SEEPAGE INDUCED CONSOLIDATION TEST: CHARACTERIZATION OF MATURE FINE TAILINGS
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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE
in
The Faculty of Graduate and Postdoctoral Studies
(Mining Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

January 2014

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Abstract

Managing oil sand slurry tailings waste is a significant issue in the oil sands industry and thus accurate characterization of the tailings is required. Conventional soil characterization tests usually involve one or more limiting assumptions such as small strains and constant coefficients of consolidation and hydraulic conductivity. These limitations are significant when testing low density slurries such as dredged soils and mining waste. One unconventional test in particular, the Seepage Induced Consolidation Test (SICT) has been shown to accurately determine compressibility and permeability relations for low density slurries. The SICT was first constructed at the Colorado University (CU) in Boulder, Colorado and has been used for the past two decades to characterize phosphate slurry tailings. Over the last two years a SICT was constructed at the University of British Columbia to provide accurate consolidation characterization of oil sand waste, in particular, mature fine tailings (MFT). Benchmark testing was initially performed on kaolinite clay at the UBC laboratory and results showed the test was repeatable and comparable to results obtained at CU. Test results on MFT at UBC also proved to be in agreement with published data from CU. The use of the SICT helps in the understanding of MFT and the characterization results can be directly used in into large strain consolidation modeling such as CONDES0 1D and SoilVision’s SVOoffice 1D, 2D, and 3D software programs. These and other similar models, which are dependent on the compressibility and permeability relations from the SICT, can be used in the design of waste disposal strategies at every stage of a mining project.
Preface

This thesis outlines the results of an experimental test, namely the Seepage Induced Consolidation Test (SICT), which was constructed and performed by the author, M. Estepho. The results are compared with published data and referenced accordingly. The author initially went to Colorado University (CU) in Boulder to learn from Dr. Znidarčić on the design, construction, and testing of the SICT which was first constructed at CU. The SICT at UBC is modeled after the design from CU but with slight modifications to improve testing and this is discussed in the thesis.

The SICT results on kaolinite clay at the CU laboratory was performed by Dr. Znidarčić and presented to compare with test results done by the author at the UBC laboratory.

Results from the SICT on mature fine tailings and kaolinite clay has been published and was presented at the Tailings and Mine Waste (TMW) 2013 Conference in Banff, Alberta, this November (Estepho, et al., 2013). Parts of section 2.3.3 SICT Procedure are published in the Banff TMW paper as well.
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I offer my sincere gratitude to the staff and students at mining engineering faculty at UBC who have not only helped a great deal in my project but have also had to put up with all the loud commotion that usually occurs during my experimental preparation of large quantities of oil sand waste. I owe particular thanks to my supervisor, Professor Dirk van Zyl, for his continuous work in organizing the project and making sure it was always moving forward.

I would also like to thank Professor Dobroslav Znidarcic for his help in understanding the theory, design, construction and analysis of the SICT experiment. Dobroslav has also taught me a great deal about soil mechanics, especially that of low density slurries and this knowledge has helped tremendously in the experimentation and analysis presented in this dissertation.

I am grateful for Suncor Energy’s sponsorship and funding of this project and without the financial support, the project may not have been pursed. Suncor Energy’s Sean Wells and Adrian Revington have also given me great insights into experimental testing on mature fine tailings and special thanks are owed to them as well.

I am also thankful to the Chemical and Biological Engineering (CHBE) workshop at UBC for providing excellent workmanship in constructing many custom designs in the construction of the SICT.
1 Introduction

1.1 Statement of Problem

The exploration and mining of in the oil sands involves the production of large quantities of low density slurry waste or tailing composed of mixtures of sand, silt, clay and small traces of residue bitumen. About 1.5 barrels of tailings is produced from every barrel bitumen mined (Mikula, 2012). The bulk of the tailings is comprised of fine slurry with solids contents ranging from 30 to 40% and about 4% bitumen by mass and is referred to as mature fine tailings (MFT). In the field the MFT undergoes extremely slow consolidation and may even appear as not consolidating at all (Wells, 2011). Depending on the fines content of the MFT, consolidation times are in the order of magnitude of decades to even centuries. This slow consolidation process is attributed to the very low permeability of the MFT and thus characterization of this material in terms of consolidation and permeability is crucial for the design of mining waste operations. Environmental concerns such as seepage of the toxic tailings water and the eventual reclamation and revegetation of the tailings ponds have also added to the need for furthering the understanding and improving the consolidation behaviour MFT (Scott & Dusseault, 1980).

The seepage induced consolidation test (SICT) was first developed at Colorado University (CU) in Boulder, Colorado and has provided accurate low density slurry characterization for materials such as phosphate tailings (Abu-Hejleh, et al., 1996) and recently, MFT (Znidarčić, et al., 2011). The use of the SICT to accurately provide MFT consolidation characterization gave rise to build another SICT at the University of British Columbia (UBC). The SICT was constructed and several tests have been performed on kaolinite, copper tailings, and mature fine tailings during the calibration process. The SICT at UBC will be used in the coming years to test a wide range of materials such as MFT with various flocculants to provide better understanding about the effectiveness of such products in terms of increasing consolidation and dewatering rates.

1.2 Objectives and Scope of Research

The objectives of the research presented in this thesis are:

- construct an experimental procedure to characterize low density slurries in terms of consolidation, and
- use the test apparatus to investigate the compressibility and permeability relations of MFT.
These objectives are met through the construction of the SICT at UBC. Benchmark testing has been conducted on low density slurries such as kaolinite and copper tailings to help build confidence in the SICT as a viable and accurate test apparatus for measuring the compressibility and permeability relations on selected samples.

The SICT is used in the investigation of MFT provided by Suncor Energy from their South Tailings Pond. The results of the SICT on MFT are compared with MFT of similar particle size distribution from published data.

1.3 Outline of Thesis

The thesis is comprised of 5 chapters and a brief description of each chapter is provided below.

Chapter 2 presents a literature review on topics presented. The formation of MFT is thoroughly discussed based on extraction processes established in the Alberta oil sands deposits. Various types of consolidation tests are reviewed and compared to the SICT at Boulder CU. Large strain consolidation theory is explained and derived to overcome limitations of the small strain theory, which is also discussed. The CU SICT apparatus and procedure as well the accompanying SICT Analysis (SICTA) program is reviewed.

Chapter 3 presents the construction of the SICT at UBC. The design changes and modifications made from the original SICT at CU are presented. A detailed procedure of the SICT as well as best practices for testing is discussed. The author has modified the SICTA program to make it user friendly and reduce time and effort in calculations. It is in the form of a Microsoft Excel document and the procedure for converting the SICTA CU Fortran program to Excel Spreadsheet is described.

Chapter 4 presents the results of SICT on kaolinite, and copper tailings. Testing on kaolinite clay served as benchmark testing to compare with similar testing results from previous tests at CU. The results show comparable and repeatable results and serve to build confidence in the UBC SICT as an accurate tool for measuring compressibility and permeability relations for low density slurries. Testing on copper tailings illustrate the versatility of the SICT for being able to test slurries with high solids content as well as very low solids content for materials such as MFT.

Chapter 5 presents the results of SIC testing on MFT at the UBC laboratory. The experience gained in MFT sample preparation and testing is discussed. A comparison of the results from UBC vs. published data from the CU laboratory is also presented and helps to further understanding the MFT behaviour.
Chapter 6 presents a discussion on the results obtained from chapter 5 for MFT SIC testing at the UBC laboratory. The results are compared to published data, including data from a large strain consolidometer test, and are shown to be in agreement which help build confidence in the SICT at UBC as a reliable technique for determining consolidation characteristics of MFT. The one dimensional large strain consolidation software, CONDES0, is used to predict the settlement with time of experimental data from MFT testing at UBC as well as a large scale MFT pond settlement. The predictions compare well with the MFT data and the results are also presented in this chapter.

Chapter 7 summarizes the use of the SICT in low density slurry consolidation characterization as well as testing results from the UBC laboratory. Conclusions on the findings as well as future testing and recommendations are proposed.
2 Literature Review

This chapter begins with a review of the oil sands industry and the generation of massive amounts of tailings in the form of slowly consolidating, high water content mature fine tailings. The chapter then covers a study of consolidation characterization testing on MFT that have been done in the past and gives reasons for the selection of the SICT as the most promising test for MFT consolidation characterization. The SICT constructed is described as well the analysis involved in obtaining the constitutive parameters determined from the SICT. The SICT analysis includes a discussion on the large strain consolidation theory that is used as well the finite element difference program developed for determining the functions for compressibility and permeability which are calculated from SIC test results.

2.1 Alberta Oil Sands Industry

Internationally 95% of the known in-place accumulations of oil sands occur in Canada, and are predominately found in Alberta. The term ‘oil sands’ refers to the crude bitumen together with the soils and rock materials as well as any other associated minerals other than natural gas. In its natural state crude bitumen is extra heavy oil and does not flow to a well (ERCB, 2013).

The geological formations and geographic areas containing the bitumen are referred to as oil sands areas (OSAs). In the Alberta oil sands, there are three designated OSAs: Athabasca, Peace River and Cold Lake deposits. They occupy an area of 142 000 km² and the known extents of the OSAs as well as select deposits are shown in Figure 2.1. Note that the right hand edge of the figure has township markers which are approximately 50 km apart (ERCB, 2013).

The mining of bitumen began in 1967 by Great Canadian Oil Sands (which later merged with Sun to form Suncor). In 1978 Syncrude followed suit followed by Shell in 2003 which launched the Alberta Oil Sands Project. In 2008, CNRL began its mining operations through the Horizon Project and produced its first barrels of crude bitumen in 2009.
Alberta is a province rich in natural resources and the production of bitumen is, as of 2012, the largest produced energy resource in Alberta. It is also forecast that bitumen production will keep increasing as well as increasing relative to all other energy resources (ERCB, 2013). This trend as well as the current and past production is shown in Figure 2.2.

Figure 2.1 Alberta oil sands areas and select deposits (Modified from ERCB, 2013)

Figure 2.2: Total primary energy production in Alberta (ERCB, 2013)
Table 2.1 shows Alberta’s energy reserves, resources and production at the end of 2012. Reserves are the known energy resource commodities. Resources are the large quantities in the ground where a portion has been or may be recovered as reserves. Production is the actual amount being mined each year (ERCB, 2013).

Table 2.1: Reserves, resources, and production in Alberta (ERCB, 2013)

<table>
<thead>
<tr>
<th></th>
<th>Crude bitumen</th>
<th>Crude oil</th>
<th>Natural gas</th>
<th>Raw coal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(million m³)</td>
<td>(billion barrels)</td>
<td>(million m³)</td>
<td>(billion barrels)</td>
</tr>
<tr>
<td>Initial in-place resources</td>
<td>293 125</td>
<td>1 845</td>
<td>12 026</td>
<td>75.7</td>
</tr>
<tr>
<td>Initial established reserves</td>
<td>28 092</td>
<td>177</td>
<td>2 922</td>
<td>18.4</td>
</tr>
<tr>
<td>Cumulative production</td>
<td>1 406</td>
<td>8.8</td>
<td>2 653</td>
<td>16.7 4</td>
</tr>
<tr>
<td>Remaining established reserves</td>
<td>26 686</td>
<td>168</td>
<td>269</td>
<td>1.7</td>
</tr>
<tr>
<td>Annual production</td>
<td>112</td>
<td>0.705</td>
<td>32.3</td>
<td>0.203</td>
</tr>
<tr>
<td>Ultimate potential (recoverable)</td>
<td>50 000</td>
<td>315</td>
<td>3 130</td>
<td>19.7 6</td>
</tr>
<tr>
<td>Shale/siltstone initial in-place resources</td>
<td>67 320</td>
<td>423.6</td>
<td>96 461</td>
<td>3 424</td>
</tr>
</tbody>
</table>

a Expressed as “as is” gas, except for annual production, which is 37.4 megajoules per cubic metre; includes coalbed methane.
b Measured at field gate.
c Annual production is marketable.
d Does not include unconventional natural gas.
e Values based on the medium estimate and include only unconventional deposits; no assumption about recoverability was made in determining these resource estimates.

In 2012, bitumen production accounted for 78 % of Alberta’s total crude oil and bitumen production increased by 10% from 2011. From Table 2.1, the total remaining established reserves for crude bitumen (in situ and mineable) is 26.7 billion m³. This correlates to 95% still remaining of the initial 28.1 billion m³ reserves since production in 1967.

In 2004, bitumen production exceeded conventional crude oil for the first time and has continued this trend to the present time. Figure 2.3 shows remaining reserves for bitumen and conventional crude oil as well as the production of both in 2012.
The decline as well as the estimated decline of conventional oil production will be offset by the increase in bitumen production. This will help ensure that Alberta is still the leading energy producer in Canada. The downside of the increased bitumen mining is the production of large amounts of tailings of which most is in the form of a slowly consolidating slurry known as mature fine tailings.

2.1.1 Bitumen Extraction Process

In the oil sands deposits there is a presence of discontinuous interbedded clay-shale seams and layers which are not separated during the mining extraction process. The clay-shale layers are dense but weak and broken up during the mining process while larger and harder pieces are screened out. The clay-shale pieces are further broken down in the bitumen extraction process and are the main source for fines being present and dispersed throughout the mature fine tailings (Scott, et al., 2013).

The extraction of bitumen from the oil sands requires that all the ore components (bitumen, sand, water film, and clay) are disintegrated. Figure 2.4 shows the in situ composition of an oil sand and it is important to note that most of the fines contained in the oil sand are found in the surrounding water film or sheath which contains the bitumen. It is has been determined that the use of hot water combined with caustic soda (or NaOH) provides for the optimal conditions for the swelling of the clay particles inside the film, which eventually disintegrates the oil sand structure (Chalaturnyk, et al., 2002).
Dr. Karl A. Clark’s caustic (NaOH) hot water extraction process patented in 1929 led to the development of commercial extraction hot water process (HWP) plants for all oil sands mining operations in Alberta. The HWP, also referred to as the Clark Process, allows for over 90% bitumen recovery at a temperature of 85 °C and a pH of 8.5. The use of NaOH increases the pH of the oil sands mixture causing the asphalitic acids present in bitumen to become water-soluble through the lowering of the surface and interfacial
surface tension, thus acting as surfactants. This results in ore disintegration and allows for bitumen recovery (Chalaturnyk, et al., 2002).

A typical HWP is shown in Figure 2.5. Oil sand ore is first slurried with caustic (NaOH) water in rotating drums at 60 to 70 % solid content (i.e. ratio of mass of solids (including bitumen) to total mass) while maintaining a temperature of 80 to 85 °C and a pH of 8.0 to 8.5. Typical caustic NaOH usage rates are 0.11 kg per ton of oil sands for Syncrude and 0.04 kg at Suncor, which reflects the higher grade of Suncor’s ore (McKinnon & Sethi, 1993). The slurried pulp is then transported to primary separation cells where the air trapped in the bitumen form froth and floats to the top. The oil rich froth is then skimmed from the top and pumped first to froth settlers or deaeration plants before heading to a solvent extraction plant. In the primary separation cell, the coarser solids settle down to the bottom and form part of the tailings stream.

Figure 2.5: Clark Process for bitumen extraction (Chalaturnyk, et al., 2002)

The intermediate stream, which is known as middlings, consists of non-buoyant bitumen and fine solids and is pumped out of the primary separation cell for further processing to the secondary separation cells. The secondary separation cells are large size air flotation units which helps raise the non-buoyant bitumen in the form of froth but which is high in water and minerals. The froth from the secondary separation cell is pumped to the froth settlers and combined with the froth from the primary separation cell. The dense fraction of the secondary separation cell is discharged and combined with the tailings stream either before or after being first sent to tailings oil recovery (TOR) units.
The whole tailings are moved to tailings disposal areas where the sand particles sediment close to the deposition point and the overlying water and fines are collected in a thin fine tails (TFT) pond. The TFT pond has a solids content of about 10% by weight. Slurry from the TFT pond is then kept in place or transferred to settling ponds where they settled out quickly for 2 to 3 years before they reached solids content of 30 to 40 % in which consolidation is very slow. At this point the slurry is referred to as mature fine tailings (MFT) and make up the bulk of the tailings. Most of the MFT is left to consolidate due to self weight for economic reasons and consolidation could take centuries (Pollock, 1988).

The area of Vancouver is 114.67 km² (NationMaster - Encyclopedia, 2003) which is 50% less than the 176 km² area occupied by tailings ponds as of 2010 (Alberta Environment & Water, 2010). The production of MFT is a large problem both economically and environmentally which paved the way for stringent government regulations on tailings management including the implementation of Directive 074.

2.1.2 Directive 074

In 2009 the Energy Resources Conservation Board (ERCB) implemented Directive 074 which set out guidelines for tailings management and reclamation timelines that all oil sands operators must abide by (ERCB, 2009). The ERCB regulates oil sands mining, processing, and waste (including tailings) operations and operators must get ERCB approval to commence, suspend or abandon an oil sands site as well as approval for waste generation. Key objectives in directive 074 involve minimizing long-term storage of fluid tailing, minimizing fresh water use, and to create a trafficable landscape from the tailings to facilitate reclamation. Specific criteria that operators must follow include:

- fluid tailings must have a minimum of 5 kPa undrained shear strength after one year of disposal
- ready for reclamation within 5 years after active deposition has ceased in which the surface is trafficable and must have a minimum undrained shear strength of 10 kPa

These stringent criteria require that oil sands operators invest more into MFT dewatering technologies as well as the need for proper characterization in terms of consolidation and permeability which are required in predicting settlement and shear strength increase with time.

2.1.2.1 Thixotropy of MFT

Mature fine tailings are thixotropic in nature which results in very slow consolidation times. Thixotropy is defined as “an isothermal, reversible, time-dependent process occurring under conditions of constant composition and volume whereby material stiffens while at rest and softens or liquefies upon
remoulding” (Mitchell & Soga, 2005). When MFT is allowed to remain undisturbed it forms a moderate gel of thixotropic strength. In order for the MFT to form a gel structure, Kessick (1979) concluded that three conditions be met:

1) Residual bitumen must be present
2) A clay-bound organic component must also be present to confer surface activity on the clay particles
3) The clay particles must be well dispersed initially in order that they can take part in subsequent structure formation

These three conditions are met by MFT and thixotropy is observed and causes an increased effective stress without lowering the void ratio, hindering consolidation. Residual bitumen is present in MFT usually at 1% by weight. Burchfield and Hepler (1979) have shown that clay-bound organic material does exist in MFT and are in part carboxylic acids. The third condition is met through the hot water bitumen extraction process which disperses the fine clay material thoroughly.

2.1.3 MFT Mineralogy
The amount of fines in soil is defined as minerals that pass through a 44 microns sieve (No. 325 sieve). Mature fine tailings consist mostly of fines materials with some MFT samples having higher than 95% fines, of which most are clay minerals. The clay fraction is made up of predominantly kaolinite and illite but with a small amount of illite-smectite, kaolinite-smectite and traces of chlorite and montmorillonite (Omotoso, et al., 2002). Figure 2.6 shows a pie chart of the average properties of the clay minerals in MFT.
2.2 Limitations of Conventional Consolidation Testing

The conventional oedometer test involves applying constant loads to a soil sample and measuring the resulting settlement with time. This allows for the compressibility or void ratio vs. effective stress to be determined. The permeability or void ratio vs. hydraulic conductivity is then calculated using the small strain consolidation theory. The small strain consolidation theory was first proposed by Terzaghi in 1923 (Clayton, et al., 1995) and relies on the following 8 assumptions:

1. The voids are filled with water (i.e. degree of saturation is 100%)
2. Darcy’s law is valid
3. No lateral strain (considered an infinitely wide layer and hence laterally confined)
4. Compressibility is not time dependent (i.e. no secondary consolidation)
5. Incompressible solid and water particles
6. Infinitesimal or small strain
7. Ignores self weight effects
8. Constant permeability and compressibility relations (i.e. constant k and a_v)

The governing equation for one dimensional small strain consolidation that Terzaghi derived (while using the above assumptions) is:

\[ c_v \frac{\partial^2 u_e}{\partial x^2} = \frac{\partial u_e}{\partial t} \]  

(2.1)

where \( u_e \) is the excess pore water pressure, \( x \) is the depth of a soil element, \( t \) is the elapsed time, and \( c_v \) is the coefficient of consolidation and is formulated as follows:
where $k$ is the coefficient of hydraulic conductivity (permeability), $e_i$ is the initial void ratio of the element, $\gamma_w$ is the unit weight of water, and $a_v$ is the coefficient of compressibility and is defined as:

$$a_v = \frac{de}{d\sigma'}$$

where $e$ is the void ratio and $\sigma'$ is the vertical effective stress.

Equation (2.1) links the change in excess pore pressure at any depth, $x$, in a soil layer to the dissipation of the excess pore pressure with time, $t$. By measuring the rate at which water was squeezed out of a clay layer, Terzaghi used this governing equation to determine the permeability of that clay layer.

Low density slurries such as MFT undergo large strains, consolidating significantly due to self weight, and have highly non-linear permeability and compressibility relations. This makes the standard oedometer not applicable for such materials. Modifications to the standard oedometer test have been proposed including the Slurry Consolidometer which does account for large strains, self weight effects, and non-linear compressibility and permeability relations.

### 2.2.1 Large Strain Slurry Consolidometer

Pollock (1988), Suthaker (1995), and Jerravipoolvarn (2005) have all provided experimental test results on MFT using a slurry consolidometer. This test is very similar to a standard oedometer test in that a step loading scheme is employed and the settlement is measured with time. The difference lies in the ability to measure permeability directly through the use of a constant head test (CHT). In the CHT, a known pressure head or gradient is applied to the slurry sample and the flow rate across the sample is measured. Knowing the surface area of the sample ($A$), the flow rate of the sample ($\Delta V/t$) (where $\Delta V$ is the volume of flow and $t$ is the time interval), then the hydraulic conductivity ($k$) can be calculated by rearranging Darcy’s Law as shown in equation (2.4). The hydraulic gradient, $i$, is the equal to the head difference ($\Delta h$ divided by the height of the sample).

$$k = \frac{\Delta V}{iAt}$$

### 2.2.1.1 Limitations of the Slurry Consolidometer

The main limitation of the slurry consolidometer is the length of time it takes to complete a test. The tests from Pollock (1988), Suthaker (1995), and Jeeravipoolvarn (2005) had completion times between one to two years. This is due to the extremely slow consolidation behaviour of MFT which requires that
step loading be slowly increased to avoid significantly disturbing the MFT. The sample sizes used in above mentioned tests ranged from 200 to 300 mm in diameter. The effective stresses for the slurry consolidometer range from less than 1 kPa to above 200 kPa. The lower effective stresses are limited by the accuracy in measuring very small flow rates for permeability measurements. The higher effective stresses are limited, in addition to the very small flow rate measurements, to the time required for consolidating the low permeable MFT to those higher stresses.

Another issue with the slurry consolidometer is in minimizing consolidation effects during the constant head test (CHT) in determining permeability. The CHT is applied once the MFT sample has consolidated due to an applied load (which can take months). A constant head difference is applied across the sample in which the flow of water is upwards through the sample. The presence of water moving through the sample causes seepage forces and consolidation will occur when these forces are greater than the previous highest stress achieved.

To overcome this problem, the applied load is clamped in place prior to the permeability test and a gradient is then applied during the CHT such that it is equivalent to that specific applied load. During this process the effective stress on the sample is essentially lowered and then raised due to the seepage forces. In obtaining the permeability through the CHT test, the known gradient is imposed and the flow of water across the sample is measured with a stopwatch and applying Equation (2.4) above to determine the coefficient of hydraulic conductivity. But MFT behaves such that the permeability is a function with time and thus the CHT must be repeated until a constant permeability value is reached. A single CHT can take minutes to hours thus repeating the process for each permeability data point is time consuming.

Although the slurry consolidometer provides direct measurement of the consolidation and permeability of MFT, several other testing procedures have been proposed to shorten completion times and are explained in Section 2.2.2 below.

2.2.2 Alternative Consolidation Testing
In this section several consolidation techniques are discussed that have been proposed to lower completion times and improve upon the slurry consolidometer in terms of determining compressibility and/or permeability relations.
2.2.2.1 **Constant Rate of Deformation Test**
The constant rate of deformation test (CRD) involves a feedback system to control the loading rate to ensure that the soil sample deforms at a constant rate and is used to determine the permeability relationship of the slurry sample (Lee, 1981). The assumptions in the CRD test are that only small strains occur, the coefficient of consolidation is constant, and that an assumption of the void ratio distribution of the soil sample or void ratio with time must be made. These assumptions are too restricting for slurry like materials and neither of the void ratio assumptions can be validated (Znidarčić, et al., 1984).

2.2.2.2 **Constant Hydraulic Gradient Test**
The constant hydraulic gradient test (CHG) was developed by Lowe (1969) and is a method for determining the permeability of a slurry sample. The CHG is similar to the CRD except that the feedback system is used to control the loading rate such that there is a constant gradient across the sample. This test requires the assumptions of small strain, constant permeability, a linear compressibility relationship and a constant void ratio across the sample, thus it is not applicable to low density slurries (Znidarčić, et al., 1984).

2.2.2.3 **Constant Rate of Loading Test**
The constant rate of loading test (CRL) was performed by Aboshi et al (1971) to determine the permeability relation of low density slurries and is restricted by similar assumptions as the CRD and CHG tests and thus not applicable for testing low density slurries that undergo large strains (Znidarčić, et al., 1984).

2.2.2.4 **Inter-connected Test**
Imai and Tang (1992) proposed an inter-connected test to measure consolidation properties of sub-specimens at different loading conditions at the same time. In this test, several thin soil sub-specimens are placed in separate consolidometers and loaded to different loads while water seeps out through them in succession. During the test, a pressure transducer and a displacement transformer measure the pore pressure and settlement, respectively, of each specimen. The permeability and compressibility are calculated from the pore pressure, settlement, and water flow velocities measured from each of the sub-specimens. The test is relatively more complex to setup than the SICT (which will be discussed in section 2.3) and is not able to provide measured consolidation data at low effective stresses (<10 kPa).
2.2.2.5  Desktop Centrifuge Test

Reid and Fourie (2012) presented results from a desktop centrifuge test on kaolinite clay slurry in terms of compressibility and permeability, which were obtained in a matter of days. Limitations to the test are that it requires approximating centripetal forces, slicing the soil sample to determine water contents, and indirectly obtaining the permeability through an iterative numerical model to match measured pore water pressure dissipations. The test does look promising since centripetal forces can rapidly increase consolidation times and testing on MFT should be performed and compared with the slurry consolidometer and the SICT. The author is not aware of any desktop centrifuge tests performed on MFT.

2.2.2.6  Seepage Test

A consolidation test using seepage force procedure was developed by Imai (1979). The test works by applying a constant head difference across a soil sample which consolidates the sample. The fundamental concept of this test is that seepage or flow through the sample imposes a seepage force that gets converted to effective consolidation stress (see section 2.3.1). When steady state conditions are obtained the effective stresses and pore pressures are measured across the sample and the sample is cut into slices to obtain water contents and hence void ratio distribution across the sample. Since the flow rate is known from the constant head difference, the permeability and compressibility functions are measured directly.

This test does not use any consolidation theory thus it serves as a direct measurement of soil properties. One issue with the test is that since the slices of the sample are cut, there will be some rebound which will give higher measured values than the actual steady state values (Znidarčič, et al., 1984). Also, this test is limited in determining a proper stress range that effectively encompasses the behaviour of the material as well as a high enough stress range to minimize disturbance to the sample when cutting it into slices. Znidarcic et al (1984) stated that using seepage forces to obtain the steady state condition can be used as the basis for back-calculating the consolidation properties of the soil sample. The SICT, as will be discussed further, does in fact use the seepage test as the basis for back-calculating the permeability and compressibility curves (see section 2.3).

2.2.2.7  Flow Pump Test

Olsen (1966) first proposed the use of a syringe pump to impose small known gradients on saturated kaolinite clay in determining permeabilities. He used it to show that Darcy's law is obeyed even at low gradients in saturated kaolinite over a wide range of porosities. Olsen et al (1985) conducted further
testing using the flow pump method on a variety of sand, sandy silt and silty clay slurries and compared it with the conventional CHT and the falling head test (FHT). The FHT is another method for determining permeability in which an imposed hydraulic gradient changes continuously with time. In the 1985 study, the use of the flow pump showed improvements over the conventional methods in that the direct measurement of flow rates is avoided. Since the flow pump imposes a known flow rate, the accuracy in the determined flow rates relies on the accuracy of the flow pump. This overcomes errors rising from contaminants on capillary menisci as well as the long length of time involved in direct flow rate measurements. The gradients that can be used in the flow pump are also significantly smaller than the CHT or the FHT which allows for obtaining permeability measurements much more rapidly (Olsen, et al., 1985).

For very low density slurries, such as MFT, flow pumps are required to accurately impose very small gradients to minimize disturbance to the sample and thus they have been avoided due to the lack of very sensitive flow pumps (Olsen, et al., 1985). Aiban and Znidarcic (1989) performed permeability testing on coarse and very fine materials using a very sensitive flow pump and compared the results with the widely used conventional constant head test (CHT). The results were very similar under similar conditions for both test types. It is this flow pump developed by Aiban and Znidarcic that serves as the basis for the construction of the SICT first at CU by Znidarčić et al (1992) and by the author as outlined in section 3.

2.3 Seepage Induced Consolidation Test at CU

In 1991, the Florida Institute of Phosphate Research (FIPR) awarded a research grant to the University of Colorado (CU) to develop a rapid technique for determining compressibility and permeability parameters for phosphatic clays (Znidarčić, et al., 1992). The test developed was the seepage induced consolidation test (SICT) which built upon the principles of seepage force developed by Imai (1979) and the flow pump test first proposed by Olsen (1966). The SICT allows for the direct measurement of compressibility and permeability of low density slurries without the need for any limiting assumption required in conventional testing that rely on small strain consolidation theory. For high void ratio phosphatic clays the SICT has the following advantages over conventional testing techniques (Znidarčić, et al., 1992):
1. Permeability determination can be done in a span of days which allows for substantial savings in time and effort versus alternative methods that take weeks or even months in obtaining the same experimental data.
2. All data acquisition and processing is performed by a computer.
3. Accurate consolidation data may be obtained.
4. The SICT is relatively inexpensive to mining operations.

The SICT has produced accurate and reliable results for slurries such as phosphate and kaolinite clays, as well as dredged materials. Znidarcic (2011) preformed SIC testing on an MFT sample and determined compressibility and permeability relations which are similar to the test results performed by slurry consolidometers Pollock (1988), Suthaker (1995), and Jeeravipoolvarn (2005). The SICT had completion times of one to two months as opposed to one to two years for the slurry consolidometers tests.

2.3.1 Principle of Seepage Force as Consolidation Effective Stress
The concept of using seepage force to consolidate soil is taken from the development of the seepage test by Imai (1979). Conventional oedometer tests consolidate soil by applying loads on top of the sample and are referred to as “surface loading”. Consolidation via seepage forces involves imposing a pressure head difference across the sample in which every element of the soil sample is consolidated. This is referred to as consolidation by a “body force” (Imai, 1979). The fundamental ideas of consolidation due to seepage forces, also referred to as hydraulic consolidation, can be seen in Figure 2.7.
When a soil sample has a constant head difference imposed on it, as shown in Figure 2.7 (a), water will flow across the sample from the higher pressure to the lower pressure and consolidate every element of the soil sample. When consolidation is complete due to any specific water head difference, a steady water flow will be achieved and referred to as the steady state condition. At this steady state condition water head will vary with depth and thus so will the effective stresses and the water content as shown Figure 2.7 (b). From Figure 2.7 (b) the water pressure head shows a parabolic curve because for low density slurries there is a void ratio gradient across the sample. Thus at the higher end of the sample the density is less than at the bottom thus the water pressure head difference has little change at the top but shows a larger difference at the bottom.

In order to fully understand the mechanism controlling consolidation by seepage force, it is necessary to understand how the seepage force is converted into effective stress. Figure 2.8 illustrates a soil element subjected to a seepage force and the resulting stress states at elevations $z$ and $z + dz$. 

**Figure 2.7: Fundamental ideas of hydraulic consolidation (Modified from Imai, 1979)**

(a) Water flow caused by a constant water head difference consolidates the specimen prepared form dredged fluid mud by sedimentation

(b) Water head distribution throughout the system at steady state
The total stress difference between the elevation $z$ and $z + dz$ of the element is only a function of the total weight of the sample and thus equals the unit weight of the element, $\gamma_t$, multiplied by the height increment $dz$:

$$
\Delta \sigma = \gamma_t dz
$$

(2.5)

Applying the principle of effective stress, the change in effective stress, $\Delta \sigma'$, is given as:

$$
\Delta \sigma' = \Delta \sigma - \Delta u = \gamma_t dz - \Delta u
$$

(2.6)

where $\Delta u$ is the total change in water pressure. But because there is a seepage flow the water pressure head difference is given by:

$$
\Delta h = \frac{\Delta u - \Delta u_s}{\gamma_w} = \frac{\Delta u - \gamma_w \cdot dz}{\gamma_w}
$$

(2.7)

where $\Delta u_s$ is the hydrostatic water pressure and $\gamma_w$ is the unit weight of water. When combining equations (2.5) and (2.6) the following fundamental equation is obtained:
where $\gamma'$ is the buoyant unit weight of the element and is equal to $(\gamma_t - \gamma_w)$. From equation (2.8), it should be noted that if there was no flow of water through the element then it would be considered hydrostatic then the term $dh/dz$ would be zero. Thus the seepage force can be defined as the first term in equation (2.8) and it is defined in terms of the force per unit soil volume, $j$, as shown below:

$$ j = -\gamma_w \frac{dh}{dz} = \gamma_w i $$

where $i$ is the hydraulic gradient and is defined as $-dh/dz$. Thus equation (2.8) can be written as:

$$ \frac{d\sigma'}{dz} = j + \gamma' $$

This means that the rate of change of effective stress on an element with depth is caused by the seepage force and the buoyant weight. Thus equation (2.10) states that the seepage force, as well as the buoyant weight, is converted to effective stress (Imai, 1979).

### 2.3.2 SICT at CU Test Apparatus

A schematic of the SICT at CU is shown in Figure 2.9 and it consists of:

- Triaxial cell and soil sample placement apparatus
- Flow pump to remove water from sample
- Water flow tubing system
- Step loading system
- LVDT to measure settlement during step loading
- Pressure transducer to continuously measure pore water pressure difference
- Sample and Refill Valves
- Data acquisition system
Figure 2.9 SICT Overall Diagram at CU
2.3.2.1 Triaxial Cell and Soil Sample Placement Apparatus

In the SICT the soil sample is placed inside a triaxial cell which is modified to allow seepage due to a flow pump through the use of a custom acrylic pedestal, casing and compression piston. The SICT at CU allows for testing on samples of three inches in diameter.

A schematic of the sample pedestal is shown in Figure 2.10. The pedestal has ports drilled into it to mount it to the triaxial cell and for connecting the tubes which allow for seepage due to the flow pump. The top of the pedestal is designed to ensure that water flowing through the sample is distributed throughout the entire sample cross sectional area. An O-ring is installed in the midsection of the pedestal to ensure that the sample is water tight once the outer casing is installed.

![Figure 2.10: Schematic of Sample Pedestal at CU](image)

The soil sample is encased in an acrylic cylinder of three inches in diameter and six inches in height which also houses a piston that is places on top of the soil sample (see Figure 2.11). This cylinder is placed directly on top of the pedestal and serves as a rigid boundary for the slurry sample.
A schematic of the top of the acrylic compression system is shown in Figure 2.12. It has holes drilled through it to allow drainage from the top of the slurry once it is placed in it. When the triaxial cell is filled with water, the piston has a very small buoyant weight and serves to ensure uniform settlement of the soil sample. The buoyant weight corresponds to 0.1 kPa and the load is applied from the beginning of the test to prevent flow channels from occurring during seepage induced consolidation as well as for uniformly loading the sample during the step loading phase (Znidarčič, et al., 1992).
2.3.2.2 Flow Pump

The main advantage of the SICT is that a low velocity flow pump is included which induces very small gradients across the soil sample to ensure minimal disturbance to the soil sample. With materials such as mature fine tailings (MFT), even very small disturbances may cause results to be unreliable. The SICT at CU (Znidarčič, et al., 1992) uses a flow pump that can produce flow rates as low as $4 \times 10^{-5}$ mL/second which is the equivalent of about $5 \times 10^{-9}$ m/sec through a sample of 3 inches in diameter. This flow velocity across the sample is referred to as the Darcian velocity and the low velocities provided with this pump make it ideal for low density slurries. The flow pump was custom built by the University of Colorado in Boulder (CU). The flow pump has a driving system or piston which is driven downwards forcing water to flow from the sample. The driving system is the Harvard Apparatus syringe Pump Model 909 and the technical details and specifications are given in the manufacturer’s literature that is provided with the pump.

A drawback of the flow pump at CU is that it is not capable of measuring the current piston position. Instead, the computer which is collecting the flow pump data calculates what the piston position is based on the specified pump flow velocity. This causes problems whenever the flow pump is either disturbed or there is some sort of electrical interference causing a brief stoppage in data collection. When this happens, the current piston position is different from the calculated position and needs to be reset by raising the piston back to its starting position and continuing from there. This problem is overcome in the SICT constructed at UBC through the use of a digital encoder to continuously monitor the pump piston position.

2.3.2.3 Water Flow Tubing System

The soil sample in the current SICT is fully pressurized by using a bucket of water raised to a sufficient height above the triaxial cell. This water pressure allows for the constant and steady flow of water through the sample via the flow pump. It is important to note that the initial design of the SICT (Znidarčič, et al., 1992) utilized an air pressure control system to pressurize the water flow lines. From experience it has been found that the air pressure would cause data readings to fluctuate due to any electrical interference that may occur. This was mitigated by entirely removing the air pressure control and to simply use a bucket of water at a sufficient height above the triaxial cell. Since the gradients imposed on the soil sample are very small a large surrounding water pressure is not required.
Referring to Figure 2.9, a water flow tube is connected from the bucket of water and flows downwards to the flow pump as well as the triaxial cell. The bucket of water serves to also refill the flow pump with water when it is reset to its starting position.

2.3.2.4 Step Loading System
The loading system at the SICT in CU consists of a simple frame and a Bellofram air cylinder which provides load on the sample. The air cylinder has a nominal area of 9 in² and is controlled via the computer. The step-loading phase is used once the seepage induced consolidation phase is complete and loads of 10 to 160 kPa can be used during this phase.

2.3.2.5 Linear Variable Differential Transformer (LVDT)
The SICT at CU has a linear variable differential transformer (LVDT) which is used to measure the sample height at steady state during the seepage induced phase as well as settlement throughout the step loading phase. It is important to note that the LVDT is a recent addition to the manual dial gauge which was used in the original SICT (Znidarčić, et al., 1992). The SICT at UBC has an LVDT similar to the one at CU but it is installed directly on the triaxial cap and can measure sample settlement throughout the whole test including the seepage induced consolidation phase.

2.3.2.6 Differential Pressure Transducer
The SICT at CU uses a Validyne Model DP215 differential pressure transducer to measure pore water pressure differences across the top and bottom of the soil sample (Znidarčić, et al., 1992). The pressure transducers has a replaceable diaphragm which allows for changing the range of pressures to measure and has a maximum pressure range of 35 kPa. The pressure transducer has on side of the diaphragm connected to the bottom of triaxial cell with a tube and at the other side of the diaphragm a tube is connected to the triaxial cell outside of the soil sample casing. The bottom of the triaxial cell corresponds to the pressure at the bottom of the soil sample and the other tube corresponds to the overall water pressure from raised water bucket or the pore pressure at the top of the soil sample. The difference between these two pressures is an accurate estimation of the pore pressure difference across the soil sample.

2.3.2.7 Sample and Refill Valves
The sample and refill valves are computer-controlled valves that control the flow of the water throughout the SICT (see Figure 2.9). When both valves are open then the triaxial cell, soil sample, and flow pump are fully pressurized from the raised bucket of water. When only the sample valve is open,
then the triaxial cell is only pressurized from the water bucket while the bottom of the soil sample does not experience this water pressure. This condition is during seepage tests when water is pumped from the soil sample to the flow pump in order to induce consolidation or measure permeability. When only the refill valve is opened, then the flow pump and the triaxial cell are pressurized from the water bucket. This condition is used when the flow pump has pumped out its maximum water before being reset via filling the inner pump chamber with water from the raised water bucket.

2.3.2.8 Data Acquisition System

A data acquisition system is used in the SICT at CU to automatically record data continuously from the following equipment:

- Flow pump
- LVDT
- Pressure Transducer
- Air pressure step loading apparatus
- Refill and sample valves

The data acquisition system consists of a Dell 333P computer with a VGA color monitor and the Validyne UPC601-L interface card mounted within the computer (Znidarčič, et al., 1992). Recent changes to the data acquisition software have been made to the SICT at CU in which the Easy Sense software from Validyne Engineering Corporation is replaced with more visual and user friendly National Instruments LabVIEW visual programming development program. LabVIEW is fully customizable and has a short learning curve for first time programmers due to the visual programming aspect of it. LabVIEW allows for a digital recording and visual presentation of the SICT data in terms of soil flow pump position, LVDT and pressure transducer readings, step load readings, and the state of the refill and sample valves. Other measurements such as current time and transducer temperature can also be programmed for continuous recording. The use of LabVIEW as the user interface to the SICT equipment has helped in selecting components in the design of the SICT at UBC due to the flexibility and ease of incorporating many different physical apparatus that LabVIEW allows for.

2.3.3 SICT General Procedure

This section presents the general procedure of the SICT. For a detailed procedure, and since the SICT at CU and UBC are very similar, refer to Appendix E for the procedure on testing at UBC.
The test involves a three step procedure:

1. Determine void ratio at zero effective stress, $e_0$
2. Measure sample height to obtain compressibility and permeability characteristics at low effective stress range (< 1 kPa)
3. Measure sample height to obtain permeability at high effective stress range (> 150 kPa) and a low average void ratio

In the first step, $e_0$ is defined as the average void ratio of a short column of slurry which is allowed to settle due to self weight in which the effective stress is near zero, or the void ratio when the soil is formed and the consolidation theory (as opposed to the sedimentation theory) applies (Znidarcic, et al., 2011). This step is discussed in detail in section 2.4.3.

In the second step, the soil sample is placed inside the modified triaxial cell and allowed to settle due to self-weight and a small buoyant weight (about 0.10 kPa). The buoyant weight consists of a loading piston and a Linear Variable Differential Transformer (LVDT) rod. Once the sample stops settling, a small flow rate is imposed on the sample with the flow pump to trigger the consolidation process using seepage forces. Steady state settlement and pore pressure measurements are recorded in this phase of the test.

In the third step, the soil sample is consolidated to a desired maximum pressure using step loading on the loading piston, usually greater than 150 kPa. Then an imposed flow rate, usually one tenth of the flow rate imposed in step two, is used to obtain the permeability at this higher effective stress and lower average void ratio. The sample is then oven dried to determine the weight of solids.

Steps two and three are the same in principle in that seepage forces are imposed on the soil sample with known external loads and pore pressures are recorded. But since the effective stresses in the second step are low, consolidation will occur due to the seepage force.

The hydraulic conductivity is calculated through Darcy’s law and the imposed flow rate across the sample from the flow pump.

$$k = \frac{v_{\text{Darcian}}}{l}$$

(2.11)

where $v_{\text{Darcian}}$ is the Darcian velocity or the velocity of water flow across the sample and $l$ is the gradient calculated from the measure pore pressure difference and the sample height of the sample.
2.4 SICT Sample Preparation

The sample preparation for clay low density slurries as well as a brief discussion on MFT is presented in this section. The full discussion on MFT sample preparation is shown in section 5.1.

2.4.1 Clay Sample Preparation

The sample preparation for clay low density slurries differs from that of because MFT requires longer mixing times to ensure all samples are uniform. The clay slurry should be homogeneous prior to placing into the triaxial cell. This is achieved by mixing thoroughly with an electric mixer until it can pour smoothly. The initial water content of the clay slurry is then determined using standard water content ASTM procedures (ASTM, 2010). From the initial water content, $w_i$, the initial average void ratio, $e_i$, can be determined using the relation:

$$e_i = w_i G_s$$

where $G_s$ is the specific gravity of solids and is defined as the ratio of the density of solids to the density of water at standard conditions.

$$G_s = \frac{\rho_s}{\rho_w}$$

Due to the nature of low density slurries with high void ratios, $e_i$ does not represent the slurry with no load or with zero effective stress placed on top. This is because at high void ratios the sedimentation process dominates and particles settle with no or little grain-to-grain contact (i.e. effective stress) until the slurry reaches a steady void ratio at which the consolidation process begins to dominate. This void ratio is termed the void ratio at zero effective stress, $e_0$, and requires the use of settling tests (see section 2.4.3).

2.4.2 MFT Sample Preparation

Preparing MFT samples differs from preparing clay samples because the mixing times are much longer and the use of a shear vane test (see section 2.4.2.1) is required to ensure samples are prepared at minimum shear strength. This is to ensure that all MFT samples are uniform. The full discussion on MFT sample preparation is shown in 5.1.

2.4.2.1 Shear Vane Test

The vane shear test and analysis as outlined by Fisher et al (2007) was used to evaluate the shear strength of the MFT. The results of the shear vane test on MFT during sample preparation are shown in
5.1.1. The test involved inserting a shear vane into the MFT sampled and rotating it with a Rheometer capable of measuring the torque with time. Figure 2.13 shows the setup for the shear vane test and Figure 2.14 shows a typical torque-time curve obtained from the shear vane test.

![Diagram of the vane and vane inserted into the sample](image1)

**Figure 2.13**: (a) Diagram of the vane (b) the vane inserted into the sample (Gutierrez, 2001)

![Torque-time curve](image2)

**Figure 2.14**: Typical torque-time curve obtained from the vane test (Gutierrez, 2001)

A vane shear with 4 thin blades and a height of 6.05 cm and diameter of 1.9 cm was used for all the samples tests. All MFT samples were taken after homogenizing the MFT. When the MFT is sheared the vane and all the material within its radius, R, is rotated at a constant angular velocity, Ω, which results in a shear region of radius R_y and an unsheared region of radius εR. The sheared and unsheared regions are shown in Figure 2.15 as well as the resulting stress profile. The shear stress at the periphery of the vane, τ_1, is the highest shear stress. τ_2 represents the shear stress at the edge of the container which contains the MFT and τ_y is the yield stress at which shearing commences. The condition shown in Figure 2.15 represents partial shearing while the condition of τ_1 > τ_2 > τ_y represents complete shearing.
Figure 2.15: Sheared and unsheared regions during a shear vane test and resulting stress profile (Fisher, et al., 2007)

The shear strength of the MFT is defined as the maximum shear strength at the periphery at which the shear rate, $\dot{\gamma}$, is zero, that is $\tau_1(\dot{\gamma}=0)$. The shear strength at the periphery is determined from the following equation as outlined by Fisher et al (2007) and first derived by Krieger & Maron, 1952:

$$\tau_1 = \frac{T_m}{2\pi R^2 H} = \frac{T_m}{K_B}$$  \hspace{1cm} (2.14)

where $T_m$ is the maximum shear vane stress at the periphery (see Figure 2.14) determined from the Rheometer, $R$ and $H$ are the radius and height of the vane, respectively, and $K_B$ is a vane constant which ignores end effects. The MFT tested was placed in a relatively large beaker compared to the shear vane diameter so end effects were minimal. The shear rate is determined from the following equation (Krieger & Maron, 1952):

$$\dot{\gamma} = \frac{2\Omega}{n}$$  \hspace{1cm} (2.15)

where $\Omega$ is the angular velocity in radians/second imposed by the Rheometer and $n$ is the local gradient of a plot of $\log(\tau_1)$ versus $\log(\Omega)$ or can be written as:
\[ n = \frac{d\tau_1}{d\Omega} \quad (2.16) \]

where \( \tau_1 \) has units of Pa, and \( \Omega \) has units of radians/second.

### 2.4.3 Settling Test for \( e_0 \) Determination

To determine the void ratio at zero effective stress, a settling or column test is performed for low density, high void ratio slurries. This is done by pouring some of the clay slurry prepared as described in section 2.4 into clear cylinders and record the change in height of the clay slurry as supernatant water rises to the top (see Figure 2.16).

![Figure 2.16: Sedimentation of slurry in settling test](image1)

In determining \( e_0 \), it is important to use the phase diagrams at initial pouring and when sedimentation is complete, as shown in Figure 2.17.

![Figure 2.17: Phase Diagram of slurry in settling test](image2)
At the initial pouring the slurry has a void ratio, $e_i$, sedimentation lowers this void ratio until the point where effective stress starts, $e_o$. Thus during consolidation in the SICT, $e_o$ acts as the starting void ratio at zero effective stress and not $e_i$. Since $e_i$ is obtained from the initial water content test, $e_o$ can be determined since the height solids, $H_s$, is constant throughout the settling test. The void ratio is defined as the volume of voids, $V_v$, divided by the volume of solids, $V_s$, and since the cross sectional areas, $A$, of both phases are the same and assuming 100% saturation, $S$, (voids are filled with water) then the void ratio can be determined as follows:

$$
e = \frac{V_v}{V_s} = \frac{V_w(S = 100\%)}{V_s} = \frac{H_wA}{H_sA} = \frac{H_w}{H_s} \tag{2.17}$$

where $H_w$ is the height of the water phase, and $H_s$ is the height of solids. Since $H_s$ is constant, it can be calculated from $e_i$ by rearranging equation (2.17) and writing $H_w$ has the difference between the initial height of the column, $H_i$, and $H_s$ (see Figure 2.17):

$$e_i = \frac{H_i - H_s}{H_s} = \frac{H_i}{H_s} - 1 \tag{2.18}$$

$$H_s = \frac{H_i}{1 + e_i} \tag{2.19}$$

Since $H_s$ is known $e_o$ can be calculated using equation (2.18) but using the final height of the slurry, $H_f$, in place of $H_i$ as follows:

$$e_o = \frac{H_f}{H_s} - 1 \tag{2.20}$$

### 2.5 Seepage Induced Consolidation Test Analysis (SICTA)

The analysis of the SICT at CU is performed using the software program SICTA (Seepage Induced Consolidation Test Analysis) which was developed at Boulder CU (Abu-Hejleh & Znidarčić, 1992). The analysis involves into the final data from step three (see section 2.3.3) into the finite or large strain nonlinear consolidation theory to back calculate the measured data from steps one and two (section 2.3.3). The SICTA program at CU is written in the Fortran language and the theory behind the program is discussed in this section.

#### 2.5.1 Large Strain Consolidation Theory

In section 2.2, the limitations of conventional consolidation testing as well as the small strain theory on testing low density slurries are discussed. From those limitations, it is apparent that any analysis
involving consolidation of low density slurries that undergo large strains must use a consolidation theory that accounts for large strain, self weight of the soil and non-linear compressibility and permeability relations. The SICTA uses the large strain consolidation theory formulated by Gibson et al (1967) and the governing equation is as follows:

$$\pm \left( \frac{\gamma_s}{\gamma_w} - 1 \right) \frac{d}{de} \left[ k(e) \frac{\partial e}{\partial z} \right] + \frac{1}{\gamma_w(1 + e)} \frac{\partial}{\partial z} \left[ \frac{k(e)}{de} \frac{\partial e}{\partial z} \right] + \frac{\partial e}{\partial t} = 0$$  \hspace{1cm} (2.21)

where $\gamma_s$ is the unit weight of solids, $\gamma_w$ is the unit weight of water, $k(e)$ is the coefficient of hydraulic conductivity as a function of the void ratio $e$, and $z$ is the reduced material or Lagrangian coordinate, and in this case the height of solids from a specified datum and will be discussed further in this section. Note that the (+) sign is used if the depth of the height of solids, $z$, is defined as positive against gravity.

The derivation of the governing equation of the large strain consolidation theory, equation (2.21), is presented in Appendix A. But before deriving a formulation for large strain it is important to present the concept of using appropriate coordinate systems in the derivation to overcome the inherent moving boundary problem.

### 2.5.1.1 Moving Boundary Problem

The biggest impediment in formulating the consolidation theory to account for large strains is when considering an element of a soil layer, as consolidation occurs that layer deforms and thus formulation must account for a “moving boundary” (Lee, 1979). In the conventional small strain theory, in deriving the governing equation in equation (2.1), an element of fixed space coordinates, $x$ and $x + dx$, was considered, which is a reasonable assumption when strains are small (see Figure 2.18).
When deformations are large, the soil element undergoes significant deformations and thus a moving boundary must be accounted for which introduces further complexity to the governing equation. To reduce the complexity of working with a moving boundary it is better to work with a material or Lagrangian coordinate system to transform the moving boundary problem above into a fixed boundary problem.

### 2.5.1.2 Lagrangian vs. Eulerian Coordinate Systems

Figure 2.19 shows the initial configuration of a soil element at time \( t = 0 \). At some time \( t \), after consolidation of the soil, the initial planes \( A_0B_0 \) and \( C_0D_0 \) will have moved in *absolute* terms from the initial positions \( a \), and \( (a + \delta a) \) to unknown locations \( \xi \), and \( (\xi + \delta \xi) \) which are functions of the initial positions as shown in Figure 2.19 (b).
The conventional or Eulerian coordinate system involves specifying the exact location of the soil element and in the case of soil consolidation this would require a moving boundary condition to be included in the governing equation. Lee (1979) derived such a formula but it increased the complexity of the problem. To simplify the formulation of the large strain theory, it is better to work with a fixed boundary coordinate system. In the Lagrangian or material coordinate system, the frame of reference is in relative terms and a plane of the soil element is identified by its initial distance from the datum; thus the Lagrangian coordinate does not change. For example, the upper boundary of the soil layer $a = a_o$ can always be identified as $a_o$ even when undergoing deformation as shown in Figure 2.19 (b). Thus the following advantage has been introduced: the boundary can always be identified ($a = a_o$) as well as the boundary conditions introduced on it in the analysis, even though the exact location is not known, which is $\xi(a_o, t)$ (Gibson, et al., 1967).

The element ABCD always contains the same volume of soil solids and thus as a further step, Gibson et al (1967) utilized the reduced material coordinate, $z$, which is defined as the volume of solids per unit area within the volume bounded by the datum line and the Lagrangian coordinate, $a$:

$$z = \int_0^a \frac{da}{1 + e_o(a)}$$

which can also be written as:

$$\frac{dz}{da} = \frac{1}{1 + e_o}$$
where the parameter \( e_0 \) is the void ratio at time \( t = 0 \) and is generally a function of the position within the soil layer, \( e_0(a) \) (Lee, 1979). Equation (2.23) can easily be derived using the phase relation of element ABCD shown in Figure 2.20. Assuming a unit value for the volume of solids than \( e_0 \) would simply equal volume of the voids and the ratio of \( dz/da \) would simply be \( 1/(1+e_0) \).

\[ \text{Figure 2.20: Phase relation of the element ABCD from Figure 2.19 (Schiffman, et al., 1988)} \]

From Figure 2.20, it is apparent that when strains are large, instead of working with the exact deformed volume at the current time \( t \) which changes, it is easier to work with the reduced Lagrangian coordinate \( z \) which is fixed in the element. And using equation (2.23) it is easy to obtain the initial Lagrangian coordinate, \( a \).

### 2.5.2 Compressibility and Permeability Functions

The use of the large strain or finite consolidation theory requires that the compressibility and permeability functions to be accounted for and to not simply assume they are constant. The SICTA uses the following compressibility and permeability models in the analysis:

\[
e = A(\sigma' + Z)^B
\]

\[
k = C e^D
\]

(2.24)

(2.25)

The compressibility function (2.24) was formulated by Liu and Znidarcic (1991) and it is widely accepted because it would overcome previous formulations that had void ratio approaching infinity at zero effective stress. The parameters \( A \) and \( B \) are unitless while \( Z \) has units of stress. The addition of the \( Z \) unit allows for a specific value of void ratio at zero effective stress, namely \( e_0 = AZ^A \).
The permeability function (2.25) was demonstrated by Somogyi (1979) to be suitable for low density soils. The coefficient \( C \) has units of permeability and \( D \) is unitless.

Bartholomeeusen et al (2002) describes an experimental exercise to predict the soil compressibility at low effective stresses of low density sediments in an attempt to standardize the determination of the material properties of low density slurry-like soils. In the prediction exercise, which was named Sidere, numerical modelers were provided with data from four calibration experiments and were then asked to predict another experiment. The formulations for the constitutive compressibility and permeability functions of the Sidere study are shown in Table 2.2.

**Table 2.2: Numerical models in the Sidere study (Bartholomeeusen, et al., 2002)**

<table>
<thead>
<tr>
<th>Participants</th>
<th>Dependent variable</th>
<th>Parameter choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bartholomeeusen</td>
<td>Void ratio</td>
<td>( e = -1.07 \sigma^{0.14} + 2.52 )</td>
</tr>
<tr>
<td>Carrier</td>
<td>Void ratio</td>
<td>( e = 0.27 \ln(\sigma') + 5.95 )</td>
</tr>
<tr>
<td>(Carrier III et al., 1983)</td>
<td>Void ratio</td>
<td>( e = 2.93(\text{[Pa]} \sigma' + 5.32)^{-0.10} )</td>
</tr>
<tr>
<td>Lin &amp; Penumadu</td>
<td>Void ratio</td>
<td>( k = 8.96 \times 10^{-3} e^{0.08} )</td>
</tr>
<tr>
<td>Masala &amp; Chan</td>
<td>Void ratio</td>
<td>( e = -0.22 \ln(\sigma') + 1.46 )</td>
</tr>
<tr>
<td>Merckelbach (Merckelbach, 2000)</td>
<td>Solids vol. fraction, ( \Phi )</td>
<td>( k = 0.0072 e^{0.75} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( e = 2.81(\text{[Pa]}^{-1}) \sigma'^{-0.102} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( k = 1.38 \times 10^{-3} \text{ m/day} e^{5.75} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \sigma' = 3 \times 10^{15} \text{ Pa}^{-1.53} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( k = 2 \times 10^{-19} \text{ Pa}^{1.53} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(26% fines)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Linear interpolation for ( k(e) ) and ( \sigma'(e) ) from a table</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \sigma' = 0.2 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( e = -0.21 \ln(\sigma') + 1.26 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \sigma' = 0.2 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( e = -0.11 \ln(\sigma') + 1.42 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( c_v = 3 \times 10^{-7} \text{ m}^2/\text{s} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \sigma' = \exp(1127 - 80 e) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( k = \exp(-21.55 + 3.6 e) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \sigma' = 6 \times 10^{-6} \Phi^{1.53} )</td>
</tr>
<tr>
<td>Pyke</td>
<td>Void ratio</td>
<td>( k = 1.6 \times 10^{-15} \Phi^{1.59} )</td>
</tr>
<tr>
<td>Sills</td>
<td></td>
<td>( e = 1.69(\sigma' + 0.046)^{-0.12} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( k = 4.14 \times 10^{-30} e^{6.59} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(26% fines)</td>
</tr>
</tbody>
</table>

*Units in kPa and m/s unless otherwise stated

From the many numerical modelers involved in the study, the most accurate prediction was by Znidarcic, in which he utilized equations (2.24) and (2.25) shown above for the compressibility and permeability curves, respectively. A comparison between the experimental data that the modelers were asked to model and that of the predicted settlement curves is shown in the Figure 2.21. The figure shows that Znidarcic’s prediction was the closest to the experimental data. The Sidere study helps confirm the use of equations (2.24) and (2.25) to model compressibility and permeability, respectively, of low density slurries.
2.5.3 SICTA Methodology

The SICTA program uses experimental data from the SICT to numerically solve for the compressibility and permeability functions, equations (2.24) and (2.25), respectively, by employing an iterative scheme (see Appendix B) to solve the governing equation of large strain consolidation at steady state. During the seepage induced consolidation phase of the SICT when the steady state is reached the pore pressures and sample height remain constant. Thus the deformation rate, \( \partial e/\partial t \), from the governing equation of large strain consolidation, equation (A.12), becomes zero and Gibson et al’s (1967) formulation (and using the notation of \( z \) as being positive with gravity) becomes:

\[
\left( \frac{\gamma_z}{\gamma_w} - 1 \right) \frac{d}{de} \left[ \frac{k(e)}{1 + e} \right] \frac{de}{dz} + \frac{\partial}{\partial z} \left[ \frac{k(e)}{\gamma_w(1 + e)} \right] \frac{d\sigma'}{dz} \frac{de}{dz} = 0
\]

The measured data at the steady state (step two in section 2.3.3) from the SICT provides information at the low effective stress range where compressibility is highly non-linear (Abu-Hejleh & Znidarčič, 1994). The steady state conditions, which are described in equation (2.26), are controlled by the compressibility and permeability functions of the soil, which makes the measured data at the steady state the basis for estimating these functions.
In the analysis the integral form of equation (2.26) is used. By writing equation (A.7) in its integral form and rearranging as a function of effective stress, the following relationship is derived:

\[
\int_{0}^{z} \frac{d\sigma'}{dz} \, dz = \int_{0}^{z} \frac{d\sigma}{dz} \, dz - \int_{0}^{z} \frac{du_{h}}{dz} \, dz - \int_{0}^{z} \frac{d\sigma_{e}}{dz} \, dz
\]

Equation (A.9) can be applied for \(d\sigma/dz\), equation (A.10) can be applied for \(du_{h}/dz\), and applying Darcy’s law for \(du_{e}/dz\), the following equation is formulated:

\[
v_D = - \frac{k}{\gamma_w} \frac{du_{e}}{dz} \frac{1}{1 + e}
\]

\[
\frac{du_{e}}{dz} = - \frac{v_D \gamma_w}{k} (1 + e)
\]

\[
\sigma'(z) - \sigma'_{o} = \int_{0}^{z} (e \gamma_w + \gamma_s)dz - \int_{0}^{z} (1 + e)\gamma_w dz + \int_{0}^{z} \frac{v_D \gamma_w}{k} (1 + e)dz
\]

At the steady state, the relative velocity is equal to the Darcian water velocity, \(v_D\), because the velocity of the solids phase is zero since the sample is not consolidating. Equation (2.30) can further be simplified to:

\[
\sigma'(z) = \sigma'_{o} + \int_{0}^{z} (\gamma_s - \gamma_w)dz + \int_{0}^{z} \frac{v_D \gamma_w}{k} (1 + e)dz
\]

This formulation is equivalent to the steady state equation of large strain consolidation, equation (2.26). It is also important to note that the first term in this formulation represents the applied load, the second term represents the self weight of the soil, and the third term is the applied seepage force.

From section 2.3.3, the following data is collected from the SICT:

1. Void ratio at zero effective stress: \(e_o\)
2. Bottom effective stress and sample height at steady state: \(\sigma'_{sb}, H_{ss}\)
3. Applied effective stress, permeability and void ratio at final step load: \(\sigma', k_{f}, e_f\)

The compressibility and permeability functions, equations (2.24) and (2.25), are determined by solving the five parameters A, B, Z, C, and D using the data from steps one and three and back calculating the measured \(\sigma'_{sb}\) and \(H_{ss}\) at steady state in step two in an iterative scheme which numerically solves the integral form of the governing equation of large strain consolidation at steady state, equation (2.31). The iterative scheme is presented in Appendix B.
3 SICT at UBC

The seepage induced consolidation test (SICT) constructed at Colorado University (CU) has provided reliable and repeatable results on low density slurries such as kaolinite clay, phosphate tailings, and mature fine tailings (MFT). Due to the success of the SICT at CU, as well as the limitations of conventional and the long test times of the slurry consolidometer (see section 2.2), a SICT was constructed at UBC to further provide testing for consolidation characterization of MFT. This section provides a detailed summary of the SICT and accompanying analysis program at UBC.

3.1 SICT Construction

A schematic of the SICT constructed at UBC is shown in Figure 3.1. The UBC SICT is very similar to that of the one constructed at the CU laboratory but there are several key differences between the two and those differences are listed below:

- Larger diameter sample size: 6 inches vs. 3 inches
- LVDT rod placed through cell cap: allows for continuous settlement measurement
- Digital encoder placed on flow pump: allows for automatic pump resets

The larger diameter sample size allows for a lower flow rate across the sample for the same imposed discharge velocity from the flow pump. This allows for finer tuning of the flow rate across the sample through controlling the pump flow velocity. This also results in significantly shortening the consolidation process because there will be smaller pore pressure build up due to the lower flow rates. The larger diameter sample also requires a larger sample chamber and load cell.

The LVDT rod for the UBC SICT was placed through the cell cap to allow for continuous measurement of the sample settlement. The disadvantage of this setup is that the water reservoir must be placed so that the water is level with the top of the SICT chamber (see Figure 3.1) to prevent water from leaking through the LVDT cap connection. This results in a lower overall water pressure than that of the CU SICT which has the water reservoir several meters above the SICT. Having a high surrounding water pressure provides better control of pore pressures measured across the sample in terms of having constant reference pressures. This modification has not been shown to affect the SICT results. Another result of having the LVDT rod through the cell cap is that it is now applying a small load to the sample that must be quantified.
Figure 3.1: SICT Overall Diagram at UBC
The buoyant weight of the LVDT rod imposed on the soil sample imposes a seating stress on the sample of about 0.03 kPa.

A digital encoder is installed on the flow pump, which allows for direct measurement of the distance that the flow pump piston has travelled and this allows for automatic resetting of the flow pump piston during testing whenever the maximum volume of water has been removed from the sample. In contrast, without an encoder to accurately measure where the flow pump piston is, it is required that the pump be manually reset.

### 3.2 SICT at UBC Test Apparatus

The SICT constructed at UBC follows the same outline of components illustrated in the CU SICT Test Apparatus, section 2.3.2. The specific components and their full specifications selected for the SICT at UBC are detailed in the appendix. They were selected to account for the larger diameter sample and for the modifications described above. Since the UBC and CU SICT are very similar, the selection of each component will not be described in this section. However, the scaling up of the custom acrylic loading piston and sample pedestal are described here.

#### 3.2.1 Loading Piston Dimensions

The loading piston is used to ensure that the sample settles uniformly. The piston is made of clear cast acrylic and is 6 inches in diameter and the height is selected to be 3.6 inches based on the empirical ratio shown in the equation that follows:

\[
\frac{\text{Height of Piston}}{\text{Diameter of Piston}} = 0.6
\]

This ratio was subjectively determined during the piston design and construction process because it minimizes the effects of uneven settlement as compared to a thinner piston while at the same time minimizing the weight of the piston.

The loading piston weighs 1.55 kg and has 54 holes of a diameter of 5/16 inches drilled through the height of it to allow for drainage at the top of the piston while maintaining uniform sample settlement and minimizing weight. It has a buoyant weight of 128 grams, producing a seating stress of about 0.07 kPa on the sample. Thus when accounting for the 0.03 kPa stress increase due to the buoyant weight of the LVDT rod, the total load on the sample due to the piston and the LVDT rod is about 0.10 kPa.
A plan view of the piston is shown in Figure 3.2. It is important to provide a balance between the area of holes versus the area with no holes to ensure adequate drainage and uniform settlement.

![Figure 3.2: Loading Piston at UBC Top View](image)

3.2.2 Sample Pedestal

The sample pedestal at UBC has a very similar design to that of the one at the CU laboratory (see Figure 2.10). The pedestal is made of clear cast acrylic and is shown in Figure 3.3. Scaling up of the pedestal requires that pedestal be larger but at the same time require more grooves on the top of the pedestal to allow for even water flow through the sample. An O-ring is fitted around the pedestal in the circular groove to form a water tight seal with the sample casing. The water flow has two holes by which they can eventually go. One of them leads to the pore pressure transducer for pressure measurements and the other leads to the water pressure from the bucket of water as well as to the flow pump.

![Figure 3.3: Schematic of Sample Pedestal at CU](image)
3.3 SICT UBC Procedure

The procedure for testing the SICT at the UBC laboratory follows the same general procedure shown in section 2.3.3. A detailed step by step test procedure at the UBC laboratory is shown in Appendix E.

3.4 SICT Analysis (SICTA) Procedure

A plot of the pore pressure difference across the sample is first produced from the data acquired from the SICT. Figure 3.4 shows the pore pressure difference across the sample with time for the UBC Kaolin 3 test. From the figure, the pore pressure differences are determined at the seepage consolidation phase and during the step loading phase. When seepage is induced by the flow pump, the pore pressure difference across the sample increases until it reaches a steady state, at which pore pressures are constant. The difference between this steady state and a zero reference reading represents the difference in the pore pressure from the top and bottom of the slurry sample. Since the sample height is measured with the LVDT, the void ratio and hydraulic conductivity can be determined for each step through equation (2.11).

![Figure 3.4: Pore pressure difference with time of UBC Kaolin 3 SICT](image)

The void ratio at each pore pressure difference described above is known from the sample height, H, and the height of solids, H_s, of the sample using the following equation derived from the phase diagram of a soil:
\[ e = \frac{H}{H_s} - 1 \]  

(3.2)

The effective stress is known from the applied load using the load cell and the buoyant weights of the LVDT rod and loading piston. The hydraulic conductivity, \( k \), is determined from equation (2.11). The SICTA program developed at CU requires the input parameters shown in Table 3.1 which are determined from the SICT, water content tests, and settling or column tests.

<table>
<thead>
<tr>
<th>Material Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Void ratio at zero effective stress</td>
<td>( e_0 )</td>
</tr>
<tr>
<td>Height of solids</td>
<td>( H_s )</td>
</tr>
<tr>
<td>Unit weight of solids</td>
<td>( \gamma_s )</td>
</tr>
<tr>
<td>Specific gravity of solids</td>
<td>( G_s )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data at Steady State of Seepage Induced Consolidation Phase</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom effective stress</td>
<td>( \sigma'_{sb} )</td>
</tr>
<tr>
<td>Sample Height</td>
<td>( H )</td>
</tr>
<tr>
<td>Darcian water velocity</td>
<td>( v_D )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data at Step Load Used for Analysis</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied effective stress</td>
<td>( \sigma'_f )</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>( k_f )</td>
</tr>
<tr>
<td>Void ratio</td>
<td>( e_f )</td>
</tr>
</tbody>
</table>

From the above data, the SICTA will output the 5 parameters A, B, Z, C, and D for the compressibility and permeability relations. The SICTA involves using the data from the step load as well as \( e_0 \) to back calculate or predict the sample height and the void ratio at the bottom of the sample at steady state during the SIC phase.

It is important to note that only one step load is required in the analysis and all other step loads serve as a check of the produced compressibility and permeability curves. The step load which is deemed most reliable in being representative of the sample is selected for the analysis. This usually involves selected step loads with high applied effective stresses since the effect of loading piston and load cell internal friction are much smaller in relative to the applied loads.

The results of the SICT analysis are presented in chapters 4 and 5.

### 3.5 SICTA UBC Modified Program

The author produced a SICTA program using Microsoft Excel, which is almost identical to the Fortran program developed at the CU laboratory. The advantages using Excel over Fortran are that analysis can
be done much faster since all the data required for the test are already in spreadsheet form. This allows building a database of test results as well as for quick inspection into the effect of varying which step load is used in the analysis. Simple modifications of input parameters such as specific gravity, unit weight of solids, and void ratio at zero effective stress can also be done and subsequent analysis takes seconds. Results can also be instantaneously compared to any or all tests in the database. This allows the user to spend more time analyzing the results as opposed to preparing the results.

This Excel version uses the same SICTA iteration scheme as the CU Fortran version but does not include the parameter estimation scheme because from experience the results on all test results performed at CU and UBC converge very rapidly without ever needing to use the parameter estimation scheme. Including the parameter estimation scheme would have greatly added to the complexity of the Excel program and it is better to deal with specific cases that require implementing the scheme but do so manually.
4 SICT Benchmark Testing

After the construction of the SICT at UBC, 6 tests were performed on kaolinite clay and compared with a test on kaolinite clay at the Boulder CU laboratory. The results of benchmark testing are presented in this chapter. The results of the kaolinite tests are also compared with published consolidation data from Rowe cell and desktop centrifuge tests and show good agreement with the published data. Test results were comparable and helped build confidence in the SICT constructed at UBC to be reliable and repeatable. A test on copper tailings provided by Golder Associates was also conducted to investigate the ability of the SICT to test high solids content material. The results of benchmark testing are presented in this chapter.

4.1 Kaolinite Clay CU Results

A SICT was performed at the Colorado University (CU) by Dr. Znidarčić on kaolinite clay. The characteristics and input data for the SICT analysis are presented in Table 4.1. The sample was prepared at an initial void ratio of 8.11 and a solids content of 24.7% by mass.

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Steady State Data</th>
<th>Step Load Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>e₀</td>
<td>Hₛ (mm)</td>
<td>Gₛ *</td>
</tr>
<tr>
<td>3.73</td>
<td>8.01</td>
<td>2.66</td>
</tr>
<tr>
<td>vₛ (kN/m³)</td>
<td>σ’sb (kPa)</td>
<td>H (mm)</td>
</tr>
<tr>
<td>26.09</td>
<td>1.49</td>
<td>28.31</td>
</tr>
<tr>
<td>Gₛ *</td>
<td>v₀ (m/s)</td>
<td>σ’f</td>
</tr>
<tr>
<td>2.66</td>
<td>1.22x10⁻⁷</td>
<td>145.74</td>
</tr>
<tr>
<td>σ’f</td>
<td>kᵣ (m/s)</td>
<td>eᵣ</td>
</tr>
<tr>
<td>145.74</td>
<td>4.73 x 10⁻¹⁰</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Note: Refer to Table 3.1 for definition of the parameters.
* The value for specific gravity is assumed based on typical values.

The resulting compressibility and permeability equations from the above input data are given as follows:

\[ e = 2.332(\sigma' + 0.075 \text{ kPa})^{-0.181} \]  
\[ k = (5.9x10^{-10} \text{ m/s})e^{4.22} \]

The equations above are plotted, together with multiple step load data, in the compressibility and permeability curves in Figure 4.1 and Figure 4.2, respectively. The measured data points show good agreement with the developed curves and the data show that kaolinite clay has a highly non-linear void ratio distribution. Thus it is clear from results such as these that large strains as well as non-linear compressibility and permeability characteristics must be accounted for in predicting soil behaviour through consolidation theory.
4.2 Kaolinite Clay UBC Results
Six SIC tests were performed at the UBC laboratory on kaolinite clay slurry. The first two tests were deemed trial tests and are not presented in this thesis because they had LVDT installation problems and thus the settlement readings were not accurate. The last four tests used factory settings for the LVDT calibration but the factory settings were confirmed to be reliable after calibration tests were conducted prior to MFT SICT testing (see Appendix H.2). The individual test results for the tests at UBC are
presented in Appendix C. The comparison of the UBC testing with CU testing and results from a desktop centrifuge test are presented in this subsection. The SIC tests on kaolinite clay typically took about 1-2 weeks until completion.

4.2.1 Comparison of Kaolinite Clay Results

The SICTA input parameters for analysis of all the tests are shown in Table 4.2. From the table it can be seen that the step load data varied from an effective stress of 45 kPa for test number UBC Kaolin 3 to an effective stress of 160 kPa for the UBC Kaolin 6 test. This allows the ability to test samples at relatively lower effective stress and still obtain the same results.

Table 4.2: SICTA Input Parameters for Kaolinite Benchmark Tests

<table>
<thead>
<tr>
<th>Test #</th>
<th>e₀</th>
<th>H₀ (mm)</th>
<th>V₀ (kN/m³)</th>
<th>Gₛ *</th>
<th>σ'₀sb (kPa)</th>
<th>H (mm)</th>
<th>V₀ (m/s)</th>
<th>σ₀</th>
<th>k₀ (m/s)</th>
<th>e₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>CU</td>
<td>3.73</td>
<td>8.01</td>
<td>26.09</td>
<td>2.66</td>
<td>1.49</td>
<td>28.31</td>
<td>1.22 x 10⁻⁷</td>
<td>145.74</td>
<td>4.73 x 10⁻¹⁰</td>
<td>0.95</td>
</tr>
<tr>
<td>UBC 3</td>
<td>3.24</td>
<td>13.36</td>
<td>26.00</td>
<td>2.65</td>
<td>3.12</td>
<td>46.46</td>
<td>1.30 x 10⁻⁷</td>
<td>45.54</td>
<td>2.97 x 10⁻⁹</td>
<td>1.47</td>
</tr>
<tr>
<td>UBC 4</td>
<td>3.10</td>
<td>13.80</td>
<td>26.00</td>
<td>2.65</td>
<td>3.37</td>
<td>48.43</td>
<td>1.30 x 10⁻⁷</td>
<td>126.96</td>
<td>8.03 x 10⁻¹⁰</td>
<td>1.15</td>
</tr>
<tr>
<td>UBC 5</td>
<td>3.53</td>
<td>11.27</td>
<td>26.00</td>
<td>2.65</td>
<td>2.08</td>
<td>40.45</td>
<td>1.30 x 10⁻⁷</td>
<td>115.93</td>
<td>6.80 x 10⁻¹⁰</td>
<td>0.97</td>
</tr>
<tr>
<td>UBC 6</td>
<td>2.84</td>
<td>8.92</td>
<td>26.00</td>
<td>2.65</td>
<td>3.27</td>
<td>28.69</td>
<td>2.17 x 10⁻⁷</td>
<td>160.09</td>
<td>7.37 x 10⁻¹⁰</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Note: Refer to Table 3.1 for definition of the parameters
* The value for specific gravity is assumed based on typical values

The results of the SIC testing on kaolinite clay from both CU and UBC laboratories are in Table 4.3, Figure 4.3 and Figure 4.4.

Table 4.3: Kaolinite Clay Benchmark SICT Results

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Compressibility (( e = A(\sigma' + Z)^B ))</th>
<th>Permeability (m/s) (( k = C e^D ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CU Boulder Kaolin</td>
<td>( e = 2.332(\sigma' + 0.075 \text{ kPa})^{-0.181} )</td>
<td>( k = (5.9 \times 10^{-10} \text{ m/s})e^{4.22} )</td>
</tr>
<tr>
<td>UBC Kaolin 3</td>
<td>( e = 2.563(\sigma' + 0.195 \text{ kPa})^{-0.143} )</td>
<td>( k = (6.6 \times 10^{-10} \text{ m/s})e^{3.89} )</td>
</tr>
<tr>
<td>UBC Kaolin 4</td>
<td>( e = 2.759(\sigma' + 0.518 \text{ kPa})^{-0.179} )</td>
<td>( k = (4.4 \times 10^{-10} \text{ m/s})e^{4.25} )</td>
</tr>
<tr>
<td>UBC Kaolin 5</td>
<td>( e = 2.548(\sigma' + 0.199 \text{ kPa})^{-0.202} )</td>
<td>( k = (7.6 \times 10^{-10} \text{ m/s})e^{3.91} )</td>
</tr>
<tr>
<td>UBC Kaolin 6</td>
<td>( e = 2.368(\sigma' + 0.357 \text{ kPa})^{-0.176} )</td>
<td>( k = (8.3 \times 10^{-10} \text{ m/s})e^{4.10} )</td>
</tr>
</tbody>
</table>
The results of the benchmark tests show that tests using the SICT at UBC are repeatable and show very similar results with the test at CU in both compressibility and permeability. At the high effective stress the variation of void ratios amongst the tests is attributed to the selection of the final step load data point. The test that varied the most from the other tests was the UBC Kaolin 3 test. That test also was loaded to the lowest final effective stress, $\sigma'_f$ (see Table 4.2), amongst the tests, which was 45.54 kPa.
This variation might be a result of the fact that any friction in the system, such as loading piston with sample casing and loading cell internal friction, will be more significantly when effective stresses are lower. Thus it is preferred that higher effective stresses be selected for step loading to minimize the influence of any loading friction in the system.

Another factor in the variation of void ratios at the high effective stress range for the UBC Kaolin 3 test might be in the experience gained by the author during testing. The tests results that compared best with the CU kaolinite were the later tests: UBC Kaolinite 5 and 6. With each test being performed the author gained experience in the overall test procedure especially the minute procedures such as sample pouring and the initial loading rod placement. This experience as well as the fact that the UBC Kaolin 3 test had the lowest final effective stress obtained (as explained above) may explain the variation of void ratios at high effective stresses.

From Table 4.3, all the parameters determined through analysis for the benchmark tests are similar except the Z parameter. This variation is mainly associated with the initial void ratio at which each test was prepared at. It represents approximately the effective stress at which consolidation phase becomes dominate over the sedimentation phase and corresponds to about the point of curvature at the low effective stress range in the compressibility curves (see Figure 4.3). Table 4.4 presents the initial conditions of the benchmark tests in terms of initial void ratio, void ratio at zero effective stress, and initial solids content as well as the determined Z parameter. From the table it can be seen that, excluding the UBC Kaolin 5 test, generally the higher the void ratio corresponds to a lower Z parameter.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Initial Prepared Void Ratio, $e_i$</th>
<th>Void ratio at zero effective stress, $e_o$</th>
<th>Initial solids Content by Mass (%)</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>CU Boulder Kaolin</td>
<td>8.11*</td>
<td>3.73</td>
<td>24.7</td>
<td>0.075</td>
</tr>
<tr>
<td>UBC Kaolin 3</td>
<td>3.43</td>
<td>3.24</td>
<td>43.6</td>
<td>0.195</td>
</tr>
<tr>
<td>UBC Kaolin 4</td>
<td>3.31</td>
<td>3.10</td>
<td>44.4</td>
<td>0.518</td>
</tr>
<tr>
<td>UBC Kaolin 5</td>
<td>4.58</td>
<td>3.53</td>
<td>36.7</td>
<td>0.199</td>
</tr>
<tr>
<td>UBC Kaolin 6</td>
<td>3.34</td>
<td>2.84</td>
<td>44.3</td>
<td>0.357</td>
</tr>
</tbody>
</table>

* This high initial void ratio illustrates the need to determine the void ratio at zero effective stress, $e_o$, as solid particles quickly settle due to self weight when the sample is left undisturbed until it reaches $e_o$ (see section 2.4.3)

4.2.2 Comparison with Desktop Centrifuge Test
The results of the UBC SICT on kaolinite clay were also compared with the results of a desktop centrifuge test (see section 2.2.2.5 for further details on the test) presented by Reid & Fourie (2012). The samples for the desktop centrifuge tests were prepared similar to that of the SICT except the void ratio at zero
effective stress was not available. The kaolinite clay for the centrifuge tests had a specific gravity of 2.58 and 40% finer than 2 μm, and is relatively uniformly graded (2012). Figure 4.5 and Figure 4.6 show the results of the compressibility and permeability of both the UBC SICT and the desktop centrifuge as well as Rowe cell test data provided by Reid & Fourie (Reid & Fourie, 2012) to compare with the desktop centrifuge at high effective stresses (> 10 kPa).

Figure 4.5: Compressibility of Kaolinite Clay: UBC SICT vs. Desktop Centrifuge
The results of the tests performed at UBC compare well with those obtained from the desktop centrifuge as well as the Rowe cell. This further confirms the reliability of the testing apparatus and provided added confidence to undergo testing on MFT.

### 4.3 Copper Tailings Results

An additional test was performed on copper tailings to investigate the ability of the SICT at UBC in testing material with high solids content. The SICTA input parameters are shown in Table 4.5. The results of the SICTA are shown in equations (4.3) and (4.4). The resulting compressibility and permeability curves as well as measured data points are plotted on Figure 4.8 and Figure 4.9. The sample had an initial void ratio of 1.44, a solids content of 64.8 % by mass, initial height of 53 mm and a pH of 7.3. The test took 8 days to complete due to many permeability measurements performed but would usually take about 2 to 3 days to complete if only the required two permeability measurements were performed.

A particle size distribution test was performed using a wet sieve technique and showed that the copper tailings had about 35% fines or 35% less than 44 μm grain size (see Figure 4.7).
Figure 4.7: Copper Tailings 1 – Particle Size Distribution (Wet Sieve) by Mass %

Table 4.5: UBC Copper Tailings 1 SICTA Input Data

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Steady State Data</th>
<th>Step Load Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_o$ (mm)</td>
<td>$H_s$ (kN/m$^3$)</td>
<td>$G_s$ *</td>
</tr>
<tr>
<td>1.35</td>
<td>21.19</td>
<td>2.65</td>
</tr>
<tr>
<td>$\gamma_s$ (kN/m$^3$)</td>
<td>26.00</td>
<td>$\sigma'^s_b$ (kPa)</td>
</tr>
<tr>
<td>2.59</td>
<td>44.57</td>
<td>$H$ (mm)</td>
</tr>
<tr>
<td>$\sigma_f$' (kPa)</td>
<td>2.60E-07</td>
<td>$v_0$ (m/s)</td>
</tr>
<tr>
<td>173.35</td>
<td>6.18E-09</td>
<td>$k_f$ (m/s)</td>
</tr>
<tr>
<td>6.18E-09</td>
<td>0.50</td>
<td>$e_f$</td>
</tr>
</tbody>
</table>

Note: Refer to Table 3.1 for definition of the parameters
* The value for specific gravity is assumed based on typical values

\[ e = 1.180(\sigma_f' + 0.451 \text{ kPa})^{-0.166} \]  \hspace{1cm} (4.3)

\[ k = (4.1 \times 10^{-8} \text{ m/s})e^{2.74} \]  \hspace{1cm} (4.4)
The measured data points compare well with the resulting curves from the SICTA program and this shows that the SICT at UBC performs well in testing material with high solids contents, such as copper tailings of 65% solids by mass.
5 MFT SICT Results

The results from the benchmarks tests added confidence in performing SIC tests on MFT at the UBC laboratory. Three tests were performed on MFT which was provided by Suncor Energy. The results of the SIC testing on MFT are presented and compared with published data from the CU laboratory in this chapter. The MFT sample preparation and best practices during testing are also presented.

The initial sample height of 70 mm which is relatively high and proved to prolong the test to about 2 months before it was completed. Since it was taking a long time, the test was stopped before the final step loading permeability was obtained. During this time the pore pressure build up of the MFT during the permeability measurement was predicted to take up to another month to complete and thus deemed too long. The pore pressure difference and sample height measurements with time are shown in Figure D.15. From the figure it can be seen at about the 1500 hours mark, test was stopped prior to the pore pressure build up due to seepage was complete. Thus the analysis of the test was performed with the first step load data point (see Figure D.13). SIC tests performed after this test were prepared at sample heights close to 35 mm and significantly reduced completion times to about a month in duration but with more step loading data points plotted. Further information on sample height selection for MFT is discussed in section 5.1.2. Performing the SICT on MFT involves longer completion times than on more permeable materials such as kaolinite clay and copper tailings; see Table 5.1 for typical UBC SICT completion times.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Typical Completion Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Tailings</td>
<td>2-3 days</td>
</tr>
<tr>
<td>Kaolinite Clay</td>
<td>1-2 weeks</td>
</tr>
<tr>
<td>Mature Fine Tailings</td>
<td>1 month</td>
</tr>
</tbody>
</table>

Also from Figure D.15, the initial steady state seepage test was also stopped short before steady state was achieved. This was because the imposed flow rate, together with the tall sample height, proved that the pore pressure build up would be really high and take several more months to achieve steady state. The imposed flow rate through the sample at this point was $2.4 \times 10^{-10} \, \text{m}^3/\text{s}$. The flow rate was then lowered by half to $1.2 \times 10^{-10} \, \text{m}^3/\text{s}$ so that pore pressure build up would be smaller and steady state achieved sooner. See section 5.3 for recommended flow rates during permeability measurements. It is important to note that lowering the flow rate causes the sample to undergo slight over consolidation but the results were not observed to be affected significantly.
5.1 MFT Detailed Sample Preparation

In order to provide consistent samples for testing it is important to first shear the MFT samples with a rotating blade mixer until it loses most of its shear strength under the time frame of several hours of mixing. Five 5-gallon buckets of MFT were provided by Suncor and they were homogenized into one barrel as shown in Figure 5.1.

![Figure 5.1: MFT Homogenization through mixing](image)

For MFT of about 31% solids content shearing for about 3 hours yields a shear strength of 2 pa. Testing at the UBC laboratory shows that the shear strength increases significantly due to small increases in solids content; about 3 pa increase in shear strength for each percent increase in solids content. It is important to note that MFT samples tested that had shear strengths between 2 and 9 pa have shown comparable consolidation results.

5.1.1 Shear Vane Tests Results on MFT

The vane shear test and analysis as outlined by Fisher et al (2007) was used to evaluate the shear strength of the MFT. The shear vane test is presented in detail in section 2.4.2.1. During the shear vane tests at UBC the average slope was taken as the n value for use in equation (2.16). Each test was run in 10 sequences of 30 seconds each with increasing angular velocity at each step up to a maximum of 799.6 RPM or revolutions per minute. Table 5.2 shows the angular velocity imposed during each time increment for the tests at UBC.
Table 5.2: Angular velocities imposed in UBC shear vane tests

<table>
<thead>
<tr>
<th>Time sequence (s)</th>
<th>Ω (RPM)</th>
<th>Ω (radians/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>60</td>
<td>89.8</td>
<td>9.4</td>
</tr>
<tr>
<td>90</td>
<td>178.6</td>
<td>18.7</td>
</tr>
<tr>
<td>120</td>
<td>267.5</td>
<td>28.0</td>
</tr>
<tr>
<td>150</td>
<td>356.0</td>
<td>37.3</td>
</tr>
<tr>
<td>180</td>
<td>444.8</td>
<td>46.6</td>
</tr>
<tr>
<td>210</td>
<td>533.4</td>
<td>55.9</td>
</tr>
<tr>
<td>240</td>
<td>622.4</td>
<td>65.2</td>
</tr>
<tr>
<td>270</td>
<td>710.9</td>
<td>74.4</td>
</tr>
<tr>
<td>300</td>
<td>799.6</td>
<td>83.7</td>
</tr>
</tbody>
</table>

The results of three shear vane tests performed at the UBC laboratory are shown in Table 5.3 and Figure 5.2 as well as which SIC test they correspond to. The shear strength is determined as the y-intercept of a linear trendline imposed for each set of data. Table 5.3 also shows the pH, which was determined for the UBC MFT 2 and 3 tests.

Table 5.3: Shear Vane Results for MFT

<table>
<thead>
<tr>
<th>Corresponds to SICT #</th>
<th>Solids Content by Mass (%)</th>
<th>Shear Strength (Pa)</th>
<th>Shear strength increase per 1 % solids increase</th>
<th>n</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBC MFT 1</td>
<td>31.6</td>
<td>2.23</td>
<td>-</td>
<td>0.308</td>
<td>-</td>
</tr>
<tr>
<td>UBC MFT 2</td>
<td>33.0</td>
<td>7.02</td>
<td>3.42</td>
<td>0.036</td>
<td>8.72</td>
</tr>
<tr>
<td>UBC MFT 3</td>
<td>33.5</td>
<td>8.72</td>
<td>3.40</td>
<td>0.051</td>
<td>8.56</td>
</tr>
</tbody>
</table>
The results show that the shear strength increases with solids content, with a shear strength of 2.23 Pa at 31.6% solids and a shear strength of 8.72 Pa at 33.5% solids. Over this small solids content range, the increase in shear strength corresponds to an increase of 3.4 Pa for a 1% increase in solids content. The increased solids content is mostly caused by evaporation during the mixing process which usually takes a few hours. Another factor is during mixing, some of the MFT is gets tossed out during homogenization due to the nature of mixing. The amount of water that is needed to be lost during the mixing process to increase the solids content of a 25 gallon barrel of MFT by 1% from 30 to 31% is only 540 mL or about 0.57% of the initial 25 gallon volume.

The UBC MFT 3 was tested 6 months after the UBC MFT 1 test. The increase of only 2% solids content over a 6 month span is not a large change but this shows that shear strength of the MFT is very sensitive to even the smallest solids content change. Another possible increase in the shear strength could be from the slight pH drop (of 0.16) from tests UBC MFT 2 to 3. But regardless of the strength drop, as noted earlier, the slight increase in solids content, slight drop in pH, and significant change in shear strength did not strongly influence the results of the SICT on MFT.
From Figure 5.2, the shear rate is inversely proportional to the n value. Thus for the 31.6% solids test, the shear rate is an order of magnitude lower than for the other two tests because the n value is an order of magnitude larger. The shear rate is also a function of the shear strength and thus lower shear strength corresponds to lower shear rate (Fisher, et al., 2007).

5.1.2 MFT Sample Height Selection
The selection of the sample height used in the SICT is very important because it controls the duration of a test, which could be over a month long. The first test conducted at UBC on MFT involved using a sample height of 70 mm and took about two months to complete the SICT. The second test was performed on a sample with a height of 34.5 mm and the test took about one month while still obtaining more compressibility and permeability data points than the first test. A sample height should be selected to yield a height of solids of 5 mm to shorten testing time while ensuring that the test results are not significantly affected due to small losses of MFT smearing on the piston side-walls during step loading. This corresponds to a sample height of 32 mm for a MFT sample of 33% solids.

5.1.3 Removing Residue Bitumen Prior to Testing
Prior to testing it is very important remove visible residue bitumen which rises to the top of the MFT sample. This is to prevent the bitumen from attaching to the filter paper and thus acting as a seal, which prevents upwards drainage and thereby limits the outflow of pore water and thus impacting the consolidation process. The residue bitumen can easily be removed by lightly placing a paper towel over the top of the sample and removing it after it “absorbed” the bitumen. Bitumen at the bottom of the sample is less of an issue because of the tendency for bitumen to rise to the top during mixing.

5.1.4 MFT Cleanup
Experience in testing with MFT has shown that the household cooking oil spray PAM works very well in cleaning up bitumen stains on all surfaces including cleaning hands covered with bitumen. Other professionals have reported similar experience informally. PAM is edible and thus makes it a safe alternative to cleaning MFT as opposed to harmful chemical cleaners such as Toluene. The use of other brands of cooking oil sprays is assumed to work just as effective but no other types were tested.

5.2 Material Properties of MFT
Suncor provided mature fine tailings (MFT) from their South Tailings Pond (STP) located on at the east side of the Athabasca River for testing at the UBC laboratory. The STP pond started in 2006 so the MFT provided is considered very young and a sample taken from about 44 ft depth would be about the age
(see Table 5.4). Five 5 gallon buckets of MFT were provided and the material characteristics of each bucket were determined by Suncor and are listed in Table 5.4. The five buckets were mixed for several hours inside a one barrel to homogenize the sample and to reduce the shear strength to a minimum to provide consistent test samples.

<table>
<thead>
<tr>
<th>Bucket #</th>
<th>Depth (ft)</th>
<th>Bitumen</th>
<th>Mineral</th>
<th>Water</th>
<th>Fines¹</th>
<th>Clay²</th>
<th>CWR</th>
<th>SFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>0.81</td>
<td>27.56</td>
<td>71.76</td>
<td>98.6</td>
<td>91</td>
<td>0.35</td>
<td>0.014</td>
</tr>
<tr>
<td>2</td>
<td>29</td>
<td>0.74</td>
<td>29.32</td>
<td>69.97</td>
<td>96.7</td>
<td>100</td>
<td>0.42</td>
<td>0.033</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>0.74</td>
<td>30.42</td>
<td>68.74</td>
<td>98.1</td>
<td>90</td>
<td>0.40</td>
<td>0.019</td>
</tr>
<tr>
<td>4</td>
<td>39</td>
<td>0.74</td>
<td>32.81</td>
<td>66.5</td>
<td>97.5</td>
<td>88</td>
<td>0.44</td>
<td>0.025</td>
</tr>
<tr>
<td>5</td>
<td>44</td>
<td>0.74</td>
<td>35.2</td>
<td>63.98</td>
<td>95.7</td>
<td>78</td>
<td>0.43</td>
<td>0.044</td>
</tr>
<tr>
<td>Average</td>
<td>33.6</td>
<td>0.75</td>
<td>31.1</td>
<td>68.19</td>
<td>97.3</td>
<td>89.4</td>
<td>0.41</td>
<td>0.027</td>
</tr>
</tbody>
</table>

¹ Fines are defined as less than 44 μm and in this case was determined by wet sieve analysis
² Clay content determined by methylene blue test

The clay to water ratio (CWR) is defined as:

\[
CWR = \frac{\text{mass of clay}}{\text{mass of water}}
\] (5.1)

The CWR is calculated by using a percentage by mass approach. Thus for bucket 1, the MFT has a CWR = \((27.56 \times 91)/71.76 = 0.35\). The average CWR of the sample is 0.41.

The sand-fines ratio (SFR) is defined as:

\[
SFR = \frac{\text{mass of sand}}{\text{mass of fines (including bitumen)}}
\] (5.2)

Calculating by considering the percentage by mass approach, bucket 1 has MFT with a SFR = \((27.56 – 27.56 \times 98.6/100)/(27.56 \times 98.6/100+0.81) = 0.014\). The average SFR for the MFT is 0.027 which shows that the role of sand in the MFT provided is very low and suggests that, as results will show, permeability will be very low.

From Table 5.4, the MFT has an average of 97.3% fines and 89.4% clay content by mass which help explain the low permeability and long consolidation times. The pH of the MFT ranged from 8.72 for the second test to 8.56 on the final test. The shear strength for the first test was 2.2 pa but increased to 8.2
prior to the third test due to a slight increase in solids content from 31.6% to 33.5%. The results of shear strength testing on MFT are discussed in detail in section 5.1.

5.2.1 Low density Slurry Void Ratio Gradient

It is important that slurry like material have a non linear void ratio gradient, as can be seen in Figure 5.3. For samples with low density or high void ratios the void ratio is more pronounced with the bottom being significantly denser than the top. For high density or low void ratio samples the void ratio is more uniform.

![Figure 5.3: Density or void ratio distribution at different void ratios](image)

The SICT provides only linear average void ratio measurements. Thus all the SICT results presented in this thesis for both CU and UBC use the linear average void ratio. At higher stresses and hence lower void ratios, the void ratios at the top and bottom of the sample coincide with the same void ratio. At lower stresses or higher void ratios the difference between the top and bottom void ratios of the sample are minimized by selecting a thin initial sample height (see section 5.1.2 for MFT sample height selection) and by imposing low flow rates through the sample during permeability measurements (see section 5.3). Low flow rates impose a smaller hydraulic gradient across the sample thus the top and bottom of the sample have more comparable stress states as opposed to high flow rates.

5.3 Recommended Flow Rates for Permeability Measurements

The recommended imposed Darcian velocities and flow rates for permeability measurements during the seepage induced and step loading phases are shown in Table 5.5 and Table 5.6, respectively.
Table 5.5: Recommended Darcian velocities during seepage induced consolidation phase

<table>
<thead>
<tr>
<th>Material</th>
<th>Recommended Darcian Velocity during seepage induced consolidation phase</th>
<th>Equivalent Flow Rates through sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite clay</td>
<td>$1.3 \times 10^{-7}$ m/sec</td>
<td>$2.4 \times 10^{-9}$ m$^3$/s</td>
</tr>
<tr>
<td>Copper Tailings</td>
<td>$2.6 \times 10^{-7}$ m/sec</td>
<td>$4.7 \times 10^{-9}$ m$^3$/s</td>
</tr>
<tr>
<td>Mature Fine Tailings</td>
<td>$6.5 \times 10^{-9}$ m/sec</td>
<td>$1.2 \times 10^{-10}$ m$^3$/s</td>
</tr>
<tr>
<td>Minimum Pump Speed</td>
<td>$8.7 \times 10^{-10}$ m/sec</td>
<td>$1.6 \times 10^{-11}$ m$^3$/s</td>
</tr>
</tbody>
</table>

Table 5.6: Recommended Darcian velocities during the step loading phase

<table>
<thead>
<tr>
<th>Material</th>
<th>Recommended Darcian Velocity during seepage induced consolidation phase</th>
<th>Equivalent Flow Rates through sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite clay</td>
<td>$4.3 \times 10^{-9}$ m/sec</td>
<td>$7.8 \times 10^{-11}$ m$^3$/s</td>
</tr>
<tr>
<td>Copper Tailings</td>
<td>$4.3 \times 10^{-8}$ m/sec</td>
<td>$7.8 \times 10^{-10}$ m$^3$/s</td>
</tr>
<tr>
<td>Mature Fine Tailings</td>
<td>$8.7 \times 10^{-10}$ m/sec</td>
<td>$1.6 \times 10^{-11}$ m$^3$/s</td>
</tr>
<tr>
<td>Minimum Pump Speed</td>
<td>$8.7 \times 10^{-10}$ m/sec</td>
<td>$1.6 \times 10^{-11}$ m$^3$/s</td>
</tr>
</tbody>
</table>

It is important to note that the recommended flow rates are very close to the lowest possible flow rate that the current flow pump can achieve. The recommended flow rate for MFT during the step load is in fact the minimum possible flow rate for the current flow pump at UBC.

It is also important to note that, as a rule of thumb, the flow rate during the step load phase should be at least one order of magnitude less than during the steady state phase. This is because the applied step load will increase the resulting excess pore pressure thus a lower Darcian velocity is desired to speed up the permeability measurement as opposed to waiting longer for higher water pressure buildup.

5.4 MFT SICT UBC Results

Three SIC tests were performed on MFT at the UBC laboratory. The result of each individual test is shown in Appendix D. The comparison of the tests with the SICT at CU is shown in section 5.5.

It is important to note that from the first test on MFT, the initial sample height was selected to be 70 mm but proved to prolong the test to about 2 months until completion. For the later tests the sample heights were about half that of the first test and this greatly reduced the completion times. See section 5.1.2 for a full discussion on the MFT sample height selection.
From the first test on MFT it was also observed that the imposed flow rate was too large during the seepage induced phase which, like the tall sample height, significantly prolonged the test. The imposed flow rate was $2.4 \times 10^{-10} \text{ m}^3/\text{s}$ and in conjunction with tall sample height, it was estimated that it would take several months to achieve the steady state. Thus the flow rate was lowered to $1.2 \times 10^{-10} \text{ m}^3/\text{s}$ so that pore pressure build up would be smaller and steady state achieved sooner. See section 5.3 for recommended flow rates during permeability measurements. It is important to note that lowering the flow rate causes the sample to undergo slight over consolidation but the results were not observed to be affected significantly.

5.5 Comparison with MFT Testing at CU

Samples of MFT from the UBC and CU laboratories were sent to Maxxam Analytics to provide a comparison of the materials properties and the results are shown in Table 5.7 and Figure 5.4.

The clay content determined by Maxxam for the MFT at UBC was 69% and was significantly lower than that determined by Suncor (see Table 5.4) which was 89.4%. The particle size distribution (PSD) analysis performed by Maxxam showed about 77% fines for the MFT at UBC. This is also significantly lower than both wet sieves results by Maxxam and Suncor which showed about 97% fines. The differences in the results may be due to slight differences in test methodology. Since both Maxxam and Suncor showed similar fines content with the traditional wet sieve analysis (about 97% fines) the actual properties of the UBC MFT should lean more towards the finer side. Thus Suncor’s clay content measurement of 89.4% may be more representative of the actual material. Nonetheless, since Maxxam performed simultaneous tests on MFT from the UBC and CU laboratories, the results allow a proper comparison to be made of the material and consolidation properties of the two materials.
### Table 5.7: MFT Material Properties: UBC vs. CU (Maxxam Testing)

<table>
<thead>
<tr>
<th></th>
<th>MFT at UBC</th>
<th>MFT at CU</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt. % fines (&lt; 44 μm) (wet sieve)</td>
<td>96.5%</td>
<td>91.7%</td>
</tr>
<tr>
<td>wt.% Clay (by Methylene Blue Index)</td>
<td>69%</td>
<td>65%</td>
</tr>
<tr>
<td>Sands to Fines Ratio</td>
<td>0.023</td>
<td>0.0740</td>
</tr>
<tr>
<td>wt.% Bitumen</td>
<td>0.62%</td>
<td>2.42%</td>
</tr>
<tr>
<td>wt.% Solids</td>
<td>32.84%</td>
<td>29.20%</td>
</tr>
</tbody>
</table>

Figure 5.4: MFT Particle Size Distribution (Laser Diffraction Test): UBC vs. CU (Maxxam Testing)

The material properties show that MFT used at the UBC SICT was finer with more clay than the MFT at CU. An interesting note is the CU MFT has a much higher bitumen content (2.42% vs. 0.62% for UBC MFT by wt.%). As the test results will show, the finer UBC MFT showed lower permeability even though the bitumen content was less.

The SICTA input data for the three tests on MFT at UBC are shown in Table 5.8. From the table it can be seen that the height of solids for the UBC MFT 1 test was double the other two tests and this is because of the higher initial sample height of 70 mm. This high initial sample height also means that the self weight of the sample would result in a higher bottom effective stress, $\sigma'_{sb}$, at steady state and this can be seen from the table.
Table 5.8: SICTA Input Parameters for UBC MFT Tests

<table>
<thead>
<tr>
<th>Test #</th>
<th>$e_o$ (mm)</th>
<th>$H_s$ (kN/m$^3$)</th>
<th>$\gamma_s$ (kN/m$^3$)</th>
<th>$G_s^*$ (kPa)</th>
<th>$H$ (mm)</th>
<th>$v_o$ (m/s)</th>
<th>$\sigma'_b$ (kPa)</th>
<th>$\sigma'_f$ (m/s)</th>
<th>$k_f$ (m/s)</th>
<th>$e_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBC 1</td>
<td>5.44</td>
<td>10.14</td>
<td>26.00</td>
<td>2.65</td>
<td>5.21</td>
<td>39.06</td>
<td>1.53x10^{-10}</td>
<td>10.05</td>
<td>1.95</td>
<td></td>
</tr>
<tr>
<td>UBC 2</td>
<td>5.26</td>
<td>5.22</td>
<td>26.00</td>
<td>2.65</td>
<td>1.66</td>
<td>24.78</td>
<td>8.88x10^{-11}</td>
<td>17.47</td>
<td>1.76</td>
<td></td>
</tr>
<tr>
<td>UBC 3</td>
<td>5.07</td>
<td>5.12</td>
<td>26.00</td>
<td>2.65</td>
<td>1.09</td>
<td>25.56</td>
<td>3.38x10^{-11}</td>
<td>87.52</td>
<td>1.06</td>
<td></td>
</tr>
</tbody>
</table>

Note: Refer to Table 3.1 for definition of the parameters

* The value for specific gravity is assumed based on typical values

The results of the tests on MFT at the UBC laboratory are compared with published data from the CU laboratory (Znidarčić, et al., 2011) on similar MFT samples. The results in terms of compressibility and permeability are shown in Table 5.9, Figure 5.5, and Figure 5.6.

Table 5.9: SICT Results – UBC SICT vs. CU SICT

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Compressibility ($e = A(\sigma'+Z)^B$)</th>
<th>Permeability (m/s) ($k = Ce^D$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CU MFT 5</td>
<td>$e = 3.27(\sigma' + 0.074 kPa)^{-0.195}$</td>
<td>$k = (2.5x10^{-11} m/s)e^{3.39}$</td>
</tr>
<tr>
<td>CU MFT 6</td>
<td>$e = 3.20(\sigma' + 0.007 kPa)^{-0.169}$</td>
<td>$k = (1.6x10^{-11} m/s)e^{3.71}$</td>
</tr>
<tr>
<td>UBC MFT 1</td>
<td>$e = 3.00(\sigma' + 0.035 kPa)^{-0.177}$</td>
<td>$k = (1.4x10^{-11} m/s)e^{3.55}$</td>
</tr>
<tr>
<td>UBC MFT 2</td>
<td>$e = 3.52(\sigma' + 0.181 kPa)^{-0.236}$</td>
<td>$k = (1.1x10^{-11} m/s)e^{3.79}$</td>
</tr>
<tr>
<td>UBC MFT 3</td>
<td>$e = 3.81(\sigma' + 0.365 kPa)^{-0.285}$</td>
<td>$k = (2.8x10^{-11} m/s)e^{3.03}$</td>
</tr>
</tbody>
</table>

Figure 5.5: Compressibility of MFT – UBC SICT vs. CU SICT
The results from the UBC laboratory compare very well with the published data from CU. The UBC tests also show that the SICT is repeatable as all the tests provided similar results. The UBC MFT 1 test had a compressibility curve that was steeper at the lower effective stress range than the other tests. This is possibility due to the slight overconsolidation that took place during the test when the pump flow velocity was lowered during the initial steady state seepage induced consolidation phase.

The UBC tests showed slighter lower permeability results than the CU tests even though the CU MFT had higher bitumen content.
6 Discussion on SICT MFT Testing at UBC

The results from the SIC testing on MFT at the UBC laboratory are compared with published data from a large strain consolidometer test and presented in this chapter. The results are comparable and help build confidence in the SICT as viable consolidation characterization tool.

The one dimensional large strain consolidation software, CONDES0, is used to simulate the seepage induced steady state consolidation phase for the MFT SIC tests at UBC. CONDES0 is also used to model the settlement of a 9 month MFT settling test at UBC as well as a large scale MFT pond. The results are comparable with the CONDES0 predictions and are also presented in this chapter.

6.1 Comparison with Large Strain Consolidometer

The results of the SICT on the three MFT tests at UBC are compared to the results present by Pollock (1988) in which a large strain consolidometer was used in determining the compressibility and permeability of MFT. From the results of Pollock’s tests, best fit lines of the data points are constructed using the following exponential relationships:

\[ e = 28.71(\sigma')^{-0.3097} \]  \hspace{1cm} (6.1)

\[ k = (7.425 \times 10^{-11} \text{ m/s}) e^{3.847} \]  \hspace{1cm} (6.2)

where the effective stress, \( \sigma' \), is measured in pascals. The compressibility equation can be converted to have effective stress measured in kPa to make comparisons with UBC SICT results and the resulting equation is as follows:

\[ e = 28.71 \left( \frac{\sigma' \cdot 1000}{kPa} \right)^{-0.3097} = 28.71(1000)^{-3.097} (\sigma')^{-0.3097} \]  \hspace{1cm} (6.3)

\[ e = 3.38(\sigma')^{-0.3097} \]  \hspace{1cm} (6.4)

where the effective stress is measured in kPa. Note that the compressibility and permeability functions are in the same form used in the SICT except that there is no \( Z \) parameter in the compressibility relation. Since there is no \( Z \) parameter the compressibility function is not defined as effective stress approaches zero, as can be seen in Figure 6.1, in which void ratio approaches infinity as effective stress goes to zero.

A comparison of the material properties between the MFT at UBC and that used by Pollock (1988) during the large consolidometer test is shown in Table 6.1. From the table the MFT from both tests are very fine and should have permeabilities in the same order of magnitude. The bitumen content for the
MFT at the large consolidometer test was 6.6% of the total solids and this is much higher than at UBC which had only 0.75% of total solids. Although the bitumen content is much higher, there is substantially more sand than for that at the UBC sample as can be seen from the 8% sand of total solids (as compared with 2.6% at UBC) and the SFR of 0.087 (as compared with 0.027 at UBC).

Table 6.1: Material Properties Comparison – UBC SICT vs. Large Strain Consolidometer (Pollock, 1988)

<table>
<thead>
<tr>
<th></th>
<th>MFT in Large Strain Consolidometer</th>
<th>MFT in UBC SICT&lt;sup&gt;(3)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Solids content</td>
<td>29.1%</td>
<td>31.6 to 33.5%</td>
</tr>
<tr>
<td>%&lt;sup&gt;(1)&lt;/sup&gt; sand of total solids&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>8%</td>
<td>2.6%</td>
</tr>
<tr>
<td>% fines of total solids</td>
<td>92%</td>
<td>95%</td>
</tr>
<tr>
<td>% bitumen of total solids</td>
<td>6.6%</td>
<td>0.75%</td>
</tr>
<tr>
<td>% clay of fines</td>
<td>Approximately 50%</td>
<td>89.4%</td>
</tr>
<tr>
<td>Specific Gravity of Solids</td>
<td>2.39</td>
<td>2.65&lt;sup&gt;(4)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sands-Fine Ratio (SFR)</td>
<td>0.087</td>
<td>0.027</td>
</tr>
</tbody>
</table>

(1) All percentages are by a mass basis
(2) Total solids is taken as sum of mineral grains and bitumen
(3) Test results shown are Suncor testing
(4) Specific gravity is assumed for MFT used in UBC testing based on typical values

The results of the large strain consolidometer are compared with results from the UBC SICT in Table 6.2, Figure 6.1, and Figure 6.2. The parameters in the equations are very similar except for the C and Z parameters. The C parameter is significantly higher (but in the same order of magnitude) for the large strain consolidometer than for the UBC data. The Z parameter, as explained earlier, is taken as zero for the large strain consolidometer and thus the void ratio goes to infinite as effective stress approaches zero.

Table 6.2: Consolidation Results – UBC SICT vs. Large Strain Consolidometer

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Compressibility (e = A(\sigma' + Z)^b)</th>
<th>Permeability ((m/s) (k = Ce^D))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Strain</td>
<td>(e = 3.38(\sigma' + 0.3097)^{0.3097})</td>
<td>(k = (7.4 \times 10^{-11} \ m/s)e^{3.847})</td>
</tr>
<tr>
<td>Consolidometer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UBC MFT 1</td>
<td>(e = 3.00(\sigma' + 0.035 \ kPa)^{-0.177})</td>
<td>(k = (1.4 \times 10^{-11} \ m/s)e^{3.55})</td>
</tr>
<tr>
<td>UBC MFT 2</td>
<td>(e = 3.52(\sigma' + 0.181 \ kPa)^{-0.236})</td>
<td>(k = (1.1 \times 10^{-11} \ m/s)e^{3.79})</td>
</tr>
<tr>
<td>UBC MFT 3</td>
<td>(e = 3.81(\sigma' + 0.365 \ kPa)^{-0.285})</td>
<td>(k = (2.8 \times 10^{-11} \ m/s)e^{3.03})</td>
</tr>
</tbody>
</table>
From the results the MFT tests performed at the UBC laboratory are less permeable even though the bitumen content is less. The main reason for this is the very high clay content, higher fines content, and much less sand content. Pollock (1988) conducted further tests using the large strain consolidometer but with sand added to MFT and showed that the amount of sand added significantly increases the
permeability. The lower final void ratio for the MFT at the large strain consolidometer is also attributed to the higher sand content. From the compressibility results the MFT used in the large strain consolidometer shows a slightly more compressible curve than the UBC SICT and this may be attributed to the lower specific gravity of the material.

The permeability measurements at the high void ratios for the large strain consolidometer show a great deal of scatter, more so than tests performed at UBC. The SICT on the other hand through the sensitive flow rates achieved with the flow pump provides more consistent permeability measurements at high void ratios. Also the main disadvantage of the large strain consolidometer, as explained earlier, is the long completion times which can take up a year or longer.

### 6.2 CONDES0 Steady State Predictions

The compressibility and permeability equations determined with the SICT for the MFT samples are required for consolidation models that account for large strains and non-linear void ratio distributions. The computer program CONDES0 was developed by Yao and Znidarcic (1997) and is a one-dimensional large strain consolidation and desiccation model which numerically solves the non-linear equations of consolidation and desiccation theory through a finite element difference implicit method. It can be used to simulate tailings deposition and the resulting settlement and solids content distributions with time for a number of boundary conditions. The numerical solution theory, derivation, numerical solution is beyond the scope of this dissertation.

The CONDES0 is used in this section to predict the sample height at steady state during the seepage induced consolidation phase for the three MFT tests. Thus the CONDES0 program serves to provide a check of the results from the SICT.

#### 6.2.1 UBC MFT 1 CONDES0 Steady State Simulation

The results of the CONDES0 numerical simulation and the measured sample height with time for the UBC MFT 1 test until steady state are shown in Figure 6.3. From the figure it is important to note that the seepage induced phase was not started until about 250 hours from the start of the test. The pump flow velocity was deemed too high, as well as the sample height being too tall, in which the pore pressure build up was prolonged (see section Appendix D). Thus the settlement is more rapid than the predicted settlement until the point when the pump velocity was lowered. Thus the overall predicted settlement from the CONDES0 is lower than that of the measured values because of slight overconsolidation that occurs due to the high flow rate imposed on the sample. Another reason for the
lower predicted settlement is the fact that the estimated height of solids by CONDES0 is higher than measured values. The predicted height of solids is 10.88 mm which is higher than the actual height of 10.14 mm. It is also noted that the settlement was not completely steady because it would have prolonged the test too long and the settlement would not be significantly more than is shown.

6.2.2 UBC MFT 2 CONDES0 Steady State Simulation

The results of the CONDES0 numerical simulation and the measured sample height with time for the UBC MFT 2 test until steady state are shown in Figure 6.4. From the figure it the results of the measured and predicted settlement are very similar. The predicted settlement at steady state is slightly higher than measured values. This is mainly due to the estimation of the height of solids of the MFT by CONDES, which is once again slightly higher than the actual value. CONDES0 estimated the height of solids to be 5.50 mm which is higher than the actual height of 5.22 mm. Another note is that the LVDT rod was jammed during the two time periods shown in the figure and gave constant sample height readings. In Figure 6.4, however they are replaced with straight lines until the point where the LVDT rod was fixed and gave proper settlement readings.
6.2.3 UBC MFT 3 CONDES0 Steady State Simulation

The numerical simulation with CONDES0 and the measured sample height with time for the UBC MFT 3 test until the steady state are shown in Figure 6.5. From the figure it is important to note that at the start of the test until about the 125 hours mark the rate of consolidation was very rapid for the measured values. This is because during the test the de-air valve on the flow pump was left open and the triaxial cell was being drained of water at an unknown rate which was higher than the imposed flow rate at steady state. This caused slight overconsolidation of the sample and as a result the measured settlement at steady state is considerably more than predicted values. The effect of this slight overconsolidation was negligible in the SICT results. Another contribution to the lower predicted settlement is the higher estimated height of solids. CONDES0 estimated the height of solids to be 5.51 mm when the actual height was 5.12 mm.
6.3 Settling Test Results on MFT

A settling or column test was performed prior to each of the MFT tests in which MFT is poured into a column sealed from evaporation and allowed to settle due to self weight. This was to determine the zero effective stress, $e_o$, as explained in section 2.4.3. The first test, UBC MFT 1, had an initial height of 301.1 mm and had recorded settlement measurements for 9 months. The second and third tests had initial heights of 50 mm and 76 mm to speed up the rate of determining $e_o$ and less settlement data was obtained because they were performed after the first test. Because of the taller initial height and longer settlement time of the first test the UBC MFT 1 settling test results as well as the predicted settlement profile with CONDES0 are presented in this section. The settlement with time for the UBC MFT 1 settling test as well as the numerical prediction by CONDES0 is shown in Figure 6.6.
From the figure it is clear that the sample is settling steadily, although very slowly, due to self weight and after 6600 hours (or 9 months) it has settled about 30.7 mm. This is very close to the predicted settlement of 34.4 mm which builds confidence in the SICT consolidation parameters used in the CONDES0 program. The initial relatively rapid drop in the measured settlement of the MFT may be due to suspended particles settling quickly soon after mixing the sample and pouring into the column. The predicted total settlement for a column of MFT with an initial height of 301.1 mm is 81.90 mm and takes about 4.5 years to fully settle due to self weight to a height of 219 mm. Further monitoring of the settlement is required to compare with the predicted settlement path with time. The UBC MFT 1 settling test column of MFT is shown in Figure 6.7.
From the figure a very interesting observation is made which is that there is hardly any supernatant water present. This means that there is no dissipation of pore water during the consolidation process. The lack of supernatant water may suggest there is considerable air entrapped in the MFT and water is being prevented from rising through the particle matrix. The fact that the MFT in the settling column has a very high fines and clay content, repulsion forces may be why the settlement is slow with little water rising to the top.

6.3.1 MFT Pond Settlement Prediction

The compressibility and permeability equations determined from the SICT for the UBC MFT 1 test were used to predict the consolidation behaviour of a MFT pond of 50 m depth using the CONDES0 program. Figure 6.8 shows the predicted total settlement with time. When scaled up to an MFT pond depth of 50 m, the total predicted settlement is 30 m and would take over 2000 years to fully settle due to self weight to a height of 20 m. Note precipitation and evaporation were not accounted for in the analysis.
This predicted settlement profile for an MFT pond of 50 m depth might explain why for several decades Suncor’s Pond 1A MFT storage pond has appeared to be static (Wells, 2011). The predicted settlement after the first 10 years is only 0.5 m while the settlement rate decreases with time. This corresponds to an initial settlement rate of 5 cm per year which is difficult to detect when considering large scale ponds. Thus the MFT may be settling too slowly for proper volume change measurements and a longer time frame is required for settlement to be accurately observed.
7 Summary, Conclusions and Recommendations

7.1 Summary

The exploration and mining of soil sands involves the production of large quantities of low density slurry tailings which once they reach about 30 % solids the consolidation is very slow. At this point the tailings are called mature fine tailings (MFT) and comprise the bulk of the oil sands waste. The consolidation times are in the order of magnitude of decades to even centuries depending on the fines content. The proper characterization of the tailings in terms of compressibility (void ratio vs. effective stress) and permeability (void ratio vs. hydraulic conductivity) is crucial for predicting the consolidation rates and thereby properly designing mining waste facilities.

Many consolidation test apparatus have been conceived to characterize MFT but most have significant limitations and making their continued use not practical for commercial or research use. The large strain consolidometer has been used to determine consolidation parameters but the completion times can take over a year which makes it not commercially viable. It is also limited in that it uses the constant head test to measure permeability which is both time consuming and raises issues about the accuracy of flow rate measurements. Other tests such as the constant rate of loading and constant rate of deformation tests require that small strain assumptions are included. The main issue with most of the testing is the measurement of permeability at very low flow rates. The use of a flow pump to impose a known flow rate for permeability measurements has been avoided in the past for low density slurries because pumps were not sensitive enough to impose such flow rates until recently.

The seepage induced consolidation test was developed at Colorado University (CU), Boulder two decades ago and has provided accurate and reliable consolidation parameters for low density slurries such as phosphate tailings and kaolinite clay. The test involves imposing a seepage force across a slurry sample which is converted to an effective stress force and consolidates the sample. This allows for the permeability to be determined at very low effective stresses (< 1 kPa) and high average void ratios to be accurately measured.

A SICT has been constructed at UBC but with modifications to improve on the testing performance and decrease completion times for the test. The SICT at UBC improves upon the SICT at CU by through the following modifications:
• A larger sample diameter can be tested which allows for finer control on the imposed flow rate across the sample for permeability measurements.
• The LVDT placement is modified so that continuous measurement of sample height can be obtained.
• The pump is equipped with an encoder to continuously track the position of the pump to allow for automatic resets once the maximum volume is pumped out through the sample.

The SICT at UBC has been shown to be reliable through benchmark testing on kaolinite clay and compared with the CU SICT. Tests on kaolinite are comparable at both the CU and UBC laboratory and results show repeatable data. This gave added confidence into testing on MFT. Test results on MFT at the UBC laboratory showed repeatable results and were comparable to published data from the SICT at CU. The MFT tests were also compared with tests performed by a large strain consolidometer (Pollock, 1988) on MFT that contained a higher content of sand. The results gave reasonable data which showed the MFT at UBC, which has a very high fines and clay content, to be less permeable which was as expected.

The compressibility and permeability relations determined from the SICT are required for large strain consolidation programs in predicting settlement and solids content distributions with time. The one dimensional numerical consolidation program CONDES0 was used to predict the steady state sample heights at the seepage induced consolidation phase and gave comparable results. CONDES0 was also used to predict the settlement with time of an MFT column of slurry which is completely sealed and gave an accurate prediction of the total settlement over a 9 month period. The predicted settlement also suggest that MFT ponds in the field might be consolidating too slowly too slowly for accurate volume change measurements. The predicted settlement involved directly inputting the compressibility and permeability equations obtain from the SICT for the UBC MFT 1 test into the CONDES0 program. This also helped validate the SICT constructed at UBC as a reliable experimental technique for determining consolidation constitutive relations of MFT.

7.2 Conclusions

The seepage induced consolidation test (SICT) has been constructed at UBC to accurately determine the compressibility and permeability relations for low density slurries. Benchmark testing has been conducted on kaolinite clay and shown comparable results with similar testing at the SICT at Colorado University (CU) in Boulder.
SIC testing has been performed on MFT provided by Suncor Energy from their South Tailings Pond. The results have been compared along side with similar MFT testing from the SICT at the CU laboratory as well as a test from a large strain consolidometer. The results are in agreement with the published data and this helps build confidence in the SICT as a reliable tool for consolidation characterization of low density slurries such as MFT.

7.3 Recommendations

7.3.1 Modifications to the SICT
For future versions of the SICT it is recommended that air pressure step loading system be replaced with an electrical powered actuator which in much the same the current flow pump at UBC constructed. This allows for an extremely fine tuning of the applied load as well as more accurately measuring the load especially at low effective stresses. This is because as opposed to conventional step loading systems no air pressure is required to expand a rubber diaphragm, which then applies a force to a loading rod. The conventional setup intrinsically brings up many possible errors in measuring the actual load applied especially since a pressure gauge is required to measure the pressure. Using a mechanical actuator to apply the load only requires an electrical signal to turn the actuator slightly to apply any given load which will be kept constant without the need for a steady supply of air pressure which is by nature never completely steady.

7.3.2 Further MFT Pond Measurements
The predicted settlement of an MFT pond of 50 m depth using the one dimensional consolidation model, CONDES0, suggest that volume change measurements in the field are not capable of measuring the very small predicted settlement with time. Longer settlement times are required before settlements become more apparent. Thus it is recommended that field measurements either be improved to accurately measure small volume changes or longer settlement times are required before obtaining accurate settlement measurements.

7.3.3 Future Testing at UBC
The results of the SICT at the UBC laboratory give confidence in exploring MFT with varying properties to accurately determine the compressibility and permeability relations. The need for dewatering and efficiently managing the large MFT ponds will require the experimentation of different flocculent and additives. But before this and other dewatering and increasing consolidation rate methods are applied in the field on a large scale they must be first tested in the laboratory. The SICT at UBC is a perfect
candidate for testing such materials to help build a better understanding of how such additives will affect the behaviour in the long term. The SICT is relatively inexpensive to overall mining operations and takes a fraction of the time that the large strain consolidometer takes to complete a test which makes it ideal for characterization a wide variety of MFT and MFT with added flocculants. This also allows for range of compressibility and permeability to be cataloged for MFT with varying properties to help in the preliminary design stages in mine planning.

7.3.3.1 SICT to test Thixotropy of MFT
The concept of thixotropy is not fully understood in terms of its affect on consolidation of MFT and the SICT could be used to test this phenomenon. A possible test procedure could be that the MFT is allowed to gel inside the test apparatus for a period of days, weeks, or even months prior to beginning the seepage induced consolidation phase. The resulting consolidation characterizations can be compared with each different length of time to show what affect, if any, the thixotropy of MFT has on consolidation.
References


Scott, J. D. et al., 2013. *Properties which affect the consolidation behaviour of mature fine tailings*. Banff, Alberta, University of Alberta.


Appendix A  Derivation of Large Strain Consolidation Theory

The derivation that follows for Gibson et al’s (1967) formulation for large strain consolidation theory, equation (2.21), is presented here. The derivation presented here is based on Lee’s (1979) derivation of the governing equation and it is identical to Gibson et al’s formulation.

Note that the formulation presented here considers depth as positive against gravity.

Since the Lagrangian element always contains the same amount of solids, the rate of fluid flow leaving a soil volume, v, will depend on the relative velocity between the solid and fluid phase (Lee, 1979):

\[ v = n(v_f - v_s) \]  \hspace{1cm} (A.1)

where \( n \) is the porosity, \( v_f \) is the fluid velocity, and \( v_s \) is the velocity of solids. The use of the relative velocity of water to solids is an important consideration that Terzaghi did not consider in his formulation of small strain consolidation theory. The water flow velocity was only considered in Terzaghi’s derivation as water flow takes place so does deformation, so solid particles must be moving in and out of an element (Lee, 1979). Since Terzaghi considered an element of a fixed total volume and if the total volume of solids did not change, no flow would occur. Although Terzaghi did not consider this in his derivation but it would not have affected the final equation he derived because the use of Darcy’s law and conservation of mass cancels the water flow velocity.

In order to obey the law of conservation of mass, the deformation with time must equal to the rate of which fluid escapes the element; thus the continuity equation is:

\[ \frac{\partial e}{\partial t} = -\frac{\partial v_D}{\partial z} = -\frac{\partial}{\partial z} \left[ n(v_f - v_s) \right] \]  \hspace{1cm} (A.2)

Assuming the soil layer obeys Darcy’s law and using the relative velocity from equation (A.2) as the velocity in Darcy’s law, the following equation is obtained:

\[ \frac{\partial e}{\partial t} = -\frac{\partial}{\partial z} (k \cdot i) = -\frac{\partial}{\partial z} \left[ k \cdot \frac{\partial h}{\partial a} \right] \]  \hspace{1cm} (A.3)

where \( \partial h \) is the pressure head across the element and \( k \) is the hydraulic conductivity. The Lagrangian coordinate \( \partial a \) can be converted to the reduced Lagrangian coordinate by rearranging equation (2.23) as follows:
\[ \partial a = (1 + e) \cdot \partial z \]  

(A.4)

Combining equation (A.4) with (A.3) along with the fact that the pressure head, \( \partial h \), is equal to the excess pore pressure, \( \partial u_e \), divided by the unit weight of water, \( \gamma_w \), the following equation for the conservation of mass is obtained:

\[ \partial h = \frac{\partial u_e}{\gamma_w} \]  

(A.5)

\[ \frac{\partial e}{\partial t} = -\frac{\partial}{\partial z} \left( k \frac{1}{\gamma_w} \frac{1 + e}{\partial z} \right) \]  

(A.6)

Equation (A.6) links the rate of deformation with the rate of dissipation of the excess pore water pressure, \( u_e \). The gradient, \( \partial u_e/\partial z \), is linked to the total and effective stresses through the following:

\[ \frac{\partial u_e}{\partial z} = \frac{\partial \sigma}{\partial z} - \frac{\partial \sigma'}{\partial z} - \frac{\partial u_h}{\partial z} \]  

(A.7)

Where \( \sigma \) is the total stress, \( \sigma' \) is the effective stress and \( u_h \) is the hydrostatic pore pressure. When accounting for the self weight of the soil and assuming it is uniformly distributed, the total stress in Lagrangian coordinates is as follows (see Figure 2.20 as reference):

\[ \frac{\partial \sigma}{\partial a} = -\frac{\gamma_s + \gamma_w e}{1 + e} \]  

(A.8)

Converting to the reduced material coordinate, \( z \), by rearranging equation (2.23) yields:

\[ \frac{\partial \sigma}{\partial z} = \frac{\partial \sigma}{\partial a} \frac{\partial a}{\partial z} = -\left( \gamma_s + \gamma_w e \right) \]  

(A.9)

Similarly, the hydrostatic pore pressure gradient, in the reduced material coordinate, \( z \), is as follows:

\[ \frac{\partial u_h}{\partial z} = \frac{\partial u_h}{\partial a} \frac{\partial a}{\partial z} = -(1 + e)\gamma_w \]  

(A.10)

Combining equations (A.9) and (A.10) into (A.7) yields the following equation for the excess pore pressure gradient:

\[ \frac{\partial u_e}{\partial z} = -\left( \gamma_s - \gamma_w \right) - \frac{\partial \sigma'}{\partial z} \]  

(A.11)

Substituting equation (A.11) into equation (A.6) and rearranging yields the governing equation for large strain consolidation theory:
Equation (A.12) is identical to the formulation by Gibson et al (1967) and as noted before, the (+) convention is taken if \( z \) is measured as positive against gravity. In this general formulation, self weight effects are accounted for, the assumption of small strain is removed and no assumptions are placed on the compressibility, \( \sigma'/\partial e \), and the permeability, \( k \). In using this formulation it is apparent that the permeability and permeability functions must be provided for.
Appendix B  SICTA Iteration Scheme

From section 2.3.3, the following data is collected from the SICT:

1. Void ratio at zero effective stress: \( e_o \)
2. Bottom effective stress and sample height at steady state: \( \sigma'_{sb}, H_{ss} \)
3. Applied effective stress, permeability and void ratio at final step load: \( \sigma'_f, k_f, \) and \( e_f \)

The compressibility and permeability functions, equations (2.24) and (2.25), are determined by solving the five parameters \( A, B, Z, C, \) and \( D \) using the data from steps one and three and back calculating the measured \( \sigma'_{sb} \) and \( H_{ss} \) at steady state in step two in an iterative scheme which numerically solves the integral form of the governing equation of large strain consolidation at steady state, equation (2.31).

For each set of the five parameters \( A, B, Z, C, \) and \( D, \) an iterative scheme is employed to approximate the void ratio distribution at steady state. The data from steps one and three in section 2.3.3 are used to write the parameters \( A, C, \) and \( Z \) as functions dependent on the values \( B \) and \( D \) as follows:

\[
A = \frac{e_o}{Z^B} \quad \text{(B.13)}
\]
\[
C = \frac{k_f}{(e_f)^D} \quad \text{(B.14)}
\]
\[
Z = \frac{\sigma'_f}{(e_f)^{1/B}} - 1 \quad \text{(B.15)}
\]

The parameters \( B \) and \( D \) are chosen as independent values and given initial guesses at the start of the program. The initial guesses will thus yield one set of the five parameters \( A, B, Z, C, \) and \( D. \) The parameters \( B \) and \( D \) will be modified in the iterative scheme that follows.

The height of solids, \( H_s \), is determined using equation (2.23) but with the initial height of the sample, \( H_i \), replacing the Lagrangian coordinate, \( a, \) as follows:

\[
H_s = \frac{H_i}{1 + e_o} \quad \text{(B.16)}
\]

In the analysis, \( H_s \) is divided into a given number of nodes, \( N. \) Then a numerical solution for the steady state void ratio distribution across every node is employed that satisfies simultaneously the governing equation (2.31) and the compressibility and permeability equations, (2.24) and (2.25), respectively. The first iteration involves determining the effective stress at each node due only to self weight and top
imposed stress. From this effective stress, the void ratio is calculated using equation (2.24) at each node. From the calculated void ratio at each node, the permeability is then calculated using equation (2.25) at each node. From the void ratio and permeability, effective stress from seepage and thus total effective stress is calculated at each node. Then a new void ratio is calculated again using equation (2.24) but for the latest effective stress at each node. This procedure is repeated until the difference between two consecutive iterations, $i$ and $i + 1$, satisfies:

$$\sum_{j=1}^{j=N} \left| \frac{e_{j+1}^i - e_j^i}{e_j^i} \right| < \epsilon$$

where $\epsilon$ is a specified small value.

A table illustrating the iterative scheme is shown in Table B.1. The first column for the effective stress, $\sigma'(z)_1$ uses equation (2.31) but without the seepage force term. An example of the iteration scheme is shown in Figure B.1, and it is important to note the quick convergence.

### Table B.1: Void Ratio Distribution Iterative Scheme

<table>
<thead>
<tr>
<th>Node #</th>
<th>$z$</th>
<th>$\sigma'(z)_1$</th>
<th>$e_1$</th>
<th>$k_1$</th>
<th>$\sigma'(z)_2$</th>
<th>$e_2$</th>
<th>......</th>
<th>$k_n$</th>
<th>$\sigma'(z)_n$</th>
<th>$e_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$H_s/N*1$</td>
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<td></td>
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</tr>
<tr>
<td>2</td>
<td>$H_s/N*2$</td>
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<tr>
<td>N – 1</td>
<td>$H_s/N*(N-1)$</td>
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<td></td>
<td></td>
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<tr>
<td>N</td>
<td>$H_s$</td>
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</tbody>
</table>

*The first column of effective stress uses equation (2.31) but without the seepage force term
B.1 Parameter Estimation Analysis

From the iteration scheme shown in the previous section, the predicted steady state height, $H_n$, is calculated by summing up the final height of each node at the final iteration as follows:

$$H_n = \int_0^{H_s} (1 + e) \, dz$$

where $H_s$ is the height of solids. The predicted bottom effective stress at steady state, $\sigma'_{sbn}$, is calculated as:

$$\sigma'_{sbn} = \left( \frac{e_{sb}}{A} \right) \frac{1}{B} - Z$$

where $e_{sb}$ is the estimated void ratio at the bottom of the sample. These numerical predictions are compared to the experimental data at steady state through a normalized difference vector, $|X|$ as follows:
\[ |X| = \begin{bmatrix} 1 - \frac{\sigma'_{sb}}{\sigma'_{sb}} \\ 1 - \frac{H_n}{H_{ss}} \end{bmatrix} \]  \hspace{1cm} (B.20)

where \( \sigma'_{sb} \) and \( H_{ss} \) are the bottom effective stress and sample height, respectively at steady state. An iterative parameter estimation algorithm based on the Newton method coupled with the line search technique (Dennis & Schnabel, 1983) was developed by Abu-Hejle & Znidarcic (1992) and is used to minimize the total normalized difference \( Q \), expressed as:

\[ Q = X(1) + X(2) \]  \hspace{1cm} (B.21)

The initial estimates of \( B \) and \( D \) are used to estimate \( X(1) \) and \( X(2) \) but after that \( B \) and \( D \) are calculate for \( k + 1 \) iteration by:

\[ \begin{bmatrix} B^{k+1} \\ D^{k+1} \end{bmatrix} = \begin{bmatrix} B^k \\ D^k \end{bmatrix} + \begin{bmatrix} \frac{\partial X(1)^k}{\partial B^k} & \frac{\partial X(1)^k}{\partial D^k} \\ \frac{\partial X(2)^k}{\partial B^k} & \frac{\partial X(2)^k}{\partial D^k} \end{bmatrix}^{-1} \begin{bmatrix} X(1)^k \\ X(2)^k \end{bmatrix} \]  \hspace{1cm} (B.22)

The derivation and the numerical finite difference used in calculating the coefficients of the matrix for the above equation are outside the scope of this dissertation. The full derivation is shown by Abu-Hejle & Znidarcic (1992). The parameters \( B \) and \( D \) have specified upper and lower limits so if the analysis yields parameters outside these limits they are brought back to that limit, as illustrated in Figure B.2.
If the total normalized error at $k+1$, $Q_{k+1}$, is larger than at $k$, in other words $Q_{k+1} > Q^k$ then the line search technique developed by Dennis & Schnabel (1983) is employed. The line search technique is shown in Figure B.3.

The technique involves first selecting the variable, $\lambda$, to represent the linear change of the optimized parameters $B$ and $K$ from the iteration $k$ where $\lambda = 0$ to $k+1$ where $\lambda = 1$. The concept behind the line search technique is the assumption that there is a $Q$ value lower than $Q^k$ which is at the optimal $\lambda$ value, $\lambda_{opt}$. Thus using an appropriate slope, $S$, and assuming $Q$ follows a quadratic curve from $Q^k$ to $Q_{k+1}$, $\lambda_{opt}$ can be calculated using a quadratic interpolation (Abu-Hejleh & Znidarcic, 1992). $\lambda_{opt}$ represents the optimized parameters $B$ and $D$, which then replace $B^{k+1}$ and $D^{k+1}$. The total normalized error, $Q^{k+1}$, is then again checked and if it is less than $Q^k$, the same line search technique is repeated ten times. If after the tenth cycle it does meet the criteria, further modification is implemented (Abu-Hejleh & Znidarcic, 1992) although during all tests performed this was never observed to be the case as convergence of $B$ and $D$ parameters occurs rapidly. The quadratic interpolation and the numerical implantation of the line search technique is outside the scope of this thesis so refer to Abu-Hejleh & Znidarcic (1992) for the complete presentation of these concepts.

A useful flowchart for the overall SICTA methodology is shown in Figure B.4.
Determine these values from SICTA and Settling Test
1. Void ratio at zero effective stress, $e_0$
2. Sample height, $H$, and bottom effective stress at steady state, $\sigma_{sb}^\prime$
3. From one Step Load Point:
   a. Final Void Ratio, $e_f$
   b. Final Top Stress, $\sigma_f^\prime$
   c. Final Coefficient of permeability, $k_f$

Assign values to B and D

Employ a Parameter Estimation scheme to modify the parameters B and D to better estimate the steady state conditions

Develop 3 equations with 3 unknowns: $A, C, Z$
1. $\sigma_f^\prime = AZ^B$
2. $e_f = A(\sigma_f^\prime + Z)^B$
3. $k_f = C e_f^D$

Iterate until error between calculated and measured steady state sample height and bottom effective stress are minimized

Solve the 3 equations for the 3 unknowns
1. $Z = \frac{\sigma_f^\prime}{(\frac{e_f}{e_0})^{1/B} - 1}$
2. $A = \frac{e_0}{Z^B}$
3. $C = \frac{k_f}{(e_f)^D}$

Employ an iterative scheme to predict the seepage induced consolidation steady state sample height ($H$) and the bottom effective stress ($\sigma_{sb}^\prime$).

Figure B.4: SICTA Procedure Flow Chart
Appendix C  

SICT at UBC Kaolinite Clay Individual Test Results

Six SIC tests were performed at the UBC laboratory on kaolinite clay slurry. The first two tests were deemed trial tests and are not presented in this thesis because they had LVDT installation problems and thus the settlement readings were not accurate. The last four tests used factory settings for the LVDT calibration but the factory settings were confirmed to be reliable after calibration tests were conducted prior to MFT SICT testing (see Appendix H.2).

These SIC tests on kaolinite clay at UBC served as a means for building best practices during testing and to test the response of the equipment to various loads, loading rates and pump velocities. The results of the tests on kaolinite clay at the UBC laboratory are presented in this section. The comparison with CU SICT laboratory testing as well as published results from a desktop centrifuge test on kaolinite clay is presented in chapter 4.

C.1 UBC Kaolin 3

The SICTA input data for the UBC Kaolin 3 SIC test is shown in Table C.2. Equations (C.23) and (C.24) show the resulting compressibility and permeability relations, respectively. The outcomes as well as the measured data points are plotted on Figure C.5 and Figure C.6. Since the final step load data point is used in the analysis, the other two data points are independent of the analysis and are used as a check of the resulting curves and shows good agreement. The sample was prepared at an initial void ratio of 3.43, a solids content of 43.6% by mass and an initial height of 61 mm.

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Steady State Data</th>
<th>Step Load Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_o$ (mm)</td>
<td>$H_s$ (kN/m$^3$)</td>
<td>$G_s^*$</td>
</tr>
<tr>
<td>3.24</td>
<td>13.36</td>
<td>26.00</td>
</tr>
</tbody>
</table>

Note: Refer to Table 3.1 for definition of the parameters
* The value for specific gravity is assumed based on typical values

\[
e = 2.563 (\sigma'+0.195 \text{ kPa})^{-0.143} \quad \text{(C.23)}
\]

\[
k = (6.6x10^{-10} \text{ m/s})e^{3.89} \quad \text{(C.24)}
\]
C.2 UBC Kaolin 4

The SICTA input data for the UBC Kaolin 3 SIC test is shown in Table C.3. Equations (C.25) and (C.26) show the resulting compressibility and permeability relations, respectively. The equations as well as the
measured data points are plotted on Figure C.7 and Figure C.8. The sample was prepared at an initial void ratio of 3.31, a solids content of 44.4% by mass, and an initial height of 62 mm.

Table C.3: UBC Kaolin 4 SICTA Input Data

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Steady State Data</th>
<th>Step Load Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_o$</td>
<td>$H_s$ (mm)</td>
<td>$\gamma_s$ (kN/m$^3$)</td>
</tr>
<tr>
<td>3.10</td>
<td>13.80</td>
<td>26.00</td>
</tr>
</tbody>
</table>

Note: Refer to Table 3.1 for definition of the parameters

* The value for specific gravity is assumed based on typical values

\[ e = 2.759(\sigma' + 0.518 \; \text{kPa})^{-0.179} \quad (C.25) \]

\[ k = (4.4\times10^{-10} \; \text{m/s})e^{4.25} \quad (C.26) \]

Figure C.7: UBC Kaolin 4 – Compressibility
Figure C.8: UBC Kaolin 4 – Permeability

C.3 UBC Kaolin 5

The SICTA input data for the UBC Kaolin 3 SIC test is shown in Table C.4. Equations (C.27) and (C.28) show the resulting compressibility and permeability relations, respectively. The equations as well as the measured data points are plotted on Figure C.9 and Figure C.10. The sample was prepared at an initial void ratio of 4.58, a solids content of 36.7% by mass, and an initial height of 66 mm.

Table C.4: UBC Kaolin 5 SICTA Input Data

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Steady State Data</th>
<th>Step Load Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_o$</td>
<td>$H_s$ (mm)</td>
<td>$\gamma_s$ (kN/m$^3$)</td>
</tr>
<tr>
<td>3.53</td>
<td>11.27</td>
<td>26.00</td>
</tr>
</tbody>
</table>

Note: Refer to Table 3.1 for definition of the parameters

* The value for specific gravity is assumed based on typical values

\[ e = 2.548(\sigma' + 0.199 \text{ kPa})^{-0.202} \]  \hspace{1cm} (C.27)

\[ k = (7.6x10^{-10} \text{ m/s})e^{3.91} \]  \hspace{1cm} (C.28)
Figure C.9: UBC Kaolin 5 – Compressibility

Figure C.10: UBC Kaolin 5 – Permeability
C.4 UBC Kaolin 6

The SICTA input data for the UBC Kaolin 3 SIC test is shown in Table C.5. Equations (C.29) and (C.30) show the resulting compressibility and permeability relations, respectively. The equations as well as the measured data points are plotted on Figure C.11 and Figure C.12. The sample was prepared at an initial void ratio of 3.34, a solids content of 44.3 % by mass, and initial height of 40 mm.

Table C.5: UBC Kaolin 6 SICTA Input Data

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Steady State Data</th>
<th>Step Load Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_o$ (mm)</td>
<td>$H_s$ (kN/m$^3$)</td>
<td>$v_s$ (kN/m$^3$)</td>
</tr>
<tr>
<td>2.84</td>
<td>8.92</td>
<td>26.00</td>
</tr>
</tbody>
</table>

Note: Refer to Table 3.1 for definition of the parameters.
* The value for specific gravity is assumed based on typical values.

\[
e = 2.368(\sigma' + 0.357 \text{ kPa})^{-0.176}
\] (C.29)

\[
k = (8.3 \times 10^{-10} \text{ m/s})e^{4.10}
\] (C.30)

Figure C.11: UBC Kaolin 6 - Compressibility
Figure C.12: UBC Kaolin 6 – Permeability
Appendix D  

SICT at UBC MFT Results

Three tests were performed on MFT which was provided by Suncor Energy and the results of each test are presented in this section.

D.1  UBC MFT 1

The SICTA input parameters for the first test on MFT at UBC, labeled UBC MFT 1, are shown in Table D.6. The results of the SICT are shown in equations (D.31) and (D.32) which are plotted on Figure D.13 and Figure D.14. The sample was prepared at an initial void ratio of 5.73, a solids content of 31.6% by mass, and an initial height of 70 mm.

Table D.6: UBC MFT 1 SICTA Input Data

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Steady State Data</th>
<th>Step Load Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_0$ (mm)</td>
<td>$H_s$ (kN/m^3)</td>
<td>$G_s^*$</td>
</tr>
<tr>
<td>5.44</td>
<td>10.14</td>
<td>26.00</td>
</tr>
<tr>
<td>$Y_s$ (kN/m^3)</td>
<td>$G_s^*$ (kPa)</td>
<td>$H$ (mm)</td>
</tr>
<tr>
<td>2.65</td>
<td>5.21</td>
<td>39.06</td>
</tr>
<tr>
<td>$G_s^*$ (kPa)</td>
<td>$H$ (mm)</td>
<td>$v_D$ (m/s)</td>
</tr>
<tr>
<td>5.21</td>
<td>39.06</td>
<td>6.51x10^{-9}</td>
</tr>
<tr>
<td>$H$ (mm)</td>
<td>$v_D$ (m/s)</td>
<td>$\sigma'_f$</td>
</tr>
<tr>
<td>5.21</td>
<td>39.06</td>
<td>10.05</td>
</tr>
<tr>
<td>$v_D$ (m/s)</td>
<td>$\sigma'_f$</td>
<td>$k_f$ (m/s)</td>
</tr>
<tr>
<td>6.51x10^{-9}</td>
<td>10.05</td>
<td>1.53x10^{-10}</td>
</tr>
<tr>
<td>$\sigma'_f$</td>
<td>$k_f$ (m/s)</td>
<td>$e_f$</td>
</tr>
<tr>
<td>10.05</td>
<td>1.53x10^{-10}</td>
<td>1.95</td>
</tr>
</tbody>
</table>

Note: Refer to Table 3.1 for definition of the parameters
* The value for specific gravity is assumed based on typical values

\[
e = 3.00(\sigma' + 0.035 \text{ kPa})^{-0.177} \quad \text{(D.31)}
\]

\[
k = (1.4x10^{-11} \text{ m/s})e^{3.55} \quad \text{(D.32)}
\]
The initial sample height of 70 mm which is relatively high and proved to prolong the test to about 2 months before it was completed. Since it was taking a long time, the test was stopped before the final step loading permeability was obtained. During this time the pore pressure build up of the MFT during the permeability measurement was predicted to take up to another month to complete and thus deemed too long. The pore pressure difference and sample height measurements with time are shown in Figure D.15. From the figure it can be seen at about the 1500 hours mark, test was stopped prior to the pore pressure build up due to seepage was complete. Thus the analysis of the test was performed with the first step load data point (see Figure D.13). SIC tests performed after this test were prepared at sample heights close to 35 mm and significantly reduced completion times to about a month in duration but with more step loading data points plotted. Further information on sample height selection for MFT is discussed in section 5.1.2.

Also from Figure D.15, the initial steady state seepage test was also stopped short before steady state was achieved. This was because the imposed flow rate, together with the tall sample height, proved that the pore pressure build up would be really high and take several more months to achieve steady state. The imposed flow rate through the sample at this point was 2.4x10^{-10} \text{ m}^3/\text{s}. The flow rate was then lowered by half to 1.2x10^{-10} \text{ m}^3/\text{s} so that pore pressure build up would be smaller and steady state achieved sooner. See section 5.3 for recommended flow rates during permeability measurements. It is
important to note that lowering the flow rate causes the sample to undergo slight over consolidation but the results were not observed to be affected significantly.

![Figure D.15: UBC MFT 1 – Pore Pressure Readings and Sample Height with Time](image)

**Figure D.15: UBC MFT 1 – Pore Pressure Readings and Sample Height with Time**

### D.2 UBC MFT 2

The SICTA input parameters for the UBC MFT 2 test are shown in Table D.7. The results of the SICT are shown in equations (D.33) and (D.34) and plotted in Figure D.16 and Figure D.17. The sample was prepared at an initial void ratio of 5.37, solids content of 33.5 % by mass, and an initial height of 34.5 mm.

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Steady State Data</th>
<th>Step Load Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_o$ (mm)</td>
<td>$H_s$ (kN/m$^3$)</td>
<td>$G_s$ *</td>
</tr>
<tr>
<td>5.26</td>
<td>5.22</td>
<td>2.65</td>
</tr>
<tr>
<td>$V_s$ (kN/m$^3$)</td>
<td>$G_s$ * (kPa)</td>
<td>$H$ (mm)</td>
</tr>
<tr>
<td>26.00</td>
<td>1.66</td>
<td>24.78</td>
</tr>
<tr>
<td>$G_s$ * (kPa)</td>
<td>$v_D$ (m/s)</td>
<td>$\sigma'_f$</td>
</tr>
<tr>
<td>2.65</td>
<td>8.68x10$^{-9}$</td>
<td>17.47</td>
</tr>
<tr>
<td>$H$ (mm)</td>
<td>$k_f$ (m/s)</td>
<td>$e_f$</td>
</tr>
<tr>
<td>24.78</td>
<td>8.88x10$^{-11}$</td>
<td>1.76</td>
</tr>
</tbody>
</table>

Table D.7: UBC MFT 2 SICTA Input Data

Note: Refer to Table 3.1 for definition of the parameters
* The value for specific gravity is assumed based on typical values

\[ e = 3.52(\sigma' + 0.181 \, kPa)^{-0.236} \]  
(D.33)
\[ k = (1.1 \times 10^{-11} \text{ m/s}) e^{3.79} \]  \hfill (D.34)

D.3 UBC MFT 3

The SICTA input parameters for the UBC MFT 3 test are shown in Table D.8. The results of the SICT are shown in equations (D.35) and (D.36) and plotted in Figure D.18 and Figure D.19. The sample was prepared at an initial void ratio of 5.27, a solids content of 33.5% by mass, and an initial height of 33.5 mm.
Table D.8: UBC MFT 3 SICTA Input Data

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Steady State Data</th>
<th>Step Load Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_o$ (mm)</td>
<td>$H_s$ (kN/m$^3$)</td>
<td>$v_s$ (mm)</td>
</tr>
<tr>
<td>5.07</td>
<td>5.12</td>
<td>26.00</td>
</tr>
<tr>
<td>$v_s$ (kN/m$^3$)</td>
<td>$G_s$ *</td>
<td>$\sigma'_sb$ (kPa)</td>
</tr>
<tr>
<td>2.65</td>
<td>1.09</td>
<td>25.56</td>
</tr>
<tr>
<td>$\gamma$ s (kN/m$^3$)</td>
<td>$H$ (mm)</td>
<td>$v_o$ (m/s)</td>
</tr>
<tr>
<td>2.65</td>
<td>1.09</td>
<td>6.51x10$^{-9}$</td>
</tr>
<tr>
<td>$\sigma'$</td>
<td>$k_f$ (m/s)</td>
<td>$e_f$</td>
</tr>
<tr>
<td>87.52</td>
<td>3.38x10$^{-11}$</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Note: Refer to Table 3.1 for definition of the parameters

* The value for specific gravity is assumed based on typical values

\[
e = 3.81(\sigma' + 0.365 \text{ kPa})^{-0.285}
\]  \hspace{1cm} (D.35)

\[
k = (2.8\times10^{-11} \text{ m/s})e^{3.03}
\]  \hspace{1cm} (D.36)

![Figure D.18: UBC MFT 3 Comparison – Compressibility](image)

![Figure D.19: UBC MFT 3 Comparison – Permeability](image)
Appendix E  SICT Detailed Procedure

The steps involved in performing a seepage induced consolidation test (SICT) are described here:

1. The first step in commencing the seepage induced consolidation test is to calibrate the load cell, pore pressure transducer, and LVDT. The calibration results are shown in the Appendix H.

2. All the water lines or tubes should be de-aired, and then filled with water through using the water pressure from the bucket of water. The pore pressure transducer and the flow pump are also de-aired in this step.

3. Preparing the slurry sample for testing depends on the material. For most slurry material adequate mixing until the slurry is homogeneous is the only requirement (see section 2.4). MFT requires more effort in required for sample preparation due to longer mixing times and this is detailed in section 5.1. Once the sample is taken, perform a water content test by placing some of the material for oven drying to obtain the initial void ratio, $e_i$ (see section 2.4).

4. Slurry materials undergo sedimentation when left to settle due to self weight thus the void ratio at zero effective stress, $e_o$, must be determined. This is done by pouring some of the material into a column sealed from evaporation and measuring the amount of settlement and determining $e_o$. This step is detailed in section 2.4.3.

5. Place a porous plastic disc on top of the sample pedestal. Place a wetted filter paper that is slightly larger in diameter than the porous disc on top of it to ensure a better seal with the sample casing. Install the sample casing around the porous plastic disc forming a water tight seal with the O-ring around the pedestal. Pour the slurry into the casing using a funnel to avoid smearing the casing at a height of 40 to 50 mm depending on the rate of settlement for the given material and the solids content. Since MFT has very long consolidation times it is recommended that a sample height should be selected to yield a height of solids of 5mm. This corresponds to a sample height of 32 mm for a MFT sample of 33% solids. MFT sample height selection is discussed further in section 5.1.2. Also with MFT it is important to remove residue visible bitumen which rises to the top of the MFT sample as is discussed in section 5.1.3.

6. Place another porous disc, but with a wetted filter paper the same diameter as it below the disc, on top of the sample. Add adequate tap water on top of the disc to allow for the loading piston to be full immersed. Place the loading piston on top of the sample. Install the rest of the triaxial cell, top cap, loading rod, and LVDT. Fill the triaxial cell with water from the raised bucket of water while closing the manual valve connected to the sample. This is to prevent water raising the sample before the cell is fully
pressurized. Once the cell is filled with water, open the manual valve to the sample. Begin recording
data with the LabVIEW controlled data acquisition system. Allow the sample to settle due to self weight.

7. After allowing the sample to settle for several hours, the seepage phase is started setting the
flow pump to a desired flow velocity and closing the refill valve. When the refill valve is closed and the
sample valve is open, the pump will start take water out of the sample only. The pump flow velocity is
selected that corresponds to an appropriate Darcian velocity across the sample. An appropriate Darcian
velocity depends on the material being tested with lower velocities for more plastic clay material
(Znidarčić, et al., 1992). One guideline to follow is to start with a low velocity and increase when the
resulting pressure difference is much less than 1.5 kPa. If the velocity is too high and a pressure
difference exceeding 10 kPa is observed, a new sample must be prepared because reducing the flow
rate would result in partially overconsolidating the sample, leading to erroneous results (Znidarčić, et al.,
1992). Table 5.5 from section 5.3 shows recommended Darcian velocities and equivalent flow rates
through the sample for the material tested at UBC. It is important to note that the recommended flow
rates are very close to the lowest possible flow rate that the current flow pump can achieve.

8. When the pore pressure transducer readings and the LVDT readings are steady, the steady state
is reached. At this point the refill valve is open and the pore pressure transducer will give out the overall
water pressure reading from the raised water bucket and will be referred to as the zero pressure
reading. The pore pressure reading at steady state corresponds to the excess pore pressure at the
bottom of the sample because the sample valve is open and refill valve is closed. The steady state
reading must be subtracted by the zero reading to get the net excess pore pressure at the bottom of the
sample.

9. At this point step loading is commenced by slowly increasing the load pressure applied to the
sample. The minimum step load is the highest pressure that the sample has experienced to avoid
effectively testing an overconsolidated sample. Once the load is applied and the sample is allowed to
settle, the seepage test in Step 8 is performed here except the Darcian velocity selected, based on
experience, should be at least one order of magnitude less than during the steady state phases. This is
because the applied loads will increase the resulting excess pore pressure thus a lower Darcian velocity
is desired to speed up the permeability measurement as opposed to waiting longer for higher water
pressure buildup. Recommended Darcian velocities as well as the equivalent flow rates through the
sample during the step loading phase are shown in Table 5.6 from section 5.3. It is important to note
that the flow rates are very close to the minimum flow rate possible with the current flow pump. The
recommended flow rate for MFT is in fact the minimum possible flow rate for the current flow pump at UBC.

This step can be repeated an indefinite number of times to serve as a check of the SICT analysis. Only one step load is required for the analysis. Any step load between 10 and 100 kPa is appropriate for the step loading (Znidarčič, et al., 1992) although loads exceeding 150 kPa are preferred to minimize the effect of errors in determining the load pressure. These errors include possible friction due to the loading piston on the side walls as well as friction inside the loading cell itself. The higher the step load the lower these errors will be relative to the load and thus serve better for using in the analysis. The current SICT at UBC can apply step loads up to a maximum of about 220 kPa.

10. After the final step load phase is complete. The bucket of water used for pressurizing the SICT is lowered and the water is drained from the triaxial cell. The soil sample is taken out of the casing; the sample height is manually measured, and is placed in the oven to dry for final water content determination. The measured sample height will serve as a check of the final void ratio, \( e_f \), determined from the water content test. Testing with MFT will result in bitumen stains on the test equipment and hands that are hard to clean off. Experience has shown that the use of the household cooking oil spray PAM works very well in bitumen stains and this is explained in section 5.1.4. Other household oil sprays brands are assumed to be as effective but no other brand had been tested.
Appendix F  SICT Equipment Specifications

F.1  Load Cell System

The load cell at the UBC SICT consists of a Marsh Bellofram air pressure cylinder, regulator, transducer for controlling the amount of air pressure is supplied to the cylinder, and pressure gauge.

F.1.1  Air Pressure Cylinder

The air pressure cylinder specifications are shown in Table F.9. The cylinder produces force on the rod through the expansion of a rubber diaphragm when pressurized air is supplied as shown Figure F.20.

<table>
<thead>
<tr>
<th>Air Pressure Cylinder</th>
</tr>
</thead>
</table>
| Company               | Marsh Bellofram  
| Model Number          | 900-020-000  

| Type                  | A “S-9-F-SM-UM” cylinder  
|                       | S = Spring return  
|                       | 9 = effective area of cylinder in inches  
|                       | F = long strong, 3 inches  
|                       | SM = Standard rod  
|                       | UM = Universal Cap Mounting Stud  

Figure F.20: Inside view of the Air Pressure Cylinder
The operating data for the Marsh Bellofram air pressure cylinder is shown in Table F.10. From the operating table it is important to factor in the increase in spring force with the extension of the stroke length. This corresponds to an initial 12 pounds of spring force at rest and increasing by 4 pounds every inch of stroke extension. Thus as a soil sample is being loaded via this air pressure cylinder, the spring force resisting the load increases and this should be accounted.

Table F.10: Air pressure operating data

<table>
<thead>
<tr>
<th>Size (Effective Area)</th>
<th>Stroke +.03</th>
<th>Stroke -.12</th>
<th>Spring Return</th>
<th>Approx. Spring Force - Zero Stroke (lbs.)</th>
<th>Approx. Increase Force Per In. Of Stroke (lbs.)</th>
<th>Double Acting Stroke +.03</th>
<th>Stroke -.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sq. In.</td>
<td>E</td>
<td>F</td>
<td>Series</td>
<td>Series</td>
<td>Series</td>
<td>Series</td>
<td>Series</td>
</tr>
<tr>
<td>4</td>
<td>2.3</td>
<td>1.80</td>
<td>6</td>
<td>3</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2.8</td>
<td>2.40</td>
<td>9</td>
<td>4</td>
<td>1.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3.4</td>
<td>2.20</td>
<td>17</td>
<td>12</td>
<td>4</td>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>12</td>
<td>3.9</td>
<td>2.30</td>
<td>18</td>
<td>18</td>
<td>6</td>
<td>6</td>
<td>1.8</td>
</tr>
<tr>
<td>16</td>
<td>4.5</td>
<td>2.62</td>
<td>24</td>
<td>24</td>
<td>8</td>
<td>8</td>
<td>2.1</td>
</tr>
<tr>
<td>24</td>
<td>5.5</td>
<td>2.60</td>
<td>36</td>
<td>36</td>
<td>11</td>
<td>11</td>
<td>2.0</td>
</tr>
<tr>
<td>30</td>
<td>6.3</td>
<td>3.07</td>
<td>45</td>
<td>54</td>
<td>13</td>
<td>14</td>
<td>2.4</td>
</tr>
<tr>
<td>36</td>
<td>6.8</td>
<td>3.55</td>
<td>60</td>
<td>54</td>
<td>16</td>
<td>14</td>
<td>2.9</td>
</tr>
</tbody>
</table>

F.1.2 Air Pressure Regulator

The air pressure regulator that was selected was a Marsh Bellofram Type 41-2 regulator and it can regulate pressures between 0 to 100 psi. Technical specifications are shown in Table F.11.

Table F.11: Air pressure regulator specifications

<table>
<thead>
<tr>
<th>Air Pressure Regulator</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Marsh Bellofram</td>
</tr>
<tr>
<td>Model Number</td>
<td>960-183-087</td>
</tr>
<tr>
<td>Type</td>
<td>Type 41-2</td>
</tr>
<tr>
<td>Details</td>
<td>Regulates 0 to 100 psi</td>
</tr>
<tr>
<td></td>
<td>Comes with optional bonnet vent port</td>
</tr>
</tbody>
</table>
F.1.3 Air Pressure Controller

A Marsh Bellofram type 1001 transducer controller was used to control the amount of air pressure is supplied to the air pressure cylinder via computer input and thus serves as way to remotely control the load to the soil sample. The controller specifications are listed in Table F.12.

<table>
<thead>
<tr>
<th><strong>Table F.12: Air pressure controller specifications</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Pressure Controller</strong></td>
</tr>
<tr>
<td><strong>Company</strong></td>
</tr>
<tr>
<td><strong>Model Number</strong></td>
</tr>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

F.1.4 Air Pressure Gauge

The air pressure gauge that was selected to manually read the pressure supplied to the air pressure cylinder is a Marsh Bellofram 160 psi capacity pressure gauge and the specifications of it are shown in Table F.13.

<table>
<thead>
<tr>
<th><strong>Table F.13: Air pressure gauge specifications</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Pressure Gauge</strong></td>
</tr>
<tr>
<td><strong>Company</strong></td>
</tr>
<tr>
<td><strong>Model Number</strong></td>
</tr>
<tr>
<td><strong>Other Details</strong></td>
</tr>
</tbody>
</table>

F.2 LVDT

For measuring settlement of the soil sample, a Daytronic linear variable differentiable e transformer (LVDT) was selected and the full specifications are shown in Table F.14. The dimensions of the LVDT used in the SICT at UBC are shown in Figure F.21.

<table>
<thead>
<tr>
<th><strong>Table F.14: LVDT specifications</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LVDT</strong></td>
</tr>
<tr>
<td><strong>Company</strong></td>
</tr>
<tr>
<td><strong>Model Number</strong></td>
</tr>
<tr>
<td><strong>Type</strong></td>
</tr>
</tbody>
</table>
The pore pressure transducer that was selected for measuring pore pressure differences across the soil sample at the UBC SICT is a Validyne P61 digital pressure transducer for USB. The transducer converts analog readings directly to digital format which allows direct connection to a computer through a USB connection. This simplifies the data acquisition process and is an improvement over the original transducer at the CU laboratory that requires an additional component to convert analog signals to a digital format. The specifications of the transducer are shown in Table F.15.

**Table F.15: Pore pressure transducer specifications**

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Linear Range (Nom.) (mm / in.)</th>
<th>Dimension &quot;L&quot; (mm / in.)</th>
<th>Dimension &quot;X&quot; (mm / in.)</th>
<th>Armature Weight (Approx.) (g / oz.)</th>
<th>Total Weight (Approx.) (g / oz.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSD1000LU5</td>
<td>±12.5 / ±0.5</td>
<td>175 / 6.9</td>
<td>43 / 1.7</td>
<td>28 / 1.0</td>
<td>213 / 7.5</td>
</tr>
<tr>
<td>DSD2000LU5</td>
<td>±25.0 / ±1.0</td>
<td>203 / 8.0</td>
<td>69 / 2.7</td>
<td>57 / 2.0</td>
<td>270 / 9.5</td>
</tr>
<tr>
<td>DSD4000LU5</td>
<td>±50.0 / ±2.0</td>
<td>317 / 12.5</td>
<td>81 / 3.2</td>
<td>71 / 2.5</td>
<td>369 / 13.0</td>
</tr>
<tr>
<td>DSD6000LU5</td>
<td>±75.0 / ±3.0</td>
<td>430 / 16.9</td>
<td>119 / 4.7</td>
<td>85 / 3.0</td>
<td>497 / 17.5</td>
</tr>
<tr>
<td>DSD8000LU5</td>
<td>±100 / ±4.0</td>
<td>475 / 18.7</td>
<td>132 / 5.2</td>
<td>99 / 3.5</td>
<td>625 / 22.0</td>
</tr>
<tr>
<td>DSD12000LU5</td>
<td>±150 / ±6.0</td>
<td>666 / 26.2</td>
<td>183 / 7.2</td>
<td>114 / 4.0</td>
<td>852 / 30.0</td>
</tr>
<tr>
<td>DSD16000LU5</td>
<td>±200 / ±8.0</td>
<td>856 / 33.7</td>
<td>259 / 10.2</td>
<td>142 / 5.0</td>
<td>1250 / 44.0</td>
</tr>
</tbody>
</table>

**F.3 Pore Pressure Transducer**

**F.4 Triaxial Cell**

The triaxial cell that is used for the SICT at UBC is a Durham Geo S-516 triaxial cell and can accommodate a maximum soil sample diameter of 6 inches.
F.5  Industrial Spill Matting

To prevent the MFT from seeping through the laboratory floor, an industrial Brady SPC Barrier Spill Matting (BSM™) is installed at the UBC laboratory. The BSM is made of needle-punched polypropylene fibers. It is designed with a 3-ply construction method that absorbs oil, water, and chemicals. The spill mat works well to prevent MFT from passing through to the ground. The specifications of the matting used at the UBC laboratory are shown in Table F.16.

Table F.16: Spill Matting Specifications

<table>
<thead>
<tr>
<th>Spill Mat/Carpets</th>
<th>Brady SPC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Company</strong></td>
<td>SORRAG36150</td>
</tr>
<tr>
<td><strong>Model Number</strong></td>
<td>Brady SPC</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>Barrier Spill Matting (BSM™)</td>
</tr>
<tr>
<td><strong>Details</strong></td>
<td>36” x 100’, 1/Bale</td>
</tr>
<tr>
<td></td>
<td>Rag Rug is a universal sorbent that provides good footing, masks dirt and absorbs spills.</td>
</tr>
</tbody>
</table>

F.6  Data Acquisition System

The data acquisition system selected for the SICT at UBC consists of computer running Windows 7 Professional, National Instruments (NI) Input and Output Analog Modules and a NI CompactDAQ chassis 4 slot USB to convert the analog signals to a digital format and sent to the computer for data processing. The specifications of the data acquisition components as well as the SICT instruments that data is collected from are detailed in Table F.17.

Table F.17: NI Data acquisition system specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Part Number / Model Number</th>
<th>Description</th>
<th>Data Directly Collected from SICT Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NI Analog Output Module</td>
<td>779012-01 / NI 9263</td>
<td>4 Channel, 16-Bit, +/- 10 V, 100 kS/s per channel</td>
<td>LVDT Load Cell Controller</td>
</tr>
<tr>
<td>NI Analog Input Module</td>
<td>781157-01 / cDAQ-9174</td>
<td>4 slot USB</td>
<td></td>
</tr>
<tr>
<td>NI CompactDAQ Chassis</td>
<td>779011-01 / NI 9215</td>
<td>4 channels, 16-Bit, +/- 10 V, 100 kS/s per channel Simultaneous sampling differential analog input</td>
<td></td>
</tr>
</tbody>
</table>
The data acquisition system is programmed with the NI LabVIEW graphical programming software. Data collected include the settlement measured with the LVDT, pore pressure, vertical load pressure readings as well as the flow pump position and velocity. Labview has good integration with the data acquisition instruments and the visual programming abilities allow for quick modifications to any new equipment requirements. It also allows for remote control of the testing in progress.

F.7 Flow Pump

The flow pump used for the SICT at UBC was custom built by the University of Colorado (CU) in Boulder. It consists of a custom made stainless steel syringe, a drive motor with the appropriate control interface for a PC and two controlled valves (Refill and Sample valves, see Figure 2.9). The pump provides a controlled flow rate in the range of $8 \times 10^6$ mL/second to 8 mL/second and has a single stroke capacity of 200 mL. For a soil sample of 6 inches in diameter the flow pump can achieve a minimum flow rate of $1.58 \times 10^{-11}$ m$^3$/sec or a Darcian velocity of $8.68 \times 10^{-10}$ m/sec.

A digital encoder is installed on the flow pump, which allows for direct measurement of the distance that the flow pump piston has travelled and this allows for automatic resetting of the flow pump piston during testing whenever the maximum volume of water has been removed from the sample.

F.8 Porous Plastic Discs for Soil Sample Placement

Before placing the soil slurry in the SICT, a porous plastic disc was placed on top of the pedestal followed by a sheet of filter paper. The slurry was then poured on top in which another filter paper was placed on top of the slurry followed by another porous disk and then the compression piston. The filter papers prevent solids from passing through and the porous discs ensure rigid boundaries while still allowing water from passing through. The porous plastic discs that were selected are Interstate Specialty Products 6 inch diameter porous plastic discs and the specifications of the discs are shown in Table F.18.

<table>
<thead>
<tr>
<th>Porous Plastic Discs</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company</td>
<td>Interstate Specialty Products</td>
</tr>
<tr>
<td>Model Number</td>
<td>POR-4905</td>
</tr>
<tr>
<td>Type</td>
<td>6 inch diameter porous plastic discs</td>
</tr>
</tbody>
</table>
| Details              | 6.000 +/- 0.015 inch diameter discs  
0.125 inches thick  
Coarse P. E. with 0.90 to 0.130 microns average pore size |
Appendix G  SICT UBC Shop Drawings

This section contains the shop drawings for the equipment listed below. These design drawings were all constructed by the Chemical and Biological Engineering (CHBE) workshop at UBC.

- Load Chamber – see Figure G.22
- LVDT Clamp (Detail 1) – see Figure G.23
- Top Loading Bit (Detail 2) - see Figure G.24
- Bottom Loading Bit (Detail 3) – see Figure G.25
- Soil Sample Pedestal – see Figure G.26
  - Pedestal Modification (Detail 4) – see Figure G.27
- Soil Sample Casing – see Figure G.28
- Soil Sample Loading Piston – see Figure G.29
- Load Chamber Top and Bottom Plates - see Figure G.30
Figure G.22: UBC SICT Shop Drawing – Load Chamber
Figure G.23: UBC SICT Shop Drawing – LVDT Clamp (Detail 1)
Figure G.24: UBC SICT Shop Drawing - Top Loading Bit (Detail 2)
Figure G.25: UBC SICT Shop Drawing – Bottom Loading Bit (Detail 3)
Figure G.26: UBC SICT Shop Drawing – Soil Sample Pedestal
remove \( \frac{1}{4} \) in. cube from existing pedestal to enable water access to \( \frac{1}{4} \) in. dia. hole

NOTE 1: Red Lines Indicate existing equipment

Figure G.27: UBC SICT Shop Drawing – Pedestal Modification (Detail 4)
Figure G.28: UBC SICT Shop Drawing – Soil Sample Casing

Note: Material Supplied is 24 Inch long tube

Break all edges.
Drill clearance holes \( \frac{5}{16} \) in. (0.3125 in.) Dia. on \( 1 \frac{1}{8} \) in. (1.125 in.) Dia. circle, 6 plc's

Drill clearance holes \( \frac{5}{16} \) in. (0.3125 in.) Dia. on \( 2 \frac{3}{8} \) in. (2.375 in.) Dia. circle, 12 plc's

Drill clearance holes \( \frac{5}{16} \) in. (0.3125 in.) Dia. on \( 3 \frac{5}{8} \) in. (3.625 in.) Dia. circle, 12 plc's

Drill clearance holes \( \frac{7}{16} \) in. (0.3125 in.) Dia. on \( 4 \frac{7}{8} \) in. (4.875 in.) Dia. circle, 24 plc's

\[ \text{Figure G.29: UBC SICT Shop Drawing – Loading Piston} \]
Figure G.30: UBC SICT Shop Drawing – Load Chamber Top and Bottom Plates
Appendix H    SICT Calibrations

H.1 Load Cell Calibrations

After construction, the SICT at UBC performed ten tests. The load cell controller was not installed for the first four tests (all of which were on kaolinite clay) and thus pressure readings were manually read from the pressure gauge.

It is important to note that since step loading was only performed in an increasing direction, hysteresis through unloading was not required.

The calibrations were performed by increasing the analog signal sent to the load cell pressure controller and recording the pressure gauge readings. The resulting calibration charts are shown in the figures that follow.

Figure H.31: Load Cell Calibration – UBC Kaolin Test 5
Figure H.32: Load Cell Calibration – UBC Kaolin Test 6
Figure H.33: Load Cell Calibration – UBC MFT Test 1

$y = 14.544x - 2.0681$
$R^2 = 0.9997$

Figure H.34: Load Cell Calibration – UBC MFT Test 2

$y = 14.589x - 2.4775$
$R^2 = 0.9996$
H.2 LVDT Calibrations

Ten tests were conducted using the SICT at UBC. The first two tests had installation problems with the LVDT so manual readings were taken. Tests 3, 4, 5, and 6 had the LVDT properly installed but not calibrated and the factory calibration was used. These six tests were all on kaolinite clay. The next four tests using the SICT all had the LVDT properly calibrated and results were very similar to the factory calibration, thus confirming that tests 3, 4, 5 on kaolinite clay are reliable.

The calibrations were performed by recording the LVDT voltage reading with varying heights of blocks that represent the sample height. The factory calibration for the LVDT is -2.49 volts/inch.
Figure H.36: LVDT Calibration – UBC MFT 1

Figure H.37: LVDT Calibration – UBC MFT 2
Figure H.38: LVDT Calibration – UBC MFT 3

Figure H.39: LVDT Calibration – UBC Copper Tailings 1
H.3 Pore Pressure Transducer Calibrations

Ten tests were performed using the SICT at UBC, of which only the final three tests, designated MFT 2, 3, and Copper Tailings 1, had pore pressure transducer calibration checks performed. The first seven tests assumed the factory calibration of the transducer. This assumption is confirmed with the three calibration checks as they show a near exact calibration as the factory calibration. These three calibrations are shown in the figures that follow.

The pore pressure transducer was calibrated by attaching the two ends of the diaphragm on the transducer to water lines that connect to beakers filled with water. These beakers are raised at varying heights relative to each other and the pressure head difference is calculated and compared with measured head differences from the transducer.

![Figure H.40: Pore Pressure Transducer Calibration – UBC MFT 2](image)

\[ y = 0.994x + 8.0273 \]

\[ R^2 = 0.9999 \]
Figure H.41: Pore Pressure Transducer Calibration – UBC MFT 3

Figure H.42: Pore Pressure Transducer Calibration – UBC Copper Tailings 1