Sensitivity of CPT-based liquefaction assessment to sleeve friction depth correction

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ABSTRACT: The cone penetration test (CPT) is one of the most widely used in-situ tests for geotechnical characterization and liquefaction assessment. When processing CPT data, the sleeve friction resistance (f_s) readings must be shifted relative to cone tip resistance (q_c) because of the difference in depth of the cone tip and the friction sleeve. There are currently two methods for correcting the sleeve friction depth: (i) based on the physical distance between the cone tip and sleeve friction, or (ii) by adopting a statistical technique called the cross-correlation function (CCF) to calculate the correction. In this paper, these two methods are investigated using high-quality CPTs performed on reclaimed soils. Results show that the CCF produced reasonable corrections for only 60% of the CPTs. For these CPTs, a parametric study investigating the sensitivity of key soil classification parameters on the two methods of shifting f_s resulted in large changes in calculated parameters F_r, I_c, and Q_{tncs}, at each depth. However, when averaging the values with depth for given soil layers, the differences are all < 5%. A parametric study on damage index calculations from liquefaction triggering analysis also resulted in < 5% differences in most cases. Thus, the choice of f_s depth correction methods makes a negligible difference for characterization and liquefaction assessment purposes. However, the CCF method did not produce a clear value of depth offset correction in 40% of the cases at this site. Therefore, a consistent f_s depth correction method that can be applied to all CPTs based on the physical distance separating the cone tip and sleeve friction is recommended.

KEYWORDS: Cone penetration test; sleeve friction correction; cross-correlation function, liquefaction triggering.

1 INTRODUCTION.

The cone penetration test (CPT) is an in-situ test which provides near-continuous readings of the cone tip resistance (q_c) and sleeve friction resistance (f_s) measured using strain gauge load cells at the tip and sleeve of the cone, respectively. Both q_c and f_s are used in geotechnical characterization, using soil classification charts (e.g., Robertson 2009a), and liquefaction triggering assessment (e.g., Robertson and Wride 1998; Robertson 2009b).

When performing CPTs, data acquisition systems often record the cone tip and sleeve friction resistances at the same time. However, at any point in time, there is a physical difference in the depth between the cone tip and friction sleeve locations (usually 8-10 cm for a standard 10 cm^2 cone). Therefore, the recorded values of q_c and f_s, and hence the inferred soil classification and liquefaction analysis, are incorrect unless a depth offset correction is applied.

Moreover, while f_s is a measure of the average stress of soil in direct contact with the sleeve gauge, q_c is influenced by a zone of soil below and above the cone tip. The extent of the zone of soil contributing to the measured q_c is a function of several factors such as cone diameter, soil rigidity, and soil stratigraphy (Teh and Houlsby 1991). Therefore, it is difficult to ascertain the true depth correction. There are currently two methods for correcting the depth offset between q_c and f_s readings:

1. Based on the physical distance between the tip of the cone to the mid-point of the friction sleeve (Schmertmann 1978; Campanella et al. 1983).
2. Adopting a statistical technique called the cross-correlation function (CCF) (Jaksa et al. 2000; Jaksa et al. 2002).

In this paper, several high-quality CPTs performed in reclaimed fill are used to investigate the applicability of these two methods, followed by a parametric study on the sensitivity of soil characterization and liquefaction assessment parameters to the two f_s depth offset correction methods.

2 CROSS-CORRELATION FUNCTION (CCF)

The CCF is a measure of the similarity of two data series (e.g., q_c and f_s) as a function of a shift applied to one of them (Box et al. 2015). This method allows q_c and f_s to be compared at each possible depth correction value to determine at which positions there are strong correlations. Consider q_c and f_s as a discrete data series with measurements at each depth, denoted as $q_{c,i}$ and $f_{s,i}$, as shown in Eq. 1a and 1b, respectively.

$$q_c = q_{c,1}, q_{c,2}, q_{c,3}, \dots, q_{c,n} \tag{1a}$$

$$f_s = f_{s,1}, f_{s,2}, f_{s,3}, \dots, f_{s,n} \tag{1b}$$

The cross-covariance coefficients between q_c and f_s at lag k (denoted as $c_{q_c f_s}$), and between f_s and q_c at lag k (denoted as $c_{f_s q_c}$), are given by Eq. 2a and 2b, respectively.

$$c_{q_c f_s}(k) = E\left[\left(q_{c,i} - \overline{q_c}\right)\left(f_{s,i+k} - \overline{f_s}\right)\right] \tag{2a}$$

$$c_{f_s q_c}(k) = E\left[\left(f_{s,i} - \overline{f_s}\right)\left(q_{c,i+k} - \overline{q_c}\right)\right] \tag{2b}$$

Here, $\overline{q_c}$ and $\overline{f_s}$ denote the means of q_c and f_s, respectively. For a discrete-depth process applied to CPT data, k is either a positive or negative integer. Since the CCF exhibits conjugate symmetry (i.e., $c_{q_c f_s}(k) = c_{f_s q_c}(-k)$), shifting q_c by $-k$ yields the same cross-covariance coefficient as shifting f_s by $+k$. This means only $c_{q_c f_s}$ needs to be determined by shifting f_s data relative to q_c for

$k = 0, \pm1, \pm2$, etc. Since the true $c_{q_c f_s}$ is estimated by means of a sample population, the sample cross-covariance coefficient at lag k, denoted $c^*_{q_c f_s}$, is given in Eq. 3.

$$c^*_{q_c f_s}(k) = \begin{cases} \frac{1}{n}\sum_{i=1}^{n-k}(q_{c,i} - \overline{q_c})(f_{s,i+k} - \overline{f_s});\ k \geq 0 \\ \frac{1}{n}\sum_{i=1}^{n+k}(f_{s,i} - \overline{f_s})(q_{c,i-k} - \overline{q_c});\ k < 0 \end{cases} \quad (3)$$

The estimate of the sample cross-correlation coefficient at lag k, denoted $r_{q_c f_s}$, which ranges from -1 to 1, is defined in Eq. 4.

$$r_{q_c f_s}(k) = \frac{c^*_{q_c f_s}(k)}{s_{q_c} s_{f_s}} \quad (4)$$

Here, $s_{q_c} = \sqrt{c^*_{q_c q_c}(k=0)}$ and $s_{f_s} = \sqrt{c^*_{f_s f_s}(k=0)}$ are the sample standard deviations of q_c and f_s, respectively. When applying the CCF technique for CPTs, a $r_{q_c f_s} - k$ relationship is commonly plotted, and the value of k which results in the highest $r_{q_c f_s}$ value, herein denoted k_{CCF}, is the calculated f_s depth correction. An example of the CCF technique applied to q_c and f_s data from a CPT is shown in Figure 1.

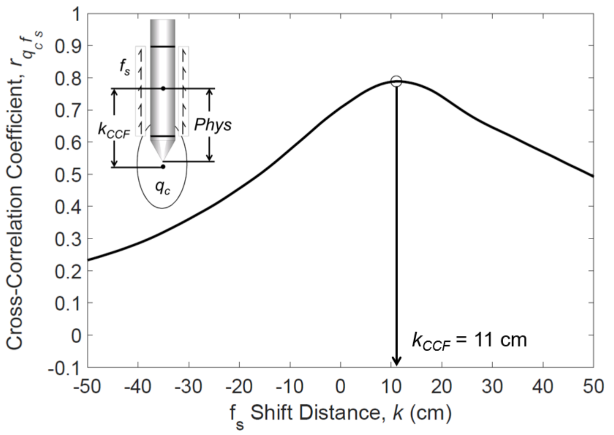

Figure 1. CCF applied on q_c and f_s data from a CPT to determine the f_s depth correction, k_{CCF}. The inset shows a schematic representation of the q_c and f_s measurements with the two possible f_s depth correction methods.

The formulation in this paper is the same as both the *crosscorr* function in MATLAB™ and the one applied in *CPeT-IT version 3.6.1.5* (Geologismiki 2020), a software commonly used for processing and interpreting CPT data. For depths associated with measured q_c values, a positive k implies that all measured f_s should be shifted to a shallower depth, so it aligns with depth where q_c is measured. Only peaks in $r_{q_c f_s}$ for $k > 0$ are considered in this study since only an upwards shift in the f_s measurement are appropriate. For the example shown in Figure 1, the f_s depth correction can be either $k_{CCF} = 11$ cm, based on the CCF technique, or 13 cm based on the physical distance from the tip of the 15 cm^2 cone to the mid-point of the friction sleeve.

3 ISSUES IN THE CCF FOR CPTS

An important assumption in applying the CCF is the two datasets are stationary. In other words, this method assumes the mean and standard deviation of q_c and f_s are constant with depth. However, this assumption is seldom true for CPT data for two main reasons:

1. q_c and f_s values are different for different soil behavior types (Robertson 2009a). Therefore, the average q_c and f_s values for inhomogeneous profiles are not constant with depth.
2. It is well understood that penetration resistance increases with in-situ vertical effective stress, which in turn increases with depth. Even for a homogeneous profile (i.e., constant density state, soil composition, fabric, overconsolidation ratio and ageing), the CPT readings are depth dependent.

The above issues pertaining to the theoretical basis of the CCF question its applicability for CPT sleeve friction depth correction. Indeed, Jaksa et al. (2000; 2002) showed several cases where the CCF did not produce reliable estimates of the f_s shift. While several reasons for such results were shown, such as data measurements which were negative, zero or beyond the limits of the measuring apparatus, the theoretical issues outlined above were not addressed.

Furthermore, studies have shown that f_s data, used in the application of the CCF, is generally the least reliable of all the CPT measurements as it shows the most variation in repeated testing (Tigglemann & Beukema 2008; Lunne 2010). Recorded f_s values are even more unreliable for gravelly soils because larger gravel-sized particles can roll around the sleeve causing damage to the sleeve friction gauge by overloading the sensor (Mitchell et al. 2010). As a result, the shift in f_s calculated by the CCF can vary considerably.

Accordingly, there are issues to consider before using the CCF approach to estimate the depth offset between q_c and f_s readings. As it is used in engineering practice, the potential implications of using the CCF approach should be investigated. It is often assumed that the commonly observed slight differences in the two depth correction methods make little difference in the overall profile interpretation, with only significant changes in friction ratio, F_r ($= f_s/q_c$) and with little impact on soil behavior index parameters (P. Robertson 2018, personal communication). However, no parametric studies have yet been published investigating the effects of different f_s shift distances on soil classification and liquefaction analysis. This paper attempts to fill this gap using a well-documented case study.

4 TEST SITE

The reclaimed land in CentrePort, Wellington city (New Zealand) comprises soils of different ages, methods of construction, and thicknesses. The port contains two primary fill types: (i) gravel-sand-silt mixtures sourced from nearby quarries constructed by end-tipping in a water sedimentation process, and (ii) hydraulic fills constructed using dredged sandy and silty soil from the seabed in the close vicinity. The top ~3 m of the fill above the water table consists of a roller-compacted layer underlain by uncompacted fill with thickness ranging from 5 m to 22 m. The fills sit atop a 1-4 m thick layer of marine sediments, which overlie Pleistocene weathered sediments.

Widespread liquefaction occurred at CentrePort during the 2016 moment magnitude (M_w) 7.8 Kaikōura earthquake (Cubrinovski et al. 2017). Following the earthquake, 121 CPTs were performed in CentrePort using 10 cm^2 and 15 cm^2 I-cones with physical distances between the cone tip and the midpoint of the friction sleeve of 10 cm and 13 cm, respectively (Cubrinovski et al. 2018; Dhakal et al. 2020a). Despite pre-collaring (with casing) the top 3 m of the compacted crust layer before beginning the CPT to maximize penetration depth (Bray et al. 2014), early refusal was still encountered during several of the tests in the gravelly fill. In 20 of the tests where early refusal at depths less than ~10 m occurred, the CPT casing was extended beyond the refusal depth and cone testing was then continued.

However, Jaksa et al. (2000; 2002) demonstrated, with several examples, that advancing the CPT in two stages lead to elastic rebound of the soil (which was termed as the "rebound phenomenon"), which can cause issues in the application of the CCF. While this issue is generally worse for clays than it is for gravels, and while there are methods to dealing with such issues, these 20 CPTs are not considered in this study to avoid problems in the application of the CCF. The remaining 101 CPTs, and the ground motion recorded during the Kaikōura earthquake at a nearby strong motion station, are considered in this study.

5 APPLICATION OF THE CCF

Negative q_c and f_s readings and values beyond the limits of the apparatus are first removed before applying the CCF technique to determine k_{CCF} for each of the 101 CPTs. In this study, k_{CCF} values in the range of 6-20 cm are considered reasonable (Jaksa et al. 2000; 2002). In general, a clear peak in $r_{q_c f_s}$ at a reasonable value of k_{CCF} is calculated for deeper profiles which encounter several soil layers. An example CCF of such a case is shown in Figure 1, for which the associated q_c and f_s profiles are shown in Figure 2a and 2b, respectively. In contrast, either a poor correlation (i.e., low values of $r_{q_c f_s}$) or a peak in $r_{q_c f_s}$ at an unreasonable value of k_{CCF} is usually calculated for shallower profiles which terminate within the fill, such as for the q_c and f_s profiles shown in Figures 2c and 2d, respectively (associated CCF shown in Figure 3 as a red line). This suggests the CCF performs better for layered deposits rather than homogeneous profiles, which has also been suggested by Mitchell et al. (2010).

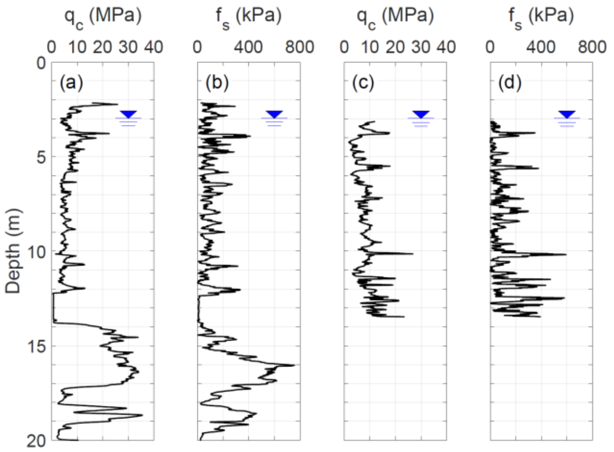

Figure 2. Profiles of raw q_c and f_s data where (a, b) k_{CCF} = 11 cm is calculated in a layered CPT profile, and (c, d) k_{CCF} = 0 cm is calculated in a homogeneous CPT profile.

The 101 CPTs are then grouped into five different categories based on how well-defined the peak values of $r_{q_c f_s}$ are, and whether the associated k_{CCF} values are reasonable. CPTs with a relatively well-defined peak in $r_{q_c f_s}$ are categorized into group A. CPTs with a moderately-well-defined peak in $r_{q_c f_s}$ is categorized into group B. Finally, CPTs with poor or no clear peak in $r_{q_c f_s}$ is categorized into group C. CPTs in categories A and B are further subdivided based on the k_{CCF} value. CPTs are categorized as A1 or B1 if k_{CCF} is considered reasonable (6-20 cm), and A2 or B2 if k_{CCF} is considered unreasonable.

Examples of typical CCFs for each of the five categories are illustrated in Figure 3. The example CPT profile in Figures 2a and 2b is in category A1 with the associated CCF shown as a black line in Figure 3, and the example CPT profile in Figures 2c and 2d is in category A2 with the associated CCF shown as a red line in Figure 3. Table 1 summarizes typical values and variation in k_{CCF} for CPTs in all five categories.

For CPTs in categories A1 and A2, the presence of a well-defined peak in $r_{q_c f_s}$ makes the choice of k_{CCF} straightforward, as shown by the examples in Figure 3. However, in the case of A1, the choice of k_{CCF} are reasonable values (7-17 cm), whereas in the case of A2, the k_{CCF} are not reasonable (0-5 cm). For CPTs in categories B1 and B2, the CCF peak is not as well-defined (though it can still exist), so there is subjectivity in the choice of k_{CCF}. In the B1 example in Figure 3, a relatively good correlation in the CCF is calculated for f_s depth corrections between 10 cm and 30 cm, with no well-defined peak like the A1 and A2 categories. A local maximum in $r_{q_c f_s}$ at a reasonable value of k_{CCF} is chosen for the B1 example in Figure 3. CPTs in the B2 category generally have k_{CCF} = 0. CPTs in category C have no clear peak in the CCF, and hence no value of k_{CCF} can be determined.

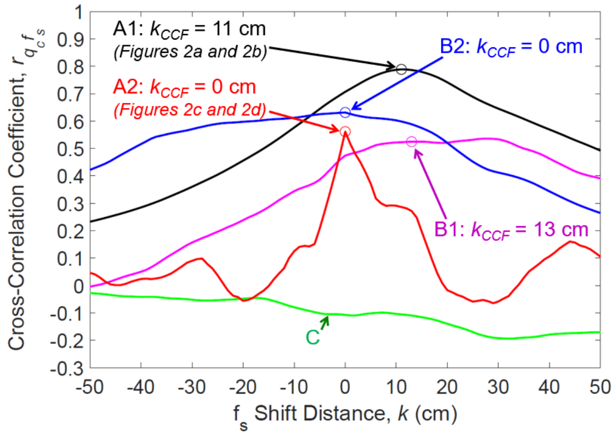

Figure 3. Example CCFs for the five CPT categories.

The 62 CPTs in categories A1 and B1 generally resulted in k_{CCF} values -1 cm to 2 cm greater than the physical separation distance (10 cm or 13 cm). Use of a depth correction slightly greater than the physical distance separating the cone tip and friction sleeve is consistent with cavity expansion theory (e.g., Vesic 1972; Teh and Houlsby 1991). Values of k_{CCF} less than the physical separation distance has also been found in some cases by Jaksa et al. (2000; 2002) and Mitchell et al. (2010), suggesting that the centroid of the failure region associated with q_c (illustrated in the inset of Figure 1) can be above the probe tip.

Table 1. Statistics of k_{CCF} based on the CCF for different CPT categories.

Category	No. CPTs	Mean k_{CCF} (cm)	Std. k_{CCF} (cm)	Range of k_{CCF} (cm)
A1	40	11.9	2.6	7 to 17
A2	21	1.3	2.0	0 to 5
B1	22	11.6	2.9	6 to 17
B2	12	0.0	0.0	0 to 0
C	6	N/A	N/A	N/A

The physical distance separating the cone tip and friction sleeve is the only basis for the f_s depth offset correction for the CPTs in categories A2, B2, and C, because a reasonable k_{CCF} is not calculated for these CPTs. The f_s depth correction for CPTs in categories A1 and B1 can be either based on the physical distance separating the cone tip and sleeve (10 cm or 13 cm) or k_{CCF} (6-17 cm). The sensitivity of characterization and liquefaction assessment parameters on the two possible f_s depth correction methods for the CPTs in categories A1 and B1 are the subject of the subsequent section.

6 SENSITIVITY STUDY

6.1 *Soil Classification Parameters*

15 CPTs in categories A1 and B1 either terminated due to a shallow gravel layer, or the pre-drill depth was too deep and

possibly missed shallow liquefiable layers. Such CPTs are not considered in liquefaction analysis, based on Dhakal et al. (2020b), and are therefore omitted herein. For the remaining 47 CPTs in categories A1 and B1, a parametric study is presented where the sensitivity of calculated soil classification and liquefaction analysis parameters on the two f_s depth correction methods (i.e., physical offset distance and k_{CCF}) are investigated.

For all 47 CPTs, the normalized friction ratio (F_r), cone tip resistance corrected for overburden stress (Q_{tn}), and soil behavior type index (I_c) are calculated at each depth using both f_s depth offset correction methods. The absolute difference at each depth using the two f_s correction methods, denoted $|\Delta F_r|$, $|\Delta Q_{tn}|$ and $|\Delta I_c|$, are averaged over the entire CPT profile and plotted against the absolute difference in the two f_s depth correction values, $|\Delta f_s^{shift}|$ ($= |k_{CCF} -$ physical separation distance$|$), in Figures 4a, 4b and 4c, respectively. $|\Delta F_r|$, $|\Delta Q_{tn}|$ and $|\Delta I_c|$ as a percentage of the value obtained using the physical distance f_s depth correction (F_r^{Phy}, Q_{tn}^{Phys} and I_c^{Phys}) are also averaged over the deposit and plotted against $|\Delta f_s^{shift}|$ in Figures 4d, 4e and 4f, respectively.

In Figure 4, the average change in all three parameters ($|\Delta F_r|$, $|\Delta Q_{tn}|$ and $|\Delta I_c|$) increase for larger $|\Delta f_s^{shift}|$. The average $|\Delta F_r|$ can be as large as 100% for a CPT profile (Figure 4d), whereas Q_{tn} and I_c are not as strongly linked to f_s, and therefore the changes in these parameters are relatively smaller. Q_{tn} (Figure 4e) is weakly linked to f_s, resulting in average changes of < 2% even for $|\Delta f_s^{shift}|$ as large as 6. I_c (Figure 4f) is slightly more sensitive to changes in f_s, though not as sensitive as F_r. Average changes in I_c can be as large as 0.12, particularly for larger $|\Delta f_s^{shift}|$ values, which is associated with approximately 6% change in I_c.

The larger values of $|\Delta F_r|$, $|\Delta Q_{tn}|$ and $|\Delta I_c|$ in Figure 4 are generally for CPTs in gravelly fill which have several spikes in q_c and f_s readings reflective of the cone interaction with larger gravel particles (Dhakal et al. 2020b). To illustrate the effects of these spikes on the sensitivity of soil classification, the I_c profile for a CPT within gravelly fill, with a relatively large $|\Delta I_c|$ ($\approx$ 4%) value as annotated in Figures 4c and 4f, is shown in Figure 5a. The spikes in q_c and f_s creates spikes in the I_c as well. Therefore, for the different f_s depth correction values, the positions of the spikes are offset by a few centimeters which results in the large $|\Delta I_c|$ at each depth.

However, actual CPT data, such as the I_c profile in Figure 5a, is often not used for rigorous characterization of soil deposits and certain aspects of liquefaction assessment (e.g., identification of critical soil layers). Simplified soil profiles with distinct soil layers are instead required. While several methods to develop simplified soil profiles using CPT measurements are available, this paper applies the algorithm developed by Ntritsos and Cubrinovski (2020). The resulting simplified I_c profiles are shown in Figure 5b.

Despite the change in I_c at each depth being > 5% on average (Figure 4f), the change in the average values of I_c for a particular soil layer in the simplified profile is largely < 2%. Similar results are observed when applying the Ntritsos and Cubrinovski (2020) algorithm to the I_c profiles of the remaining 46 CPTs. Therefore, while large differences in soil classification parameters can be observed at a particular depth, the average I_c values within soil layers are not sensitive to the choice of f_s depth correction.

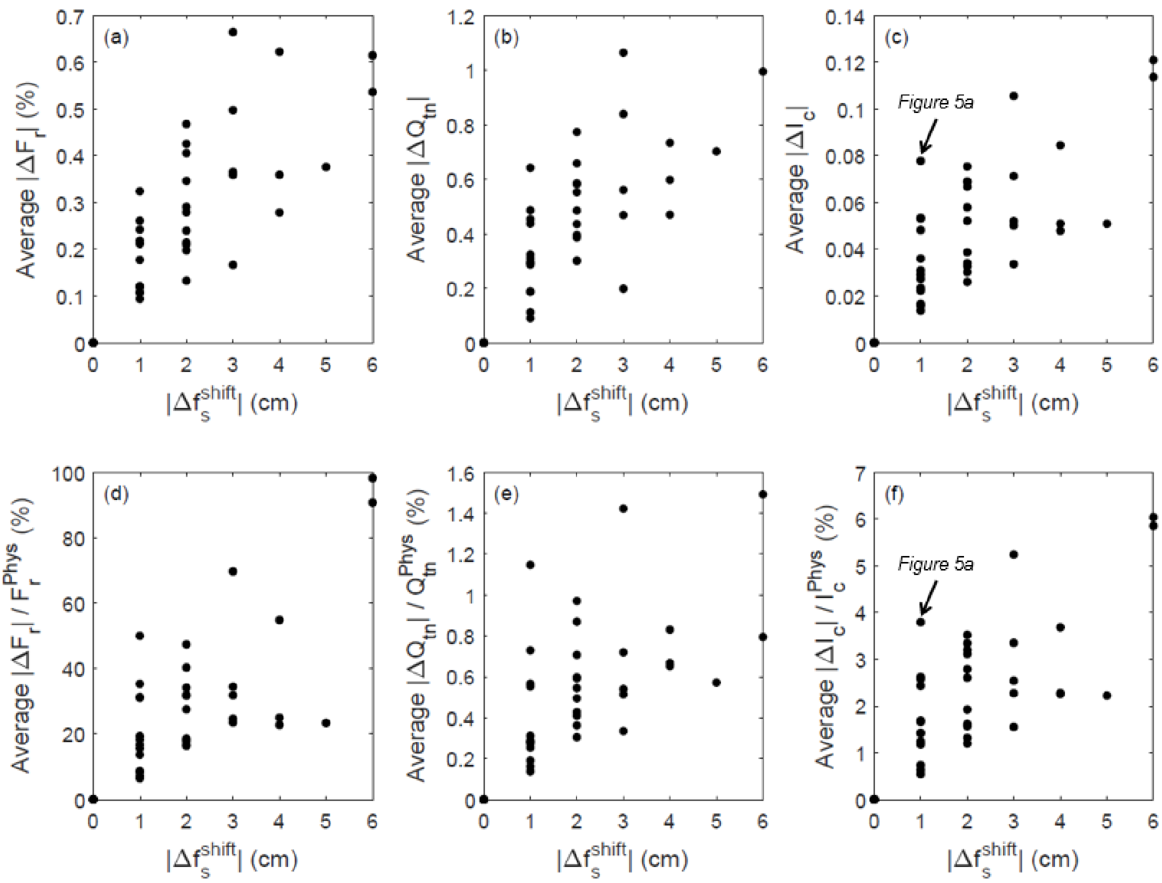

Figure 4. Sensitivity studies on 47 CPTs showing the average absolute difference in (a) F_r, (b) Q_{tn} and (c) I_c at each depth as a function of $|\Delta f_s^{shift}|$. The associated average absolute differences are shown as a percentage on (d), (e) and (f), respectively.

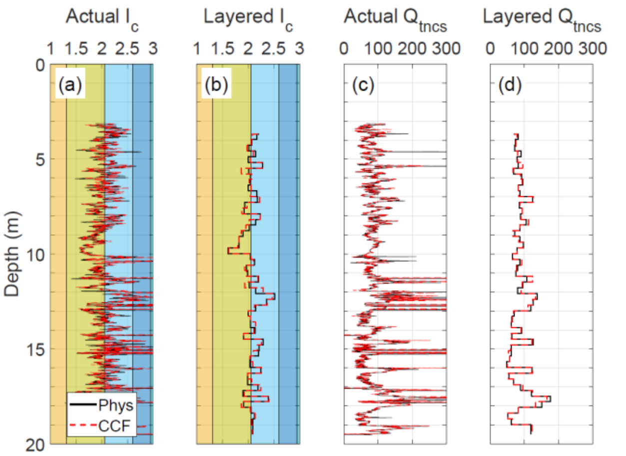

Figure 5. CPT profile of (a) actual I_c, (b) layered I_c, (c) actual Q_{tncs}, and (d) layered Q_{tncs} data using f_s depth corrections based on the physical separation (black line) and the CCF (red line) for reclaimed gravelly fill.

6.2 *Liquefaction Triggering Parameters*

This subsection investigates how the small differences in soil classification for the 47 CPTs affect the liquefaction triggering analysis by investigating the sensitivity of liquefaction triggering results on the two possible depth correction methods. Liquefaction triggering is evaluated for the seismic demand of the Kaikōura earthquake (M_w 7.8 and PGA = 0.25g) using the Robertson and Wride (1998) CPT-based procedure with the Robertson (2009b) update. In this method, the penetration resistance is first normalized by overburden pressure to obtain Q_{tn} which is then corrected to a clean-sand equivalent cone tip resistance (Q_{tncs}) using I_c calculated from the CPT. The resulting Q_{tncs} value is then empirically correlated to liquefaction resistance. Therefore, studying the effects of different f_s depth offset correction on Q_{tncs} incorporates the combined effects of Q_{tn} and I_c on the triggering results.

The absolute difference between Q_{tncs} obtained using both methods is calculated for each depth, denoted $|\Delta Q_{tncs}|$, and then averaged over the entire profile. This is plotted against $|\Delta f_s^{shift}|$ in Figure 6a for all 47 CPTs, while Figure 6d shows the same data as a percentage of the value calculated using the physical distance f_s depth correction (Q_{tncs}^{Phys}). Like in Figure 4, $|\Delta Q_{tncs}|$ tends to increase as $|\Delta f_s^{shift}|$ increases. The average change in Q_{tncs} values due to the different f_s depth correction methods can be generally as high as 5 to 15%, which is significantly larger than for Q_{tn} and I_c (Figures 4e and 4f).

Like in Figure 4, the largest values of $|\Delta Q_{tncs}|$ shown in Figures 6a and 6d are for CPTs in gravelly fill with several spikes in q_c and f_s. As shown by the CPT profile of Q_{tncs} in Figure 5c (same CPT as Figure 5a), which has a relatively large $|\Delta Q_{tncs}|$ (≈ 13%) value as annotated in Figures 6a and 6d, the spikes in q_c and f_s also creates spikes in the calculated Q_{tncs}. Again, these spikes are offset by a few centimeters for the different f_s depth correction values, resulting in large $|\Delta Q_{tncs}|$ of approximately 12. In contrast, profiles of hydraulic fill which do not exhibit such spikes in the CPT readings generally have $|\Delta Q_{tncs}| < 10\%$. When applying the Ntritsos and Cubrinovski (2020) algorithm, the change in the average values of Q_{tncs} for a particular soil layer in the simplified profile reduces to < 5%, as shown in Figure 5d. Hence, despite the change at each individual depth reading potentially being as large as 5 to 15% (typically), there is a much smaller change in the average Q_{tncs} values within a soil layer.

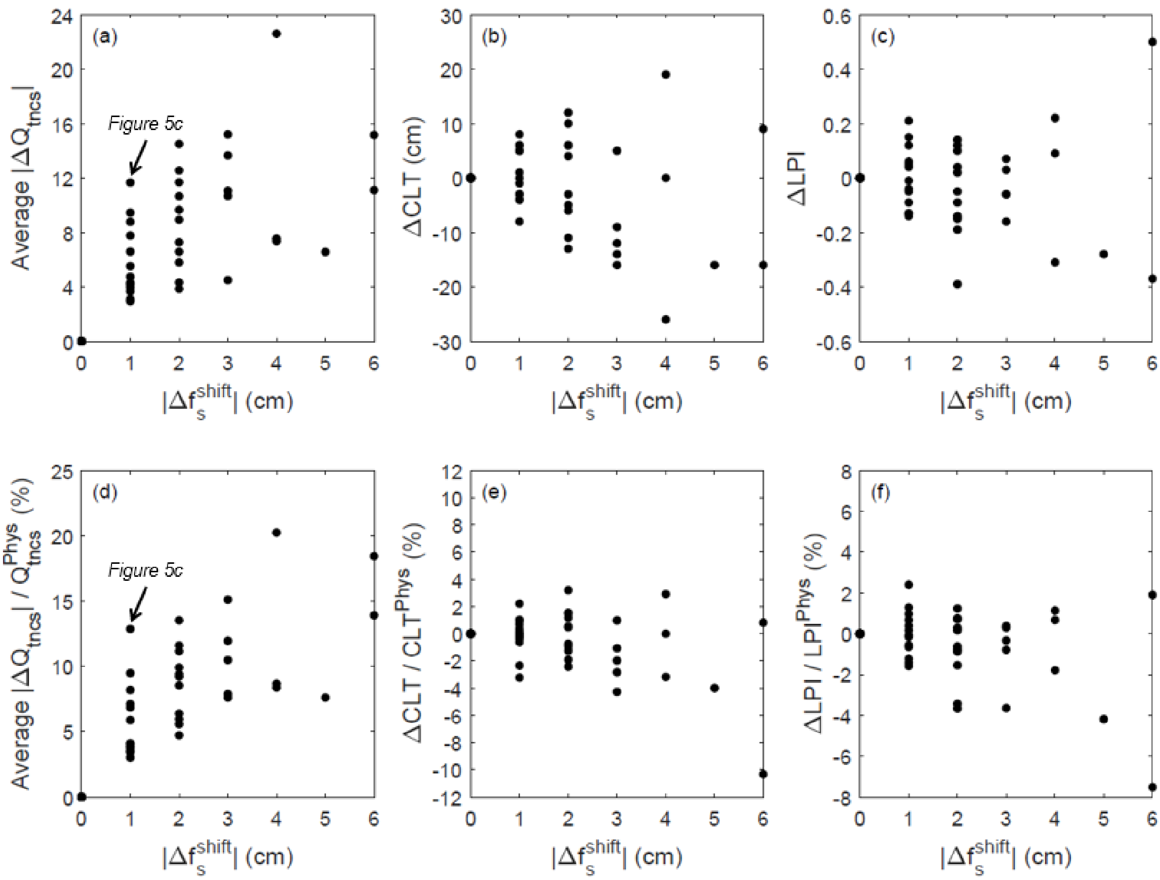

Figure 6. Sensitivity studies on 47 CPTs showing (a) the average absolute difference in Q_{tncs} at each depth, (b) difference in CLT and (c) difference in LPI as a function of $|\Delta f_s^{shift}|$. The associated differences are shown as a percentage on (d), (e) and (f), respectively.

To better understand the cumulative-depth effect of these changes to liquefaction triggering results, the sensitivity of two damage indices on the two f_s depth correction methods are also investigated. Damage indices considered in this study are the Cumulative Liquefied Thickness (*CLT*), which is the total thickness of the deposit where liquefaction is estimated to trigger, and Liquefaction Potential Index (*LPI*; Iwasaki et al. 1981). The difference between the *CLT* calculated using the k_{CCF} correction and the physical separation correction, denoted ΔCLT, is shown in Figure 6b, and reproduced in Figure 6e as a percentage difference. The difference between the *LPI* calculated using the k_{CCF} correction and the physical separation correction, denoted ΔLPI, is shown in Figure 6c, and reproduced in Figure 6f as a percentage difference.

With the exception of one CPT, *CLT* and *LPI* change by less than 20 cm and 0.4, respectively, which is associated with < 5% change. Both the absolute and relative changes for *CLT* and *LPI* are small suggesting little sensitivity of these parameters to the f_s depth correction methods. The one CPT with > 5% $|\Delta CLT|$ and $|\Delta LPI|$ has very low base values of *CLT* and *LPI* of 1.6 m and 5, respectively, so the overall calculated damage index is still expected to remain at the same (minor) level.

Results from the sensitivity study have shown that even when the f_s depth offset correction differs by as much as 6 cm, the soil classification and liquefaction triggering results are not significantly affected for a given soil layer. Therefore, it is recommended that a method that can be consistently applied across all CPTs be used. As reasonable f_s depth corrections using the CCF technique could not be calculated for 40% of the 101 CPTs at this site, the physical vertical distance separating the cone tip and midpoint of the friction sleeve should be used when applying the f_s depth offset correction to achieve consistency.

7 CONCLUSION

This paper first studies the applicability of the CCF for 101 CPTs performed on reclaimed gravelly and hydraulic fills. The CCF produces reasonable shift distances (6-20 cm) for only 60% of the profiles. The CCF shift distances are generally -1 to 2 cm greater than the physical distance from the tip of the cone to the mid-point of the friction sleeve for these cases. The remaining 40% of the CPTs either have no clear cross-correlation peaks or have a peak at an unreasonable f_s shift distance (0-5 cm), and therefore the physical distance separating the cone tip and sleeve is the only basis for applying the f_s depth correction.

47 CPTs with reasonable CCF depth corrections are then used to investigate the sensitivity of key soil classification and liquefaction triggering assessment parameters based on two possible f_s depth correction methods (i.e., physical distance between the cone tip and sleeve, or the CCF). While there can be a significant change to calculated parameters, such as F_r, I_c and Q_{tncs}, at a particular depth, the average values for given soil layers change by < 5%. In liquefaction triggering assessment, small differences in the calculated damage indices such as *CLT* and *LPI* do not cause changes to the outcomes of the assessment. A consistent f_s depth correction method that can be consistently applied across all CPTs should be used. Therefore, the depth offset correction should be made using the physical distance separating the cone tip and the midpoint of the friction sleeve.

8 ACKNOWLEDGEMENTS

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