Soil Classification using CPTu in Fort McMurray

Mahmoud Elbanna
AMEC Earth & Environmental, Nanaimo, British Columbia, Canada
Makram El Sabbagh
AMEC Earth & Environmental, Burnaby, British Columbia, Canada
James Sharp
ConeTec Investigations Ltd., Richmond, British Columbia, Canada

ABSTRACT
Piezocone Penetration Testing (CPTu) with dissipation data has shown to be a useful tool in geotechnical engineering practice to provide near continuous soil profiling and material properties. CPTu tip resistance and sleeve friction combined with pore pressure measurement has proven to provide useful evaluation of subsurface soil types. A number of CPTu soil behaviour type classification charts are available in literature. Occasionally, these charts can provide different soil classification for the same subsurface conditions. Therefore, local experience and engineering judgement are required to make an appropriate selection of applicable charts to use in a given geological condition. This paper presents analyses of CPTu data collected from three different sites near Fort McMurray, northern Alberta, Canada. The application of four different CPTu soil behaviour type charts are reviewed and compared to adjacent borehole logs, laboratory results, and other in-situ test data for the three sites. Recommendations regarding the applicability of each CPTu soil classification method are provided for typical Fort McMurray overburden deposits.

RÉSUMÉ
L'essai de pénétration au cône (CPTu) avec enregistrement des données de dissipation de la pression interstitielle s'est révélé être un outil géotechnique utile dans la pratique pour fournir un profil quasi-continu du sol et les propriétés méchaniques des sols. Les données de penetration (à savoir la resistance de pointe et la résistance du fût) avec la mesure de la pression interstitielles se sont avérées utiles pour l'évaluation des différents types de sols. Différents abaques pour la classification des sols à partir des données du CPTu sont disponibles. Ces abaques peuvent parfois donner des classements différents pour les mêmes conditions de sol. Par conséquent, l'expérience locale et le jugement de l'ingénieur sont nécessaires pour sélectionner les abaques propres aux conditions géologiques données. Cet article présente l'analyse des données de CPTu recueillies dans trois sites différents à Fort McMurray, dans le nord de l'Alberta, au Canada. En plus des examens en laboratoire et des donnés d'essais in situ, les méthodes de classification des sols basées sur les données du CPTu ont été examinées et des recommandations ont été fournies quant à l'applicabilité de chaque méthode de classification des sols pour les dépôts qui se trouvent généralement dans la région de Fort McMurray.

1 INTRODUCTION

Cone Penetration Testing is increasingly utilized in geotechnical and geoenvironmental engineering as a tool that offers rapid, economical and continuous soil profiling. Over the years, researchers have developed a number of Soil Behaviour Type charts, which are empirically based on a given data set. No individual chart is considered capable of providing accurate soil classification in all conditions. Therefore, engineering judgement, local experience, and understanding of soil behaviour are required to make an appropriate selection of the charts that are most applicable for given geological conditions (Lunne et al. 1997).

The interpretation of CPTu data is dependant upon many geologic factors. For fine grained soils, the CPTu response is dependant on changes in overconsolidation ratio (OCR), age, undrained shear strength, sensitivity, degree of saturation, and hydraulic conductivity. For coarse grained soils, the CPTu response is mainly dependant on OCR, age, cementation, and friction angle. In addition, in-situ stresses, stiffness, macrofabric, mineralogy, and void ratio influence the measurements of CPTu and the resulting interpretation as it relates to soil type and strength characteristics.

Traditional CPTu classification charts use a combination of cone tip resistance and sleeve friction to describe soil behaviour type based on soil response to those measurements. Generally, sandy soils tend to show high tip resistance and low friction ratio while clayey soils tend to show high friction ratio and low tip resistance. Organic soils tend to produce very low tip resistance and very high friction ratio.

In addition to standard tip and sleeve measurements, pore pressure transducers have been added to cones in various positions in order to measure dynamic and static water pressures. Geophones are also included in the cone body such that shear and compression wave velocities can be measured (SCPTu). The seismic piezocone offers the potential to determine SBT using the measurement of cone tip resistance, sleeve friction, pore water pressure, and shear wave velocity (Robertson et al. 1986; Robertson 1990; Eslami and Fellenius 1997; and Robertson et al 1995).

This paper evaluates four CPTu classification methods, developed by Robertson et al. (1986) and Robertson (1990), using data from three different sites near Fort McMurray, northern Alberta. At all sites, other in-situ tests, field observations, and laboratory tests were performed in close proximity to the CPTu soundings, which allowed for direct comparison between the CPTu interpretations and laboratory based classification methods.

Four main soil groups are evaluated in this paper. (i) pleistocene sand and (ii) sand till deposits with low fines content. Profiling these deposits is particularly important as they are typically considered as borrow material for earth retaining structure construction in the majority of the oilsands projects. The other two deposits evaluated in this paper are (iii) pleistocene clay and (iv) clay tills that are often considered as low permeability borrow material to be used for seepage control. The pleistocene clay is also important because in thick layers it can result in foundation problems for oilsands projects.

2 BACKGROUND

At all three sites, a 15 cm^2 ConeTec seismic peizocone penetrometer (SCPTu) was employed, which is shown in the schematic illustration in Figure 1. At all locations, heavy 25 ton CPT rigs were used in order to push to the desired depths through the dense and hard till materials. A photograph of a typical CPT rig used at the three sites is presented in Figure 2.

3 SBT CLASSIFICATION METHODS

An attempt to correlate CPT data to soil classification was first made by Bergmann in 1965. Over the years, researchers have proposed several methods and charts to interpret soil types from CPTu measurements. This is perhaps best described by Fellenius and Eslami (2000), as it details the progression of the CPT and CPTu classification methods.

CPTu classification methods have traditionally relied on two parameters; the cone resistance, and the sleeve friction. Later, pore water pressure transducers were incorporated with the CPT measurements allowing for better understanding of the soil behaviour. Additionally, it allows for the correction of the tip resistance measurement, q_c, by taking into account the pore water pressure acting against the shoulder of the conical tip. This correction is shown in Equation 1, where (u_2) represents the dynamic pore pressure reading measured behind the shoulder of the conical tip, and (a) is the net area ratio which is a geometric constant specified by the cone manufacturer.

$$q_t = q_c + u_2(1-a)$$
[1]

Robertson et al. 1986, produced a SBT chart by plotting the corrected tip resistance, q_t, against the friction ratio, R_f (Figure 3a), where the friction ratio is calculated as:

$$R_f = \frac{f_s}{q_t} \times 100\%$$
[2]

Additionally, Robertson et al. 1986, proposed the use of the pore pressure parameter, B_q, in soil classification using the SBT BQ chart shown in Figure 3b, where B_q is calculated as:

$$B_q = \frac{u_2 - u_o}{q_t - \sigma_{vo}}$$
[3]

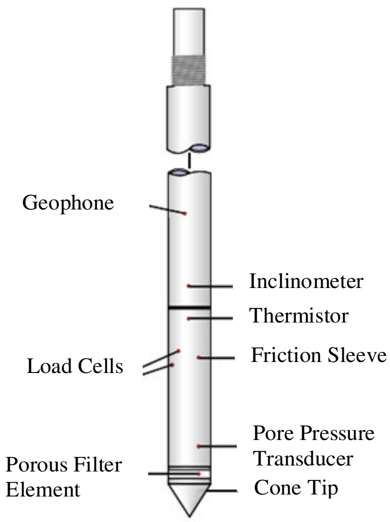
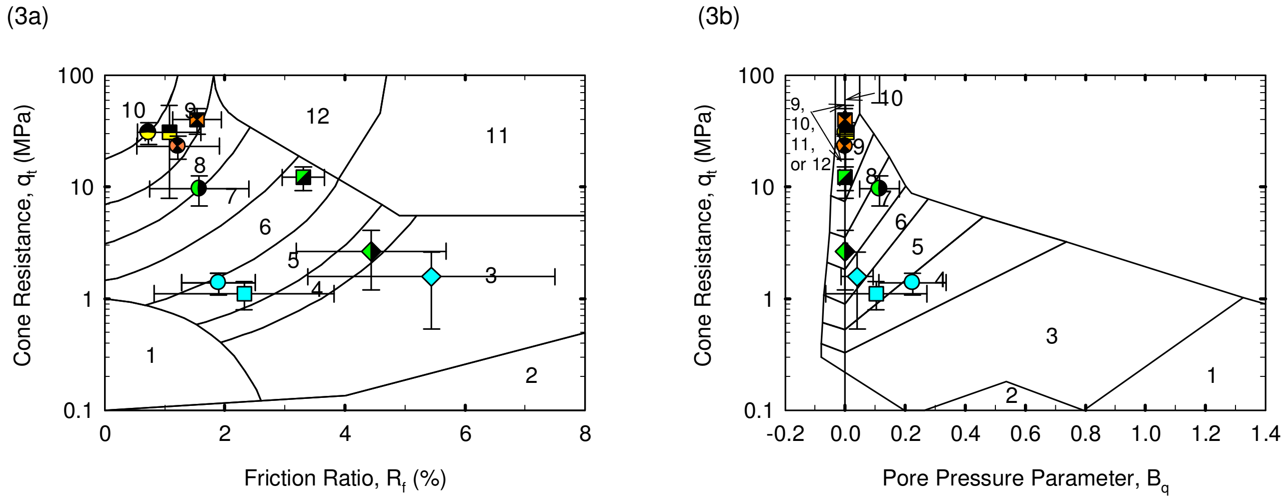


Figure 1. Schematic of a ConeTec Seismic Piezocone

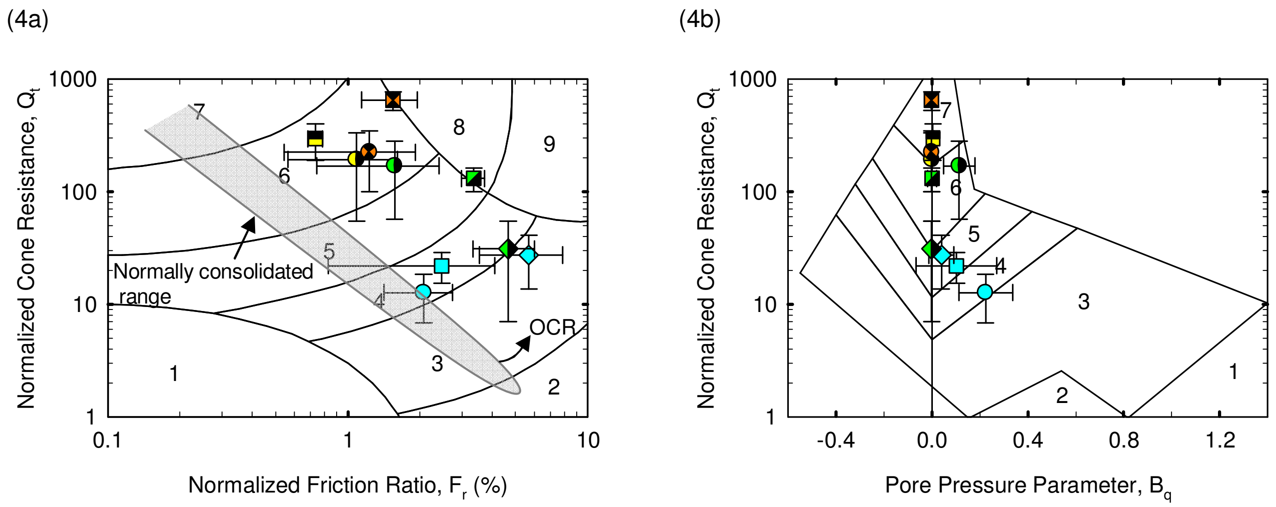
Figure 2. Typical ConeTec Track Mounted Rig Used at Fort McMurray Sites.

Robertson (1990) recommended the use of normalized parameters (normalized tip resistance "Q_t" and normalized friction ratio, "F_r", Figure 4) to compensate for the increase in overburden stress with depth which may significantly affect q_t and f_s measurements. Lunne et al. (1997) suggested that increases in overburden stress may affect soil behaviour type interpretations with non-normalized parameters at depths exceeding 30 metres.



1- sensitive fine grained
2- organic material
3- clay
4- silty clay to clay
5- clayey silt to silty clay
6- sandy silt to clayey silt
7- silty sand to sandy silt
8- sand to silty sand
9- sand
10- gravely sand to sand
11- very stiff fine grained*
12- sand to clayey sand*

Figure 3a (SBT), and 3b. (SBT BQ) Non-Normalized Classification Charts (after Robertson et al. 1986)
Every data point represents the mean value and the range bars, in X and Y directions, represent ±1standard deviation



1- sensitive fine grained
2- organic soils-peats
3- clays-clay to silty clay
4- silt mixtures clayey silt to silty clay
5-sand mixtures -silty sand to sandy silt
6- sands-clean sands to silty sands
7- gravely sand to sand
8-very stiff sand to clayey sand
9- very stiff fine grained

Figure 4a (SBTn), and Figure 4b (SBT BQn) Normalized Classification Charts (after Robertson 1990)
Every data point represents the mean value and the range bars, in X and Y directions, represent ±1standard deviation

In Alberta stiff overconsolidated deposits it is observed that normalized charts are more applicable even at shallow depths (Elbanna et al. 2008). It should be noted that knowledge of phreatic surface and material unit weight is required for the normalized parameters calculations. The SBTn and SBT BQn charts with normalized parameters are shown in Figures 4a and 4b, respectively. The Q_t and F_r parameters are calculated as:

$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma_{vo}'}$$

[4]

$$F_r = \frac{f_s}{q_t - \sigma_{vo}} \times 100\%$$

[5]

4 SOIL DESCRIPTIONS

4.1 Fine grained Soils

4.1.1 Pleistocene Clay

In general, the pleistocene clay near Fort McMurray typically consists of 60% to 95% fines content (material finer than 75 µm), and classifies as low to high plasticity clay (CL to CH), with a Plasticity Index (PI) varying between 10 and 40 and a Liquid Limit (LL) between 20% and 60%.

The pleistocene clay is typically firm to stiff with in-situ undrained shear strengths between 25 kPa and 75 kPa. With the exception of an upper desiccated crust, the pleistocene clay is typically lightly overconsolidated.

4.1.2 Clay Till

In general, the clay till near Fort McMurray contains 50% to 80% fines (material finer than 75 µm), and generally classifies as low to high plasticity clay (CL to CH). The typical range of particle size distribution of the clay till is presented in Figure 5. The range of particle size distribution presented in Figure 5 represents the upper and lower bound of combined data sets from sites considered in this paper.

The clay till is typically very stiff to hard, with undrained shear strengths generally in excess of 100 kPa.

4.2 Coarse Grained Soils

4.2.1 Pleistocene Sand

This unit consists of fine to medium grained sand, typically with trace to some fines. The typical range of particle size distribution of the pleistocene sand is presented in Figure 6. The range of particle size distribution presented in Figure 6 represents the upper and lower bound of combined data sets from sites considered in this paper.

The pleistocene sand is generally compact to very dense with overburden corrected SPT blow counts typically in the range of 20 to 60.

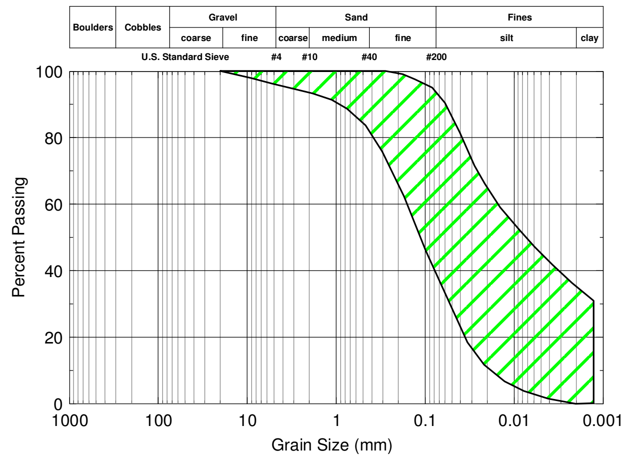


Figure 5. Range of Gradation for Clay Till

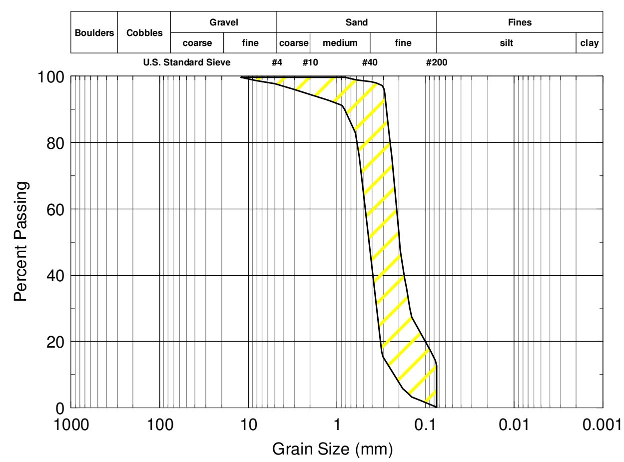


Figure 6. Range of Gradation for Pleistocene Sand

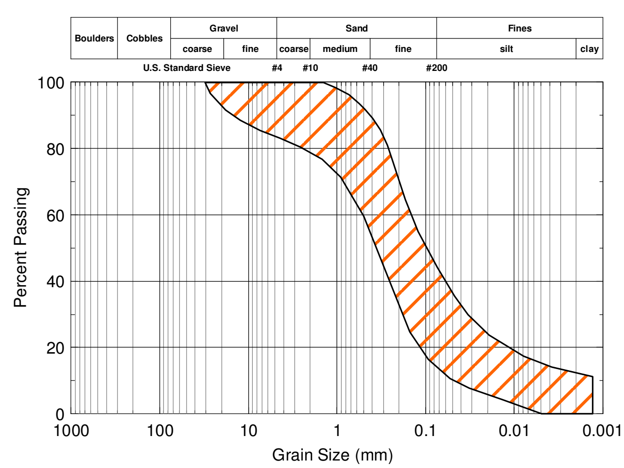


Figure 7. Range of Gradation for Sand Till

4.2.2 Sand Till

The sand till generally consists of dense to very dense fine silty sand with overburden corrected blow counts typically greater than 30. The range of particle size distribution is illustrated in Figure 7.

5 ANALYSES

A total of 42 CPTu tests were analysed in conjunction with visual descriptions presented in associated borehole logs, Standard Penetration Test (SPT) results, and laboratory test results. CPTu parameters were then calculated as described in Section 3 and Equations 1 to 5. For each soil group (i.e. pleistocene clay, clay till, pleistocene sand, and sand till), CPTu parameters from each site were arithmetically averaged and superimposed onto the SBT charts (Figures 3 and 4). The mean data points are presented with range bars in X and Y direction that represent ±1 standard deviation.

6 RESULTS OF THE ANALYSES

6.1 Soil Behaviour Type for Fine Grained Soils

Clayey soils usually exhibit low tip resistance and high friction ratio. This can be clearly demonstrated by looking at the preceding Figures 3 and 4. Moreover, normally or lightly overconsolidated saturated clayey materials produce excess dynamic pore water pressure. It should be noted, however, that dilative silts and heavily overconsolidated clays will produce dynamic pore pressures less than hydrostatic (dilative behaviour).

As a general observation for the clayey materials in this study, the SBTn chart shows that the clays in sites A, B, and C are likely in the overconsolidated range as the data points fall to the right of the shaded normally consolidated zone (Figure 4a). This is confirmed with laboratory consolidation tests carried out at several locations. Due to space constraints in this paper, consolidation data is not discussed further.

6.1.1 Pleistocene Clay

Pleistocene clays for sites A, B, and C fall between zones 3 and 6 in the SBT and SBT BQ Charts, which are described as clays (zone 3) to sandy silt or clayey silt (zone 6). This description is in general agreement with the pleistocene clay description based on field observation and index testing (see section 4). The SBT BQ chart that incorporates the pore pressure parameter, Bq, seems to provide a clearer distinction between the pleistocene clay and clay till deposits.

The SBT BQ chart also provides a more accurate description for site A data when compared with the SBT chart. The SBT BQ chart shows that site A material is more of a silty clay to clay or clayey silt, which was found to be similar to what was observed in the field and from index tests. On the other hand, based on the SBT chart, the pleistocene clay from site A appears to have a sandy behaviour (between zones 5 and 6).

Pleistocene clay from site C, in contrast, showed to have mainly clay behaviour in the SBT chart as the majority of the data falls within zone 3. However, a better description is made by the SBT BQ chart where the majority of the data points are observed to fall in zones 5 and 6. The Pleistocene clay in site C is described as having trace to some sand.

Similar observations are found for the normalized charts, SBTn and SBT BQn. A better description for site A pleistocene clay is made by the SBT BQn chart in comparison with SBTn.

6.1.2 Clay Till

SBT for site C clay till appears well described by SBT and SBTn charts as silty clay or clayey silt material which is in general agreement with field observations and laboratory test results. In contrast with the above, normalized and non-normalized Bq charts describe the clay till material in site C as having more sand content. Also, clay till deposits from Sites A and B were generally described by CPTu charts to have more sand content than what would be expected based on gradation analyses (Section 4).

6.2 Soil Behaviour Type for Coarse Grained Soils

Sandy deposits generally tend to produce a low friction ratio and high tip resistance as reported in the literature and shown in Figures 3 and 4. In addition, sands generate low to no excess pore pressure. Dense sands often show dilative behaviour with measured dynamic pore pressures less than hydrostatic.

6.2.1 Pleistocene Sand

Generally, all of the CPTu classification charts, considered in this paper, provide a good description for pleistocene sands when compared to descriptions provided in Section 4 and gradation analyses in Figure 7.

6.2.2 Sand Till

The SBT and SBTn charts provided a very close description for the sand till deposit encountered in sites A and B, which, as described in Section 4, is classified as silty sand with trace to some gravel deposits. On the other hand, charts with Bq parameters have a tendency to erroneously describe the sand till material as mainly clean sand to gravely sand deposits.

The SBTn chart provides the best soil description for site B sand till, as the mean data point falls between sands (zone 6) and very stiff to clayey sand (zone 8). Furthermore, clearer distinction between pleistocene sands and sand till can be observed in the SBTn chart when compared with the SBT chart.

7 CASE STUDIES

In this section, two full CPTu profiles are presented along with borehole log descriptions, laboratory test results and other in-situ test results.

Although the CPTu data was collected at 5 cm intervals, CPTu measurements used for soil behaviour type interpretations were arithmetically averaged over 50 cm intervals. This averaging interval is selected to be similar to the thin-walled Shelby tube and/ or SPT sampler height that is used to provide an independent soil classification. The soil samples were obtained within a 1 to 5 m horizontal distance from the CPTu sounding locations.

7.1 Case Study 1

The subsurface conditions at case study 1 are comprised of interbedded silty sand and silty clay deposits underlain by layers of very stiff to hard silty clay and silty sand till layers. Soil samples and index testing indicate the silty clay till to be of low to medium plasticity with sand and trace gravel. Clean sand was encountered at an approximate depth of 7.5 m. Figure 8 presents the borehole description as well as SPT and index test results.

Figure 9 presents CPTu data (q_t, R_f, u) measured in the vicinity of the case study 1 borehole. Soil behaviour type interpretations using the four CPTu classification charts described in the preceding sections are provided in Figure 9.

As shown in Figure 9, the clean sand deposit below 7.5 m is best described using the SBT and SBTn charts. In contrast, charts that incorporate the B_q parameter (normalized chart SBT BQn and the non-normalized chart SBT BQ) showed a less accurate classification when compared with the borehole log description presented in Figure 8.

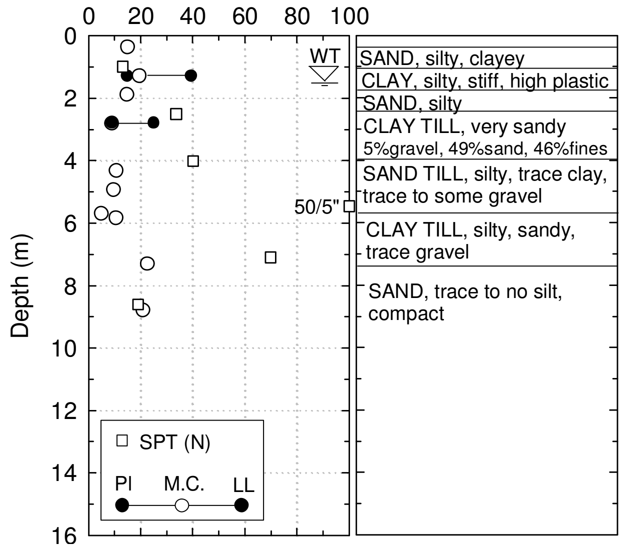


Figure 8. Borehole Log Description, SPT Test Results and Index Properties for Case Study 1

For the shallow interbedded sand, clay, sand till, and clay till encountered in the upper 7 m, SBT and SBTn charts appear to provide reasonable classification. However, the SBTn chart provided a more accurate description for the lower sand and clay till deposits. It also gives a better description of the material's in-situ density or consistency. This is in agreement with what is observed by Elbanna et al. (2008) in Alberta stiff soils.

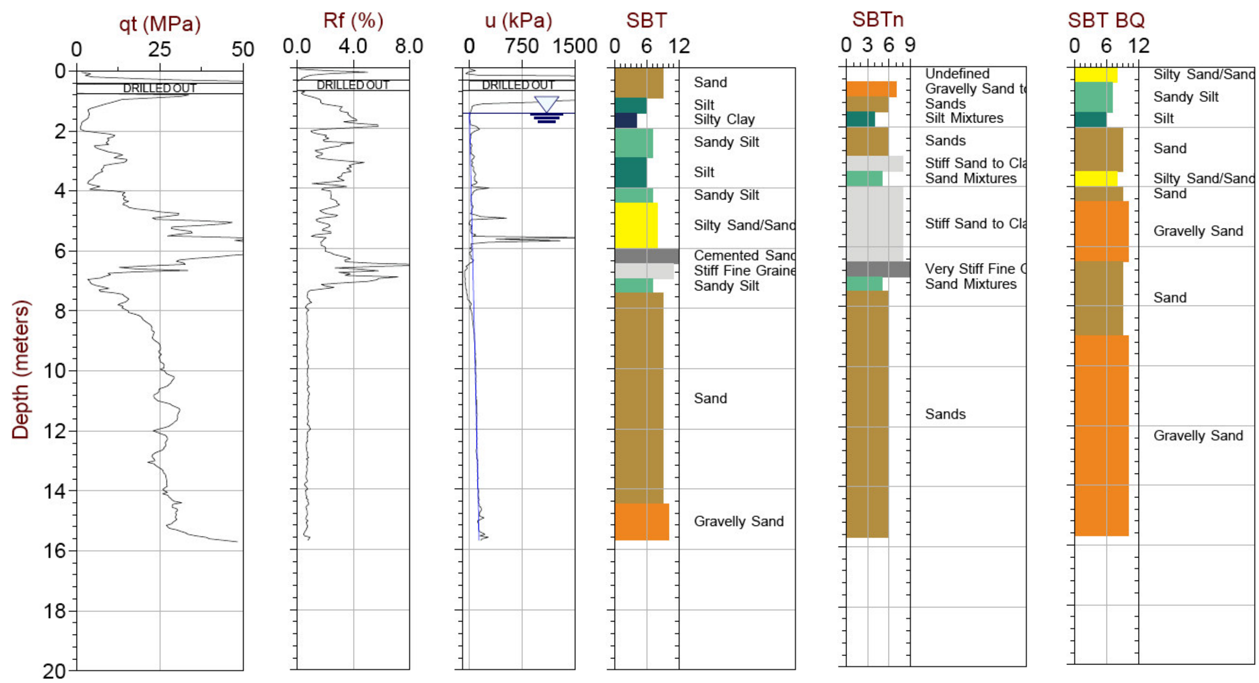


Figure 9: CPTu profile and soil behaviour type interpreted using different classification methods for case study 1

7.2 Case Study 2

The subsurface conditions at the location of case study 2 consist of a shallow peat layer followed by medium plastic silty clay, which is underlain by a very stiff sandy silt deposit (Figure 10). Based on a geologic interpretation of the field observations, SPT results, and laboratory test results, the very stiff sandy silt deposit was interpreted as clay till.

In the clay till deposit, SBT and SBTn charts appear to provide a better soil description when compared to the SBT BQ chart (Figure 11).

As shown in Figure 11, SBT and SBTn provide a good description for the upper silty clay deposit (between depths of 0.4 m and 7 m) that matches those observed in the borehole log. The silty behaviour of this deposit however can be observed from the SBT BQ classification.

It should be noted that the shallow peat layer was frozen at the time of testing resulting in the high tip resistance and sandy like soil behaviour types.

As indicated in section 6.1.1, the classification charts that incorporate the pore pressure measurement seem to provide a better description for the pleistocene clay behaviour. This can be observed in the upper pleistocene clay in case study 2.

Based on the analyses discussed in section 5 and data presented in this case study, both SBT BQ and SBTn should always be considered together in order to assess pleistocene and till deposits typically found in the Fort McMurray region.

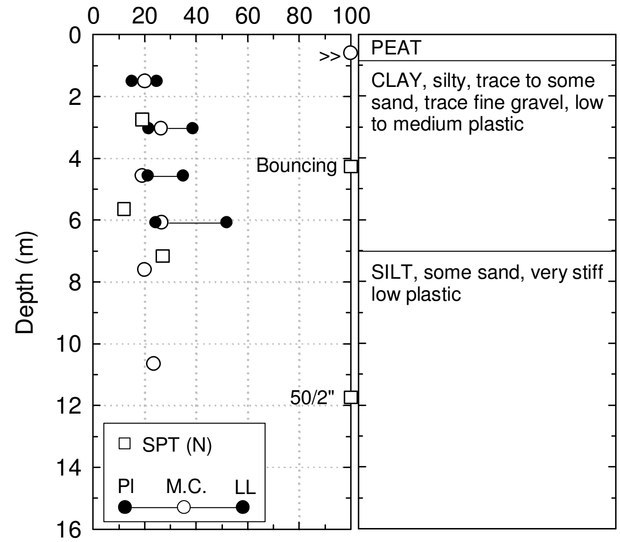


Figure 10. Borehole Log Description, SPT Test Results and Index Properties for Case Study 2

8 DISCUSSION

Considering the large scale of oilsands projects near Fort McMurray, sufficient subsurface profiling and detailed soil characteristics can be difficult to achieve using conventional site investigations techniques alone.

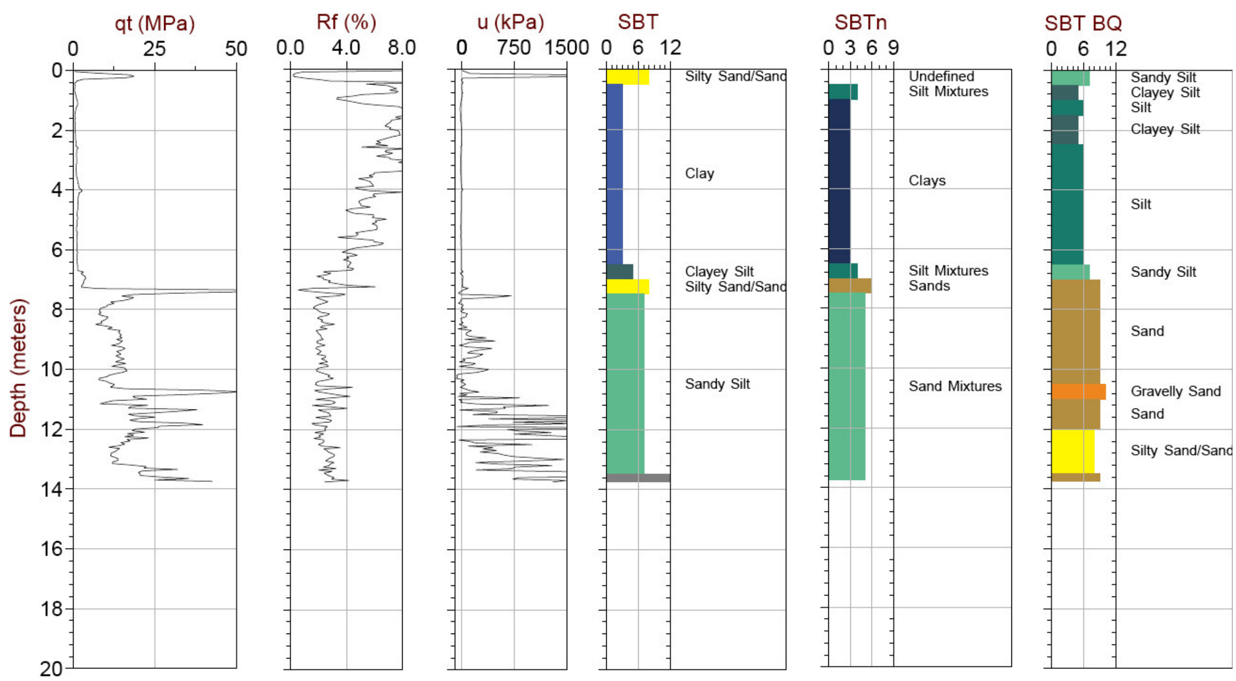


Figure11: CPTu profile and soil behaviour type interpreted using different classification methods for case study 2

The CPTu is considered a reliable and economic tool to be used in conjunction with conventional site investigation techniques.. Based on the data presented in this paper and experience with CPTu interpretations, sufficient soil classification can be achieved using SBT or SBTn charts in conjunction with the SBT BQ chart. The SBT BQ appears to be particularly useful in normally consolidated or lightly overconsolidated deposits. CPTu classification using q_t and f_s measurement alone did not show the dilative (silty) behaviour of the silty clay. This dilative behaviour is better observed from the pore pressure measurements and by using SBT BQ charts.

As demonstrated in Figures 3, 4 and case study 1, the SBTn chart provides the best classification of stiff fine grained soils (clay till) and stiff granular deposits (sand till). As well, SBTn chart appeared to provide a better description of the consistency of the clay till and the compactness of the sand till.

SBTn charts are also found to give a reasonable qualitative snapshot of the overconsolidation state of soils. This is simply noted when looking at the position of the data points with respect to the shaded normally consolidated area in the SBTn chart (Figure 4a).

9 CONCLUSIONS AND RECOMMENDATIONS

CPTu can provide a rapid, reliable and economic solution for effective soil classification in northern Alberta soils.

Although all of the CPTu classification charts have proven to provide reasonable soil classification in typical soil conditions, local experience and understanding of soil behaviour are required to make an appropriate selection of the most applicable charts in a given geological condition.

In typical Fort McMurray overburden deposits, the SBTn chart should be used for general profiling. If pleistocene clays are encountered, the SBT BQ chart can aid to better evaluation of soil type.

In addition to standard CPTu soil behaviour type data presented versus depth, it should be common practice to present CPTu data directly on the SBT chart, similar to that shown in Figure 4a. This assists in showing variation within a soil unit, and can provide a reasonable indication of the overconsolidation state of soils. Should that overconsolidation state appear to be of a concern, further laboratory testing will be required.

ACKNOWLEDGEMENTS

The authors are grateful for assistance provided by Mr. Bill Chin of AMEC Earth & Environmental to obtain the required permission to use data from site C and for providing technical advice throughout the research program presented in this paper.

The authors would like to thank Mr. David Woeller of ConeTec Investigations Ltd. for his assistance obtaining permission to use data from sites A and B.

The authors are thankful for valuable comments, recommendations, and technical advice provided by Mr. James Grieg of ConeTec Investigations Ltd.

REFERENCES

Begemann, H.K.S., (1965), The Friction Jacket Cone as an Aid in Determining the Soil Profile. Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering, ICSMFE, Montreal, September 8 - 15, Vol. 2, pp. 17 - 20.

Elbanna, M., Sharp, J., Grieg, J., Grass, J. (2008), Interpretation of SCPTu Data in Stiff Soils and Soft Rock, 61st Canadian Geotechnical Conference, Edmonton, Alberta.

Fellenius, B.H., and Eslami, A., (2000), Soil Profile Interpreted From CPTu Data. “Year 2000 Geotechnics” Geotechnical Engineering Conference, Asian Institute of Technology, Bangkok, Thailand, November 27 - 30, 2000, 18 p.

Lunne, T., Robertson, P.K. and Powell, J.J.M., (1997), Cone Penetration Testing in Geotechnical Practice, Blackie Academic and Professional.

Robertson, P.K., Campanella, R.G., Gillespie, D., and Grieg, J., (1986), Use of Piezometer Cone Data. Proceedings of American Society of Civil Engineers, ASCE, In-Situ 86 Specialty Conference, Edited by S. Clemence, Blacksburg, June 23 - 25, Geotechnical Special Publication GSP No. 6, pp. 1263 - 1280.

Robertson, P.K., (1990), Soil Classification Using the Cone Penetration Test. Canadian Geotechnical Journal, Vol. 27, No. 1, pp. 151 - 158.

Robertson, P.K., Sasitharan, S., Cunning, J.C., and Segs, D.C., (1995), Shear Wave Velocity to Evaluate Flow Liquefaction. Journal of Geotechnical Engineering, ASCE, 121(3), 262-273.