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Strength and Stress Estimation in Soil Bentonite Slurry Trench Cutoff Walls using Cone Penetration Test Data

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ABSTRACT

The Cone Penetration Test (CPT) is widely used for classifying soils and assigning soil properties to the subsurface because it is robust and can be used to quickly collect continuous data with depth. During and subsequent to the construction of a very deep soil-bentonite (SB) slurry trench cut-off wall in Mayfield NSW, Australia, the CPT was used to check the continuity and quality of the SB backfill material. The numerous CPT profiles conducted in the Mayfield wall provided a unique research opportunity for examining how shear strength and effective stress vary with depth. A method is proposed to estimate the undrained shear strength of the Mayfield Wall from the CPT combined with some vane shear data. The results support previous studies that show that the shear strength and the effective stress distributions in SB slurry trench cutoff walls are less than would be expected from a geostatic stress distribution. While there is some increase in shear strength with depth, these data show the increase is modest and consistent with the less than geostatic stresses. In addition, the authors recommend a general procedure for shear strength and horizontal stress estimation using CPT data in any SB slurry trench application.

INTRODUCTION

Continuous readings with depth, a robust testing system, and ease of use make the Cone Penetration Test (CPT) an important tool for classifying soils and assigning engineering properties to the subsurface. Although not commonly specified for quality control (QC) assessment of vertical cutoff walls due to measurement accuracy limitations and cost constraints, the CPT has been used on a select number of soil-bentonite (SB) slurry trench cutoff wall projects to gauge backfill homogeneity and to assess *in-situ* strength development over time.

The CPT with pore pressure readings (CPTu) was used as part of the QC program on the deepest SB wall ever built. The wall was constructed in 2006 in Mayfield, Australia as part of a brownfield redevelopment project. Two papers written about the project, Jones et al. (2007) and Ryan and Spaulding (2008), address the wall construction and shear strength, respectively. The Mayfield wall was constructed in a broad alluvial plain bordering the Hunter River near Newcastle in New South Wales, Australia. The wall was installed through a medium sand alluvial layer that varied from 30 to 50 meters thick. Sandstone bedrock was encountered across approximately half of the wall and a fine-grained aquaclude over the remainder. At its deepest point, the wall was installed to a depth of 49 m and it has an overall length of 1500 m. The QC testing program for this project included 24 CPTu profiles.

Although the state-of-stress in SB cutoff walls has been shown to be less than geostatic, the stress distribution is not fully understood. Earlier works (Evans et al. 1985, Evans et al. 1995, Filz 1996, Ruffing et al. 2010) explore how the state-of-stress varies with depth and the impact of stress state on the hydraulic conductivity of SB backfill material. The main objective of the Mayfield data analysis was to improve understanding of the magnitude and variability of the undrained shear strength (S_u) in SB backfill and to use these results to estimate the horizontal effective stress.

SHEAR STRENGTH ESTIMATION FROM CPTu DATA

Five different relationships between CPTu data and S_u, presented in Powell and Lunne (2005), were used to investigate the correlation between shear strength and depth for the flowable SB fill. Undrained shear strength is highly dependent on the initial stress state, direction of loading, rate of loading, and stress history of a soil (Mayne 2001). Methods used to predict S_u from CPTu data must therefore rely on empirical correlations developed from data collected in soils with similar stress and depositional histories. The five shear strength estimation methods (Powell and Lunne 2005) that were evaluated in this study are shown on Table 1.

TABLE 1. Investigated Shear Strength Estimation Methods for CPTu Data

Method Name	Equation	Where:	Equation Number
Excess Pore Pressure	$S_u = \dfrac{\Delta u}{N_{\Delta u}}$	$N_{\Delta u}$ = a theoretical cone factor that generally falls between 7 and 10, $\Delta u = u_2 - u_0$, and u_2 = pore pressure measured just behind cone tip shoulder, u_0 = static pore pressure	(1)
Total Cone Resistance	$S_u = \dfrac{(q_t - \sigma_{vo})}{N_{kt}}$	N_{kt} = a theoretical cone factor that generally falls between 10 and 20, q_t = corrected tip resistance, σ_{vo} = vertical effective stress	(2)
σ_{vo} Theory	$S_u = \dfrac{(q_c - \sigma_{vo})}{N_c}$	N_c = a theoretical cone factor, q_c = un-corrected tip resistance, σ_{vo} = vertical effective stress	(3)
σ_{mean} Theory	$S_u = \dfrac{(q_c - \sigma_{mean})}{N_c}$	N_c = a theoretical cone factor, q_c = un-corrected tip resistance, σ_{mean} = mean total stress	(4)
Effective Cone Resistance	$S_u = \dfrac{(q_t - u_2)}{N_{ke}}$	N_{ke} = a theoretical cone factor that generally falls between 1 and 13, q_t = corrected tip resistance, u_2= pore pressure measured just behind cone tip shoulder	(5)

For very soft clays, Powell and Lunne suggest using the method based on excess pore pressures. Since the backfill material in a SB wall can be described as very soft clayey material, this "excess pore pressure" method was the first examined. However, using the excess pore pressure method and data from a representative CPTu log resulted in both unreasonable and infeasible shear strength values. For example, many of the shear strength values resulting from the application of this method to the Mayfield CPTu test results were negative. Negative shear strength values are clearly not possible and therefore this method was deemed inappropriate for SB cutoff wall backfill.

Three of the methods, the “total cone resistance”, “σ_{vo} theory”, and “σ_{mean} theory” require knowledge of the state of stress in at least one dimension. As indicated in the introduction, the state of stress in SB walls is not known with sufficient certitude and thus methods that required input of stress state are considered inappropriate for predicting S_u from CPTu data collected in SB cutoff walls. Due to the inapplicability of these three methods requiring knowledge of the stress state and the infeasible results obtained from the analysis using the “excess pore pressure” method, the “effective cone resistance” method remained as the sole potential method for predicting S_u vs. depth for the Mayfield Project, and more broadly for any SB wall.

Unlike the four methods just discussed, the effective cone resistance method requires no prior knowledge of the stress state or static pore pressure, but, like the other methods, does require the user to select a cone factor, N_{ke}. Previous studies, as described in Powell and Lunne (2005), indicate that N_{ke} correlates well with the pore pressure parameter, B_q. The pore pressure parameter data from the Mayfield data set and the presentation in Powell and Lunne (2005) indicate that a value of 12 for N_{ke} would be appropriate.

Alternatively, if S_u is measured independently by other means on a project, then the N_{ke} factor can be directly calculated using this additional coupled CPTu-S_u data. On the Mayfield project, the QC program included a limited number of vane shear tests to measure S_u. In order to assess the cone factor on this project, the coupled CPTu and vane shear data was used to calculate cone factors. This analysis also provided an opportunity to investigate whether or not the N_{ke} factor varies with depth. The N_{ke} factors as a function of depth obtained from comparison of the vane shear and CPTu data in the Mayfield wall are shown in Fig. 1 along with a best-fit, power function trend line.

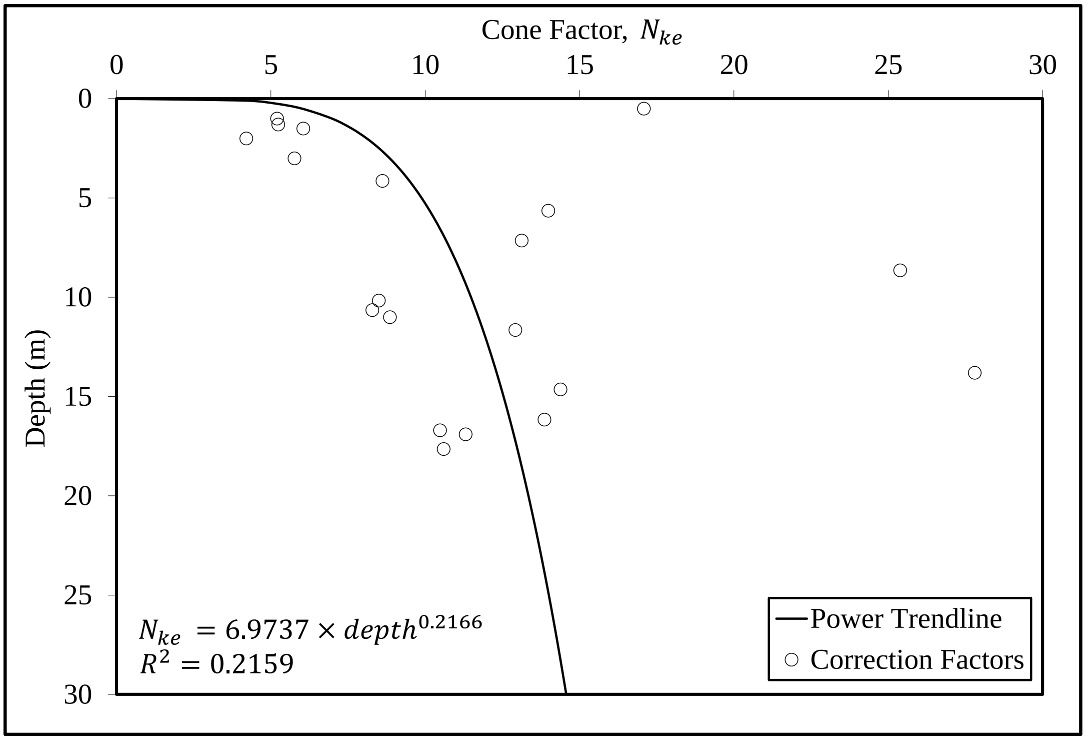

FIG 1. Cone Factor, N_{ke}, vs. Depth

The data presented in Fig. 1 shows considerable scatter. This scatter is probably due to small sand and gravel or other non-representative inclusions to which both the CPT and the vane shear are known to be sensitive. Small sand or gravel inclusions in this wall could be expected from the soils at this site. Despite the scatter, the conceptual relationship between cone factor and depth indicates that the cone factor increases with depth to an approximate maximum of 15. The arithmetic average of the data in Fig. 1 results in a cone factor of 11.5. The authors note that the average cone factor calculated using the vane shear data, 11.5, compares well to the cone factor, N_{ke} = 12, predicted from the pore pressure parameter discussed earlier.

The "effective cone resistance" method and correction factor, N_{ke}, were then used with the CPTu data to determine the undrained shear strength. The first step in determining S_u from CPTu data was to correct the measured tip resistance was for pore pressure effects using the following equation:

$$q_t = q_c + (1 - a) \times u_2 \tag{6}$$

Where, q_t = corrected tip resistance, q_c = raw tip resistance, a = area ratio (0.73 for this project), and u_2 = pore pressure measured at the shoulder of the cone

After tip resistance correction, excessively large values of cone resistance found near the bottom of the CPT profiles were removed. These values were likely the result of the cone encountering the trench bottom making them unrepresentative of the strength of the backfill. In addition to editing out values near the bottom, other values at all depths were deleted if they were significantly larger than the surrounding data points. The authors believe that the uncharacteristically high readings observed in some of the profiles may have been caused by pieces of gravel suspended in the backfill and are therefore not representative of the overall strength of the backfill. The elimination of this "anomalous" data was performed using the authors' judgment, but the deleted data primarily consisted of values of tip resistances above 300-500 kPa.

Finally, after the tip resistance was corrected for pore pressure effects and anomalous values of tip resistance were removed, the shear strength was calculated using the "effective cone resistance" method presented on Table 1. Shear strength was calculated individually for each data point. Once S_u was calculated for each depth point for each of the 24 data sets, all 24 data sets of S_u vs. depth were averaged to create one data set representing the average S_u in the wall vs. depth. This average S_u data set was then "smoothed" using a three point running average. The combined, smoothed S_u data set is presented in Fig. 2.

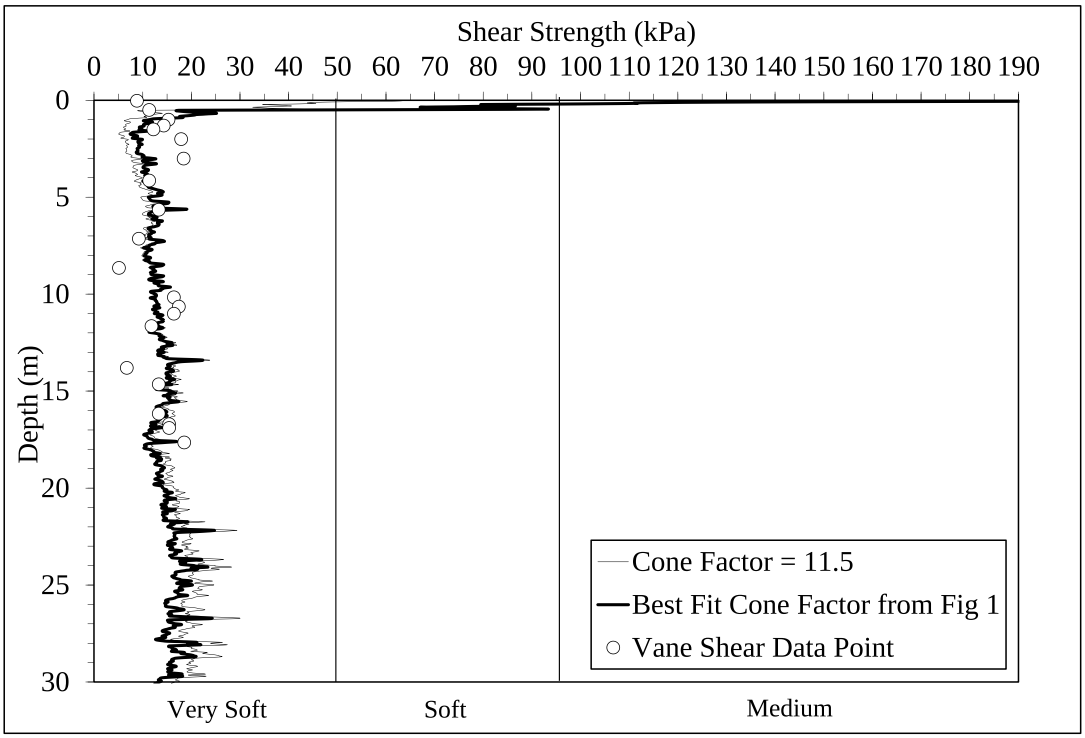

FIG 2. Shear Strength vs. Depth for Mayfield Wall

The plots of S_u vs. depth, presented in Fig. 2, show the predicted shear strength using both a constant cone factor of 11.5 and a varying cone factor calculated from coupled CPT and vane shear data. For comparison, Fig. 2 also includes the vane shear data and typical clay shear strength classifications. The presentation in Fig. 2 shows that regardless of the choice of constant or varying cone factor, the shear strength calculated from the CPT data increases only slightly with depth and is indicative of a very soft clayey material. The shear strength calculated using the constant cone factor is used in subsequent analyses in this paper because the results are similar between the constant and varying cone factor and the cone factor developed for this study, 11.5, compares well with that suggested in the literature.

EFFECTIVE STRESS FROM SHEAR STRENGTH

Shear strength is known to be directly related to the effective confining stress (Lambe and Whitman 1969, Holtz and Kovacs 1981,) and there should be a linear gain in shear strength with depth for effective confining stresses increasing linearly with depth. In contrast, if the effective stress is constant with depth, the shear strength should be constant with depth. The relationship between shear strength and effective stress has been the topic of numerous publications. Several published relationships between shear strength and vertical effective stress for a normally consolidated soil, in the form of the S_u/σ'_{vo} ratio, are presented on Table 2.

TABLE 2. Relationships between Shear Strength and Vertical Effective Stress

Source	Details	S_u/σ'_{vo}
Lambe and Whitman 1969	OCR = 1	0.3 +/– 0.1
Mayne 2001	Theoretical Wroth-Prevost Model (Φ'=26°, OCR = 1)	0.1-0.3
	Normalized Ratio from Critical State Model (Φ'=26°, OCR = 1)	0.1-0.3
Degroot 2001	SHANSEP at OCR = 1 to 4: $S_u/\sigma'_{vo} = 0.19(OCR)^{0.75}$	0.23[a]
	SHANSEP at OCR = 1: $S_u/\sigma'_{vo} = 0.18(OCR)^{0.73}$	0.22[a]
Robertson and Cabal 2007	Φ'=26° in direct simple shear	0.22

[a] OCR = 1.3 for SB materials (Evans and Ryan 2005)

For S_u in the relationships shown on Table 2, the effective vertical stress is generally the major principal stress. In “normal” soils the vertical effective stress is the major principal stress and therefore the largest contributor to the soil strength. For the S_u derived from CPTu data collected in SB backfill, it is not clear whether the relationship between shear strength and effective stress is one between the vertical, horizontal, or mean stress. While the state of stress in soil bentonite slurry trench cutoff walls is not fully understood and is expected to vary in all three directions, it can be reasonably assumed, at significant depths, that the horizontal effective stress is the major principal stress and therefore controls the soil backfill strength. With the assumption that the major principal stress is horizontal, the calculated backfill shear strength from the CPT test coupled with the S_u/σ' relationship from the information in Table 2 can then be used to calculate the horizontal effective stress in the cutoff wall. This calculation of horizontal stress inherently assumes that the σ'_{vo} component of the published S_u/σ'_{vo} ratios represents the major principle stress for normal soils and thus the same relationship can be directly applied to horizontal stress calculation in the SB backfill where the major principle stress is expected to be the horizontal stress. The calculated horizontal effective stress from the CPTu data is plotted next to the stress values predicted by geostatics, the arching model (from Evans et al 1995) and the modified lateral squeezing (MLS) model (from Ruffing et al 2010) in Fig. 3. Equations and information used for Fig. 3 are presented on Table 3.

TABLE 3. Effective Stress Equations for Presentation in Figures 3a & 3b

Stress Direction	Model	Effective Stress Equation	Equation Number
Horizontal	Geostatics	$\sigma'_h = \gamma'_b \times \text{depth} \times k_{ob}$	(7)
	Arching	$\sigma'_h = \sigma'_{v-\text{arching}} \div k_{ob}$	(8)
	MLS	$\sigma'_h = \sigma'_{h-\text{MLS}}$	(9)
Where: the soil properties, $\sigma'_{v-\text{arching}}$, and, $\sigma'_{h-\text{MLS}}$ are from Ruffing et al (2010), γ'_b = unit weight of backfill, σ'_v = vert. effective stress, $k_{ob} = 0.5$, σ'_h = horiz. effective stress			

The presentation in Fig. 3 includes two plots of the horizontal effective stress calculated using the consensus S_u/σ' ratio (0.22) for a normally consolidated soil and using the upper bound of the S_u/σ' ratio (0.3), both from Table 2.

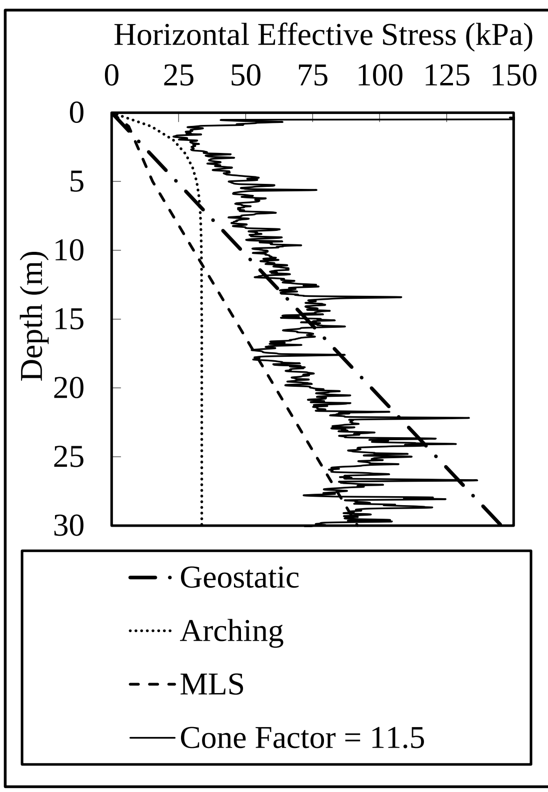

FIG 3a. Horizontal Effective Stress vs. Depth (S_u/σ' = 0.22)

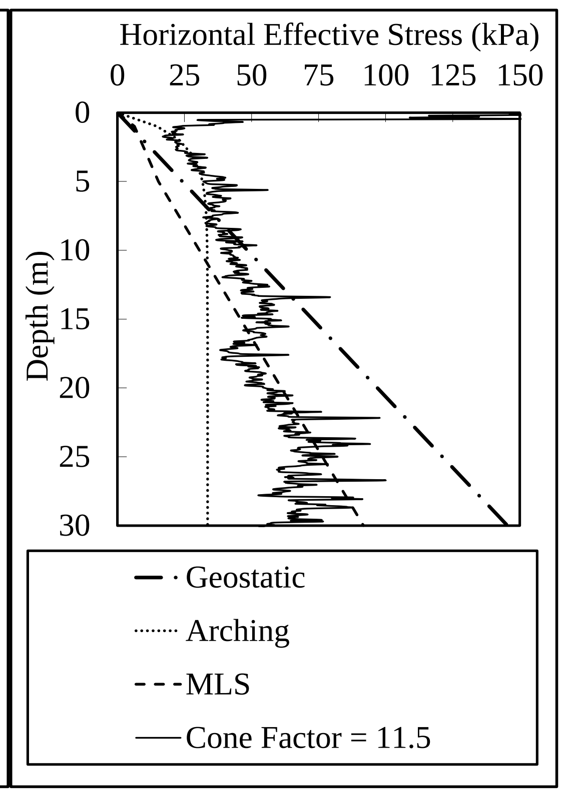

FIG 3b. Horizontal Effective Stress vs. Depth (S_u/σ' = 0.3)

Fig. 3a shows that the horizontal effective stresses predicted from the shear strength calculated from the Mayfield CPTu data using the consensus S_u/σ' ratio (0.22) are significantly higher than the horizontal effective stresses predicted by the MLS model in the depth range of 0 - 15 m. The predicted stress from the MLS model matches most closely after a depth of about 15 m. Above 15 m the calculated effective stress from the CPTu data is higher than that predicted by any of the models presented.

Fig. 3b shows that the horizontal effective stress calculated using the shear strength calculated from the Mayfield CPTu data and a S_u/σ' equal to the upper bound of the published ranges (0.3) matches well with the horizontal effective stress predicted by the arching model from approximately 0 – 10 m and with the MLS model from approximately 10 – 30 m.

DISCUSSIONS

Ryan and Spaulding (2008) presented calculated the shear strength in the Mayfield wall using the "total cone resistance" method. An assumption of the vertical effective stress and the in situ pore pressure in the wall, both of which are not well known, are required for this calculation method. The shear strength calculated in Ryan and Spaulding (2008) has the same shape as that presented in Fig. 2 using a constant correction factor, but the values presented there tend to be even less than those presented herein. This is due to inherent differences between the total and effective cone resistance methods and the choice of a larger cone factor (Ryan and Spaulding used an N_{kt} of 15). Both the calculation method choice and cone factor selection are critical in determining the shear strength from CPTu data.

Since the CPTu data is, in reality, a function of mean effective stress and that the controlling major principal stress is likely not the vertical stress for the entire depth of the wall makes calculating the shear strength of SB backfill from CPTu data very complicated. A principal stress rotation from vertical to horizontal in a direction perpendicular to the axis of the wall, no doubt occurs with depth. Also, the stress may be expected to vary in all three dimensions with the longitudinal stress being the lowest. Therefore, as mentioned, the stress conditions in an SB wall are different than those in a normally consolidated soil where the vertical stress is the major principle stress and the minor principal stresses are equal. The effect of these differences in stress conditions upon the CPTu test results is not known although the authors believe that the horizontal effective stress is the major principal stress in SB cutoff walls and therefore the largest contributor to strength development in SB backfill, particularly at great depth where lateral squeezing controls rather than arching.

It is important to note that nearly all commercially available CPTu systems were developed for use in a wide range of soil conditions and are therefore of limited precision when used in evaluating a normally consolidated material of a very soft consistency. This limitation must be considered when selecting the CPTu test for use in an overall QC program on an SB cutoff wall.

CONCLUSIONS

In summary, the effective cone resistance method using a constant cone factor is a reasonable method for calculating S_u from CPTu data collected in a SB wall because it does not require any prior knowledge of the in-situ stress state or the initial pore pressure in the wall. In addition, this method produces shear strength values of a magnitude that are consistent with those from other studies. Based on the analysis presented herein, the authors recommend the following equation for calculating soil bentonite backfill shear strength from CPTu data:

$$S_u = \frac{\left(\left(q_c + (1-a)\cdot u_2\right) - u_2\right)}{N_{ke}} \qquad (10)$$

Where, q_c = raw tip resistance, a = area ratio, and u_2 = pore pressure measured at the shoulder of the cone. A cone factor, N_{ke}, of 11.5 was selected for this project.

A limitation of this method (and many others) is its dependence on the choice of the cone factor. Cone factor choice in this application should be evaluated further. In this case, there was sufficient data in the form of vane shear tests to support a cone factor of 11.5.

The shear strength in the Mayfield Wall, calculated using Eq. 10, was generally 10 – 25 kPa which is 60% – 100% higher than the estimated shear strengths presented in Ryan and Spaulding (2008). In both cases, however, the shear strength of soil-bentonite backfill results in a "very soft" classification of the backfill.

The shear strength calculated using Eq. 10 can also be used to calculate the horizontal effective stress in a cutoff wall using a S_u/σ_h' ratio of 0.2 - 0.3. The upper bound of this range, 0.3, is recommended because this will conservatively result in the lowest calculated stress. The resulting equation for calculating horizontal effective stress from CPTu data is:

$$\sigma_h' = \frac{\left(\left(q_c + (1-a)\cdot u_2\right) - u_2\right)}{0.3\cdot N_{ke}} \qquad (11)$$

The horizontal effective stress calculated using the CPTu data collected in the Mayfield wall and a S_u/σ_h' ratio of 0.3 closely matched the horizontal effective stress predicted by the arching model from 0 – 10 m and the MLS model from 10 – 30 m.

As discussed above, it is important to recognize the general limitations of the CPTu test in the testing of SB cutoff walls. These include the accuracy of the load cells in the cone as well as the heterogeneity of the wall. Many of the cones currently available are intended for use in a wide range of soils, including heavily over-consolidated deposits with high strength. For this reason, the load cells may not be accurate in the low stress conditions found in SB walls. Also, despite efforts by designers and contractors to ensure homogeneity in SB backfill, there can be significant differences in the shear strength of the backfill due to the presence of large clay lumps, rocks, and sand. These "anomalies" result in measured values of shear strength that may be higher than that of the bulk cutoff wall. Engineering judgment will always be required to account for these inherent issues when using CPTu data to calculate the in-situ shear strength or effective stress of SB backfill.

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