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Revisiting the large strain consolidation test for oil sands

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ABSTRACT

The large strain consolidation test is a one-dimensional multi-step loading compression test used to obtain one-dimensional volume change properties of high water content material. These properties include compressibility (stress-strain behaviour) and hydraulic conductivity (ability to transmit water). The test is used worldwide for slurry and tailings work including for Alberta oil sands tailings since the 1970's. This paper revisits this test method for use in the oil sands through the authors' laboratory practice and a literature review. Key practical considerations and learnings are summarized to date.

Key Words: large strain consolidation test, compressibility, hydraulic conductivity

1 INTRODUCTION

The large strain consolidation (LSC) test, also known as the slurry consolidation test, is a one-dimensional multi-step loading compression test. The test is used to obtain two key consolidation properties:

1. Compressibility – the relationship between vertical effective stress and void ratio.
2. Hydraulic conductivity – the relationship between void ratio and hydraulic conductivity.

These relationships are obtained for two purposes: to provide material parameters for finite strain consolidation analysis; and to compare consolidation behaviour between materials (Figure 1).

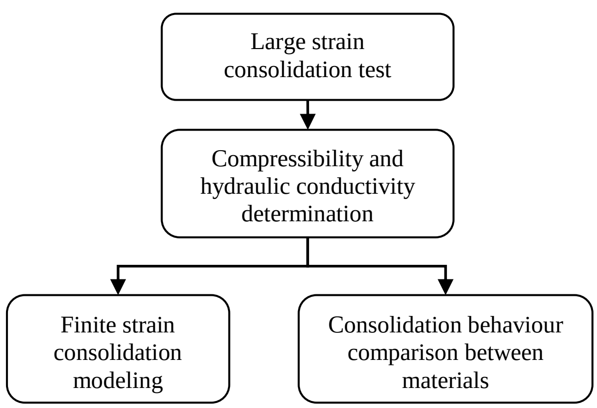

Figure 1. LSC test objectives

The modeling aspect requires that the test conditions be as close as possible to the actual field production and deposition. Whereas for the comparison purposes, the test needs to be performed in a similar fashion for all materials subjected to the comparison. Regardless of this difference, the former approach should always be preferred.

The first article on the LSC test was published in 1971 by Sheeran and Krizek. Different from the conventional consolidation test, the LSC test allows material with high water content and large volume change to be tested, and permits a direct measurement of the hydraulic conductivity of a material.

The test therefore has particular applications in high water content materials, such as dredging and tailings work, where the rate and amount of compression of such material are of great importance. With the extensive use worldwide, historical successes and limitations of the test provide engineers a rational approach in their design and engineering judgment.

In this paper, we revisit the LSC test for oil sands industry by summarizing the test methodology, assumptions, data analysis, considerations and lesson learned from the application of this type of test. The paper also documents a list of complementary and supporting tests that can be performed along with the consolidation test. A list of test facilities providing the multi-step loading LSC test in Canada at the time this paper was written is also provided.

2 THE LARGE STRAIN CONSOLIDATION TEST

2.1 Test setup

A generic setup of the multi-step loading LSC test is shown in Figure 2. The test equipment consists of the following key components:

1. Sample chamber (i.e. cell)
2. Loading piston
3. Pressure source
4. Settlement measuring device
5. Pore pressure measurement device
6. Top drainage line
7. Bottom drainage line
8. Hydraulic conductivity test device

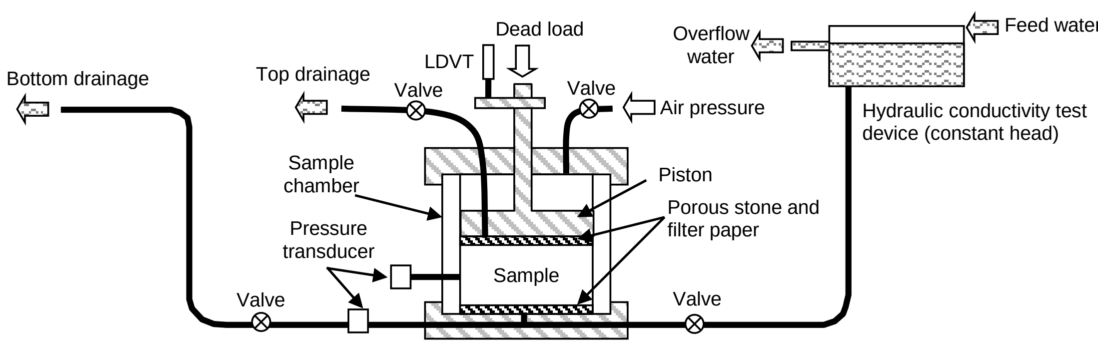

Figure 2. Generic multi-step loading LSC test.

In the 1970's and 1980's the sample chamber was made of aluminum or stainless steel. Nowadays the chamber is made of acrylic glass or Plexiglas. The function of the chamber is to contain the material under a wide range of test pressure, and to be transparent for visual observation.

The piston is either made of stainless steel, aluminium or polyethylene. The gap between the cell chamber and the piston is sealed using an O-ring to prevent material leakage around the piston. The piston can also be designed to be just flush to the chamber wall so a frictionless operation may be assumed. A porous stone and a filter paper or a geotextile are used between the sample and the piston to prevent material migration and drainage clogging. As a general rule, the porous stone and the filter paper together must have a hydraulic conductivity of at least two orders of magnitude greater than the highest conductivity of the tested material. The piston and the cell bottom are also specially grooved to facilitate water drainage and air bubble flushing.

The pressure source is typically: i) dead load and lever system; ii) air pressure system; or iii) a combined system. The choice of different pressure sources lies in the control of the stress level – dead load typically provides a feasible low to moderate pressure source (typically 0.5 kPa to 10 kPa but can go higher with a lever system), while the air pressure system is typically best suited for higher pressures (typically at 5 kPa and above) and provides a greater amount of control.

A dial gauge or Linear Variable Displacement Transducer (LVDT) is installed on the piston to measure compression of the material. A light weight LVDT without an internal spring is typically best in order to minimize its impact on the applied pressure.

Pore water pressure measurement by either pressure transducer or manometer is performed to measure the initial applied stress, and to track the progress of consolidation (pore pressure dissipation). Pore pressure measurement ports are typically provided at the cell base, and in some cases along the side of the chamber.

During consolidation, the water can be released from the sample using either single or double drainage. The single drainage condition is where the water is allowed to flow out of the sample from the top part of the sample. The water is released to a predefined pressure head (either atmospheric pressure or a back pressure). The double drainage condition is when both the top and the bottom are allowed to dissipate to the hydrostatic pressure or back pressure. For the bottom drainage, a porous stone and filter paper are required, similar to the piston setup.

The last component of the test is the hydraulic conductivity measurement device. A constant head hydraulic conductivity test (ASTM D2434) is normally performed due to its ability to control hydraulic gradient. The falling head hydraulic conductivity testing is seldom performed with the LSC setup.

2.2 Test procedure

A simplified LSC test procedure is as follows:

1. Prepare the test cell by saturating the base porous stone and drainage lines.
2. Pour sample of known initial solids content into the chamber to a specified height.
3. Allow the sample to complete self-weight consolidation while monitoring the tailings-water interface settlement and excess pore water dissipation at the bottom.
4. Insert the piston and apply the first load increment. Allow the material to complete consolidation while monitoring the interface settlement and excess pore water dissipation.
5. Once consolidation is complete, perform the hydraulic conductivity test.
6. Repeat Steps 4 and 5 with additional loads (typically double the magnitude of the previous load).
7. After the last load increment is complete, unload the pressure to a specified value. Monitor interface (rebound) and excess pore pressure changes. This stage can be performed using a few unloading steps, if desired.
8. Once the rebound stage is complete, disassemble the test cell and collect samples for solids content measurement.

2.3 Test assumptions – discussion

The principal test assumptions are as follows:

9. No solids migration (neither mineral nor organic materials) during the test.
10. The test material is saturated.
11. No friction between material and the side wall. The applied stress is fully transferred to the soil skeleton at the end of consolidation.
12. Friction between the piston and the side wall is either negligible by using a frictionless piston, or taken into account by measuring pore pressure, total stress, or the friction.

13. Self-weight is negligible and the material has a uniform void ratio profile at the end of every load step.
14. Consolidation is complete when the tailings-water interface stops moving and when the excess pore water pressure is fully dissipated.
15. Steady flow velocity during the hydraulic conductivity test can be used for the hydraulic conductivity calculation.
16. Darcy's law is valid.
17. Void ratio does not change during the hydraulic conductivity test.
18. The variations in test conditions (e.g. temperature, light exposure) do not change compressibility and hydraulic conductivity behavior of the material.

Test Conditions

In order to prevent mineral particle segregation during the test, the slurry sample is prepared at a solids content equal to or greater than the static segregation boundary. If segregation is thought to have occurred during sample loading or testing then the sample can be dissected and tested for segregation at the conclusion of the test. For the special case where bitumen exists, little can be done to prevent its migration during loading. To manage this issue, increases of hydraulic gradient should be kept as small as practical during loading and hydraulic conductivity testing. Any observations of organic material migration should be documented and reported.

Most slurry materials tested for a large strain consolidation behaviour are saturated. In some cases, however, they can generate gas or contain gas. In such cases the degree of saturation is no longer 100%. Special test setups complemented with specific geotechnical expertise are required to deal with this type of slurry.

Wall friction is controlled by both the cohesion and friction angle of the test material as well as the friction between the piston and the sidewall. The wall friction therefore depends on the test setup and the sample material. As a practical guide, to minimize the effects of wall friction from the material the initial sample height should be selected such that, when the material is compressed (to stresses of 10 kPa and greater), the specimen maintains a diameter-to-height ratio of about 2 to 1 or greater (Caughill 1992). To minimize the piston friction, a frictionless piston may be utilized – this type of test however may cause the tested material to migrate around the piston, especially at the higher loads. Alternatively, a sealed piston can be used and the actual applied pressure can be monitored by using a total stress cell or a pore water pressure transducer. Such a setup would provide more reliable test results.

The height of a LSC sample is typically in a range of 10 to 30 cm. The difference between the top and bottom effective stresses, due to self-weight, is in a range of a kilopascal. This difference causes a slightly non-uniform void ratio profile for most materials, and is most pronounced when the applied load is small. Since compression of the sample at the initial low solids content range is typically fast, and an actual tailings deposit is typically deep, this small stress variation is practically inconsequential. In addition, an engineer can choose to perform additional standpipe tests to obtain a more representative compressibility profile at the low effective stress level.

For high water content materials, the end of the primary consolidation may be challenging to define strictly from deflection of the settlement curve only. Measurement of excess pore water pressure as well as data analyses are needed to define the end point of primary consolidation. For the excess pore water, a high precision transducer is strongly recommended so the dissipation of low pressures can be detected.

Determination of Consolidation End Point

Several methods are also available to assess the end of the primary consolidation including:

1. Log time
2. Square root time

3. Rectangular hyperbola

The above methods are not always necessary if the material does not creep. In such cases a direct measurement of interface settlement and pore water pressure would provide adequate indication of the end point. In other cases, the square root time method (Taylor 1942) and rectangular hyperbola method (Sridharan et al. 1987) are found to provide a reasonable estimate. The log time method (Casagrande and Fadum 1940) usually requires a longer period of time to develop an S-shape compression curve for the end point identification. Whichever method is selected, it should be specified and documented in the test report.

Hydraulic Conductivity Testing

The hydraulic conductivity test with a constant gradient should always be conducted after full dissipation of excess pore pressure because when residual excess pore water pressure remains, the applied gradient and the measured hydraulic conductivity will be impacted. During the test, it is typically observed that the steady flow rate through the material is not always achieved instantaneously, especially at low stress levels. Figure 3 shows an example of flow velocity measurement with time for a mature fine tailings material. To ensure the steady state was obtained in this case, flow monitoring of up to 10 hours was performed. Current practice is to allow the steady flow rate to establish and then the steady state portion of the dataset is utilized for the hydraulic conductivity determination. The hydraulic conductivity is a highly sensitive parameter for consolidation prediction at high water contents. The flow velocity with time and the flow rate selected for the hydraulic conductivity calculation should be documented and reported.

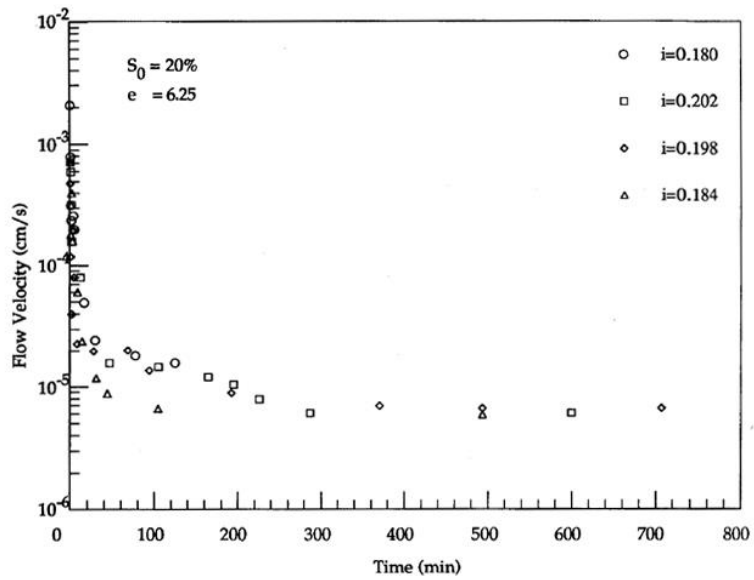

Figure 3. Flow velocity with time for mature fine tailings at a high void ratio (Suthaker 1995).

To calculate hydraulic conductivity, Darcy's law (Equation 1) is assumed.

$$v = - k \cdot i \quad (1)$$

where v is the apparent flow rate, k is the hydraulic conductivity and i is the hydraulic gradient.

In most cases, the law is valid, however, when a new type of material is tested, it is always wise to perform the hydraulic conductivity test using several gradients to verify that the hydraulic conductivity does not vary with the gradient. When practical, it is also recommended that the hydraulic conductivity test be performed as close as possible to the expected hydraulic gradient in the field.

Laboratory Environment Factors

Since the hydraulic conductivity test exerts seepage pressure to a sample, it is typically performed with the seepage flow moving from the bottom of the sample to the top. This is to minimize the potential for consolidation occurring as a result of the seepage forces.

The last assumption is that the test environment in laboratory does not impact the compressibility and hydraulic conductivity behaviour. Setting a laboratory condition to be identical to a field condition is not, in general, reasonably achievable. For example, temperature fluctuation and light exposure are generally controlled in the laboratory whereas the material in the field is exposed to the variable natural environment. For practical purposes, in order to minimize the difference between the laboratory and the field conditions, the test should be setup in a way that the key controlling field condition is replicated. This type of judgment must be made on a case by case basis. For example, if the material is sensitive to change in pH, the fluid used in the test must be of the same type as the fluid found in the field. Another example would be that if the material is sensitive to microbial activity at room temperature, and the field condition has a much lower temperature, then the test should ideally be performed at the field temperature condition. Geotechnical and tailings engineers can be consulted to select the appropriate test conditions, or evaluate their potential impact on the data.

2.4 Key practical considerations

The key considerations while ordering/performing the LSC test lies on the objectives of the test, as discussed earlier, whether the field simulation or the relative comparison is needed. To this end, some of the key considerations are summarized as follows:

1. Segregation: the sample must be prepared such that it is non-segregating.
2. Initial water content: the sample must be prepared at the expected water content in the actual application.
3. Sample preparation: an undisturbed field sample is preferred over a laboratory constituted sample. If a laboratory constituted sample is used, simulation of the field conditions should be attempted. A detailed report on material preparation is mandatory.
4. Stress range: the test stress range should be selected to cover the expected stress range that the material will experience in the field.
5. Reliability and repeatability of test data: the reliability of the test data is highly influenced by the test method, setup, data interpretation and related assumptions. Documentation of this information is mandatory.
6. Sample representativeness: a single test provides only a single data set for a single sample. Often in the actual applications, the volume of the material is large and can be in the order of millions of cubic meters. Reasonable bounds for the data can be established by testing a selective range of material to improve data representativeness.
7. Data application: the LSC test is a one-dimensional test with its related assumptions. Similarly, any predictive tools also come with a certain set of assumptions. These assumptions must be borne in mind and taken into account for proper analysis and judgment.
8. Scale effect: the test represents specific loading and seepage conditions within the laboratory time frame. Other scale-dependent behaviour (such as channelization, creep, and lateral drainage) that may be expected in the field must also be kept in mind.

2.5 Supporting and complementary tests

Mandatory tests to support data calculation for the LSC test include:

- Specific gravity test
- Water content test

The specific gravity and water content are required to calculate void ratio. Due to a wide variety of composition in slurry and tailings materials, these tests must be performed along with the

LSC test. The water content should be measured both before and after the LSC test to validate the void ratio calculation.

Other complementary tests that provide valuable data include:

- Particle size distribution
- Atterberg limit
- Static segregation
- Hindered sedimentation
- Compression standpipe

Particle size distribution is a fundamental composition test for soil, and would aid interpretation of the consolidation behaviour obtained from the LSC test. Similarly, the Atterberg limit test provides empirical correlation with engineering properties and possible causes of behavioural changes.

The static segregation test is used to ensure that the test material is non-segregating for laboratory testing purposes. In the field it is also required to consider that the material may undergo other dynamic processes (such as pipelining and beaching). Such processes can cause the material to become segregating and must be considered as part of the test preparation and data interpretation.

The constant head hydraulic conductivity measurement is not always possible at the high water content because the material can undergo hindered sedimentation. In this case, the determination of the hydraulic conductivity can be done using the hindered-sedimentation test (Pane and Schiffman 1997). Similarly at the low effective stress range, determination of compressibility using load control and pressure sensor monitoring can be challenging. An alternative compression standpipe test can be performed instead (Scott et al. 2008). These two tests can be used when material behaviour at a low effective stress level (several kPa or less) is of interest.

3 CASE HISTORIES

A few public domain case histories that used LSC results for large scale work in the oil sands industry are summarized below.

3.1 Case 1: 1982 Syncrude mature fine tailings 10 m standpipe

A 10 m high and 0.9 m diameter HDPE standpipe in a laboratory at the University of Alberta was filled with Syncrude mature fine tailings in 1982 and was monitored for about 30 years to study its long-term self-weight compression behaviour under a single drainage condition. The tailings had an initial solids content of about 30% and a fines content of about 90% (< 45 µm). LSC tests were performed on the material to obtain its expected consolidation behaviour. When the standpipe was modelled using the relationships obtained from the LSC test, it was found that the initial settlement rate in the first 5 years can be captured by the model (Figure 4). After this period, the model overestimates the rate of settlement.

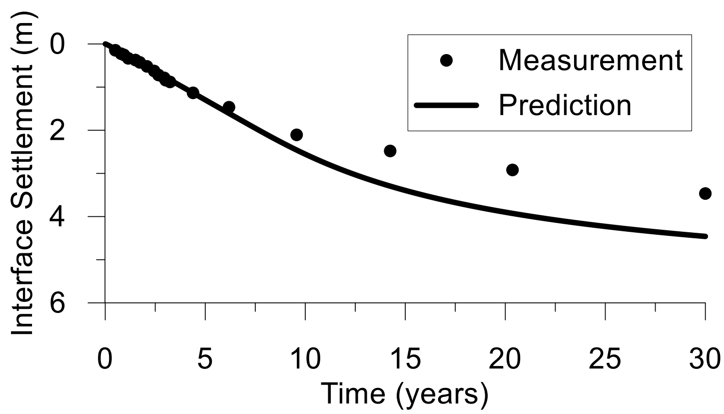

Figure 4. Interface settlement comparison for 10 m mature fine tailings standpipe (Kawbe et al. 2013).

In this case the test conditions were well defined but an unexpected excessive compression behaviour of the material near the surface was observed in the standpipe leading to a disagreement between the model using the LSC test data and the observed behaviour. Time-dependent compressibility and hydraulic conductivity behaviour – that were not considered in both the large strain test and the numerical model – were hypothesized to cause the disagreement. More information of the 10 m standpipe can be found in Kabwe et al. (2013) and Jeeravipoolvarn et al. (2009).

3.2 Case 2: 1997/1998 Syncrude composite tailings prototype

In 1997 and 1998 Syncrude Canada Ltd. conducted a field-scale experiment on composite tailings (CT), also known as the CT prototype. The 10 Mm^3 prototype deposit was about 1100 m long, 400 m wide and 10 m deep. CT is a mixture of fine tailings and tailings sand with a gypsum coagulant to prevent sand segregation. The initial solids and fines content of the material were about 60% and 20% respectively. The tailings was deposited in two pours – one in 1997 and another in 1998. The consolidation behaviour of the CT was determined in the laboratory by Caughill (1992) and Suthaker and Scott (1996) using LSC tests at various fines contents. To model the field behaviour, the finite strain consolidation model was used with the LSC data as input, with adjustments of the compressibility and hydraulic conductivity relationships. The comparison between the field interface settlement and the model predictions (using the adjusted parameters) shows good agreement (Figure 5). It is noted that the field material appeared to be slightly more compressible and more permeable compared to the LSC test data (Pollock et al. 2000). The dynamic effects during placement and channeling were hypothesized to be the reasons for these slight differences.

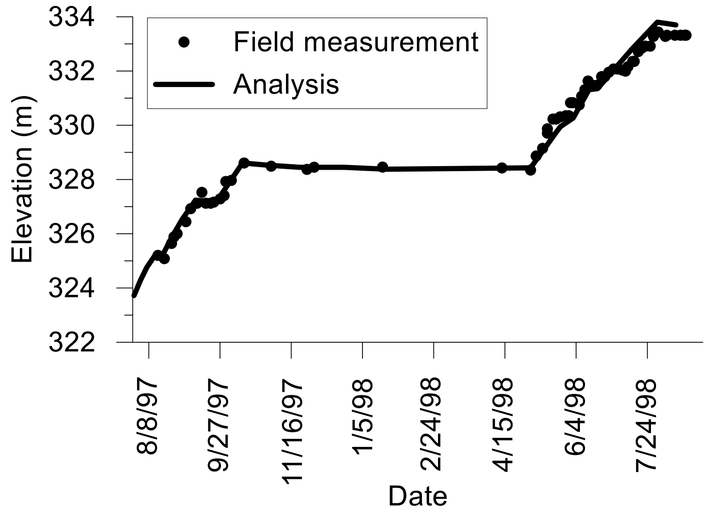

Figure 5. Interface settlement comparison for CT prototype (Pollock et al. 2000).

3.3 Case 3: 2005 Syncrude in-line thickened fine tailings pilot

Syncrude's in-line thickened tailings pilot pond was 50 m wide and 100 m long. The pond was continuously filled with the thickened tailings to a depth of about 2 m. The material was then allowed to compress under its own weight. The thickened tailings contained mostly fines material (about 90% fines) and was deposited at a solids content of about 10%. The thickened tailings was a product of three-stage flocculation intended to create a flocculated tailings that would dewater rapidly. The comparison between the field data and the modeling results using compressibility and hydraulic conductivity data measured by a LSC test (and a hindered sedimentation and compression standpipe test) is shown in Figure 6. Good agreement was obtained between the prediction based on the LSC data and the field measurements, with the field performance showing slightly higher permeability (which is observed as more rapid consolidation). In generating the material for the LSC tests, every effort was made to replicate the field conditions as much as was reasonably possible. This included the initial flocculation, initial water content, and feed material. The low energy deposition method was also simulated. The only item of the process not simulated was the flow of material travelling down the beach. Further information regarding this comparison can be found in Jeeravipoolvarn (2010).

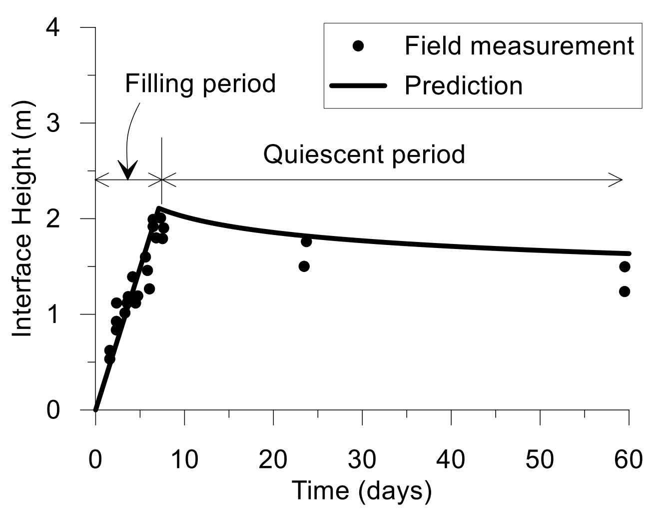

Figure 6. Interface settlement comparison for in-line thickened tailings pilot (Jeeravipoolvarn 2010).

3.4 Case 4: DuPont Particlear™ treated mature fine tailings 10 m column

DuPont's Particlear™ is a tailings treatment technology that utilizes the in-situ polymerization of silica to stabilize the fluid fine tailings, and improve its strength even at low solids contents. The compressibility and hydraulic conductivity of Particlear™ treated tailings were studied in a series of LSC experiments (Moore et al. 2013). A large scale experiment (a 10 m column test with Particlear™ treated mature fine tailings) was conducted to physically simulate the large scale compression behaviour (Moore et al. 2014). Particlear™ treated mature fine tailings with an initial solids content of 39% and a fines content of 96% were deposited into the column. The material was allowed to undergo self-weight consolidation with top and bottom drainage. The results of the 10 m column test were modelled using a finite strain model with the material relationships obtained from the LSC test. The comparison between the predicted and measured column settlement is given in Figure 7.

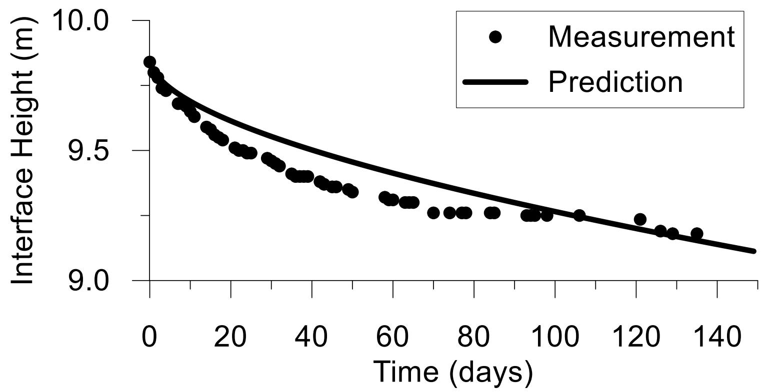

Figure 7. Interface settlement comparison for DuPont Particlear™ treated mature fine tailings.

In general the prediction agreed reasonably with the measured values over the monitoring period of 150 days. It was also observed that initially the actual settlement was slightly faster than the prediction. This unexpected behaviour was related to the densification of the material near the top portion of the standpipe which was hypothesized to be caused by other phenomena, including gas generation, channeling and creep compression at the lower solids content stage.

The agreements and disagreements observed in these examples provide a glimpse of the key considerations stated previously. There are other numerous case histories not available in the public domain that support these considerations. It could also be observed that general agreement between the model using the laboratory data and the actual performance was on average within a range of about ±20% accuracy in these particular cases. The practitioners should keep these key points in mind when utilizing the LSC test data.

4 SHORT LIST OF AVAILABLE TEST FACILITIES IN CANADA

A short list of available LSC test facilities in Canada is given in Table 1. Different facilities provide different test setups and techniques. Practitioners should inquire about the test methodologies and analysis methods used to determine if they are suitable for their project needs.

Table 1. Multi-step loading LSC test facilities.

Test facility	Stress range (kPa)[1]	Load type[1]	Hydraulic conductivity test[1]	Sample size[1]		Instrumentation[1]	
				Diameter	Height	LDVT	Pressure transducer
Golder Associates	Self-weight to 1500 kPa	A load frame through non-sealed piston	GDS constant flow pump with gradient measurement using burettes	0.15 m	Up to 0.2 m	✓	✓
MDH Engineered Services	0.5 to 1000 kPa	Dead load through a pulley, yoke and counter weight system	Constant head using either burette or reservoir	0.10 m, 0.15 m	Up to 0.10 m	✓	Equipped with mano-meters
Thurber Engineering	Self-weight to 1000 kPa	Dead load and air pressure through sealed piston	Constant head using controlled vertical water column	0.15 m	Up to 0.50 m	✓	✓
University of Alberta	Self-weight to 1000 kPa	Dead load and air pressure through a non-sealed piston	Constant head using horizontal glass tube	0.14 m, 0.17 m	Up to 0.12 m	✓	✓
University of Regina	Self-weight to 80 kPa	Dead load through a sealed piston	Falling head using calibrated burette	0.10 m	0.10 m	✓	-

1. This table represents publically available information at the time of review. The test facilities are continuously developing new techniques and internal knowhow to improve the accuracy and capability of the test. For more information regarding test details, the facilities can be contacted directly.

5 COMPARISON TO OTHER TESTS

The multi-step LSC test is only one of the test methods available to investigate slurry consolidation behaviour. Table 2 compares the test with other tests available. Some of these tests are available at the test facilities listed in Table 1. Benefits and drawbacks for these different test options are beyond the scope of this paper and further information can be obtained from the cited references.

Table 2. Slurry consolidation test comparison.

Test	Typical stress range (kPa)[1]	Method type[2]	Test setup complexity	Test speed	Level of Data analysis	Reference
Large strain consolidation	5 to 1000	Direct	Simple	Slow	Moderate	Monte and Krizek (1976)
Seepage induced consolidation	1 to 1000	Direct	Moderate	Slow	Moderate	Imai (1979)
Constant rate of deformation	1 to 1000	Indirect	Complex	Modera te	Complex	Znidarcic et al. (1986)
Restricted flow consolidation	1 to 1000	Direct	Moderate	Fast	Simple	Sills et al. (1986)

1. Typical range based on publicly available information. Lower stress level test than indicated can be achieved. Such setup requires additional sensor calibration and validation documentations.
2. An indirect method requires theoretical assumptions/inverse analysis and/or assumed relationships to obtain test results. A direct method is the method that does not require such items.

6 SUMMARY

The multi-step large strain consolidation test is a non-standard geotechnical test used to measure compressibility and hydraulic conductivity of high water content materials. To produce representative/useful data, the test requires understanding of the test objectives, knowledge of consolidation phenomena, laboratory skill, and proper equipment. The intent of this paper was to review and document the test methodology, assumptions, and the key considerations. This information is important for engineers, researchers and laboratory technicians who either practice or utilize data from this test method. The information can be used to improve the current test technique; aid in decision making and judgment when performing this test; as well as in the application of the test results in geotechnical practice.

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