Characterization of muskeg soils for soil-pipe interaction analysis – Some preliminary findings

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ABSTRACT
Muskeg soil is geo-material that possess low density, stiffness, and strength, which could lead to concerns for pipelines placed in these soils. For example, buckling caused by thermally-induced large deformations in pipelines buried in muskeg (organic) soils is identified as concern of stress concentration due to the low restraint between the pipe and the surrounding soil at locations of pipe direction changes such as bends. Engineering design of buried pipelines in such materials is challenging due to a lack of understanding of the mechanical behavior of the organic soil itself. In turn, this lack of understanding has led to the absence of solid design guidelines for assessing soil-pipe interaction in organic soils in the current practice. As a part of a research program undertaken to advance the knowledge on this subject, a range of geotechnical field investigations including seismic cone penetration testing (SCPTu), ball penetrometer testing (BCPT), electronic field vane shear test (eVST), and full displacement pressuremeter testing (PMT) were undertaken at a muskeg soil site. This paper presents the initial findings from the completed work.

RÉSUMÉ
Le sol muskeg est un géo-matériau qui possède une densité, rigidité et résistance faibles, ce qui pourrait poser des problèmes pour les pipelines placés dans ces sols. Par exemple, le flambage causé par des grandes déformations thermiques dans les pipelines dans les sols muskeg (organique) est considéré une préoccupation liée à la concentration des contraintes due à la faible retenue entre le pipeline et le sol aux changements de direction du pipeline, comme les coudes. La conception technique des pipelines enfouis dans ces matériaux est difficile en raison d'un manque de compréhension du comportement mécanique du sol organique lui-même. À son tour, ce manque de compréhension a conduit à l'absence de lignes directrices de conception solides pour évaluer l'interaction sol-pipe dans les sols organiques dans la pratique actuelle. Dans le cadre d'un programme de recherche entrepris pour approfondir les connaissances sur ce sujet, une série d'études géotechniques incluant les pénétrations des cônes sismiques (SCPTu), le test de pénétromètre à balle (BCPT), le test girouette de cisaillement électronique (eVST), et le test pressiomètre à déplacement complet (PMT) ont été effectués dans un site de sol muskeg. Cet article présente les premiers résultats du travail achevé.

1 INTRODUCTION

Pipelines provide one of the safest methods of transportation of liquids and gas over large distances and buried pipelines are a key aspect of the transportation of oil and gas in Canada. Over 1.5M km^2 of Canadian landscape is covered with muskeg, which is low in density and stiffness, and weak in strength (Muskeg Engineering Handbook 1969). The low stiffness and strength presents a challenge for the design of buried pipelines against potential relative ground movements, due to operational or environmental reasons, that can affect the structural integrity of pipeline. For example, due to significant relative deformations that may take place under thermal variations, large strains leading to possible buckling could take place in buried pipelines, primarily due to the insufficient lateral soil restraint development from soft/weak muskeg soils. It is also of importance to note that, due to incidents in recent years, there has been an increasing demand from governing bodies for utility owners and pipeline operators to pay attention to pipeline safety and integrity in muskeg soils.

In the current practice, pipe stresses/strains are computed by representing the pipe interaction with surrounding soil using analytical “soil springs”. The determination of such soil springs are typically undertaken using the guidelines available from the American Lifelines Alliance (ALA, 2001) and Pipeline Research Council International (PRCI, 2009). The current guidelines provide ways to develop the soil springs for design of buried pipelines in granular soils and cohesive soils, but none specifically for those pipelines buried in organic soils such as muskeg. This is primarily due to the lack of information on the understanding of soil stiffness and strength with respect to such soils, including their significant variability arising due to the influence of environmental, operational, and soil disturbance effects.

For the above reasons, there is a strong need to provide specific guidance to pipeline engineers for stress analyses of pipelines buried in muskeg soils, and as a result, to accurately quantify strength and stiffness parameters of muskeg as a geo-material. With this background, a research program has been undertaken at the University of British Columbia to characterize muskeg soil behaviour with the specific focus to contribute to solve soil-pipe interaction problems. This paper presents initial work undertaken on this front; some initial summary results from collected field data along with strength and stiffness parameters determined for design are presented.

2 INPUT PARAMETERS REQUIRED FOR SOIL-PIPE INTERACTIONS

From a high-level viewpoint, the approach for the detailed design of buried pipelines involves numerical analysis of soil-pipe interaction to assess the stress/strain development along pipelines. In a systematic way, this process would involve: determining the basic properties of the soil surrounding the pipe; generating "soil springs" using these basic soil properties to numerically model the soil force development on the pipeline due to any relative movements between the pipe and surrounding soil; then, conducting numerical soil-pipe interaction (e.g., finite-element) analysis using the pipe structural elements and the developed soil springs to assess the pipe stress/strain development. The recommended approach shown in PRCI (2009) is illustrated schematically in Figure 1.

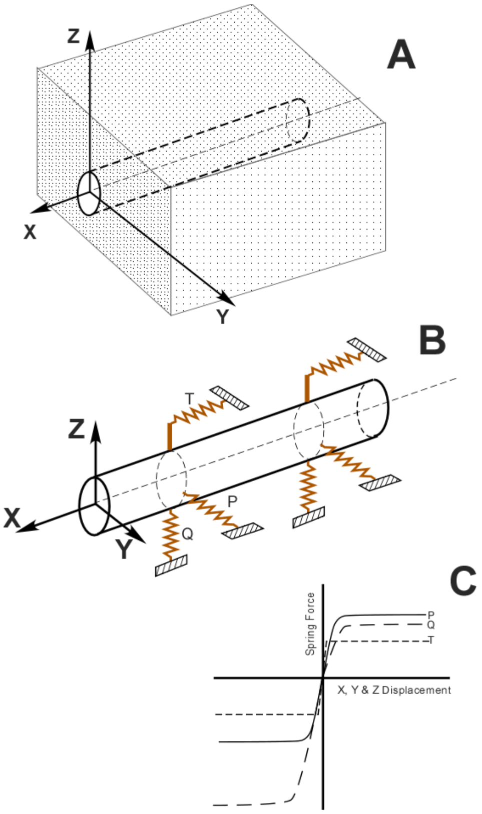

Figure 1. Spring analog for analyzing pipeline-soil interaction (from PRCI 2009)

The determination of the soil strength, whether it be friction angle (ϕ') for sands or undrained shear strength (s_u) for clays, is required to calculate the lateral and axial soil restraints. The stiffness of the soil [i.e., Young's modulus (E) or the shear modulus (G)] is also required to estimate the stiffness of the soil restraints. Using these soil parameters, combined with other pipe and soil characteristics, such as soil bulk density, pipe coating, diameter, and depth of cover, the representative soil springs can be determined as per practice guidelines.

Previously, it has been common practice to treat muskeg as clay rather than sand when using these guidelines, likening it to a very soft clay. Keeping this in mind, a field investigation program comprising seismic cone penetration testing (SCPTu), ball penetrometer testing (BCPT), full displacement pressuremeter testing (PMT), supplemented by electronic field vane shear test (eVST), and auger and Shelby tube sampling was performed. The next sections outline the tests undertaken, the location of the testing, and the results and interpretations of those tests.

3 FIELD INVESTIGATION PROGRAM

The field investigation program was completed during February 6 through 10, 2017 at a selected site in Northern Alberta along TransCanada Corp.'s Liege Lateral Loop No. 2 line right-of-way. The residential camp used during the testing and site location, respectively, are shown in Figures 2(a) and 2(b). The testing program consisted of two SCPTu tests, two BCPT tests, four successful eVST tests, and four usable PMT tests, solid-stem auger and Shelby tube sampling, all performed using field-testing equipment provided by ConeTec Investigations Ltd., Richmond, B.C. A summary of the testing equipment used is shown in Table 1. The BCPT ball tip and PMT probe are shown in Figure 3(a) and 3(b) respectively.

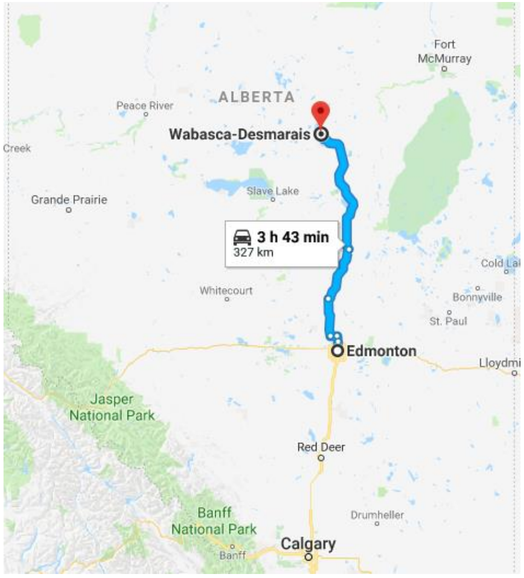

Figure 2(a) Location of camp relative to Edmonton, Alberta (Google Maps, 2018)

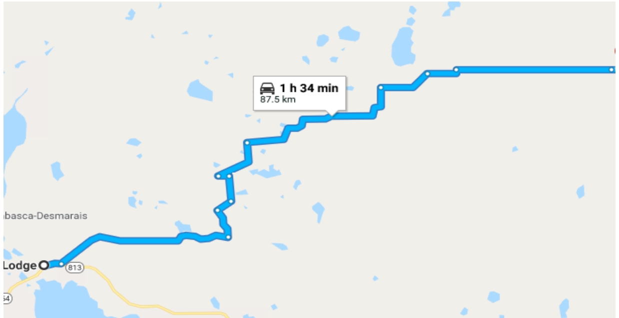

Figure 2(b) Location of test site relative to camp (Google Maps, 2018)

In addition to the widely used SCPTu and eVST tests, it was decided that BCPT could also be a suitable test for probing the soft/weak muskeg material. BCPT is primarily used to explore soft/weak subsurface materials found in offshore mudline and tailings impoundments. Due to the spherical shape of the probe, BCPT is considered as a full flow penetrometer test when the soil being tested behaves as a fluid. As such, the combination high moisture content and low strength of muskeg soils provided the opportunity to examine whether BCPT would be a viable test. The BCPT test also displaces a large mass/volume of soil compared to the SCPT test – in turn, can be argued analogous to the displacement of bulk soil mass/volume arising from the displacement of a relatively large diameter energy pipeline. The PMT test was also considered relevant as involves mimicking and resistance to significant large lateral displacements in muskeg, and in turn, would directly reflect the stiffness of the surrounding soil.

Table 1. Summary of testing equipment dimensions

Field Test	Equipment Dimensions
SCPTu	15 cm^2 cone (4.37 cm dia)., net area ratio: 0.8
BCPT	150 cm^2 ball (13.8 cm dia.)
eVST	Double tapered 75 x 150 mm vane
PMT	Effective volume of probe: 1724 cm^3 ; (46 cm height)

The layout of the site and a cross-section view of the test holes is shown in Figures 4(a) and 4(b), respectively. The maximum depth reached for the SCPTu and the BCPT was 6.35 m and the targeted depth locations for the eVST and PMT were 1.50 m, 3.00 m, and 4.50 m. The maximum depth and target depths were chosen based on the authors' understanding of typical soil depths of influence of buried pipelines subject to ground displacements (i.e., soil depth of cover for typical transmission energy pipelines), as well as limiting soil disturbance from adjacent tests that could affect the quality of the data obtained.

Figure 3(a) BCPT ball tip

3(b) PMT probe

4 SITE STRATIGRAPHY AND DATA INTERPRETATION

4.1 Soil and Groundwater Conditions

Based on the auger sampling and SCPTu data, the soil stratigraphy was found to consist of approximately 4.6 m of muskeg, the top 0.5 m of which was frozen, underlain by clay with the water table resting 0.3 m below the surface. The average moisture content determined from the samples retrieved from the auger flights was approximately 200%.

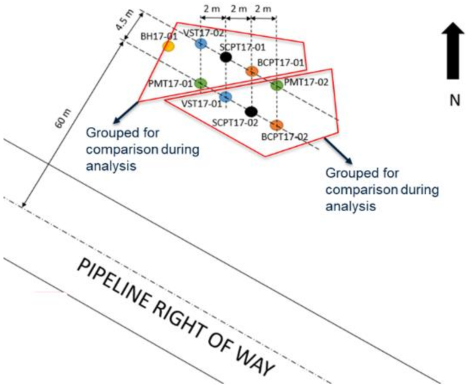

Figure 4(a) Plan view of test site layout

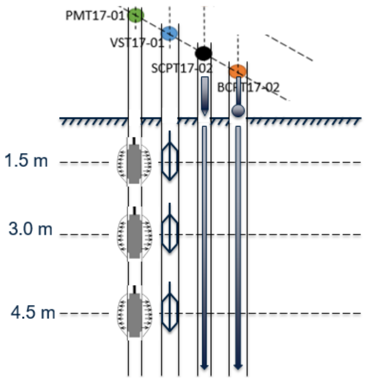

Figure 4(b) Cross-sectional profile showing target test depths for PMT and eVST along with SCPTu and BCPT holes

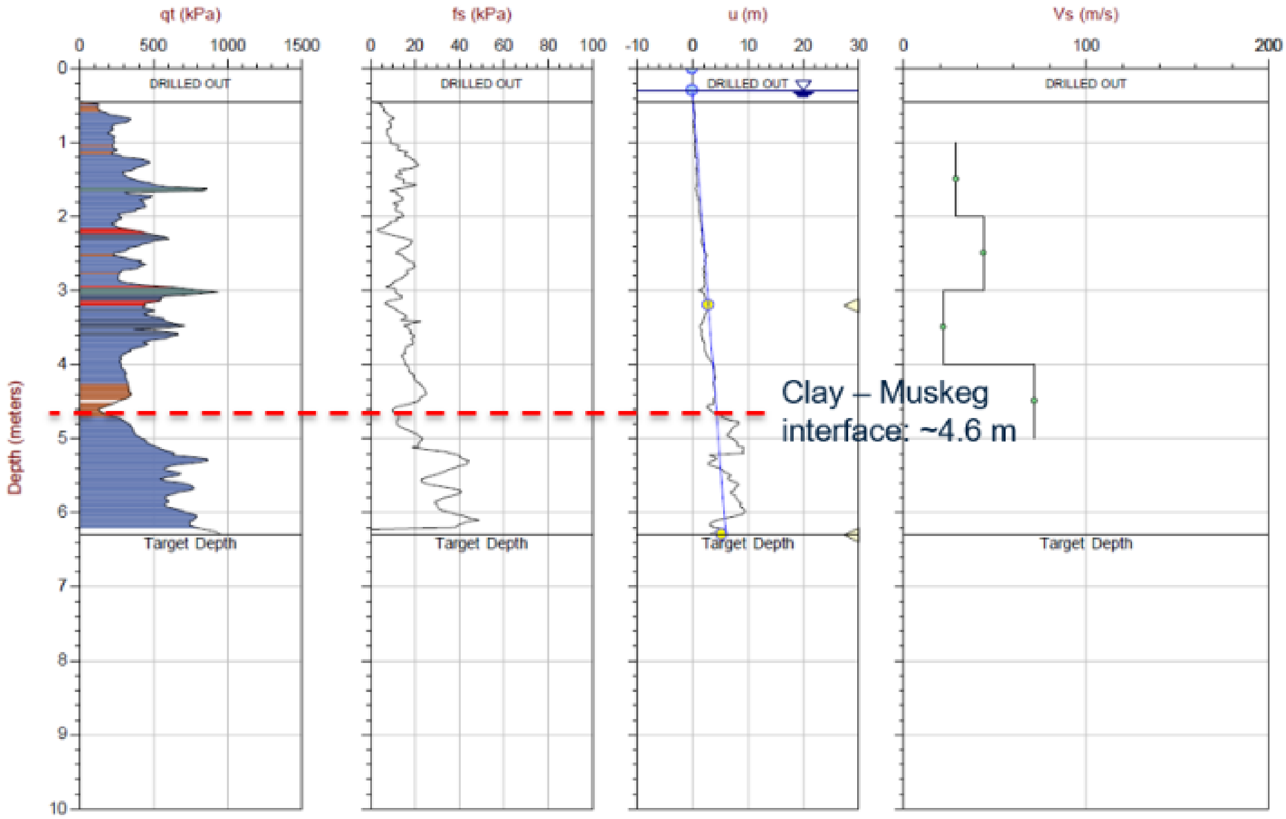

Figure 5. Data from a typical SCPTu test

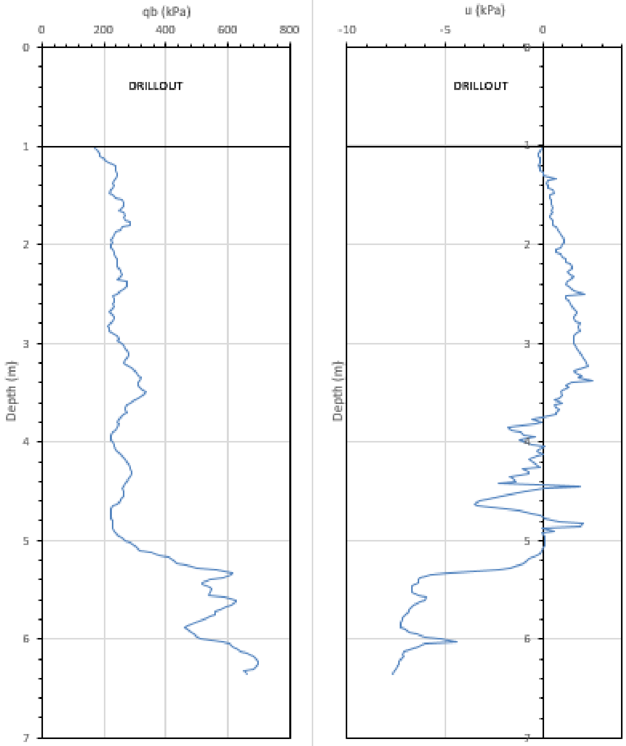

Figure 6. Typical BCPT plots for one hole [from the test hole BCPT 17-02, see Figure 4(b)]

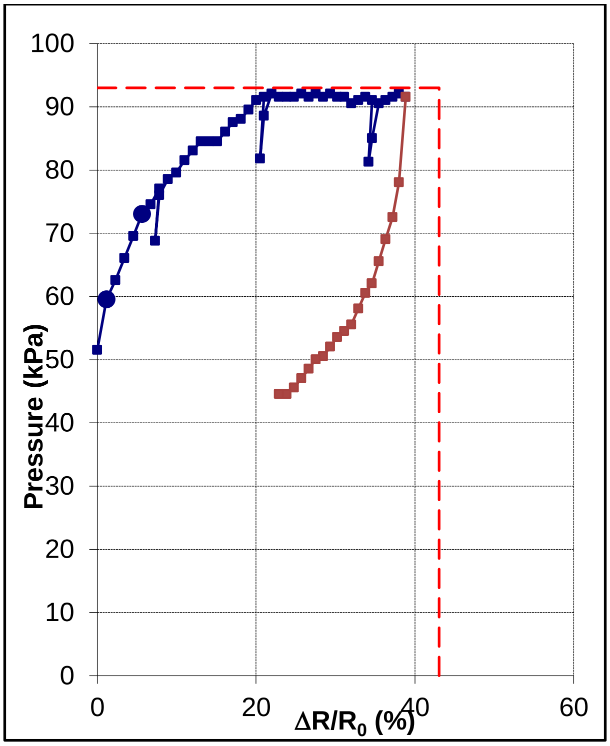

Figure 7. Typical data derived from PMT testing (PMT17-02; Depth = 4.25 m)

The SCPTu data, when interpreted using the soil behaviour type (SBT) classification system proposed by Robertson and Campanella (1986), would classify most of the muskeg material as clay (see Figure 5). This interpretation of the soil as a clay is based on the SCPTu friction ratio and tip resistance; however, assessments based on the pore-water pressure and pore pressure dissipation test information, the soil can be classified to behave as a drained material. A visual inspection of samples retrieved from the nearby solid-stem auger hole, the soil was clearly observable as brown fibrous muskeg.

The SCPTu test data indicated that the muskeg soil in the tested depth zone has mean shear wave velocities ranging from 20 m/s to 40 m/s. It is noteworthy to compare that, according to Borcherdt (1994), typical mean shear wave velocities for soft clays and silty clays would range from 100 m/s to 200 m/s. This measured low shear wave velocity indicates an extremely soft (porous) soil matrix for muskeg (as expected).

A typical data set derived from BCPT test (ball penetration resistance q_b versus depth and excess pore water pressure recorded behind the ball at the u_2 position versus depth is shown in Figure 6. The applied pressure to the PMT chamber versus $ln(\Delta R/R_0)\%$ (where ΔR = change in pressuremeter radius and R_0 = radius of the pressuremeter at lift-off) from a typical PMT test conducted at a given depth is presented in Figure 7. Some limited interpretations made on those results are discussed in the next sections.

4.2 Undrained Shear Strength

Using available empirical approaches for fine-grained soils (silts/clays), the undrained shear strength of muskeg (S_u) was interpreted from SCPTu and BCPT data using the Equation below (Boylan et al. 2011).

$$S_u = q_{net}/N_{kt} \qquad \text{or} \qquad S_u = q_{net}/N_{ball} \qquad [1]$$

q_{net} for SCPTu and BCPT were determined, respectively, using Equation 2 and 3 given below (Boylan et al. 2011) :

$$q_{net} = [qc+(1-a)u_2] - \sigma_{vo} \qquad [2]$$

$$q_{net} = [qb+[(1-a)u2]As/Ap] - [\sigma_v \times As/Ap] \qquad [3]$$

where a = 0.8, As = shaft area, and Ap is the ball plan area.

As a first step, following suggestions by Campanella and Howie (2005) for fine-grained soil, it was decided to try an N_{kt} factor of 15 to assess S_u from SCPTu. Similarly, S_u from BCPT data were assessed using an N_{ball} factor of 11 as per information/experience available from ConeTec Investigations (Weemees et al. 2006) and also suggested by Boylan et al. (2011) for BCPT in organic soils.

The data from PMT was also used to determine S_u using the method proposed by Gibson and Anderson (1961) essentially considering the slope of the applied pressure to the PMT chamber versus $ln(\Delta R/R_0)\%$. In addition, the value of S_u was also determined using eVST data following the general equation outlined in ASTM D2573 (2008) for double tapered vanes.

All the interpreted undrained shear strengths (S_u values) variation with depth for muskeg [from the data from test holes identified in Figure 4(b)] are plotted on the graph in Figure 8, for the ease of comparison. Note: The lower values in Figure 8 correspond to the remolded S_u values obtained from eVST and BCPT (cycling tests).

From an overall point of view, the interpreted S_u values for the SCPTu and BCPT agree quite well with each other (for the chosen N_{kt} and N_{ball} values of 15 and 11); they also compare well with the data from the well-completed eVST. The values of S_u determined from the PMT seem to be a more comparable to the remolded strengths determined from the BCPT and the eVST than the peak strength.

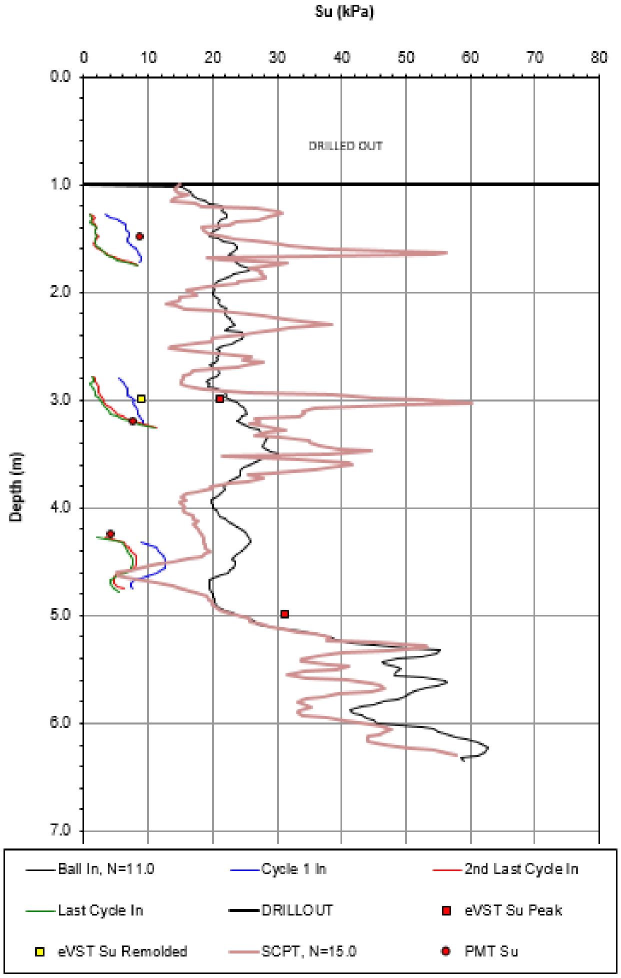

Figure 8. S_u comparison for a set of analyses using the data from test holes identified in Figure 4(b).

It is to be noted that the S_u values derived from eVST in fibrous organics may not yield the representative results. Mesri and Ajlouni (2007) summarizes that the vane test compresses and drains the fibers, creates cavities, and measures a tearing resistance. While the values that were successfully obtained compare well with the SCPTu and BCPT results, it is worth noting that there were also unsuccessful tests with the eVST, due to the fibrous nature of the soil, that were discarded.

4.3 Shear Stiffness

The data from SCPTu and PMT were used to interpret the soil shear modulus (G). The maximum shear stiffness (stiffness at very small strain) G_{max} can be determined from the shear wave propagation velocity (V_s) data from SCPTu testing with the use of Equation 4. Considering information from moisture content testing, and obtaining bulk density by weighing Shelby tubes, the average bulk unit weight of the soil was estimated as 12.5 kN/m^3 for use in Equation 4 (after converting to a bulk mass density in terms of kg/m^3).

$$G_{max} = \rho\ V_s^2 \qquad [4]$$

The value of G was determined from the PMT data based on small strain cavity expansion theory (Hughes and Robertson 1984) which states that the slope of an unload-reload cycle on a pressure versus circumferential strain plot would be twice the shear modulus. As noted by O'Neill, (1985), this method however, does not account for hysteresis if it should occur. Table 2 summarizes the interpreted G_{max} and G values, respectively, from the two testing methods SCPT and PMT conducted at the test holes shown in Figure 4(b).

Table 2. Summary of interpreted G values

Depth (m)	SCPT – G_{max} (kPa)	PMT – G (kPa)
1.50	1072	995
3.21	2467	1095
4.25	796	785

The PMT interpreted G values were lower than the SCPTu interpreted G_{max} values; this is expected, since the PMT interpreted G values correspond to a significantly larger shear strain level compared to the those from shear wave velocity measurements correspond to an extremely low shear strain level. Considering the sensitivity of G values to strain level, no detailed assessment is conducted herein other than to state that many factors such as site variability and level of soil disturbance during the PMT pocket preparation, could affect the variations observed in the values presented in Table 2. Additional work on the soil stiffness will be conducted as a part of the ongoing research.

5 SUMMARY

A field investigation was undertaken with the intent of providing engineering strength and stiffness parameters required for soil-pipe interaction analysis for the design of buried pipelines in muskeg soil terrain. It is shown that a variety of testing methods, including SCPTu, BCPT, eVST, and PMT, can be used to obtain these parameters.

The initial comparisons indicate that the values of S_u interpreted from the four different tests showed reasonable agreement suggesting that reliable strength parameters could be derived to potentially support soil-pipe interaction assessments. The interpretation of stiffness can be challenging, due to many factors such as site variability, level of soil disturbance during testing, etc.

In an overall sense, the initial results suggest that the current research program is promising and with additional careful work undertaken using field testing combined with numerical analyses should lead to not only obtaining stiffness/strength, but also for developing empirical/semi-empirical ways of obtaining soils springs for soil for soil-pipe interaction analysis of buried pipelines in muskeg soils.

6 ACKNOWLEDEMENTS

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