Consolidation Testing of Oil Sand Fine Tailings

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Abstract

The paper presents the results of several tests performed on a sample of Mature Fine Tailings (MFT) in which the consolidation is induced by seepage forces in the laboratory and by increased gravity level in a geotechnical centrifuge. These tests are particularly suitable for testing soft slurries. The test with seepage forces, the Seepage Induced Consolidation Test (SICT), is used to obtain compressibility and permeability characteristics of the tailings material while the centrifuge modeling test is used to independently verify the obtained properties. The analyses for both tests recognize that the void ratio (solids content) within each sample is variable and no restrictive assumptions are made on the variability of the consolidation properties of the sample.

The presented results confirm that the SICT is applicable to the testing of oil sand MFT, and produce repeatable datasets that are useful in building an understanding of the behaviour of these high void ratio materials. While these findings are encouraging, some peculiarities observed in the experiments suggest that more detailed studies will be required before the results could be applied to field conditions with confidence.

Introduction

Oil sand tailings disposal presents a challenge for mining companies from both an operational standpoint and to satisfy environmental protection requirements. Field evidence of the tailings behavior indicates that the consolidation process for this material is extremely slow and even brings into question if the material behaves like a soil slurry undergoing consolidation under its own weight. These uncertainties are especially evident for tailings at low solids contents, for which standard consolidation testing procedures are inadequate.

The Seepage Induced Consolidation Test (SICT) has been successfully used over the last two decades to determine consolidation properties of soft soil slurries, such as mine tailings and dredging spoils. The procedure is particularly suitable for very soft and compressible materials of low permeability similar to the Mature Fine Tailings (MFT) of oil sands. This paper presents the results of a testing program in which the SICT is used to determine consolidation properties of an MFT sample. In addition to the SICT, a centrifuge experiment was also used to trigger consolidation of an MFT sample. The centrifuge results were then compared to a numerical model prediction based on the consolidation properties obtained from the SICT.

The presence of residual oil in the sample created some challenges that required special attention during testing and data interpretation. Despite these difficulties the results presented in this paper confirm that under the laboratory conditions, the MFT material behaves like regular soil slurry and undergoes a consolidation process that can be described by a nonlinear finite strain consolidation

theory. Based on the laboratory experimental observations and field evidence, which suggests that the consolidation process might be inhibited under realistic tailings disposal conditions, a hypothesis is suggested that could explain the observed discrepancies. The examination of this hypothesis requires additional testing and consolidation theory modification before a definite conclusion on its validity could be made.

Seepage Induced Consolidation Test

The SICT is an experimental procedure used for determining the consolidation characteristics of soft soils and soil-like materials (slurry mine waste, dredged spoils, sludge from waste water treatment plants etc.) (Abu-Hejleh and Znidarcic, 1996). The testing procedure typically consists of three steps.

In the first step, the void ratio at the effective stress of zero is determined by allowing a slurry column about 0.05 m high to consolidate under its own weight. The average void ratio of the settled slurry is considered the void ratio at an effective stress of zero, or the void ratio at which the soil is formed and the consolidation theory (as opposed to the sedimentation theory) applies. In some cases, like for the MFT sample, the intial void ratio already corresponds to the void ratio at zero effective stress and no appreciable settlement is detected. It should be noted, however, that this consideration is only valid if the transition from settling to consolidation is not hindered in some way within the timeframe of the test procedure.

In the second step, seepage at a constant flow rate is applied through the soil by means of a flow pump and the sample is allowed to consolidate completely, i.e. until the steady state is reached. The steady state is determined from the pressure difference across the sample that is continuously monitored during the test. At steady state, the pressure difference and the final height of the sample are recorded. It is recognized that during this phase of the test the void ratio within the sample is non-uniform and this is correctly accounted for in the test analysis.

In the third step, the sample is consolidated under the maximum desired stress level and the hydraulic conductivity is measured with the flow pump using a low flow rate to maintain sample uniformity during the test. At the end of the test the sample is dried and the total volume of solids is determined.

The analysis of the test is performed using the software package SICTA (Seepage Induced Consolidation Test Analysis) (Abu-Hejleh and Znidarcic, 1994). The procedure is based on the inverse problem solution approach and the theory used is compatible with the finite strain nonlinear consolidation theory (i.e. no simplifying or restrictive assumptions are made in the analysis). The input data for the SICTA program are all obtained from the described test. The output gives five parameters A, B, Z, C and D that define the consolidation properties for the sample. The compressibility and hydraulic conductivity relations with the five parameters are defined as Eq. 1 for compressibility and Eq. 2 for hydraulic conductivity.

$$e = A \, (\sigma' + Z)^B \qquad (1)$$

$$k = C \, e^D \qquad (2)$$

The more detailed description of the testing equipment and testing and analysis procedures can be found in the cited references.

Test Results

The results of two seepage induced consolidation tests are presented in Figures 1 and 2 and the obtianed compressibility and hydraulic conductivity equations are given in Table 1.
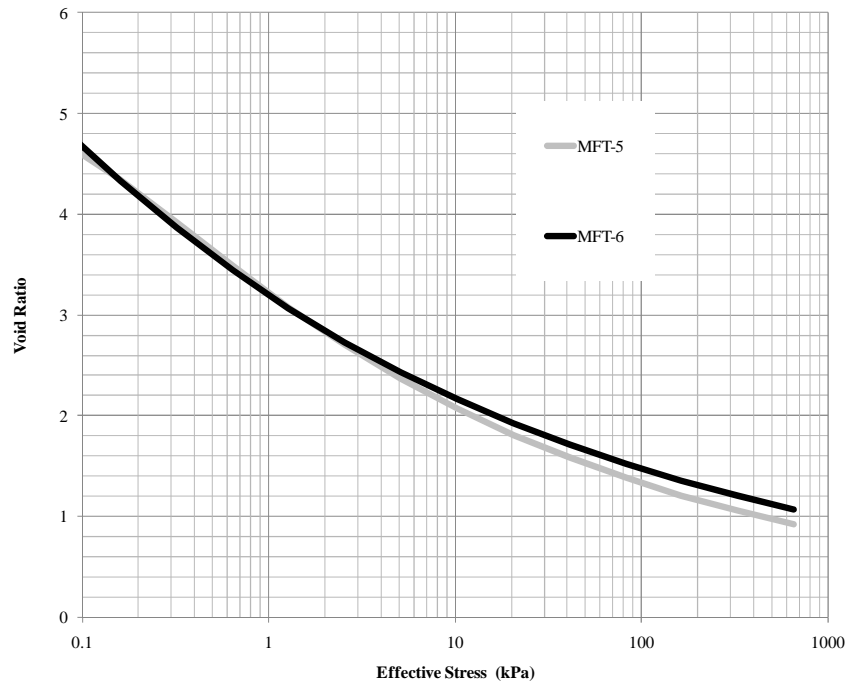
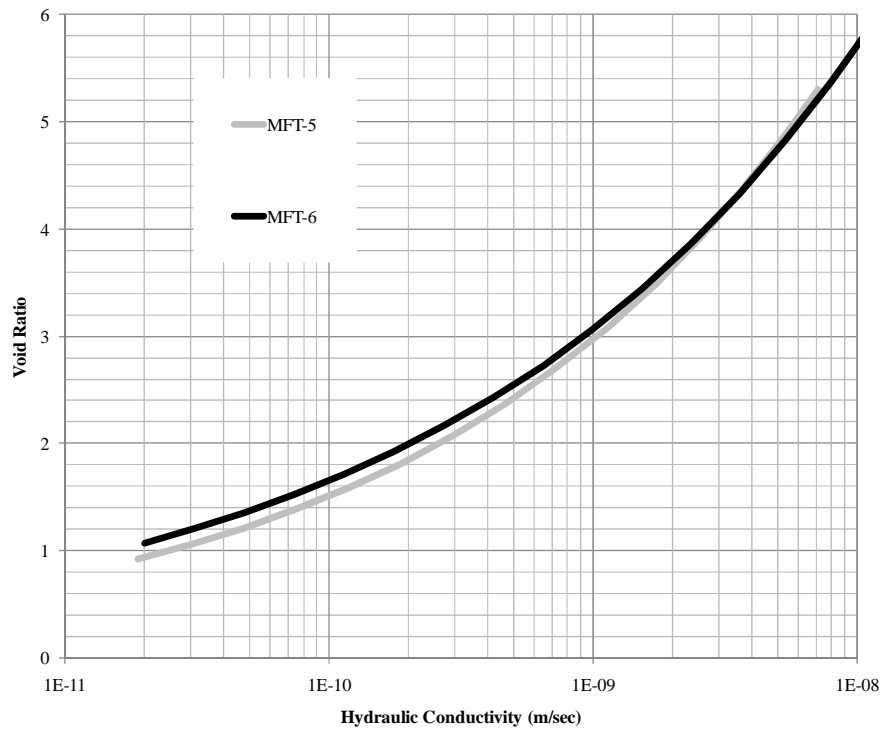**Figure 1:** **Void ratio – effective stress relationship for the MFT sample**

Figure 2: **Void ratio – hydraulic conductivity relationship for the MFT samples**

Table 1: **Compressibility and hydraulic relationships for MFT 5 and 6**

	Compressibility (kPa)	Hydraulic Conductivity (m/sec)
MFT-5	$e = 3.27 \, (\sigma'+0.074)^{-0.195}$	$k = 2.5*10^{-11} \, e^{3.39}$
MFT-6	$e = 3.20 \, (\sigma'+0.007)^{-0.169}$	$k = 1.6*10^{-11} \, e^{3.71}$

The results suggest that the MFT is a highly compressible material with low hydraulic conductivity values even at high void ratios. Such a material exhibits considerable settlements under the self weight of the material and a long consolidation time. For example, a layer of MFT, 5 meters thick, at a starting dry density of 420 kg/m^3 (1264 kg/m^3 total density), would consolidate under its own weight to a final height of 2.7 meters, but it would take over 100 years to reach that state and an initial settlement rate of only 6.5 cm per year. While this is a very slow process that would be difficult to detect over a short period of time, there is some field evidence that in the actual tailing ponds, the process could be even slower or the consolidation process might not even be triggered (Wells, 2011) without additional input. Careful field investigations, accompanied by laboratory testing and detailed analyses, are required to shed more light on the consolidation behaviour of MFT under field conditions.

A centrifuge consolidation test was performed on the same MFT material as tested by the seepage forces in the laboratory. An 82 mm high soil column was subjected to an acceleration level of 45 times the Earth gravity and the induced settlement was recorded by a camera. Figure 3 shows the MFT layer during testing.
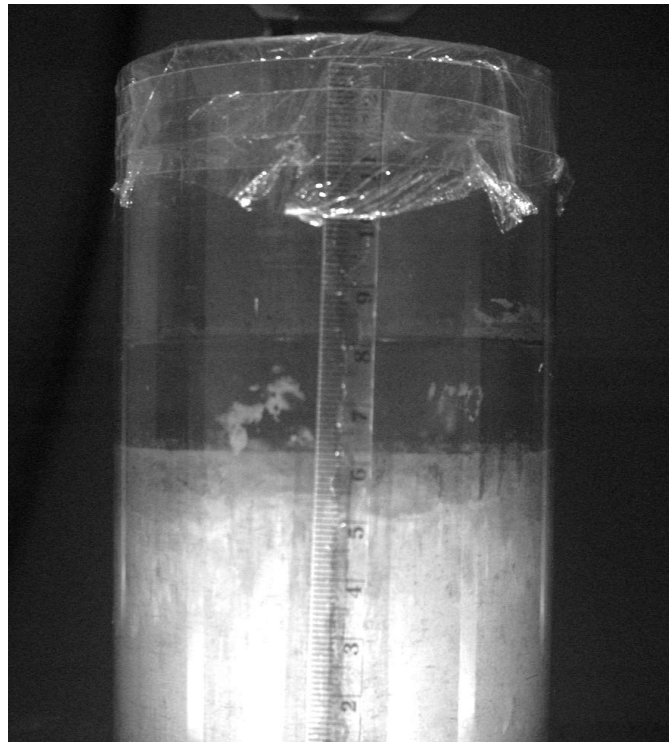

Figure 3: **Void ratio – hydraulic conductivity relationship for the MFT sample**

The recorded settlements with time are presented in Figure 4 and compared to the finite strain consolidation model prediction using the parameters for MFT-6 from Table 1. Figure 5 shows the final void ratio distribution obtained in the experiment compared to the numerical model prediction.
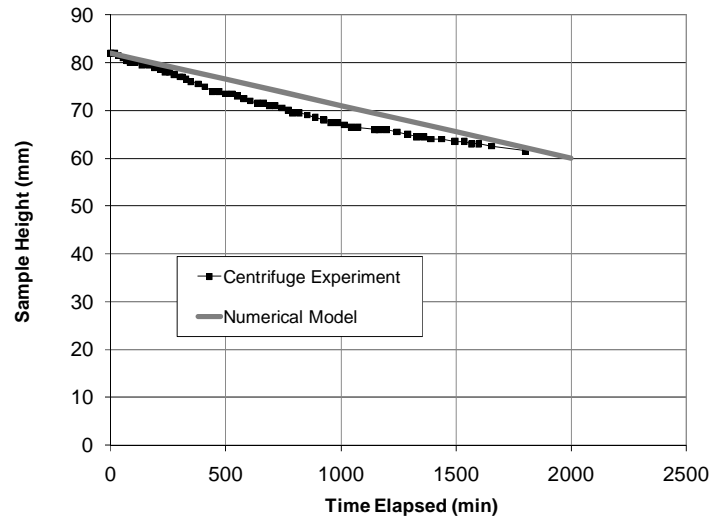

Figure 4: **Centrifuge results comparison to the numerical model prediction**
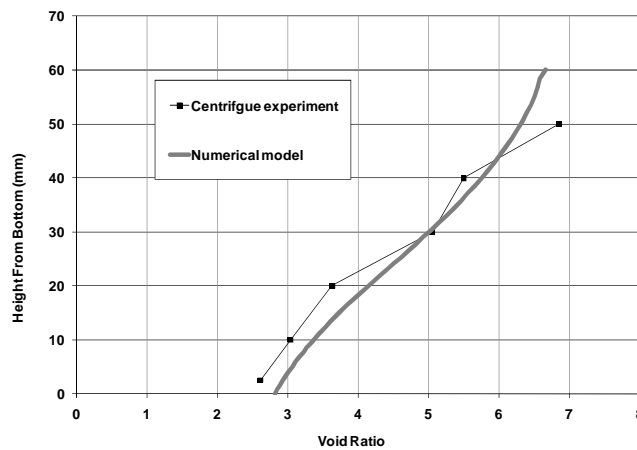

Figure 5: **Centrifuge results comparison to the numerical model prediction**

A general agreement between the experimentally obtained results and the numerical model predictions is noted in both the settlement rate and the final void ratio distribution. These results confirm that the MFT material exhibits usual consolidation behaviour when subjected to the proper flow driving forces in laboratory tests.

Discussion

The results obtained in this testing program clearly demonstrate that the oil sands MFT behave like other slurries and undergo consolidation process when subjected to loading, seepage forces or increased self weight stresses in a centrifuge. The obtained consolidation characteristics indicate extremely low values of hydraulic conductivity and consequently a very slow consolidation process. The material also

poses a significant challenge for testing as it requires long testing time and low flow rates in the SICT. The presence and release of the oil blobs during testing could also affect the obtained results and the tests must be analyzed with great care to make sure that these effects do not invalidate the test results. While there is no doubt in our minds that the MFT readily consolidates under the controlled laboratory conditions there are some questions that need further investigation. Field observations of the MFT behavior appear to suggest that the material doesn't settle as expected based on the consolidation analyses. It is too early to speculate what could explain the apparent discrepancy between the consolidation behavior in the field and laboratory experiments but here we propose a hypothesis that might help explain the phenomenon.

In 1960 Professor Sven Hansbo suggested a concept of the so called "threshold gradient" by which the hydraulic conductivity of a soil will be significantly reduced, or even equal to zero, when the hydraulic gradient is very low (Hansbo, 1960). Other researchers (e.g. Olsen, 1965) disputed this concept and offer an explanation that other driving forces (such as electric, chemical or osmotic potentials) might interfere with hydraulic potential and change the flow velocity of a pore fluid.

Whatever the reason for the deviation, it appears that there is enough evidence to suggest that at low hydraulic gradients the water flow might not be governed by Darcy's Law, or at least that the relationship between the hydraulic gradient and discharge velocity is nonlinear. As the conventional consolidation theories, including the nonlinear finite strain theory, assume the validity of Darcy's Law it is worth exploring if the concept of threshold gradient could explain the apparent discrepancy between the consolidation behavior in the field and laboratory experiments.

In a field situation when MFT are disposed into the tailings disposal facilities an upward hydraulic gradient is created due to the self weight of the material. This gradient is equal to the critical gradient for the material, i.e. to the buoyant unit weight of the slurry divided by the unit weight of water. As a typical disposed MFT has high initial void ratio and a very low buoyant unit weight this initial gradient has very low value (0.23 for the MFT tested in this project) it is conceivable that this gradient is below the threshold value. Wells and Caldwell (2009) present an example where the hydraulic gradient under field conditions is significantly increased over the values due to the self weight of the material only, thus exceeding any possible threshold gradient.

On the other hand the laboratory consolidation experiments, including the SICT and centrifuge test, subject the material to much higher hydraulic gradients that are almost sure to be above any potential threshold value. In other words, the laboratory tests do not subject the slurry to the same driving forces as experienced in the field and thus there is no guarantee that the material will behave similarly in the two diverse conditions. We propose that the threshold gradient concept be thoroughly explored in the continuation of the project and that a suitable experimental procedure be developed that will allow for the determination of the threshold gradient for any MFT. If this hypothesis is experimentally verified, a modified nonlinear finite strain consolidation theory should be developed in order to provide a proper analyses tool for the field condition.

It is noted that the concept of the threshold gradient proposed here is an effort to explain the macro scale behavior of the slurry (for the purpose of field scale modeling), while the cause of its existence could be found at the micro scale. Indeed, it would be the balance of attractive and repulsive forces at the particle level and their interaction with the surrounding fluid that might finally give an explanation why the MFT exhibit the threshold gradient phenomena, while other similar slurries might not.

References:

Abu-Hejleh, A.N. and Znidarcic, D., 1994, Estimation of the Consolidation Constitutive Relations, <u>Computer Methods and Advances in Geomechanics</u>, Siriwardane & Zaman (eds) Balkema, Rotterdam, pp. 499-504.

Abu-Hejleh, A. N. and Znidarcic, D., 1996, Consolidation Characteristics of Phosphatic Clays, <u>Journal of Geotechnical Engineering</u>, ASCE, New-York, Vol. 122, No. 4. pp. 295-301.

Hansbo S., 1960 Consolidation of clay with special reference to influence of vertical sand drains. Swedish Geotechnical Institute;18:45–50.

Olsen HW. Deviation from Darcy's law in saturated clays. Proceedings of Soil Science Society of America 1965;29(2):135–40.

Wells, P.S. and Caldwell, J (2009) Vertical "Wick" Drains and Accelerated Dewatering of Fine Tailings in Oil Sands, Proceedings of Tailings and Mine Waste 2009, Vail, Colorado, Taylor and Francis.

Wells, P.S. (2011) Long Term In-Situ Behavior of Oil Sands Fine Tailings in Suncor's Pond 1A, Proceedings of Tailings and Mine Waste 2011, Vancouver, B.C., UBC Mining Engineering.