Comparison of CPT-V_s Relations Developed for Loess and General Christchurch New Zealand Soils Using SCPTu

Christopher R McGann, Brendon A Bradley & Seokho Jeong
Department of Civil & Natural Resources Engineering – University of Canterbury, Christchurch, New Zealand

ABSTRACT
Seismic piezocone (SCPTu) data compiled from loess soil sites in the greater Christchurch, New Zealand area are used with multiple linear regression to develop an empirical correlation for predicting shear wave velocity (V_s) from cone penetration test (CPT) data. The performance of the model is assessed through analysis of the variation in prediction bias with different CPT parameters and through comparisons of measured and predicted V_s profiles. Comparisons with the recently-developed Christchurch-specific general soil CPT-V_s correlation show that this general soil correlation (based on alluvial, marine, estuarine, and peat/swamp soils) significantly underpredicts the V_s of the loess soils, likely due to the cemented nature of these deposits, thus demonstrating the need for the loess-specific correlation presented here.

1. INTRODUCTION

A significant portion of the recovery in Christchurch, New Zealand following the events of the 2010-2011 Canterbury earthquake sequence (Bradley and Cubrinovski 2011; Bradley 2012) has involved the characterization of near-surface soils. Thousands of soil characterization tests, such as standard penetration tests (SPT) and cone penetration tests (CPT), have been performed for various reasons throughout the greater Christchurch urban area and made available through the New Zealand Geotechnical Database (NZGD 2014) project (formerly Canterbury Geotechnical Database).

Seismic CPT (SCPTu) data in the region were used to develop a Christchurch-specific correlation between CPT data and soil shear wave velocity (CPT-V_s correlation) by McGann et al. (2015a,b). This empirical relation was based on the 86 SCPT sites shown in Figure 1 (as red markers) that are located throughout the Christchurch area. Previous studies show that the Christchurch-specific CPT-V_s model is generally applicable to the alluvial, marine, estuarine, and peat/swamp soils that comprise the soil deposits (majority of sites informing the model were alluvial or marine soils) in Christchurch and the surrounding Canterbury plains (McGann et al. 2015a,b,c). This general soil applicability does not appear to extend to

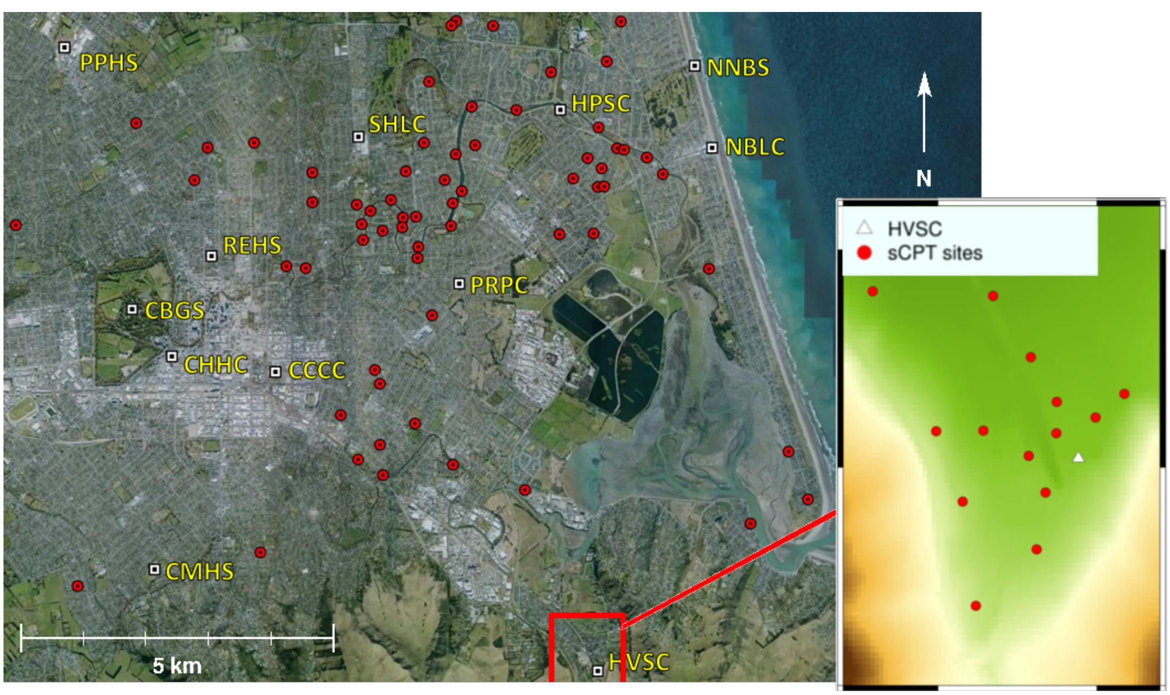

Figure 1. SCPTu sites used in alluvium CPT-Vs model (red dots in main map) and Heathcote Valley SCPTu sites (inset at right). Locations of Christchurch strong motion stations indicated for reference.

the loess deposits located on the boundaries and within the valleys of the Port Hills located directly south of Christchurch city. In particular, previous comparisons between surface wave-derived V_s and CPT-derived V_s profiles at the Heathcote Valley Primary School (HVSC) strong motion station suggest that the general Christchurch-specific correlation is not applicable to the Port Hills loess soils, as it significantly underpredicts the V_s of the primarily-loess soil profile at this site (McGann et al. 2015c). This paper uses a new set of Heathcote Valley SCPTu to further examine the applicability of the Christchurch specific general soil CPT-V_s model to these loess soil sites and to develop a new loess-specific CPT-V_s correlation.

2. EVALUATION OF LOESS SCPT MEASUREMENTS

As part of site characterization efforts in support of ongoing site amplification effects studies (Jeong and Bradley 2015), fourteen SCPTu were obtained in varying locations throughout the upper part of the Heathcote Valley as shown in Figure 1. These subsurface explorations were performed with seismic piezocone devices collecting tip resistance (q_c), frictional resistance (f_s), and dynamic pore pressure (u) on 2 cm intervals, and taking pseudo-interval travel time measurements at approximately 0.5 m intervals. Shear wave velocities were obtained from the travel time data using the cross-over method (Robertson et al. 1986). The following sections discuss comparisons between the V_s profiles obtained from these SCPTu and profiles predicted using the general soil Christchurch-specific CPT-V_s correlation of McGann et al. (2015a,b), in terms of both specific site profiles and the bias observed in the model predictions.

2.1 Comparison of specific V_s profiles

Figures 2 to 4 present summaries of the SCPTu data collected at three of the fourteen considered Heathcote Valley sites. These plots show q_c, f_s, and u as measured by the SCPTu and the soil behaviour type index, I_c, (Robertson and Wride 1998; Robertson 2009), alongside

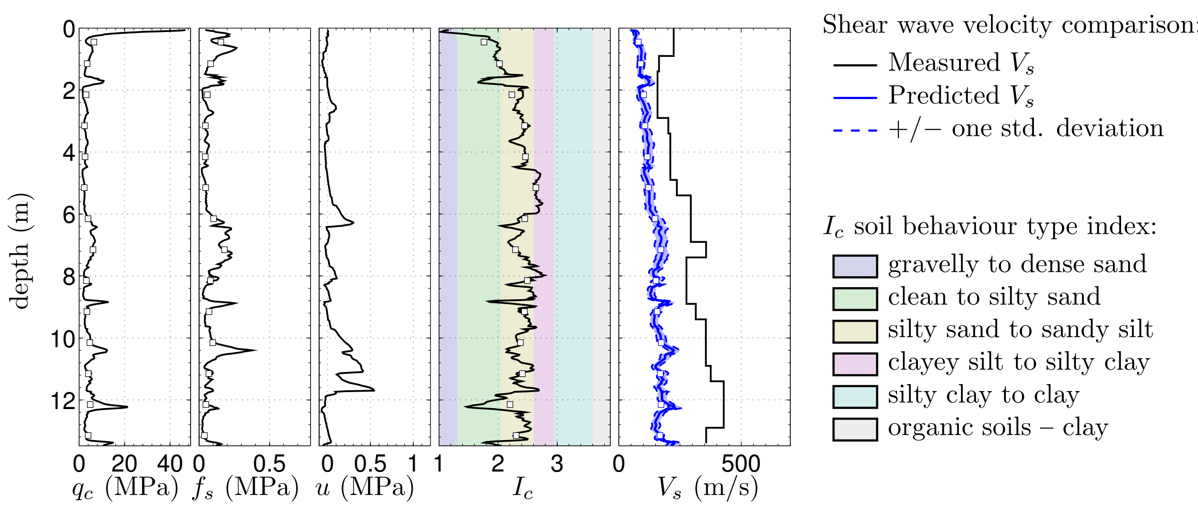

Figure 2. CPT-V_s profile summary for site SCPT1. Predicted V_s from general soil CPT-V_s model.

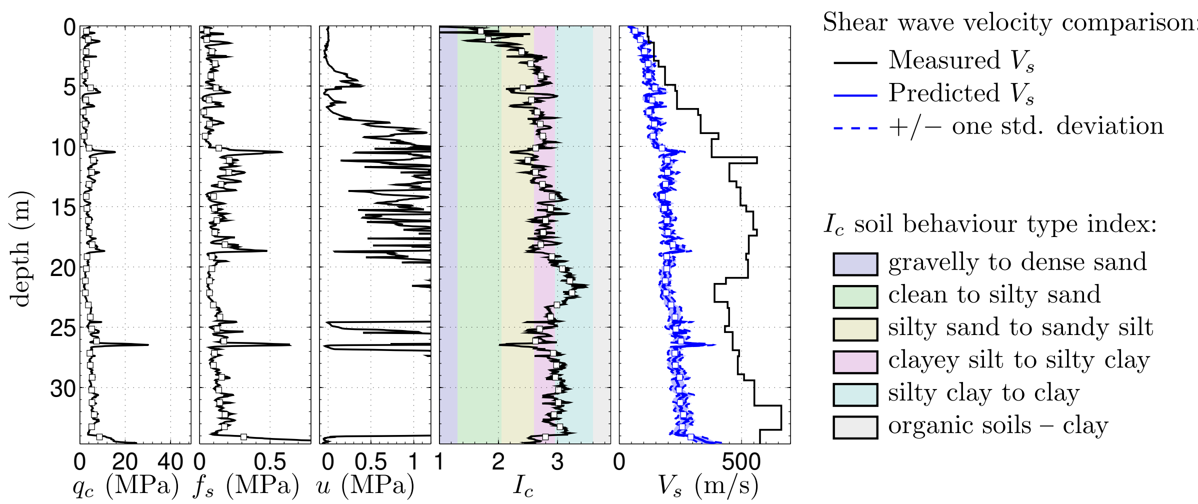

Figure 3. CPT-V_s profile summary for site SCPT3. Predicted V_s from general soil CPT-V_s model

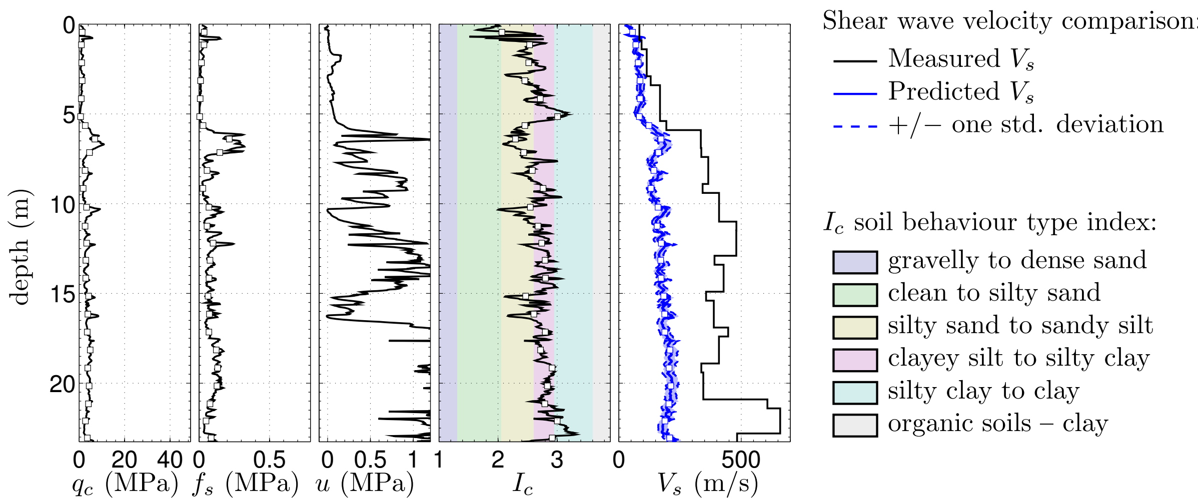

Figure 4. CPT-V_S profile summary for site SCPT8. Predicted V_s from general soil CPT-V_s model

the measured V_s profile and the V_s profile predicted by the general soil CPT-V_s model. The plus/minus one standard deviation model predictions are included for reference. As shown, the soil profiles at these sites are characterized by relatively low tip resistances (generally < 10 MPa), particularly at depths beyond the first 1-4 m below the surface. The Heathcote sites are also characterized by I_c values predominantly in the silty sand to sandy silt (2.05 < I_c < 2.6) and clayey silt to silty clay (2.6 < I_c < 2.95) zones. This is in contrast to the general soil sites used to develop the CPT-V_s model of McGann et al. (2015a,b), which were primarily composed of soil behaviour types in the clean to silty sand (1.31 < I_c < 2.05) zone

In addition to these differences in soil composition, it is clear from Figures 2 to 4 that the general soil CPT-V_s model is not applicable to these sites. With the exception of depths in the immediate near surface, where the measured and predicted V_s are similar (likely due to crustal layers of soils similar to those located in the majority of Christchurch), the general soil CPT-V_s model tends to underpredict the measured V_s profiles at all three sites shown, and all of the other Heathcote Valley SCPTu sites not shown here.

2.2 Prediction bias for general soil CPT-V_s model at loess sites

In order to quantify the prediction bias, Figure 5 shows the residuals between the general soil CPT-V_s prediction and the SCPTu measurements for all 14 Heathcote Valley sites. The residuals are defined as

$$\varepsilon = [\ln(V_{sM}) - \ln(V_{sP})]/\sigma_{\ln VsP} \qquad [1]$$

where V_{sM} is the measured shear wave velocity, V_{sP} is the predicted shear wave velocity, and $\sigma_{\ln VsP}$ is the standard deviation in the natural logarithm of V_{sP} as reported by McGann et al. (2015b). The solid and dashed lines in Figure 5 show the moving average with 95% confidence intervals. As shown, the general soil model systematically underpredicts the V_{sM} values (positive bias) and, with the exception of I_c, the average bias trend is relatively even with changes in the considered CPT parameters. In the case of I_c, it appears that there is a general trend of increasing underprediction (higher positive bias) with increasing I_c value.

There are several potential mechanisms that likely contribute to the inapplicability of the general soil CPT-V_s model to the Heathcote Valley sites, though further research is required to isolate the precise mechanisms. Based on available evidence, the Port Hills loess soils are very different in composition and behaviour relative to the soils in the Canterbury plains. This suggests fundamentally different relationships between initial stiffness (V_s) and shear strength (q_c, f_s) for these soil types.

Furthermore, laboratory tests on Port Hills loess soils (not from Heathcote Valley specifically, but presumably similar soils) by Glassey (1986) and McDowell (1989) show that the shear strength increases with moisture-curing, which suggests cementation, though there is no direct evidence of cementation in the Heathcote Valley soils. Glassey (1986) also demonstrated significant strength increases in air-dried samples of Port Hills loess soils consistent with capillary action and negative pore pressures. This level of strength increase due to capillary water may not be found in the general Christchurch soils.

3. DEVELOPMENT AND ASSESSMENT OF LOESS-SPECIFIC CPT-V_S CORRELATION

The differences observed between the measured and predicted V_s values discussed in the previous sections motivated the development of a separate loess-specific CPT-V_s correlation for use in the Heathcote Valley and other areas of the Port Hills. In the absence of borehole data, or previous experience, indicating the presence of loess soils at a particular site, it is recommended that this new CPT-V_s model should be applied in regions classified as loess soils in the QMAP surficial geologic mapping of Forsyth et al. (2008).

Multiple linear regression analysis for the Heathcote valley sites was performed using the same functional form and general procedure used by McGann et al. (2015a,b)

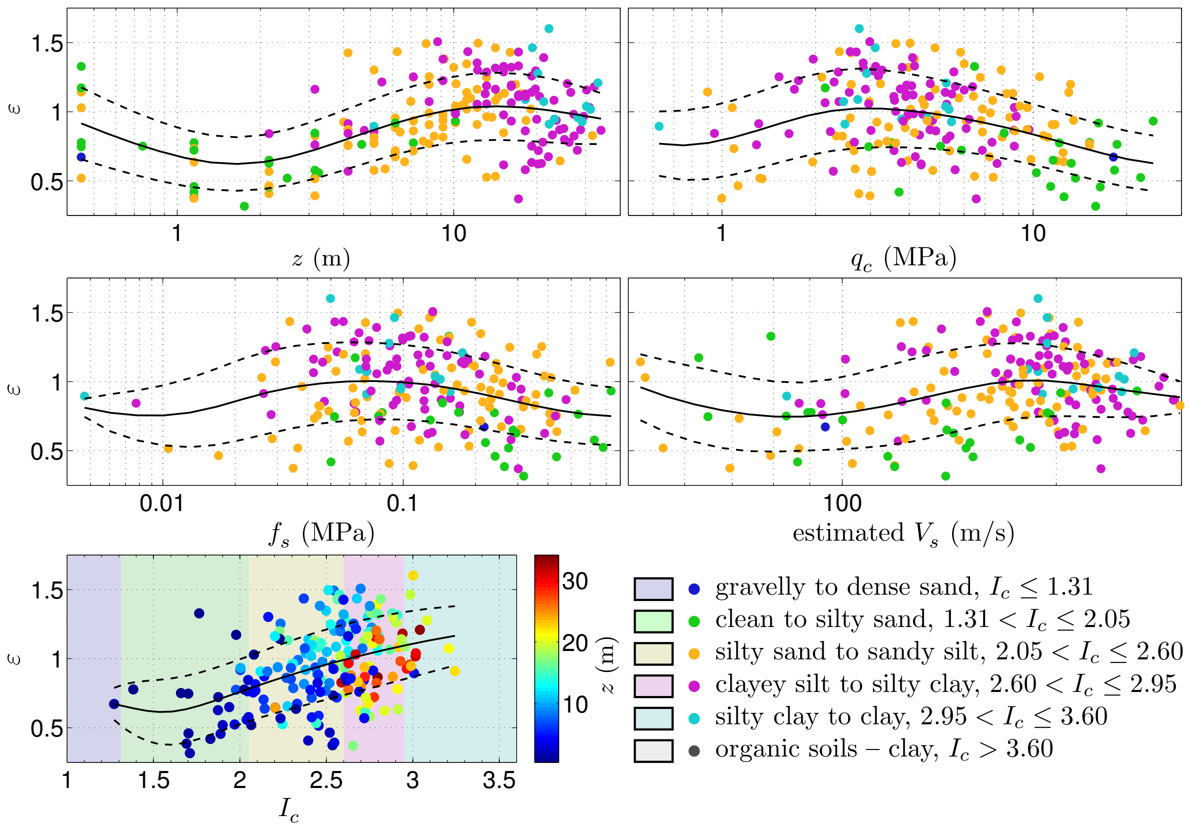

Figure 5. Variation of residuals between general soil CPT-V_s model prediction and Heathcote SCPTu measurements with various CPT parameters. Marker colour notes I_c (or depth, z) as indicated

to create the Christchurch-specific general soil CPT-V_s model. The following loess-specific CPT-V_s empirical prediction equation was obtained through this process:

$$V_s(z) = 104.4\, q_t(z)^{0.0149} f_s(z)^{0.0793} z^{0.321} \qquad [2]$$

where q_t, and f_s are the pore pressure corrected tip resistance and frictional resistance, respectively, at depth z (q_t, and f_s in kPa; z in m; V_s in m/s). Similar to the general soil model, the use of q_c or q_t makes little difference in the overall predictive capability of the loess-specific model, but q_t is preferred if available. As with the general soil CPT-V_s model, this new model considers non-constant conditional variance with depth to account for the generally higher variability in the upper 5 m and lower variability at greater depths. The piecewise standard deviation is given by:

$$\sigma_{\ln(V_s)} = \begin{cases} 0.3135 & \text{for } z \le 5 \text{ m} \\ 0.4180 - 0.0209z & \text{for } 5 < z < 10 \text{ m} \\ 0.2090 & \text{for } z \ge 10 \text{ m} \end{cases} \qquad [3]$$

3.1 Bias in loess-specific model predictions

Figure 6 shows the variation in the bias for the loess-specific CPT-V_s model as plotted against the same set of CPT-based parameters as Figure 5. The bias shown here is computed following the form of Equation 1 using the loess-specific V_s prediction and associated standard deviation provided in Equations 2 and 3, respectively. Again, the solid and dashed black lines indicate the moving average with 95% confidence intervals. As shown, the average bias in the new model is nearly zero for most of the considered CPT parameter values and ranges. The exceptions are overpredictions for very shallow depths (z < 2-3 m), very low tip and frictional resistances, and for the lower end of the estimated V_s range.

Interestingly, there is no corresponding zone of I_c that results in a model overprediction, as the average bias is essentially zero for all I_c values. The regions of overprediction could correspond to portions of the soil profile that consist of lower percentages of loess material, and therefore are not well represented by the loess-specific CPT-V_s model. This hypothesis is supported by the observation that at the shallow depths where the model tends toward overprediction, the measured values tend to coincide with the lower predicted V_s values, thus providing evidence for a non-loess crust driving some of the bias shown in Figure 6. It is also worth noting that both the CPT and shear wave velocity measurements at very shallow depths are generally much less reliable than deeper measurements. Thus, factors related to the tests themselves could also contribute to some of the evident bias in the model predictions.

Despite the minor overpredictions for shallow depths, a comparison of Figures 5 and 6 clearly demonstrates the gain in predictive ability provided by the new loess-specific CPT-V_s correlation for these Heathcote Valley

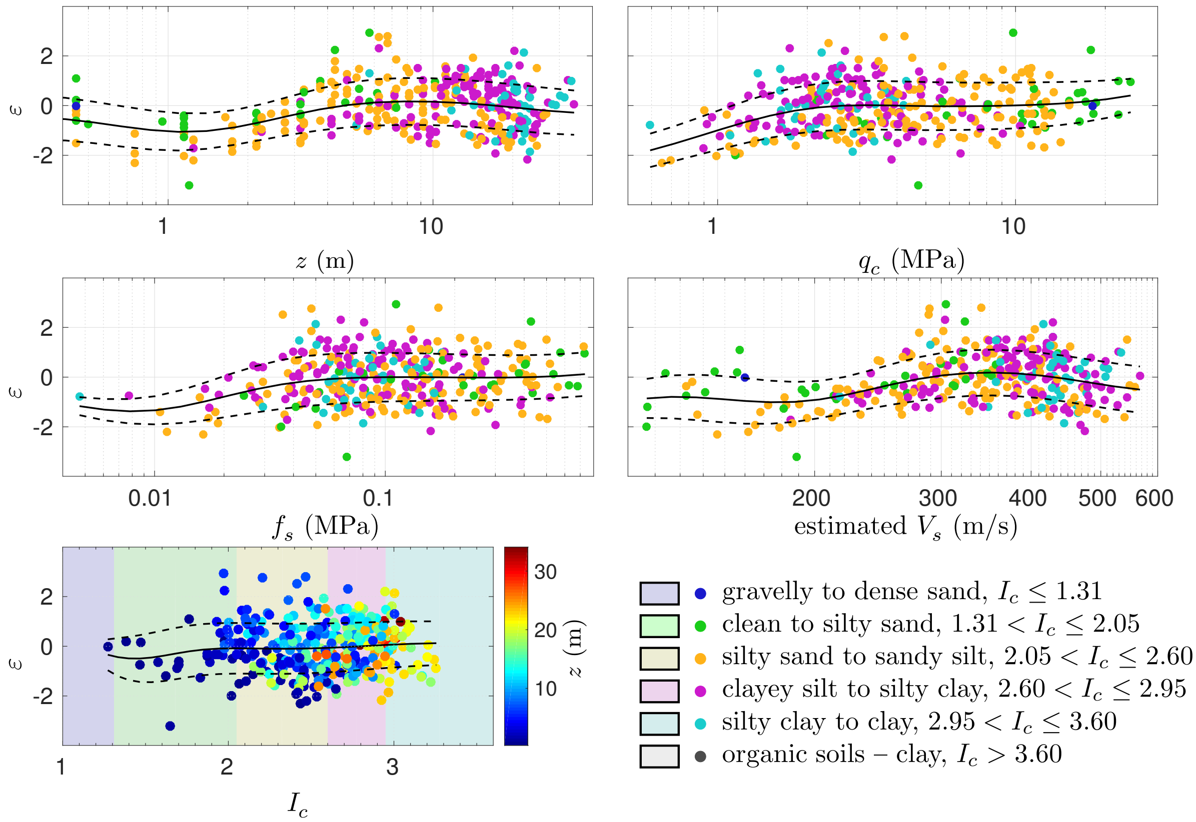

Figure 6. Variation of residuals between loess CPT-V_s model prediction and Heathcote SCPT measurements with various CPT parameters. Marker colour notes I_c (or depth, z) as indicated.

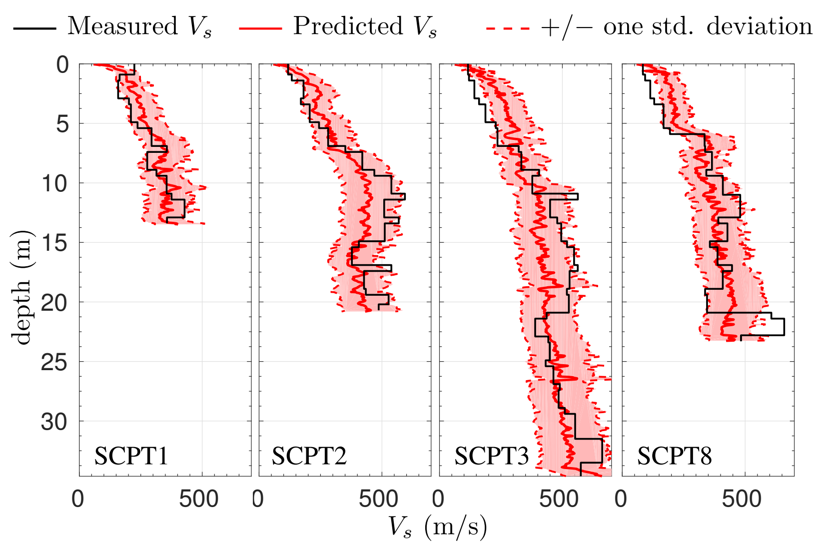

Figure 7. Comparison of loess-specific CPT-V_s and measured V_s profiles for four sites.

sites. The average bias for the new correlation is essentially zero, where the bias for the general soil CPT-V_s model tends toward systematic underprediction. Additionally, the clear soil behaviour type index dependence displayed by the general soil CPT-V_s model (shown in the I_c subplot of Figure 5) is not present in the new loess-specific CPT-V_s model. To further demonstrate the improved ability of the loess-specific CPT-V_s model to represent the shear wave velocity profiles of these Heathcote Valley sites, comparisons between the measured and predicted Vs profiles at specific sites are made and discussed in the next section.

3.2 Comparisons for specific V_s profiles

Figure 7 presents a comparison between the measured and predicted V_s profiles at four of the 14 Heathcote Valley SCPTu sites. This comparison is made in terms of the median prediction and the plus/minus one standard deviation predictions (shown as the solid and dashed red lines, respectively). Sites SCPT1, 3 and 8 are also shown in Figures 1 to 3 with the general soil CPT-V_s predictions. As shown in Figure 7, the V_s profiles predicted by the loess-specific model are much more similar to the measured profiles, and there is general agreement between the Vs profiles indicated by each approach. There is not a perfect correlation between the profiles shown, however, the measured profiles generally sit within the $\pm\sigma$ bounds for each case.

4. CONCLUSION

Comparisons between SCPTu-measured V_s at 14 sites in the Heathcote Valley area of Christchurch, New Zealand and V_s profiles predicted by a previously-developed Christchurch-specific general soils CPT-V_s correlation have demonstrated the non-applicability of the general soil model to the primarily loess soils in the Heathcote Valley. It is hypothesized that issues related to cementation and capillary action in the loess, and fundamental differences between the loess material and the soils described by the previous general soil model contribute to this non-applicability. The SCPTu data is used to develop a loess-specific CPT-V_s model for use in predicting soil V_s from CPT in the Heathcote Valley and other similar soil deposits in the Port Hills. Together, the Christchurch-specific general soil and loess-specific CPT-V_s models provide coverage of the primary soil types encountered in the Christchurch, New Zealand area, enabling V_s prediction from nearly any available CPT in the area.

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