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Challenges from North to South
Des défis du Nord au Sud

Evaluation of the undrained shear strength of Champlain Sea clays (Leda clay) in Ottawa using CPT

Raymond Haché, Athir Nader & Simon Gudina
Stantec Consulting Ltd., Ottawa, Ontario, Canada
Mamadou Fall
Department of Civil Engineering – University of Ottawa, Ottawa, Ontario, Canada

ABSTRACT
An evaluation of the empirical cone factors, N_{kt}, which are used to define the undrained shear strength (s_u) profile of a deposit on the basis of cone penetration test (CPT) has been carried out for eleven Ottawa Leda clay sites. Both CPT and field-vane tests were carried out at each site as part of the evaluation of the N_{kt} values. The field-vane apparatuses used were friction compensated digital and Nilcon vanes. N_{kt} values presented in the literature typically range from 10 to 20 with recommended values of 14 to 16 in the cases where site specific information is not available. The Ottawa Leda clay sites investigated mostly produced N_{kt} values in the range of 8 to 12. The practice of using SPT N-values to estimate the undrained shear strength is also briefly discussed and it is demonstrated to be unsuitable for use within Leda clay deposits.

RÉSUMÉ
Une évaluation des facteurs empiriques de cône, N_{kt}, qui servent à définir le profil de résistance (s_u) au cisaillement non drainé d'un dépôt sur la base de l'essai de pénétration au cône (CPT), a été effectuée pour onze sites d'argile de Leda d'Ottawa. Des essais de CPT et de scissomètre ont été effectués sur chaque site dans le cadre de l'évaluation des valeurs N_{kt}. Les appareils de scissomètre de chantier utilisés étaient d'affichage digital avec friction compensée et des ailettes de Nilcon. Les valeurs N_{kt} présentées dans la littérature varient en général entre 10 et 20 avec des valeurs recommandées allant de 14 à 16 dans les cas où il n'existe pas d'informations spécifiques sur le site. Les sites d'argile de Leda d'Ottawa étudiés donnent principalement des valeurs N_{kt} de l'ordre de 8 à 12. La pratique d'utiliser les valeurs N de SPT pour estimer la résistance au cisaillement non drainé est aussi brièvement discutée; et on a démontré que cette pratique n'est pas appropriée pour les dépôts d'argile de Leda.

1 INTRODUCTION

Soil specific cone factors (N_{kt} and $N_{\Delta u}$) are unique characteristics of each deposit or site. However, values of these factors are commonly generalized for a variety of soils especially when little specific site information is available.

N_{kt} and $N_{\Delta u}$ values are commonly used to estimate the undrained shear strength of a soil profile when Cone Penetration Test (CPT) data is available. As these factors appear in the dominator of the correlations (as shown later), geotechnical engineers tend to use higher values of these factors to get conservative strength estimates in cases of uncertainties. However, this practise can significantly underestimate the strength of the Champlain Sea clay. This research paper was initiated for the purpose of helping geotechnical engineers in selecting more appropriate ranges of N_{kt} and $N_{\Delta u}$ for Champlain Sea clays in Ottawa.

2 GEOLOGY AND ORIGIN

Relatively thick deposits of sensitive marine clays were deposited within the Champlain Sea basin which was a temporary inlet of the Atlantic Ocean created by retreating glaciers during the close of the last ice age. The sea lasted from 12500 to 10000 years BC during which it was continuously reducing in size as the continent gradually rebounded in response to the huge pressure relief as the Wisconsin ice sheet, up to 3 km thick, retreated (Cronin 1975, Gadd 1975, Johnston 1917, Kenney 1964, and Quigley 1976). The Champlain Sea was generally within the areas currently referred to as the Ottawa River Valley and the St. Lawrence River Valley and it is believed that its floor was temporarily depressed by as much as 225 m.

Evidence suggests that the Champlain Sea clays were generally deposited within brackish water resulting from the mix of fresh water ice melt and intruding water from the rising Atlantic Ocean; the sea level is believed to have risen from 60 m to 20 m below its current level during this period. The salt content within the deposition environment is believed to have provided a stabilizing internal strength due to ionic bonds which allowed the mineral particles to resist consolidation as overlying minerals were being deposited. With time natural groundwater flow washed away much of the initial salts reducing the stabilizing strength but with no ensuing consolidation within the deposit since a calcification like process had occurred at the particle contact points. Frequently the resulting soil matrix is compared to a playing card structure sensitive to changes in loading and environmental conditions.

Today the typical profile of a Champlain Sea clay deposit includes a surficial crust of stiffer and drier clay underlain by weaker and more compressible clay. The upper crust layer is weathered and desiccated as a result of being above the groundwater level for prolonged periods, whereas the unweathered compressible portions have always been below the groundwater level. The consistency of the upper crust layer is typically described as stiff to hard whereas that of the lower unweathered clay deposit is typically soft to firm with local variations due to the mineralogy and the depositional history. The thickness of the surficial crust can range from non-existent to several metres.

3 STUDY SITES

Ten sites in the Ottawa area were selected for this study. All sites fall within the area known to be formerly occupied by the Champlain Sea. These sites cover a wide area within the National Capital region. Figure 1 shows the locations layout of the selected sites.

Figure 1. Layout of site locations

4 METHODOLOGY USED IN EVALUATING SOIL SPECIFIC CONE FACTORS

The field-vane apparatuses used were friction compensated digital and Nilcon vanes. Field vane tests were carried out at various depths. Therefore, undrained shear strength was available at various depths for all sites. Using Equation [1] and Equation [2] (Lunne et al. 1997), N_{kt} and $N_{\Delta u}$ were adjusted until the continuous undrained shear strength profiles were in agreement with the values collected from the field vane tests. Figure 2 through Figure 7 show the undrained shear strength profiles from vane tests and from CPT results using N_{kt} and $N_{\Delta u}$ for six selected sites.

$$S_u = (q_t-\sigma_{vo})/N_{kt} \quad [1]$$

$$S_u = \Delta u/N_{\Delta u} \quad [2]$$

where, S_u is the undrained shear strength of the soil from field vane test, q_t is the corrected tip resistance, σ_{vo} is the total overburden pressure, Δu is the excess porewater pressure with respect to the static porewater pressure.

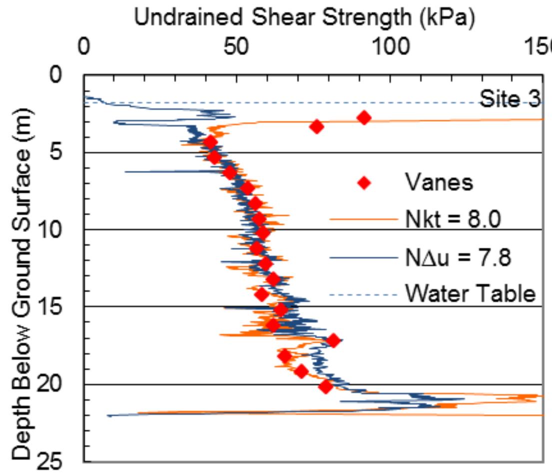

Figure 2. Undrained shear strength profiles from vane tests and soil specific cone factors for Site 3

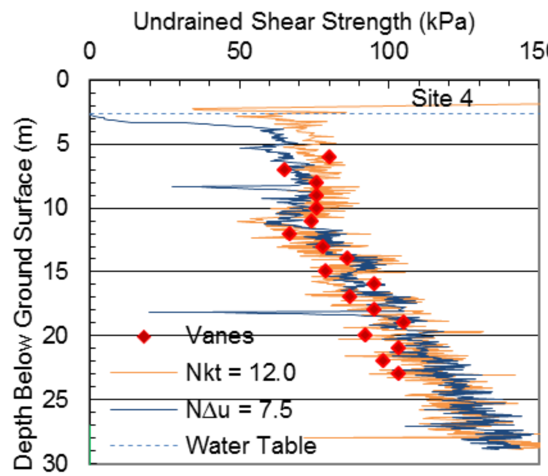

Figure 3. Undrained shear strength profiles from vane tests and soil specific cone factors for Site 4

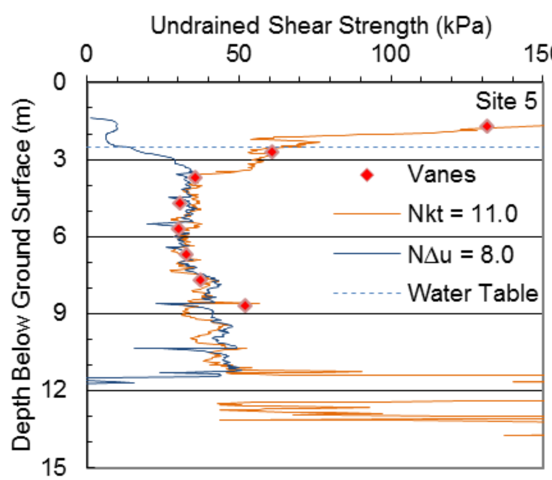

Figure 4. Undrained shear strength profiles from vane tests and soil specific cone factors for Site 5

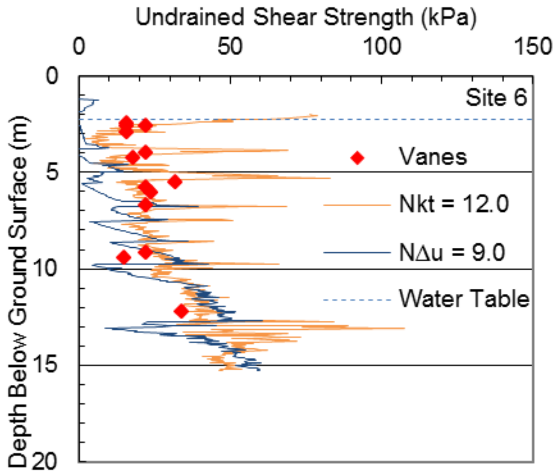

Figure 5. Undrained shear strength profiles from vane tests and soil specific cone factors for Site 6

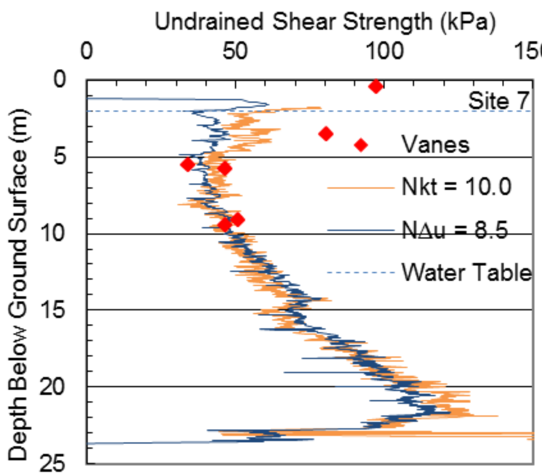

Figure 6. Undrained shear strength profiles from vane tests and soil specific cone factors for Site 7

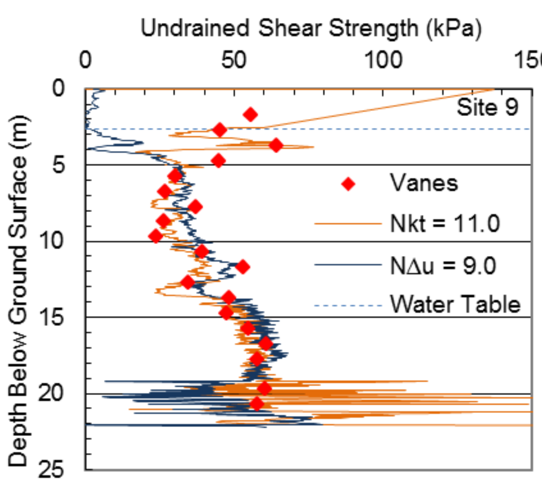

Figure 7. Undrained shear strength profiles from vane tests and soil specific cone factors for Site 9

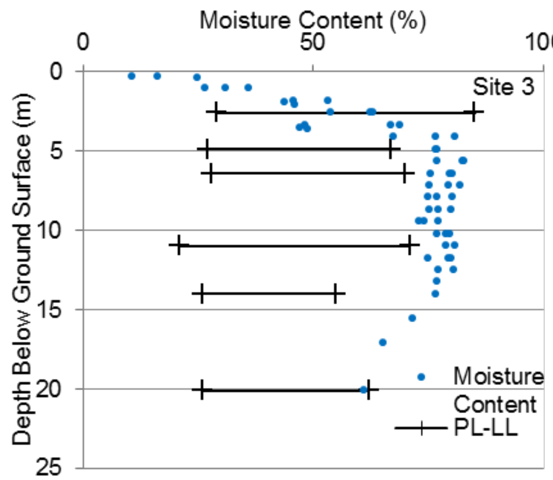

Figure 8. Moisture contents and Atterberg limits profiles for Site 3

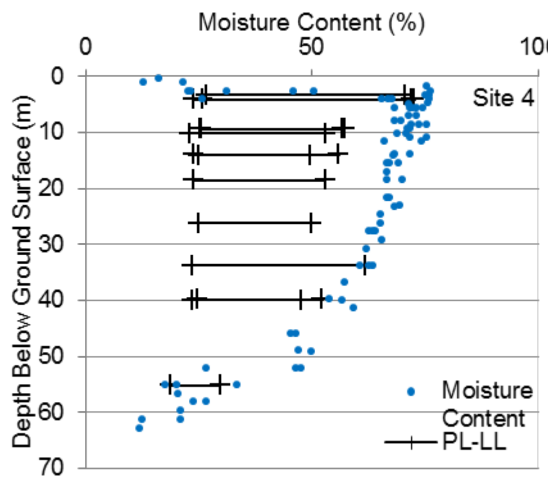

Figure 9. Moisture contents and Atterberg limits profiles for Site 4

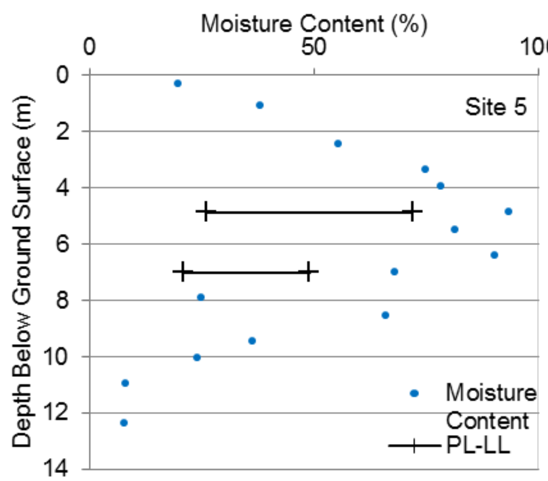

Figure 10. Moisture contents and Atterberg limits profiles for Site 5

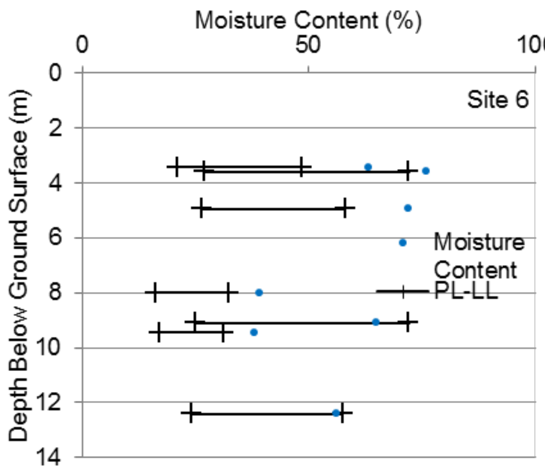

Figure 11. Moisture contents and Atterberg limits profiles for Site 6

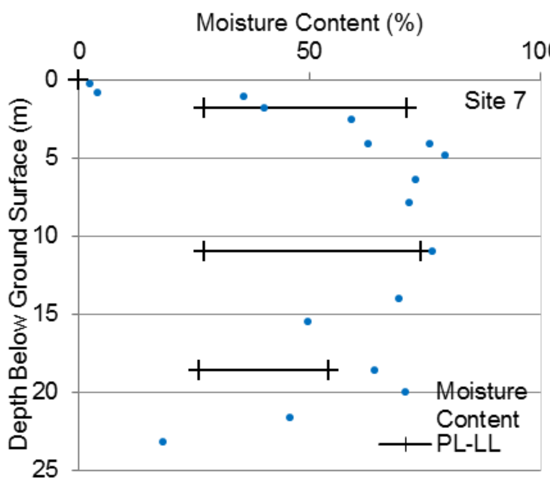

Figure 12. Moisture contents and Atterberg limits profiles for Site 7

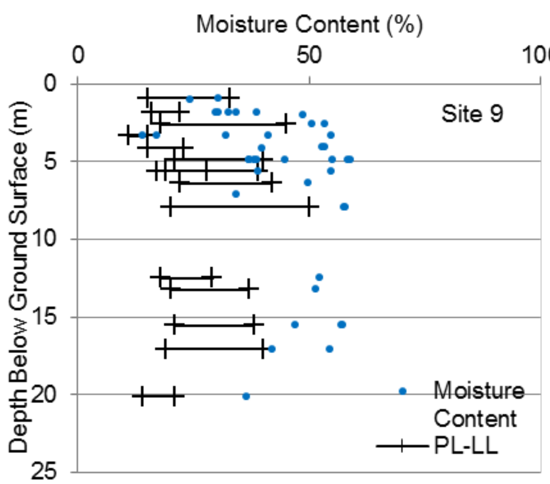

Figure 13. Moisture contents and Atterberg limits profiles for Site 9

5 SOIL PARAMETERS AVAILABLE FOR SITES

5.1 Moisture Content and Atterberg Limits Profiles

Moisture contents and Atterberg limits profiles are presented for six selected sites in Figure 4 through Figure 13. It is noted that the Ottawa clays have moisture contents close to or exceeding the liquid limit. According to the Canadian Foundation Engineering Manual (CGS 2006), the sensitivity category ranges from low sensitivity to quick clay. Sensitivity of the sites is shown in Table 1.

5.2 Soil Parameters available for all sites

Soils parameters such as over consolidation ratio (OCR), plasticity index (I_p), and sensitivity (S_t) are shown in Table 1. Gradation and soil types are shown in Table 2.

Table 1. Soil parameters

Site	N_{kt}	$N_{\Delta u}$	OCR	I_p	S_t
Site 1	12.0	8.0	1.1-1.5	24.0-47.0	3-12
Site 2	10.0	9.0	1.6-2.0	28.0-49.0	5-15
Site 3	8.0	7.8	0.7-0.9	29.0-56.0	N/A[1]
Site 4	12.0	7.5	1.7-2.7	24.0-49.0	2-93
Site 5	11.0	8.0	0.9	28.0-46.0	5-7
Site 6	12.0	9.0	2.0-7.1	30.0-46.0	2-12
Site 7	10.0	8.5	1.4-1.9	28.0-47.0	3-13
Site 8	9.0	9.0	N/A[1]	5.0-30.0	3-15
Site 9	11.0	9.0	N/A[1]	7.0-58.0	4-23
Site 10	9.4	8.7	0.7-1.4	11.5-28.1	2-24

N/A[1] = not available

Table 2. Gradation and soil types

Site	Gr[1] (%)	Sa[2] (%)	Si[3] (%)	Cl[4] (%)	Soil Type
Site 1	N/A	N/A	N/A	N/A	CH[5]
Site 2	0	0	27	73	CH[5]
Site 3	0	0	24-39	61-76	CH[5]
Site 4	N/A	N/A	N/A	N/A	CL-ML[8]
Site 5	0	0-1	28-46	53-72	CL[6], CH[5] & ML[7]
Site 6	0	7-20	25-78	15-55	CL[6] & CH[5]
Site 7	0	0-4	37-51	55-63	CH[5]
Site 8	0	0	46	54	CL[6]
Site 9	0-10	0-49	32-67	12-55	ML[7] & CH[5]
Site 10	0	0-6	22-37	57-88	CL-ML[8]

[1]gravel fraction
[2]sand fraction
[3]silt fraction
[4]clay fraction
[5]fat clay
[6]lean clay
[7]silt
[8]silty clay

In the literature, N_{kt} values ranging from 10 to 20 are considered typical and a value of 15 is usually recommended for the cases where site specific information is not available (Robertson 2004 and Robertson and Cabal 2010). The N_{kt} values for Leda clay reported in Table 1 range from 8 to 12 with an average value of 10. This behavior suggests that Leda clay provides a lower resistance to CPT penetration when compared to other clays with the same undrained shear strength. Using a value of 15 for Champlain Sea clays in Ottawa would underestimate the shear strength of the soils by 33% according to Equation [1]. Figure 14 shows undrained shear strength profiles from vane tests and different soil specific cone factors for visual comparison.

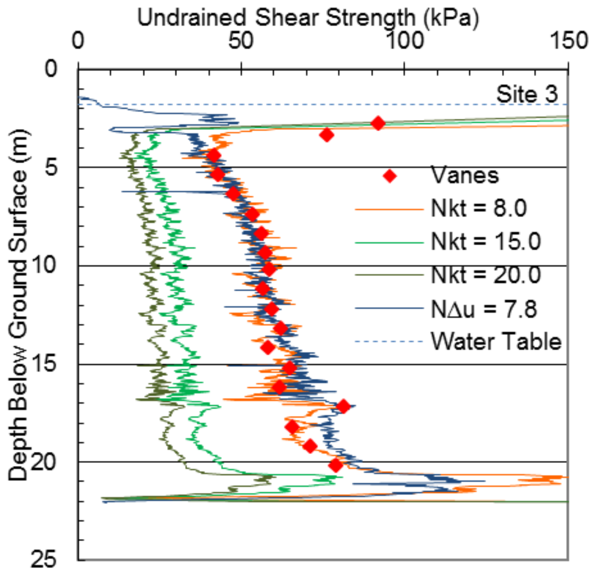

Figure 14. Undrained shear strength profiles from different N_{kt} values and from field vane tests for Site 3

In the literature, $N_{\Delta u}$ values typically range from 4 to 10 where it is recommended to use an upper limit value for conservative estimation (Robertson 2004 & Roberson and Cabal 2010). The $N_{\Delta u}$ values provided in Table 1 range from 7.5 to 9. This behavior suggests that the pore pressure response when the CPT is pushed within the Leda clay is at the high end of the scale when compared to other clays.

5.3 Soil Behaviour Type

Figure 15 through Figure 20 show the Soil Behavior Type (SBT) for six selected sites. It can be noted that the results fall randomly in all three areas designated as normally consolidated clays, overconsolidated clays, and clays with increasing sensitivity.

Table 3. Soil behavior type from Robertson et al. (1990)

Zone	Soil Behavior Type
1	Sensitive fine grained
2	Organic soils - clay
3	Clay - silty clay to clay
4	Silt mixtures - clayey silt to silty clay
5	Sand mixtures - silty sand to sandy silt
6	Sands - clean sand to silty sand
7	Gravelly sand to dense sand
8	Very stiff sand to clayey sand
9	Very stiff fine grained

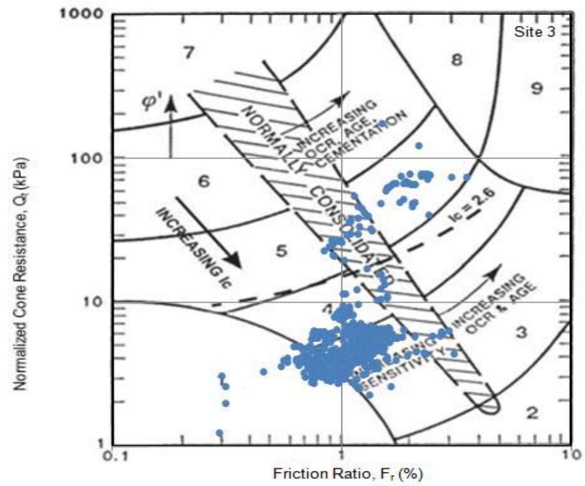

Figure 15. Soil Behavior Types based on CPT data from Site 3

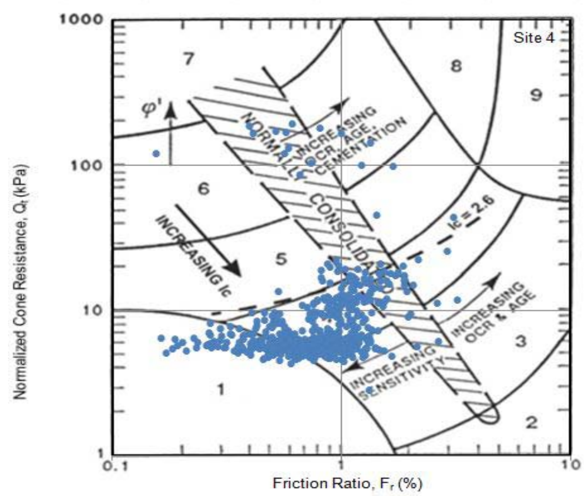

Figure 16. Soil Behavior Types based on CPT data from Site 4

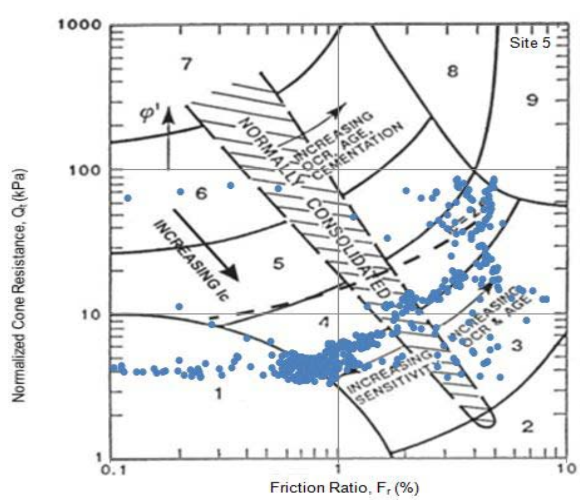

Figure 17. Soil Behavior Types based on CPT data from Site 5

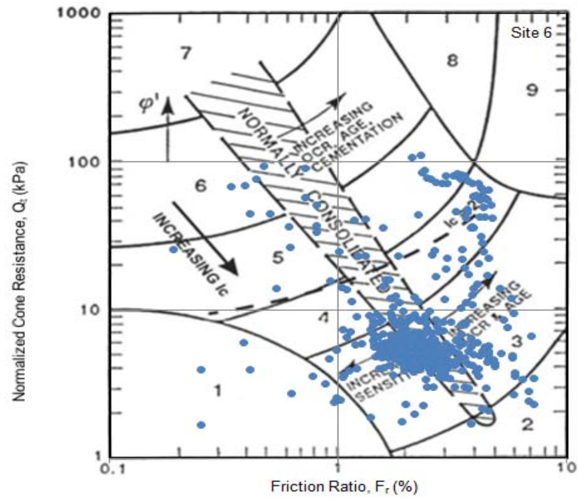

Figure 18. Soil Behavior Types based on CPT data from Site 6

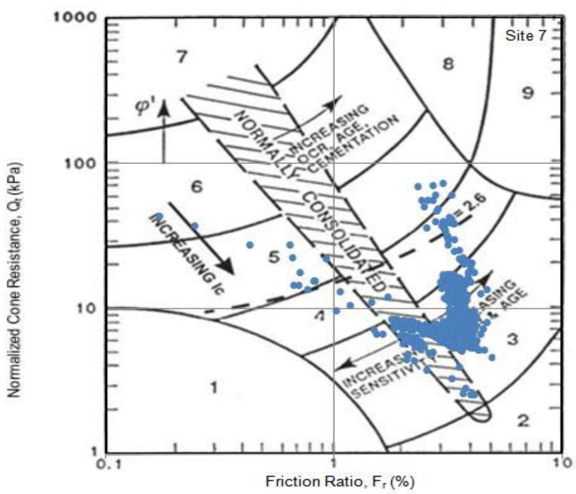

Figure 19. Soil Behavior Types based on CPT data from Site 7

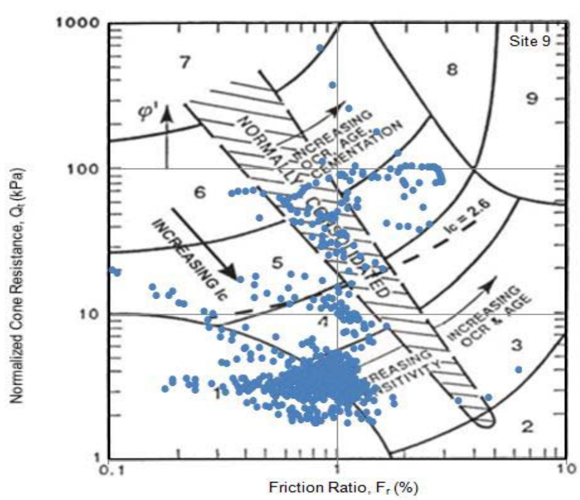

Figure 20. Soil Behavior Types based on CPT data from Site 9

5.4 SPT N-values

In many parts of Canada, Standard Penetration Test (SPT) N-values are used to estimate the undrained shear strength on the basis of Table 4 presented below. Within the Champlain Sea Clays the N-value based correlations grossly underestimates the undrained shear strength of the clay as discussed below.

A variety of sources in the literature provide correlations between the undrained shear strength and SPT N-value. Equation 3 is a typically used relationship.

$$S_u = f_1 * \text{N-value} \quad [3]$$

Mayne and Kemper (1988) indicated that f_1 ranges from 3.5 to 6.5 with an average of 4.4. Look (2007) indicated that f_1 ranges from 2 to 8 with an average of 5 and that "sensitivity of clay affects the result". Sower (1979) recommended f_1 to be 4 for high plasticity clay and 15 for low plasticity clays. In addition, Stroud and Butler (1975) recommended f_1 to be 4.5 for clays with plasticity index greater than 30 and 8 for clays with plasticity index of 15.

The Canadian Foundation Engineering Manual (CGS 2006) recommends average value of f_1 to be about 6.5 and does not recognize the sensitivity or the plasticity of clays in the estimation of undrained shear strength from N-values.

A typical undrained shear strength profile is presented in Figure 21 from an example site. Undrained strength profiles are shown that reflects field vane tests and f_1 value of 6.5. It can be noted from the figure that an f_1 value of 6.5 underestimates the undrained shear strength of Leda clays. For this example, f_1 values ranging from 25 to 50 would be required to obtain a rough estimate of S_u, demonstrating that SPT N-values cannot be used to estimate the undrained shear strength within a Leda clay deposit.

Table 4. Consistency and undrained shear strength based on CFEM (CGS 2006)

Consistency	Undrained Shear Strength (kPa)	SPT-N-value
Very Soft	<12	<2
Soft	12-25	2-4
Firm	25-50	4-8
Stiff	50-100	8-15
Very Stiff	100-200	15-30
Hard	>200	>30

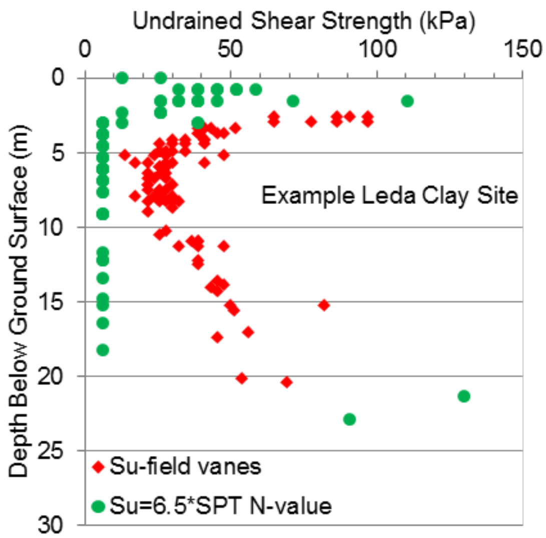

Figure 21. Undrained shear strength profiles from field vane tests and SPT N-values for example Leda clay site

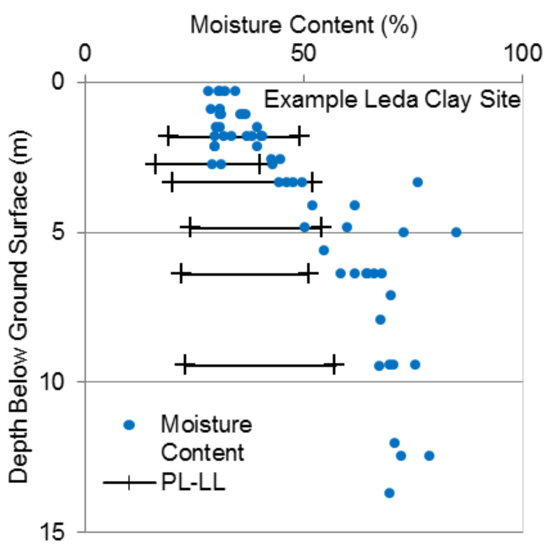

Figure 22. Moisture content and Atterberg limits profiles for example Leda clay site

6 CONCLUSION

Based on the results of the study discussed above, the following conclusions can be drawn:

- CPT is a valuable field tool when continuous strength profile is desired for Leda clay deposits.
- N_{kt} and $N_{\Delta u}$ reported for Leda clay range from 8 to 12 and from 8 to 9, respectively. However, a larger database of N_{kt} and $N_{\Delta u}$ values should be developed to confirm the repeatability of these values and to allow for CPT to be used to estimate the undrained shear strength of Leda clays without the need to calibrate with site specific information.
- $N_{\Delta u}$ values are not valid above the water table. However, $N_{\Delta u}$ have a smaller range and may provide better estimation to the undrained shear strength than N_{kt} when site specific vanes are not available.
- It is observed that N_{kt} for Leda clay is at the lower limit of the 10 to 20 range recommended in the literature, suggesting a relatively lower resistance to CPT penetration than other clays. Moreover, $N_{\Delta u}$ for Leda clay is at the higher limit of the 4 to 10 range recommended in the literature, suggesting a relatively higher pore pressure response to CPT penetration by Leda clay than other clays.
- Within Leda clay and the remaining of the Champlain Sea deposits, estimating the undrained shear strength from SPT N-values is a gross underestimation by more than an order of magnitude. This approach is not applicable to sensitive marine deposits.

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