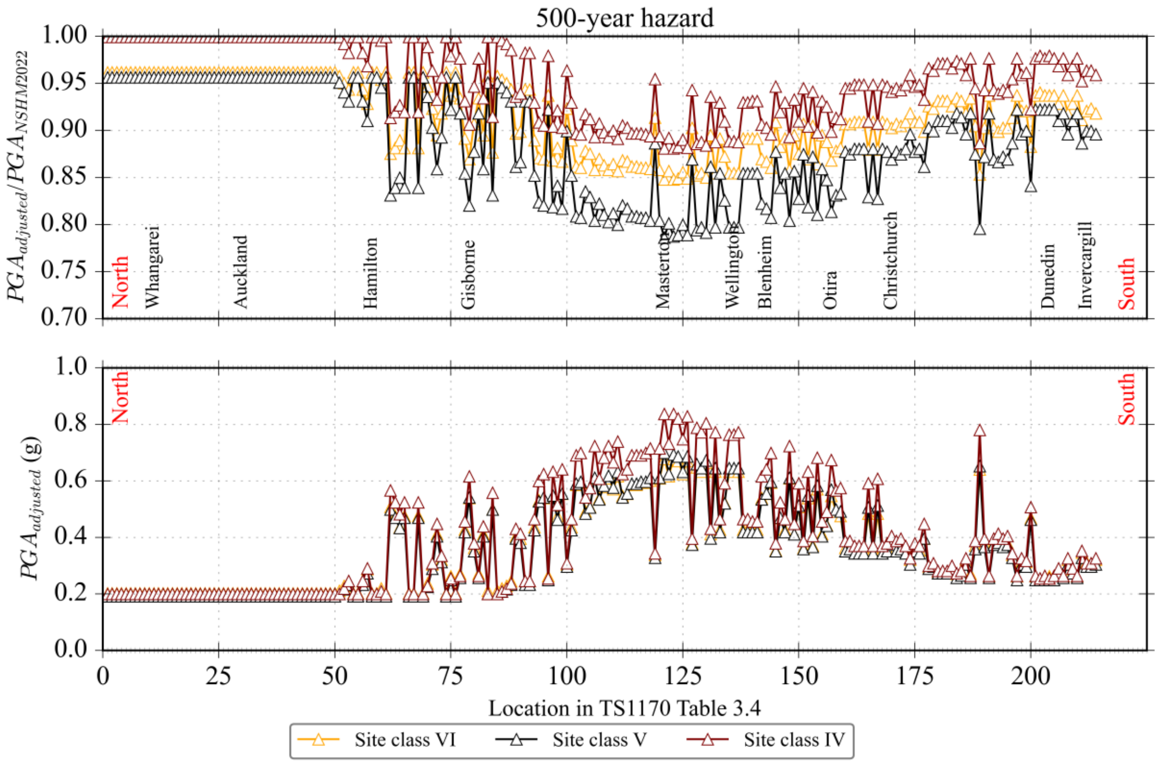

Figure 1: Top: Ratios of the adjusted PGA to the PGA from NSHM2022 for all cities in Table 3.4 of TS1170 for the 500-year hazard. Bottom: The $PGA_{adjusted}$ values for the three site classes and all cities. The x-axis represent the position of the city in the tables going from North on the left side of the figure to South on the right.

8 CONCLUSIONS

This paper summarises the findings in de la Torre et al. (2025a, 2025b), in which the PGA output by the 2022 NZ NSHM and the modelling of soil nonlinearity in empirical ground-motion models (GMMs) was carefully scrutinised. The results suggest that the PGA from the NSHM2022 on soft soil sites were likely overpredicted given the oversimplified treatment of soil nonlinearity in GMMs, which has conventionally been constrained using equivalent-linear simulations at high ground-motion intensities. The hazard calculation was rerun using improved nonlinear models, constrained on New Zealand-specific nonlinear site response simulations that rigorously account for the effects of soil nonlinearity. The nonlinear simulations suggest greater deamplification of PGA for high input motion intensities. To account for this, an adjustment factor that reduces PGA was developed. The adjustment factor was developed only for soft soil site classes (i.e. Site Class IV, V, and VI) and is a function of the PGA output directly from NSHM2022. As the PGA hazard increases, the adjustment factor produces more reduction in PGA, resulting in reductions to PGA of approximately 10-20% and 15-30% for the 500- and 2500-year hazards, respectively, for the highest hazard regions of New Zealand.

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