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PGA ADJUSTMENT FACTORS FOR NONLINEAR SITE-RESPONSE EFFECTS ON SOFT SOIL SITES: APPLICATION TO TS1170.5

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ABSTRACT

This paper discusses the development of an adjustment factor for PGA from the 2022 update of the New Zealand (NZ) National Seismic Hazard Model (NSHM2022) and its implementation in the NZ technical specifications TS1170.5:2024 (TS1170). The study focuses on soft soil sites with $V_{S30} \leq 300$ m/s (i.e., Site Classes IV, V, and VI in TS1170). The adjustment factor is based on nonlinear site-response simulations 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.* [1], while the focus of this paper is the parametrisation of the proposed adjustment factor for implementation into TS1170. The adjusted PGAs are compared to the PGAs obtained directly from NSHM2022, and the PGAs from the 2004 NZ seismic loading standard NZS1170.5:2004 for many cities. Application of the adjustment factor results in a reduction to PGA for all three site classes. The amount of reduction increases with increasing intensity of the NSHM2022 predicted ground motion (i.e., PGA), resulting in approximately 15-25 % reduction to the 2500-year return period PGA in the highest hazard regions of NZ. However, even with the proposed reduction factors, 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.

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INTRODUCTION

In 2022, the New Zealand (NZ) National Seismic Hazard Model was updated (Gerstenberger *et al.* [2]) for the first time since 2010 (Stirling *et al.* [3]). The wide-ranging update included the latest scientific advancements in earthquake source characterisation and ground-motion modelling (Gerstenberger *et al.* [4], Bradley *et al.* [5]). The 2022 update (i.e., NSHM2022) incorporated a completely new set of ground-motion models (GMMs) and a significantly improved source model. One significant outcome of the update is that 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.* [6], Bora *et al.* [7]). The significant increase in the PGA resulted in exceptionally high PGA > 1.0 g even on soft soil sites, which triggered the need to scrutinise this particular output of NSHM2022.

The objective of this study 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).

As described in de la Torre *et al.* [1], the GMMs used in NSHM2022 were either partially or fully constrained using results from equivalent-linear site-response simulations (e.g., Walling *et al.* [8], Kamai *et al.* [9], Seyhan and Stewart [10]). However, it is well known that equivalent-linear analyses are deficient in modelling severe soil nonlinearity resulting from high ground-motion intensities (e.g., $PGA > 0.3 - 0.5$ g). In addition to this study, several previous studies have shown that equivalent-linear analyses can overpredict PGA for soil sites and high ground-motion intensities, relative to fully nonlinear analyses (Kaklamanos *et al.* [11], Kim *et al.* [12]).

This paper presents the parametrisation of nonlinear site effects and the implementation of an adjustment factor to PGA that accounts for PGA overprediction from NSHM2022. The scientific background and supporting analyses used in this study are described in detail in de la Torre *et al.* [1]. First, we provide a comparison of PGAs obtained from NSHM2022 with historical

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earthquake observations, and then use nonlinear site-response simulations for NZ sites to investigate the adequacy of the GMM approximations for nonlinear effects for sites with $V_{S30} < 300$ m/s. Next, using the findings from this scrutiny, we develop a framework to revise the nonlinear site-amplification models of GMMs from NSHM2022. Then, we describe the parameterised adjustment factor and how it is applied to the TS1170 PGA for geotechnical analysis. Finally, we quantify the influence of the adjustment factor by comparing the adjusted PGAs to those obtained directly from NSHM2022 and respective PGAs in NZS1170.5:2004.

COMPARISON OF NSHM2022 PGA WITH HISTORICAL OBSERVATIONS

The PGA output from NSHM2022 was compared to PGAs from historical observations from national and global ground-motion databases such as: Japanese KiK-Net [13], European Engineering Strong Motion (ESM) [14], NGA-Sub [15], 2023 Turkey Sequence [16], NZ GMDB [17], NGA-West3 (Brendon Bradley, pers. comm. Oct. 2024). Figure 1 shows PGA versus V_{S30} for all records available in these databases, as well as the draft TS1170 PGAs obtained from NSHM2022 for the 500-year and 2,500-year return periods for Wellington. The figure is zoomed into PGA > 0.4 g and $V_{S30} < 350$ m/s, as these conditions are the focus of this study.

Figure 1 shows that the NSHM2022 500-year return period PGAs for Wellington nearly envelope the historical observations for $V_{S30} < 250$ m/s. Only three historic records, which are labelled in the figure, meet or exceed the 2500-year PGA in Wellington. These three records are: 1) 2024 M7.6 Noto Peninsula, Japan earthquake recorded at ISK005 with $V_{S30} = 139$ m/s, 2) the 1994 M6.7 Northridge, California earthquake recorded at Tarzana Cedar Hill A with $V_{S30} = 257$ m/s, and 3) the 2011 M9.1 Tohoku, Japan earthquake recorded at IBR003 $V_{S30} = 299$ m/s. As elaborated below, these are exceptional ground motions that generally do not represent typical ground conditions or/and contain particular site-response features that amplify PGA. The hazard in high-seismicity areas of NZ (e.g., Wellington) is controlled by earthquakes of similar magnitude and source-to-site distance as those of Group 1 in Figure 1, with PGA > 0.8 g and $V_{S30} < 300$ m/s. Therefore, the data indicate that such PGAs are possible, but exceptionally rare in the context of the available records to date. Metadata for the records in Groups 1 and 2 are provided in de la Torre *et al.* [1].

The ISK005 site is an extremely soft peat site, at which liquefiable sandy soils are also present (Garini and Gazetas [18]). The acceleration and velocity time series display extremely strong resonance due to the very soft peat over rock, and cyclic mobility spikes in the PGA. The Tarzana record has been thoroughly investigated by many researchers and has been shown to include strong topographic amplification effects, as the site sits on top of a hill (Spudich *et al.* [19], Bouchon and Barker [20]). Finally, the IBR003 Tohoku record, is a near fault ground motion with one of the highest short-period spectral accelerations and PGA across all sites that recorded the earthquake (Goto and Morikawa [21]). This high short-period accelerations decays quickly, with increasing period, resulting in significantly more modest long-period accelerations. More details on these records are included in de la Torre *et al.* [1].

MODELS FOR NONLINEAR SITE RESPONSE IN NSHM2022 GMMS

The empirical ground motion models used in NSHM2022 are described in detail in Bradley *et al.* [5] and de la Torre *et al.*

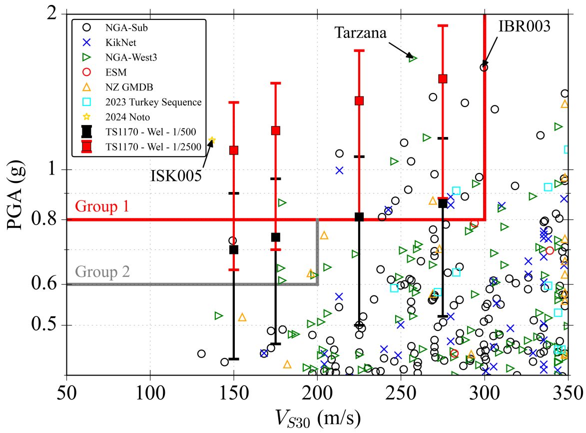

Figure 1: Comparison of globally-observed PGA on soft soil sites, from existing earthquake databases, to the 500-year and 2,500-year draft TS1170 PGA values (based directly on NSHM2022) in Wellington. The symbols and error bars for the TS1170 values reflect the mean, and 10th and 90th percentiles of the hazard.

[22]. For shallow crustal sources, the NGA-West2 GMMs (Bozorgnia *et al.* [23]), and two NZ-specific GMMs (Atkinson [24] and Stafford [25]), developed as part of the NSHM2022, were used. For subduction slab and interface sources, the NGA-Sub (Bozorgnia *et al.* [15]), and Atkinson [24] GMMs were used. The nonlinear site-response models incorporated in these GMMs were compared and scrutinised in detail to quantify the particular effect of this modelling detail on the total seismic hazard and understand the approach used to constrain these GMMs at high PGAs where historic records are either scarce or not available. The nonlinear site-response relationships within the GMMs are a function of ground-motion intensity, and reduce the PGA on soft soil, for rock $PGA^r > 0.1$ g. Importantly, as shown in de la Torre *et al.* [1], the nonlinear relationships in all GMMs are consistently modelling these effects and predict similar reductions in PGA, for the V_{S30} range considered here.

Given the scarcity of records with PGA > 0.3 g on soft soil sites, the nonlinear site-response models used in GMMs were predominantly based on simulations using equivalent-linear site-response analyses (Walling *et al.* [8], Kamai *et al.* [9], Seyhan and Stewart [10]), even at high ground-motion intensities (e.g., $PGA > 0.5$ g). It is well-known that, due to the assumptions in equivalent-linear analysis (Idriss and Seed [26]), it poorly represents highly-nonlinear soil behaviour, and that equivalent-linear analysis provides reasonable results when the maximum shear strain in any given soil layer at the site is $< 0.5\%$ (e.g., Kramer and Paulsen [27], Kaklamanos *et al.* [11], Kim *et al.* [12]). However, GMMs have developed site-response functions for modelling nonlinear effects based on equivalent-linear analyses, and such models are conventionally applied to probabilitic seismic hazard analyses (PSHA), which are unconstrained in relation to shaking intensity. Thus, in high seismicity regions, such models are applied within PSHA to estimate PGA on soft soil sites even when PGA on reference rock (PGA^r) is > 1 g. Many studies have demonstrated that fully nonlinear analysis is more appropriate for soft sites under high shaking intensity, where large shear strains can occur. Studies that have compared the results of equivalent-linear and nonlinear site-response analyses have shown that equivalent-linear analyses can predict higher surface PGAs than nonlinear analyses (Zalachoris and Rathje [28], Kim *et al.* [12]). For this reason, we consider fully nonlinear analyses, for sites in NZ, to constrain the nonlinear models used in the hazard calculation.

While significant challenges, limitations, and uncertainties exist with 1D nonlinear analyses (e.g., the 1D simplification, the treatment of hysteretic damping, and the modelling of stress-strain behaviour at very large shear strains), it is inappropriate to model the highly nonlinear response of soils at very large intensities with the equivalent linear simplification. Thus, we consider the approach outlined in this paper an improvement to how site effects are currently modelled in GMMs.

FINDINGS FROM RIGOROUS NONLINEAR SITE-RESPONSE SIMULATIONS

Given that time-domain nonlinear site-response analyses are considered more appropriate than equivalent-linear site-response analyses for strong shaking, we tested the sensitivity of the PGA hazard to alternative modelling of nonlinear effects in the GMMs. For this purpose, more rigorous nonlinear site-response analyses were performed for selected sites in NZ. The nonlinear simulations considered are those by de la Torre *et al.* [22] for 9 sites in Wellington, and by Cubrinovski and Ntritsos [29] for 13 sites in Christchurch. The de la Torre *et al.* [22] nonlinear total-stress analyses were performed in OpenSees with the pressure-dependent multi-yield surface (PDMY) and pressure-independent multi-yield surface (PIMY) constitutive models, and in DEEPSOIL with the General Quadratic/Hyperbolic Model (GQ/H) coupled with a non-Masing unload-reload formulation. The Cubrinovski and Ntritsos [29] total-stress and effective-stress analyses were performed in DIANA-J with the stress-density constitutive model [30,31].

The results from all sites were binned by V_{S30}, and group averages were computed to constrain the adjusted nonlinear functions of GMMs. The V_{S30} bins that were used were $150-200$, $200-250$ and $250-300$ m/s, with representative V_{S30} values of 175, 225, and 275 m/s corresponding to TS1170 Site Classes VI, V, and IV, respectively. There were insufficient existing simulations for sites with $V_{S30} > 300$ m/s to constrain adjusted nonlinear functions for stiffer site classes. Future work should evaluate stiffer sites to avoid a step change in the response between Site Class IV and Site Class III (i.e., the next stiffer site class). However, we anticipate the effects of soil nonlinearity to be less severe for sites with $V_{S30} > 300$ m/s.

Figure 2 shows the results from nonlinear site-response analyses for the three V_{S30} bins by plotting the nonlinear site-response factor as a function of PGA for a reference condition of 760 m/s (PGA^r). The nonlinear factors are calculated by normalising the site amplification by the site amplification calculated for weak input motions (i.e., the linear site response). The figure includes results from total-stress nonlinear (NL) and equivalent-linear (EL) analyses by de la Torre *et al.* [22] (T24) and nonlinear total-stress (TSA) and effective-stress (ESA) analyses by Cubrinovski and Ntritsos [29] (CN23). Note that unlike the linear shear stress-shear strain relationship adopted in EL, highly nonlinear stress-stress curves are used in both TSA and ESA, with ESA also incorporating effects of excess pore-water pressures on the stress-strain behaviour. The nonlinear site-response function by Seyhan and Stewart [10] (SS14), which is adopted in several of the NSHM GMMs (e.g., Boore *et al.* [32] and Atkinson [24]), is shown with a dashed black line for reference. These results highlight that the rigorous nonlinear simulations result in steeper slopes and greater deamplification of PGA relative to PGA^r than those suggested by equivalent-linear analyses and by the GMMs using the SS14 model, particularly for the $V_{S30} = 225$ m/s bin. The equivalent linear analyses results are close to the SS14 model, which is consistent with the fact that the SS14 model was partially constrained using equivalent-linear analyses at high PGAs.

Given the deviation of the nonlinear analyses results from the GMM relationships, these results were used to develop three additional relationships for the nonlinear effects on soft soil sites. Figure 2 shows these three nonlinear functions with dashed green, yellow and red solid lines. The terms ‘Mild’, ‘Moderate’, and ‘Aggressive’ for the models are used, in a relative sense, to reflect the level of deviation of the model from the SS14 model, capture the variability observed in nonlinear simulations, and assess the sensitivity of these modelling aspects on the resulting PGA on soft soil sites. All three models result in more significant reduction in PGA than the currently used SS14 model (and other similar models), particularly for high PGA^r.

The PGA at the ground surface, estimated by the nonlinear simulations and the resulting three models are plotted in Figure 3 as a function of the rock input PGA (PGA^r) for the three V_{S30} bins. To calculate the surface PGA, the linear site response model from SS14 was combined with the different nonlinear factors for consistency. As expected, the maximum surface PGAs are significantly lower for the nonlinear simulation results and the proposed models, especially in the case of the ‘Aggressive’ model.

INFLUENCE OF THE ADJUSTED NONLINEAR MODELS ON THE PGA HAZARD

The adjusted ‘Mild’, ‘Moderate’, and ‘Aggressive’ nonlinear functions for $V_{S30} = 175$, 225, and 275 m/s were implemented in the Atkinson [24] and Abrahamson and Gülerce [33] GMMs. A PSHA was then performed with these modified GMMs for the full NSHM2022 earthquake source model, to estimate the influence of these modifications on the PGA hazard. The resulting PGA hazard curves for Atkinson [24] with the default and three alternative nonlinear functions are plotted in Figure 4 for the $V_{S30} = 175$ and 225 m/s bins (i.e., Site Classes VI and V). The results show that the proposed nonlinear functions reduce the PGA hazard. The reduction is particularly pronounced at low annual probabilities of exceedance (i.e., high ground-motion intensities).

The percent reduction in the PGA hazard, relative to the PGA from respective GMMs with their default nonlinear site-response functions, was then calculated for all cases. Figure 5 plots the percent reduction as a function of PGA from the default nonlinear model case for the Atkinson [24] GMM with V_{S30} = 175 and 225 m/s. The hazard was calculated for six cities (Gisborne, Napier, Wellington, Blenheim, Christchurch, and Otira), and each of the thin lines in Figure 5 represent the result for one location. The clustering of relationships shows that the result is relatively independent of location and earthquake sources that control the hazard, and primarily dependent on ground-motion intensity. 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 weights are based on the authors’ judgement and the results of the nonlinear simulations, with greater weight assigned to total-stress nonlinear analyses, and less weight to effective-stress analyses and the default models based on equivalent-linear analyses. The weighted average percentage reduction in the PGA hazard is also shown in Figure 5 (bold black lines). The weighted averages were then used to develop the adjustment factors for the TS1170 PGA, as elaborated in the next section.

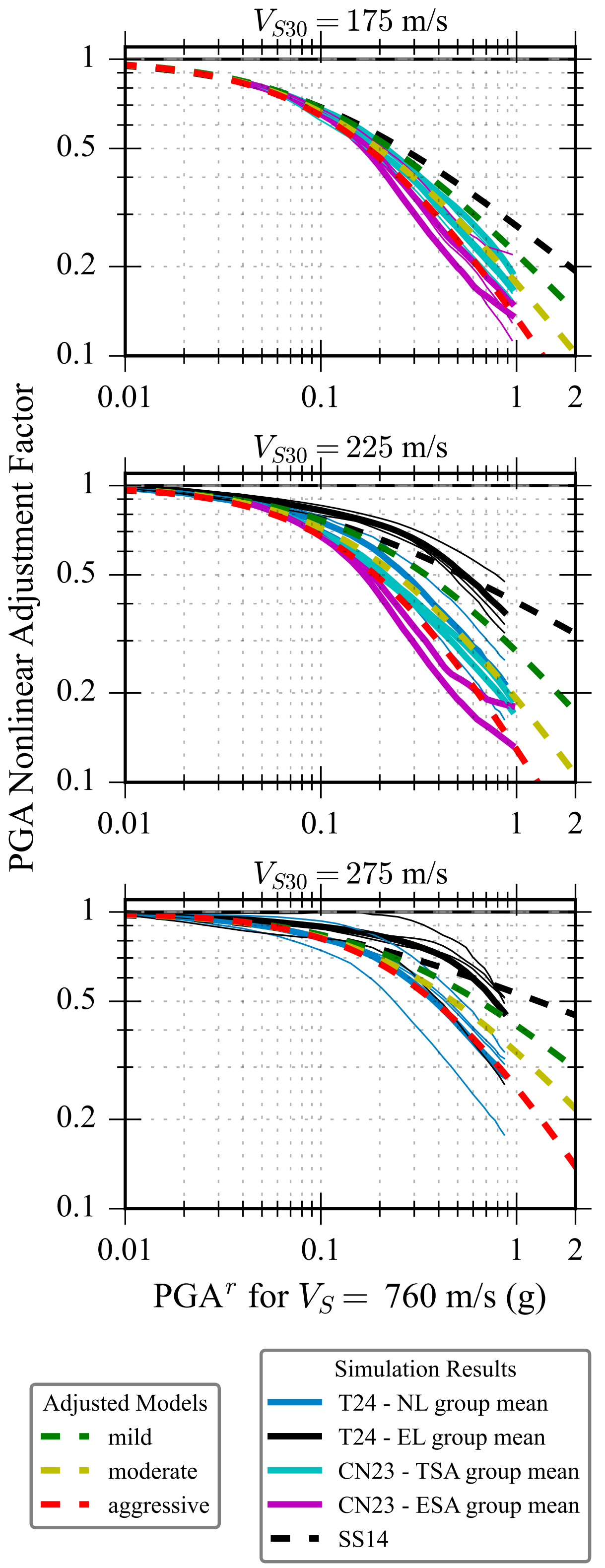

Figure 2: Adjusted nonlinear site-response models for PGA, as a function of PGA^r for a reference condition of $V_{S30} = 760$ m/s, based on site-response simulations results from [22] [T24] and [29] [CN23]. Results and modelling approximations are shown for three V_{S30} groups (i.e., site classes) in the different panels. The nonlinear simulation results and the adjusted models are compared to one of the default nonlinear site-response models by [10] (SS14). For the simulation results, the thinner lines represent the output for an individual site, and the thicker lines are the average of all sites within each V_{S30} bin.

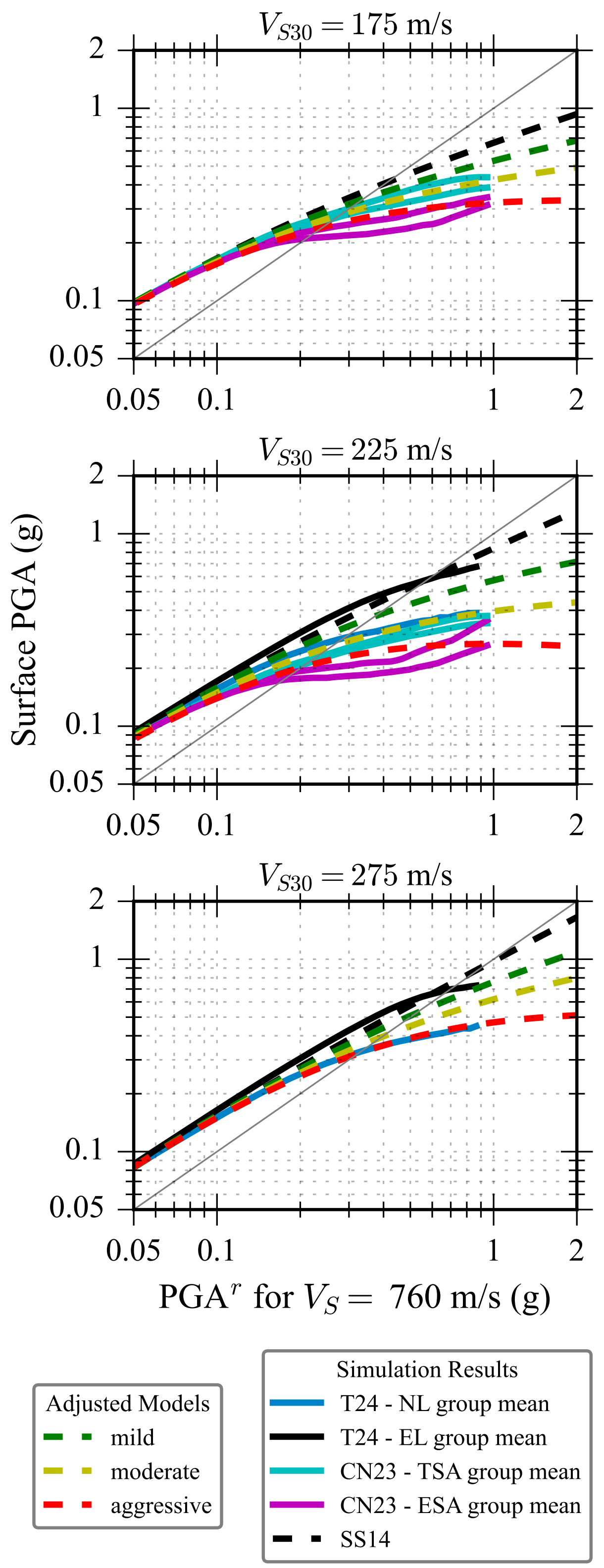

Figure 3: Estimated ground surface PGA, as a function of PGA^r for a reference condition of $V_{S30} = 760$ m/s, for the adjusted models, the nonlinear simulation results, and SS14 as plotted in Figure 2. Each panel shows the results for a different V_{S30} bin (site class). The SS14 linear site amplification model was combined with the respective nonlinear models to estimate the surface PGA for all cases.

PROPOSED ADJUSTMENT FACTORS FOR THE TS1170 PGA FOR GEOTECHNICAL ANALYSES

The adjustment factors for the PGA hazard were developed using the methodology presented above with the following additional considerations:

1. The weighted average results (i.e., the percent reduction) from the two GMMs (A22: Atkinson [24], and AG20: Abrahamson and Gülerce [33]) were combined by giving equal weight to each GMM.

2. Weighted-average relationships for the percent reduction in the PGA hazard (equivalent to that illustrated in Figure 5) were developed separately for Site Classes IV, V, and VI.

3. The resulting weighted means were approximated with simplified linear functions for determination of PGA in TS1170, as shown subsequently.

The resulting means, based on two GMMs, were applied to the overall PGA hazard. This approach is justified given the following: 1) the same nonlinear functions are applied to all GMMs, 2) the default PGA nonlinear functions in all GMMs are similar for the V_{S30} range considered herein and 3) a significant contribution to the hazard comes from GMMs that use exactly the default nonlinear models considered in A22 and AG20 (i.e., [32], [34], [33], [35], and [24], which make up 76% of the total weight for subduction GMMs and 41% of the total weight for crustal GMMs). The weighted mean percent reduction models were simplified and approximated with a linear function, in $\ln(PGA_{NSHM2022})$ space, for easier application to the PGA hazard across NZ and more transparent documentation of the approach adopted for the PGA adjustment. The final weighted percent reduction relationships and the adopted modelling approximations are shown in Figure 6 for all three site classes.

The simplified linear models were applied to calculate the adjusted PGA ($PGA_{adjusted}$) as follows:

$$PGA_{adjusted} = PGA_{NSHM2022} \times (1 - R_{PGA}) \qquad (1)$$

where $PGA_{NSHM2022}$ is the PGA, in g, directly output by NSHM2022, and R_{PGA} is the PGA reduction factor calculated using Equation 2:

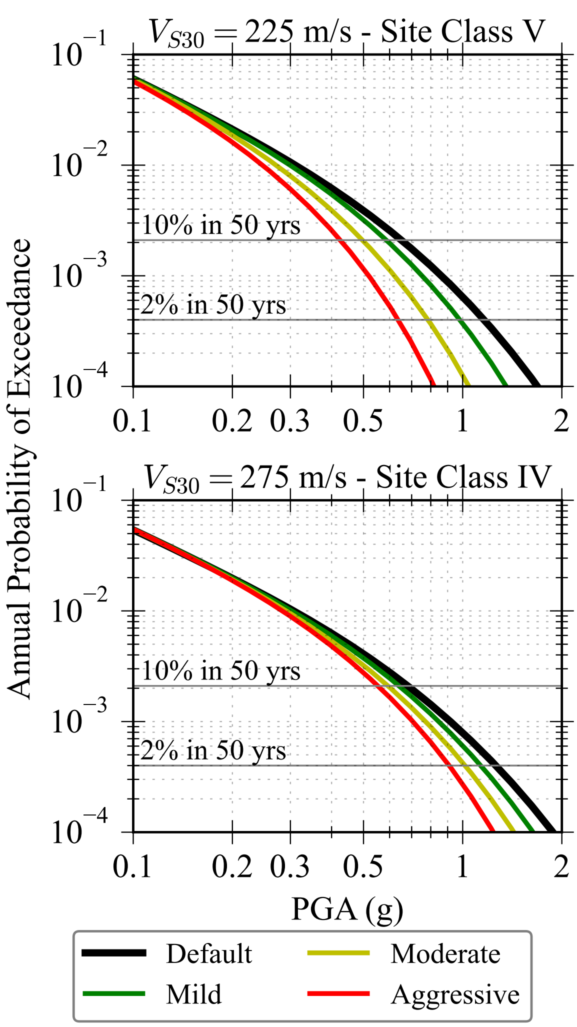

Figure 4: PGA hazard curves for Wellington and the full NSHM2022 seismic source model using the Atkinson (2022) [A22] GMM with the default and three adjusted nonlinear site response models (shown in Figure 2) for V_{S30} = 225 m/s (top) and 275 m/s (bottom).

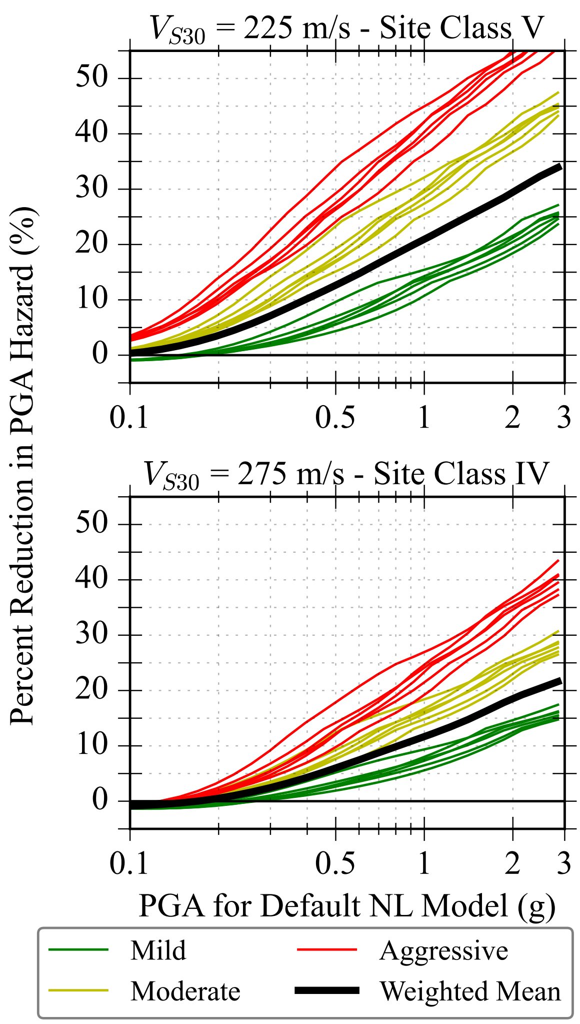

Figure 5: Percent reduction in the PGA value for Site Class V (V_{S30} = 225 m/s; top) and Site Class IV (V_{S30} = 275 m/s; bottom) as a function of the unmodified PGA hazard for several cities across NZ using the three adjusted nonlinear models (shown in Figure 2) in the A22 GMM.

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

where A_0 and A_1 are coefficients for the linear models as defined in Table 1; and
PGA_{thresh} is the threshold PGA, in g, below which PGA values do not require adjustment.

All coefficients for Equations 1 and 2 are summarised in Table 1. Further details on the adopted background methodology are given in de la Torre *et al.* [1].

Table 1: Coefficients for 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

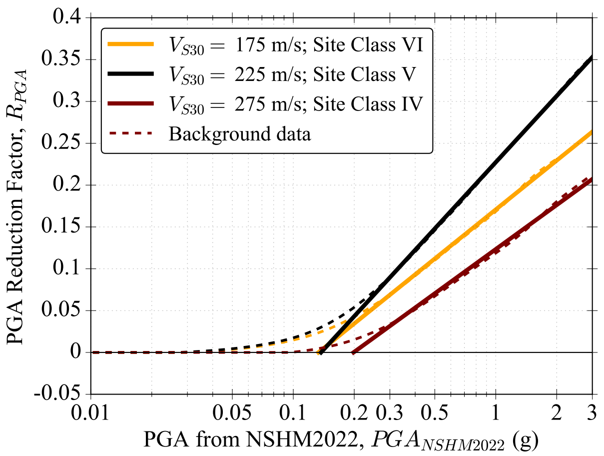

Figure 6: Recommended weighted mean percent reduction in the PGA hazard as a function of the NSHM2022 PGA values for V_{S30} = 175, 225, and 275 m/s, including the proposed simplified linear models given in Equation 2 and Table 1.

APPLICATION OF THE PGA ADJUSTMENT FACTORS TO THE TS1170

The adjustment factors (i.e., the percent reduction in PGA) in Figure 6 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 ($PGA_{NSHM2022}$) for the 500- and 2,500-year return periods are plotted in Figure 7 for all locations. As the percent reduction increases with increasing PGA value, the highest hazard cities in NZ have the lowest ratios in Figure 7, with reductions in PGA of approximately 17% for Site Class IV, 28% for Site Class V, and 20% for Site Class VI. The greatest reductions occur for Site Class IV, as previously observed in Figure 6. This is because, for Site Class IV, the adjusted nonlinear site-response models deviate furthest from the default nonlinear models (e.g., Seyhan and Stewart [10]), as illustrated in Figure 2. 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 Figure 8 and Figure 9. 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 Figures 7 and 8 are caused by cities with similar latitude being distributed between the east coast and the west coast.

COMPARISON OF THE ADJUSTED PGA TO PGAS FROM NZS1170.5

In a similar manner as above, the adjusted PGAs were compared to PGAs of NZS1170.5. Figure 10 plots the ratios of the proposed PGA for Site Class V to the NZS1170.5 PGA for Site Class D, and the actual PGA values themselves, as function of the location number according to Table 3.3 of NZS1170.5. The NZS1170.5 PGA values are provided as equivalent PGA values for a magnitude 7.5 earthquake, therefore, the adjusted PGA values were also scaled accordingly, for a better comparison, using the magnitude scaling factor proposed in Cubrinovski *et al.* [36]. Figure 10 shows that for most of the lower hazard areas of NZ, with PGA less than approximately 0.3 g (i.e., North of about Rotorua, and south of Christchurch and north of Dunedin), the adjusted PGAs are not significantly different than the current NZS1170.5 values. However, for higher hazard regions (e.g., between Rotorua and Blenheim, particularly for the Wellington area and the east coasts), the values have increased by approximately 30-60%. For Dunedin and further south, including Southland, the values have increased by 20-80%. The increase is generally larger for areas influenced by subduction zone earthquakes (i.e., from Hikurangi and Puysegur subduction zones), illustrating the influence of the NGA-Sub GMMs and the revised subduction source models on the NSHM2022 hazard. Note that there is no direct overlap of site conditions between the TS1170.5 and NZS1170.5 site classes, and therefore, there is an added factor contributing to the differences depicted in Figure 10 between the PGAs of TS1170.5 and NZS1170.5 at a given location. However, these differences due to the lack of full compatibility between site classes of the two standards are not a significant factor for the observed outcomes and trends observed in Figure 10.

CONCLUSIONS

This paper described the implementation of an adjustment factor to the PGA from NSHM2022 for adoption into TS1170.5. The adjustment factor is intended to more rigorously capture effects of soil nonlinear behaviour at soft soil sites, which is modelled simplistically in the GMMs adopted for NSHM2022 in cases of high ground-motion intensities. These GMMs either partially or fully constrain the nonlinear site-response model embedded in the GMMs using equivalent-linear site-response analyses. It has been shown here, and by others, that equivalent-linear site-response analyses can overpredict the surface PGA relative to fully nonlinear analyses, which are considered more robust for modelling soil nonlinear behaviour. To account for this possible overprediction, this study constrained the nonlinear site-amplification models of the GMMs using results from fully nonlinear site-response simulations of New Zealand sites.

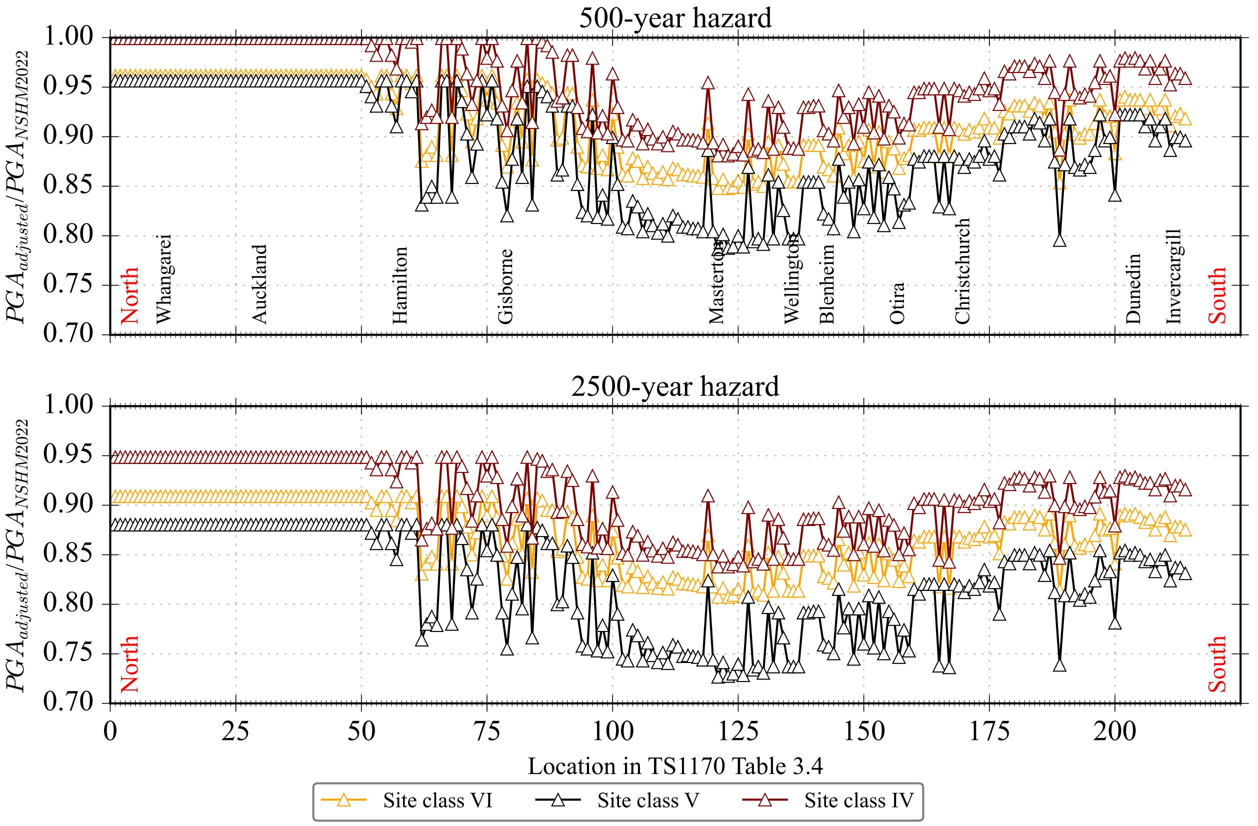

Figure 7: Ratios of the adjusted PGA to the PGA from NSHM2022 for all cities in Table 3.4 of TS1170. The top panel is for the 500-year hazard and the bottom panel for the 2,500-year hazard. The x-axis represent the position of the city in the tables going from North on the left side of the figure to South on the right.

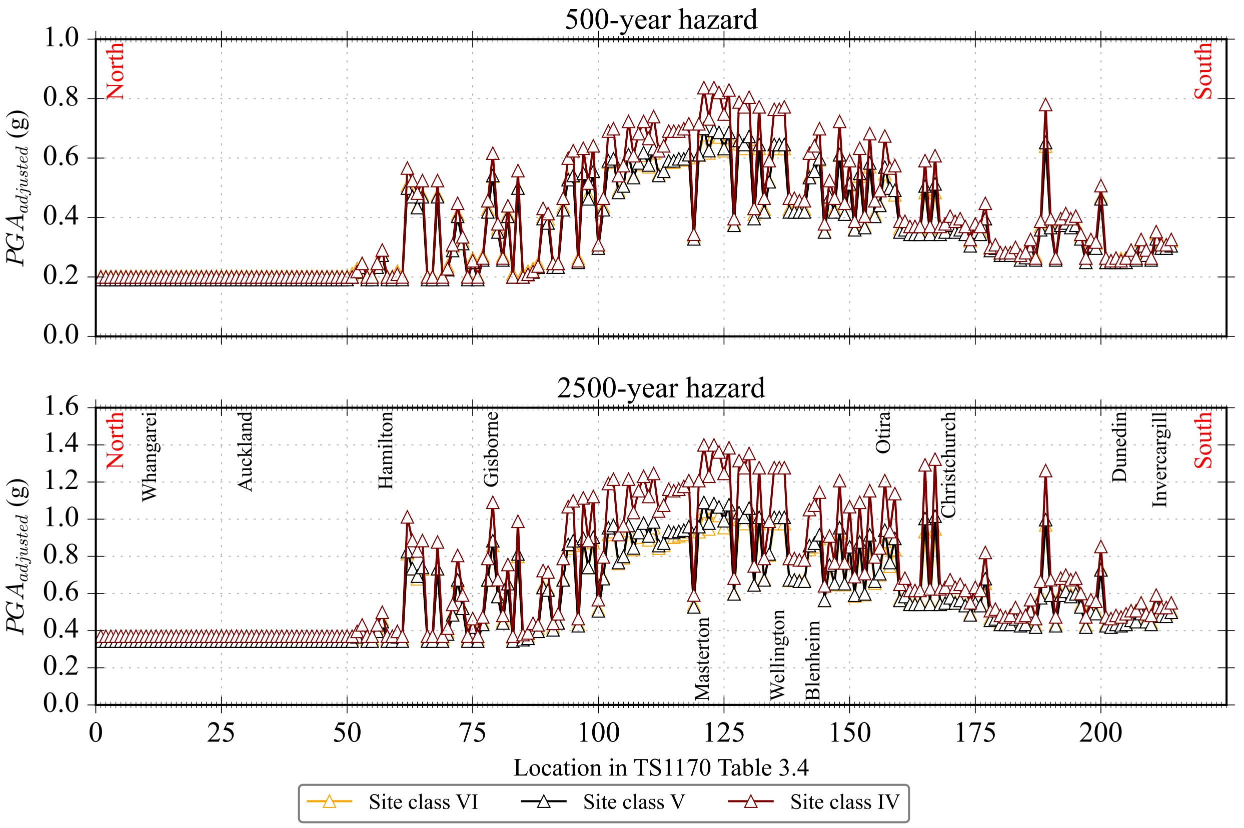

Figure 8: Adjusted PGA values for all cities in Table 3.4 of TS1170. The top panel is for the 500-year hazard and the bottom panel for the 2,500-year hazard. The x-axis represent the position of the city in the tables going from North on the left side of the figure to South on the right.

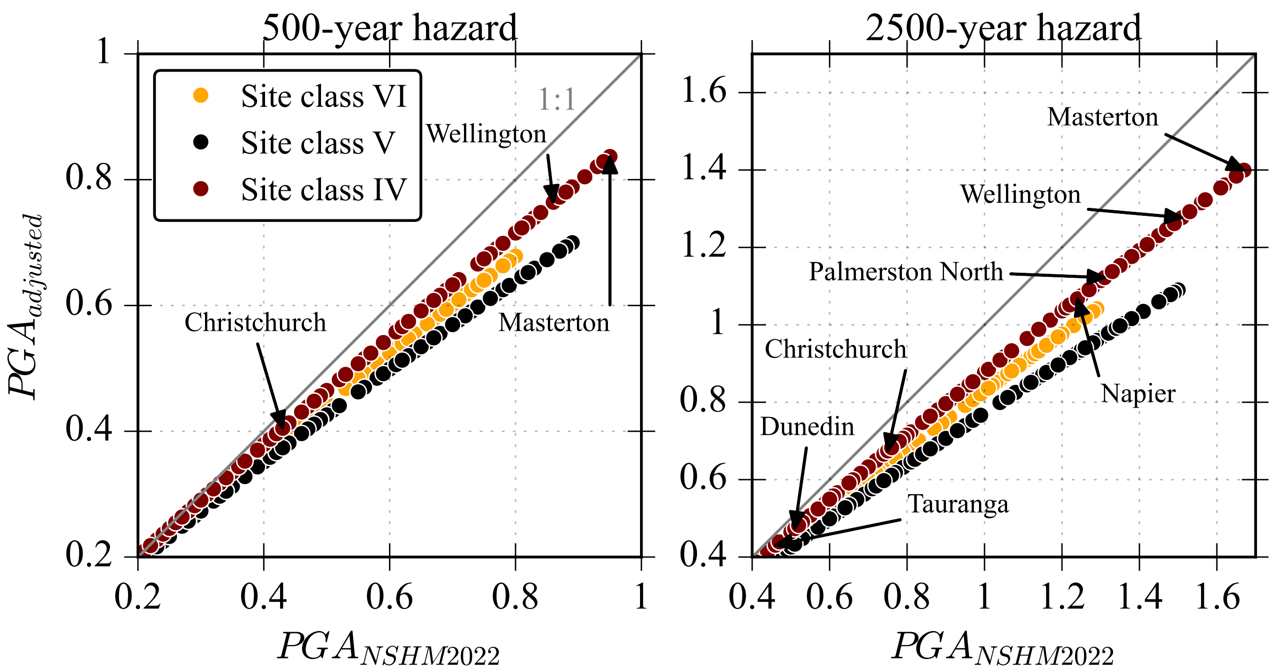

Figure 9: Adjusted PGA versus PGA from NSHM2022 for all named cities in Table 3.4 of TS1170, for the 500-year hazard on the left and 2,500-year hazard on the right.

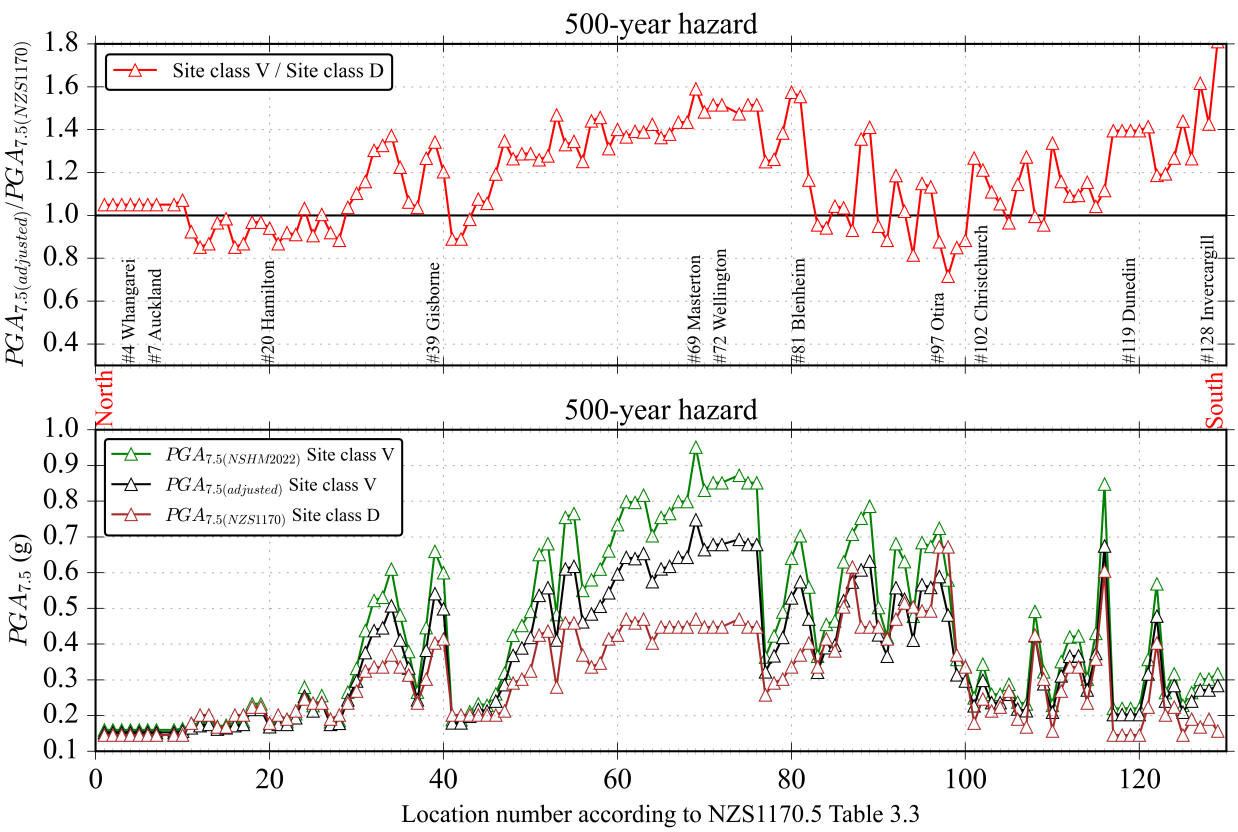

Figure 10: Ratios of proposed adjusted $PGA_{7.5}$ to $PGA_{7.5}$ from NZS1170 (top), and the $PGA_{7.5}$ values themselves (bottom) plotted versus the location number for named cities in NZS1170.5 Table 3.3.

The results of these simulations suggest that the deamplification caused by soil nonlinearity is greater than what is predicted by the default nonlinear site-response models in the GMMs, especially at high input ground-motion intensities.

The parametrised results from the nonlinear simulations were implemented into GMMs, and a PSHA was re-run using these GMMs with modified nonlinear functions and the full earthquake source model from NSHM2022 to quantify the influence on the hazard. The percent reduction in the hazard was calculated and parametrised using simple linear approximations in $\ln(PGA_{NSHM2022})$ space. On this basis, a percent reduction model was developed for Site Classes IV, V, and VI, with representative V_{S30} values of 275, 225, and 175 m/s, respectively. The percent reduction increases with increasing PGA and can be applied as an adjustment factor to the NSHM2022 PGA output.

The adopted adjustment factor results in reductions of approximately 15-25 % for the 2500-year PGA hazard at the highest hazard cities in NZ. Compared to the 2004 NZ loading standard of NZS1170.5, the adjusted PGAs for these high-hazard regions remain approximately 40-50 % higher at the 500-year return period. Several factors contribute to these differences, including the adoption of entirely different ground-motion models [7], the overly simplistic treatment of subduction zone sources in the previous source model [37], and other factors related to the assumptions, interpretations and modelling details of the NSHM2022.

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REFERENCES

1 de la Torre CA, Cubrinovski M, Bradley B and Bora SS (2025). "Examination of Very High PGA and Short-Period Spectral Accelerations on Soft Soil Sites from the New Zealand National Seismic Hazard Model – the Role of Soil Nonlinearity". *Earthquake Spectra* (Under Review).

2 Gerstenberger MC, Bora S, Bradley BA, Dicaprio C, Kaiser A, Manea EF, Nicol A, Rollins C, Stirling MW, Thingbaijam KK, Van Dissen RJ, Abbott ER, Atkinson GM, Chamberlain C, Christophersen A, Clark K, Coffey GL, de la Torre CA, Ellis SM, Fraser J, Graham K, Griffin J, Hamling IJ, Hill MP, Howell A, Hulsey A, Hutchinson J, Iturrieta P, Johnson KM, Jurgens VO, Kirkman R, Langridge RM, Lee RL, Litchfield NJ, Maurer J, Milner KR, Rastin S, Rattenbury MS, Rhoades DA, Ristau J, Schorlemmer D, Seebeck H, Shaw BE, Stafford PJ, Stolte AC, Townend J, Villamor P, Wallace LM, Weatherill G, Williams CA and Wotherspoon LM (2024). "The 2022 Aotearoa New Zealand National Seismic Hazard Model: Process, Overview, and Results". *Bulletin of the Seismological Society of America*, **114**(1): 7–36. https://doi.org/10.1785/0120230182

3 Stirling M, McVerry G, Gerstenberger M, Litchfield N, Van Dissen R, Berryman K, Barnes P, Wallace L, Villamor P, Langridge R, Lamarche G, Nodder S, Reyners M, Bradley B, Rhoades D, Smith W, Nicol A, Pettinga J, Clark K and Jacobs K (2012). "National Seismic Hazard Model for New Zealand: 2010 Update". *Bulletin of the Seismological Society of America*, **102**(4): 1514–1542. https://doi.org/10.1785/0120110170

4 Gerstenberger MC, Van Dissen R, Rollins C, DiCaprio C, Thingbaijim KKS, Bora S, Chamberlain C, Christophersen A, Coffey GL, Ellis SM, Iturrieta P, Johnson KM, Litchfield NJ, Nicol A, Milner KR, Rastin SJ, Rhoades D, Seebeck H, Shaw BE, Stirling MW, Wallace L, Allen TI, Bradley BA, Charlton D, Clark KJ, Fraser J, Griffin J, Hamling IJ, Howell A, Hudson-Doyle E, Hulsey A, Jurgens VO, Kaiser AE, Kirkman R, Langridge RM, Maurer J, Rattenbury MS, Ristau J, Schorlemmer D, Townend J, Villamor P and Williams C (2024). "The Seismicity Rate Model for the 2022 Aotearoa New Zealand National Seismic Hazard Model". *Bulletin of the Seismological Society of America*, **114**(1): 182–216. https://doi.org/10.1785/0120230165

5 Bradley BA, Bora SS, Lee RL, Manea EF, Gerstenberger MC, Stafford PJ, Atkinson GM, Weatherill G, Hutchinson J, de la Torre CA, Hulsey AM and Kaiser AE (2023). "The Ground-Motion Characterization Model for the 2022 New Zealand National Seismic Hazard Model". *Bulletin of the Seismological Society of America*, **114**(1): 329–349. https://doi.org/10.1785/0120230170

6 Kaiser AE, Hill MP, de la Torre C, Bora S, Manea E, Wotherspoon L, Atkinson GM, 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". *Bulletin of the Seismological Society of America*, **114**(1): 399–421. https://doi.org/10.1785/0120230189

7 Bora SS, Bradley BA, Manea EF, Gerstenberger MC, Lee RL, Stafford PJ, Atkinson GM, Kaiser A, DiCaprio CJ and Van Dissen RJ (2023). "Hazard Sensitivities Associated with Ground-Motion Characterization Modeling for the New Zealand National Seismic Hazard Model Revision 2022". *Bulletin of the Seismological Society of America*, **114**(1): 422–448. https://doi.org/10.1785/0120230167

8 Walling M, Silva W and Abrahamson N (2008). "Nonlinear Site Amplification Factors for Constraining the NGA Models". *Earthquake Spectra*, **24**(1): 243–255. https://doi.org/10.1193/1.2934350

9 Kamai R, Abrahamson NA and Silva WJ (2014). "Nonlinear Horizontal Site Amplification for Constraining the NGA-West2 GMPEs". *Earthquake Spectra*, **30**(3): 1223–1240. https://doi.org/10.1193/070113EQS187M

10 Seyhan E and Stewart JP (2014). "Semi-Empirical Nonlinear Site Amplification from NGA-West2 Data and Simulations:". *Earthquake Spectra*, **30**(3): 1241–1256. https://doi.org/10.1193/063013EQS181M

11 Kaklamanos J, Baise LG, Thompson EM and Dorfmann L (2015). "Comparison of 1D linear, equivalent-linear, and nonlinear site response models at six KiK-net validation sites". *Soil Dynamics and Earthquake Engineering*, **69**: 207–219. https://doi.org/10.1016/j.soildyn.2014.10.016

12 Kim B, Hashash YMA, Stewart JP, Rathje EM, Harmon JA, Musgrove MI, Campbell KW and Silva WJ (2016). "Relative Differences between Nonlinear and Equivalent-Linear 1-D Site Response Analyses". *Earthquake Spectra*, **32**(3): 1845–1865. https://doi.org/10.1193/051215EQS068M

13 Dawood HM, Rodriguez-Marek A, Bayless J, Goulet C and Thompson E (2016). "A Flatfile for the KiK-net Database Processed Using an Automated Protocol". *Earthquake Spectra*, **32**(2): 1281–1302. https://doi.org/10.1193/071214eqs106

14 Lanzano G, Luzi L, Russo E, Felicetta C, D'Amico MC, Sgobba S and F P (2018). "Engineering Strong Motion Database (ESM) flatfile [Data set]". *Istituto Nazionale di Geofisica e Vulcanologia (INGV)*. https://doi.org/10.13127/esm/flatfile.1.0

15 Bozorgnia Y, Abrahamson NA, Ahdi SK, Ancheta TD, Atik LA, Archuleta RJ, Atkinson GM, Boore DM, Campbell KW, Chiou BSJ, Contreras V, Darragh RB, Derakhshan S, Donahue JL, Gregor N, Gulerce Z, Idriss I, Ji C, Kishida T, Kottke AR, Kuehn N, Kwak D, Kwok AOL, Lin P, Macedo J, Mazzoni S, Midorikawa S, Muin S, Parker GA, Rezaeian S, Si H, Silva WJ, Stewart JP, Walling M, Wooddell K and Youngs RR (2022). "NGA-Subduction research program". *Earthquake Spectra*, **38**(2): 783–798. https://doi.org/10.1177/87552930211056081

16 Buckreis T, Guryuva B, Icen A, Okcu O, Altindal A, Aydin M, Pretell R, Sandikkaya A, Kale A, Askan A, Brandenberg S, Kishida T, Akkar S, Bozorgnia Y and Stewart J (2023). "Ground Motion Data from the 2023 Türkiye-Syria Earthquake Sequence [Version 5]". *DesignSafe-Cl*. https://doi.org/10.17603/ds2-t115-bk16

17 Hutchinson JA, Zhu C, Bradley BA, Lee RL, Wotherspoon LM, Dupuis M, Schill C, Motha J, Manea EF and Kaiser AE (2024). "The 2023 New Zealand Ground-Motion Database". *Bulletin of the Seismological Society of America*, **114**(1): 291–310. https://doi.org/10.1785/0120230184

18 Garini E and Gazetas G (2024). *"The M_{JMA}7.6 Noto Peninsula Earthquake of January 1^{st} 2024, Japan: Preliminary Report with Emphasis on Recorded Motions and Soil Effects"*. Technical report. https://doi.org/10.13140/RG.2.2.12972.85129

19 Spudich P, Hellweg M and Lee WHK (1996). "Directional topographic site response at Tarzana observed in aftershocks of the 1994 Northridge, California, earthquake: Implications for mainshock motions". *Bulletin of the Seismological Society of America*, **86**(1B): S193–S208. https://doi.org/10.1785/BSSA08601BS193

20 Bouchon M and Barker JS (1996). "Seismic response of a hill: The example of Tarzana, California". *Bulletin of the Seismological Society of America*, **86**(1A): 66–72. https://doi.org/10.1785/BSSA08601A0066

21 Goto H and Morikawa H (2012). "Ground motion characteristics during the 2011 off the Pacific Coast of Tohoku Earthquake". *Soils and Foundations*, **52**(5): 769–779, special Issue on Geotechnical Aspects of the 2011 off the Pacific Coast of Tohoku Earthquake. https://doi.org/10.1016/j.sandf.2012.11.002

22 de la Torre CA, Bradley BA, Kuncar F, Lee RL, Wotherspoon LM and Kaiser AE (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. https://doi.org/10.1177/87552930231209726

23 Bozorgnia Y, Abrahamson NA, Atik LA, Ancheta TD, Atkinson GM, Baker JW, Baltay A, Boore DM, Campbell KW, Chiou BSJ, Darragh R, Day S, Donahue J, Graves RW, Gregor N, Hanks T, Idriss IM, Kamai R, Kishida T, Kottke A, Mahin SA, Rezaeian S, Rowshandel B, Seyhan E, Shahi S, Shantz T, Silva W, Spudich P, Stewart JP, Watson-Lamprey J, Wooddell K and Youngs R (2014). "NGA-West2 Research Project". *Earthquake Spectra*, **30**(3): 973–987. https://doi.org/10.1193/072113EQS209M

24 Atkinson G (2022). *"Backbone ground-motion models for crustal, interface, and slab earthquakes in New Zealand"*. Technical report, GNS Science Consultancy Report 2022/11.

25 Stafford PJ (2022). *"A Model for the Distribution of Response Spectral Ordinates from New Zealand Crustal Earthquakes Based Upon Adjustments to the Chiou and Youngs (2014) Response Spectral Model"*. GNS Science Technical Report 2022/15, GNS Science.

26 Idriss IM and Seed HB (1968). "Seismic response of horizontal soil layers". *Journal of the Soil Mechanics and Foundations Division*, **94**(4): 1003–1031. https://doi.org/10.1061/JSFEAQ.0001163

27 Kramer SL and Paulsen SB (2004). "Practical use of geotechnical site response models". *Proc. Int. Workshop on Uncertainties in Nonlinear Soil Properties and their Impact on Modeling Dynamic Soil Response*, Univ. of California Berkeley, p. 10.

28 Zalachoris G and Rathje EM (2015). "Evaluation of One-Dimensional Site Response Techniques Using Borehole Arrays". *Journal of Geotechnical and Geoenvironmental Engineering*, **141**(12). https://doi.org/10.1061/(ASCE)GT.1943-5606.0001366

29 Cubrinovski M and Ntritsos N (2023). "8th Ishihara lecture: Holistic evaluation of liquefaction response". *Soil Dynamics and Earthquake Engineering*, **168**: 107777. https://doi.org/10.1016/j.soildyn.2023.107777

30 Cubrinovski M and Ishihara K (1998). "Modelling of Sand Behaviour Based on State Concept". *Soils and Foundations*, **38**(3): 115–127. https://doi.org/10.3208/sandf.38.3_115

31 Cubrinovski M and Ishihara K (1998). "State Concept and Modified Elastoplasticity for Sand Modelling". *Soils and Foundations*, **38**(4): 213–225. https://doi.org/10.3208/sandf.38.4_213

32 Boore DM, Stewart JP, Seyhan E and Atkinson GM (2014). "NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes". *Earthquake Spectra*, **30**(3): 1057–1085. https://doi.org/10.1193/070113EQS184M

33 Abrahamson N and Gülerce Z (2020). "Regionalized Ground-Motion Models for Subduction Earthquakes Based on the NGA-SUB Database (Report 2020/25)". *Pacific Earthquake Engineering Research Center (PEER)*.

34 Campbell KW and Bozorgnia Y (2014). "NGA-West2 Ground Motion Model for the Average Horizontal Components of PGA, PGV, and 5% Damped Linear Acceleration Response Spectra". *Earthquake Spectra*, **30**(3): 1087–1115. https://doi.org/10.1193/062913EQS175M

35 Kuehn N, Bozorgnia Y, Campbell KW and Gregor N (2020). "Partially Non-Ergodic Ground-Motion Model for Subduction Regions using the NGA-Subduction Database (Report 2020/04)". *Pacific Earthquake Engineering Research Center (PEER)*.

36 Cubrinovski M, Bradley BA, Wentz F and Balachandra A (2022). "Re-evaluation of New Zealand seismic hazard for geotechnical assessment and design". *Bulletin of the New Zealand Society for Earthquake Engineering*, **55**(1): 1–14. https://doi.org/10.5459/bnzsee.55.1.1-14

37 Bradley B, Cubrinovski M and Wentz F (2022). "Probabilistic seismic hazard analysis of peak ground acceleration for major regional New Zealand locations". *Bulletin of the New Zealand Society for Earthquake Engineering*, **55**(1): 15–24. https://doi.org/10.5459/bnzsee.55.1.15-24