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COMPARISON OF A CHRISTCHURCH-SPECIFIC CPT-V_S CORRELATION AND V_S DERIVED FROM SURFACE WAVE ANALYSIS FOR STRONG MOTION STATION VELOCITY CHARACTERISATION

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ABSTRACT

The Christchurch-specific empirical correlation between shear wave velocity (V_S) and cone penetration test (CPT) data developed by McGann et al. [1-3] for the non-gravel soils of the Christchurch and Springston Formations is evaluated through comparison to V_S profiles obtained using surface wave analysis techniques at twelve Christchurch strong motion stations. These comparisons highlight the similarities and differences between the V_S profiles obtained from each approach, and allow for an assessment of the relative strengths and weaknesses of each. It is shown that, with known differences, the results of the surface wave analysis and CPT correlation compare well in terms of their independently obtained V_S magnitudes. The sources of the differences between the results of each method are identified and discussed.

INTRODUCTION

The shear wave velocity of surficial soil deposits is an important parameter for characterising dynamic site response. The importance of this parameter stems from the relationship between shear wave velocity, V_S, and the small strain shear modulus of the soil, which is difficult to directly measure, as well as from the observation that V_S is a fundamental property of the soil that correlates more strongly to dynamic response than other in-situ measurements such as standard penetration test (SPT) or cone penetration test (CPT) resistance. There are several techniques available for obtaining estimates, or measurements, of in-situ V_S for various soil types, including crosshole, downhole, and uphole techniques [4, 5]; active-source surface wave techniques such as spectral analysis of surface waves (SASW) [6] and multi-channel analysis of surface waves (MASW) [7]; passive-source surface wave techniques such as microtremor array methods [8-11]; the seismic cone penetration test (SCPT) [12]; P-S suspension logging [13]; and empirical correlations between V_S and SPT- or CPT-based data [14-17]. Each of these listed approaches have specific advantages and disadvantages with respect to the time, tools, and training involved and to the resolution and accuracy of the V_S profile that is returned.

One aspect of the various direct and indirect V_S measurement and estimation approaches that is of particular importance is the way in which the form and depth resolution of the resulting V_S profiles affect dynamic site response analyses. For example, surface wave analysis techniques such as SASW and MASW provide a good description of the general stratigraphy and corresponding V_S values of a particular site, however, the V_S profiles obtained from these techniques are often depth-averaged in nature with potentially large differences in V_S between the various assumed layers in the profile. When such a velocity model with depth is applied within a site response analysis model, the resulting impedance contrasts can lead to discrepancies between the model surface response and that which has been observed in previous events, and/or is expected in future events. Indirect V_S estimation techniques based on empirical correlations with CPT data can potentially provide an improved depth resolution, as the CPT provides a nearly continuous description of the soil conditions with depth (and hence so too does the obtained V_S profile). However, there is a necessary level of uncertainty in the V_S values obtained from such correlations, and the CPT-based V_S values may not adequately reflect the properties of dense layers at the test refusal depth (typically the top of the Riccarton Gravel Formation for applications in urban Christchurch [18]). It is therefore useful to evaluate correlation-based V_S profiles using more direct V_S measurement techniques.

The greater Christchurch, New Zealand area is instrumented with a large network of strong ground motion recording stations that has grown in size following the 2010-2011 Canterbury earthquake sequence [19-24]. These strong motion stations (SMS) are part of both the New Zealand National Strong Motion Network (NSMN) and the Canterbury Accelerograph Network (CanNet) [25], with all stations part of the GeoNet project [26]. Several recent studies have focused on characterising the soil profiles at the Christchurch SMS sites [27-29], using borehole/SPT, CPT, surface wave analysis methods, and H/V spectral ratio techniques to gain a better understanding of the subsurface conditions at each SMS location. The combination of high-quality surface-wave estimated V_S profiles at the Christchurch SMS with CPT data in close vicinity provides a unique opportunity to evaluate the Christchurch-specific CPT-V_S correlation developed in McGann et al. [1-3], as well as an opportunity to examine the relative merits of the V_S profiles estimated by each approach.

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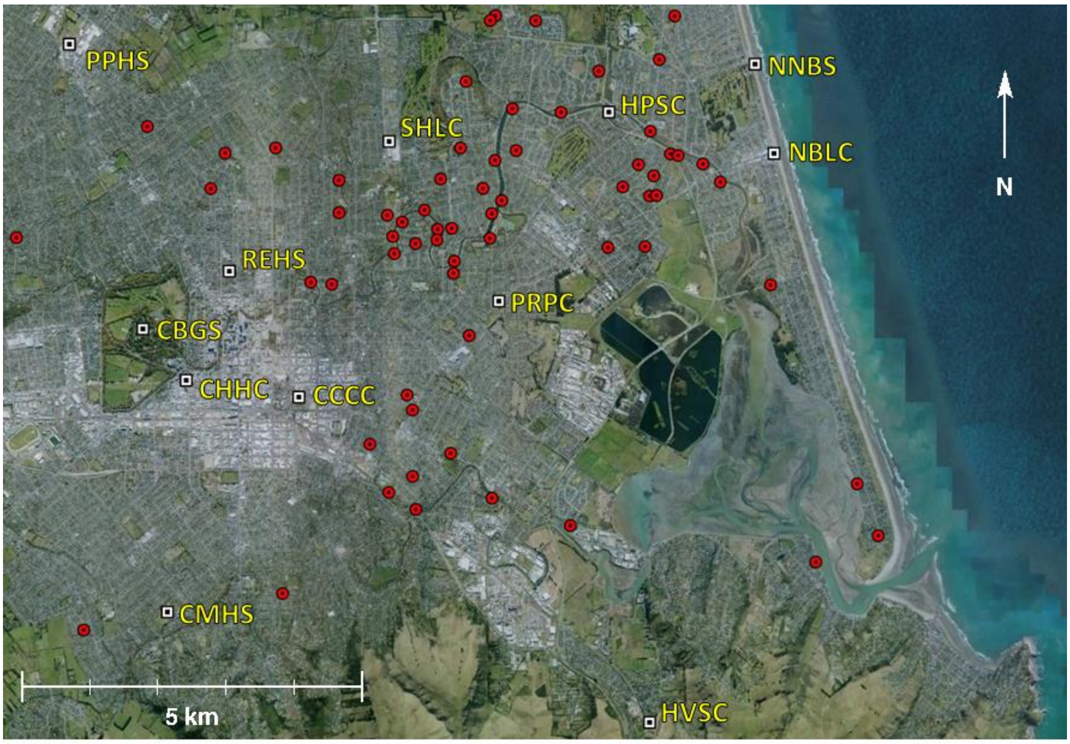

Figure 1: Christchurch SMS considered in V_s comparison study (labelled white markers). Red markers indicate SCPTu sites (within the map bounds), used to develop the Christchurch-specific CPT-Vs correlation of McGann et al. [1-3].

This paper presents an assessment of the previously developed Christchurch-specific CPT-V_S empirical shear wave velocity prediction correlation [1-3] through the comparison of 12 V_S profiles at Christchurch SMS derived using surface wave techniques. The details of the considered SMS sites are briefly discussed, with particular consideration for the surficial geology at each station. The V_S vs. depth profiles estimated from the surface wave analysis and CPT-based techniques are then compared, highlighting the general similarity in the profiles obtained by both approaches, along with several systematic differences that may have implications for dynamic site response analysis. Finally, the significant differences observed between the surface wave and CPT-based V_S profiles at the Heathcote Valley Primary School (HVSC) station are presented and discussed. Apart from the HVSC station, the CPT-V_S correlation is shown to estimate V_S profiles possessing magnitudes consistent with the independent intra-layer V_S values obtained from surface wave analysis techniques (with known differences and discrepancies) for all of the considered SMS sites.

CHRISTCHURCH STRONG MOTION STATIONS

Table 1 summarises the 12 SMS sites considered in the current comparison study, and Figure 1 shows the locations of the SMS sites on a map of the Christchurch urban area. The locations of the seismic piezocone test (SCPTu) sites [1, 3] used to create the empirical Christchurch-specific CPT-V_S correlation of McGann et al. [2] are shown to depict the relative locations and spatial density of the data behind the correlation. The SMS sites are located primarily within the non-gravel portions of the Christchurch and Springston Formations [18], coinciding exactly with the applicable surficial geologic units and soil types of the considered correlation. The only exceptions are the Christchurch Botanical Gardens (CBGS) and HVSC sites, with the former displaying a predominantly gravel composition in the first 9 m below the ground surface, and the latter located in the mixed loess and volcanic colluvium deposits of the Banks Peninsula loess formation. The gravel soils at the CBGS site are not an issue for the current study beyond the lack of CPT information for this portion of the soil profile. However, as discussed in more detail later, the soils at the HVSC site appear to potentially possess a different strength-to-stiffness relationship than that at the remaining SMS and SCPTu sites, and the surface wave-derived V_S profile at the HVSC site is not represented well by the Christchurch-specific CPT-V_S correlation.

The surface wave-derived V_S profiles were estimated at the Christchurch SMS sites listed in Table 1 using the dispersion data of Wood et al. [27] and additional/more refined surface wave inversions as described by Wotherspoon et al. [28]. A combination of active and passive-source surface wave testing techniques was used. Active-source methods always included a combination of SASW [6] and MASW [7] techniques. When

Table 1: Summary of SMS sites considered in study. Surficial geologic formations after Brown and Weeber [18].

SMS ID	Station Name	Surficial Geology
CBGS	Christchurch Botanical Gardens	Springston Fm.
CCCC	Christchurch Cathedral College	Springston Fm.
CHHC	Christchurch Hospital	Springston Fm.
CMHS	Christchurch Cashmere High School	Springston Fm.
HPSC	Hulverstone Drive Pumping Station	Springston Fm.
HVSC	Heathcote Valley Primary School	Banks Peninsula Loess
NBLC	New Brighton Library	Christchurch Fm.
NNBS	North New Brighton School	Christchurch Fm.
PPHS	Papanui High School	Springston Fm.
PRPC	Pages Road Pumping Station	Springston Fm.
REHS	Christchurch Resthaven	Springston Fm.
SHLC	Shirley Library	Springston Fm.

needed, passive 2D microtemor array methods [9, 11], were used to extend the depth of profiling. The testing methods, setup parameters, and complete subsurface exploration data at each SMS location are detailed in Wotherspoon et al. [28]. The surface wave analysis data compiled at the SMS sites are of high quality, and the associated V_S profiles are the result of several iterations through the inversion process. The V_S profile at each location was developed by fitting a 3D theoretical solution to a composite active- and passive-source experimental dispersion curve using the WinSASW software [30]. SPT and CPT testing allowed for refinements to the V_S profiles based on better constrained inversions, both in terms of layer thickness and the relative properties of each layer. As shown in Figure 2, the Wotherspoon et al. [28] V_S profiles (used in the current study) vary from those developed without prior knowledge of the subsurface layering by Wood et al. [27]. Though the layering of the surface wave V_S profiles in the current study is not truly independent from the CPT-V_S profiles (both are based on the same CPT data) the magnitude of V_S within each layer is independent for each approach and is used as the primary means of comparison in this paper.

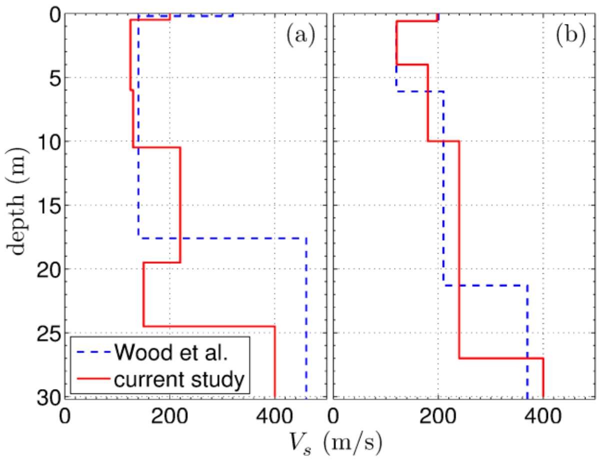

Figure 2: Comparison of original blind Vs profiles [27] with those of Wotherspoon et al. [28] used in the current study. (a) CCCC station; (b) SHLC station

SURFACE WAVE AND CPT BASED V_S PROFILES

Figures 3 and 4 provide comparisons between the surface wave-derived V_S (hereafter denoted as SW-V_S for brevity) and CPT-V_S profiles for the Christchurch Cathedral College (CCCC) and Shirley Library (SHLC) stations. In the V_S plots, the red lines indicate the SW-V_S profiles and the solid black lines represent the median prediction CPT-V_S profiles, while the shaded regions bounded by dashed lines indicate a range of +/- one standard deviation from the median. The raw cone tip resistance, q_c, frictional resistance, f_s, and pore pressure, u, profiles measured by the CPT, as well as the corresponding I_c soil behaviour type index [31], are shown for reference. Similar plots are available for the remaining 12 considered SMS sites (with the exception of HVSC) in Figures 10-18 in Appendix A.

The CCCC and SHLC sites shown in Figures 3 and 4 are highlighted here for several reasons. Firstly, as shown for these sites, the V_S magnitudes within the profiles compare favourably.

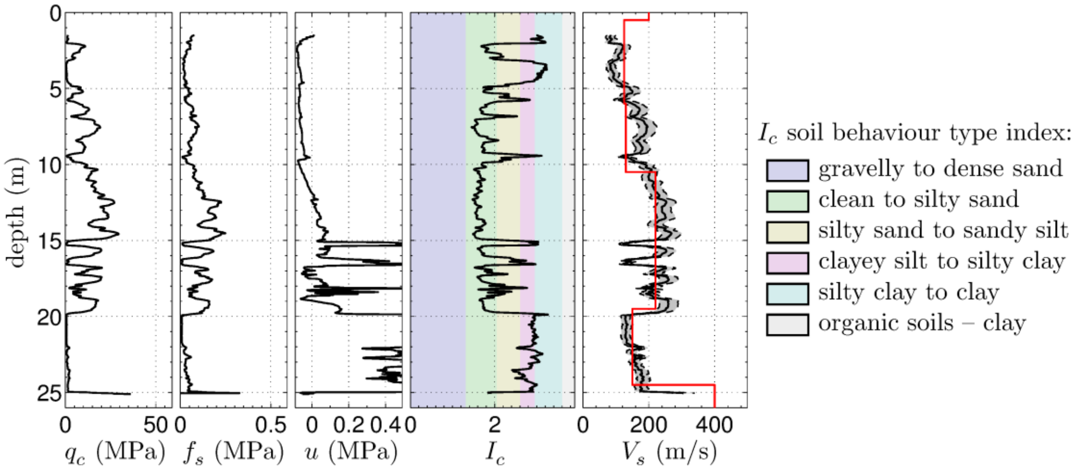

Figure 3: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the Christchurch Cathedral College (CCCC) strong motion station.

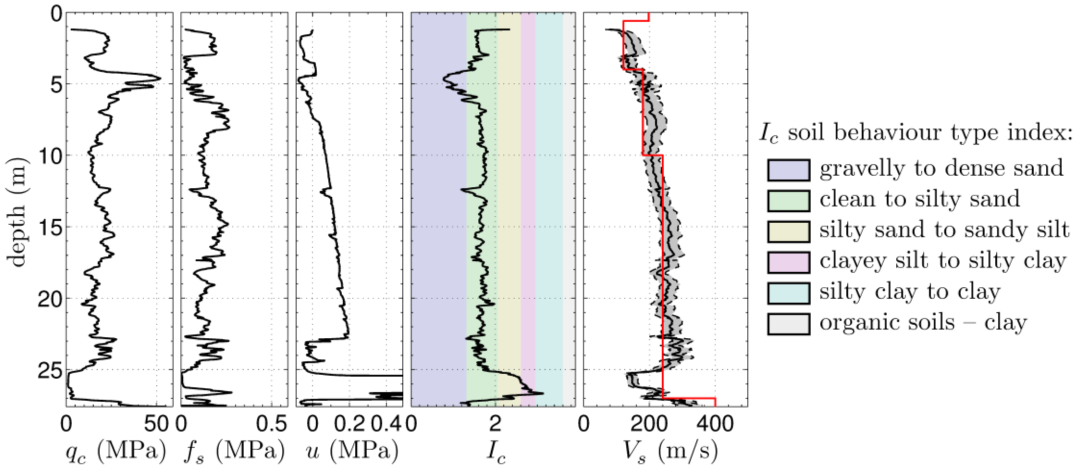

Figure 4: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the Shirley Library (SHLC) strong motion station.

Secondly, the comparisons at these sites illustrate the typical differences of such comparisons between estimation methods, which can be attributed to known differences in sampling resolution. In general, the relatively fine CPT measurements can capture localised features (thin layers), while the relatively coarse surface wave V_s measurements provide a more global profile description that is an average over the extent of the receiver array. Overall, the V_s values in each profile are of similar magnitude with depth for the SMS sites shown in Figures 3 and 4, and this correspondence between the independently estimated V_s magnitudes of the two approaches is representative of that shown by nearly all of the 12 considered SMS sites.

The SW-V_s profiles at the SMS presented in this paper were derived using layer thicknesses that were constrained for each analysis based on subsurface investigation data. An increased number of layers could have been used in the development of the SW-V_s profiles, increasing the subsequent similarity of the SW- and CPT-V_s profiles, however, the layering presented herein was considered to be a good representation of the overall profile at each SMS. Another source of the differences in the V_s profiles of Figures 3 and 4 could be related to inherent spatial variations in the soil stratigraphy, however minor, in the area surrounding each SMS. The CPT and SW tests were not performed at identical locations (the considered CPT soundings are typically located within 45 m of the SW lines [28]); therefore, though the CPT logs and boreholes reported by Wotherspoon et al. [28] in the areas surrounding the SMS showed that in most cases the soil stratigraphy below the tested areas was fairly consistent, any spatial variability between the locations of the two tests would result in differences in the V_s profiles.

Differences Between SW- and CPT-Based V_s Profiles

The first primary difference between the SW- and CPT-derived V_s profiles is related to the V_s in the base (lowest) layer of the CPT profiles. The surficial alluvial and marine soil deposits present in central Christchurch city and the eastern suburbs are directly underlain by the Riccarton Gravel [18]. The cone penetration tests presented here typically meet refusal near the interface between the softer surficial deposits and this gravel layer, and never truly penetrate far enough into the gravel layer to characterise more than the uppermost portions. The application of the CPT-V_s correlation to such data provides a good indication of the depth to the base gravel layer (as indicated by a sudden increase in q_c and V_s), but not necessarily an adequate assessment of the V_s of the base layer where only a partial description is provided by the CPT. In contrast, the SW-derived V_s profiles, when well constrained by the subsurface data provided by the CPT, provide a good indication of the depth to the base gravel layer in addition to a more appropriate representation of the shear wave velocity of the gravel layer as a whole. As shown in Figures 3 and 4 (and in Figures 10-18 in Appendix A) the SW-V_s estimates in the base gravel layers are typically greater than or equal to the corresponding CPT-based values, which makes sense in the context of how each method characterises this layer.

The second primary difference is attributed to the difficulty in isolating thin layers during SW inversions, where the general observation is that accurate layer resolutions requires layer thickness to be greater than approximately one-fifth of the layer depth [32]. The resulting depth averaging due to unresolved thin layers at deeper locations is often exacerbated by the fact that the inversion analyst must pre-define layer thicknesses and use a smaller amount of layers to avoid an under-constrained problem; essentially, the SW-V_s profile is non-unique [33], as is the case for any under-determined inversion problem. Figures 3 and 4 both highlight this second primary difference between the two approaches, with the SW profile not capturing the thin layers apparent in the CPT traces from 15-20 m for the CCCC site and missing the layer of reduced V_s from 25-27 m at the SHLC site. Figures 3 and 4 also demonstrate that the averaging nature of the SW-V_s profiles provide a broad overview of the soil stratigraphy and are particularly useful for estimating site parameters such as V_{s30}, the average V_s over the first 30 m below the surface. Depth averaging in the SW-V_s approach is not problem for the current results because the V_s profile layering is well-constrained by CPT data. In cases of blind SW-V_s measurements (e.g. Figure 2), the SW-V_s can be strongly depth-averaged and inherently less accurate for individual layers and can be problematic if incorporated into site response analyses where impedance contrasts are critical.

Figure 5 directly compares the shear wave velocities obtained by the SW and CPT-V_s techniques for all 12 considered SMS sites. To produce this comparison, the geometric mean of the CPT-estimated V_s profiles are obtained over each constant V_s interval in the SW profiles. This method of comparison is imperfect, as some of the SW profiles contain relatively large constant intervals (e.g. Figure 4), however it allows for an overall evaluation of the two data sets. The black markers in Figure 5 correspond to V_s values at the HVSC site, which, for reasons discussed later, are significantly underpredicted by the Christchurch-specific CPT-V_s correlation. The red markers correspond to the base layers at each SMS, the green markers to near surface layers (intervals in first 1 m below ground), and the blue markers to the remaining V_s intervals. As shown in Figure 5, with the exception of the HVSC values, the two estimation techniques tend to agree for the lower V_s values (approximately

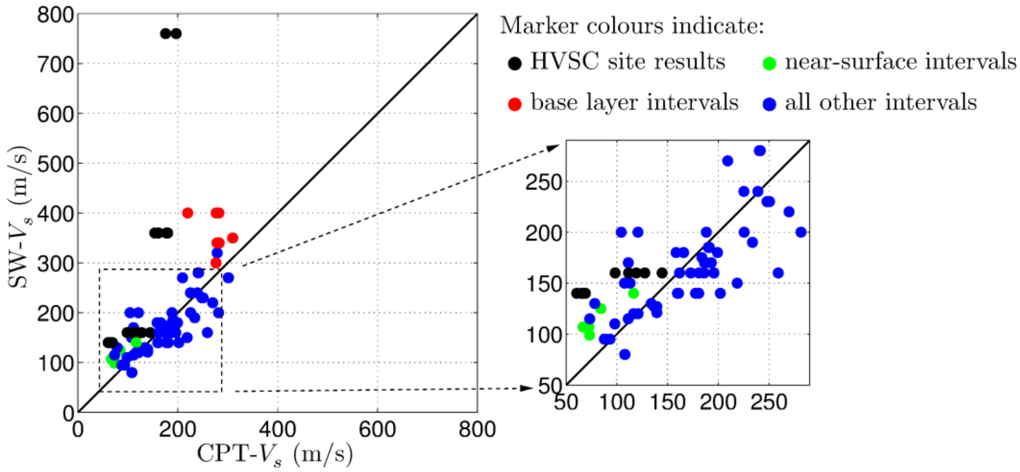

Figure 5: Comparison of shear wave velocity profiles estimated by surface wave analysis and CPT-Vs correlation. The plotted CPT-Vs values are the geometric mean over the SW-Vs intervals.

V_s < 250 m/s) and begin to diverge with increasing V_s magnitude as the SW-V_s values tend to become larger than the CPT-V_s values. The largest SW-V_s values correspond to the base gravel layers (red markers), indicating that the previous observations made with respect to the CPT- and SW-derived estimates in this layer are a main source of the observed differences in Figure 5.

A second perspective on the overall similarity of the SW- and CPT-based V_s profiles is provided in Figure 6, which plots the shear wave travel times through the soil indicated by each velocity profile. The HVSC values are plotted using square markers and all other sites are indicated using circular markers. Each data point represents one CPT-SW pair; the SMS sites (e.g. CHHC) with multiple CPT have multiple data points in Figure 6. The dashed lines represent +/- 20% error bounds from an exact correlation between the travel times for each method, and the marker colour indicates the magnitude of the average shear wave velocity for the CPT profile, computed as $V_{s\,avg} = H/(\Sigma(h_i/V_{si}))$ where $H = \Sigma(h_i)$ is the total thickness of the profile (taken as the lesser of the CPT or SW profiles), h_i is the thickness of each measurement interval, and V_{si} is the shear wave velocity over each measurement interval. The results of Figure 6 show that, again with the exception of HVSC, there is generally good overall agreement between the SW- and CPT-based methods. Many of the profile travel time pairs have a relative error < 10% and all but CMHS (blue marker near centre of plot) have < 20% error. The HVSC results fall well below the 1:1 correlation line, suggesting that the CPT-V_s profiles represent softer soil conditions than the SW-V_s profile at this site.

Bias Variation between Methods with CPT-Based Terms

Figures 7 and 8 present an alternative means of comparison between the SW and CPT-V_s estimates of the in-situ shear wave velocity. The plots in Figure 7 show how the V_s bias, defined as the ratio of the SW-V_s in each constant interval to the geometric mean of the CPT-V_s over the same interval, varies with the magnitude of the SW- and CPT-V_s values. The marker colouring scheme is shared with Figure 5 (red markers are base layers, green are near-surface layers, blue are remaining layers). The HVSC site is omitted here to avoid obscuring the results for the other SMS locations. The solid black lines in Figure 7 indicate moving averages (dashed lines show 95% confidence intervals) for the V_s bias. These bias plots indicate that the lower CPT-V_s values (approximately V_s < 90 m/s) also compare poorly with the SW-V_s values. This difference is likely due in part to thin near-surface layers of high V_s present in some of the SW profiles (e.g. Figure 3) where a ground covering such as asphalt may be influencing the SW-V_s profile, but would not be present in the CPT results.

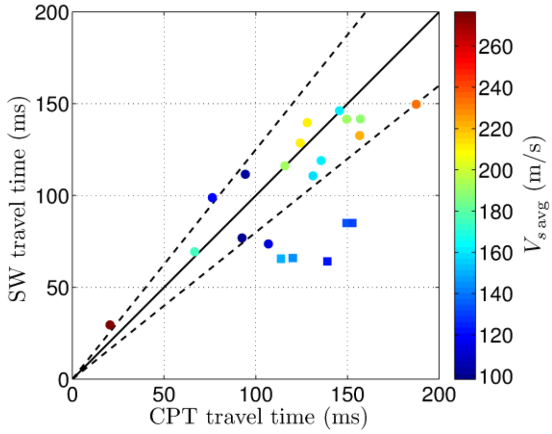

Figure 6: Comparison of V_s travel times through profiles for SW- and CPT-based methods.

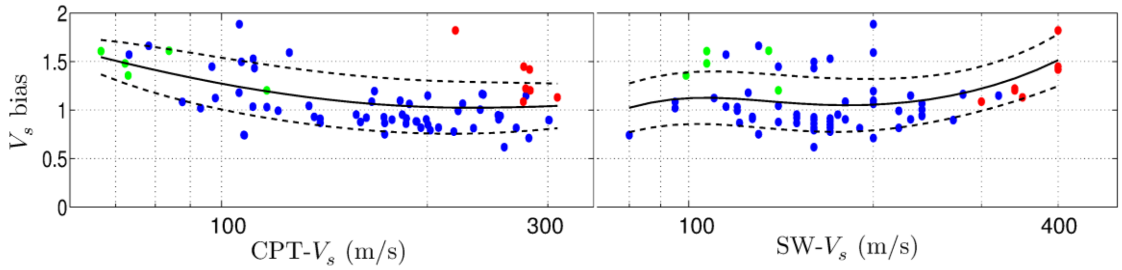

Figure 7: Variation of V_s bias with SW-V_s and geometric mean of CPT-correlated V_s over constant SW-V_s intervals. Red markers indicate base layers at each SMS site, green markers indicate near-surface layers.

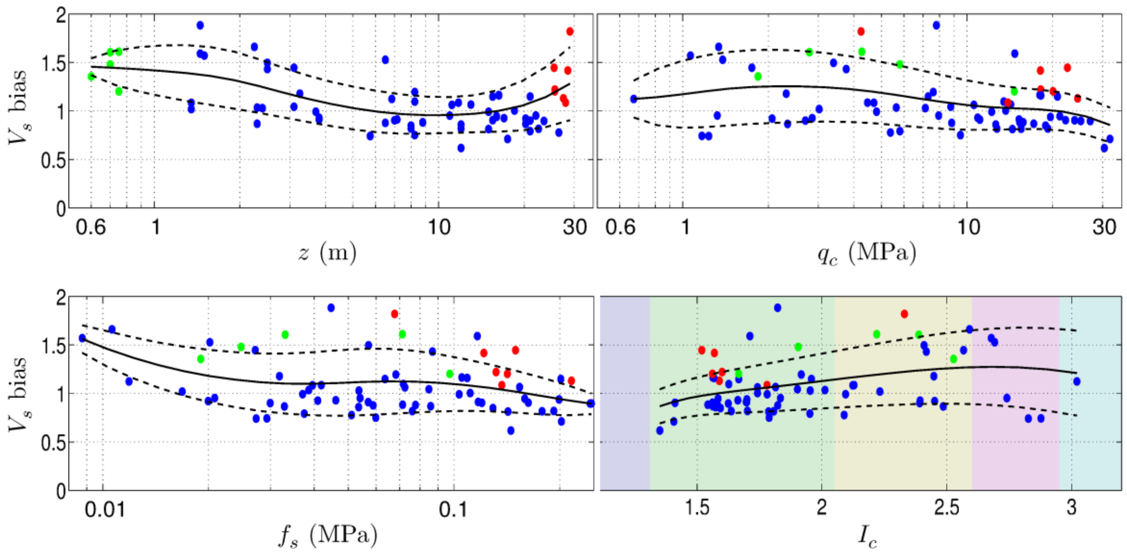

Figure 8: Variation of V_s bias with centre depth of SW-Vs intervals, z, and geometric means of q_c, f_s, and I_c over constant SW intervals. Red markers indicate base layers at each SMS site, green markers indicate near-surface layers.

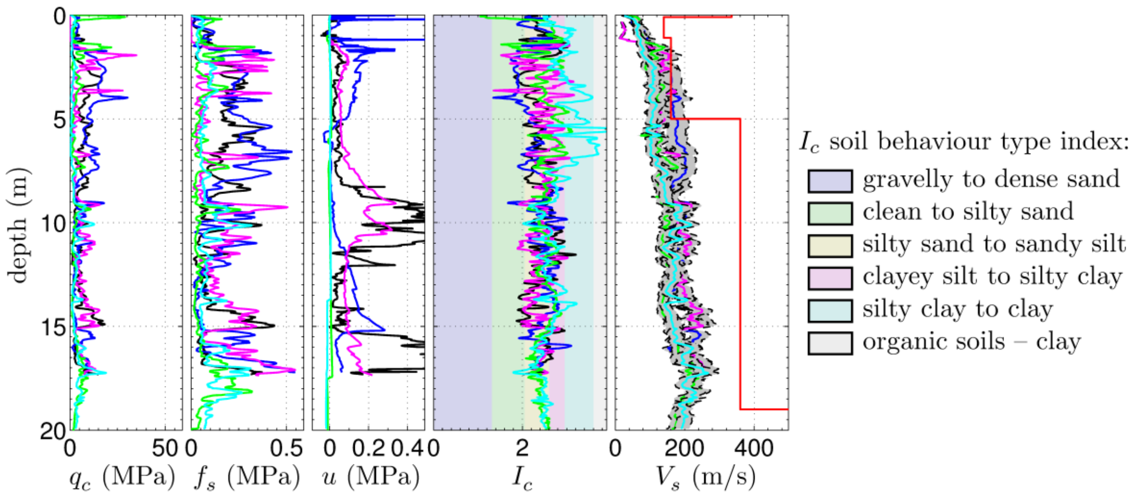

Figure 9: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the Heathcote Valley Primary School (HVSC) strong motion station.

Figure 8 shows the variation in V_s bias with the mid-point depth of the constant SW-V_s intervals, z, and the geometric means over the same intervals of q_c, f_s, and I_c. As shown, the ratio between the SW- and CPT-V_s values remains relatively constant across the considered ranges of q_c, f_s, and I_c, though the elevated average bias in each plot indicates that the SW-derived V_s tend to be higher than those returned by the CPT-V_s correlation. The plot in Figure 8 that shows the variation of the bias with depth, z, confirms some of the observations made previously in terms of the differences between the CPT and SW base layer velocities (red markers) leading to larger bias at depth, and the near-surface layers of higher SW-V_s contributing to the larger bias at shallower locations. The spread evident in all of the bias plots shown in Figures 7 and 8 is likely due to a combination of these differences and the differences between the CPT- and SW-based V_s profiles noted previously (e.g. depth averaging in SW).

HEATHCOTE VALLEY PRIMARY SCHOOL (HVSC) STATION

The trends defining the similarities and differences between the SW- and CPT-derived V_s profiles at the CCCC and SHLC sites shown in Figures 3 and 4 are representative of those evident at nine of the remaining ten SMS sites (see Appendix A), with the Heathcote Valley Primary School (HVSC) station being the lone exception. Figure 9 shows the SW- and CPT-V_s profiles for the HVSC site, which as noted previously, is located within the Banks Peninsula loess geologic formation. Five CPT were conducted in the vicinity of the HVSC station (≈ 2-45 m from surface array [28]), and the data for each test is indicated using a distinct (non-red) colour in Figure 9. As shown, not only is there a large amount of variability between the readings of the five CPT soundings, the magnitudes of the CPT-V_s values are significantly lower than the SW-V_s profile, especially for depths > 5 m below the surface. The reason for this large discrepancy is likely due to differences in composition and ageing between the soil deposits at the HVSC site and those that comprise the SCPTu database used as the basis for the CPT-V_s correlation. Additionally, the poor agreement between the two profiles at this site may have been influenced by significant lateral variation in the soil conditions and the inclined shallow impedance contrast at the site from the underlying Port Hills volcanics.

The geologic age and depositional environment for the loess and volcanic colluvium deposits at the HVSC site differ greatly from those of the Christchurch and Springston Formation soil deposits where the SCPTu database sites are located, and it is reasonable to assume that the stiffness (directly related to V_s) is naturally higher relative to the strength (directly related to CPT) for the soils at the HVSC station. Based on these noted differences in the original depositional and current states of the HVSC and SCPTu database sites, it is clear that the current Christchurch-specific CPT-V_s correlation was developed from a set of soils with an entirely different strength-to-stiffness relationship, and therefore provides a poor estimate of the in-situ V_s at the HVSC station. These findings are supported by some preliminary work with SCPTu-based V_s records obtained in the loess and volcanic colluvium of the Banks Peninsula loess and Mt. Pleasant Formations, which similarly indicate greater V_s values than those predicted using the CPT-V_s correlation; however, further research is required to assess whether the observations made for the HVSC site are a systematic feature of these soil deposits or an isolated outlier.

CONCLUSIONS

Shear wave velocity profiles estimated using surface wave techniques at 12 Christchurch strong motion stations were compared to V_s profiles estimated from adjacent CPT data using the Christchurch-specific CPT-V_s correlation developed in McGann et al. [1-3]. These comparisons indicated that overall, the two methods produced reasonably similar descriptions of the variation in subsurface V_s at the SMS sites. The inversions used to produce the SW-V_s profiles were constrained in part by the CPT data, thus, the agreement on general stratigraphy for the two approaches is expected; however, the V_s magnitudes returned by each approach are independent and the agreement between the SW- and CPT-based results in this regard provides further support for the effectiveness of the Christchurch-specific correlation.

For eleven of the twelve considered SMS locations, the primary differences between the SW- and CPT-based V_s estimates are attributable to limitations in the ability of the CPT to characterise the properties of the gravel base layer underlying each profile and well-known features of V_s profiles estimated using surface wave techniques; namely, the depth averaging associated with velocity inversion from a dispersion curve. The twelfth SMS site (HVSC) is located within the Banks Peninsula loess, a geologic deposit with soils completely different than the Springston and Christchurch Formation soils comprising the SCPTu sites used to develop the correlation. It was shown that the SW-V_s profile at HVSC was significantly underpredicted by the current CPT correlation. This underprediction is likely due to some combination of differences in soil type, original depositional environment, and post-earthquake state for the Banks Peninsula loess with respect to the soils of the Christchurch and Springston Formations, as well as the difficult conditions for surface wave testing present at the HVSC site.

The results of this study have shown that, with known exceptions, the Christchurch-specific CPT-V_S correlation [2] is able to produce reasonable estimates of V_S for sites in the greater Christchurch area located within the non-gravel soils of the Christchurch and Springston Formations, providing increased confidence in the use of this correlation for future research involving these regional soils. These comparisons have also highlighted the differences in how the V_S profile is represented with depth by each approach (essentially continuous variation for CPT-V_S, depth averaged layers for SW) and provided some commentary on how these differences may affect subsequent analysis.

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APPENDIX A: SHEAR WAVE VELOCITY COMPARISONS AT REMAINING STRONG MOTION STATIONS

Figures 10-18 show the SW-V_s (red lines) and CPT-V_s profiles for the 9 SMS sites not shown previously. For sites with more than one CPT, the results from the individual CPT soundings are plotted using distinct (non-red) colours. The shaded regions bounded by dashed lines in the V_s plots indicate a range of +/- one standard deviation from the median CPT-V_s profile.

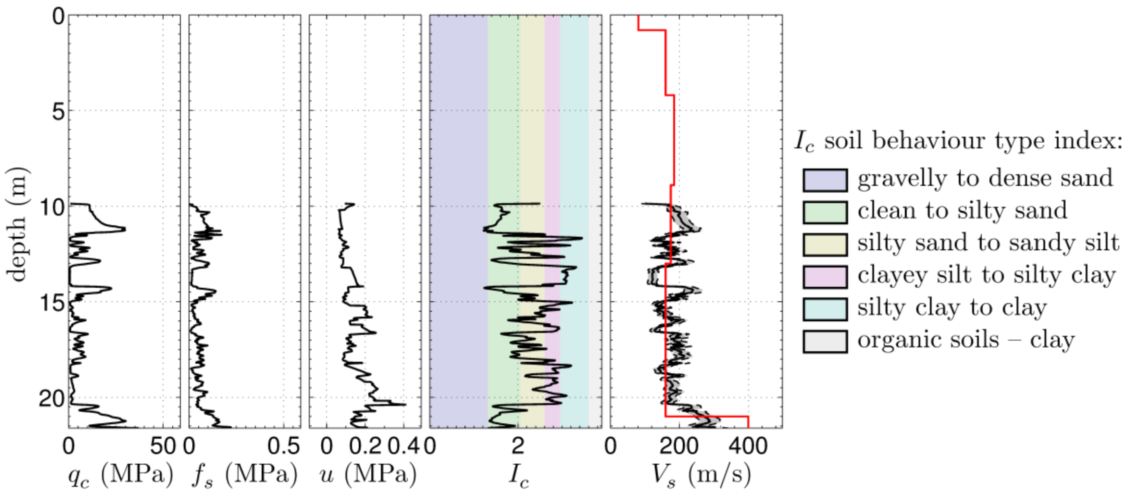

Figure 10: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the Canterbury Botanical Gardens (CBGS) strong motion station.

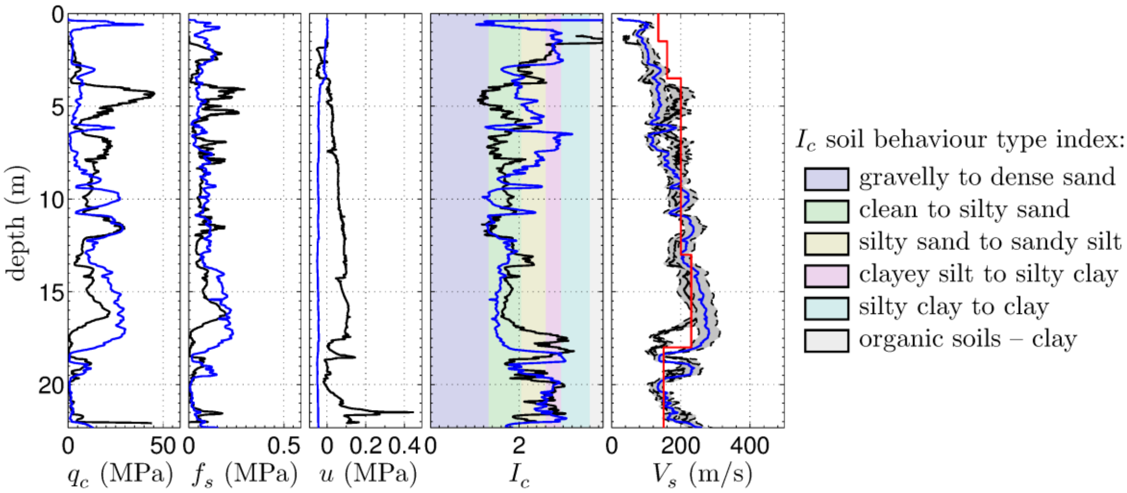

Figure 11: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the Christchurch Hospital (CHHC) strong motion station.

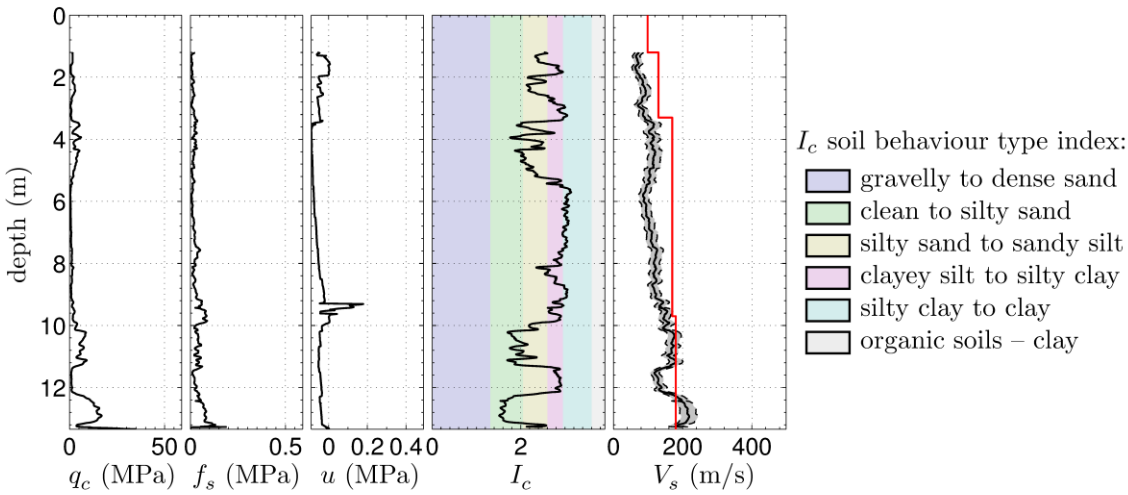

Figure 12: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the Cashmere High School (CMHS) strong motion station.

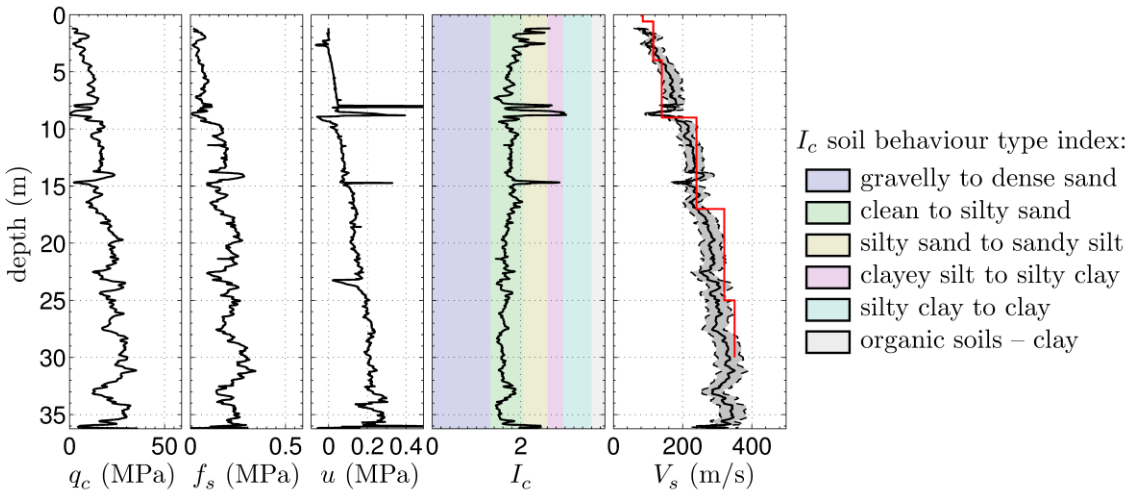

Figure 13: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the Hulverstone Drive Pumping Station (HPSC) strong motion station.

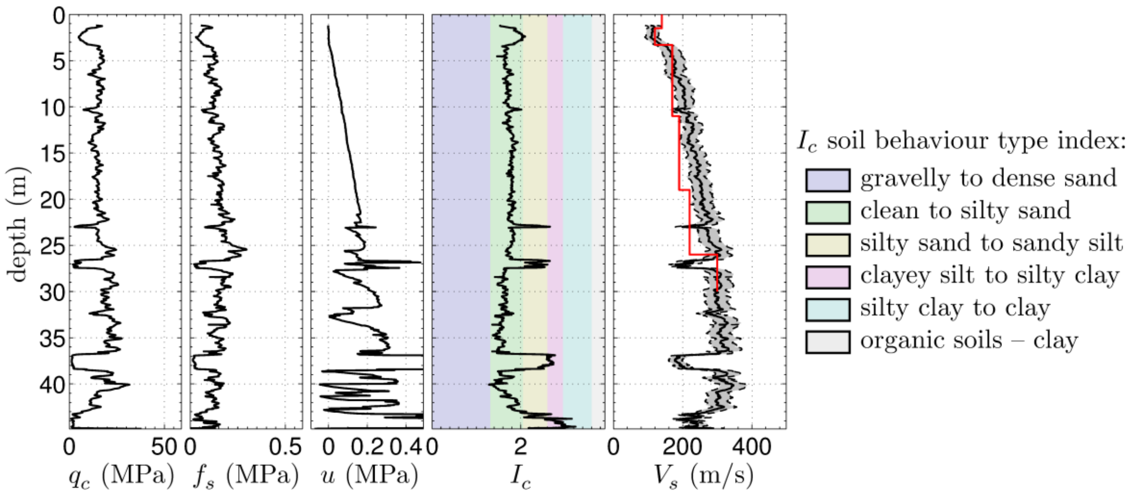

Figure 14: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the New Brighton Library (NBLC) strong motion station.

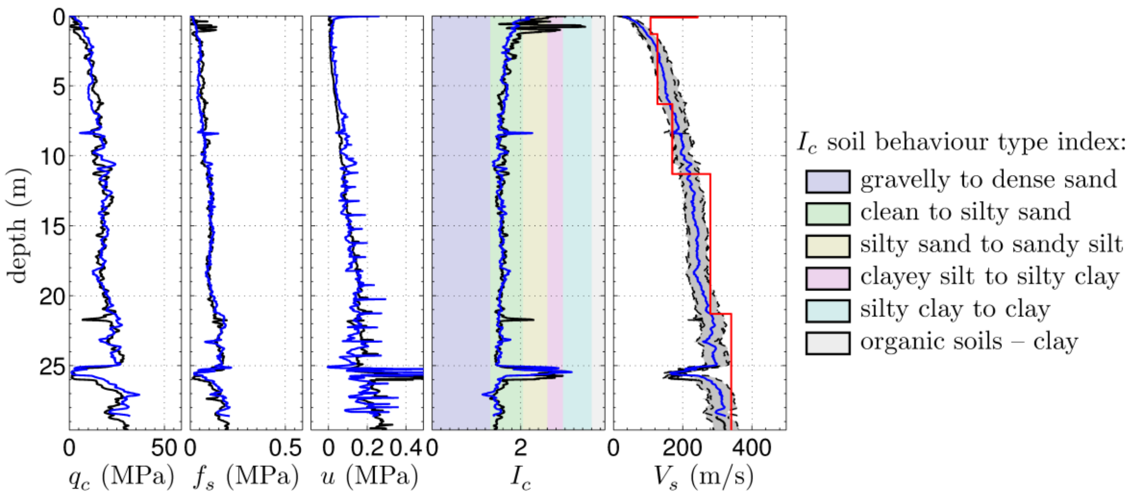

Figure 15: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the North New Brighton School (NNBS) strong motion station.

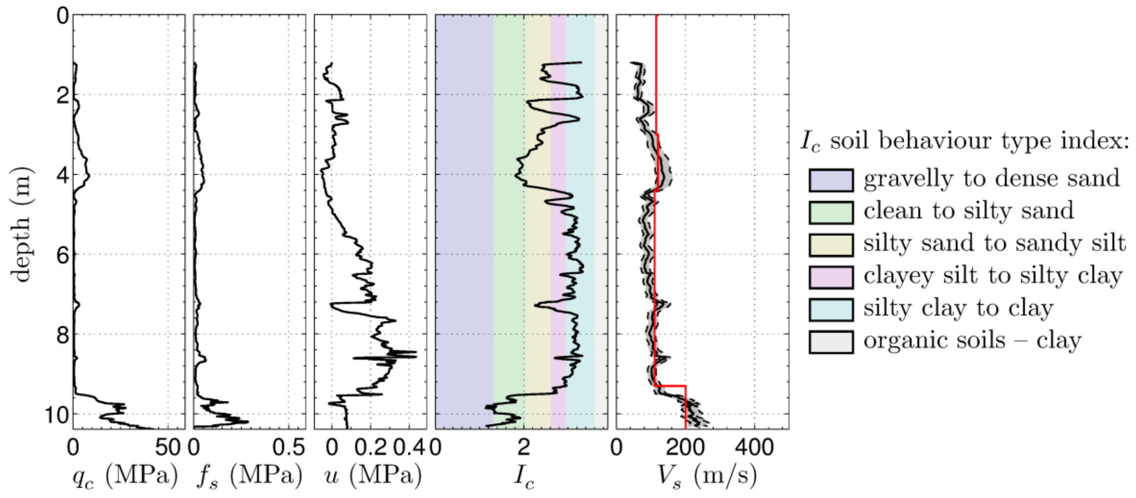

Figure 16: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the Papanui High School (PPHS) strong motion station.

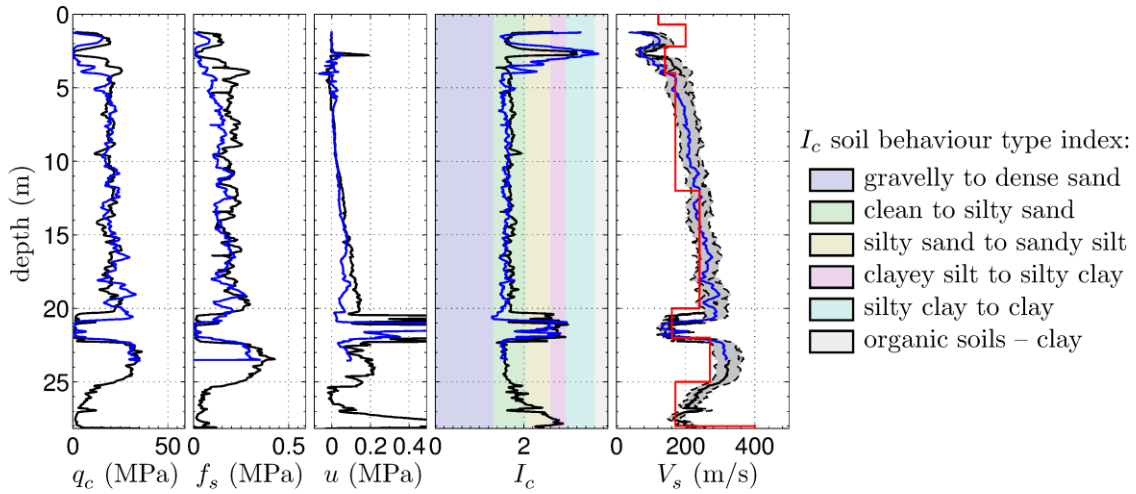

Figure 17: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the Pages Road Pumping Station (PRPC) strong motion station.

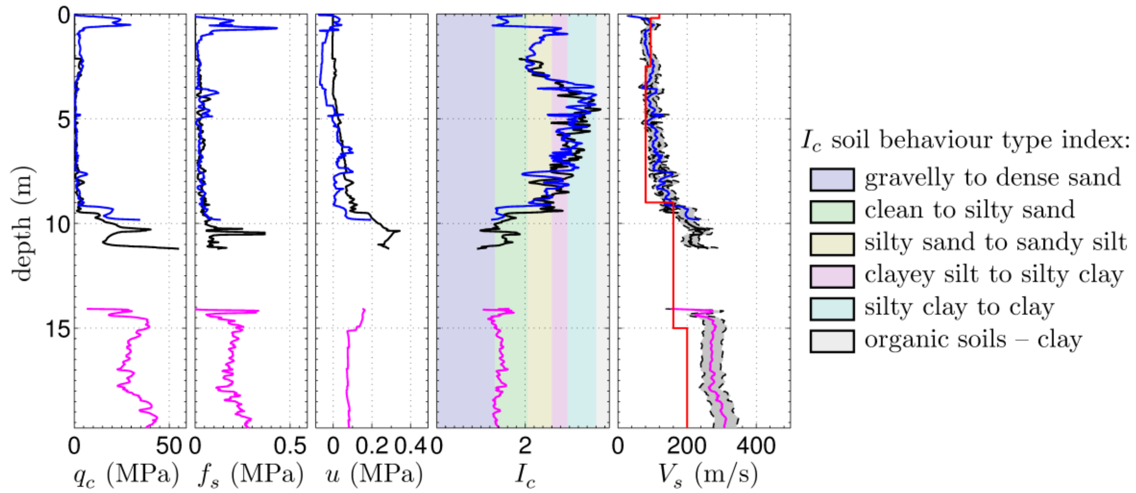

Figure 18: Comparison of shear wave velocity profiles estimated using surface wave analysis (red line) and CPT-V_s regression model for the Christchurch Resthaven (REHS) strong motion station.