Interpretation of SCPTu Data in Stiff Soils and Soft Rock

Elbanna, M AMEC Earth & Environmental, Nanaimo, British Columbia, Canada Woeller, D; Greig, J; Sharp, J; Grass, J ConeTec Investigations Ltd., Richmond, British Columbia, Canada

ABSTRACT



Recent advances in Cone Penetration Testing (CPT) probes and deployment rigs have allowed for testing to occur in much stiffer soil conditions than previously possible, including glacial tills and weathered rock. Many soil classification techniques rely on empirical relationships based on datasets with limited experience in these conditions. Investigations have been conducted at two Alberta sites, with CPTu, SCPTu and traditional Standard Penetration Testing (SPT). Six classification techniques were employed based on the CPT data and compared to the results of the SPT testing and laboratory testing. Appropriate classification charts are recommended based on the data set. It is recommended that additional CPTu and SCPTu data in these subsurface conditions be cross-correlated with physical samples in order to develop larger datasets and better empirical relationships between in-situ testing and soil classification in stiff soils

RÉSUMÉ

Les avances récentes dans les sondes d'Évaluation de Pénétration au Cône (EPC) et les foreuse de déploiement pétrolières ont permis des essais dans des conditions de sol beaucoup plus rigides qu'auparavant, en incluant des tills glacial et la roche érodé. Beaucoup de techniques de classification de sol s'appuient sur des relations empiriques basés sur des jeux de donnés avec de l'expérience limitée dans ces conditions. Des recherches ont été accomplies à deux sites en Alberta, avec CPTu, SCPTu et l'Évaluation de Pénétration Standard traditionnelle (EPS). Six techniques de classification ont été employées basées sur les données d'EPC. Ils ont eu des résultats comparables à celles de l'EPS et du laboratoire. Des graphiques de classification appropriés sont recommandés basés sur le jeu de donnés obtenu. Il est recommandé que des jeux de donnés supplémentaire de CPTu et SCPTu dans ces conditions souterraine soient trans-corrélés avec des échantillons pour développé des plus grandes jeux de donnés et des meilleurs rapports empiriques entre l'évaluation in-situ et la classification de sol dans des sols rigides.

1 INTRODUCTION

Cone Penetration Testing offers rapid, economical and continuous soil profiling for geotechnical and environmental site investigations. Traditionally, the CPT has been used for soft soil investigations due to relatively delicate equipment and small deployment equipment. Recent years have seen the development of large advanced CPT rigs that can now push into much harder soils including, but not limited to, stiff glacial tills and soft rock. In addition to the standard tip and sleeve measurements, pore pressure transducers have been added to cones in order to measure dynamic and static water pressures (CPTu). Geophones have been included in the cone body such that shear and compression wave velocities can be measured (SCPTu) as shown in Figure 1. SCPTu offers the potential to determine Soil Behaviour Type (SBT) using the measurement of cone tip resistance, sleeve friction, pore pressure and shear wave velocity (Robertson et al. 1986; Robertson 1990; Eslami and Fellenius 1997; and Robertson et al 1995).

The interpretation of SCPTu data is dependant upon many geologic factors. For fine grained soils, the SCPTu response is dependant on changes in over consolidation (OCR), age, sensitivity, undrained strength and permeability. For coarse grained soils, the SCPTu response is dependant on OCR, age, cementation and friction angle. In addition, stress history, in situ stresses, stiffness, macrofabric, mineralogy and void ratio also influence the SCPTu and hence its interpretation as it relates to soil type and strength characteristics.

This paper evaluates several CPT and SCPTu classification methods against traditional laboratory based testing methods at two sites located in Fort McMurray and Calgary, Alberta. In each case, the sites exhibited subsurface conditions that were of glacial origin.



Figure 1. Schematic of a ConeTec Seismic Piezocone

a)

b)



Figure 2. a) Track Mounted Rig Used at Fort McMurray Site, b) Truck Mounted Rig Used at Calgary Site

2 BACKGROUND

At both test sites, a 15cm² ConeTec SCPTu cone was used, as illustrated on the preceding page in Figure 1. Both test locations, employed the use of very large CPT rigs in order to achieve the desired design depths. The Fort McMurray site employed a 25 ton tracked CPT rig due to soft surface conditions, while the Calgary site employed the use of a 30 ton truck mounted rig. Photographs of both are shown in Figures 2a and 2b.

3 SBT CLASSIFICATION METHODS

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

Soil Behaviour Type (SBT) classification has traditionally relied on two parameters; the cone resistance q_c , and the sleeve friction, f_s . Recently, pore pressure transducers have been incorporated allowing for an increased 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 against the shoulder of the conical tip. This correction is shown in Equation 1, where u_2 represents the dynamic pore pressure reading, located behind the shoulder of the cone and a, the net area ratio, is a laboratory based variable that is specific to cone design.

$$q_{t} = q_{c} + u_{2}(1-a)$$
^[1]

Robertson et al. 1986, plotted the corrected tip resistance against the friction ratio, Rf. This calculation is displayed as Equation 2 and the classification chart is displayed as Figure 3a.

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

Additionally, Robertson et al. 1986, proposed the use of the pore pressure parameter, Bq, displayed as Equation 3 and as Figure 3b.

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

Robertson 1990 recommended the use of normalized tip resistance and friction sleeve parameters to compensate for the increased values that were observed to occur at deeper depths. It is suggested that this method be used at depths exceeding 30 metres. These calculations are denoted as Equation 4 & 5 and the normalized charts displayed as Figures 4a and 4b.

$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma_{vo}'}$$
^[4]

$$F_r = \frac{f_s}{q_t - \sigma_{vo}} \times 100\%$$
[5]

Eslami and Fellenius 1997 developed a classification chart, Figure 5, by plotting the effective tip resistance, q_E , as a function of the sleeve friction, f_s , shown in Equation 6.

$$q_E = q_t - u_2 \tag{6}$$

The reasoning behind this method was to avoid plotting the variable, q_t , against itself as R_f .



Figure 3a, 3b. SBT Classification Charts (after Robertson et al. 1986) Range bars, in X and Y directions, represent ±1standard deviation Every data point represents the average of 3 tests except Calgary-B that represent only one test



1- sensitive fine grained4- silt mixtures clayey silt to silty clay2- organic soils-peats5-sand mixtures -silty sand to sandy silt3- clays-clay to silty clay6- 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, 4b. SBT Classification Charts (after Robertson 1990) Range bars, in X and Y directions, represent ±1standard deviation Every data point represents the average of 3 tests except Calgary-B that represent only one test



1- collapsive soil - sensitive soil 4- silty sand – sandy silt 2- soft clay – soft silt 5- sand - gravel 3- silty clay – stiff clay

Figure 5. SBT Chart (after Eslami and Fellenius 1997) Range bars represent ±1standard deviation Every data point represents the average of 3 tests

The last classification method this paper will discuss was proposed by Robertson et al. 1995, and involves the use of seismic data (Figure 6). In this case the soil behaviour type is interpreted based on the normalized cone tip resistance, Q_t , against the ratio of small strain shear modulus, G_0 , to cone resistance (G_0/q_t). The small strain shear modulus is directly related to the shear wave velocity, V_s , by the relationship shown in Equation 7.

$$G_o = \rho (V_s)^2 \tag{7}$$

Where ρ is the soil mass density

All of these SBT classification methods have been evaluated for both Alberta sites discussed in this paper.





Figure 6. Soil Behaviour Type Charts (Robertson et al. 1995)

CASE STUDY

CPTu, SCPTu, SPT and conventional laboratory based soil testing data collected at both Alberta sites have been summarized in Figure 7. Parameters measured from drilling and lab testing include grain size distribution, Atterberg limits, Standard Penetration Testing and physical soil descriptions. CPTu and SCPTu parameters include tip resistance, sleeve friction, pore pressure (both u_2 and u_0) and shear wave velocity, for two of the four trials.

Eslami and Fellenius 1997 recommended the geometric averaging as it is more representative in non homogenous material. both arithmetic and geometric averaging for CPTu and SCPTu data have been used in the analysis. However, it was realized that there is no significant deference between the two averaging techniques, at least with the data presented in this paper. This is basically due to the consistency of the material. Therefore, only the results from the arithmetic averaging are presented in this paper. The authors, however, agree that the geometric averaging might be advantages with non homogenous material.

4.1 Site Descriptions

The subsurface condition in Fort McMurray site is generally comprised of interbedded stiff to hard sandy silt and clay layers with medium to low plasticity. Two zones of material are considered in this paper where the material seemed to be very dense and hard to drill. These zones are referred to as Fort McMurray-A and Fort McMurray-B.

The subsurface conditions at the Calgary site are comprised of interbedded sand, silt and silty clay that are lacustrine in origin, followed by very stiff to hard silty clay till. Soil samples indicate the till to be low plastic silty clay and silt containing trace amounts of sand, gravel and coal fragments. Data from this zone is referred to as Calgary-Α In this zone, Atterberg limits, moisture content, and SPT data are available. A very dense layer that is about 4 meters thick was encountered at the Calgary site. This layer is described in the borehole logs as low plasticity silt with trace sand. Data from this zone is referred to as Calgary-B. CPT tip resistance and sleeve friction in this zone are approximately an order of magnitude higher than the silty clay zone (Calgary-A). Seismic CPT is available for this zone as well as SPT and moisture content. SPT refusal (greater than 50 blows per 6") was encountered in this zone.

4.2 Analysis

Summarized results for both sites are shown in Figure 7.

A total of 10 CPT soundings associated with adjacent boreholes are presented in Figure 7. Shear wave velocity data is available only from two soundings (Fort McMurray-A and Calgary-B). At each sounding, excluding Calgary-B, the data points for q_t , f_s , R_f , SPT and the laboratory test values represent the average of 3 soundings/boreholes that were carried out in the same area. The range bars shown in Figure 7 represent ±1 standard deviation. The results are plotted in this fashion to illustrate the repeatability of the CPT data obtained from three different soundings in the same material.

SBT interpreted for Fort McMurray-A, Fort McMurray-B and Calgary-B sites do not have the same degree of accuracy.

Charts with pore pressure parameter B_q , shown in fugure 3b, did not appear to provide accurate SBT in all trials. It is important to note the importance of sub-surface groundwater conditions when employing this method,

.....

Site	Borehole soil description	q _t (MPa)	f _S (MPa)		Rf (%)	VS (m/s)	SPT (N)	vel (%	(%) pi	(%) (%)	(%)	(%)	(%)
		0 20 40	60 0 1	2 0	2 4	6 0 200 400 6	000 10 20 30 40 50	Gra	Sar	Silt Cla	×	≥	≥
Ft. McMurray-A	CLAYEY SILT, very dense, med. plastic, moist, gray		\$		\$			0	1	79 20	16	39	19
Ft. McMurray-B	SILT-SAND, some clay, trace gravel, moist, gray	4	A		ы		Å	2	35 (50 12	15	40	16
Calgary-A	SILTY CLAY, trace sand, trace gravel (till), moist, grey	¢	ä		Ю						17	28	17
Calgary-B	SILT, trace sand, very dense (till), wet, grey	0	0		0	o	>>0				24		

Figure 7. Data Summary

Range bars represent ±1standard deviation

Every data point represents the average of 3 tests except Calgary-B that represent only one test Averaging depth = 0.5m and COV over the averaging depth ranges between 3% and 10%

Although CPT data was collected at 5 centimeter intervals, the results are arithmetically averaged over an interval of 50 centimeters. Over the averaging depth, the coefficient of variation (COV) ranges between 3-10% in both sleeve friction and tip resistance measurements, indicating consistent sub-surface conditions. SPT blow counts and laboratory data shown in Figure 6 are obtained from within the 50 centimeter averaging interval of the CPT data.

Figure 7 also shows that refusal was encountered with the SPT in Fort McMurray-A and Calgary-B sites. In addition, fairly wide scatter can be observed for SPT blow counts in Fort McMurray-B site.

Recorded parameters from all CPTu and SCPTu soundings have been applied to all SBT classification techniques discussed in Section 3. The results have been superimposed on Figures 3-6 and can be compared to the physical samples shown in Figure 7.

4.3 Discussion

Geometric averaging recommended by Eslami and Fellenius 1997, was considered in the analyses. However, there was not an appreciable difference between the results of the two techniques with the data presented in this paper. This is due to the uniformity of the material. The authors agree that geometric averaging might be advantageous in non homogenous soils.

The standard classification chart in Figure 3a, provides accurate soil behaviour type interpretations for Calgary-A.

particularly in native Albertan soils. There are often very low water tables, dynamic hydrologeologic conditions and dilative soils that can make analysis through this method difficult.

Charts with the normalized parameters Q_t and F_r , Figure 4a, provided accurate SBT interpretation in all the cases. Additionally, this method is able to accurately classify soils at depths less than 30 meters.

The Eslami and Fellenius chart, Figure 5, shows accurate SBT interpretation for Fort McMurray-B and Calgary-A sites. It should be noted that the SBT of extremely stiff material such as that encountered in Calgary-B site can not be captured with Eslami and Fellenius charts. In this case f_{s} , which was over 1400kPa, is beyond the 1000kPa sleeve friction limit of the chart.

Interpretations based on the seismic based chart in Figure 6 were not accurate for this case study. However, this chart has been recommended for identification of unusual soils such as cemented, highly compressible and aged soils (Lunne et al. 1997).

5 CONCLUSIONS

CPTu and SCPTu testing can provide fast, reliable and continuous soil profiling. Advances in rig and cone design have allowed testing to occur in very stiff soil conditions, not previously possible.

Several empirical relationships have been developed in the past decades which correlate several cone parameters to soil classification and soil behaviour categorization. As many of these methods come from different data sets and can be specialized towards particular subsurface conditions, care should be taken when selecting classification techniques.

Additionally, collecting as many parameters as possible greatly increases the ability to accurately classifying soil types.

It is the opinion of the authors that increased data collection and cross correlation to traditional drilling and laboratory based testing should occur. This will develop stronger empirical relationships between CPTu and SCPTu parameters in stiff soils and greatly aide in soil classification. Future work will include the development of a stiff soil behaviour type chart.

ACKNOWLEDGEMENTS

The authors would like to thank the Calgary Health Region for permission to use for the data presented in this paper. The writers are grateful for assistance provided by Ms. Brooke Reilly for translation services.

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.
- Eslami, A. and Fellenius, B.H. (1997). Pile Capacity by Direct CPT and CPTu Methods Applied to 102 Case Histories, Canadian Geotechnical Journal 34 (6), 886-904.
- 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.