Comparison of consolidation characteristics from CPTu, DMT and laboratory testing at Ashbridges Bay, Toronto, Ontario

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ABSTRACT
The Toronto Transit Commission (TTC) carried out geotechnical and geo-environmental investigations in 2009 and 2010 for a proposed streetcar maintenance and storage facility near Toronto's waterfront at Ashbridges Bay. Since the 1920s, this part of Toronto's waterfront was reclaimed with fill, consisting of variable soil and debris, overlying stiff to very stiff organic soils and stiff silty clay. In support of the proposed foundations and grade raise at the site, the geotechnical investigation consisted of conventional borehole sampling, in-situ testing and geotechnical laboratory testing. In-situ testing within the organic soils and silty clay consisted of field shear vane, piezocone (CPTu), and seismic dilatometer (DMT) tests. Geotechnical laboratory tests within these soils consisted of index properties, oedometer and consolidated undrained triaxial tests.

This paper presents a comparison of the constrained modulus, compression index and coefficient of consolidation of the organic soils and silty clay from laboratory test results using published correlations with measured index soil properties, DMT and CPTu test results. The horizontal and vertical coefficient of consolidation from laboratory tests is also compared to the horizontal coefficient of consolidation derived from CPTu dissipation tests.

RÉSUMÉ
La Commission de Transport de Toronto (CTT) a effectué des études géotechniques et géo-environnementales en 2009 et 2010 pour un aménagement d'entretien et de stockage des tramways proposé près du secteur riverain de Toronto à la baie d'Ashbridges. Depuis les années 1920 cette partie du secteur riverain de Toronto a été amendée par un remblai, constitué de sols et débris variables, sus-jacents aux sols organiques raides à très raides et d'argile limoneuse raide de till glaciaire. Pour appuyer la conception des fondations et le rehaussement du terrain proposé sur le site, l'étude géotechnique a consisté d'échantillonnages par forage classique, d'essais insitu et d'essais laboratoire géotechnique. Les essais insitu dans les sols organiques et l'argile limoneuse ont consisté en la réalisation d'essais de cisaillement insitu, de piézocône (CPTu), et de dilatomètre sismique (DMT). Les essais en laboratoire géotechnique pour ces sols ont consisté en la determination des propriétés caractéristiques, d'essais oedométriques et d'essais triaxiaux consolidés non drainés.

Cet article présente une comparaison du module de déformation, de l'indice de compression et du coefficient de consolidation des sols organiques et de l'argile limoneuse dérives des résultats d'essais en laboratoire en utilisant des corrélations publiées avec les propriétés caractéristiques des sols, avec ceux mesurés avec les essais insitus de DMT et de CPTu. Les coefficients horizontal et verticaux de consolidation obtenus des essais de laboratoire sont également comparés avec le coefficient horizontal de consolidation découlant des essais de dissipation insitu de CPTu.

1 INTRODUCTION

Estimating settlements is part of most geotechnical projects. Accurate results are essential to provide cost effective geotechnical solutions. In fine grained soils the most common practice is to obtain relatively undisturbed samples of the soil and carry out laboratory oedometer testing to obtain various consolidation characteristics. Due to the costs involved with obtaining these samples and time to carry out this testing, only a limited number of tests are carried out at a site to evaluate consolidation characteristics. As an alternative to laboratory testing, in-situ testing using DMT or CPTu can provide fast and continuous to near continuous profiles of data that can be used to estimate the consolidation characteristics of the soil at a site, with depth.

This paper evaluates and compares the estimated consolidation characteristics from the results of CPTu, DMT and laboratory testing at the site of a proposed Light Rail Transit (LRT) maintenance and storage facility near Toronto's waterfront at Ashbridges Bay.

2 PUBLISHED CORRELATIONS

Time dependent compressibility of clay and organic soils is generally carried out on relatively undisturbed samples by consolidation tests in oedometer equipment. The following consolidation characteristics are compared between laboratory oedometer test results, and published correlations with in-situ tests and index soil tests:

- Constrained Modulus, M
- Compression Index, C_c
- Coefficient of Consolidation, C_v

2.1 Constrained Modulus

Constrained Modulus, M, is equivalent to the inverse of the coefficient of volume compressibility, m_v. This coefficient is calculated from the change in void ratio and pressure data obtained during oedometer (consolidation) tests on relatively undisturbed samples. It is defined as the decrease in volume per unit volume of the soil due to an increase in pressure and is a function of the stress history, stress level, drainage condition and the stress path direction of the soil.

For DMT testing, M is a function of the dilatometer modulus (E_D), material index (I_D) and horizontal stress index (K_D), as shown in the equation below proposed by Marchetti (1980):

$$M = R_M E_D \quad [1]$$

where R_M is a function of K_D and I_D as follows:

If $I_D \leq 0.6$, $R_M = 0.14 + 2.36 \log K_D$ [1a]
If $I_D \geq 3$, $R_M = 0.5 + 2 \log K_D$ [1b]
If $0.6 < I_D < 3$, $R_M = R_{M,0} + (2.5- R_{M,0})\log K_D$ [1c]
where $R_{M,0} = 0.14 + 0.15 (I_D-0.6)$
If $K_D > 10$, $R_M = 0.32 + 2.18 \log K_D$ [1d]
If $R_M < 0.85$, $R_M = 0.85$ [1e]

For CPTu testing, M has been correlated to the corrected total cone resistance (q_t) and measured cone resistance (q_c) by several authors (Sanglerat, 1972; Senneset et al, 1982,1989; Kulhawy and Mayne, 1990; Robertson, 2009). For fine grained soils, Sanglerat (1972) proposed the following correlation:

$$M = \alpha_m q_c \quad [2]$$

where α_m = constant, as per Table 1.

Table 1 (Sanglerat, 1972)

q_c <0.7 MPa 0.7<q_c<2.0 MPa q_c >2.0 MPa	3< α_m<8 2< α_m<5 1< α_m<2.5	Clay of low plasticity (CL)
q_c >2.0 MPa q_c >2.0 MPa	3< α_m<6 1< α_m<3	Silt of low plasticity (ML)
q_c <2.0 MPa	2< α_m<6	Highly plastic silts and clays (MH. CH)
q_c <1.2 MPa	2< α_m<8	Organic Silts (OL)
q_c <0.7 MPa 50%<w<100% 100%<w<200% w>200%	1.5< α_m<4 1< α_m<1.5 0.4< α_m<1	Peat and organic clay (Pt, OH)

where w = natural moisture content

Senneset et al (1982, 1989) proposed the following correlation with q_t:

$$M = \alpha_{(i \text{ or } n)} (q_t - \sigma_{vo}) \quad [3]$$

where α_i = constant in preconsolidation range
α_n = constant in normally consolidated range

For overconsolidated material, α_i ranges from 5 to 15 in most clays, while in the normally consolidated state α_n ranges between 4 and 8. Kulhawy and Mayne (1990) suggested a more general use of α as 8.25.

Lunne, Robertson and Powell (1997) suggested that the above correlations for M be used with caution as the CPTu is an undrained test in fine grained soils and M is a one dimensional drained modulus. Site specific correlations are recommended.

Robertson (2009) proposed a more direct method of selecting the appropriate α in order to estimate M. The following equation was proposed for fine-grained soils (I_c > 2.2), with a maximum value of α = 14:

$$\alpha = (q_t - \sigma_{v0})/\sigma'_{v0} \quad [4]$$

where

σ_{v0} = in-situ total vertical stress
σ'_{v0} = in-situ effective vertical stress

2.2 Compression Index

Compression Index, C_c, is determined directly from oedometer tests, and can be defined as the variation in void ratio with changes in vertical effective stress (σ'_v). Bartlett and Lee (2004) found that CPTu was not a reliable method to estimate C_c. More commonly published empirical correlations are used as a more cost effective method of estimating C_c. However there are more than 70 different correlations with considerable scatter amongst the different correlations. Table 2 below lists some of the more common correlations using natural moisture content (w_n), liquid limit (w_L), plasticity index (I_P), specific gravity (G_s), dry unit weight (γ_{dry}) and in-situ void ratio (e_0).

Table 2

Correlation	Reference	Applicable
C_c=0.009 (w_L-10)	Terzaghi & Peck (1967)	normally consolidated clays
C_c=0.006(w_L-9)	Azzous et al (1976)	all natural soils
C_c=0.012 w_n -0.098	Lav & Ansal (2001)	normally consolidated clays
C_c=0.481 ln w_n -1.376	Lav & Ansal (2001)	overconsolidated clays
C_c=0.30 (e_0 -0.27)	Hough (1957)	silty clays
C_c=0.43e_0 -0.122	Lav & Ansal (2001)	normally consolidated clays
C_c=0.556-0.769 ln γ_d	Lav & Ansal (2001)	normally consolidated clays
C_c=0.5 G_s (I_P / 100)	Wroth & Wood (1978)	clays

2.3 Coefficient of Consolidation

The coefficient of consolidation, both horizontally and vertically, can be defined as the rate of consolidation of the soil for a specified stress range. The coefficient of vertical consolidation (C_v) and coefficient of horizontal consolidation (C_h) are difficult to estimate and are typically measured during laboratory consolidation testing on relatively undisturbed samples. However due to the method of deposition of the soil these results are typically different in field conditions due to the presence of layering, varves, sand seams/lenses, etc. which affect the permeability of the soil on a much larger scale than the small samples tested in the laboratory. For this reason in-situ testing, such as DMT or CPTu, is typically carried out to determine more representative estimates and variation with depth for these parameters, where warranted. Dissipation tests carried out with DMT are not addressed in this paper.

The parameter C_h of the soil can be estimated from CPTu pore pressure dissipation test results. The most common methods to interpret these results are those described by Torstensson (1975), and Houlsby and Teh (1988). Generally the horizontal component of pore pressure dissipation at 50% is estimated and correlated to C_h by theoretical solutions or estimating a rigidity index.

There have been numerous papers on interpretation of dissipation test results (Sully et al 1999; Burns and

Mayne 1995; Chen and Mayne 1994; Kabir and Lutenegger 1990; etc.). Due to the dilative nature of some soils, the excess pore pressure increases during the test before dissipating. In order to determine 50% dissipation, the test measurements are typically plotted for excess pore pressure versus root time scale. The initial excess pore pressure is then estimated by extrapolating back to time zero.

Due to the nature of soil formation, C_v is typically lower than C_h. Jamiolkowski et al. (1985) suggest the following empirical correlation:

$$C_v = C_h \, kv/kh \quad [5]$$

where kv/kh ratio is suggested in Table 3.

Table 3

Nature of Clay	k_v/k_h
No macrofabric or slightly developed macrofabric (homogeneous deposit)	0.67 to 1
Fairly well to well developed macrofabric (eg. sedimentary clays with discontinuous lenses and layers of more permeable material)	0.25 to 0.5
Varved clays and other deposits containing embedded and more or less continuous permeable layers	0.07 to 0.33

A case study comparing CPTu and laboratory oedometer results is presented by Leroueil et al (1995) for a Champlain Sea clay site where C_h measurements range from 10^{-6} to 10^{-3} cm^2/s. Several reasons are presented for this range of values measured between field and laboratory test results, with some of the main reasons noted below:

- Small size laboratory samples may underestimate the hydraulic conductivity of stratified soils.
- Inaccuracy of models to interpret insitu tests
- Anisotropic permeability and 3-D field effects

3 INVESTIGATION SITE

A geotechnical investigation was carried out at the site of a proposed LRT storage and maintenance facility at Ashbridges Bay adjacent to the Toronto waterfront. This area of Toronto consists of reclaimed land composed generally of silty sand to sandy silt fill to a depth of 5 m below grade, overlying organic soils (organic silts, clays and peat), sands, silty clay, glacial tills and shale bedrock. The groundwater table was encountered at a depth of about 3 m below grade.

At three borehole locations (BHs 1, 2 and 3) DMT, CPTu, extensive oedometer and index testing was carried out adjacent to one another. Figure Nos. 1 to 5 summarize the results of the laboratory index testing, measured DMT and CPTu data, and derived geotechnical parameters.

Based on the in-situ and laboratory testing, the organic soils, peat and silty clay soil characteristics are summarized in Table 4.

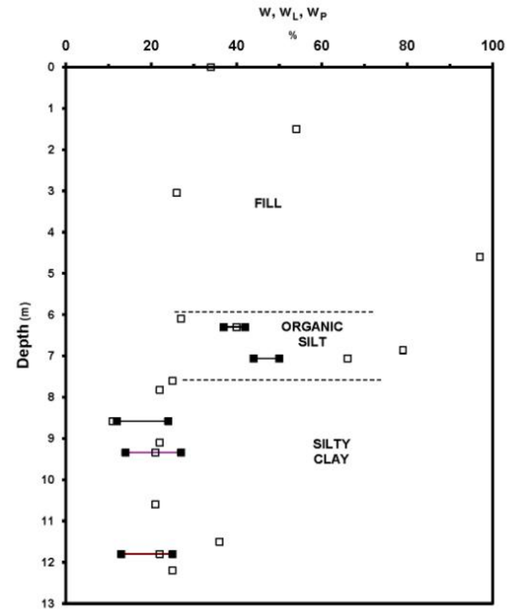

Figure No.1. Index laboratory test results for BH 1.

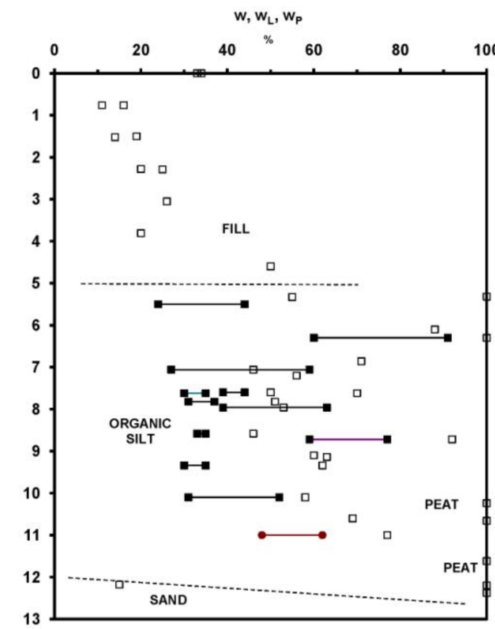

Figure No.2. Index laboratory test results for BH 2 and 3.

Table 4

Soil Type / Parameter	Organic soils	Peat	Silty Clay
w_n w_L I_P	20 to 110 % 22 to 91 % 2 to 29 %	48 to 317 % - -	8 to 36 % 22 to 34 % 11 to 19 %
e_0	0.7 to 2.2	2.7 to 5.6	0.3 to 0.7
G_s	1.5 to 2.7	1.3 to 1.7	2.7
Organic content	1 to 28 %	39 to 42 %	<1 %
γ_{dry} (kN/m^3)	6.0 to 17.0	2.4 to 3.5	17.1 to 21.0
Mean OCR	1.3	1.1	2.2
Measured Φ'	33^0 to 40^0	42^0	27^0
Mean N_{60} (blows/0.3m)	2	6	8
Consistency	stiff - very stiff	very stiff	stiff
USCS Symbol	OL to OH	Pt	CL

where USCS = Unified Soil Classification System
X^{CPTu} = geotechnical parameter derived from CPTu
Φ' = measured effective friction angle from triaxial testing

Boreholes 2 and 3 encountered about 5 to 6 m of sandy silt to silty sand fill followed by about 5 m of stiff to very stiff organic silts to organic clays and 1 m of buried peat, underlain by competent sands, glacial till and shale bedrock. Borehole 1 was advanced in the northern portion of the site and encountered 6 m of fill underlain by about 2 m of stiff organic silts and stiff silty clay. Borehole 1 was advanced adjacent to a 12 m high fill mound.

4 COMPARISON OF RESULTS

4.1 Constrained Modulus

Constrained modulus was measured in nineteen oedometer tests on specimens obtained from BHs 1, 2 and 3 using a piston sampler. CPTu and DMT testing was carried out adjacent to these borings. The CPTu results for fine-grained soils are compared in Figure No. 3. Equations 3 and 4 were used and compared to the oedometer results to determine the most suitable value of α for the various soil deposits.

Based on the results of the oedometer and CPTu testing, the constant α in the correlations by Senneset et al (1982, 1989) and Sanglerat (1972) were back calculated for Equations 2 and 3. The typical constants determined are noted below and are in good agreement with those proposed by Sanglerat (1972):

Organic Silts/Clays	2 to 3
Peat	0.7
Silty Clay	3

The results obtained from Equation 4 (Robertson 2009) generally overestimate M compared to the oedometer test results, especially for the peat as the cone poorly detects the peat layer.

Figure No. 4 presents the DMT results compared to the oedometer test results. The DMT provides excellent correlation with M for the organic soils. The DMT overestimates M in the peat and the silty clay. The overestimation within the silty clay may be due to the surcharge loads from the adjacent 12 m high fill mound. For the peat, the following modification to Equation 1b is proposed and Equation 1e ignored:

$$\text{If Peat, } R_M = 0.5 + 0.19 \log K_D \quad [6]$$

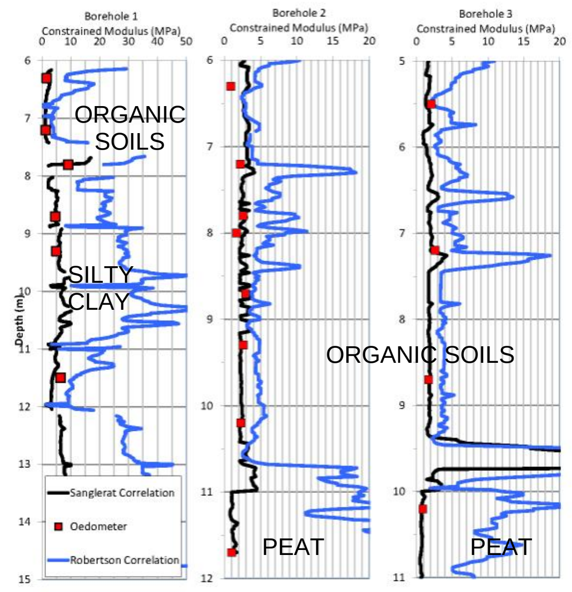

Figure No.3. CPTu and laboratory test results for Constrained Modulus at BH 1 and 3.

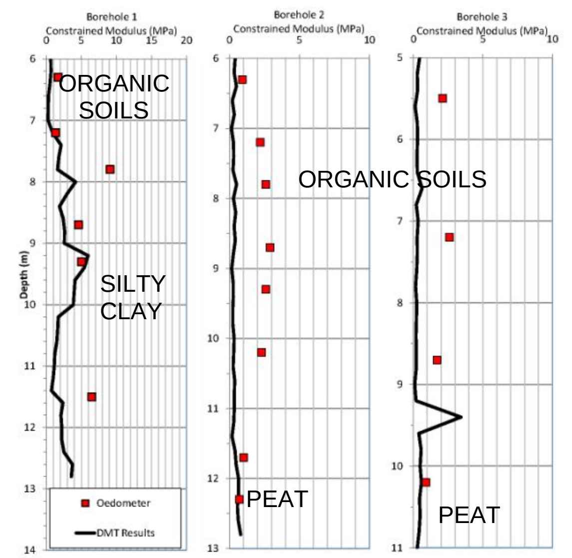

Figure No.4. DMT results and laboratory test results for Constrained Modulus.

4.2 Compression Index

Compression Index was measured in nineteen oedometer tests carried out within the organic soils, peat and silty clay. Figure No. 5 presents the variation with depth of the measured compression and recompression indices in the three boreholes.

Atterberg Limits were also carried out on thirteen of the oedometer samples from the organic soils to

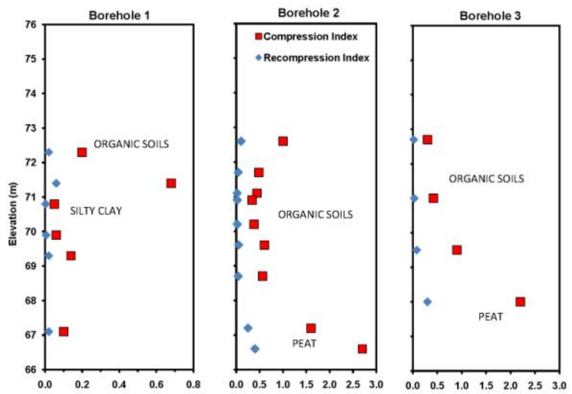

Figure No.5. Measured compression and recompression indices from oedometer tests.

determine which published correlation is most relevant within the organic soils. Based on the comparisons it was determined that none of the published correlations in Table 2 adequately correlated with the oedometer results. The following correlations are instead proposed and were determined to be the best fit for compression and recompression indices.

$$C_c = 0.0085\ (w_n - 1) \quad [7]$$

$$C_r = 0.00014\ (w_n - 28) \quad [8]$$

Figure No. 6 presents a comparison of the above correlations with the values of C_c and C_r determined from the oedometer tests. The R-squared (R^2) results of 0.9808 to 0.9951 provides good confidence in the correlations above for the organic silts, organic clays and peat tested.

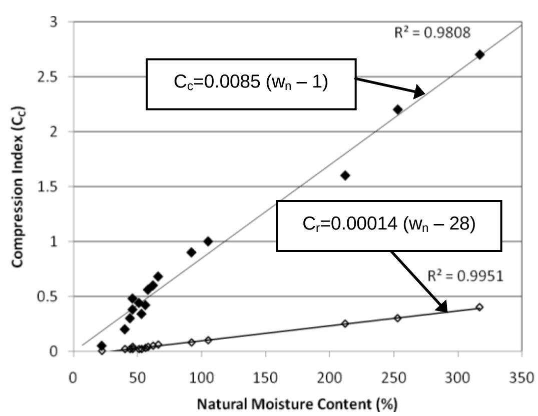

Figure No. 6. Compression and Recompression Index trends for organic soils at Ashbridges Bay.

4.3 Coefficient of Consolidation

The vertical coefficient of consolidation within the organic soils, peat and silty clay was measured in nineteen oedometer tests carried out on horizontally cut samples from BHs 1, 2 and 3. Fourteen vertically cut samples were taken of the above samples and the horizontal coefficient of consolidation was measured in oedometer testing for comparison. Eleven in-situ CPTu dissipation tests were carried out in BHs 1 and 2 and compared to the results obtained from the oedometer tests. Figure No. 7 presents the comparison graphically.

Based on Figure No. 7, Table 5 summarizes the comparison of C_v to C_h.

Table 5

	Lab C_v (cm^2/min)	CPTu C_h (cm^2/min)	Lab C_h (cm^2/min)	C_v/C_h C_vLab/C_hCPTu [C_vLab/C_hLab]
Organic Soils	0.06 to 0.67	0.15 to 28.9	0.33 to 4.86	0.01 to 0.64 [0.07 to 2.03]
Clay interbed within Organic Soils	0.24 to 0.44	-	0.13 to 0.22	- [0.5 to 1.85]
Peat	0.002 to 0.15	4.17	1.5 to 1.9	0.001 [0.003 to 0.08]
Silty Clay	0.06 to 0.49	0.11 to 9.17	0.39 to 5.97	0.12 [0.03 to 1.26]

The results show a wide range of variability which is expected within the organic soils, peat and silty clay, and summarized below.

- The layered structure of the organic soils is in good agreement with Table 3 (mean $\mathbf{c_v/c_h}$ of 0.27 to 0.47).
- It is clear that horizontal flow predominates within the peat due to its nature of deposition (mean $\mathbf{c_v/c_h}$ of 0.03).
- The influence of sand filled fractures within the silty clay are likely the cause of the high C_h value within the CPTu dissipation test(mean $\mathbf{c_v/c_h}$ of 0.5). Lower C_h to C_v ratios have been observed within glacial till deposits in other areas of Toronto.

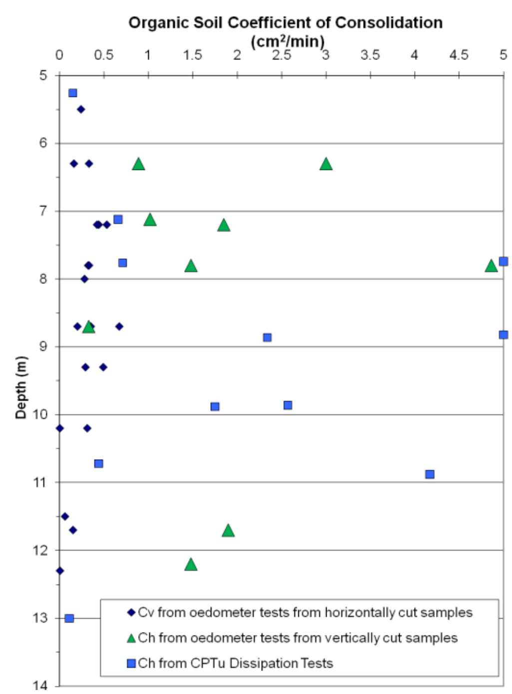

Figure No. 7. CPTu and oedometer laboratory test results for Coefficient of Consolidation.

5 CONCLUSIONS

Based on the results of this investigation, using both laboratory and in-situ testing, the site specific consolidation characteristics of the organic soils, peat and silty clay have been determined. In-situ CPTu and DMT testing carried out at the site were compared to the laboratory test results. The following conclusions can be made with regards to Constrained Modulus, Compression Index and Coefficient of Consolidation.

- CPTu provided good correlation with the measured laboratory constrained modulus. Correlation constant α was back calculated for the organic soils, peat and silty clay.
- DMT provided excellent correlation with the measured laboratory constrained modulus for the organic soils at the site. The DMT provided poor correlation for the peat and silty clay. R_M was back calculated to provide a better fit to the site specific DMT correlation for M for peat. Overestimation of M for the silty clay may be due to the adjacent surcharge from the 12 m high soil mound.
- Published correlations to determine the Compression Index did not correlate well to the organic silts, organic clays and peat. A new site specific correlation is proposed based on the natural moisture content of the soil.
- Coefficient of consolidation measured from vertically cut oedometer samples, horizontally cut oedometer samples and dissipation CPTu test results were compared. Site specific C_h to C_v ratios were presented and generally agreed with published results, while higher C_h results were found within the peat.

During the proposed construction at Ashbridges Bay, preloading of the site will be carried out and ground settlements will be measured. A further comparison of the laboratory and in-situ test results will be made with actual field monitoring data to further assess the advantages of CPTu and DMT testing in organic soils.

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