Model bearing capacity tests in a large laboratory simulation of polymer amended MFT

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GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
This paper investigates the increase in undrained shear strength and bearing capacity in a laboratory simulation of multilayer deposition of in-line flocculated oil sand mature fine tailings (MFT). Vane shear tests were conducted before the deposition of each new layer. From these tests, the tailings, demonstrated relatively high shear strength in a comparably short period of dewatering time, reaching an undrained shear strength of > 5kPa, once they were dried out to 55-60% solids concentration in the top layer. Plate load tests were performed directly on the tailings, after the top layer was dried to approximately 60% and 70% solids concentrations, with a circular plate with a diameter of 10.5cm. The model bearing capacity tests results were compared to values obtained using the effective stress approach without and with considering the influence of matric suction.

RÉSUMÉ
Cet article examine l'augmentation de la résistance au cisaillement non drainée et la capacité portante d'un dépôt multicouche de résidus de sables bitumineux fins et matures (MFT) floculés en ligne dans une simulation en laboratoire. Des essais de cisaillement au scissomètre ont été menés avant la déposition de chaque nouvelle couche. De ces essais, les résidus ont démontré une résistance au cisaillement relativement élevée durant une courte période de temps comparable au temps de déshydratation. Ils ont atteint une résistance au cisaillement non drainée de > 5 kPa une fois qu'ils ont été séchés à 55-60 % de la concentration des matières solides dans la couche supérieure. Des essais de charge sur plaque ont été effectués directement sur les résidus, après que la couche supérieure ait été séchée à environ 60 % et 70% de la concentration des matières solides, avec une plaque circulaire de 10,5 cm de diamètre. Les résultats des tests de capacité portante du modèle ont été comparés aux valeurs obtenues en utilisant l'approche de la contrainte effective modifiée, étant donné l'influence de la succion matricielle.

1 INTRODUCTION

One of the greatest challenges in oils sand mining is the management of the large volumes of waste that are generated. The mining of oil results in the generation of large volumes of waste, called oil sand tailings. Tailings are stored in dammed ponds, which pose significant risks to the surrounding environment. The problematic portion of tailings is known as mature fine tailings (MFT). This fraction of the tailings exhibits poor consolidation and settling behaviours which delays the land reclamation process. In order to regulate tailings management, the Energy Resource Conservation Board (ERCB), Alberta's governing body that oversees the oil sands industry, had released Directive 074: *Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes* in 2009. The purpose of this directive is to allow the affected areas to achieve trafficability for future reclamation of these areas. In order to obtain a trafficable surface, the minimum undrained shear strength, S_u, of the tailings is required to be 10 kPa. Directive 074 states that the minimum undrained shear strength of any tailings deposited in the previous year must be 5 kPa. Any material that does not meet this requirement must be removed or remediated. In five years, after active deposition has ended, the deposit must achieve trafficability or an undrained shear strength of 10 kPa (Energy Resources Conservation Board 2009). These regulations allow the monitoring and measurement of progress of the deposit towards the reclamation goal. Even though Directive 74 has been recently repealed, the 5 kPa criteria is retained in the new regulations, albeit there is no firm timeline as to when this has be achieved. Achieving 5 kPa shear strength presents some geotechnical engineering challenges, mainly in modifying the geotechnical properties of the oil sands tailings in order to increase dewatering due to self-weight consolidation and desiccation. The shear strength parameters affect the bearing capacity of the soil, or the ability to carry the imposed loads without undergoing a shear failure.

This current study attempts to determine the bearing capacity of an oil sands tailings deposit that corresponds to a deposit that is considered "on the road to trafiicability" (a deposit that has achieved the 5 kPa requirement). The model bearing capacity test results are compared to estimated bearing capacities using the effective stress analysis considering the contribution of matric suction.

2 EXPERIMENTAL SET-UP

2.1 Drying Box Test

The experimentail set-up for the drying box test is shown in Figure 1. Flocculated oil sand tailings were deposited into a plexiglass box with steel framing with dimensions of 98.7 x 69.7 x 63.0 cm (LxWxH) in three layers and allowed to dry to a target solids concentration between each deposition. The set-up was similar to the experiments conducted by Innocent-Bernard et al. (2013) and Daliri et al. (2012). The dry box was surrounded by various sensors to monitor different measurements related to dewatering behaviour; load cells (mass change, and evaporation), rain gauge (drainage), senix sensors (height), Deagon 5TE sensors (volumetric content, temperature and bulk electric conductivity) and UMS T5 tensiometers (pore-water pressure and matric suction). The Deagon 5TE and UMS T5 sensors were placed at every 16 cm height interval in the box to monitor the variability of consolidation and drying in the soil profile. Two electrical fans were placed at opposite ends of the box in order to simulate wind conditions.

The tailings were deposited in three layers of a thickness of approximately 31, 35, and 33 cm, at average solids concentrations of 35%, 34%, and 33% respectively, with a flocculant dosage of approximately 650 mg/kg per dry mass of tailings. The layers were left to consolidate and dessicate to the shrinkage limit of the material, before the deposition of the subsequent layer.

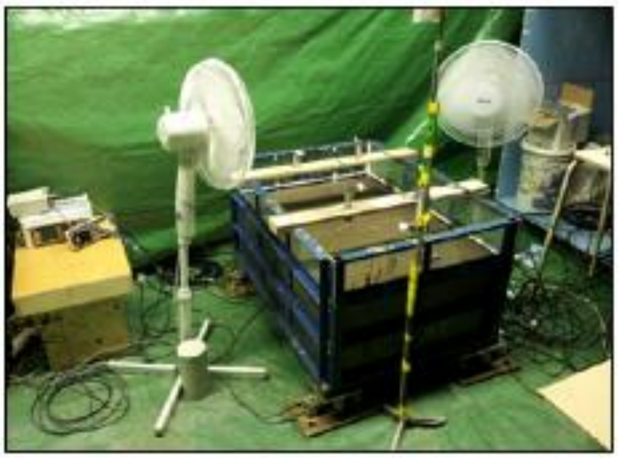

Figure 1. Drying box in profile

2.2 Vane Shear Tests

Vane shear tests were conducted once the topmost layer had achieved a solids contents corresponding to the shrinkage limit in order to verify for regulatory compliance. A vane of various diameters was inserted into the soil approximately every 5 cm. Once the vane was at the zero position, it was rotated slowly at a uniform rate. The point where the vane reaches the maximum torque and the soil fails in shear on a cylindrical surface around the vane is the undrained shear strength of the soil. Specific factors were applied for the appropriate correction depending on the size of the vane.

2.3 Plate Load Tests

To determine the bearing capacity of soils, in-situ plate load tests, which track the vertically applied load with the corresponding surface settlement, are usually conducted. These tests are commonly carried out in unsaturated soils, and usually the contribution of suction is not taken into account in the analyses of the results of the plate load tests.

To determine the validity of an effective stress analysis to unsaturated oil sand tailings, once the third and final layer achieved solids contents of approximately 60% and 70%, in-situ plate load tests based on a modified ASTM 2003 method, were conducted on the tailings in the dry box at both solids concentrations. A “screw mechanism”, as shown in Figure 2, was used to apply a uniformly increasing load to the material, while being recorded on a data acquisition system through a load cell. The screw mechanism worked by converting a torque into a linear force to the load cell. , at a uniform rate until failure was observed. For the test at 60% SC, a dial gauge held by a stand was used to measure the displacement of the load cell at regular time intervals. For the 70% SC test, LVDT position sensors connected to a data acquisition system replaced the dial gauge. This permitted more readings at smaller time intervals. The model footing was 10.5cm in diameter to allow a uniform distribution of the load. The ratio of the width of the dry box (W) to the diameter of the footing (D) was chosen in order to match previous studies as closely as possible (ie. W/D~6) (Adams and Collin, 1997;. Hanna and Abdel-Rahnam, 1998; Dash et al,. 2003; Bera et al., 2007; Oh and Vanapalli, 2013).

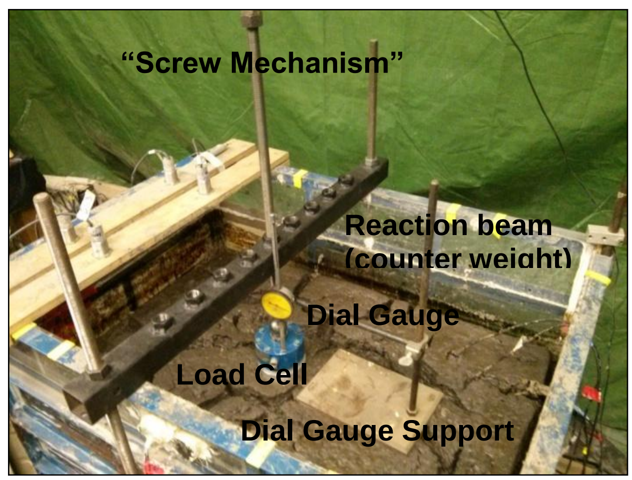

Figure 2. Plate load test set-up

3 MATERIAL

The MFT and the high molecular weight anionic polymer, A3338, used in this study came from Shell Canada’s Muskeg River Mine. Any release water that had accumulated on top of the MFT during transportation was mixed back into the MFT. The raw MFT had an initial solids content of approximately 36 % and a sands to fines ratio of 0.27. The geotechnical properties of the MFT are shown in Table 1. Flocculant solutions of 0.4% (w/w) were prepared by adding 4 g of polymer to 996 g of reclaimed water from the same mine. The preparation of the floc solution and flocculated MFT are outlined in Mizani et al. (2013), to replicate the properties of material produced in the field. During the deposition of each layer, slump and moisture content samples were taken at regular intervals to ensure the consistency of the flocculated MFT.

Table 1 Geotechnical properties of raw MFT used in this study (Mizani et al., 2013)

Property	Value
Specific gravity (dimensionless)	2.2
D_{10}, D_{50}, D_{60} (microns)	0.8, 6.4, 11.1
Cu (D_{60}/D_{10}) (dimensionless)	14.1
Liquid limit (%)	62
Plastic limit (%)	26.7
Fines content (<44 µm) (%)	78.7

4 BEARING CAPACITY OF SOILS

According to the Canadian Foundation Engineering Manual, the ultimate bearing capacity of a shallow foundation on uniform soil can by calculated as follows:

$$q_u = cN_cS_c + q_sN_qS_q + \frac{1}{2}\gamma BN_\gamma S_\gamma \quad (1)$$

Where,
q_u = ultimate bearing capacity;
N_c, N_q, N_γ = dimensionless bearing capacity factors;
S_c, S, S_γ = dimensionless modification factors for foundation shape, inclination, depth and tilt, and ground slope;
q_s = vertical stress acting at the elevation of the base of foundation;
B = width of foundation or at least plan dimension of the foundation;
c = soil cohesion;
γ = soil unit weight;

Equation (1) considers a foundation that is subjected to a general shear failure.

The bearing capacity of saturated soils is usually estimated using the total stress analysis (TSA) [ie. short-term stability, undrained conditions, c=S_u (undrained shear strength) and Φ=0 based on (Skempton, 1948)] or the effective stress analysis (ESA) [ie. long-term stability, drained conditions, c=c' (effective cohesion intercept) and Φ= Φ' (effective angle of friction of the soil) based on (Terzaghi, 1943)], based on the type of soil and the drainage state.

Once the influence of suction is considered, the ESA can be extended to apply to both, fine and coarse-grained soils, since unsaturated coarse-grained soils will be under a drained condition for pore-air and pore-water pressures. The application of this approach to unsaturated fine-grained soils is questionable since the drainage conditions of pore-air and pore-water pressures have some uncertainties under plate load tests compared to unsaturated coarse-grained soils. Some work has been done to interpret the in-situ plate load test results in unsaturated soils considering the influence of matric suction by introducing modifications to the conventional ESA (Oloo, 1994; Costa et al., 2003; Vanapalli and Mohamed, 2013).

4.1 Modified Effective Stress Approach (MESA)

In unsaturated fine-grained soils, numerous studies have observed that bearing capacity values increase with greater matric suction, but eventually reaches a maximum value despite increasing suction. Unlike the modified total stress approach (MTSA), where the measurement of matric suction is not required, this measurement is important for the MESA as seen in Equation 2.

One equation for the MESA approach was developed by Oloo et al. (1997):

$$q_{ult\ (unsat)} = \{c' + (u_a - u_w)_b[1 - S^{(\psi_{BC})}\tan\emptyset'] + (u_a - u_w)_{AVR}S^{(\psi_{BC})}\tan\emptyset'\}N_c\xi_c + 0.5B\gamma N_\gamma\xi_\gamma \quad (2)$$

Where,
$q_{ult(unsat)}$ = ultimate bearing capacity of unsaturated soils;
$(u_a - u_w)_b$ = air-entry value;
$(u_a - u_w)_{AVR}$ = average matric suction;
S = degree of saturation;
γ = soil unit weight;
ψ_{BC} = fitting parameter with respect to bearing capacity;
B = width of footing;
$N_c\ and\ N_\gamma$ = bearing capacity factors from Terzaghi (1943) and Kumbhokjar (1993); and
$\xi_c\left\{= \left[1.0 + \left(\frac{N_q}{N_c}\right)\left(\frac{B}{L}\right)\right]\right\}$ $and\ \xi_g\{= 1.0 - 0.4\left(\frac{B}{L}\right)]\}$ are shape factors from Vesić (1973).

This model, known as the modified effective-stress approach (MESA), uses the effective shear strength parameters and the soil-water characteristic curve (SWCC) with a fitting parameter. The MESA, however is not applicable for suction values greater than the residual suction value since the bearing capacity of UFG soils converges to a certain value at the residual state.

In order to account for punching shear failure in the tailings a reduction-factors approach can be applied. In the reduction-factors approach, the soil cohesion, and the internal angle of friction are reduced as follows:

$$c' = \frac{2}{3}c \quad (2)$$

$$\phi' = \tan^{-1}\left(\frac{2}{3}\tan\phi'\right) \quad (3)$$

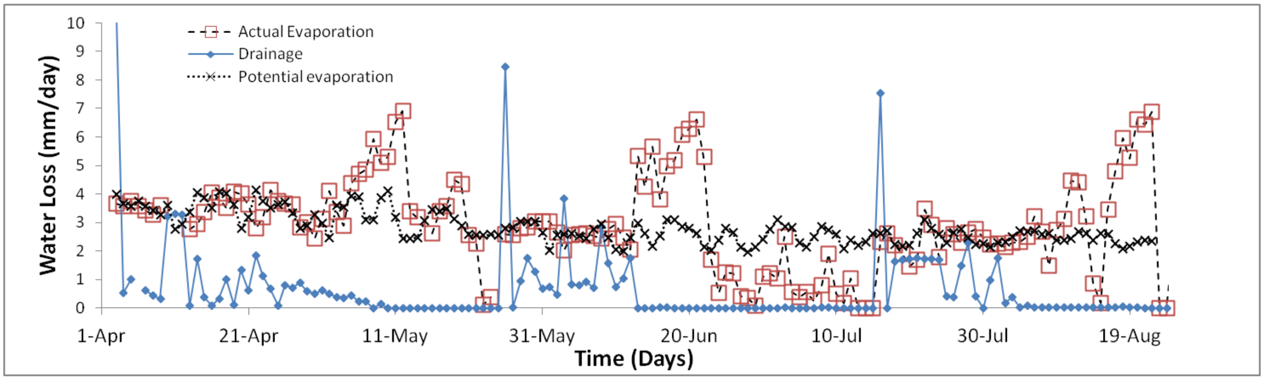

Figure 3. Dewatering behaviour of the dry box (Rozina et al., 2015)

5 RESULTS

5.1 Dewatering Behaviour

The key finding with respect to dewatering was the role of cracks in evaporation. It was found that the appearance of cracks corresponded to an increase in evaporation rate. Moreover, the actual evaporation rate exceeded potential evaporation for times that coincided with ongoing crack growth. Subsequent to the cessation of crack growth, evaporation rates declined to or below the value of potential evaporation. Figure 3 illustrates the dewatering of the dry box.

Volumetric water content (VWC) sensors placed at various heights in the dry box were used to estimate the change in solids concentration in each of the top layers during dewatering. For Layer 1, the VWC sensors showed a faster increase in density. This is because the overall solids concentration includes the supernatant water, but the VWC sensors measure actual water content in the layer. Results show that the 5 kPa strength requirement was achieved once the top layer of these tailings had reached solids concentrations of 55-60%. These solids concentrations were reached within a month after deposition as shown in Figure 4.

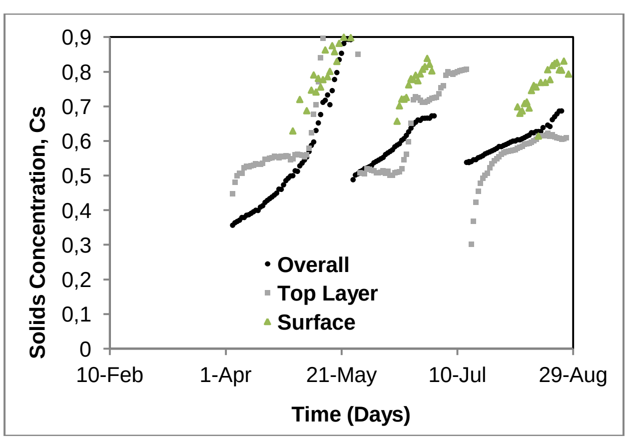

Figure 4. Solids concentrations overall and for top layers, estimated by VWC sensors (Rozina et al., 2015)

The dewatering process of the dry box is described in detail in Rozina et al. (2015).

5.2 Undrained Shear Strength

Figure 5 summarizes the results for vane shear tests conducted for the 2nd and 3rd layers at various solids concentrations in some locations in the dry box. As shown in Figure 5, the values at the mid-depth to the bottom for all tests seem to converge around similar values, regardless of the solids concentration or the thickness of the material. There is some discrepancy seen in the vane shear test conducted at 60% solids concentration in Layer 3. The tailings were found have a lower undrained shear strength at surface than at the bottom. These tests were conducted in order to ensure that the 5 kPa undrained shear strength requirement was attained before the in-situ plate load tests.

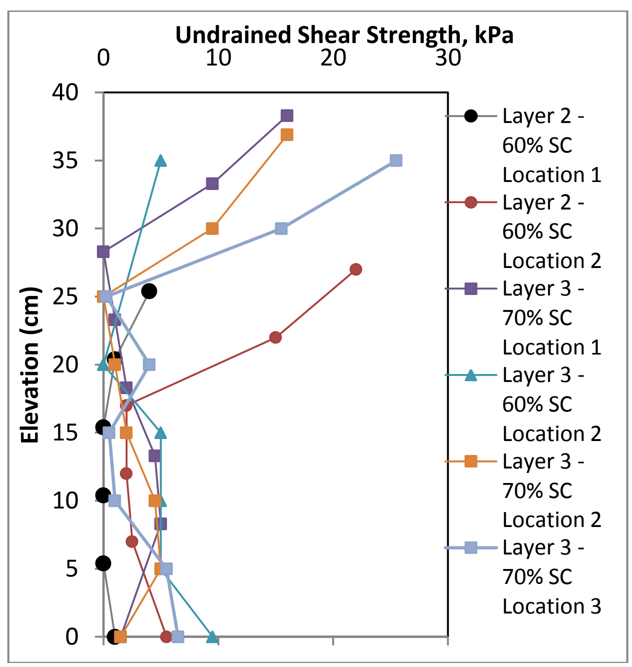

Figure 5. Vane shear test results

5.3 SWCC and Contribution of Matric Suction

The SWCC was established using the axis-translation method with volume change measurement for low suctions, and with the use of a dewpoint hygrometer to measure total suction in the high range by Soleimani and Simms (2014). According to Figure 6, the air-entry value is approximately 50 kPa

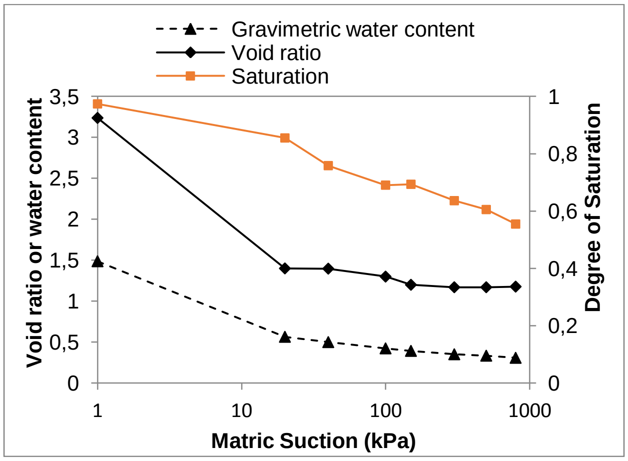

Figure 6. SWCC for oil sand tailings (Soleimani and Simms, 2014)

Several tensiometers were installed at various intervals in the dry box to monitor the variation of matric suction in the tailings. Figures 8 and 9 provide matric suction distribution profiles with depth as the tailings became unsaturated. Figure 9 is the matric suction distribution in the first layer.

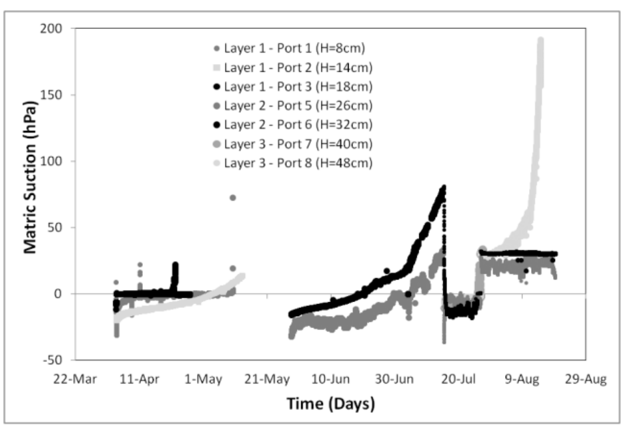

Figure 7. Matric Suction/pore-water pressures (Rozina et al., 2015)

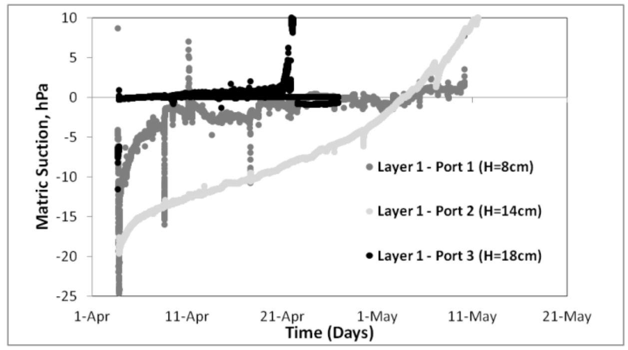

Figure 8. Matric suction/pore-water pressure in Layer 1 (Rozina et al., 2015)

The tensiometer readings were inconsistent as shown in Figures 8 and 9, since cracking exposed them to air as the tailings dried, and caused cavitation. However, the tensiometers do provide good data where the pore-pressures passed from negative to positive values.

5.4 Estimation of Bearing Capacity

The tailings used in the present study were assumed to have a cohesion of zero degrees, and a friction angle of 30 degrees (Qiu and Sego, 2001). From the soil water characteristic curve shown in Figure 6, the air-entry value of these tailings is approximately 50 kPa. From the tensiometer data shown in figures 8 and 9,and the soil water characteristic curve shown in Figure 6, it can be seen that the tailings never reached the air entry value, therefore the bearing capacity was estimated using equation 1. The bearing capacity was estimated without the contribution of matric suction and with it. The values obtained are shown in Table 1. The contribution of matric suction increased the estimated bearing capacity significantly in both cases. With 60% solids content, the bearing capacity was increased by nearly twice the value without the contribution of matric suction. In the case of 70% solids content, the contribution was even greater, resulting in 86.1 kPa as opposed to 9.48 kPa without considering matric suction.

5.5 Plate Load Test Results

As shown in Figure 10, the material was found to fail in the “punching shear” mode in all 3 attempted tests, similar to an unsaturated fine-grained soil (Oh and Vanapalli, 2014).

Table 1. Bearing Capacity Results

Solids Content (%)	Gravimetric Water Content (%)	Degree of Saturation	Wet Unit Weight (kN/m^3)	Dry Unit Weight (kN/m^3)	Estimated Bearing Capacity (without contribution of matric suction)	Matric Suction (kPa)	Estimated Bearing Capacity (With contribution of matric suction)
60	66.7	0.802	12.5	7.53	8.85	0.9	19.5
70	42.9	0.515	13.4	9.41	9.48	6.0	86.1

Figure 9 “Punching Shear” failure mechanism after the 70% SC bearing capacity test

The results for each of the plate load tests are summarized in Figure11 below. The shape of the load versus settlement figure, the indentations in Figure 11, and the picture in Figure 10 taken right after failure demonstrate punching shear failure (Vesic 1973). Where the point of failure of the soil is ambiguous, the ultimate bearing capacity can be estimated as the stress coinciding with either (1) a settlement corresponding to 10% of the footing width (0.1B settlement method) (Cerato and Lutenegger 2007; Oh and Vanapalli 2013) or (2) the intersection of the tangents to the initial and latter portions of the stress-settlement curve (slope tangent method) (Consoli et al. 1998; Costa et al. 2003; Oh and Vanapalli 2013).

According to the 0.1B settlement method, the bearing capacity from these plate load tests is approximately 18 kPa for 60% SC and 82 kPa for 70% SC which are almost in agreement the estimated bearing capacities considering the contribution of matric suction as summarized in Table --. From the same table, it can be seen that the estimate considering the contribution of matric suction is in more agreement to the values from the plate load tests. As shown in Figure 11, the slope tangent method, corresponding to a value of approximately 20.7 kPa, is also in agreement with the estimated bearing capacity considering the contribution of matric suction at 60% SC, . However, this method overestimates the bearing capacity at 70% slightly as shown in Figure 11, corresponding to a value of approximately 90 kPa.

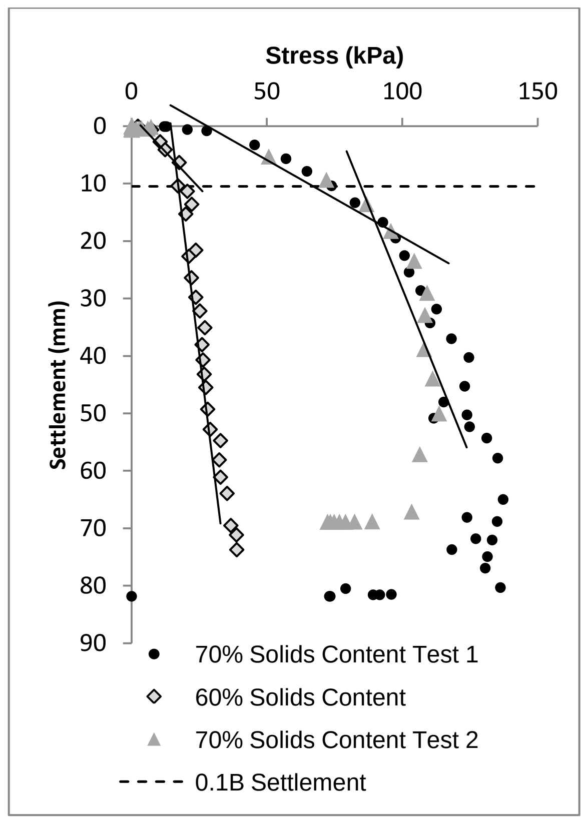

Figure 10. Dry box plate load test results

6 CONCLUSIONS

This study investigated the bearing capacity of a flocculated oil sand tailings deposit that would correspond to a deposit that would be considered “on the road to trafficability” or correlates to an undrained shear strength of 5 kPa. In-situ plate load tests were performed on a laboratory simulation of a multi-layered in-line flocculated MFT deposit once the top most layer had achieved solids concentrations of 60 and 70%. From the tests, the bearing capacities were estimated to be 18.0 kPa and 82.0 kPa for 60 and 70 % SC respectively using the 0.1B settlement method. Using the slope tangent method, the bearing capacities were approximately 20.7 kPa and 90 kPa for the same tests. The values from the 0.1B settlement method were found to have more agreement with bearing capacities estimated by using the ESA, which were 19.5 kPa and 86.1 kPa considering matric suction for 60 and 70% respectively.

The strong influence of matric suction on bearing capacity has two consequences. Firstly, dry weather will facilitate trafficability, but secondly, and more importantly, measuring undrained strength or bearing capacity in unsaturated deposits can over-predict the reliable long term bearing capacity of a deposit, as dissipation of suction will greatly lower strength.

ACKNOWLEDGEMENTS

Robert Mahood and Gavin Freeman at Shell Canada provided invaluable material and logistical support on the project. The project is funding jointly by COSIA (Canadian Oil Sands Innovation Alliance) and NSERC (Canada's Natural Science and Engineering Research Council).

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