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24-26 March 2021 • Dunedin • New Zealand

Applicability of empirical SPT-CPT correlations for New Zealand soils

H. Zhou, L. M. Wotherspoon & C. Hayden

Department of Civil and Environmental Engineering, University of Auckland, Auckland.

C. R. McGann & A. Stolte

Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch.

I. Haycock

McMillan Drilling Group, Southbridge.

ABSTRACT

Using a database of 230 co-located cone penetration tests (CPT) and boreholes with standard penetration tests (SPT) from sites across Christchurch, New Zealand, this paper assesses the applicability of a range of existing SPT-CPT correlations from international studies. Both simple linear CPT-SPT relationships for soil types identified from borehole logs, and correlations based on the soil behaviour type index (I_c) from CPT data are assessed. Across all correlations there is a large spread in the data, suggesting relatively poor performance, with greater than 50% under and over prediction for a large number of datapoints. The effects of both SPT and CPT-based parameters (i.e., N_{60} , q_c and f_s) on representation have been further studied and showed significant variation in assessment. These results highlight the significant uncertainty involved in the application of these correlations and the care required when they are used in any geotechnical assessment.

1 INTRODUCTION

There are a range of approaches that can be taken to estimate soil properties in geotechnical engineering practice. While sampling and lab testing can be advantageous for soil characterisation, in-situ investigation methods, such as the standard penetration test (SPT) and the cone penetration test (CPT), have more extensive application across projects of all scales. A range of correlations are often used to convert the measured data from CPT and SPT tests to a range of different soil properties to inform design. These correlations have typically been developed based on fairly regionally specific databases, and their applicability in other regions is often not clear. A range of SPT-CPT correlations have been developed from relatively independent international databases and are also applied worldwide. This paper discussed several widely used empirical

SPT-CPT correlations and divided them into two categories with respect to the approach used to represent soil deposit characteristics.

The simplest correlations (Category 1) are linear relationships based on the ratio between CPT cone tip resistance, q_c and different SPT N-value metrics for each soil type. Schmertmann (1970) suggested several linear relationships for different soil types using data from 16 sites in 10 countries. These took the form of $n = q_c/N$, where n varied for different soil types. Robertson et al. (1986) proposed a linear relationship for different soil types based on $n = (q_c/p_a)/N_{60}$ where p_a is the atmospheric pressure. The details of both correlations are summarized in Table 1.

Table 1: Details of Category 1 SPT-CPT correlations for a range of soil types.

Source	Soil type	n ratio
Schmertmann (1970)	Silt, sandy silt and slightly cohesive silt-sand mixture	$n=(q_c/N)$ 0.2
	Clean, fine to medium sand and slightly silty sand	0.35
	Coarse sand and sand with little gravel	0.5
	Sandy gravel and gravel	0.6
Robertson et al. (1986)		$n= (q_c/p_a)/N_{60}$
	Sensitive fine grained	0.2
	Organic material	0.1
	Clay	0.1
	Silty clay to clay	0.15
	Clayey silt to silty clay	0.2
	Sandy silt to clayey silt	0.25
	Silty sand to sandy silt	0.3
	Sand to sandy silt	0.4
	Sand	0.5
	Gravelly sand to sand	0.6
Very stiff fine grained	0.1	
Sand to clayey sand	0.2	

Category 2 correlations make use of the soil behaviour type, I_c to represent the influence of different soil types on the SPT-CPT correlation. Jefferies and Davies (1993) proposed a correlation based on 195 SPT-CPT data pairs for fine-medium sand with trace silt at five sites using the mud rotary drilling method. Lunne et al. (1997) updated the Jefferies and Davies (1993) correlation using a ratio between q_c and p_a . The equation takes the form:

$$\frac{q_c/p_a}{N_{60}} = 8.5 \left(1 - \frac{I_c}{4.6} \right) \quad (1)$$

This equation is considered to be an improvement on the original Jefferies and Davies (1993) correlation for soil types ranging from gravelly sand to organic soils. Robertson (2012) suggested that the Lunne et al. (1997) equation underestimated N_{60} values for some clays when applying the correlation in North America. The study also suggested that N_{60} may be overestimated for highly sensitive fine-grained soils. Robertson developed a new equation with the form:

$$\frac{\left(\frac{q_t}{p_a} \right)}{N_{60}} = 10^{(1.1268 - 0.2817I_c)} \quad (2)$$

This paper assesses the applicability of these empirical SPT-CPT correlations using a New Zealand specific database of 230 co-located CPT soundings and boreholes with SPT from sites in the South Island of New Zealand (199 of which are in the greater Christchurch area). The details of the dataset development are presented and the measured and estimated N_{60} values compared. To assess the influence of SPT and CPT parameters on the correlation performance, the bias between the measured and estimated values are compared as a function of these parameters. The key observations are then discussed and conclusions drawn.

2 DATASET DEVELOPMENT

Co-located CPT soundings and boreholes with SPT data were collected from 230 sites in the South Island of New Zealand. Most of the sites were located in the greater Christchurch area with the rest of the sites in other parts of the South Island (1 in Nelson, 3 in Queenstown, 6 in Blenheim, 5 in Ashburton, 4 in Lincoln, and 12 in Lyttelton). Fig. 1 summarizes the locations for the 199 BH-CPT data pairs in the greater Christchurch area and their location within the surficial geologic map (Brown & Weeber 1992). Many of the sites in Christchurch are located along the banks of two main rivers, the Avon and Heathcote Rivers, or near other small streams across the city.

The surficial geologic map in the greater Christchurch area (Brown & Weeber 1992) is shown in the inset in Fig. 1, indicating predominately postglacial fluvial deposits across the area. The Christchurch Formation represented by blue and grey-blue color consists of beach, estuarine, lagoonal, dune, and coastal swamp deposits. Fluvial channel and overbank sediment deposits form the Springston Formation and are indicated by yellow and yellow-grey shading in the map. Both the Christchurch and the Springston Formation are Holocene deposits (< 10,000 years). The Mt. Pleasant Formation (red and light-red in Fig. 1 inset) consists of volcanic rock deposits (\approx 11,000 years), with no sites located in these deposits (Brown et al., 1995). As shown in Fig. 1, the majority of the 199 BH-CPT location pairs were located in Springston Formation. The sites outside of the Christchurch area are also located in young alluvial deposits of Holocene age.

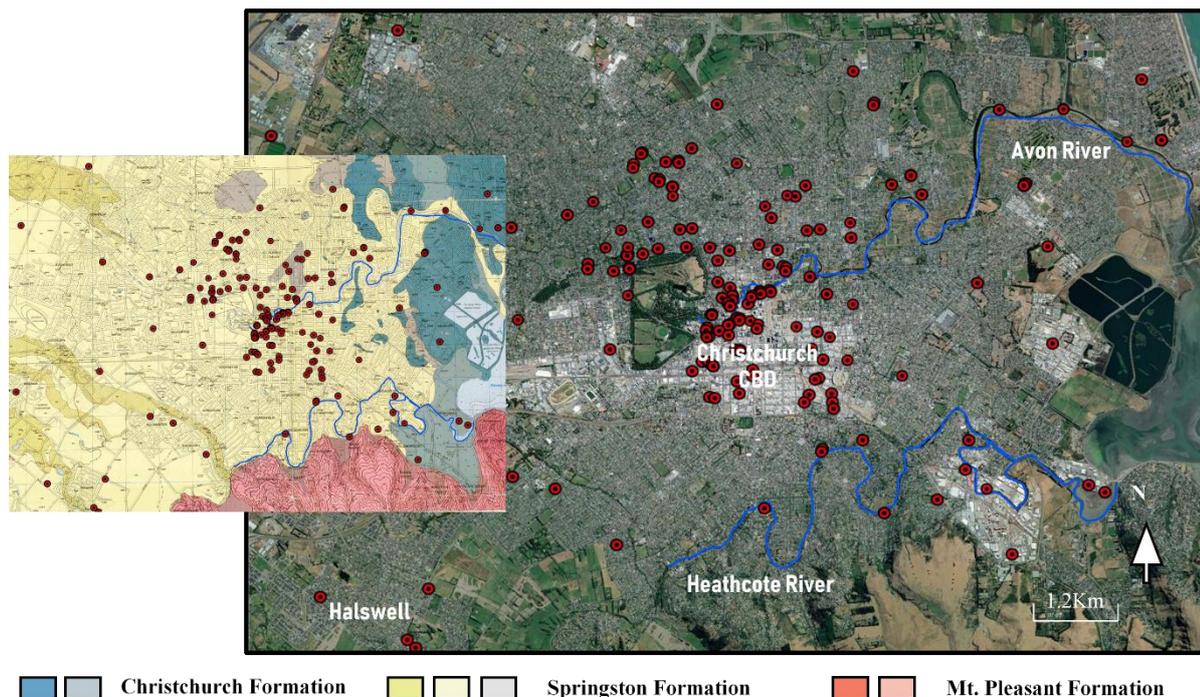


Figure 1: Map of the location of the 199 BH-CPT pairs in greater Christchurch area, New Zealand. The surficial geologic map for this area is inset at left.

The raw data from the co-located CPT and boreholes was processed and screened to ensure a high quality dataset. This dataset is comprised of tests from different operators and equipment with SPT hammer energy efficiencies from calibration tests ranging from 47.9% to 102%. The raw SPT N-values were corrected to N_{60} values, adjusting for 60% energy efficiency and to account for the effects of rod length, anvils, and the weight of hammer. The cone tip resistance was adjusted to corrected cone tip resistance q_t which accounts for the effects of unequal end area and pore water pressure. For coarse-grained soils, the value of q_c and q_t is similar and the correction is insignificant. All the CPT-based parameters were adjusted to calculated average values within each 300 mm testing interval corresponding to the SPT measurement midpoint.

The raw database contained 1208 SPT-CPT data pairs across all sites. The overall database was then screened based upon the following criteria:

- Locations affected by heave and artesian water effects as noted in drillers logs were removed due to the potential for soil disturbance.
- SPT tests with drive lengths less than 450 mm were removed as they were considered incomplete.
- SPT readings of zero were removed.
- N_{60} over 50 were removed because of the limitation of hammer energy.
- CPT variables with values less than zero were removed.
- Locations where the distance between CPT soundings and borehole was greater than 15 m were removed due to the anticipated effect of horizontal inhomogeneity (e.g., soil lensing, dipping layers, variable deposition).
- Tests in gravel were removed due less reliable CPT and SPT test results.

After screening, there were total 896 SPT-CPT data pairs left as a based dataset. For the selected SPT-CPT correlations in Category 1, a reduced number of data pairs were used to align with the soil types that were applicable for each correlation. For the Schmertmann correlation, 491 SPT-CPT data pairs were left after assigning the soil types based upon descriptions from sampling. For the Robertson et al. correlation, I_c values corresponding to clean sand to silty sand were used, resulting in 499 SPT-CPT data pairs. Correlations in Category 2 could be applied for the whole dataset of 896 SPT-CPT data pairs.

3 RESULTS

Selected empirical SPT-CPT correlations introduced in the previous sections were applied to the database, and the predicted N_{60} from each correlation was compared to the measured N_{60} for each SPT-CPT data pair. To assess performance of the Category 2 correlations, the bias (φ) between the predicted and measured N_{60} was defined as expressed in equation (3) as differences between these values could be large.

$$\varphi = \ln(N_e) - \ln(N_M) \quad (3)$$

where N_e is the estimated N_{60} -value and N_M is the measured SPT N_{60} -value.

The variation in bias between the estimated and measured SPT N_{60} values was explored for various SPT and CPT testing parameters and used to analyze the effect of these parameters on the existing empirical correlations. When $\varphi > 0$ this represented an overestimation from the correlation, and $\varphi < 0$ represented an underestimation.

3.1 Category 1

For the clean sand to silty sand soil type (refer to Table 1), the n ratio for the Schmertmann (1970) correlation is 0.35, and 0.5 for the Robertson et al. (1986) correlation. As noted above, in this study, q_t is used instead of q_c for these correlations as the difference between two is negligible for sandy soils. q_t is also another step to standardize CPT tests from different cones/contractors and improves comparisons between individual CPT soundings. Fig. 2a and b compare the measured and estimated N_{60} values for the Category 1 empirical SPT-CPT correlations. There is considerable scatter for both comparisons, suggesting poor performance of these correlations. Over 55% and 40% of total applied data points sit outside the $\pm 50\%$ dashed lines for Schmertmann correlation and Robertson et al. correlation respectively, and there is a tendency for overestimation of the N_{60} values for both correlations, as indicated by a higher density of points above the 1:1 line. Quantitatively, the Robertson et al. correlation showed slightly better estimates of the measured data, as indicated by an R^2 value of 0.38 as compared to the R^2 value of 0.24 for the Schmertmann correlation. Given the scatter in the data, there should be skepticism when applying these correlations to the soil deposits within this dataset.

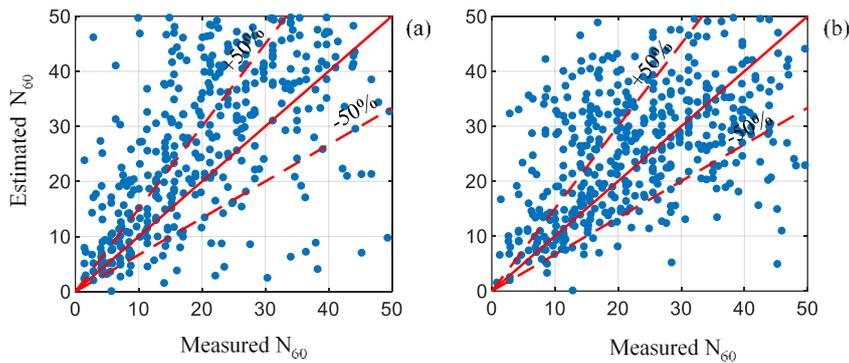


Figure 2: Comparison of the measured N_{60} and estimated N_{60} using: a) Schmertmann (1970) Correlation for 491 SPT-CPT datapoints; b) Robertson et al. (1986) Correlation for 499 SPT-CPT datapoints.

3.2 Category 2

Fig. 3a and b compare the measured and estimated N_{60} values for the Category 2 empirical SPT-CPT correlations, with each point classified based on the soil behavior type index (I_c). Similar to the Category 1 correlations, there is significant scatter in this data, with R^2 values of 0.428 and 0.431 for the Lunne et al. and Robertson correlations, respectively. Again, poor performance of both correlations is evident, with around 47% of the datapoints outside the $\pm 50\%$ dashed lines. The majority of the points are clean sand to silty sand, and these span a wide range of measured N_{60} values. Most points with an $I_c > 2.05$ have N_{60} less than 20 and dominate the comparison in this range.

To provide some context to the performance of these correlations, the original 195 data pairs that were used to develop the Jeffries and Davies (1993) correlation are presented in Fig 3c, again comparing the measured and estimated N_{60} values. Due to the smaller range of soil types that make up this dataset, there is better performance of this correlation, with an R^2 value of 0.607. Nevertheless, there is clearly still some scatter in the data, with points beyond the $\pm 50\%$ lines, highlighting the uncertainty inherent in this original correlation.

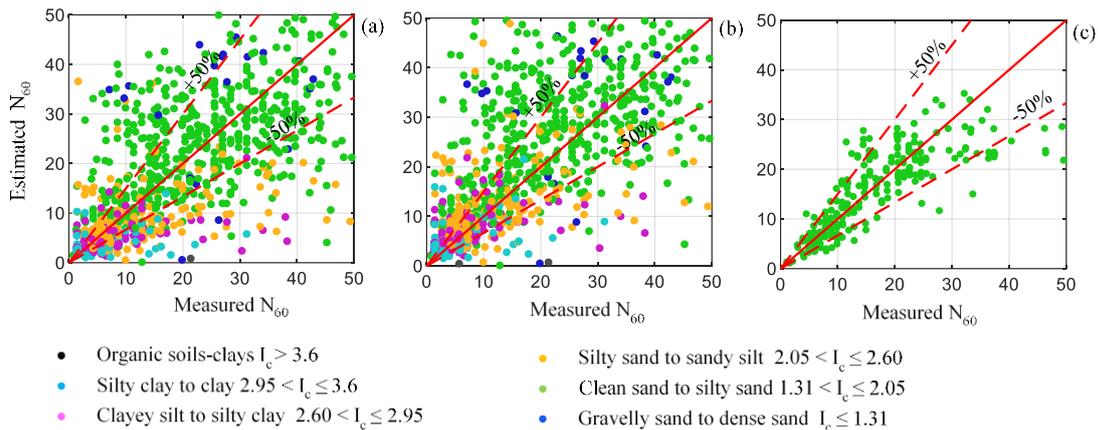


Figure 3: Comparison of the measured N_{60} and estimated N_{60} for: a) 896 SPT-CPT datapoints using Lunne et al. (1997) Correlation; b) 896 SPT-CPT datapoints using Robertson (2012) correlation; c) 195 SPT-CPT datapoints applied in Jeffries and Davies (1993).

Fig. 4 presents the variation of bias between the estimated and measured N_{60} with respect to the measured N_{60} value. The black line is the moving average of the bias, and the 95% confidence interval is represented by the dashed lines. For each data point in these figures the corresponding I_c value is identified. As shown in Fig. 4a and b, the wide range of bias, as indicated by the large 95% confidence interval bounds across all N_{60} values, reinforces prior observation of large scatter and low R^2 values in Fig. 3a and b. For measured N_{60} values less than 5, the range dominated by soils with I_c greater than 2.05, both correlation methods overestimate the measured values. The range of this overestimation is larger for the Robertson correlation, up to N_{60} values of 15. The tendency of the correlations to provide overestimates may be a result of: (1) disturbance of these soils during drilling, resulting in lower measured N_{60} values, or (2) the lack of representation of these soils in the original datasets used to develop these correlations.

The average bias is close to zero in the 10-20 measured N_{60} range for Lunne et al. and 20-30 range for Robertson, where the dataset is dominated by clean sand-silty sand ($I_c < 2.05$), albeit with the large confidence interval range. Above these values, both correlations underestimate the measured values, with much of the 95% confidence intervals shifting into the negative bias range. These results suggest that the dependence on N_{60} to ensure the applicability and reliability of the considered correlations is not been adequately accounted in relation this dataset.

For the 195 data points from the Jefferies and Davies (1993) study (refer to Fig. 8c), the bias is stable around zero for N_{60} values below 25. Above this range, the correlation underestimates the measured N_{60} values. The 95% confidence interval range is much smaller for this dataset, again likely a result of the self-consistent soil deposits used in the development of this correlation.

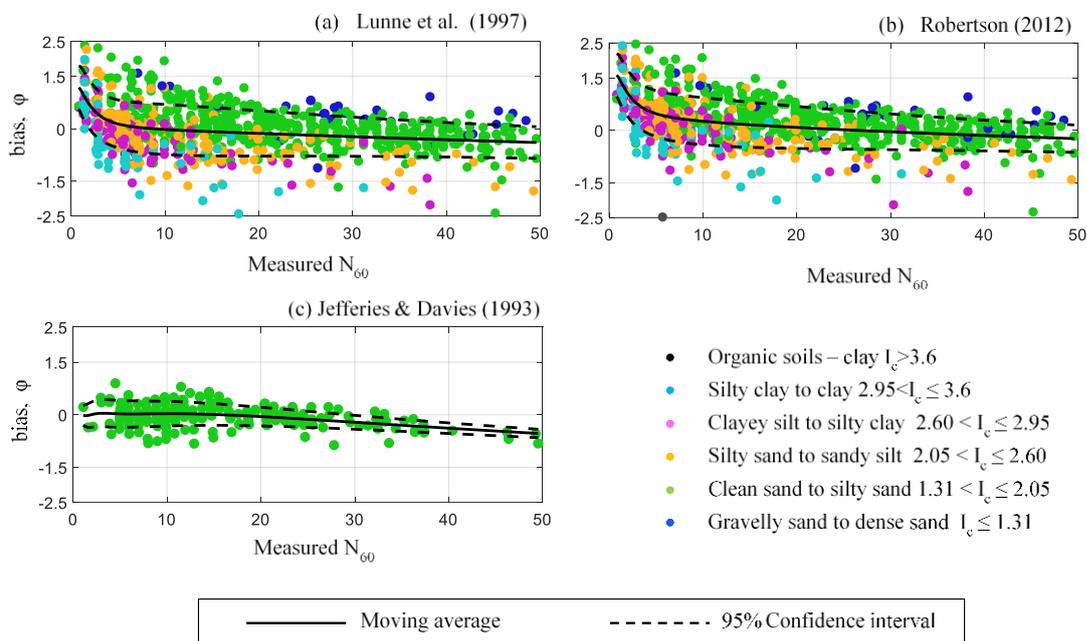


Figure 4: Comparison of the bias as a function of the measured N_{60} for: (a) 896 SPT-CPT datapoints using Lunne et al. (1997) Correlation; (b) 896 SPT-CPT datapoints using Robertson (2012) Correlation (c) 195 SPT-CPT datapoints applied in Jefferies and Davies (1993)

Fig. 5 summarizes the variation in bias with respect to CPT-based parameters (q_t and f_s). Again, the 95% confidence interval of the bias is large, across all the parameters considered. The bias with respect to q_t in Fig. 5a and b shows an underestimation for the Lunne et al. correlation when q_t is less than 10 MPa, while the bias in the Robertson correlation suggests an underestimation at very low q_t values. The points in the low q_t range are dominated by I_c values greater than 2.05, representative of silty sand to clayey silt. The negative bias transitions to a positive bias as q_t increases, shifting much of the 95% confidence interval into a range indicative of an overestimation by the correlations. In the positive bias range, the vast majority of data points are clean sand to silty sand based on I_c . Similar trends are evident for the bias in terms of f_s in Fig. 5c and d, shifting from an underestimation to an overestimation as f_s increases with the change at about 0.05 MPa. There are various soil types when f_s is less than 0.05 MPa, however, the underestimates are again dominated by soils with an I_c greater than 2.05.

The poor performance of the two empirical correlations, and the large bias in the lower range of the CPT and SPT-based parameters could be explained by the differences between the global original dataset and current study dataset. In the dataset presented here, there are a wide range of soil types, from organic to gravelly, compared to the more consistent soils used in the development of the empirical correlations, and this could be the reason why these soils are concentrated in areas of larger bias.

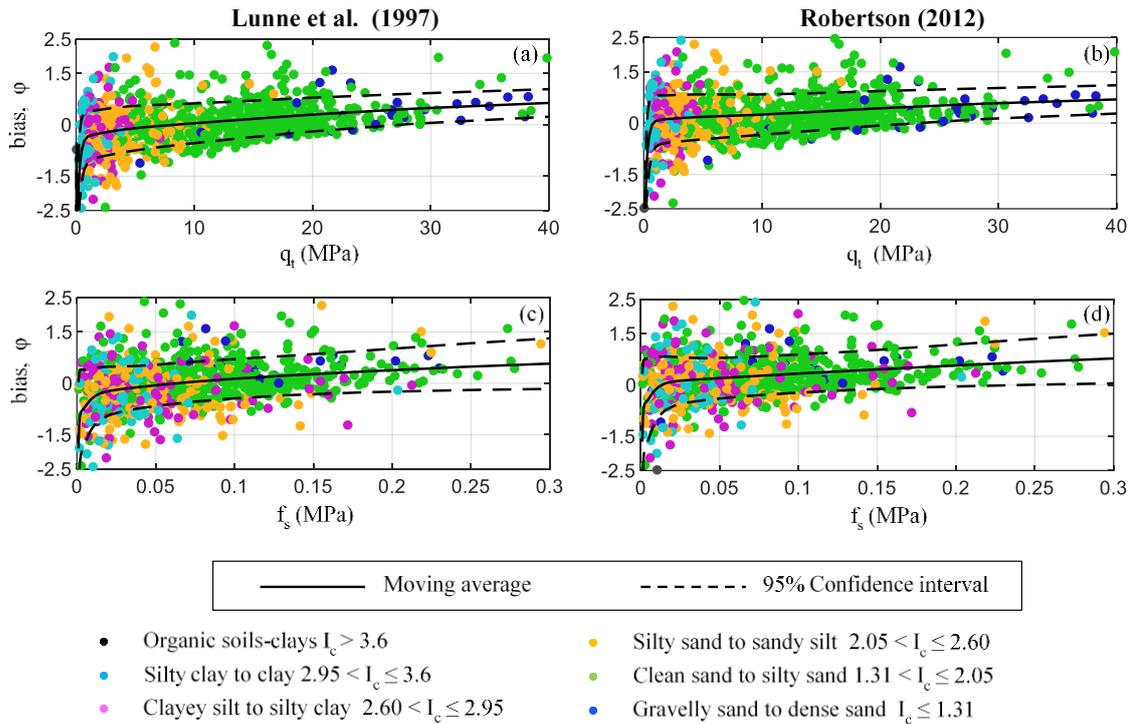


Figure 5: Comparison of the bias with corrected cone tip resistance, q_t , cone friction resistance, f_s , for the Lunne et al. correlation and Robertson correlation.

4 CONCLUSIONS

The applicability of four existing empirical SPT-CPT correlations were assessed using a New Zealand database of 230 sites (199 in the greater Christchurch area) with co-located CPT soundings and boreholes with SPT testing. Category 1 simple linear relationships between q_c and N_{60} and a fitted coefficient based on soil type provided a poor fit of the NZ-based dataset for the soil type of sand identified by sampling. Category 2 correlations directly incorporating CPT soil behaviour type index, I_c , into their empirical functions and showed improvement over the Category 1 correlations with slightly higher R^2 , however estimates of the measured N_{60} values were over/under-estimated by more than 50% for over 47% of base dataset, with a greater tendency for over-prediction.

To further assess the influence of SPT-based measured N_{60} value, the CPT-based q_t and f_s , the bias between predicted and measured N_{60} values was used, and it declined with increasing SPT N_{60} which was in contrast with the trend variation of CPT-based parameters (i.e., q_t and f_s). The results showed that these empirical correlations generally should be applied with care beyond the region and soil types from which the correlations were developed. If applied elsewhere, these correlations should only be used to provide initial insight into site conditions and further in-situ testing is recommended.

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