Empirical Correlation for Estimating Shear-Wave Velocity from Cone Penetration Test Data for Banks Peninsula Loess Soils in Canterbury, New Zealand

Christopher R. McGann[1]; Brendon A. Bradley[2]; and Seokho Jeong[3]

Abstract: Seismic piezocone data obtained from Banks Peninsula loess soil sites in the Port Hills south of Christchurch, New Zealand, are used with multiple linear regression to develop a new Banks Peninsula loess-specific CPT-V_s correlation for predicting shear wave velocity (V_s) from cone penetration test (CPT) measurements. The need for this new correlation is demonstrated through comparisons with existing CPT-V_s models, including a recently developed Christchurch-specific general soils model, with the loess V_s measurements. It is shown that the existing general soil CPT-V_s models tend to systematically underpredict the loess V_s, and it is demonstrated that this underprediction is due to fundamental differences in how the properties of loess and general soil types affect both CPT measurements and shear-wave velocity, and that aging effects alone cannot account for the observed differences. **DOI: 10.1061/(ASCE)GT.1943-5606.0001926.** *© 2018 American Society of Civil Engineers.*

Author keywords: Shear-wave velocity; Loess soils; Aging effects; CPT-V_s models.

Introduction

A significant portion of the recovery in Christchurch, New Zealand, following the events of the 2010–2011 Canterbury earthquake sequence (Christophersen et al. 2013; Quigley et al. 2016) has involved the characterization of near-surface soils to understand geotechnical impacts on the built and natural environment. Tens of thousands of cone penetration tests (CPTs) have been performed throughout the greater Christchurch urban area and made available through the New Zealand Geotechnical Database (NZGD 2014) project (formerly the Canterbury Geotechnical Database). The availability of this unprecedented subsurface data set opens many possibilities for research that were not possible to address in the past, including the liquefaction hazard mapping by van Ballegooy et al. (2014) and Lacrosse et al. (2017), the lateral spreading work by Bastin et al. (2017) and Russell et al. (2017), and the assessment of the liquefaction potential index and CPT-based liquefaction evaluation by Maurer et al. (2014, 2015), among others.

In order to take further advantage of this unprecedented data set, seismic piezocone (SCPTu) data from the New Zealand Geotechnical Database (NZGD) 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). The SCPTu sites used to inform this model were located in a variety of surficial geologic regions and soil deposit types, and, in the absence of more direct measurements such as downhole, crosshole, or surface wave–V_s, the McGann et al. (2015b) model allows for an approximation of site-specific V_s profiles from any CPT for general soils in the Canterbury region. A follow-on study by McGann et al. (2015c) suggests that the applicability of the Christchurch-specific general soils model does not appear to extend to loess deposits located in the foothills and valleys of the Port Hills located south of Christchurch city. In particular, comparisons between surface wave–derived V_s and CPT-derived V_s profiles at the Heathcote Valley Primary School (HVSC) strong-motion station strongly suggest that the general soils correlation is not applicable to the loess soils, because it was found to significantly underpredict the V_s of the primarily loess soil profile at this site.

This paper uses a new set of SCPTu data obtained from 26 Banks Peninsula loess soil sites to further examine the applicability of the Christchurch-specific general soil CPT-V_s model, and other existing CPT-V_s models, to these loess sites, and ultimately to develop a new loess-specific CPT-V_s correlation. The SCPTu data set used in this study is presented and subsequently used to assess the applicability of several existing general soils CPT-V_s models to these loess soil sites through an examination of the bias observed in the model predictions. Several potential underlying reasons for the observed nonapplicability of these existing models are explored, including the effects of aging, cementation, capillary pressure, and generally incompatible expected soil behavior, leading directly to the development and evaluation of the new loess-specific CPT-V_s model from the loess SCPTu data.

SCPTu Data Sets

Fig. 1 shows the 86 SCPTu sites (circles) used by McGann et al. (2015a, b) to create the Christchurch-specific general soils CPT-V_s model. These 86 sites are located throughout the Christchurch area and distributed across the alluvial, marine/dune, estuarine, and peat/swamp surficial geologic units as shown. Previous studies (McGann et al. 2015a, b, c) showed that the Christchurch-specific

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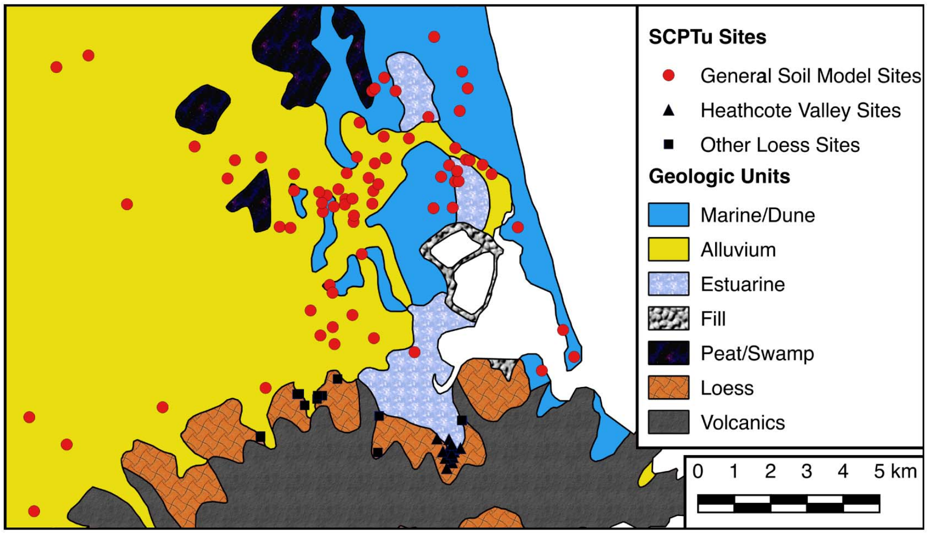

Fig. 1. SCPTu sites used to develop the general soil CPT-V_s model of McGann et al. (2015a, b) (circles) and loess SCPTu sites (triangles and squares) used to develop the loess-specific model. Surficial geologic QMAP units (Forsyth et al. 2008) shown for reference.

CPT-V_s model is generally applicable to the soil deposits in Christchurch and the surrounding Canterbury plains (the majority of sites informing the model were alluvial or marine soils). These studies also demonstrated the improved performance of this Christchurch-specific general soils model to Christchurch sites relative to the existing CPT-V_s relations developed from other global data sets by Andrus et al. (2007), Robertson (2009), and Hegazy and Mayne (2006).

Fig. 1 also shows 26 additional SCPTu sites obtained from loess deposits based on the QMAP classification of Forsyth et al. (2008). These 26 loess sites are further divided into two subgroups. The first 13 sites are located in the upper part of the Heathcote Valley (triangles in Fig. 1). These data were obtained as part of site characterization efforts in support of the site amplification effects studies of Jeong and Bradley (2017a, b). The second 13 sites (squares in Fig. 1) comprised loess soil SCPTu performed in support of post-earthquake assessments following the 2010–2011 Canterbury earthquake sequence, and these data were obtained from the New Zealand Geotechnical Database (NZGD 2014).

Fig. 2 shows the density distributions of the primary CPT-based parameters considered in this work: interval midpoint depth z, cone tip resistance q_c, sleeve frictional resistance f_s, measured V_s, and soil behavior type index I_c (Robertson and Wride 1998). As shown, the majority of the CPT data are for $z \leq 20$ m, $q_c \leq 5$ MPa, $f_s \leq 0.1$ MPa, and $I_c > 2$, and the measured V_s values primarily fall between 250 and 550 m/s. All of the sites are expected to consist of loess material over the entire range of CPT investigation depths with the exception of a crust in the uppermost 0.25–0.5 m at some sites, which as discussed later, falls in a range of depths that is excluded from the current study.

For both site subgroups, the subsurface explorations were performed with seismic piezocone devices collecting q_c, f_s, and dynamic pore pressure u at 2-cm intervals. For the 13 Heathcote Valley sites, the cones had two geophones spaced at 0.5-m intervals.

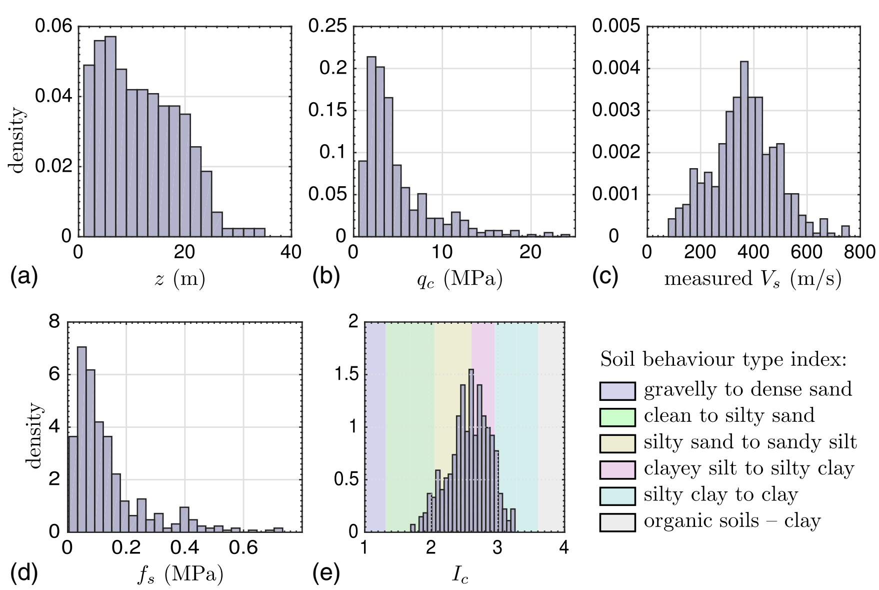

Fig. 2. Density distributions of CPT parameters in loess SCPTu data set: (a) midpoint depth, z; (b) q_c; (c) measured V_s; (d) f_s; and (e) I_c.

Shear-wave velocities at these sites were obtained using alternating true and pseudo-interval travel time measurements (Robertson et al. 1986) and the cross-over method (Campanella and Stewart 1992). At most sites, the measurements were performed every 2 m, resulting in alternating 0.5- and 1.5-m intervals, whereas, at other sites, the measurements were performed every 1 m, resulting in 0.5-m intervals. The travel time measurements were obtained and processed by Fugro Geotechnical NZ (Canterbury, New Zealand) and the results were provided as V_s profiles for each site. Further details, including the coordinates and refusal depths for these sites are available in Jeong and Bradley (2017a). For the remaining 13 sites not in Heathcote Valley, the cones had a single geophone and shear-wave velocities were obtained from pseudo-interval travel time measurements using the cross-over method at 1–2-m intervals. The V_s profiles at all sites are shown as part of a discussion later in this paper (Figs. 11 and 12). There are no significant or systematic differences between the two subsets of data; however, it appears that the sites with 0.5-m measurement intervals are particularly sensitive to the travel time interpretation (e.g., SCPT11 shown in Fig. 11), and it is likely that 0.5 m is too small an interval for SCPT velocity measurements.

Applicability of General Soil CPT-V_s Models to Loess Sites

The Christchurch-specific general soils CPT-V_s model of McGann et al. (2015a, b) provides a median prediction of shear-wave velocity from the following function:

$$V_s = 18.4 q_c^{0.144} f_s^{0.083} z^{0.278} \tag{1}$$

where z is in meters, q_c and f_s are in kilopascals, and V_s is in meters per second.

The functional form of this model was chosen based on an examination of several trial forms based on existing CPT-V_s correlations, and the model was developed with consideration for nonconstant variance with depth, leading to a piecewise standard deviation given as

$$\sigma_{\ln(V_s)} = \begin{cases} 0.162 & \text{for } z \leq 5 \text{ m} \\ 0.216 - 0.0108z & \text{for } 5 \text{ m} < z < 10 \text{ m} \\ 0.108 & \text{for } z \geq 10 \text{ m} \end{cases} \tag{2}$$

Figs. 3 and 4 show examples of the SCPTu data collected at two of the Banks Peninsula loess sites as compared with the V_s profile predicted by the McGann et al. (2015b) general soils model of Eq. (1). These plots also show the profiles of q_c, f_s, u, and I_c at these sites, and the plus/minus one standard deviation predictions ($\pm\sigma$) of V_s computed from Eq. (2) were included for reference. It is clear from Figs. 3 and 4 that the general soil CPT-V_s model is not applicable to these sites. The results shown here were typical for the full data set. In all cases, the general soil CPT-V_s model tends to underpredict the measured V_s profiles to varying degrees with depth, and the measured profiles were far beyond the $\pm\sigma$ bounds of the predicted profiles. For example, at site SCPT2, shown in Fig. 3, the measured V_s is more than 10 standard deviations above the median prediction at a depth of 11 m.

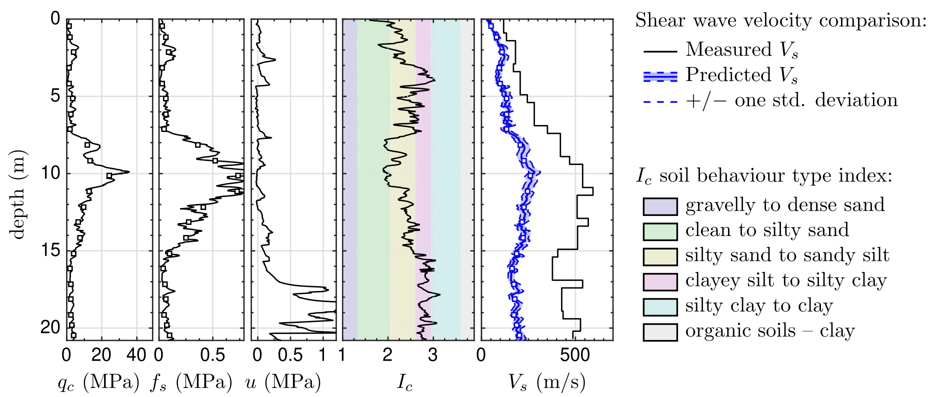

Fig. 3. CPT-V_s profile summary for Site SCPT2 showing the CPT-V_s profile from the general soils model and the measured V_s profile.

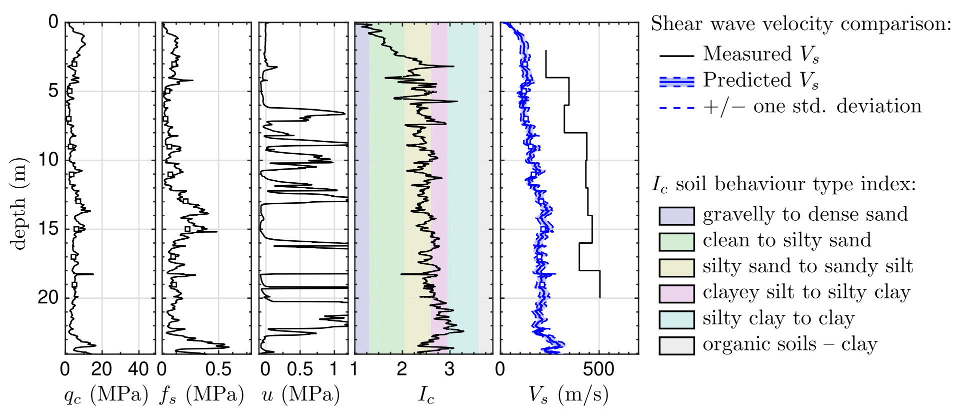

Fig. 4. CPT-V_s profile summary for Site RSN-02 showing the CPT-V_s profile from the general soils model and the measured V_s profile.

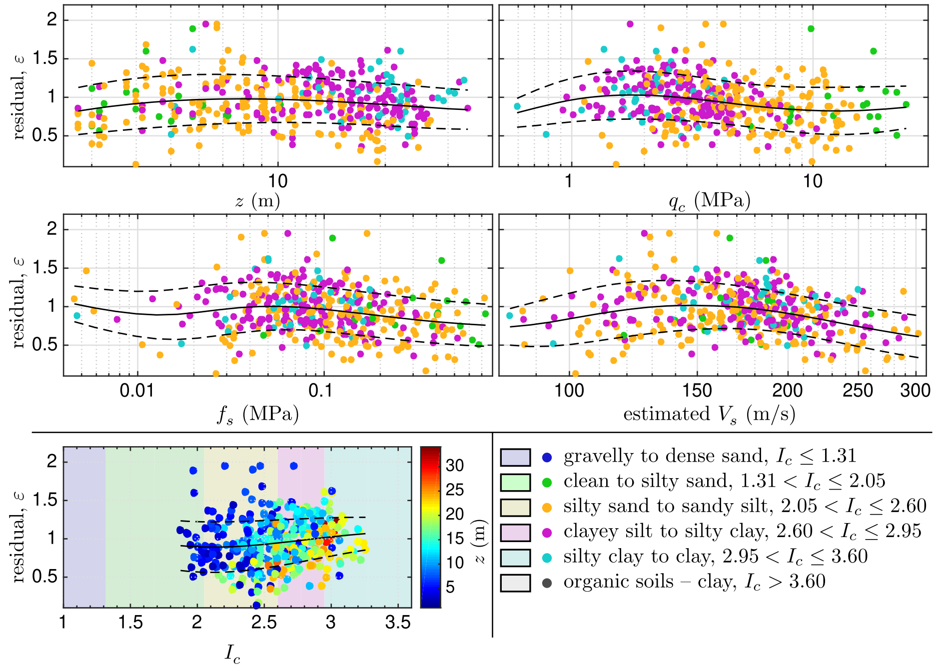

Fig. 5. Variation in residuals between general soil CPT-V_s model of McGann et al. (2015b) and loess soil SCPTu measurements with various CPT-based parameters.

In order to quantify the prediction bias evident in Figs. 3 and 4 (which are representative of all 26 loess sites), Fig. 5 shows the residuals between the general soil CPT-V_s predictions and the SCPTu measurements for all 26 loess sites. The residuals are defined as

$$\varepsilon = \frac{\ln(V_{sM}) - \ln(V_{sP})}{\sigma_{\ln(V_{sP})}} \tag{3}$$

where V_{sM} = measured shear-wave velocity; V_{sP} = predicted shear-wave velocity; and $\sigma_{\ln(V_{sP})}$ = standard deviation in the natural logarithm of V_{sP} computed from Eq. (2).

The solid and dashed lines in Fig. 5 show the moving average with 95% confidence intervals. As shown, the general soils model systematically underpredicts the V_{sM} values (positive bias), and the average bias is relatively even with changes in all of the considered CPT parameters. The estimated V_s plot shows a slight tendency for less underprediction at the upper and lower ends of the V_s range, but this effect is minor. The even distribution of bias in Fig. 5 is indicative of a fundamental inability of the general soils model to represent the shear-wave velocity of the loess sites rather than a specific deficiency for certain conditions as would be suggested by significant variations in the average bias trends.

Other CPT-V_s Models

Before exploring the potential mechanisms behind the systematic differences between the shear-wave velocities measured at the Banks Peninsula loess sites and those predicted by the McGann et al. (2015b) Christchurch-specific CPT-V_s model, it is of interest to gauge the applicability of other existing CPT-V_s models to this data set. Fig. 6 compares the measured and predicted V_s values for the models of Andrus et al. (2007), Robertson (2009), and Hegazy and Mayne (2006) alongside the corresponding comparison for the McGann et al. (2015b) general soils model.

As shown, the performance of the Andrus et al. (2007) and Robertson (2009) models is similar, with both models tending toward systematic underprediction of the loess V_s. The degree of underprediction in these two models is less than that in the McGann et al. (2015b) model, but the difference is not significant. The Hegazy and Mayne (2006) model displays more balance between under- and overprediction, although the majority of the data are still underpredicted. This model also displays the most variance, with the wide spread of the data points in stark contrast to the tighter groupings displayed by the other three models. Based on this analysis, none of these models are particularly applicable to the loess data set. The Robertson (2009) model displays perhaps the best performance of the four, but it is still heavily biased toward underprediction.

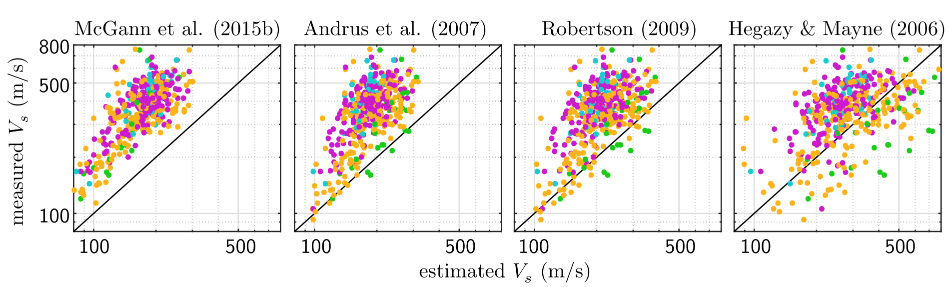

Fig. 6. Comparison of existing CPT-V_s model estimates and loess soil SCPTu measurements.

Potential Mechanisms Leading to Observed Model Bias

Soil Composition

There are several potential mechanisms that likely contribute to the inapplicability of the general soil CPT-V_s model to the loess soil sites. As shown in Figs. 3 and 4, the soil profiles at these sites are characterized by relatively low tip resistance (generally <10 MPa), particularly at depths beyond the first 1–4 m below the surface. These loess sites are also characterized by I_c values predominantly in the silty sand to sandy silt zone ($2.05 < I_c < 2.6$) and the clayey silt to silty clay zone ($2.6 < I_c < 2.95$). This is in contrast to the general soil sites used to develop the CPT-V_s model of McGann et al. (2015a, b), which generally displayed higher tip resistance at depth and were primarily composed of soil behavior types in the clean to silty sand zone ($1.31 < I_c < 2.05$). For further information, all 86 SCPTu profiles used in the development of the general soils model are available in McGann et al. (2014).

The fundamental differences in soil type and expected behavior between the deposit types comprising the general soils model data set and the loess deposits are further demonstrated in Fig. 7, where the two data sets are plotted in the normalized soil behavior type classification (SBTn) chart of Robertson (1990). In this chart, the area centered around a diagonal line passing from the upper left to the lower right corner is indicative of normally consolidated soil behavior; the increasing distance away from this line toward the upper right corner is indicative of increasing overconsolidation ratio, age, or cementation. As shown in Fig. 7, in addition to the clear differences in soil behavior type between the two data sets, the loess site SCPTu data are generally situated closer to the upper right corner than the centrally located general soils data, suggesting effects related to aging, cementation, or overconsolidation that are not prevalent in the general soils data.

Aging Effects

As discussed in McGann et al. (2015a), all of the SCPTu data used in the development of the Christchurch-specific general soils model were obtained after the September 4, 2010, Darfield earthquake, and it is likely that the majority of the data set represents soil that was critically disturbed in one or more events in the Canterbury sequence. The loess soil SCPTu were also performed following the earthquake sequence and, although the loess sites were essentially subjected to the same set of earthquakes as the general soil sites, it is possible that aging effects may not have been wiped out due to the absence of liquefaction in this material. To investigate this further, age-corrected V_s profiles were determined at the loess sites using estimated depositional ages and the age correction scheme developed by Andrus et al. (2009) for correcting the liquefaction resistance of aged sands.

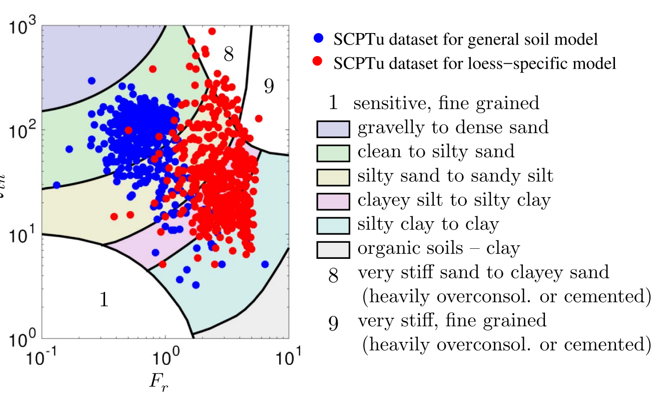

Fig. 7. SBTn chart for general and loess soil SCPTu data sets.

According to Brown and Weeber (1992), radiocarbon dating of a moa bone found at a 10-m depth in a deposit of Banks Peninsula loess suggests that approximately 0.36 mm of new loess material is deposited each year on northwest-facing slopes in the Port Hills. This 0.36-mm/year value is used to estimate depth-dependent age profiles for all of the loess SCPTu sites (for example, this assumption yields ages of 2.8-, 5.6-, 13.9-, 27.8-, and 55.6-k years for depths of 1, 2, 5, 10, and 20 m, respectively). The estimated depositional ages are fed into the model of Andrus et al. (2009), who provided a relationship for the time in years since initial deposition or critical disturbance, t, and the measured-to-estimated shear-wave velocity ratio, R_{V_s}, given as

$$R_{V_s} = 0.0820 \log_{10} t + 0.935 \tag{4}$$

Age-corrected V_s profiles are then determined by dividing the SCPTu V_s measurements by the computed R_{V_s} values at each site. The age-corrected V_s profiles determined in this fashion are plotted alongside the original measurements and the Christchurch-specific general soils CPT-V_s model predictions for five sites in Fig. 8 (results shown are typical of the full data set). As shown, the age-corrected profiles are closer to the CPT-V_s model predictions, particularly in the uppermost 4–6 m where the difference between the measured and estimated V_s is already small relative to that at deeper locations; however, there is still a systematic underprediction evident in the general soils model profiles.

The persisting differences between the V_s profiles estimated by the general soils model and the age-corrected loess measurements suggest that the Andrus et al. (2009) model may not be fully applicable to the loess material, or that some mechanisms beyond age (e.g., cementation) are contributing to the differences evident in Figs. 7 and 8. The degree of microstructure effects in a given soil can be assessed using the normalized small-strain rigidity index, K_G^*, of Robertson (2016), computed as

$$K_G^* = \frac{G_0}{q_n} (Q_{tn})^{0.75} \tag{5}$$

where $G_0 = \rho V_s^2$ = small strain shear modulus determined from the measured shear-wave velocity; $q_n = q_t - \sigma_v$ = net cone tip resistance; and Q_{tn} = normalized cone tip resistance (Robertson 2009).

Schneider and Moss (2011) showed that most young and uncemented sands (i.e., little or no microstructure) have $100 < K_G^* < 330$, and it follows that soils with $K_G^* > 330$ tend to have significant microstructure, with increasing significance with increasing K_G^*. Fig. 9 plots the loess and general soils data sets on the normalized rigidity index chart ($Q_{tn} - I_G$) chart, where $I_G = G_0/q_n$) proposed by Robertson (2016). As shown, the two data sets plot in significantly different regions. The general soils data set falls primarily in the range of $100 < K_G^* < 330$, indicating little or no microstructure for these predominantly alluvial sites, whereas nearly all of the loess data points have $K_G^* > 330$, indicating that microstructure is present for the loess soils. These results provide further evidence as to the inapplicability of the general soils model and other CPT-V_s models to the loess sites, as correlations developed for soils without microstructure should not be expected to apply to soils with microstructure.

Laboratory tests on Banks Peninsula loess soils by Glassey (1986) and McDowell (1989) provide further support for these observations. They show that the shear strength of the loess soil increases with moisture curing, which suggests that cementation

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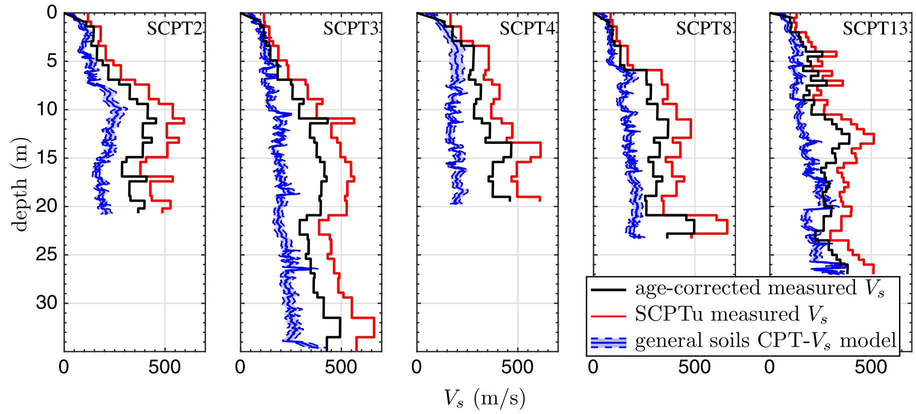

Fig. 8. Age-corrected measured V_s profiles compared with Christchurch-specific general soils CPT-V_s model prediction and original measurements.

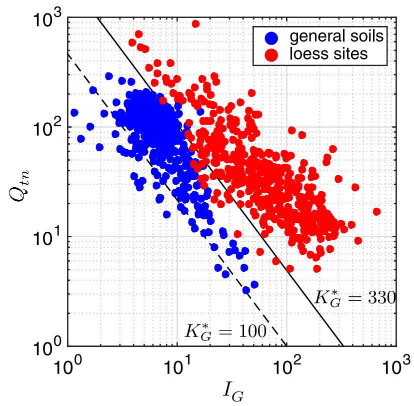

Fig. 9. Normalized rigidity index chart for general and loess soil SCPTu data sets.

effects can be significant in this material. Although there is no direct evidence of cementation at the 26 tested loess sites, Fig. 9 shows that cementation was almost certainly not present at any of the 86 general soil sites, and thus any degree of cementation present at the loess sites could have led to the observed differences in the V_s values. Glassey (1986) also documented significant strength increases in air-dried samples of Port Hills loess soils that are consistent with capillary action and negative pore pressures. This level of strength increase due to capillary water is similarly unlikely to be present in the primarily alluvial and marine Christchurch soils represented by the general soils model and could be further driving the differences evident in the measured and estimated shear-wave velocities.

Development and Assessment of a Loess-Specific CPT-V_s Model

The compositional and behavioral differences between the loess and general soils evident in Figs. 7 and 8, along with the properties of the Port Hills loess indicated by the laboratory work of Glassey (1986) and McDowell (1989), are significant evidence for the presence of fundamentally different relationships between initial shear stiffness (linked to V_s) and shear strength (linked to q_c, f_s) for these soil types. Such differences would naturally lead to the inapplicability of the general soils CPT-V_s model to the loess sites. Due to this systematic inapplicability of the existing Christchurch-specific model to the Port Hills loess sites, and the corresponding inapplicability of the existing CPT-V_s models of Andrus et al. (2007), Robertson (2009), and Hegazy and Mayne (2006) as shown in Fig. 6, a new and distinct loess-specific CPT-V_s correlation is developed for use in the loess soil–dominated areas of the Port Hills and the Banks Peninsula. In the absence of borehole data or previous experience, it is recommended that this new CPT-V_s model be applied in regions of Canterbury classified as loess soils in the QMAP surficial geologic mapping of Forsyth et al. (2008), and that the general soils CPT-V_s be applied to CPTs located in other surficial geologic units in Canterbury.

This new correlation is developed using multiple linear regression with the same functional form and general procedure used by McGann et al. (2015b) to create the Christchurch-specific general soil CPT-V_s model. The following loess-specific median CPT-V_s empirical prediction equation was obtained through this process:

$$V_s = 103.6 q_t^{0.0074} f_s^{0.130} z^{0.253} \tag{6}$$

where q_t and f_s = pore pressure–corrected tip resistance and sleeve frictional resistance, respectively, at depth z (q_t and f_s in kPa; z in m; V_s in m/s).

The loess model is presented in terms of q_t; however, just as was observed for the general soils model in McGann et al. (2015b), the use of the uncorrected or pressure-corrected tip resistance (q_c or q_t) made a negligible difference in the loess-specific model predictions. In the case under study, this effect is exacerbated by the small exponent on tip resistance relative to those for f_s and depth. As with the general soils model, the new loess-specific model is presented here in terms of nonnormalized parameters measured directly by the CPT because of the region-specific nature of the model and the relatively uniform conditions in this region, and so that the need to rely on parameters not measured directly by the CPT, such as soil unit weight, in order to estimate V_s could be eliminated.

One key difference between the methodology used to develop the two models is consideration of conditional variance with depth. During the development of the general soils model, it was found that the inclusion of nonconstant depth variance in the regression resulted in a more even distribution of bias with depth. In the case of the loess-specific model, it was found that consideration of constant conditional variance with depth led to the most even distribution of bias in the model. The standard deviation in the loess model thus becomes constant with depth:

$$\sigma_{\ln(V_s)} = 0.2367 \tag{7}$$

A comparison of the model coefficients in the loess-specific model of Eq. (6) and the general soils model of Eq. (1) indicates some interesting features of the strength-to-stiffness ratios for the materials used to develop each correlation, particularly because the same units are used for all terms in both models, and q_c f_s also share the same units. First, the exponents on the depth term are reasonably similar, 0.253 for Eq. (6) and 0.278 for Eq. (1), indicating that the dependence of V_s on depth or overburden pressure is similar, thus emphasizing the other factors as key to the significant differences in shear-wave velocity for the two material databases. The first such factor is indicated by the much larger leading coefficient (103.6) for the loess-specific model relative to the general soils case (18.4). Based on the work of Andrus et al. (2007, 2009), this leading coefficient largely accounts for effects related to aging. As shown in the previous section, attempting to account for aging effects based on the Andrus et al. (2009) approach did not fully account for the differences between the general soils model predictions and loess soil measurements; thus, it is hypothesized that cementation in loess may be a significant driver of the increased V_s indicated by the much larger leading coefficient in the loess model. The second such factor is indicated by the relative importance of the tip and frictional resistances in each model. In the general soils model, the exponent for q_c is much larger than that for f_s, indicating that for these general Canterbury soils, V_s is more strongly correlated with tip resistance than frictional resistance. As the general soils data are largely characterized by clean to silty sands (Fig. 7), this matches expectations. In contrast, the loess-specific CPT-V_s model is much more strongly correlated with f_s. In fact, the exponent on q_t is so low that tip resistance could be left out entirely and the model predictions would not be changed to a significant degree.

A final difference between the two models is the that the variance in the loess-specific model is quite a bit larger than in the general soils model. This increased variance is due in part to the decision to use unaltered measured V_s profiles in model development despite evidence of potential interpretation issues (particularly for some Heathcote Valley sites, as will be seen in Fig. 11). Sensitivity studies using manually smoothed measured V_s profiles showed that, whereas the variance in the model prediction was reduced when the large velocity swings were removed, the median predicted V_s profiles were not significantly changed. It was decided that the best approach was to use the unaltered data and live with a larger variance, rather than use altered data with a potential false sense of accuracy and precision.

Bias in Loess-Specific CPT-V_s Model Predictions

The bias in the new loess-specific model is computed following the form of Eq. (3) using the loess-specific V_s prediction and associated standard deviation provided in Eqs. (6) and (7), respectively. Fig. 10 shows the variation in the bias for the loess-specific CPT-V_s model plotted against the same set of CPT-based parameters shown in Fig. 5. Again, the solid and dashed black lines indicate the moving average with 95% confidence intervals. As shown in Fig. 10, the average bias in the new model is essentially zero across all of the considered CPT parameter ranges. The exceptions to this zero-bias average trend are the slight tendencies for overpredictions at very shallow depths ($z < 2$–3 m), at very low cone tip resistances ($q_c < 1$ MPa), and at the lower end of the estimated V_s range ($V_s < 250$ m/s).

Interestingly, there is no corresponding zone of I_c where the average trend indicates a model overprediction or underprediction, as the average bias is essentially zero for all I_c values. The regions of overprediction may correspond to portions of the soil profile that consist of lower percentages of loess material and therefore may 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 nonloess crust driving some of the bias shown in Fig. 10. It is also worth noting that both the CPT and shear-wave

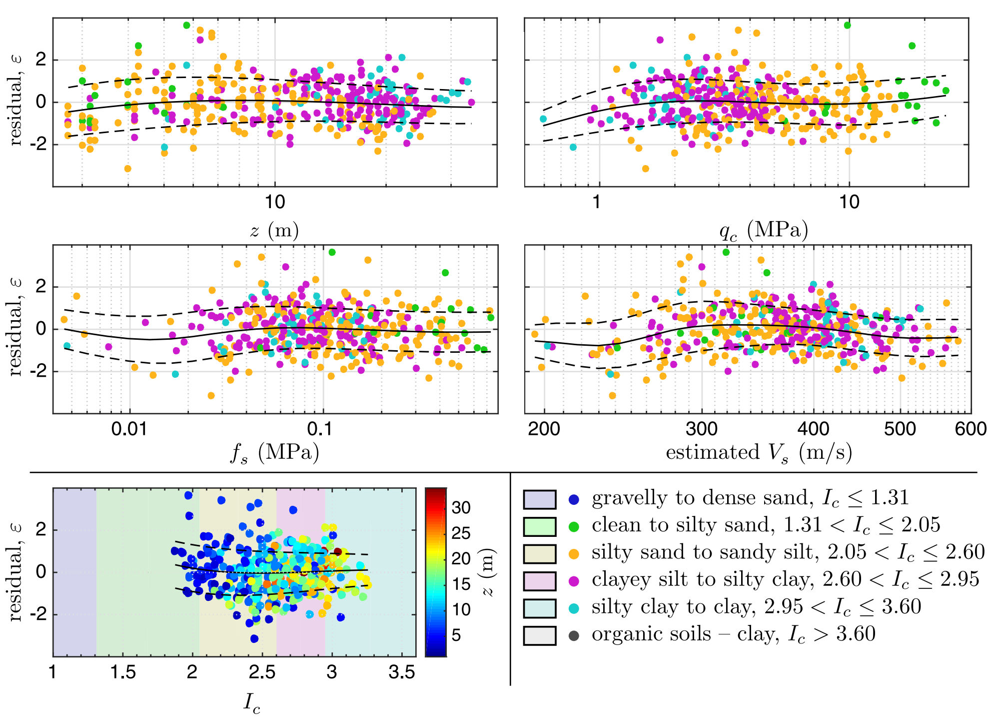

Fig. 10. Variation in residuals between loess-specific CPT-V_s model and loess soil SCPTu measurements with various CPT-based parameters.

velocity measurements at very shallow depths are generally much less reliable than deeper measurements. Thus, factors related to the tests themselves could have also contributed to some of the evident bias in the model predictions. Despite the minor overpredictions for shallow depths, a comparison of Figs. 5 and 10 clearly demonstrates the gain in predictive ability provided by the new loess-specific CPT-V_s correlation for these loess 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.

A comparison of the two individual subsets of the loess data (i.e., 13 Heathcote Valley sites and 13 other locations) indicates a few things of note. The first is that there are far more data points in the Heathcote subset due to the shorter V_s measurement interval used during data collection. For this reason, the loess CPT-V_s model is biased toward the conditions at these sites relative to the other locations, although the model is representative of each subset when applied individually. The second observation is that the variance in the CPT-V_s model appears to stem largely from the Heathcote Valley data, as the points with the largest underprediction bias in Fig. 10 are in the Heathcote Valley subset, whereas the points with the largest overprediction bias are equally represented by data points from the two subsets.

Shear-Wave Velocity Profile Comparisons

To further demonstrate the improved ability of the loess-specific CPT-V_s model to represent the shear-wave velocity profiles of the loess sites, Figs. 11 and 12 compare the measured (SCPTu) and predicted (CPT-V_s) shear-wave velocity profiles at all of the loess SCPTu sites (Fig. 11 shows the Heathcote Valley sites; Fig. 12, the remaining sites). This comparison is made in terms of the median prediction and the $\pm\sigma$ predictions for the loess-specific model and the general soils model. As shown in Figs. 11 and 12, the loess-specific CPT-V_s profiles are more in agreement with the measured profiles, particularly at depths beyond the crustal zone (upper 2–3 m).

Although it is important to verify the performance of the loess CPT-V_s model against the measured profiles at the 26 loess sites shown in Figs. 11 and 12, these sites were used in the development of the model and thus the ability of the model to represent them is expected. An independent shear-wave velocity profile comparison is made in Fig. 13, which plots the general and loess soil CPT-V_s profiles against the V_s profile obtained using surface wave methods (SW-V_s) by Wotherspoon et al. (2014) at the Heathcote Valley Primary School (HVSC) strong-motion station. As shown, the loess-specific model prediction is quite representative of the

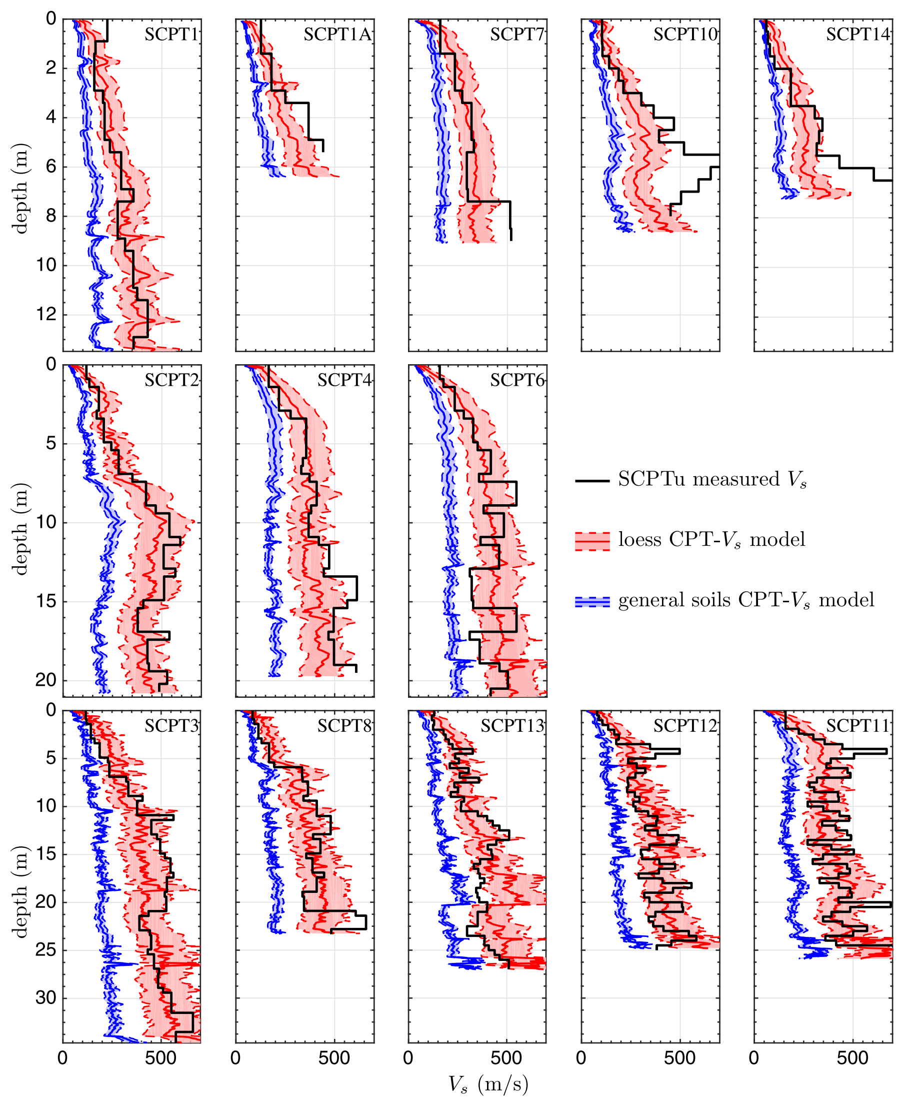

Fig. 11. Comparison of loess-specific and general soil CPT-V_s profiles and measured SCPTu-V_s profiles at 13 Heathcote Valley loess soil SCPTu sites.

J. Geotech. Geoenviron. Eng., 2018, 144(9): 04018054

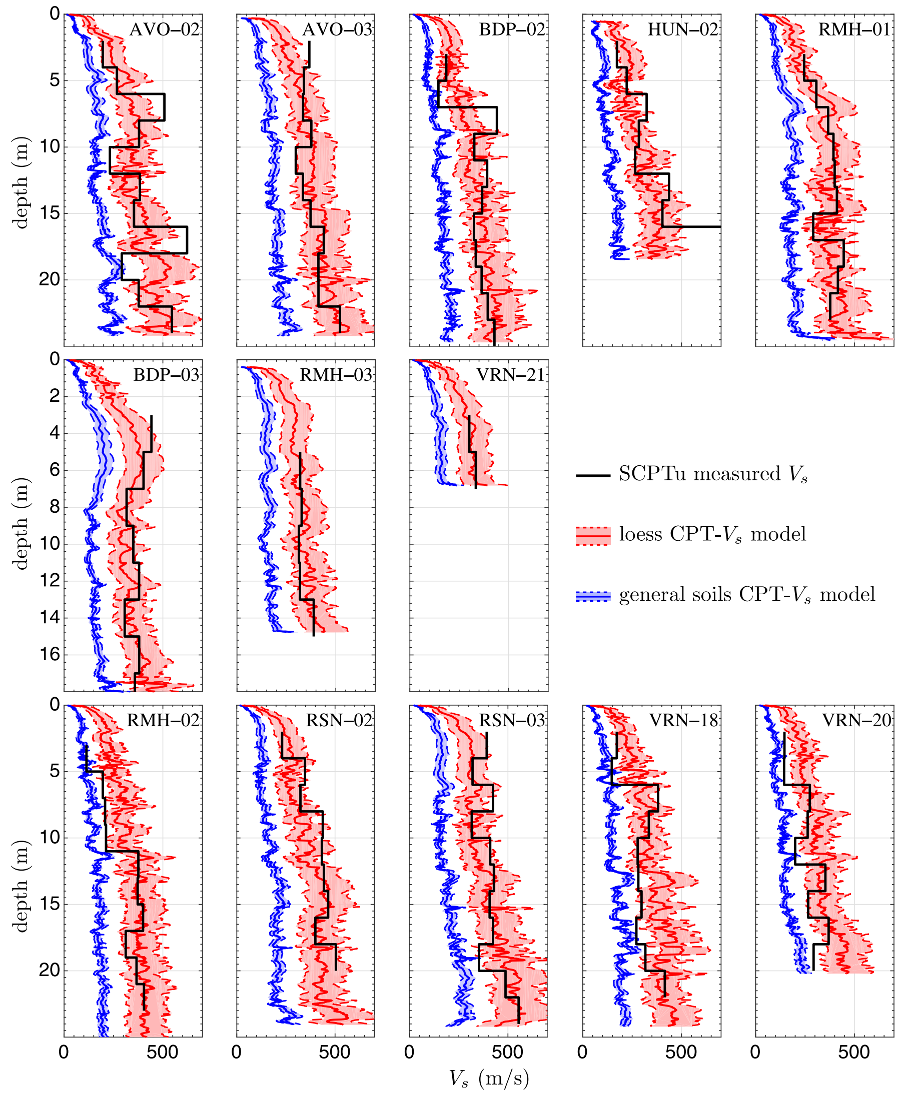

Fig. 12. Comparison of loess-specific and general soil CPT-V_s profiles and measured SCPTu-V_s profiles at 13 non-Heathcote Valley loess soil SCPTu sites.

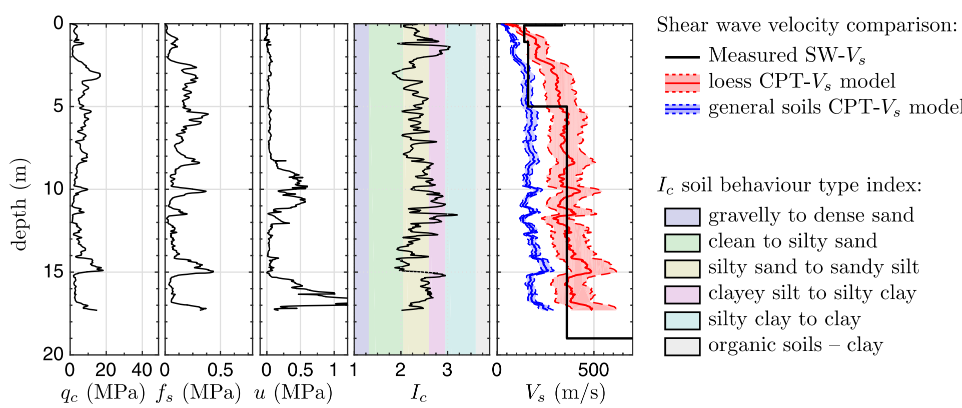

Fig. 13. Comparison of loess-specific and general soil CPT-V_s profiles and SW-V_s profile at HVSC strong-motion station.

independently obtained SW-V_s profile for $z \geq 5$ m. Although the general soils model is more representative of the SW-V_s profile for $z < 5$ m, the lower velocity in the SW-V_s profile here is likely related to the inversion process used to produce the velocity profile, and it is likely only a coincidence that it agrees well with the general soils model prediction. The key observation is the applicability of the loess-specific model to the majority of this independent V_s profile.

Summary and Conclusions

An assessment of the shear-wave velocity profiles measured by SCPTu at 26 loess sites located in the Banks Peninsula, south of Christchurch, New Zealand, has demonstrated the inapplicability of the previously developed Christchurch-specific general soils CPT-V_s model (McGann et al. 2015a, b), as well as several other existing CPT-V_s models (Andrus et al. 2007; Robertson 2009; Hegazy and Mayne 2006), to these loess sites. It is shown that all of the considered CPT-V_s models are biased toward underprediction of the measured loess V_s values, with the Christchurch-specific general soils model showing the most systematic underprediction. The potential causes of these differences were explored. It is hypothesized that the increased V_s in the loess is attributable to some combination of aging effects, cementation, and capillary pressures present in the loess but not in the general soils data set, and to the demonstrated compositional differences between the two soil groups. Due to the inapplicability of the existing CPT-V_s models to these loess sites, the SCPTu data were used to developed a new loess-specific CPT-V_s model for use in predicting soil shear-wave velocity in the loess deposits of the Port Hills and Banks Peninsula. Together, the Christchurch-specific general soil and loess-specific CPT-V_s models provide coverage of the primary soil types encountered in the Canterbury area, enabling V_s prediction from nearly any available CPT in that area.

In regard to the use of this new loess-specific correlation in other regions, both in New Zealand and internationally, it may prove to be applicable to other deposits with normalized small strain rigidity indices $K_G^* > 330$. Caution is advised in any such applications, however, this new model provides the potential for a reduced burden of data collection for other regions/deposits with similar microstructure effects. For example, 10 SCPTu tests from a hypothetical new region may be sufficient to show that the model is applicable to that region, whereas the development of a new robust model for this new region would generally require much more data. In this sense, the primary utility of the loess-specific CPT-V_s correlation outside of the Banks Peninsula is this general reduction in data needed to validate a new model for other regions with similar soil types, or as a key ingredient in the development of a global model for soils with significant microstructure.

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