Characterization of the geotechnical properties of a carbonate clayey silt till for a shallow wind turbine foundation

Caractérisation des propriétés géotechniques d'un silt argileux carbonaté glaciaires pour une fondation superficielle d'éolienne

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ABSTRACT: Wind energy is a major source of renewable energy and is projected to capture 11% of the energy generation capacity for Ontario by 2018. A number of problems that the energy industry currently faces stem from a lack of understanding of cyclic loading of Ontario soils and a paucity of regional regulatory guidance for site investigation and design methods for wind turbine foundations. A multi-disciplinary research project is underway to integrate laboratory testing, field monitoring and numerical modeling of a commercial wind turbine on a shallow foundation. This paper describes an initial part of the study to characterize the geotechnical properties of the clayey silt till soils on the site. Emphasis has been placed on comparison of different *in situ* and laboratory methods, and correlations for determining key geotechnical parameters for wind turbine foundation design.

RÉSUMÉ : L'énergie éolienne est une source importante d'énergie renouvelable et doit permettre de satisfaire 11 % de la capacité de production d'énergie de l'Ontario d'ici 2018. Un certain nombre de problèmes auxquels l'industrie de l'énergie est actuellement confrontée provient d'un manque de connaissances des sols de l'Ontario sous charges cycliques et de directives réglementaires régionales pour les méthodes d'investigation et de conception des fondations d'éoliennes. Un projet de recherche multidisciplinaire est en cours pour intégrer les tests en laboratoire, l'instrumentation et la modélisation numérique d'une éolienne commerciale sur fondation superficielle. Cet article décrit la partie initiale de l'étude pour caractériser les propriétés géotechniques du silt argileux glaciaire du site. L'accent a été mis sur la comparaison de différentes méthodes *in situ* et en laboratoire ainsi que les corrélations pour déterminer les paramètres géotechniques clés pour la conception de fondation d'éoliennes.

KEYWORDS: wind turbine, clay, till, shallow foundation, soil-structure interaction, elastic, anisotropy, *in situ*, geophysical.

1 INTRODUCTION

1.1 Wind energy and turbine design in Canada

Wind is a major source of renewable energy and is projected to capture 11% of the energy generation capacity for Ontario by 2018 (CANWEA, 2011). However, to achieve this expansion some major technical and policy issues must be addressed by the Canadian wind sector. Some of these issues are associated with the construction and design of foundations for wind turbines. Foundations for onshore wind turbines usually consist of large gravity bases and monopiles (e.g. DNV/Risø, 2002). The geometry and foundation type depends on the wind climate, power regulation philosophy, physical characteristics of the machine, uplift criteria, required foundation stiffness and geotechnical characteristics of the site (Bonnett, 2005). The critical analyses for design include bearing capacity and overturning resistance, horizontal and rotational displacements, and dynamic soil-structure interaction (Harte et al., 2012).

Although there has been much recent research associated with foundations for offshore wind turbines (e.g. Byrne and Houlsby, 2003), the literature on onshore systems is still relatively sparse. Consequently, despite similar issues for wind turbine foundations across the industry, there is often diverse interpretation of design codes and understanding of the behavior of foundations (Morgan and Ntambakwa, 2008). This can lead to quite different foundation designs on different wind farms with the same turbines and comparable geotechnical profiles. This issue is exacerbated in Canada, since there is currently no regional regulatory guidance for site investigation and design methods for wind turbine foundations. Hence it is not surprising that rather generic approaches have developed for site investigation and design, which are relatively crude and can lead to quite conservative designs. To capture more wind energy, the industry is continuing to develop larger turbines and is considering more marginal sites in terms of geotechnical characteristics, which will only complicate the current situation.

1.2 Project overview and objectives

A number of the above issues are being addressed as part of a multi-disciplinary research project that includes an integrated laboratory testing, field monitoring and numerical modeling program investigating the behaviour of a fully operational Canadian commercial wind turbine throughout its service life. The equipment installed on the turbine will enable an integrated, life cycle assessment of the wind turbine and its foundation. This paper describes the portion of the study that involves preliminary characterization of the geotechnical properties of the wind farm site. In particular, a comparison between the *in situ* testing, laboratory testing and commonly used correlations are presented. It is anticipated this process will guide future projects on clayey silt tills in Ontario and provide cost effective site investigation and design methods for turbine foundations.

2 SOIL PROFILES & MATERIAL CHARACTERISATION

2.1 Wind farm and geological environment

The wind farm is located in a simple geographical and environmental area in the Great Lakes region of Southern Ontario. The farm has horizontal axis 2.3 MW turbines with an

80 m hub height and triple bladed rotors with a 93 m diameter. The tower has a typical tapered tubular steel design and is founded on a 16 m diameter hexagonal reinforced concrete shallow foundation at 3.6 m depth. The site is underlain by carbonate-rich clayey silt tills that are a ubiquitous feature of the Great Lakes basins and is located at the confluence of four major geological deposits. These consist of the Port Stanley and Tavistock tills, glaciolacustrine sand and gravel, and glaciolacustrine clayey silt**.** These materials were laid down in the Port Bruce Stade (c. 14,800 years bp.) during the re-advance of the Laurentide Ice Sheet of the Late Wisconsin. These subglacial lodgement tills are calcareous and fine-grained, suggesting that the ice overrode and incorporated fine-grained glaciolacustrine sediments deposited during the previous Erie Interstade. This has created approximately 40-45 m thickness of clayey silt tills with interbedded glaciolacustrine sediments. The bedrock is shale with limestone-dolostone-shale interlayers.

2.2 *Overview of site investigation*

The site investigation was designed to establish detailed stratigraphic and geotechnical characteristics for the soils beneath the wind turbine foundation. Forty metre deep boreholes were drilled on the site to evaluate the soil profile, perform *in situ* tests and collect high-quality samples for laboratory testing. A track-mounted drill was used for the drilling activities. Three boreholes were drilled 10-16 m adjacent to the turbine foundation (to ensure minimal stress change from the foundation). The wash boring method was used for two of the holes and the PQ coring method for the other hole. The boreholes were drilled to depths of twice the foundation diameter and were spaced at 3 m to allow for later cross-hole geophysical testing. Thin-wall shelby tube sampling was completed to obtain minimally disturbed samples for the laboratory testing. *In situ* testing adjacent/in to the boreholes consisted of SPT, field shear vane, cross-hole geophysics and seismic SCPTu, and was conducted to depths of 30 m. To complement the *in situ* test results, laboratory tests were conducted for soil classification and geotechnical properties.

2.3 *Soil description and basic properties*

This deposit can be separated into three zones: a heavily weathered oxidized upper crust from 0–1.5 m, a partially weathered lower crust that transitions from an oxidized to an unoxidized state from 1.5–4.5 m and an unweathered clay till below 4.5 m to greater than 40 m depth. The intensity of fissuring in the upper crust is very intense and the deposit becomes nearly unfissured below 4.5 m. The fissures are vertically dipping planar joints striking at right-angles. The fissure spacing at 1.5 m depth is 15 cm and this increases to 0.6-1.2 m at 4.5 m depth. The variation in moisture contents and the Atterberg limits with depth are shown in Figure 1.

The upper crust zone of this deposit is weathered, mottled brown-grey or brown-green with a stiff to very stiff consistency. This weathered zone generally has higher moisture contents (22-32%) due to the infiltration of surface water into the fissures of the clay. The underlying lower crust is prevalently brown in colour and has a very stiff consistency and relatively lower natural moisture content (16-20%). At several locations this layer has clayey silt, sandy clay and silt seams. A soil colour change occurs from brown to grey between 3 and 4 m below the ground surface. Below the crust, the unweathered till extends beyond the maximum depth of sampling. This zone is characterized by a uniform grey appearance, a stiff to very stiff consistency and relatively uniform moisture contents (16-24%).

Atterberg test results (Table 1) indicate that the material can be classified as CL-ML to CL (silty clay or low plasticity clay). There is an increase in liquid limit and plasticity towards the upper crust and the clay content is also found to increase near the surface, leading to little change in activity (0.5).

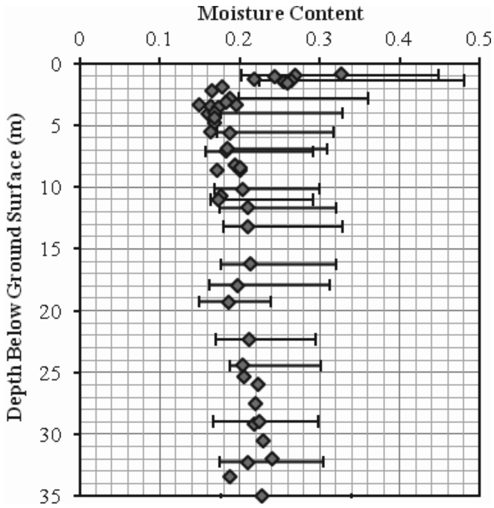

Figure 1. Moisture contents and Atterberg limits with depth.

The liquidity index (I_L) is found to range from 0.2 to 0.4 in the virgin till, is *below* zero in the lower crust and ranges from 0.15 to 0.25 in the upper crust. The bulk unit weights of the profile are generally uniform and range from 20.3 to 21.6 kN/m^3.

Table 1. Atterberg Limits and Particle Size Distributions.

Layer	*Liquid Limit (%)*	*Plastic Limit (%)*	*Clay (%)*	*Silt (%)*	*Sand (%)*
Upper Crust	46	21	40	45	15
Lower Crust	34	19	29	49	20
Unweathered Till	30	17	31	45	21

Semi-quantitative XRD shows that the unweathered till is predominantly composed of quartz/feldspar (39%), carbonate (25-35%), mica/illite (16%), chlorite/kaolinite (7%) and trace minerals. In the 2 micron range the minerals are dominated by illite, calcite and chlorite. The lower crust has a similar composition, with more quartz/feldspar (49%), lower carbonate (22%), mica/illite (18%), chlorite/kaolinite (7%) and swelling clay (2%) and other trace minerals. In similar deposits (Quigley and Obunbadejo, 1974) downwards leaching has removed carbonates from the near surface and redeposited lower in the crust. Table 2 shows the values of total carbonates, dolmite and calcite (from the gas evolution method) in the three zones, confirming the removal of carbonates from the near surface.

Table 2. Carbonate Contents in the Soil Profile.

Layer	*Total Carbonates (%)*	*Dolomite (%)*	*Calcite (%)*	*C/D ratio*
Upper Crust	0	0	0	-
Lower Crust	19.9	6.2	13.7	2.2
Unweathered Till	24.8	6.2	18.6	3.0

2.4 *Compressibility and strength properties*

In common with other tills around the world the compressibility, permeability and strength characteristics of this material are generally a function of the clay content. Estimates of undrained shear strength (s_u) using various methods are shown in Figure 2. All of the profiles show that the values of s_u are relatively constant with depth below 7 m and are in the range of 100-130 kPa. The lower crust material (2-4.5 m) increases in strength rapidly, in excess of 250 kPa and the upper crust material has a similar strength to the lower till. The usual hierarchy of strengths is seen for the different methods, due to the different modes of shearing. However, the field vane (FSV) shows higher values than the triaxial compression (CIU) test. This is likely due to partial drainage and problems rotating the vane slowly enough for an undrained state. Two estimates have also been determined from the CPT (Mayne, 2007):

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

$$s_u = \Delta u/B_q.N_{kt} \quad (2)$$

where N_{kt} is a cone factor (taken as 15), Δu is the excess pore pressure and B_q is the ratio of excess pore pressure to the net cone resistance (q_t - σ_{vo}). The approach based on excess pore pressures appears to give better estimates for the strengths, but the cone would be anticipated to provide lower values than CIU triaxial, since the shearing mode is a complex combination of triaxial compression/extension and plane strain. The depth of the foundation base and one base diameter (B) are also shown.

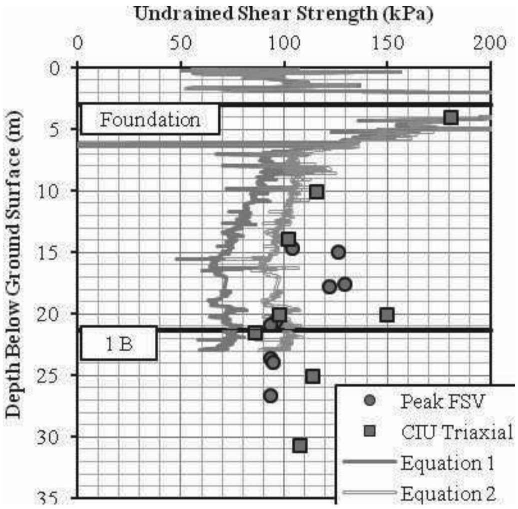

Figure 2. Undrained shear strength with depth.

From oedometer testing, average compression index (c_c) for the three layers was found to be 0.072 and average recompression index (c_r) was 0.008, giving a ratio of 0.12, which is in the usual range in the literature. The values of the two indices are quite low and are typical for sandy clays/silts, and the values from the crustal material are lower than those for the weathered till.

The pre-consolidation pressures (σ_{vp}') from oedometer tests have been estimated using the method of Boone (2011) and the corresponding overconsolidation ratio (OCR) is shown in Figure 3. This shows low OCRs in the weathered till, with a relatively small increase in the crustal material, up to an OCR of 4. Another estimate of OCR is shown using the relationship of Ladd et al. (1977), equation (3), with m = 0.8 and the ratio of undrained shear strength (from CIU triaxial testing) to the *in situ* vertical effective stress $[s_u/\sigma_{vo}']_{nc} = 0.22$:

$$\frac{[s_u / \sigma'_{vo}]_{oc}}{[s_u / \sigma'_{vo}]_{nc}} = OCR^{m} \quad (3)$$

This shows similar values of OCR at depths below 15 m, but much higher OCR values for shallower depths, up to an OCR of 15 at 4 m. Two further estimates of over-consolidation ratio have been made using the CPT data with expressions for the preconsolidation pressure (σ_{vp}'), after Mayne (2007):

$$\sigma_{vp}' = 0.33.(q_t - \sigma_{vo})^{\mu} \quad (4)$$

$$\sigma_{vp}' = 0.161.G_o^{0.478}.\sigma'_{vo}{}^{0.42} \quad (5)$$

where G_o is the small-strain stiffness determined from the seismic cone data, μ takes a value of 0.85 for silts and q_t is the cone tip pressure. These relationships show similar characteristics to the previous estimates, with the small-strain expression closely following the oedometer derived data and the CIU triaxial derived data following the CPT expression. Interestingly, the ratio of undrained shear strength to the *in situ* vertical effective stress in the upper crust $[s_u/\sigma_{vo}']_{oc}$ shows quite high values of 2.7-3.4, dropping to 0.3 at depth. This suggests values of K_o in excess of 1 and as high as 2.4 in the crust.

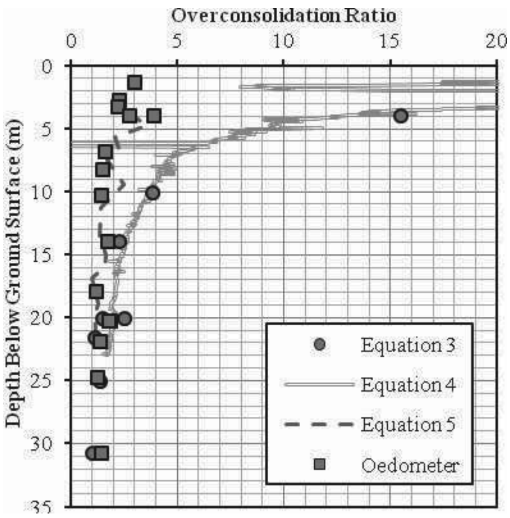

Figure 3. Overconsolidation ratio with depth.

2.5 *Small-strain stiffness properties*

Small-strain stiffness (G_o) is presumed to be a function of the void ratio, stress history and ratio of horizontal (h) to vertical stresses (v). It is also thought to be related to the soil macro-fabric and can often display cross-anisotropic characteristics (where the vertical axis is an axis of radial symmetry). The characterization of cross-anisotropic elastic materials can be reduced to five independent elastic moduli (E_h, E_v, ν_{vh}, ν_{hh} and G_{hh}; Pennington et al., 1997). *In situ* and laboratory estimates of small-strain stiffness often use measurements of shear wave velocity (V_s) travelling and polarized in different directions to determine shear modulus. Hence various methods of determining *in situ* elastic moduli provide often provide different components of the elastic stiffness tensor $G_{o(ij)}$.

Estimates of the small-strain stiffness (G_o) from different *in situ* tests are shown in Figure 4. This includes cross-hole geophysics, seismic cone and two correlations; one using standard CPT output parameters (Long and Donohue, 2010) and one based on soil properties (Hardin and Black, 1969):

$$V_s = 1.961.q_t^{0.579}.(1+B_q)^{1.202} \quad (6)$$

$$V_s = (159-53.5e_o).OCR^{0.18/2}.\ \sigma'_{vo}{}^{0.25} \quad (7)$$

where V_s is the shear wave velocity, e_o the *in situ* void ratio, small-strain shear modulus $G_o = \rho.V_s^2$ and ρ is density. The values of G_o appear to generally increase with depth and range from 50 to 350 MPa, with the majority of values being between 75 and 150 MPa. The cross-hole measurements were made with an axial hammer system and thus provide estimates of G_{ohv}; these values are generally constant with depth and give the highest *in situ* estimates of shear modulus. The seismic cone provides estimates of G_{ovh} and these values are lower than those of the cross-hole testing. The Long and Donohue (2010) CPT correlation (from equation 6) shows comparable variations in G_o with depth and falls between the two other *in situ* test datasets. However the Hardin and Black (1969) method based on OCR and overburden (equation 7) shows much higher estimates of G_o (despite using the lower values of OCR from Figure 3).

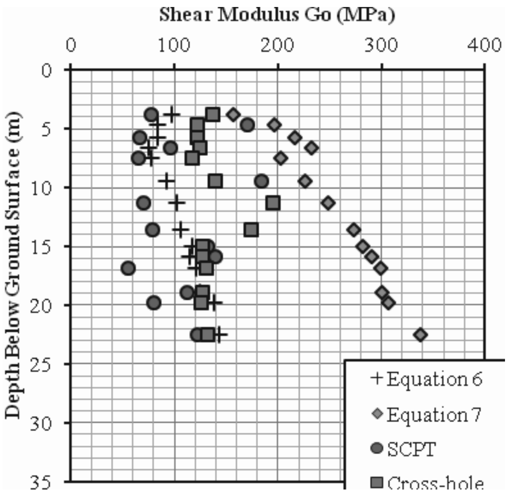

Figure 4. Small-strain shear modulus with depth.

Similar variations in the elastic shear moduli (G_{ovh} and G_{ohv}) have been observed with *in situ* tests previously (Pennington et al. 1997). These would be expected to be equal for a perfectly cross-anisotropic material. However, the different travel times may result from the averaging of the shear wave velocity through layered strata (for vertical travel), compared to lateral wave velocity through the stiffest layers. This leads to cross-hole measurements tending to measure the stiffest layers, rather than the average stiffness for SCPT measurements.

3 DISCUSSION

The design of gravity base foundations for onshore wind turbines requires accurate estimates of strength parameters for bearing capacity and stiffness parameters for displacements, within at least 1B of the founding level. The adoption of the most appropriate methods for site investigation to determine these parameters is debated in the industry and various published correlations are commonly used. Unfortunately many of these correlations have been previously developed for geologically young and relatively simple materials, and their applicability beyond their original databases can be uncertain.

The different methods of determining the undrained shear strengths show the crustal materials are quite strong, particularly near the founding depth, with undrained shear strength of up to 300 kPa reducing to 100 kPa at the crust base. Given the relatively high c_v (and permeability) and field vane values, there is a possibility that the CPT and vane estimates may be artefacts due to partial drainage. The crustal zone also has fissuring related to drying/wetting and frost action, and field shearbox tests on similar materials have indicated that bulk strengths can reduce considerably, and therefore representative values may be closer to 60-80 kPa (Lo, 1970). However, whether crustal fissures and associated strength changes are significant for such large shallow foundations is questionable.

Since overconsolidation ratio is often used as a component of correlations to determine geotechnical parameters, accurate estimation is important. Overconsolidation in tills is often attributed to loads from the overlying ice, however if drainage is inhibited, then only a small degree of consolidation will occur. The measurement of preconsolidation pressure in tills using laboratory testing has been found to be quite difficult due to the high pressures often required to fully define compression curves and the effects of sample disturbance (which lead to under-estimation of σ_{vp}'). The difficulties with this process are evident in the wide range of estimates for OCR shown in Figure 3.

Stiffness anisotropy is often evident in soils from *in situ* and laboratory measurements. The data in Figure 4 shows the general difficulties in choosing appropriate estimates of the small-strain stiffness (G_o). Indeed cross-anisotropy in till may be difficult to justify, since sub-glacial shear and consolidation could have effects on the anisotropy of the *in situ* stress and fabric. Rocking stiffness (k) for circular surface loads (radius, R) is estimated using equation 8, (DNV/Risø, 2002):

$$k = \frac{8R^3G}{3(1-\nu)} \quad (8)$$

where ν is Poisson's ratio and G is the shear modulus determined from the shear modulus ratio G/G_o that corrects the stiffness for degradation due to strain level (this is typically 0.25 for the presumed strain levels of 10^{-3} for wind turbines). Manufacturers recommend criteria for rocking stiffness to ensure the natural frequency of the turbine remains above the main excitation frequencies. The range of small-strain moduli in Figure 4 indicate rocking stiffnesses from 50 to 170 GNm/rad, which is in excess of typical requirements of 40 GNm/rad, but still represents quite a significant range of stiffness.

4 CONCLUSIONS

There is currently little guidance for choosing cost effective site investigation methods and interpreting the results for this type of geotechnical structure on glacial tills in Ontario. It is anticipated that the completion of this project will provide some of the missing knowledge and insight required in this area.

5 ACKNOWLEDGEMENTS

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