Progress on the NZ-Wide V_{S30} Map Update

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ABSTRACT

This paper presents ongoing work on updating the NZ-Wide V_{s30} map by integrating recent V_{s30} measurements and estimates, along with examining methods to incorporate CPT data. We have integrated approximately 1,000 recent V_{s30} data points from the 2022 NZ NSHM site database and V_s profiles currently available on the NZGD. Based on this updated V_{s30} database, we have developed an interim update to the Foster et al. (2019) NZ V_{s30} map and evaluated the effects of the updated V_{s30} data. This V_{s30} map should not be used directly in seismic design practice or as a substitute for site-specific investigations. Additionally, we summarize the initial efforts towards including the extensive volume of geotechnical investigation data from the NZGD. We collected 88 sCPT and 42 sDMT results, combining them with co-located or nearby CPT data, to assess the suitability of existing CPT-V_s correlation models for NZ. Preliminary analysis indicates that the Andrus et al. (2007) Pleistocene CPT-V_s correlation currently appears to be the best fit for NZ, except in Christchurch, where regional CPT-V_s correlations developed by McGann et al. (2015, 2018) are more appropriate. In follow-up studies, we will estimate V_{s30} values for approximately 15,000 locations across NZ with CPTs deeper than 20m to contribute to the NZ V_{s30} map modelling effort. Additionally, we will test down-sampling of CPT-inferred V_{s30} values and non-uniform weight assignments to prevent systemic bias arising from the substantial and densely clustered V_{s30} values in some geological and terrain categories.

1 INTRODUCTION

To account for the influence of site response, V_{s30} (the time-averaged shear wave velocity in the upper 30 meters of the ground) is commonly used in ground motion modelling and site classification. Several empirical ground motion models (GMMs) have been developed using V_{s30} as a parameter to account for site response. Seismic design provisions have also adopted V_{s30} as a site parameter for determining site class and site factors (e.g., BSSC, 2020). In particular, Technical Specification 1170.5 (TS 1170.5), the forthcoming update to New Zealand's seismic design provisions, adopts V_{s30} as the primary site parameter for determination of site class.

In New Zealand (NZ), there have been instances of nationwide V_{s30} map development using site proxies such as geological information (e.g., geological units) and topographical data (e.g., terrain categories, elevation, slope gradient) of the ground surface, notably by Perrin et al. (2015) and Foster et al. (2019). Perrin et al. (2015) established ranges of V_{s30} values for different geological classifications by using multiple V_{s30} measurements and estimates across NZ. Foster et al. (2019) introduced a rigorous framework to develop a nationwide V_{s30} map for NZ, incorporating Bayesian updates and a Multivariate Normal (MVN) method. Bayesian updates were used to develop V_{s30} models for each geology and terrain category, assigning median V_{s30} values and standard deviations by integrating V_{s30} measurements across NZ. Subsequently, V_{s30} values were estimated using each geology and terrain model, and then combined using the MVN method to generate the nationwide V_{s30} map.

However, limitations of NZ V_{s30} maps, which were developed by Perrin et al. (2015) and Foster et al. (2019), have been noted in subsequent studies. The low resolution and significant uncertainties of V_{s30} maps developed by Perrin et al. (2015) and Foster et al. (2019) were highlighted as major shortcomings (Manea et al., 2024; Kaiser et al., 2024). Regarding the Foster et al. (2019) V_{s30} map, Lee et al. (2022) argued that it predicted considerably low V_{s30} values for stiff rock and stiff gravel soil sites, not accurately representing site conditions as it was based on limited V_{s30} measurements for these sites that were predominantly characterized by relatively lower V_{s30} values.

In this paper, we present progress on updating the NZ-wide V_{s30} map. We integrate recently measured V_s profiles and estimated V_{s30} values, obtained from the NZ Geotechnical Database (NZGD) and the site database of the 2022 NZ National Seismic Hazard Model (NSHM) (Wotherspoon et al., 2024), we produce a provisionally updated NZ-wide V_{s30} map and compare it with the NZ Foster et al. (2019) V_{s30} map. Additionally, we evaluate various CPT-V_s correlation models to consider the inclusion of V_{s30} values which are inferred through empirical relationships as part of the modelling framework.

2 APPLIED DATASET

The applied dataset can be categorized according to the two main purposes of this study: (1) updating the V_{s30} database by integrating recently measured V_s profiles and V_{s30} data, and (2) considering the inclusion of inferred V_{s30} values to the site database by evaluating existing CPT-V_s correlation models for NZ. To update the V_{s30} measurement data, we collected V_s profiles obtained from sCPT and sDMT results from the NZGD. For V_s profiles obtained from the NZGD that do not reach 30m, we estimate V_{s30} using the V_{sz} (the time-averaged V_s over a range of depths z)-V_{s30} correlation model developed by Boore (2004). Also, numerous V_{s30} values were sourced from the site database of the 2022 NZ NSHM.

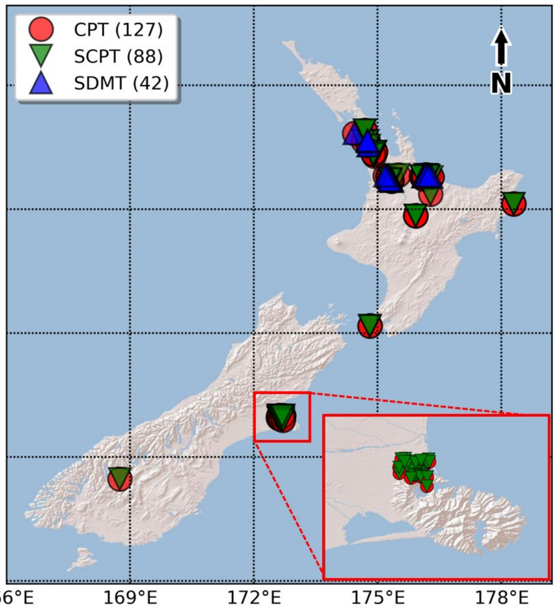

Figure 1: Locations of applied dataset.

Additionally, this study also aims to consider the inclusion of V_{s30} values, which were inferred from CPT-V_s correlation models, as part of the site database, for which an evaluation process is necessary. To assess the performance of the existing CPT-V_s correlation models, we collected multiple CPT results measured at the same locations or close to the V_s profiles from the NZGD. The majority of the CPT results and co-located V_s profiles were obtained from sCPT. For V_s profiles obtained from sDMT, we also collected CPT results within 50m and included them in the evaluation process.

In this study, we only considered V_s profiles with a depth of 15m or more from the collected data to minimize biases and uncertainties in the evaluation and estimation process. Based on this criterion, we filtered the dataset, resulting in 88 sCPT, 42 sDMT, and 127 CPT results (Figure 1).

3 PROVISIONAL UPDATE ON NZ-WIDE V_{S30} MAP

3.1 Bayesian Updates

The process for updating the NZ-wide V_{s30} map leverages the rigorous framework presented by Foster et al. (2019). To perform Bayesian updates, the V_{s30} database has been updated to include recent V_s profiles and V_{s30} data obtained from the NZGD and the 2022 NZ NSHM. By categorizing V_{s30} values according to the geology and terrain categories defined by Foster et al. (2019) (Table 1), we performed Bayesian updates to revise the geology and terrain V_{s30} models based on the updated V_{s30} database, and have indicated the number of V_{s30} data utilized in updating the posterior distributions for each of the geology and terrain categories on the upper x-axis (Figure 2). Based on the results of these Bayesian updates, we confirmed a relatively significant increase in the median V_{s30} values for terrain categories compared to geology categories. Specifically, the median V_{s30} values for all terrain categories increased (Figure 2 (b)). Regarding the geology categories, we could confirm a clear increase in the median V_{s30} values for G04, G06, G08, G09, G10, G15, and G17 (Figure 2 (a)).

Table 1: Descriptions of the geology and terrain categories in NZ defined by Foster et al. (2019).

GID	Description	TID	Description
G01	Peat	T01	Well-dissected alpine summits, mountains, etc
G04	Artificial fill	T02	Large volcano, high block plateaus, etc
G05	Fluvial and estuarine deposits	T03	Well-dissected low mountains, etc
G06	Alluvium and valley sediments	T04	Volcanic fan, foot slope of high block plateaus, etc
G08	Lacustrine	T05	Dissected plateaus, etc
G09	Beach, bar, dune deposits	T06	Basalt lava plain, glaciated plateau, etc
G10	Fan deposits	T07	Moderately eroded mountains, lava flow, etc
G11	Loess	T08	Desert alluvial slope, volcanic fan, etc
G12	Glacigenic sediments	T09	Well-eroded plain of weak rocks, etc
G13	Flood deposits	T10	Valley, till plain, etc
G14	Glacial moraines and till	T11	Eroded plain of weak rocks, etc
G15	Undifferentiated sediments and sedimentary rocks	T12	Desert plain, delta plain, etc
G16	Terrace deposits and old alluvium	T13	Incised terrace, etc
G17	Volcanic rocks and deposits	T14	Eroded alluvial fan, till plain, etc
G18	Crystalline rocks	T15	Dune, incised terrace, etc
-	-	T16	Fluvial plain, alluvial fan, low-lying flat plains, etc

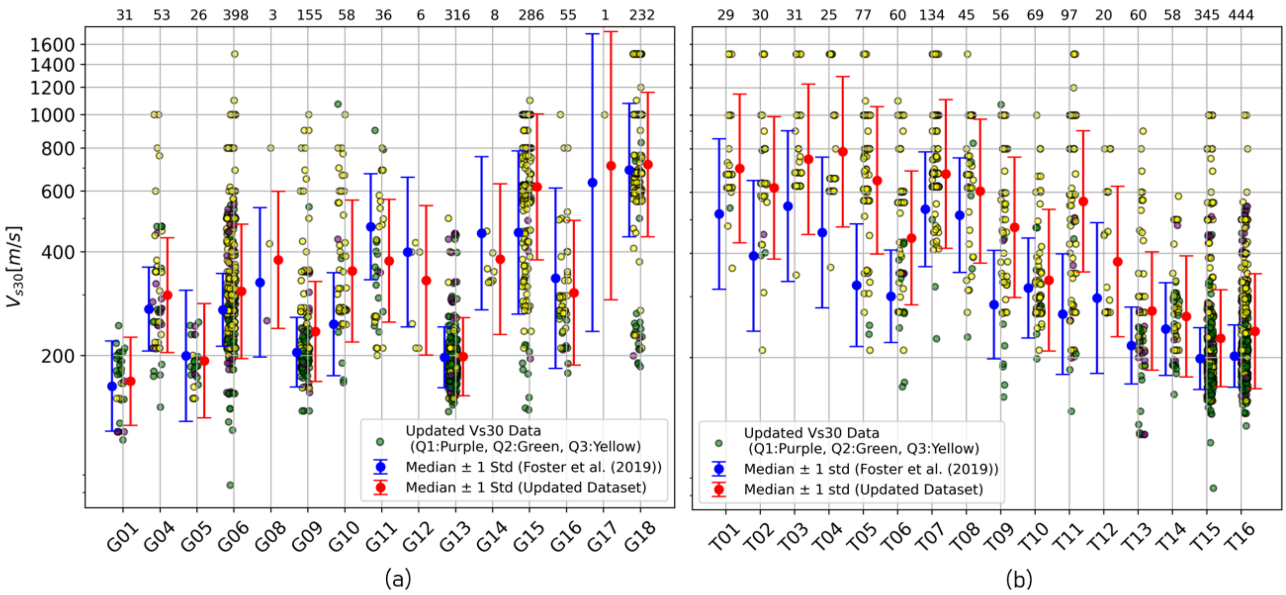

Figure 2: Results of the Bayesian updates for (a) geology and (b) terrain V_{s30} models.

3.2 Updated NZ-Wide V_{s30} Map

Lognormal standard deviations (σ_{meas}) are assigned to each measured or inferred V_{s30} value used to develop the map to account for uncertainty in measurements. These are currently based on the quality factor criteria from Wotherspoon et al. (2024) (updated from Kaiser et al. 2017). V_{s30} data labelled with Q1 and Q2 are assigned σ_{meas} values of 0.1 and 0.2, respectively. While Foster et al. (2019) excluded Q3 V_{s30} data (estimated from a national scale V_{s30} map or with poor constraints), we included Q3 V_{s30} data in the V_{s30} dataset with a σ_{meas} of 0.5 since many sites with Q3 values are associated with geologic and terrain categories with few V_{s30} data otherwise.

Using each of the updated V_{s30} models (geology and terrain) and the assigned σ_{meas} values, we developed geology-based and terrain-based NZ V_{s30} maps using the MVN method. Subsequently, both V_{s30} maps were combined with equal weights. Figure 3 shows (a) the Foster et al. (2019) NZ-wide V_{s30} map, (b) the updated NZ-wide V_{s30} map from this study, and (c) the residual map calculated by the natural logarithmic ratio of the updated V_{s30} values and those from Foster et al. (2019), with a 1 km grid. Based on Figure 3 (c), we confirmed that the updated NZ-wide Vs30 map shows relatively stiffer V_{s30} values (red) across much of NZ as a result of the updated V_{s30} database. Methods to validate the model development (e.g., K-fold cross validation) are being considered, in addition to sense-checking the results. Further validation is expected through its application in subsequent research, such as for site amplification in physics-based ground motion simulations.

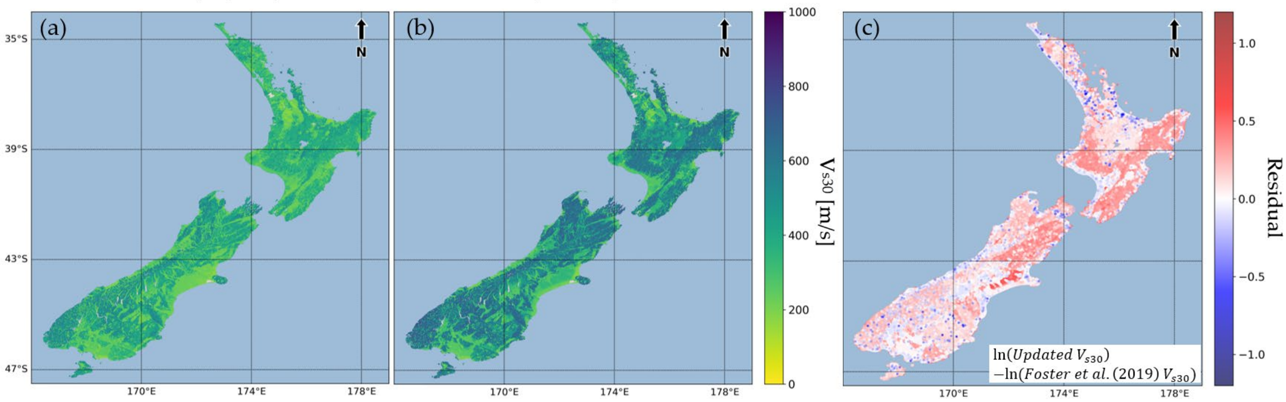

Figure 3: (a) Foster et al. (2019) NZ-wide V_{s30} map, (b) Updated NZ-wide V_{s30} map, and (c) Residual map between the updated and Foster et al. (2019) V_{s30} values.

4 CPT-V_{S30} CORRELATION MODELS

Near-surface shear wave velocities (V_s) can be measured directly using either invasive methods (e.g., drilling boreholes) or non-invasive methods (e.g., surface wave techniques). However, direct V_s measurement methods require significant time and cost. As an alternative way to estimate V_s profiles, various empirical correlation models have been developed by regression analysis of the relationship between V_s and parameters obtained from conventional geotechnical investigations such as cone penetration test (CPT) and standard penetration test (SPT).

Several CPT-based correlation models have been developed to estimate V_s using various parameters from the CPT. Hegazy and Mayne (2006) and Robertson (2009) developed CPT-based correlation models that incorporate parameters such as normalized cone tip resistance (Q_{tn}) and the soil behavior type index (I_c). Andrus et al. (2007) adopted pore pressure corrected cone tip resistance (q_t) and also included geological age in their correlation model (e.g., Pleistocene and Holocene age). In NZ, two region-specific CPT-based correlation models were developed for Christchurch (McGann et al., 2015; McGann et al., 2018). McGann et al. (2015) proposed a CPT-V_s correlation model for general soils in the Christchurch region, based on multiple sCPT results. McGann et al. (2018) developed a new CPT-V_s correlation model specifically for loess sites in the Christchurch region, as existing CPT-based empirical correlation models, including the Christchurch-specific model by McGann et al. (2015), tended to underpredict V_s in loess soils. The CPT-V_s correlation models evaluated in this study are shown in Table 2. The Hegazy and Mayne (2006) model was not considered because the predicted values seemed abnormal, but it can be included later once appropriate attention has been spent towards better understanding the model and its predictions.

Table 2: Summary of the considered existing CPT-based Vs correlation models.

Reference	Equation [m/s]
Andrus et al. (2007) – Pleistocene (A07-P)	$Vs = 2.62{q_t}^{0.395} * {I_c}^{0.912} * D^{0.124} * 1.12$
Andrus et al. (2007) – Holocene (A07-H)	$Vs = 2.62{q_t}^{0.395} * {I_c}^{0.912} * D^{0.124} * 0.92$
Robertson (2009) (R09)	$Vs = \left[10^{1.68+0.55I_c} (\frac{q_t - \sigma_{v0}}{Pa})\right]^{0.5}$
McGann et al. (2015a) (Mc15)	$Vs = 18.4{q_c}^{0.144}{f_s}^{0.0832}z^{0.278}$
McGann et al. (2018) (Mc18)	$Vs = 103.6{q_t}^{0.0074}{f_s}^{0.130}z^{0.253}$

5 EVALUATION OF THE EXISTING CPT-V_{S30} CORRELATION MODELS

It is common for CPT-V_s correlation models to be developed on regional datasets, or datasets foreign to the region considered for application. Therefore, applying them in areas not part of the data used for their development and validation may not be appropriate (Zhou et al., 2023). Based on this, McGann et al. (2015b) and Zhou et al. (2023) assessed the applicability of the existing CPT-V_s correlation models for general soils and shallow Holocene soils in Christchurch, respectively. However, these studies focused solely on the Christchurch region and did not evaluate across NZ.

Recently, existing CPT-V_s and V_{sz}-V_{s30} correlation models were evaluated by Lee et al. (In Press) to assess the suitability of inferred V_{s30} values for site class determination within the TS 1170.5 framework. By comparing the V_{sz}-V_{s30} correlation models from Boore (2004) and Boore et al. (2011) with V_s profiles in NZ, Lee et al. (In Press) found that the Boore (2004) extrapolation model is recommended for estimating V_{s30} using V_{sz} (for sites within sedimentary basins) since the model provides unbiased V_{s30} estimates for investigation depths (z) of 15 meters or more. Additionally, by comparing V_{s30} values extrapolated from measured V_s and inferred V_s based on various CPT-V_s correlation models, Lee et al. (In Press) found that Christchurch-specific models of McGann et al. (2015) and McGann et al. (2018) showed the best match for the region, while for other regions, Andrus et al. (2007) Pleistocene models provided the best match.

5.1 Residual Analysis

To provide deeper insights into the CPT-V_s correlation model evaluation process, this study compared measured and inferred V_s values at each depth, as well as V_{sz} values. Additionally, we assessed the correlation models against subsets of data located in the Christchurch region and of different geologic ages, as appropriate. To perform the residual analysis, CPT-based V_s profiles were derived using CPT results and CPT-V_s correlation models. Based on the derived CPT-based V_s profiles, we calculated the residuals as the logarithmic ratio of measured V_s and inferred V_s at each depth, and also estimated the mean and standard error using bootstrapping based on each of the calculated residuals. Additionally, we conducted further residual analysis for V_s and V_{sz} using various subset categories based on surficial geology and region:

1. All Pleistocene sites outside the Christchurch region with the A07-P model – (a)
2. All Holocene sites outside the Christchurch region with the A07-H model – (b)
3. All sites outside the Christchurch region with the R09 model – (c)
4. All Christchurch region sites excluding loess sites with the Mc15 model – (d)
5. Christchurch loess sites with the Mc18 model – (e)

In the evaluation process, geological ages were considered in order to categorize the dataset by surficial geology into Pleistocene and Holocene sites based on the NZL GNS 250K Geology (4th edition) maps (Heron et al., 2023).

5.1.1 Comparison of Inferred V_s and Measured V_s at each depth

Figure 4 shows the results of the residual analysis between measured V_s and inferred V_s at each depth across all considered sites (the red solid line and filled area correspond to the locally weighted mean and 95% confidence interval of the residuals, respectively). From most of the results, we observed larger uncertainty at both shallower and deeper depths. Most of the existing CPT-V_s correlation models tend to underpredict V_s values across a wide range of depths or show a continuously increasing mean trend, except for the A07-P and Mc18 models. The Mc18 model expectedly predicted significantly higher V_s values across most of the depth range (Figure 4 (e)) since it is only suitable for loess soils. Since the A07-P model shows mean values close to zero across the entire depth range, we conclude that the A07-P model appears most appropriate for use in NZ to estimate the V_s profile based on the CPT-V_s correlation model (Figure 4 (a)).

The results of the residual analysis for V_s, based on various subset categories (described in Section 5.1) of surficial geology and region, are illustrated in Figure 5. The A07-P model predicts V_s values well for all Pleistocene sites outside the Christchurch region, although it shows a slight increase in mean values over depths greater than 20m (Figure 5 (a)). In contrast, for all Holocene sites outside the Christchurch region, the A07-H model shows no significant trends over most of the depth range but slightly underpredicts V_s values across the entire depth range. Additionally, we confirmed that the R09 model is not suitable for estimating V_s values for New Zealand (Figure 4 (c) and Figure 5 (c)) as it has a strong depth-dependent trend. Based on Figures 5 (d) and (e), we found that the Mc15 and Mc18 models provide the best V_s predictions for the Christchurch region, excluding loess sites and for loess sites, respectively. Both the Mc15 and Mc18 models show mean values close to zero, with no observable trends. Based on these findings, we recommend using the Mc15 and Mc18 models to estimate V_s values in the Christchurch region, as they align with the development objectives of these models.

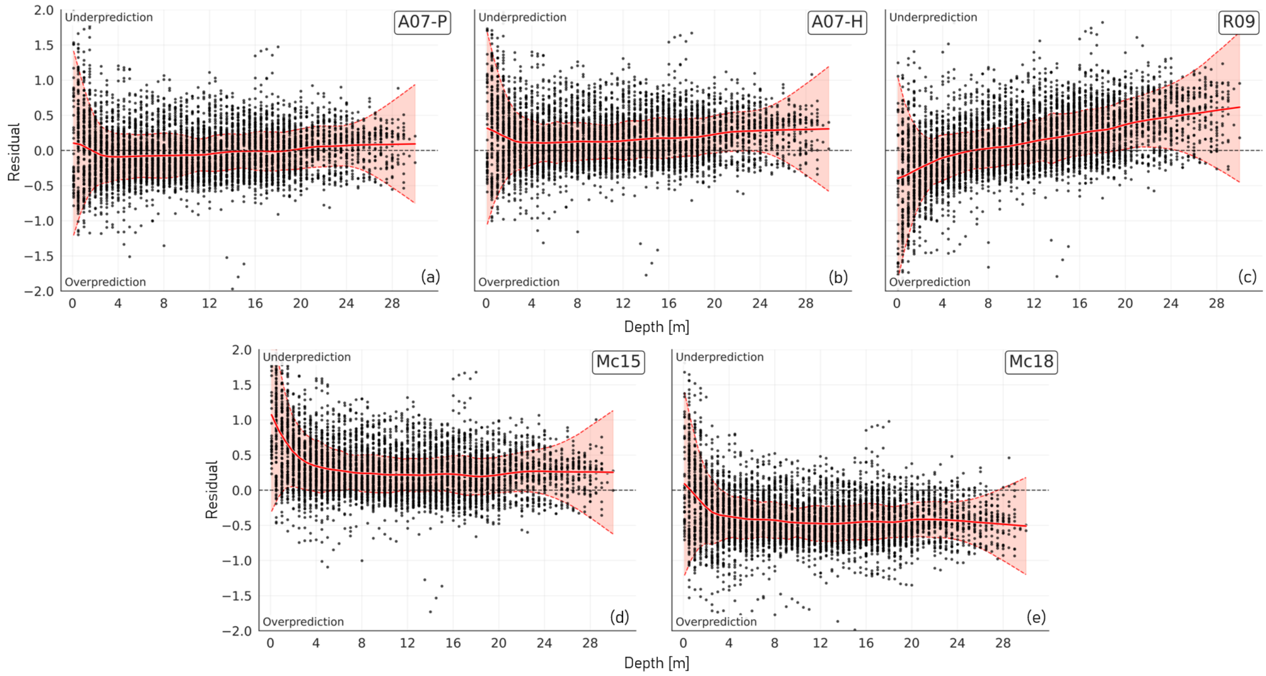

Figure 4: Results of the residual analysis for V_s values at each depth across New Zealand.

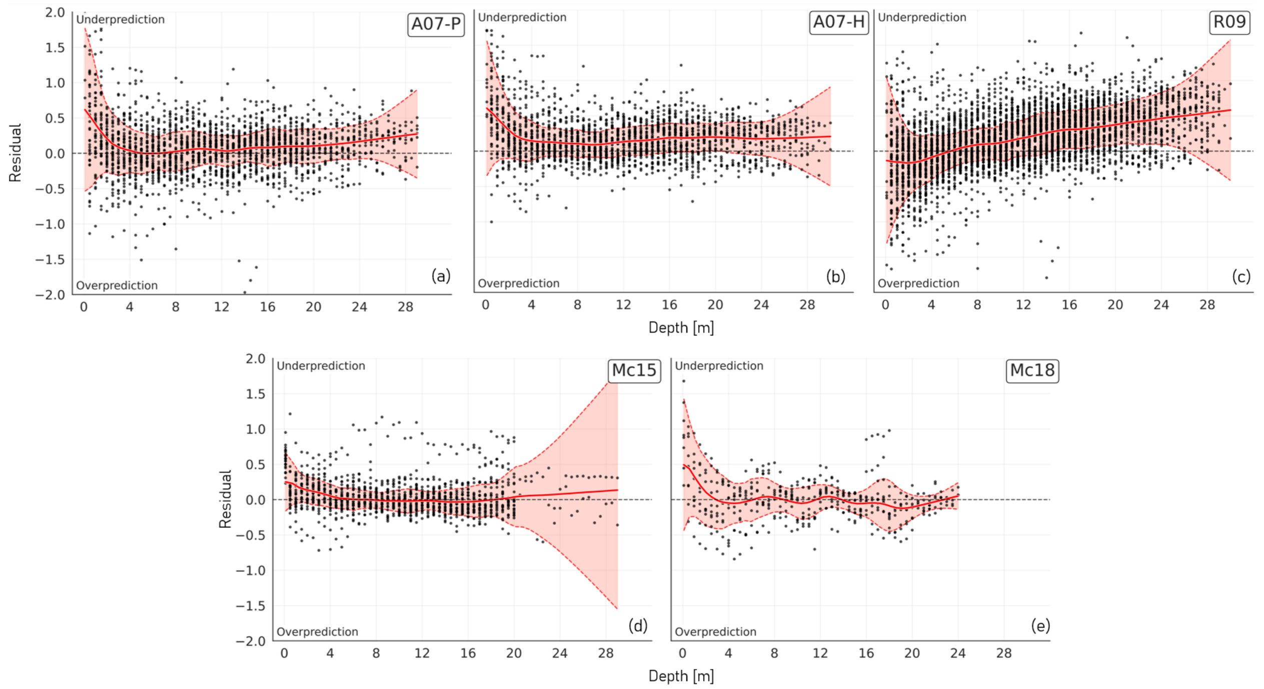

Figure 5: Results of the residual analysis for V_s values at each depth using various subset categories (see text).

5.1.2 Comparison of Inferred V_{sz} and Measured V_{sz}

Figure 6 shows the residuals between inferred and measured V_{sz} values based on the subset categories described in Section 5.1. We confirmed that the A07-P model shows well-matched results outside the

Christchurch region (Figure 6 (a)). For the Christchurch region, however, the Mc15 and Mc18 models provide the best predictions with the smallest variance of residuals for their respective subset categories. Based on the results of this study, we found that the A07-P correlation model is suitable for predicting V_s using CPT results outside the Christchurch region, while both Christchurch-specific models are appropriate for use within the region, aligning with the findings of Lee et al. (In Press).

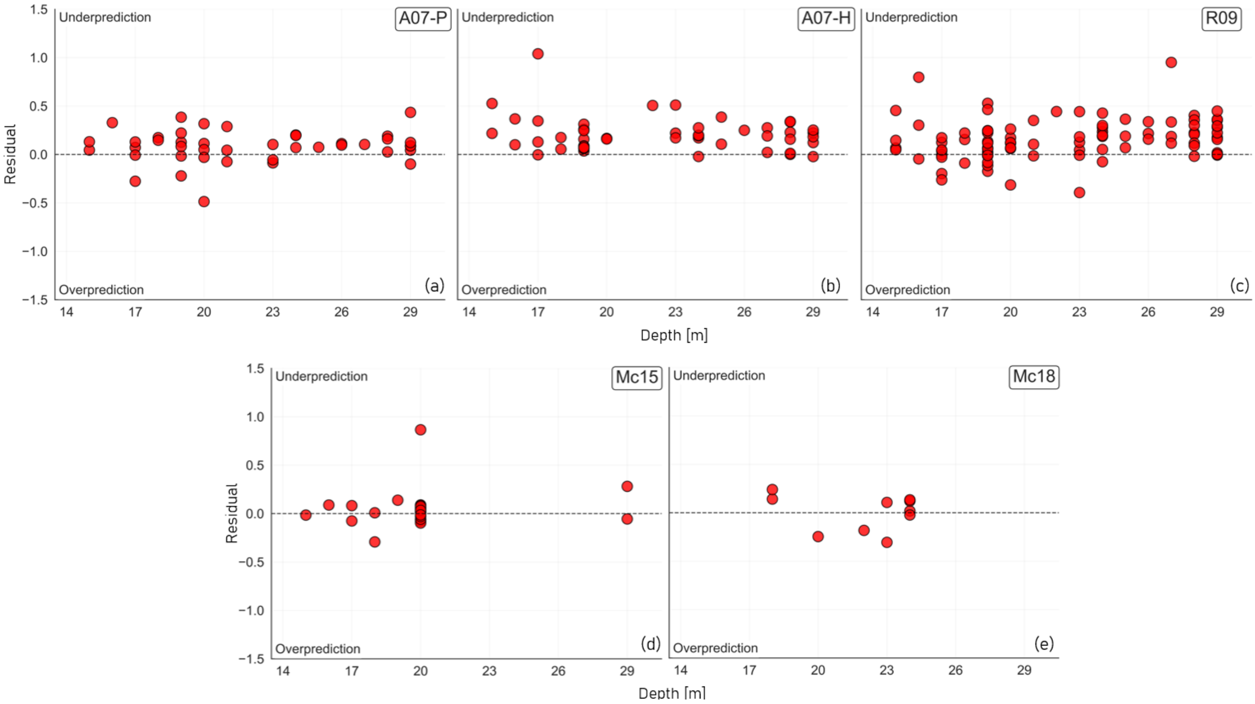

Figure 6: Results of the residual analysis for V_{sz} using various subset categories (see text).

6 CONCLUSION

This paper presents the progress on the NZ-wide V_{s30} map update. We updated the V_{s30} database to include the 2022 NZ NSHM site database and obtained V_s profiles from the NZGD. Based on the updated V_{s30} database, we produced a provisional NZ-wide V_{s30} map by conducting Bayesian updates, confirming relatively stiffer V_{s30} values in some regions. The V_{s30} map is currently intended for research-only purposes and specifically for regional hazard and risk assessments. Specifically, they are not intended for direct use in seismic design practice or as a substitute for site-specific investigations. The final results will be publicly available for the intended research purposes and regional applications. Additionally, we evaluated several CPT-V_s correlation models to consider the inclusion of inferred V_{s30} values as part of the V_{s30} database in the modelling framework. The results of this study show that the Andrus et al. (2007) Pleistocene CPT-V_s correlation model provides the best match for NZ, except for the Christchurch region, where region-specific or geology-specific models were developed by McGann et al. (2015, 2018), consistent with Lee et al. (In Press). In future studies, we will estimate V_s profiles using CPT results from approximately 15,000 locations, based on the findings of this study, investigate the inclusion of SPT data, and test various modelling assumptions to minimize systematic biases when including inferred V_{s30} values in the modelling framework.

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