Interpretation and Correlation of CPTu and Vane Shear Tests for Very Soft Varved Silty Clays – A Case Study

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
A geotechnical testing program has been carried out for site characterization for the design of an earthfill dyke at the south limit of the Northern Quebec region. The preliminary program involved piezocone testing (CPT_u) and field vane shear testing (VST) associated with sampling of the very soft varved silty clay foundation. The undrained shear strength profiles estimated from the VST tests were much lower than expected, based on the CPT_u tests results. The N_{kt} coefficient used to compare the VST and CPT_u results were in the typical range for the clay present on site.
Additional VST tests were carried out with a manual vane apparatus in several locations down to a depth of about 6 m. The results of the second field test program did not correlate with the CPT_u results, even if the additional vane tests seemed to be more representative. As a result, a new testing program was recommended in order to obtain high quality measurements along the dyke alignment. This third testing program has been made taking into account the difficulties and uncertainties of the previous testing programs: therefore vane tests were carried out with care in order to eliminate any remoulding of the soft clay and CPT_u tests were performed using a more accurate probe.
This paper presents the site background, the testing programs and results, and highlights the difficulties encountered in the testing of very soft varved silty clays and in the calibration of CPT_u profiles using the VST data.

RÉSUMÉ
Un programme d'essais géotechniques a été réalisé pour la caractérisation d'un site en vue de la conception d'une digue en terre à la limite sud de la région Nord-du-Québec. Le programme préliminaire comprenait des essais au piézocône (CPT_U) et au scissomètre de chantier (VST) ainsi que l'échantillonnage de l'argile silteuse varvée et très molle de la fondation. Les profils de résistance au cisaillement non drainé estimés à partir des essais VST étaient beaucoup plus faibles que prévu, sur la base des résultats des essais CPT_U. Le coefficient N_{kt} utilisé pour comparer les essais VST et CPTU étaient dans la gamme typique pour le type d'argile présente sur le site.
Des essais VST supplémentaires ont été réalisés à plusieurs endroits avec un appareil manuel jusqu'à une profondeur d'environ 6 m. Les résultats du deuxième programme d'essais sur le terrain ne correspondaient pas bien avec les résultats du CPT_U ; toutefois, ces essais VST supplémentaires semblaient être plus représentatifs. En conséquence, un nouveau programme d'essais fut recommandé afin d'obtenir des mesures de haute qualité le long du tracé de la digue projetée. Ce troisième programme d'essais a été réalisé en tenant compte des difficultés et des incertitudes des programmes d'investigation précédents: les essais VST ont été réalisés en prenant soin d'éviter tout remaniement de l'argile molle et des essais CPT_U ont été effectués en utilisant une sonde plus précise.
Cet article présente l'emplacement du site, les programmes d'investigation et leurs résultats, et met en lumière les difficultés rencontrées dans l'investigation l'argile silteuse varvée et très molle et dans l'étalonnage des profils CPT_U utilisant les données VST.

1 INTRODUCTION

Tailings storage facility (TSF) of Matagami Mine contains three (3) main basins: West, Central and South, as shown in Figure 1. The West Basin has been closed in 2008, the deposition of tailings in the Central Basin ended in 2014 and the tailings are presently discharged into the South Basin. South Basin has been used in the past to store small amounts of tailings but it was until recently used as a polishing pond. From now on, the water level in the South Basin will be raised progressively based on deposition and freeboard considerations up to a nominal closure water level of 265.5 m with external dikes at a nominal crest elevation of 266.5 m (Phase I). Three peripheral dikes will be required for operations and for closure to maintain adequate freeboard: the South-west dike, a new South dike and a dike called South-east dike. There might be further in time a Phase II where the water level could reach 267.5 m and the containing dikes 269 m. Soft varved silty clay is present in the foundation of these dikes. An assessment of the shear strength of the clay was necessary for the design of the projected dikes.

A geotechnical testing program has been carried out for site characterization for the design of an earthfill dyke at the south limit of the Northern Quebec region. The preliminary program involved piezocone testing (CPTu) and field vane shear testing (VST) associated with sampling of the very soft varved silty clay foundation. The values of undrained shear strength on profiles estimated from the VST tests were much lower than expected, based on the CPTu tests results. The N_{kt} coefficient used to compare the VST and CPTu results were in the typical range for the clay present on site.

Additional VST tests were carried out with a manual vane apparatus in several locations down to a depth of about 6 m. The results of the second field test program did not correlate with the CPTu results, even if the additional vane tests seemed to be more representative. As a result, a new testing program was recommended in order to obtain high quality measurements along the dyke alignment. The main results of these three testing will be presented and compared. In particular, the few incoherent results of the 2012 campaign for the clay undrained shear strength will be examined in the light of the 2013 confirmation data.

This paper presents the site background, the testing programs and results, and highlights the difficulties encountered in the testing of very soft varved silty clays and in the calibration of CPTu profiles using the VST data.

2 SITE GEOLOGICAL DESCRIPTION

The topography of the Matagami area is essentially flat; the level of the natural surface of the ground relative to sea level generally varies from 250 m to 300 m. However, some small isolated hills such as Mount Laurie (466 m) and Mount McIvor (380 m) can be found. The bedrock is irregular, flushing in some places or having the appearance of small mounds. The last glaciation has largely shaped the current topography. This region is part of the bio-geographic region of Abitibi Plateau which includes lowlands (plains and valleys) slightly inclined towards James Bay.

2.1 Regional Geology

The Matagami area is located in the central part of the Canadian Shield. The Matagami mining camp is part of the Superior Lake province, which is composed of successive and generally discordant sequences of volcanic and sedimentary rocks of Archean age (2.7 Gyr), invaded by granitic and gabbroic intrusive elongated masses. This set of rocks underwent intense deformation, intrusion, metamorphism and granitization.

2.2 Surficial Geology

Soils overlying the bedrock are from glacial and post-glacial origin. The most recent unconsolidated deposits include alluvial and organic deposits (peatland) in poorly drained areas.

Deposits overlying the bedrock consist of till layers of varying thickness, a deposit of silt and sand and a thick layer of varved silty clay. The grain size of the varved clay deposit becomes coarser with depth. The transition between layers of silt-sand and the basal till is gradual, so it is very difficult to clearly identify the layers. The overburden thickness varies from 0 m (rock outcrops) to over 30 m in the valleys.

The varved clay deposits of the Matagami area were formed during the last phase of Lake Ojibway. These clays are highly compressible, have low shear strength and are sensitive to remoulding.

2.3 Tailings Storage Facility

The tailings storage facility (TSF) is located approximately 10 km to the west of the city of Matagami and 3 km to the south-east of Matagami's airport. The tailings impoundment of Matagami Mine has been in operation since the early 60s. Figure 1 shows the TSF site.

3 TYPICAL SITE STRATIGRAPHY

The typical natural ground profile found at the TSF site is composed of about 0.5 to 2.5 m thick of peat, 1 to 3 m thick of brown clay and up to 20 m thick of grey clay. The brown clay is silty clay generally stiff. The grey clay is very soft varved silty clay. Between the grey clay and the rock, the presence of relatively thin and variable layers of fine sand and till has often been observed.

Table 1 describes the typical geotechnical parameters of the brown silty clay and the grey varved silty clay typically found at the TSF site.

Table 1. Typical parameters of clays on TSF site

Parameter	Brown clay	Grey clay
γ (Unit weight, kN/m^3)	15.5 - 16.5 (16)	14.0 - 16.0 (15)
w (water content, %)	27 - 50 (35)	60 - 110 (80)
w_L (liquid limit, %)	55 - 70	45 - 90
w_P (plastic limit, %)	22 - 30	25 - 35
I_P (plastic index, %)	35 - 40	30 - 60
S_u (undrained shear strength, kPa)	30 - 105 (40)	5 - 25 (15)
Parentheses () indicates average values		

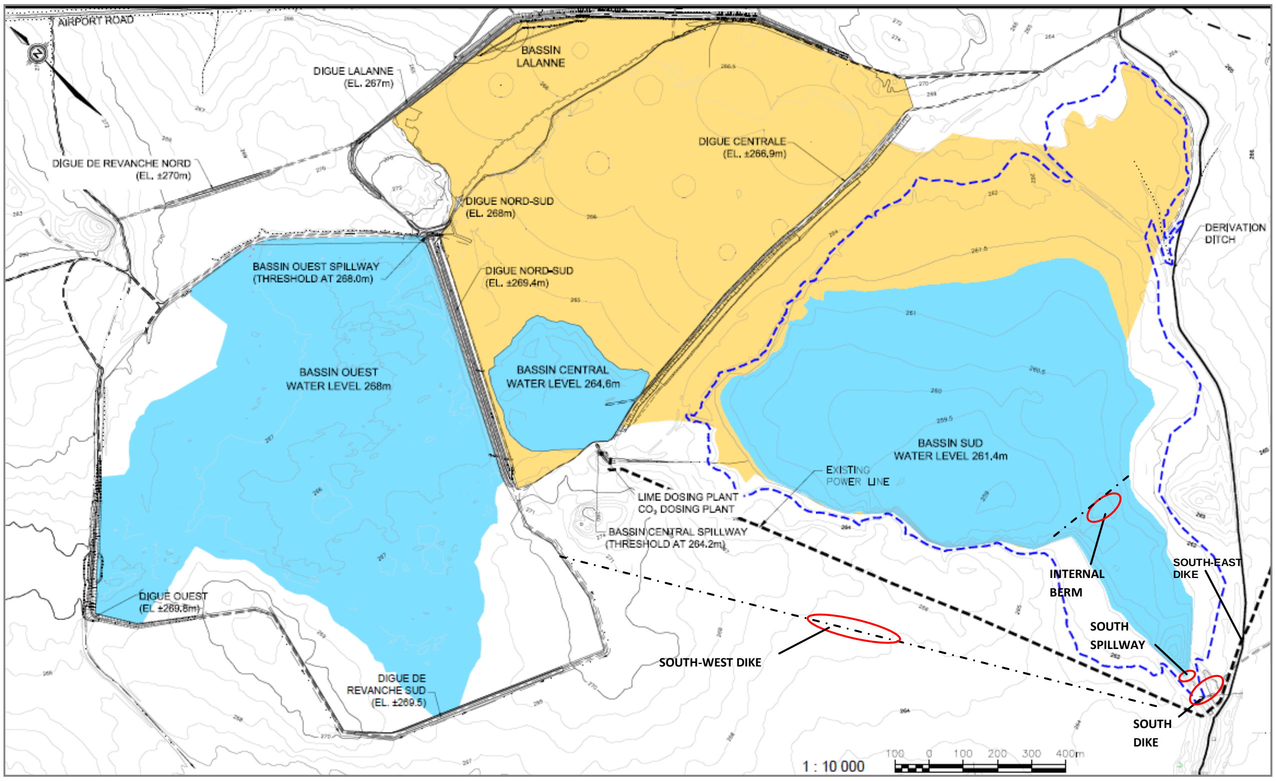

Figure 1. Tailings Storage Facility and Location of Tests (indicated in red) Performed on Existing and Projected Dikes

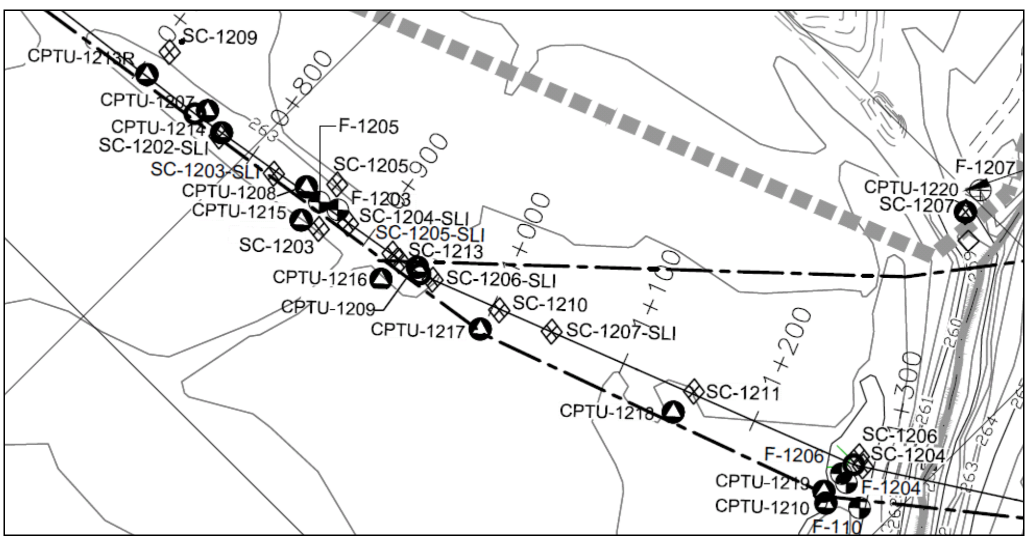

Figure 2. Location of Tests Performed at the Projected South-West Dike Site

Table 2. List of Tests Performed at the Projected South-West Dike Site

Chainage (m)	2012 Campaign	2012 Manual VST	2013 Campaign(2)
0+710			SC-1209 CPTU-12-13R (Nk1 = 13)
0+770	CPTU-12-07	SC-1202-SLI	CPTU-12-14
0+820		SC-1203-SLI	
0+850	SC-12-03 CPTU-12-08 (N_{kt} = 17)	SC-1204-SLI	SC-1205 CPTU-12-15 (N_{kt} = 13)
0+930	CPTU-12-09	SC-1205-SLI SC-1206-SLI	SC-1213 CPTU-12-16 (N_{kt} = 11)
1+000			SC-1210 CPTU-12-17 (N_{kt} = 11)
1+050		SC-1207-SLI	
1+150			SC-1211 CPTU-12-18 (N_{kt} = 11)
1+290	SC-12-04 CPTU-12-10 (N_{kt} = 17)		SC-1206 CPTU-12-19 (N_{kt} = 18)

Note:
(1) The piezocone tests in the 2012 campaign were performed using a 10 tons probe.
(2) All the piezocone tests in the 2013 campaign were performed using a 5 tons probe except for CPTU-1205 that was performed with a 2,5 tons probe for a greater precision on the strength of the solft clay below the center of the South-west dike.

4 GEOTECHNICAL INVESTIGATION RESULTS ANALYSIS

The interpretation of VST and CPTu tests for the soft varved silty clay of Matagami will be presented and discussed mainly using the tests performed at the site of the projected South-West Dike. The location of the dike is indicated on Figure 1 and these tests performed are listed on Table 2 and located in Figure 2.

4.1 2012 Geotechnical Campaign

In the South-West Dike sector, three (3) piezocone tests (PZ-12-07 to -12-09) and one (1) borehole (F-12-03) were performed by «Company A» (2012). The borehole profile shows a peat layer of about 0.76 m followed by grey silty clay that becomes saturated at depth 2.29 m (or 260.67 m as elevation).

The Vane shear field tests performed show that the undrained shear strength of the clay varies between 10 and 20 kPa which indicates a soft to very soft clay consistency.

Laboratory results indicate that the clay is highly plastic with high water content (> 100%). Liquidity indices are high (> 1.3) at depths greater than 2 m.

According to the preconsolidation measured in oedometer tests, the clay is over consolidated.

Based on the piezocone tests performed, the clay layer becomes silty and sandy below a depth of 12 m. This was not confirmed by borehole F-12-03 which was stopped at a depth of 10.5 m.

Figure 3 presents the undrained shear strength (Su) profiles of the clay measured by «Company A» (2012) with a shear vane field apparatus and a piezocone test. The profiles presented in Figure 3 correspond to tests results obtained at the center of the South-west dike projected site.

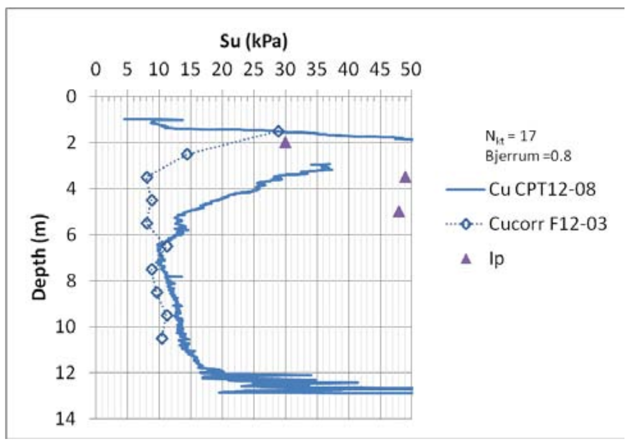

Figure 3. Undrained Shear Strength from Vane Shear and Piezocone Tests («Company A, 2012) at the Center of the South-West Dike

A N_{kt} value of 17 was selected to correlate piezocone and field shear tests and used as representative of the entire South basin sector.

Some undrained shear strength values obtained from field vane shear tests of the 2012 investigation realised near borehole F-12-03 (center of the projected South-west dike) were found to be lower than expected based on values measured previously at the TSF and lower than what was estimated from nearby piezocone based on usual correlations (N_{kt} between 10 and 20). After Bjerrum correction (factor = 0.8, corresponding to an I_P of about 50%), shear strength (Su) values of about 8 kPa were reported, mostly between 3 and 7 m depth. These were lower than the minimum value of 10 kPa that had been measured previously under the other dikes of the TSF.

4.2 2012 Pocket Shear Vane Tests

Since a SLI (SNC-Lavalin Inc.) team member was on the field, some verification vane shear measurements were performed at six (6) locations on the South-west dike alignment using a pocket apparatus (see Tableau 2 and Figure 2 for location).. The maximum depth that could be reached was about 6.5 m.

Figure 4 shows the values of Su obtained from VST at SC-1204-SLI near borehole F-12-03 and also the profiles obtained by «Company A» near F-12-03 (presented at figure 2), at the center of South-west dike.

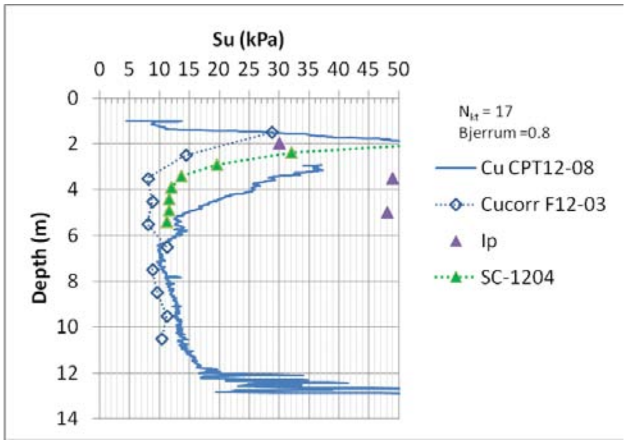

Figure 4. Su Profiles from «Company A» (2012) and SLI (2012) at the Center of the South-West Dike

The values of Su from manual VST were higher than about 11 kPa after Bjerrum correction (factor = 0.8) near borehole F-12-03, i-e 3-5 kPa lower than that measured in 2012 campaign..

Based on this finding, it was decided to perform additional tests on the South-west and South dike. The additional tests were integrated to the geotechnical campaign carried out by «Company B» in 2013.

4.3 2013 Geotechnical Campaign

The 2013 Investigation program was carried out by «Company B» (Qualitas, 2014). Given the inconsistency problems encountered in the 2012 campaign, great care was given to the selection of testing equipement and to testing procedure. In particular, the vane size was varied in function of the shear strength of the clay to be tested and before being driven into the ground, the blades were covered with a non-stick spray (PAM) to minimize the sticking effect by clay. In addition, all the piezocone tests were performed using probe with a maximum capacity of 10 tons except for CPTU-12-05 that was performed with a 2,5 tons probe for greater precision on the strength of the solft clay below the center of the South-west dike.

On the alignment of the South-west dike, seven (7) piezocone tests, six (6) field vane shear tests and two (2) boreholes were performed. See Figure 2 and Table 2 for location.

4.3.1 Center of the dike

Borehole F-12-05 has been done near F-12-03 (2012 campaign) in the center of the Sout-West dike. It shows a peat layer of about 0.15 m followed by grey silty clay that presents traces of silt (varved silty clay). The clay is becoming clayey silt starting at a depth of 13.47 m (or 248.65 m as elevation). Silty sand underlies the clayey silt below a depth of 16.50 m (or 245.62 m as elevation). A layer of till (sand and silt) goes from 23.60 m to 28.05 m of depth. Bedrock has been found below the till. The bedrock presents an excellent rock quality (RQD ~90%).

Vane shear field tests performed near borehole F-12-05 on the grey silty clay layer show that shear strength varies from about 15 to 30 kPa. Clay consistency is soft. Figure 5 presents the Su profiles measured with a shear vane field apparatus and a piezocone test. The profiles presented on Figure 2 correspond to tests results obtained at the center of the South-west dike.

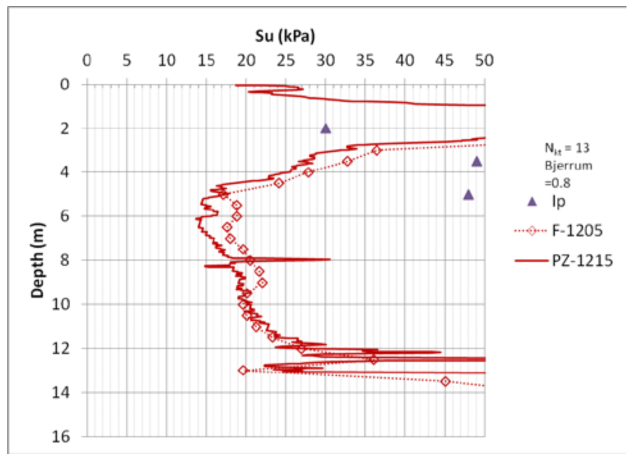

Figure 5. Su Profiles from Field Shear and Piezocone Tests («Company B», 2014) at the Center of the South-West Dike

The piezocone profile compares well with the field vane profile; a correlation factor N_{kt} of 13 was selected by «Company B» to estimate the Su profile from the piezocone tip resistance. The selection of the correlation factor N_{kt} will be discussed later.

4.3.2 South end of the dike

Borehole F-12-06 has been done at the south end of the South-West dike. It shows a backfill layer of about 4.5 m of clayey material with organic matter, probably from the excavation of the nearby channel. Grey silty clay similar to the one described before (F-12-05) underlays the backfill. The clay becomes varved and finally a soft silt at a depth of 12 m (or 254.5 m as elevation). Under the silt, a layer (1.25 m thick) of sand with traces of silt and gravel was observed. The presence of till (sand and gravel) at a depth of 17.25 m was noticed.The borehole ended at a depth of 23.9 m without finding bedrock.

The vane shear field test performed on the grey silty clay layer shows that shear strength varies from about 14 to 40 kPa. Clay consistency is soft to stiff.

As can be observed on Figure 6, the estimated piezocone strength profile compares well with the corrected field vane profile when using a N_{kt} of 18.

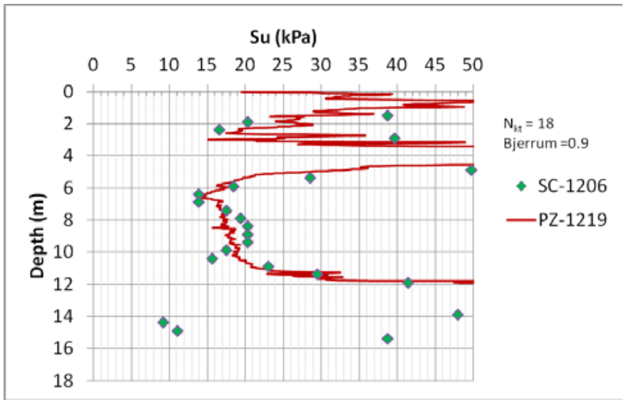

Figure 6. Su Profiles from Field Shear Test and Piezocone Test («Company B», 2014) at the South of the South-West Dike

4.3.3 Existing South Spillway

In the sector downstream of the South Spillway, one (1) piezocone test (PZ-1220), one (1) field vane shear test (SC-1207) and one (1) borehole (F-1207) have been done.

The borehole profile shows a backfill layer of about 4.0 m of altered clayey material with organic matter. Grey silty clay similar to the one described in previous boreholes (at this level) follows. The clay alternate with thick silt layers by a depth of 12.0 m). A silt layer with traces of clay goes from a depth of 13.0 m to 19.5 m. This material has been judged ultra sensible. The till layer starts at a depth of 19.5 m. Bedrock starts at a depth of 22.88 m, the rock quality varies from good to excellent (RQD 78-100%). The borehole ends at a depth of 38.27 m (or 242.6 m as elevation).

The vane shear field test performed on the grey silty clay layer shown that shear strength varies from about 13 to 35 kPa. Clay consistency is soft to stiff.

Figure 7 presents the Su profiles measured with a shear vane field apparatus and a piezocone test. The piezocone profile compares well with the field vane profile when using a N_{kt} of 11

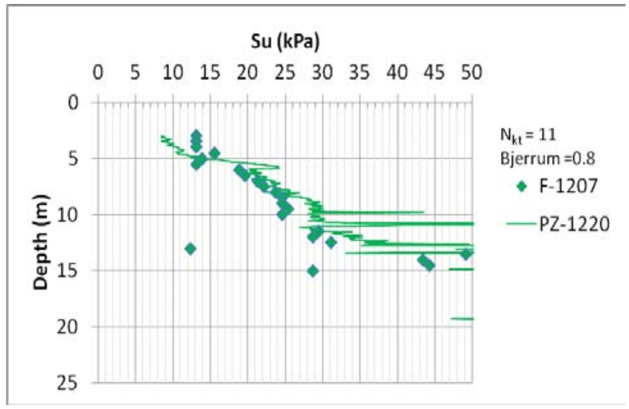

Figure 7. Su Profiles from Field Shear Test and Piezocone Test («Company B», 2014) Downstream of South Spillway

5 SELECTION OF N_{kt}

N_{kt} values are used to estimate the Su profile from the piezocone tip resistance. As shown above, the values were selected through a correlation with nearby Vane shear strength profile. As can be seen on Table 2 above, for the 2012 campaign, a N_{kt} of 17 had been selected based on only two sites with both VST and CPTu tests. However, for the seven such sites of the 2013 campaign, the N_{kt} value was found to vary through the TSF and even along the alignment of the projected South-West dike.

A comparison of geotechnical tests performed in the central sector (critical section) of the South-West dike alignment has been done. Figure 8 presents the Su profiles measured in 2012 and2012. Some Ip (plastic index) values are also shown to justify the use of a Bjerrum correction of 0.8 corresponding to an Ip of about 50.

In Figure 8, F-12-05 and PZ-1215 have been fitted with N_{kt} factor 13; this fit shows to be acceptable. In the same figure, F-1203 and CPT-1208 have been fitted with N_{kt} factor 17 selected in 2012. This fit does not show a good correlation between the two profiles, mostly for the 6 first meters of depth from the surface. However, if a value of 13 as N_{kt} is used for the piezocone CPT-1208, the Su profile shows a good correlation with F-1205 and PZ-1215 (see Figure 9). Then, N_{kt} = 13 seems to be the factor that corresponds to the clay in this sector of the South-West alignment.

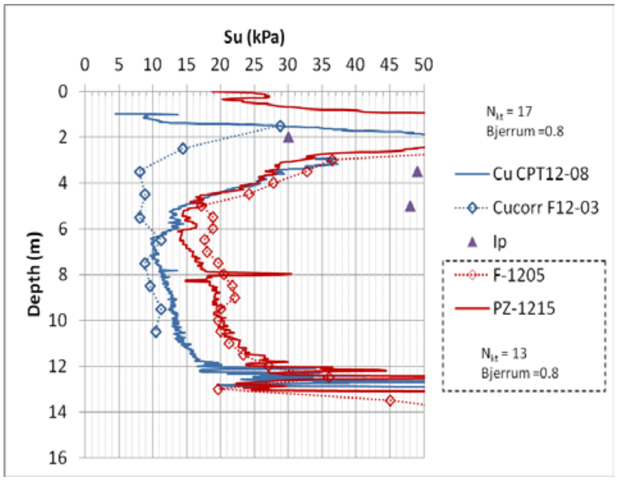

Figure 8. Comparing S_u Profiles from Vane and Piezocone Tests at the Center of the South-West Dike – N_{kt} 17 and 13 for CPT-1208 and PZ-1215 Respectively

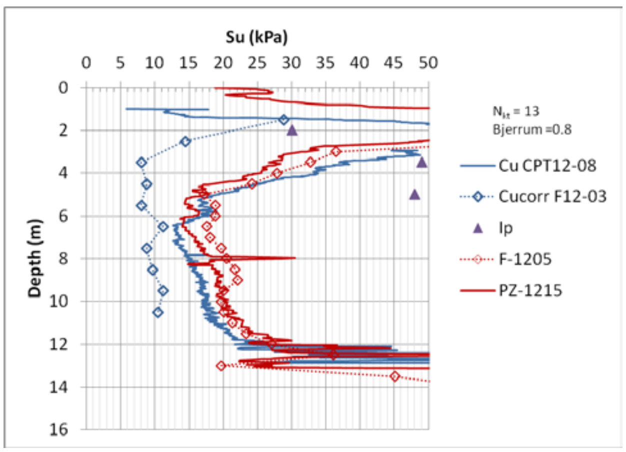

Figure 9. Comparing S_u Profiles from Vane and Piezocone Tests in the Center of the South-West Dike – N_{kt} 13 Adopted for Both Piezocone Tests

Looking at Figure 9, it seems evident that field vane test F-12-03 does not follow a pattern similar to the other tests made at a short distance. Lower values of Su in the 2012 campaign could be explained by clay being stick to vane blades in between two consecutives measurements or other imprecision.

Similarly, the higher N_{kt} value needed to correlate CPTU-1219 to VST SC-1206 might be explained by clay sticking in SC-1206. This would make sense because higher shear strength is expected at this site because of the 4.5 m fill that was deposited above natural ground at the time of the excavation of the nearby channel.

6 DISCUSSION AND CONCLUSIONS

The conclusions of this review and integration of the geotechnical data presently available for the south part of the South Basin are the following:

- N_{kt} values to calibrate piezocone measurements to field vane measurements were shown to vary from about 11 to 18 within the South Basin. It is usually accepted that N_{kt} values are relatively constant for a given site. However, in the case presented here, this can be explained by the variability of varved silty clay and the precision of the measurement methods of very soft clays.
- Large N_{kt} variation has been reported for clayey soils (Almeida et al., 2010; Been et al., 2010 and Zsolt, 2013). In addition, values found are in the accepted range of N_{kt} 10 to 18 (Robertson, 2012);
- Varved clays that have alternate layers of “silt” and “clay” have a high degree of inherent anisotropy (Löfroth, 2008) and Leroueil et al. (1983) have reported dispersion of measurements using field vane as well as the plasticity index and preconsolidation pressure determination of more than 20%.
- The layer of grey soft silty clay that presents low shear strength shows to vary from about 10 to 12 m thick going generally from near the surface to about 12 meters of depth;
- Minimum values of Su on the clay foundation (after Bjerrum correction) are about 13 kPa. This is more than 50% higher than the minimum Su (after Bjerrum correction) presented on the 2012 campaign. Lower values of Su in the 2012 campaign could be explained by clay being stick to vane blades in between two consecutives measurements or other imprecision;
- This clay sticking problem could also have led to lower measured Su values in SC-1206 and a high N_{kt} of 18 to correlate CPTU-12-19 to these values.

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