Applicability of existing CPT-V_s correlations for shallow New Zealand soil deposits

Hui Zhou,
University of Auckland, Auckland, New Zealand.
Central South University, Changsha, China.

Liam Wotherspoon, & Andrew Stolte
University of Auckland, Auckland, New Zealand.

Christopher McGann
University of Canterbury, Christchurch, New Zealand.

ABSTRACT

A number of empirical correlations have been proposed to estimate shear wave velocity (V_s) using cone penetration test (CPT) data as a result of the growing availability of global databases. The performance of four existing CPT-V_s correlations in New Zealand conditions were assessed using a database of nearly 2000 CPT-V_s data pairs compiled from 52 co-located CPT and direct push crosshole (DPCH) sites across four regions in New Zealand. Different ranges of over- or under-predicted V_s for each region were presented based on various characteristics of the regional databases. In general, greater underestimates or overestimates were evident for fine-grained soils with lower measured V_s, while estimates were more reasonable for coarse-grained soils with higher measured V_s. Across all considered correlations, the Christchurch-specific correlation based on a sCPT database generally underestimated V_s, with significant underestimates dominated by data pairs from depths less than 4 m for majority of the considered regions. This may be a result of the use of different V_s measurement methods. These results underscore the potential for the development of new empirical relationships for different regions across New Zealand.

1 INSTRUCTION

The shear wave velocity (V_s) of soil deposits is a critical aspect of geotechnical earthquake engineering. The use of V_s measurement or estimation approaches, including laboratory testing, direct field-based testing, and empirical correlation, are typically defined by the scope and budget of an individual project. Compared with direct field-based testing and correlation-based methods, the main difficulty of laboratory testing is to achieve "undisturbed" sampling conditions and obtain high-quality samples (e.g. Yoshimi et al. 1989; Hight et al. 1992; Donohue and Long 2010; Wichtmann et al. 2013; Trafford and Long 2020).

Both invasive and non-invasive direct field-based seismic geophysical methods are used to determine V_s. This paper focuses on the invasive crosshole (e.g. direct push crosshole, DPCH) and downhole (e.g. seismic cone penetration tests, sCPT) methods. Based on the previous studies (i.e. Stolte and Cox 2019; Zhou et al., 2023), DPCH V_s profiles are more representative of the real V_s near the ground surface (depths < 3-4 m) compared with V_s profiles measured by sCPT, due to issues with the assumed ray paths from source to cone.

Empirical correlations between CPT-based parameters (i.e. cone tip resistance, q_c, and sleeve friction, f_s) and V_s exist for a wide range of soil types based on different test databases. These correlations have generally been based on test databases that do not represent a wide range of deposits or regions. Therefore, their applicability outside of the scope of the test databases is often not well understood.

This paper examines the applicability of four commonly used empirical correlations using co-located CPT and V_s profiles based on DPCH from 52 Holocene-aged soils sites across four regions in New Zealand. The geologic characteristics of these regions and the CPT and DPCH test data consisting of the database are introduced. The applicability of some correlations and the bias with respect to variables including CPT-based parameters (e.g. q_c and f_s) based on each regional database are assessed. The variation of the bias with respect to depth is further explored to identify the influence of V_s measurement differences. The main findings from the study are then summarized before drawing key conclusions.

2 DATABASE DEVELOPMENT

CPT and V_s data pairs were collected from co-located CPT soundings and DPCH tests at 52 sites from four regions in both North and South Island in New Zealand, including thirty-one in Christchurch, eight in Blenheim, eight in Hawkes Bay, and five in Whakatane. In general, the surficial soils across all regions are dominated by Holocene-aged deposits (<10,000 years).

Table 1: Summary of the characteristics of the regional databases.

Region	CPT-V_s data pairs	Soil type	Range of q_c (MPa)	Range of f_s (MPa)	Range of I_c	Range of V_s (m/s)
Whakatane	150	Gravel and sand	$0.29 < q_c < 20.39$	$0.003 < f_s < 0.22$	$1.34 < I_c < 3.20$	$59 < V_s < 244$
Hawkes Bay	174	Gravel, sand, silt and mud	$0.27 < q_c < 18.34$	$0.002 < f_s < 0.12$	$1.42 < I_c < 3.34$	$101 < V_s < 207$
Blenheim	171	Gravel, silt, mud peat and sand	$0.25 < q_c < 21.22$	$0.004 < f_s < 0.34$	$1.36 < I_c < 3.47$	$66 < V_s < 225$
Christchurch	1472	Gravel, silt and sand	$0.20 < q_c < 25.66$	$0.004 < f_s < 0.21$	$1.32 < I_c < 3.71$	$78 < V_s < 285$

This paper uses the data from testing depths less than 10 meters. Each V_s measurement was representative of the soil deposits within a range above and below each testing depth, and this range will vary depending on the characteristics of the source frequency and the soil properties (Backus 1962). To enable the comparison between the measured and estimated V_s from CPT parameter correlations, the V_s was assumed to be representative of the soil within each 200 mm DPCH interval and paired with the arithmetic mean of each CPT parameter within each DPCH test interval. This data filtering process was applied to all 52 sites to develop the databases of CPT-V_s data pairs. Table 1 summarizes the characteristics of each regional database, including the number of data pairs, soil type and the ranges of cone tip resistance (q_c), sleeve friction (f_s), soil behaviour type index (I_c) and V_s.

3 EXISTING CPT-V_S CORRELATIONS

Some of the existing empirical correlations specify the soil types that they are applicable to based on global database used in their development, with most applicable to fine- to coarse-grained soils of a relatively young age (i.e. Holocene soils) (Andrus et al. 2007; Hegazy and Mayne 2006; McGann et al. 2015b; Robertson 2009). Among the empirical CPT-V_s correlations available in the literature, the four commonly used correlations for Holocene-aged soils that were considered in this paper are summarized in Table 2. All considered correlations were proposed based on V_s values derived mainly from sCPT, with good performance when applied to the databases where they developed from, as indicated by the high coefficient of determination (R^2) values (where reported).

Table 2: Summary of empirical CPT-V_s correlations considered in this paper.

Reference	Number of data pairs	Regression functional form	Soil type	Coefficient of determination (R^2)
Andrus et al. (2007)	72	$V_s = 2.27 q_t^{0.412} I_c^{0.989} z^{0.033}$	Holocene-aged deposits	0.779
Hegazy and Mayne (2006)	558	$V_s = 0.0831 Q_{tn} e^{1.786 Ic} \left(\frac{\sigma'_{vo}}{P_a}\right)^{0.25}$	General soils	0.85
McGann et al. (2015)	513	$V_s = 18.4 {q_c}^{0.144} {f_s}^{0.0832} z^{0.278}$	Holocene-aged deposits	0.856
Robertson (2009)	1,035	$V_s = \left[10^{1.68+0.55 I_c} \left(\frac{q_t - \sigma_{vo}}{P_a}\right)\right]^{0.5}$	Holocene-and Pleistocene-aged deposits	N/A

(q_t is corrected cone tip resistance, σ_{vo} is total vertical stress, σ'_{vo} is effective vertical stress, P_a is the atmospheric pressure (101.3 kPa), Q_{tn} is the normalized cone tip resistance, z is measurement depth).

4 CORRELATION ASSESSMENT RESULTS

Figure 1 compares the measured and estimated V_s from the four correlations for each regional database, respectively. The marker colour for each data point represents the I_c for the respective test interval, with the higher measured V_s dominated by coarse-grained soils ($I_c \leq 2.05$). The Andrus et al. (2007) correlation generally showed the best performance when applied to the regional databases, as indicated by the highest R^2 values and with over 92% of the data points falling within the ±50% limits. Compared with a balance over- and under-prediction for the Blenheim and Christchurch database, the Hawkes Bay database was dominated by underestimates, while overestimates dominated the Whakatane database. In contrast, the Hagazy and Mayne (2006) correlation showed the worst performance with the lowest R^2 values and underestimated V_s values for all the regional databases apart from the Christchurch database, whose V_s values were dominated by overestimates. Even though the Robertson (2009) correlation had relatively high R^2 value and approximately 90% of the data points within the ±50% limits for most of the regional databases, around 75% of the data points were above the 1:1 line for the Blenheim, Christchurch and Whakatane databases, indicating a general bias towards overestimation. The Hawkes Bay database showed the opposite, with over 63% of the data points below the 1:1 line representative of underestimation. Across all considered empirical correlations, the estimated V_s values using the McGann et al. (2015) correlation were dominated by underestimates, with over 90% of the data points falling below the 1:1 line for all regional databases. The data points beyond the ±50% bounds representing large underestimates and overestimates were generally dominated by fine-grained soils (I_c > 2.05) across all considered correlations.

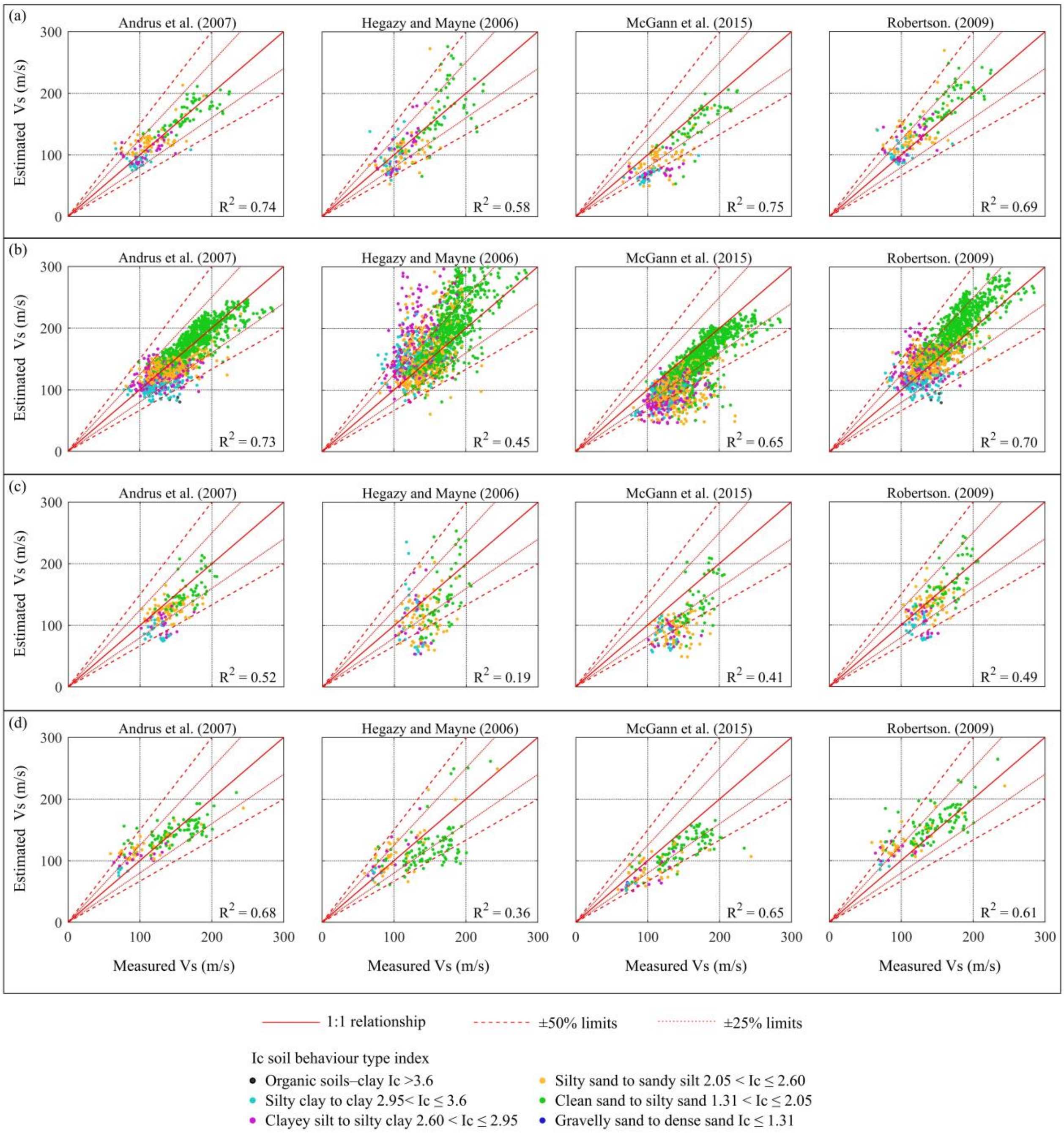

Figure 1: Comparison of the measured and estimated V_s using the Andrus et al. (2007), Hegazy and Mayne (2006), McGann et al. (2015), and Robertson (2009) correlation for the (a) Blenheim database, (b) Christchurch database, (c) Hawkes Bay database, and (d) Whakatane database.

In order to further explore the parameters with the greatest influence on the performance of the CPT-V_s correlations, the bias (φ) between the natural logarithm of the predicted and measured V_s was used as expressed in Eq. 1:

$$\varphi = ln(V_{sE}) - \ln(V_{sM}) \quad (1)$$

where V_{sE} is the estimated V_s value and V_{sM} is the measured V_s value. A positive bias indicates an over-prediction, while a negative bias represents an under-prediction.

Figures 2 and 3 summarize the variation in bias with respect to q_c, f_s, and measurement depth (z) for each regional database using the Andrus et al (2007) and McGann et al. (2015) correlation respectively. These were chosen for further assessment based on the best performance of the Andrus et al. (2007) correlation for current databases and the development of the McGann et al. (2015) correlation from a Christchurch-based sCPT database. The moving average of the bias is represented by the solid line and the 95% confidence interval by dashed lines. The moving average of the bias was defined using normal linear and Epanechnikov kernel regression methods, while the 95% confidence interval bandwidth was determined by the Gaussian and Epanechnikov kernel regression methods (Ruppert et al. 1995). Each point in Figure 3 and 4 is colored based on the I_c value representative of each test interval.

For the Andrus et al, (2007) correlation, the average bias was smaller, had a narrower 95% confidence interval and was more stable compared with the McGann et al. (2015) correlation when applied to the regional databases in Figure 2. The McGann et al. (2015) correlation consistently underestimated V_s for all regional databases across the parameter ranges considered, with much of the 95% confidence interval in the negative bias range in Figure 3. The biggest difference between these two considered correlations was the variation of the bias with respect to depth. The Andrus et al. (2007) correlation showed fairly small variation in bias with respect to depth, fluctuating at a value of approximately zero across the depth ranges considered (the most variation with depth was evident for the Whakatane database). The average bias of McGann et al. (2015) correlation showed significant variation with respect to measurement depth, with large underestimates at depths less than 4 m, which were dominated by silty sand to clay soil behaviour types. At greater depths the degree of underestimation reduced, with a bias near zero at a depth of 10 m.

The analysis presented here shows that the applicability of the empirical correlations to the region/nation beyond the data used in their development needs to be accounted for. Zhou et al. (2023) discussed the differences between the sCPT and DPCH in V_s measurement. Caution is recommended when applying the McGann et al. correlation to CPT data at measurement depths less than 4 m, particularly when these depths are characterized primarily by soil with I_c exceeding 2.05. This is likely a result of a combination of factors, including S-wave travel path assumption used in sCPT data processing, over-extrapolation of the correlation beyond the range of data used in its development, and the variable nature of the soil deposits in the region where the data was used in correlation sourced. Overall, the mixed performance of the existing empirical CPT-V_s correlations when applied to New Zealand soils highlights the utility of developing new empirical relationships between CPT data and V_s obtained from DPCH based on the nationwide and region-specific CPT-V_s databases.

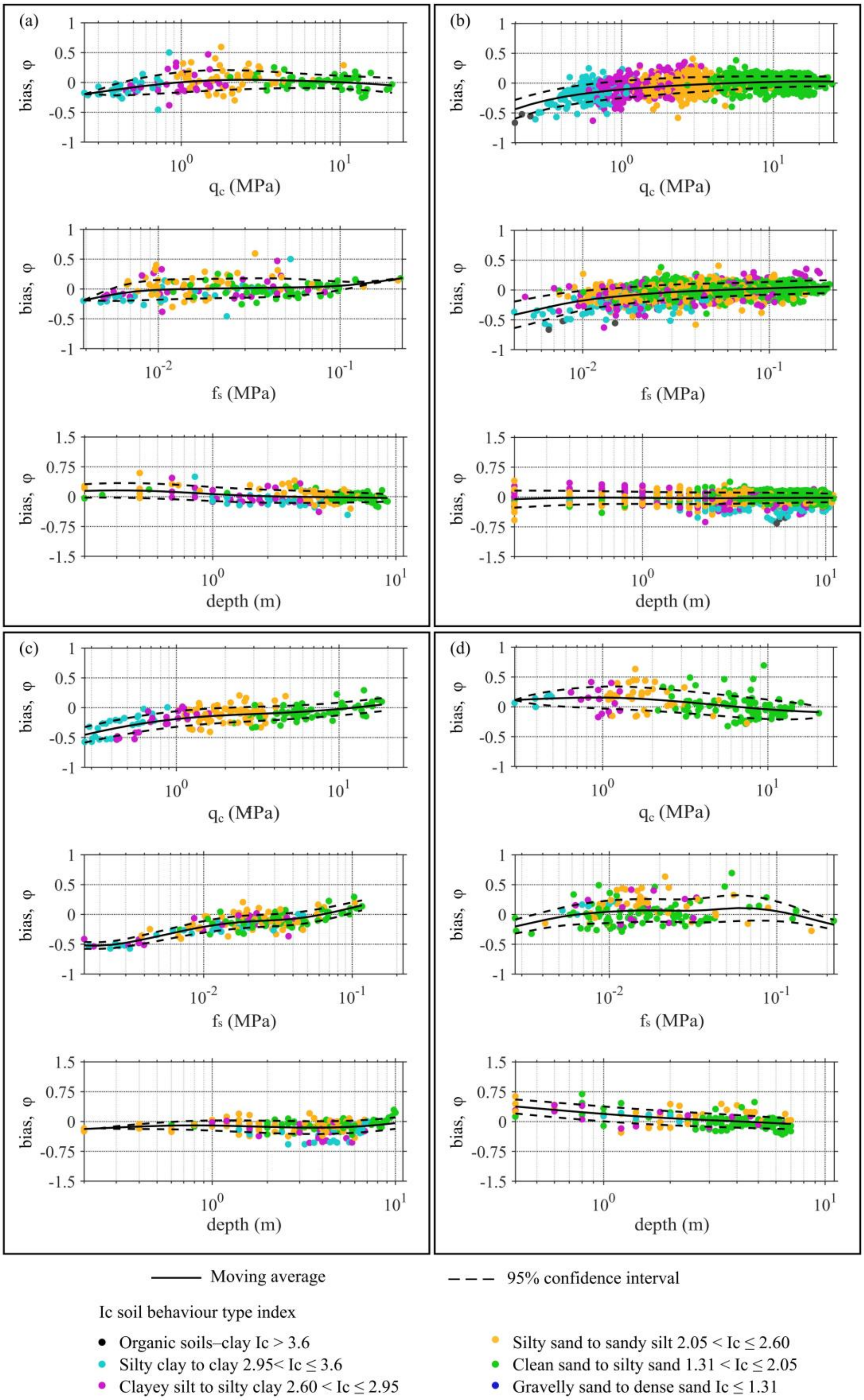

Figure 2: Variation in bias with respect to q_c, f_s, and z using the Andrus et al. (2007) correlation for the (a) Blenheim database, (b) Christchurch database, (c) Hawkes Bay database, and (d) Whakatane database.

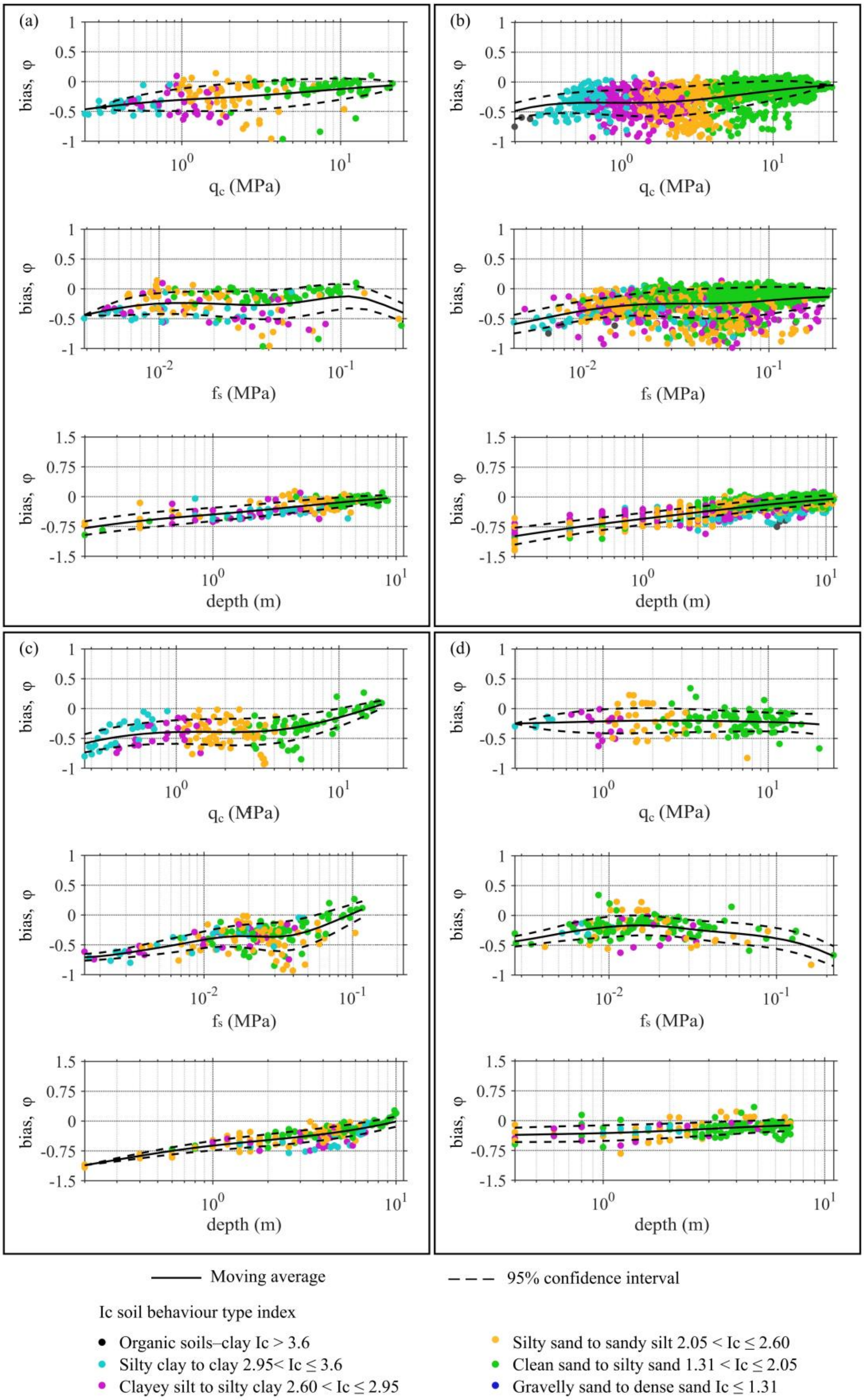

Figure 3: Variation in bias with respect to q_c, f_s, and z using the McGann et al. (2015) correlation for the (a) Blenheim database, (b) Christchurch database, (c) Hawkes Bay database, and (d) Whakatane database.

5 CONCLUSIONS

A database with over 1900 CPT-V_s data pairs for Holocene-aged soils at shallow depth was developed from co-located CPT soundings and DPCH tests at 52 sites across New Zealand. Each regional database had its own geologic characteristics with various range of measurement results. Four empirical CPT-V_s correlations were applied to the regional databases to assess their applicability and potential influence of various parameters (e.g. CPT-based parameters, measurement depth, and V_s measurement technique) on estimates of V_s were also explored. The Andrus et al. (2007) correlation for Holocene-aged deposits provided the best fit with the highest R^2 value compared with the worst performance for the Hagazy and Mayne (2006) correlation with the lowest R^2 value. The Robertson (2009) correlation generally overestimated V_s for most of the regional databases. While the McGann et al. correlation (2015) was developed from a Christchurch sCPT database, the V_s values were consistently underestimated across all regional databases, which may be attributed in part to the differences between DPCH and sCPT V_s measurements.

The comparison between the measured and estimated V_s from four empirical CPT-V_s correlations underscores potential issues with the applicability and uncertainty of empirical correlations when use in a specific region/nation. Possible CPT-V_s correlations with V_s obtained from DPCH database could be developed in future studies. Estimated V_s values should be used only to provide initial insight into in-situ soil proprieties, and caution is recommended when using these values in engineering applications. Direct in-situ measurement of V_s is strongly encouraged whenever and wherever possible.

REFERENCES

Andrus, R. D., Mohanan, N. P., Piratheepan, P., Ellis, B. S., & Holzer, T. L. (2007). "Predicting shear-wave velocity from cone penetration resistance." *4th International Conference on Earthquake Geotechnical Engineering*, Thessaloniki, Greece, Paper No. 1454, 25-28.

Backus, G. (1962). "Long-wave elastic anisotropy produced by horizontal layering". *Journal of Geophysical Research*, 64(11): 4427-4440.

Donohue, S., & Long, M. (2010). "Assessment of sample quality in soft clay using shear wave velocity and suction measurements." *Géotechnique*, **60**(11), 883-889. https://doi.org/10.1680/geot.8.T.007.3741

Hegazy, Y. A., & Mayne, P. W. (2006). "A global statistical correlation between shear wave velocity and cone penetration data." *Site and Geomaterial Characterization*, 243-248. https://doi.org/10.1061/40861(193)3

Hight, D. W., Böese, R., Butcher, A. P., Clayton, C. R. I., & Smith, P. R. (1992). "Disturbance of the Bothkennar clay prior to laboratory testing." *Géotechnique*, **42**(2), 199-217. https://doi.org/10.1680/geot.1992.42.2.199

McGann, C. R., Bradley, B. A., Taylor, M. L., Wotherspoon, L. M., & Cubrinovski, M. (2015). "Development of an empirical correlation for predicting shear wave velocity of Christchurch soils from cone penetration test data." *Soil Dynamics and Earthquake Engineering*, **75**, 66-75. https://doi.org/10.1016/j.soildyn.2015.03.023

Robertson, P. K. (2009). "Interpretation of cone penetration tests—a unified approach." *Canadian Geotechnical Journal*, **46**(11), 1337-1355. https://doi.org/10.1139/T09-06

Ruppert, D., Sheather, S. J., & Wand, M. P. (1995). "An effective bandwidth selector for local least squares regression." *Journal of the American Statistical Association*, **90**(432), 1257-1270. https://doi.org/10.1080/01621459.1995.10476630

Stolte, A. C., & Cox, B. R. (2019). "Towards consideration of epistemic uncertainty in shear-wave velocity measurements obtained via seismic cone penetration testing (SCPT)." *Canadian Geotechnical Journal*, **57**(1), 48-60. https://doi.org/10.1139/cgj-2018-068

Trafford, A., & Long, M. (2020). "Relationship between shear-wave velocity and undrained shear strength of peat." *Journal of Geotechnical and Geoenvironmental Engineering*, **146**(7), 04020057. https://doi.org/10.1061/(ASCE)GT.1943-5606.000229

Wichtmann, T., Andersen, K. H., Sjursen, M. A., & Berre, T. (2013). "Cyclic tests on high-quality undisturbed block samples of soft marine Norwegian clay." *Canadian Geotechnical Journal*, **50**(4), 400-412. https://doi.org/10.1139/cgj-2011-0390

Yoshimi, Y., Tokimatsu, K., & Hosaka, Y. (1989). "Evaluation of liquefaction resistance of clean sands based on high-quality undisturbed samples." *Soils and Foundations*, **29**(1), 93-104. https://doi.org/10.3208/sandf1972.29.93

Zhou, H., Wotherspoon, L. M., Hayden, C. P., Stolte, A. C., & McGann, C. R. (2023). "Applicability of existing CPT-Vs correlations to shallow Holocene Christchurch soils based on direct push crosshole testing." *Engineering Geology*, **313**, 106927. https://doi.org/10.1016/j.enggeo.2022.106927