

Soil Profiling of Pleistocene Deposits in the Athabasca Oil Sands using SCPTu



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ABSTRACT

Pleistocene deposits including glaciofluvial sand, glaciolacustrine clay, and glacial till are commonly encountered within tailings dam foundations in the Athabasca oilsands region north of Fort McMurray, Alberta. These deposits, where present, may control the stability of tailings dams. Over the years, site investigation programs have been carried out in the region to characterize the Pleistocene deposits using in-situ and laboratory testing. The Seismic Cone Penetration Test (SCPTu) is a reliable and a cost-effective tool for profiling soil deposits based on soil behaviour characteristics. Initial screening with SCPTu profiling in combination with understanding the deposition history and loading conditions enables engineers to determine an appropriate combination of in-situ and laboratory testing to obtain design parameters for geotechnical analysis. This paper provides a high-level description of the geologic deposition history for the Pleistocene deposits in the Athabasca Oil Sands region and presents SCPTu profiling for three major Oil Sands sites.

RÉSUMÉ

La stabilité des digues à stériles de la région des sables bitumineux de l'Athabasca, au nord de Fort McMurray, Alberta, est parfois gérée par la présence de sables fluvioglaciaires, d'argiles glaciolacustres, et de tills glaciaires du Pléistocène à leur base. Plusieurs essais en-place et de laboratoire ont été menés pour caractériser ces dépôts. L'essai de pénétration au cône sismique (SCPTu) est une méthode économique et fiable pour établir un profil de sol selon ses caractéristiques de comportement. Le dépistage initial des profils SCPTu combiné à la compréhension de l'historique des dépôts et des conditions de chargement permet aux ingénieurs de déterminer une sélection d'essais en place et de laboratoire appropriés afin d'obtenir les paramètres pour l'analyse géotechnique. Cet article fournit une description de haut niveau de la déposition géologique des dépôts du Pléistocène et présente les profils SCPTu obtenues pour trois des principales mines d'exploitation de sables bitumineux de l'Athabasca.

1 INTRODUCTION

The Athabasca Oil Sands is the largest oil reserve in Alberta (Figure 1), where the surficial geology is largely influenced by glacial processes of the Pleistocene epoch. Typical geological and soil behavioural characteristics of these Pleistocene deposits are discussed in this paper using data from three major Oil Sands sites within approximately 70 km north of Fort McMurray, Alberta. The sites are referred to in this paper as A, B, and C.

In-situ soil behaviour depends on many factors including stress history, density, gradation and mineralogy, which are a function of depositional and post-depositional geologic processes. Understanding the behaviour of the foundation soil units controlling dam stability is an essential first step to determine the appropriate soil strength for the analysis. For example, the Mount Polley tailings dam failure in 2014 was believed to be due to failure to identify the appropriate strength for a continuous glaciolacustrine clay layer, which was susceptible to undrained failure when subject to the stresses associated with the failed embankment (Independent Review Panel 2015).



Figure 1. Athabasca Oil Sands location (Source: <http://history.alberta.ca>).

Index testing such as particle size distribution and Atterberg limits are standard methods used by geotechnical engineers to classify soils and correlate their physical characteristics (such as plasticity) to in-situ behaviour. However, these correlations may have limited predictive capability of in-situ behaviour because the index testing is done on soils in a remolded state (Robertson 2016).

The Seismic Cone Penetration Test with Pore Water Pressure (PWP) measurements (SCPTu) is a reliable and cost-effective tool for profiling soil deposits based on in-situ behaviour characteristics. Soil Behaviour Type (SBT) charts link in-situ soil behavior with SCPTu measurements (Robertson et al. 1986; Robertson 1990; Schneider et al. 2008; Robertson 2009; Schneider and Moss 2011; Robertson 2016). Robertson (2016) recommended that soil classification should be done using SBT charts that are based on the cone tip resistance, PWP, and shear wave velocity (V_s) in combination with index testing and good understanding of the geologic conditions.

This paper provides a brief description of the geologic deposition history for the Pleistocene deposits in the Athabasca Oil Sands region and presents SCPTu profiling for three major Oil Sands sites. The main objectives of this paper are to recommend an approach for soil profiling using a combination of published SBT charts and to share our interpretation of the in-situ soil behaviour of Pleistocene soil units in the Athabasca Oil Sands region based on the geologic history, SCPTu and index testing.

2 GEOLOGIC SETTING

The geomorphology of the Athabasca Oil Sands region was influenced by glacial processes of the Pleistocene

epoch. During Pleistocene glaciations, multiple ice advances and retreats created a complicated assemblage of glacial, glaciofluvial and glaciolacustrine deposits. The landforms have been locally in-filled with Holocene-aged sediments, or locally down-cut by erosion in the Holocene epoch. The recent sediments unconformably overlay the Cretaceous deposits (Clearwater and McMurray Formations) (McPherson and Kathol 1977). The upper member of the Cretaceous McMurray Formation and the overlying Cretaceous Clearwater Formation have been eroded away in some localities within the study area during the Pleistocene epoch. The Cretaceous deposits overlie the Devonian Waterways Formation (Figure 2).

2.1 Holocene Deposits

The Holocene deposits can be divided into muskeg (organic soil/peat), lacustrine and fluvial sediments. The muskeg deposits consist of peat and highly organic soils which typically range from fresh, fibrous, organic matter near the surface to severely decomposed mineral soil near the base of thicker sections. Holocene lacustrine deposits are mainly silt and clay with minor amounts of fine sand. Based on borehole data within the study area of this paper, the muskeg and lacustrine deposits are typically continuous over low lying areas or sporadic elsewhere in variable thicknesses of up to 10 m. The Holocene fluvial deposits occur near the current ground surface and are mainly associated with modern day creeks and drainages. These soils occur in mostly thin isolated pockets that are less than 3 m thick.

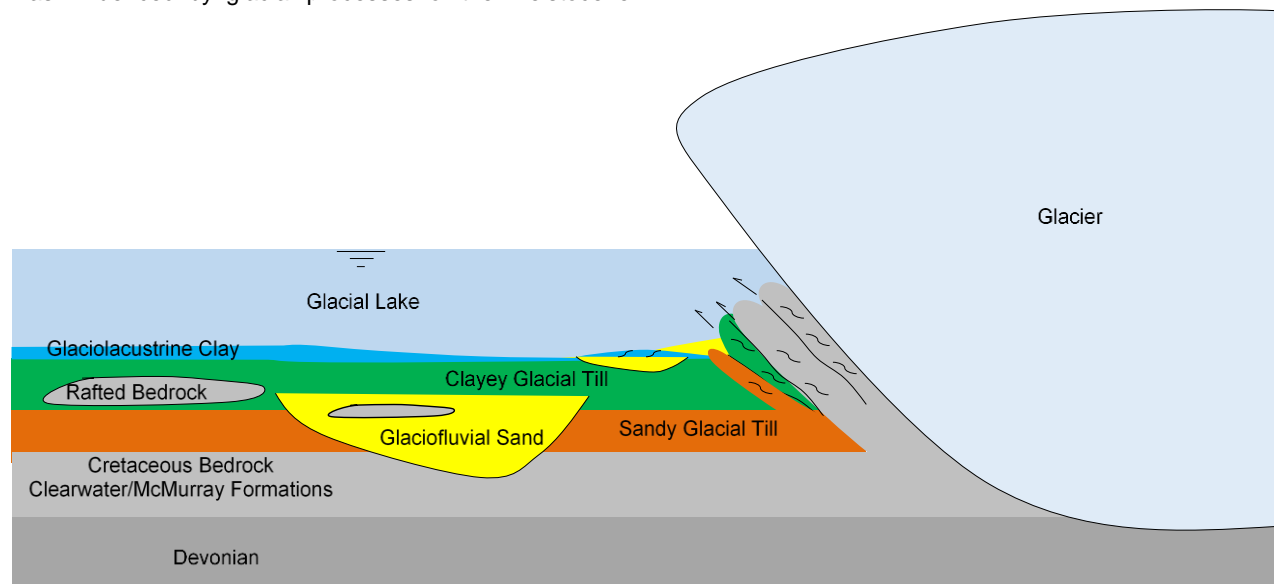


Figure 2. Schematic Illustration of typical stratigraphy and development of post-glacial geologic assemblage of study area. Note that the soil colours shown on this figure are used consistently to represent test data from those soils throughout the paper.

2.2 Pleistocene Deposits

The Pleistocene deposits of the Athabasca Oil Sands surficial geology can be broadly subdivided into glacial (i.e. relating to direct deposition by a glacier), glaciofluvial deposits (i.e. deposited in a proglacial or subglacial river channel) and glaciolacustrine (i.e. deposited in a proglacial lake) (Sisson et al. 2012; Stephens et al. 2006; Bayliss et al. 2013; Bayliss et al. 2014). These deposits are highly variable in distribution due to a complex glacial history with multiple glacial advances and interglacial retreats, and associated glaciofluvial, and glaciolacustrine environments. The assemblage is further complicated by possible remobilization/rafting of bedrock units and glacial deposits by subsequent ice sheets. A summary of typical particle size distributions, natural moisture contents and Atterberg limits is shown on Figures 3 and 4.

During glacial retreats, a lake or a series of lakes developed from meltwater where the glaciolacustrine sediments were deposited (Figure 2). Observations from boreholes and test trenches suggest that some of the glaciolacustrine clays may have been overridden and remobilized by glacial ice. The glaciolacustrine lake-bottom deposits mainly consist of silt and clay that locally contain sandier intervals and sand beds. The structure and fine grain size of these sediments indicate that they were deposited far from the ice margin (McPherson and Kathol, 1977). The glaciolacustrine lake-shore deposits are fine-grained silty and sandy soils that are interpreted to have formed on the margins of Pleistocene lacustrine environments; they are typically found interbedded with and/or on the margins of lake-bottom glaciolacustrine deposits (McPherson and Kathol, 1977; Bayliss et al. 2013; Bayliss et al. 2014).

Glaciofluvial deposits were formed by meltwater flowing from, on top of, within or under glacial ice, and are typically highly variable. These deposits range from silt and clean sand to gravel and are commonly mixed with tills.

Glacial sediments are unstratified deposits that were deposited directly by the glacier and are generally referred to as "till". This generalized term encompasses a range of subglacial and proglacial depositional environments, covering a range of ablation till and lodgement till-type deposits. The glacial till is widely spread in the Athabasca Oil Sands region within the flanks of the bedrock uplands of the Muskeg Mountain, the Birch Mountain and the Athabasca Hills (McPherson and Kathol, 1977). The composition varies from sand and gravel to silt and clay, and the units are generally over-consolidated to varying degrees due to glacier loading or other processes such as post-depositional erosion, desiccation or changing water levels. Observations from exploration logging indicate that the glacial till may be re-worked lacustrine deposits in some areas. Glacial till can include rafted blocks of bedrock that were excavated by the glaciers and incorporated into the till. Till commonly occurs in layers up to 30 m thick that are inter-layered with glaciofluvial deposits.

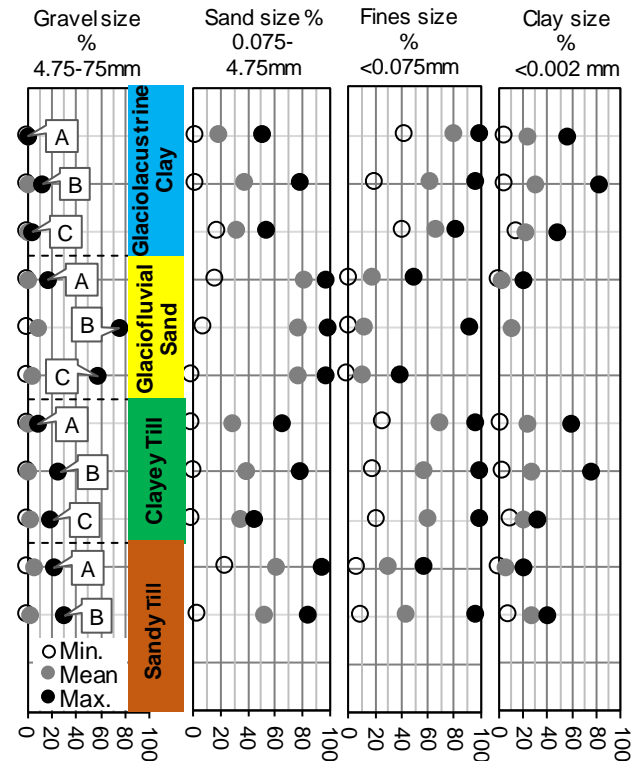


Figure 3. Grain size distribution summary (Sites A, B and C).

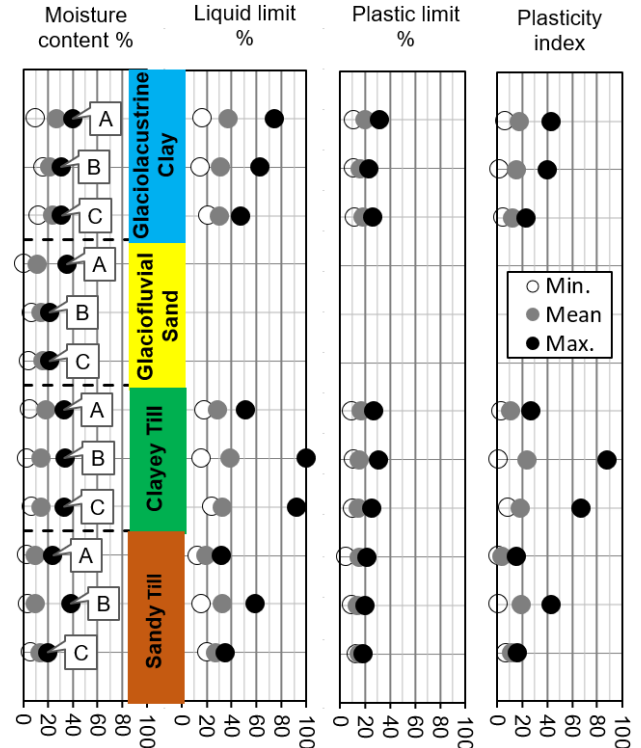


Figure 4. Atterberg limits summary (Sites A, B and C).

3 SOIL PROFILING USING CPT

Cone Penetration Testing with PWP measurements (CPTu) offers rapid, economical and continuous soil profiling. The basic CPTu measurements are the tip resistance (q_c), sleeve friction (f_s), and dynamic PWP (u_2). In addition, SCPTu provides measurement of in-situ shear wave velocity (V_s). The SCPTu data used in this study were collected using cones with a cross sectional area of 15 cm² and a load cell capacity of 20 tons. Measurements were made at 10 mm depth increments and typical push rate of 20 mm/s. The test procedures were carried out in accordance with the ASTM D5778-07 standard. In this study, 58 CPTu soundings (including 20 soundings with V_s measurements) were assessed along with 58 borehole logs. The top and bottom of the glaciolacustrine, glaciofluvial and clayey glacial till units were identified based on the CPTu profile then verified using the adjacent boreholes. In general, CPTu tip resistance and PWP measurements provide consistent responses at Sites A, B, and C through similar soil units.

Figure 5 shows an example CPTu sounding and soil type based on the adjacent borehole. As shown on this figure, the corrected tip resistance is relatively low through the glaciolacustrine clay and clayey till deposits, and high through the glaciofluvial deposits and the sandy till units. The PWP is typically high in the lake-bottom glaciolacustrine clay and the clayey till units, which is likely due to low permeability and contractive behaviour. The PWP in the lake-shore glaciolacustrine units is often close to or slightly below the hydrostatic pressure as these units typically comprise more sandy mixtures compared to the lake-bottom units; Figure 5 shows a typical dynamic PWP response in lake-shore deposits. The PWP is generally lower than the hydrostatic pressure or negative in the glaciofluvial deposit and the sandy till deposits due to dilative behaviour.

4 SOIL MICROSTRUCTURE

Older soil deposits tend to have a more complex microstructure due to aging and cementation, which may lead to less reliable classification using the SBT charts compared to the younger deposits. For example, aged over-consolidated clay may show in-situ behaviour similar to dense sand on the SBT charts. Therefore, Robertson 2016 recommended to first identify if soils have such complex micro-structure using the V_s measurements since the small strain modulus ($G_0 = \rho(V_s)^2$ where ρ is the soil mass density) tends to increase with soil aging and cementation. Robertson (2016) also recommended the empirical, modified normalized rigidity index $K^*_G = (G_0/q_n) (Q_{tn})^{0.75}$, as shown on Figure 6 where, generally, 'aged' deposits would have $K^*_G > 330$ and soils with $K^*_G < 330$ are likely 'young' with little to no micro-structure.

As shown on Figure 6, most SCPTu from the three sites plot in the zone with $K^*_G < 330$ for the Pleistocene deposits assessed in this study indicating that these deposits are generally young with little to no micro-structure. There is one exception where the SCPTu in a sandy glacial till shows $K^*_G > 330$; this may be rafted cretaceous bedrock

which is commonly encountered within the Pleistocene deposits based on observations from borehole logs and test pits, although this was not logged as rafted bedrock in the adjacent borehole (~5 m away).

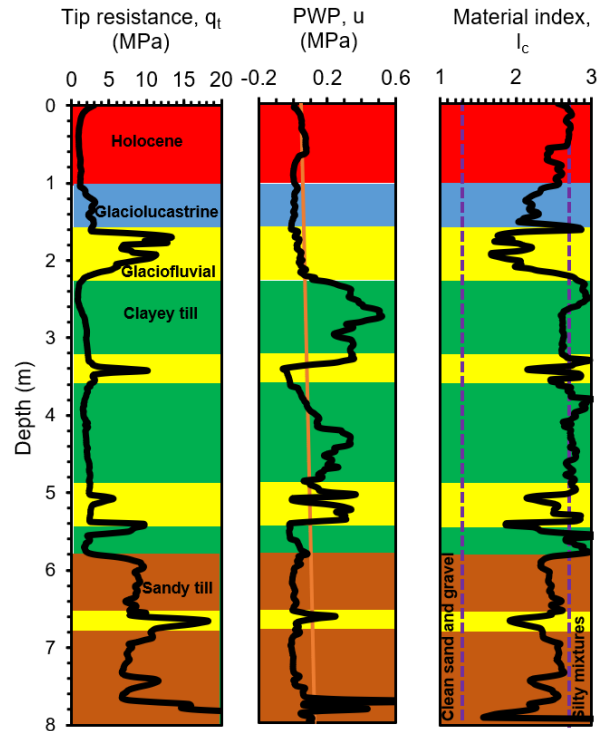


Figure 5. Example CPTu profile.

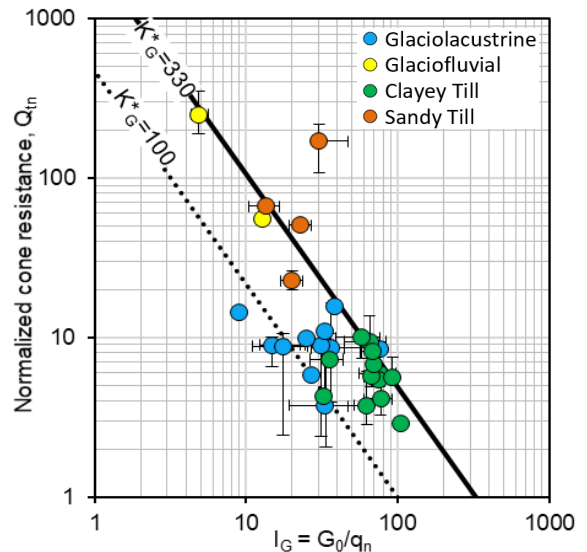


Figure 6. Identification of soils with microstructure using SCPTu (after Robertson 2016) (colours and SBT as per Figure 2 and Table 1; bars indicate data range between 25th and 75th percentile).

5 SOIL BEHAVIOUR TYPE

Dilatancy is a fundamental soil behaviour that describes a soil's tendency to change volume due to shearing. Course-grained soils with a tendency to contract (decrease in volume) during rapid (undrained) shearing may liquify and mobilize an undrained shear strength significantly lower than the strength during slow (drained) shearing. On the other hand, course-grained soils with a tendency to dilate (increase in volume) during rapid shearing may mobilize an undrained strength that is either equal to or higher than their strength under drained loading conditions. Heavily over-consolidated fine-grained soils tend to dilate and gain strength when subjected to undrained shearing at confining stresses lower than their pre-consolidation pressure. Whereas normally-consolidated or lightly over-consolidated fine-grained soil tends to contract and lose strength when subjected to undrained loading conditions. Understanding a soil's tendency to contract or dilate aids engineers to focus the site characterization on obtaining the appropriate soil parameters for geotechnical analyses.

Robertson (1990) and Robertson (2009) recommended a SBT chart based on normalized tip resistance (Q_{tn}) and friction ratio (F_r). This SBT chart provides soil classification based on in-situ behaviour where a textual soil description is given (i.e. gravel, sand, clay, etc.). This SBT chart was later updated by Robertson (2016) as shown on Figures 7, 9, and 11 to incorporate the following changes:

- A more hyperbolic shape to better capture the SBT boundaries suggested by Schneider et al. (2012), which can be expressed as I_B (SBT index) = $100(Q_{tn}+10)/(Q_{tn}F_r+70)$;
- Soils in different zones of the chart are described based on in-situ dilatancy behaviour (Table 1)
- A recommended screening level contractive-dilatative boundary $CD = 70 = (Q_{tn} - 11) (1+0.06F_r)^{17}$ with a lower bound contractive-dilatative boundary shown by the black dashed line, which can be expressed as CD (lower bound) = $60 = (Q_{tn} - 9.5) (1+0.06F_r)^{17}$.

Table 1. Soil Behaviour Type (used for Figures 7 to 12)

Appreciation	Description
CCS	Clay-like – Contractive – Sensitive
CC	Clay-like – Contractive
CD	Clay-like – Dilative
TC	Transitional – Contractive
TD	Transitional – Dilative
SC	Sand-like – Contractive
SD	Sand-like - Dilative

Robertson (2016) indicated that the $I_B=32$ line represents the lower boundary of most sand-like soil with little to no micro-structure and a plasticity index $<10\%$; the upper boundary of most clay-like soils with plasticity index $>18\%$ is represented by the $I_B=22$ line.

SBT charts based on PWP measurements (Figures 8, 10, and 12) can be useful tools to classify soils based on their in-situ behaviour since contractive soils tend to generate excess PWP during undrained large-strain shearing whereas dilative soils tend to show a negative PWP response. This is clearly illustrated in the example CPT sounding on Figure 5 where the clayey glacial till unit shows high PWP indicating contractive behaviour and the sandy glacial till unit shows negative PWP indicating dilative behaviour.

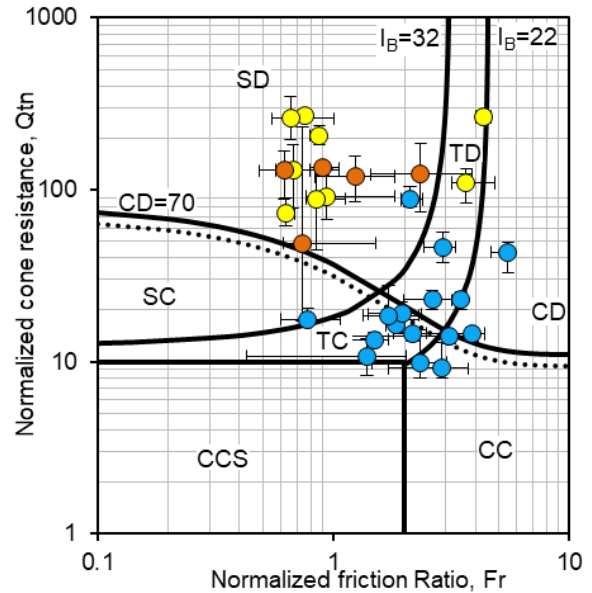


Figure 7. Q_{tn} - F_r SBT chart with Site A data (after Robertson 2016) (colours and SBT as per Figure 2 and Table 1; bars indicate data range between 25th and 75th percentile).

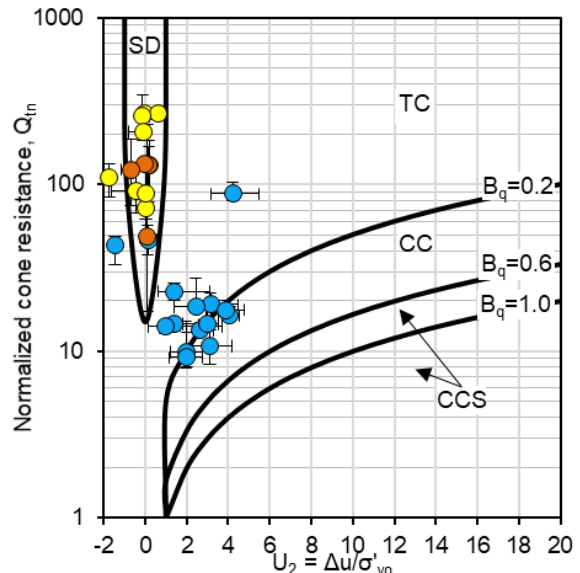


Figure 8. Q_{tn} - U_2 SBT chart with Site A data (after Robertson 2016) (colours and SBT as per Figure 2 and Table 1; bars indicate data range between 25th and 75th percentile).

Schnider et al. (2012) proposed a SBT chart using normalized PWP U_2 which was modified by Robertson (2016) (Figures 8, 10, and 12) to include the following:

- Use the same SBT terms used on Figures 7, 9, and 11 (Table 1); and
- Use the generalized normalized tip resistance Q_{tn} instead of the Q_t used in Schnider et al. (2012).

The SBT chart based on PWP generally provides a consistent interpretation with the Q_{tn} - F_r SBT chart for young deposits that have little to no micro-structure. Discrepancies may occur in aged/cemented units such as cretaceous deposits if, for instance, data plot with $Q_{tn} > 12$ on the Q_{tn} - F_r chart (indicating over-consolidated behaviour) while data from the same deposit show excess PWP on the Q_{tn} - U_2 chart (indicating contractive behaviour). This kind of discrepancy indicates that the deposit may have micro-structure. Therefore, Robertson (2016) recommended using both SBT charts, especially if there is no V_s data available to identify soils with micro-structure as discussed in Section 4.

6 DISCUSSIONS

Data from sites A, B, and C are plotted on both SBT charts (Q_{tn} - F_r and Q_{tn} - U_2) as shown on Figures 7 to 12 for four Pleistocene units (glaciolacustrine clay, glaciofluvial sand, glacial clay till and glacial sandy till). The glaciolacustrine clay and the glacial clay till units are showing contractive behaviour (i.e. plotting between the CC and the TC zones). This behaviour indicates that these units are likely to be normally to lightly over-consolidated. Therefore, further characterization of these units should be focused on identifying the undrained design parameters. This may be overlooked, especially for the glacial clay till units, if relying purely on borehole logs for characterization as the visual observations of till matrix and index testing may lead to mischaracterizing these units as purely dilative material.

Few data points in the glaciolacustrine from each site plot above the CD line indicating localized possible dilative behaviour (Figures 7, 9, and 11). This is likely due to a combination of desiccation near surface and the stratified nature of this unit due to its deposition environment in relation to the glacial front (i.e. clayey lake-bottom deposits far from the glacier and lake-shore deposits near the glacier margin as discussed in Section 2). The glacial clay till assessed in this study, on the other hand, is consistently below the CD as it has not been exposed to desiccation due to its deposition sequence.

The glaciofluvial sand and the sandy glacial till units examined in this study are generally dilative under the in-situ loading conditions at the time of the CPT soundings as indicated by the Q_{tn} - F_r and the Q_{tn} - U_2 charts. Further characterization of the glaciofluvial units should be focused on drained design parameters. Although the glaciofluvial deposits are typically dilative materials as shown on Figures 7 to 12), in the authors experience at other Oil Sands sites, glaciofluvial deposits can be contractive in localized areas.

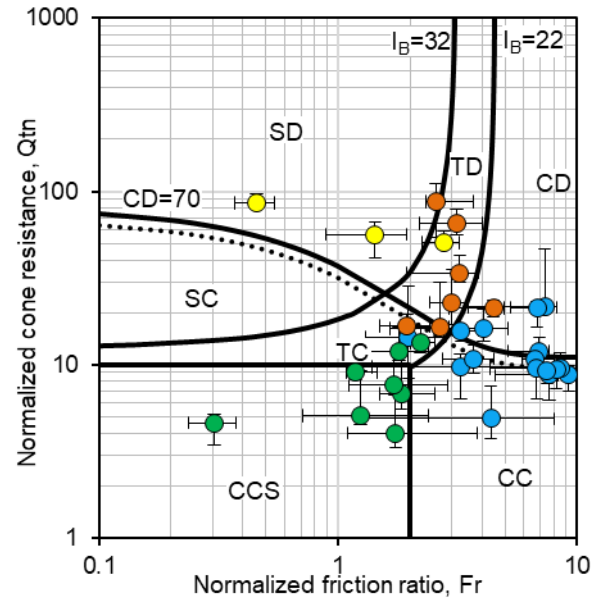


Figure 9. Q_{tn} - F_r SBT chart with Site B data (after Robertson 2016) (colours and SBT as per Figure 2 and Table 1; bars indicate data range between 25th and 75th percentile).

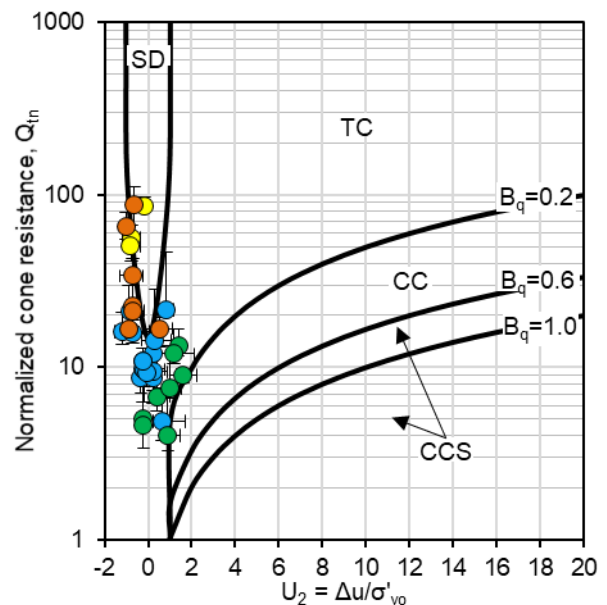


Figure 10. Q_{tn} - U_2 SBT chart with Site B data (after Robertson 2016) (colours and SBT as per Figure 2 and Table 1; bars indicate data range between 25th and 75th percentile).

The PWP charts show more tendency towards the TC behaviour but this could be due to a slow response of the PWP transducer after passing through dilative units. An example of this is the PWP response at an approximate depth of 3.3m in the example CPT plot shown on Figure 5.

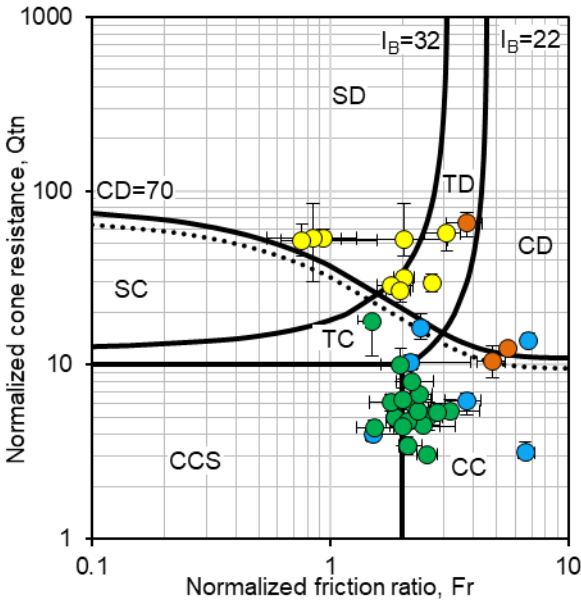


Figure 11. Q_{tn} - F_r SBT chart with Site C data (after Robertson 2016) (colours and SBT as per Figure 2 and Table 1; bars indicate data range between 25th and 75th percentile).

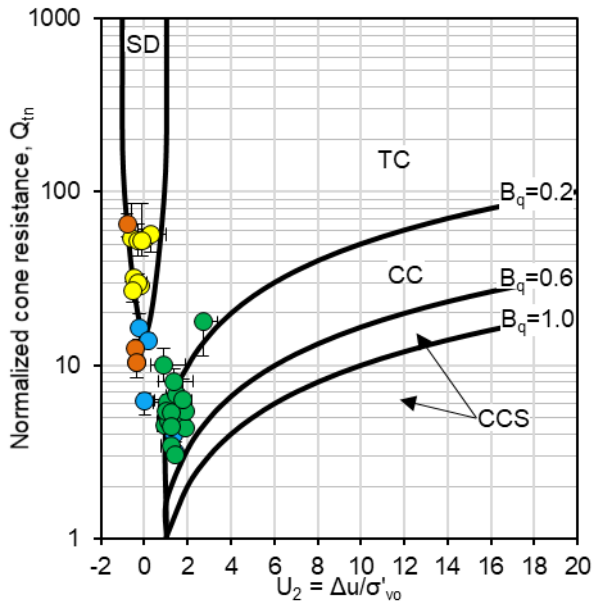


Figure 12. Q_{tn} - U_2 SBT chart with Site C data (after Robertson 2016) (colours and SBT as per Figure 2 and Table 1; bars indicate data range between 25th and 75th percentile).

At this depth, there is a transition from a dilative dense glaciofluvial sand (with negative PWP) into a contractive glacial clay till unit (with positive PWP) where the PWP appeared to have recovered slowly over an approximately

1m depth interval. This slow response is common and is likely due to desaturation on the PWP filter (immediately behind the conical CPT tip) when passing through heavily dilative units.

Figure 8 shows higher dynamic excess PWP measured in the glaciolacustrine clay unit at Site A (i.e. U_2 plots more to the right on Figure 8) compared to Sites B and C (Figures 10 and 12). This is because Site A has thicker glaciolacustrine deposits (up to 12m); therefore, the desiccation effect on the average U_2 is not as pronounced as in Sites B and C, where the thickness of the glaciolacustrine unit is typically less than 2m.

Figure 12 shows higher excess dynamic PWP in the clay till unit at Site C compared to Figure 10 at Site B because the thickness of this unit at Site C is up to 30m over large lateral extents; whereas, the thickness of the clay till at Site B is generally thinner (typically under 2m) and laterally discontinuous resulting in different drainage boundary conditions between the two sites.

7 CONCLUSIONS

A combination of an understanding of the geological history with index testing and SCPTu provides useful insights about soil in-situ behaviour and can guide efforts in obtaining appropriate soil parameters that represent the soil behaviour under the anticipated design loading conditions.

The SBT charts with V_s and PWP measurements should be examined in combination with the Q_{tn} - F_r chart to obtain an improved soil classification based on in-situ soil behaviour. Discrepancies between the PWP and the Q_{tn} - F_r charts may arise as a result of soil micro-structure (aging/cementation) or desaturation of the PWP filter.

There is apparent similarity between the glaciolacustrine clay and the glacial clay till in the Athabasca Oil Sands sites indicated by index properties and SBT. This may indicate that some of the clayey glacial till may be re-worked glaciolacustrine deposits.

The lake-bottom glaciolacustrine clay and clayey glacial till presented in this paper are typically contractive. Therefore, further characterization effort should be focused on the undrained design parameters for these units.

The glaciofluvial sand and the glacial sandy till are typically dilative under the in-situ stress conditions at the time of the CPT soundings.

The geologic description of the glacial clay till based on visual logging, and index testing can lead to mischaracterizing these units as dilative which is clearly not the case based on the data presented in this paper.

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