IOSI PROJECT FINAL REPORT

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Project Title	Evaluation of Granular Cap Success Conditions and Failure Potential on Treated Fine Tailings
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DISCLAIMERS

EXECUTIVE SUMMARY

Conventional practice limits sand cap placement to tailings that have already achieved trafficable strengths. Most fine tailings deposits in the oil sands industry will not achieve this strength until they have consolidated and dewatered for some time. Sand cap or sand layer placement using hydraulic delivery methods offers great potential as a cost-effective, technically feasible capping method for treated fine tailings of the oil sands industry. The project presented here was a first phase for defining successful conditions of hydraulic sand capping of treated fine tailings deposits. This involved three steps: 1) develop a 2D model of granular capping of soft tailings to predict the potential for tailings failure as the cap is placed; 2) bench-scale testing intended to demonstrate the potential for oil sands tailings to support a sand cap; and 3) identify scale-up considerations to bridge the gap between small-scale tests and implementation in the field.

Two forms of hydraulic capping were modelled: subaqueous advancement of a uniform lift ("sand-raining") and subaerial advancement of a sloped cover ("deltaic capping"). Both forms were modelled using FLAC, a geotechnical model that represents a wide range of soil mechanics behaviour, including deformation. Major inputs to the modelling included physical properties of both the underlying tailings and cap materials (sand and petroleum coke), fundamental geotechnical relationships (e.g. void ratio versus effective stress and hydraulic conductivity), the geometry of the systems. A matrix of cap profiles and cap advancements were evaluated. It was found that a subaqueous sand cap of 0.2 m was not practical for tailings weaker than 0.5 kPa undrained shear strength. Such weak tailings should be capped with lighter weight material or with sand lifts thinner than 0.2 m. For practical capping with an advancing sand cap of between 0.5 m to 1 m thick on the leading front, the tailings should be greater than about 1 kPa undrained shear strength. A lighter weight material as a cap can be placed on weaker tailings.

In both scenarios, it was found that front slope of the cap and the deposit solids content profile are very important factors to success. A flatter front slope was found to be more stable than a steeper front slope, reducing the magnitude of the shear at the cap edge, and possibly acting as a "counter balance" to minimize upward displacement at the front of cap. Cap advance rate had an inconsequential effect on cap success, since the advance rate would have to be impractically slow to gain any benefit from strength gain of underlying tailings. The model predicted cap failure by displacement and the failure mechanism for most cases appeared to be rotation failure at the leading edge of the cap. It was also discovered that a small strain model (as was used here) may not capture excessive vertical displacements for assessing some failure mechanisms; large strain models appear to be necessary to assess the interaction between deltaic cap advance and settlement of weak fine tailings.

Bench testing was conducted to cost-effectively evaluate the potential for treated oil sands tailings to support a sand cap, and to corroborate the suitability of FLAC modelling for representing tailings behaviour in response to capping. Preliminary modelling was conducted to help inform the scale of the test, location of instruments, and predict likely failure mechanisms. A glass-walled 1,000 L aquarium (tank) approximately 1.8 m long, 0.6 m wide and 0.9 m tall was partly filled with about 600 L of 100 Pa shear strength centrifuged fluid fine tailings sourced from Jackpine Mine. Nine lifts of dry sand were placed subaerially by hand to build a 0.4 m long cap with the slope extending another 0.2 m (i.e. the remaining 1.2 m length of tailings were not capped). The test was run until failure, which was defined by no further rise in the cap with placement of additional sand. The tank was well instrumented throughout to monitor pore pressure and vertical

and horizontal displacement of the tailings during loading of the sand cap. FLAC 2D large-strain mode modelling was used in planning the test and showed that the sand cap was likely to fail in a bearing capacity mode, progressively displacing the tailings but not sinking to the bottom of the test vessel, and also suggested the beginnings of a rotational failure mode by the time the total cap thickness had been added. In general, the experiment and model showed large displacements in the same general areas: significant downward motion below the cap, turning more horizontal beneath the cap slope, and motioning upward to the right of the cap. In addition, the experimental excess pore pressure generation generally matched that computed on a theoretical basis in the FLAC model. Overall, the bench testing program showed that modelling prior to physical testing was valuable for instrument and monitoring planning, that a sand cap could be successfully placed subaerially at bench scale on tailings of about 100 Pa undrained shear strength, and that deformation modelling (FLAC in large-strain mode) is promising as a tool to reasonably represent tailings response to capping, even for tailings above the liquid limit.

An evaluation of scale-up effects using findings from the bench testing and the literature was conducted to provide guidance for accounting for differences between the bench test and scaling up to pilot test or full-scale application. Beyond the obvious difference in geometric scale, other considerations for scale-up include time effects (e.g. shear softening and thixotropic hardening), environmental exposure, tailings and cap heterogeneity, gas production, temperature, water table level, and depositional methods and dynamics. Specific aspects of each of these effects are discussed in detail in the main body of this report.

Overall, the project delivered on the objectives of developing the first steps of a model (FLAC 2D) useful for predicting success or failure of cap advance on soft tailings, and identification of potential failure mechanisms. Physical testing was conducted to compare cap success and failure conditions to expectations based on model predictions. Finally, critical factors were identified that should be considered when assessing how to bridge the gap between the small-scale tests conducted here and eventual implementation in the field.

The project contributed significantly to understanding the potential for hydraulic capping of treated fine tailings deposits in the oil sands, but it can be considered a first step. There remain a number of areas to study for establishing a more developed conceptual foundation for success and failure potential of this technology. High priority areas include in-depth analysis of the bench test data with the goal of producing a more accurate model for use in scale up; tailings self-weight strength development; assessing the impact of surface strengthening and cap/tailings heterogeneity; deposition method and dynamics; and improving the understanding of conditions needed to support ultimate reclamation activity on capped soft tailings. The importance of some of these has been recognized by the industry since IOSI has awarded three upcoming projects (two in 2019 and one in 2020) that will help further knowledge in the areas of boundary effects, strain dependant behaviour, and surface strengthening.

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1 INTRODUCTION

Conventional practice limits sand cap placement to tailings that have already achieved trafficable strengths. Most fine tailings deposits in the oil sands industry will not achieve this strength until they have consolidated and dewatered for some time. Sand cap or sand layer placement using hydraulic delivery methods offers great potential as a cost-effective, technically feasible capping method for treated fine tailings of the oil sands industry.

The work presented in this report is a step toward demonstrating the feasibility of using hydraulic sand capping on treated tailings. This project demonstrated through modelling the promise of this approach, and confirmed the potential through small scale physical testing of sand capping on weak tailings. One of the key values of this project is the identification of important factors controlling scale-up of tests, and illustrating the importance of accounting for scale effects in interpreting the results of bench-scale work. This also points to approaches to interpreting bench-and-pilot-scale results to help operators better plan both their bench-scale work and their up-scaled tests of capping. A second key value is the learnings from the cap advance model, which strongly support the viability of using hydraulic methods to advance a sand cap over soft treated tailings. These are critical provisions for developing the path forward towards implementation of hydraulic sand capping at commercial scale.

This work is intended as a step toward development of a tool for assessing the behaviour of the fine tailings deposit as a granular layer is advanced across it. The deformation-based modelling tool used for this work shows great promise for planning and evaluating field trials as well as full-scale implementation of granular layer placement.

The potential benefit to the Oil Sands industry of this work are significant. Capping soft tailings with granular materials effectively and efficiently will be a major step forward in the oil sands industry. Sand capping using subaerial hydraulic delivery of the capping material enables a more cost-effective and faster way to reclaim fine tailings in compliance with regulatory requirements.

1.1 Project Team

This work has been performed by a project team is composed of staff from Barr Engineering and Environmental Science Canada, Ltd., Deltares, and Itasca Consulting Group, Inc. Barr and Deltares have worked together on soft sediment and oil sands tailings behaviour studies for nearly 20 years and have successfully performed bench-, pilot- and field-demonstration-scale testing of oil sands behaviour for multiple operators. Itasca, located near Barr's Minnesota office, originally developed the FLAC (Fast Lagrangian Analysis of Continua) models. Barr has collaborated closely with Itasca for decades, and Itasca has supported Barr's use of FLAC for addressing challenging tailings and geotechnical conditions. Barr uses FLAC routinely for modelling tailings and behaviour, because actual deformations can be measured and used to calibrate FLAC for better predictions.

The team members selected for this project have extensive research and applied experience with soft tailings and sediment capping, as well as design, performance and analysis of scaled test programs to evaluate soft materials behaviour progressing from bench to pilot and field demonstration of oil sands and modelling. Key members of the team are: Philip B. Solseng, P.Eng., Jim Langseth, P.Eng., Ben Sheets, PhD., Nav Dhadli, P.Eng., and Jed Greenwood, P.Eng., P.Geo., of Barr, Dirk Luger, Luca Sittoni, and Ebi Meshkati Shahmirzadi, PhD., of Deltares, and Branko Damjanac, PhD., of Itasca.

Nav Dhadli was the project manager of the overall program and the physical trial, Jed Greenwood was the project manager of the cap advance modelling, and Dirk Luger was the leader of the scale-up evaluation. Jim Langseth was the project principal.

1.2 Report Organization

Due to the size and multiple facetted nature of the project, this report includes an executive summary (Section 1.0) and this introduction (Section 2.0) to provide an overall sense of the project. The overall scope and objectives of this project, including the scopes and objectives for each of the three primary elements of the project are presented in Section 3.0. The work is then presented in the same sequence it was performed, with a Section for each primary element: modelling of cap advancement in Section 4.0; bench-scale physical test data along with some preliminary interpretation in Section 5.0; and scale-up considerations for tailings of this character in Section 6.0. Although conclusions and recommendations for follow-up work are presented within individual Sections, the primary conclusions from the work are summarized in Section 7.0, and recommendations for follow-up and additional work are in Section 8.0 so the reader can find them in one place.

Figures and tables are embedded in the text. Appendices provide laboratory data, design basis for the bench-scale physical test, photographs from the physical test, and modelling used in planning the bench-scale physical test. An electronic-only appendix, provided separately, contains the FLAC models used in the cap advance modelling portion of the project, and the FISH functions that were developed to simulate the cap advance over the subaqueous deposit and the subaerial deposit. The cap advance FISH functions are embedded in the input files used for modelling the cap advance and are called out in the input file notes for ease of identification.

2 BACKGROUND

2.1 Project Scope and Objectives

This project is a first phase of defining the conditions for success of hydraulic sand capping treated fine tailings deposits. This involved three steps: 1) develop a model of granular capping of soft tailings to predict the potential for tailings failure as the cap is placed; 2) bench-scale testing intended to demonstrate the potential for treated weak fine oil sands tailings to support a sand cap; and 3) identify critical factors to consider for scale-up to pilot or commercial scale.
The overall objectives of this project included:

- Developing an initial assessment of the factors that affect success or failure of a hydraulically-placed cap advancing either subaqueously or subaerially.
- Identifying the apparent mechanisms for tailings failure as a cap advances.
- Demonstrating cap success and failure conditions in a physical test.
- Identifying scale-up considerations to help practitioners bridge the gap between small-scale tests and implementation in the field.

The scope and objectives are explained in more detail in the following sections.

2.2 FLAC 2D Modelling

The intent of the modelling work was to identify the main contributing factors and conditions for stable advancement of a granular cap over soft treated tailings. Advanced numerical modelling of the capping advancement process was performed to evaluate the main factors affecting deposit stability in response to granular capping.

The scope of the modeling work for the assessment of capping over soft tailings consisted of three tasks: (1) design basis memorandum related to material characterization and the development of the capping profiles, (2) development of a base model in FLAC 2D and related FISH functions to simulate the cap advance, (3) modelling of selected scenarios. Selected factors studied in this project included:

- Capping material:
    - Sand
    - Coke
- Cap slope
- Cap thickness
- Cap rate of advance
- Water table location:
    - Cap submerged
    - Water level at cap front slope

This report presents the design basis and assumptions used in the modeling, summarizes the results from the FLAC simulations, and makes observations about conditions for the stable advancement of granular material over soft tailings and capping methods that lead to unstable conditions. Recommendations for further development of the numerical modelling of the capping advancement are noted.

The objective of the modelling was to identify conditions under which the advancement of granular capping over soft treated tailings would be stable or would induce failure from a geotechnical perspective (ignoring erosion, sedimentation behaviour of the granular slurry, and other considerations which could compromise success of a cap). Geotechnical FLAC (Fast Lagrangian Analysis of Continua) software developed by Itasca was used to model the capping phenomenon. FLAC is a numerical modelling software utilizing an explicit finite difference formulation with a time marching scheme in complex advanced geotechnical analysis. The version used in the cap advance modelling was FLAC2D version 8.00.453.

2.3 Physical Testing (Laboratory Bench Test)

The physical testing (laboratory bench-scale test) was included in the program to cost-effectively evaluate the potential for treated oil sands tailings to support a sand cap, and to corroborate the suitability of FLAC modelling for representing tailings behaviour in response to capping.

The scope of the bench test program was to use available operator-provided treated fine tailings and sand in a bench-scale aquarium to place a sand cap in subaerial conditions, and collect data on the sand placement as well as the tailings response. Prior to bench testing, preliminary modelling was conducted to help design the bench test, specifically the thickness of tailings needed to allow failure modes to be expressed and the thickness of sand cap needed to produce failure, and also to inform instrumentation deployment. In addition, because practical constraints limited the physical testing to a single bench-scale trial, a small preliminary test was conducted to verify instrument behaviour, test techniques for cap placement, and assess likely response of the tailings, including failure behaviour.

In the bench test program, the treated tailings were placed in an instrumented aquarium, and sand was placed in a controlled manner over a portion of the aquarium in successive layers. The response of the tailings beneath the cap as well as the adjacent non-capped tailings was monitored. The tailings were successively loaded to demonstrate whether they respond in a manner consistent with the modelled case, and to load them until a condition of failure was induced.

The aims of the physical test work were:

- Demonstrating the feasibility of sand capping treated fine tailings by doing so at bench scale
- Accounting for the scale requirements for expression of the primary geotechnical failure mechanisms for tailings of various strengths
- Collecting enough information to support
    - assessment of critical factors for scaling corrections and

- strategies for prediction and testing at larger scales

Although the original intent was to use the physical test results to calibrate the analytical model, budgetary constraints as well as the scope of work needed to correctly translate the test results to full scale forced deferral of that work.

2.4 Scale-Up Effects and Considerations

The scope of this work was to use the literature and the findings of the bench tests to present considerations for the upscaling of the sand capping methodology. The assessment addresses various types of differences:

- Reduced Scale Geometry Effects
- Time Effects, Including Shear Softening and Strength Profile Development
- Environmental Exposure effects
- Heterogeneity in the Tailings or in the Cap
- Gas Production
- Temperature
- Water Table Level
- Deposition Method and Dynamics

The objective was to provide initial guidance on accounting for the differences that exist between a small-scale lab test and a larger scale capping trial such as a pilot test or practical full-scale application.

The original intent of including FLAC 3D modelling of the bench-scale test and post-bench-scale test calibration of the model had to be deleted from the scope due to budgetary constraints. However, a recommendation to perform FLAC 2D modelling of the test is made in this report, with the switch from FLAC 3D to FLAC 2D based in part on the scale-up analysis included in this report.

3 EXPERIMENTAL, RESULTS, AND DISCUSSION

3.1 Modelling Cap Advance

The modelling of cap advance over treated tailings is the foundation for the rest of the work done on this project. Two forms of hydraulic capping of treated tailings were modelled: sand raining, the subaqueous advancement of a uniform lift of sand over the tailings; and deltaic capping, the subaerial advancement of a sloped sand cover, using hydraulic delivery methods. Modelling was done using FLAC, a geotechnical model that represents deformation as well as a wide range of material behaviours in the "soil mechanics regime."

This section summarizes the various FLAC cases that were modelled and the associated success and failure conditions. Also summarized are the tailings properties, tailings deposit geometry, cap material properties, cap geometry, and cap advancement for both the subaqueous and subaerial cases. Sufficient modelling was performed to establish the anticipated success or failure of a cap and behaviour of tailings as a cap is placed. This section presents a "representative case" from the matrix in **Table 1** below. Variations on that case were modelled using relevant modelling parameters shown in **Table 1** (cap thickness, cap slope, and advance rate) to determine under what conditions the capping advancement over soft tailings is stable.

Table 1 Matrix of Granular Capping over Soft Tailings Simulation

	Conditions		
Capping Material	**Cap Thickness**	**Cap Slope(s)**	**Advance Rate**
Sand	Thin	Flat	Slow
Coke	Intermediate	Intermediate	Medium
	Thick	Steep	Fast

The modelling was intended to capture key mechanisms in the capping process, which include:

(1) large-strain consolidation of soft tailings (though FLAC does not need to be run in large-strain mode to compute large strain responses, as explained later),
(2) progressive advancement of granular cap over tailings,
(3) coupled flow-mechanical response of capping and soft tailings material,
(4) dewatering and dissipation of excess pore-water pressure, and
(5) various failure modes including
  (a) bearing capacity failures by punching, local shear, and general shear (the cap is able to deform along with the tailings; this is a "flexible" foundation versus a rigid foundation normally used in soil mechanics for bearing capacity),
  (b) squeezing of the fine tailings, and
  (c) deformation within the fine tailings that could have an impact on the likelihood of strain-induced liquefaction in the granular cap.

3.1.1 Tailings Parameters

The tailings material selected for capping in this work was based on the COSIA Capping Challenge Accelerated Dewatered Tailings (ADW), whose properties are listed below.

- Undrained Shear Strength, s_u [Pa]: 300–2,500 (1)
- Solids Content - Geotechnical, *s* [%]: 40 (1) (2)
- Fines Content - Geotechnical I, *f* [%]: 85 (1) (2)
- Clay Content, *c* [%]: 25 (1)
- Bitumen Content, b_m [%]: 5 (1) (2)
- Plastic Limit, *PL* [%]: 30
- Liquid Limit, *LL* [%]: 60
- Specific Gravity - Solids, G_s: 2.30 (2)
- Specific Gravity - Fines, G_f : 2.65 (2)
- Specific Gravity - Bitumen, G_b : 1.03 (2)
- Specific Gravity – Process Water, G_w : 1.02
- Degree of Saturation, S_r : 1.00 (2)
- Water Density, ρ_w [kg/m^3]: 1,020

[1] COSIA Challenge, Appendix 1, table
[2] Scott, J.D., Multiphase Mass Volume Relationships for Tailings, Department of Civil and Environmental Engineering, University of Alberta, Revised April 14, 2003.

For purposes of this study, the geotechnical relationships representing ADW material were gathered from several sources of data for similarly flocculated MFT. These relationships between various parameters are described in later sections.

Undrained shear strength was used as the primary input parameter and all other parameters were correlated back to this value. The initial undrained shear strengths at the mudline and associated solids contents that were considered in the FLAC simulations, are shown in **Table 2**.

Table 2 Initial Undrained Shear Strengths and Associated Solids Contents

Undrained Shear Strength, s_u (kPa)	**0.1**	**0.25**	**0.5**	**0.75**	**1.0**	**2.0**	**5.0**
Solids Content (%)	32	40	46	49	51	56	62

The "input" undrained shear strengths named above are the values at the top of the fine tailings deposit (mudline). This strength was correlated with a solids content according to the relationship described in the following sections. An initial solids content profile, increasing linearly with depth (25% increase in 15 m), was assumed, and was used to generate an undrained shear strength profile for the deposit. In addition, the pore pressure profile at the beginning of cap advancement was assumed to be 20 percent above the hydrostatic pore pressure profile to account for existing excess pore pressure due to very low permeability of tailings and consolidation process. These are broadly consistent with the flocculated MFT "deep stack" properties, aged one year, shown in the Muskeg River Mine 2014 Annual Report submitted to the AER.

While the initial undrained shear strength listed was used as a starting point for each FLAC simulation, the model was allowed to bring the profile to equilibrium prior to cap advancement, resulting in small changes to the void ratio (solids content) and effective stress profiles. This included alteration of the undrained shear strength profile. Once the cap advance began, all these parameters could change over time and space with consolidation (provided the rate of sand cap advancement and permeability allowed for consolidation to occur).

3.1.1.1 Other Relationships

The FLAC model uses FISH functions to represent relationships that require recomputation as the model runs. FISH is an embedded scripting language in the software that enables the user to define new variables and functions. The sections below describe the FISH function relationships that were used for the initial input parameters in addition to the parameters that were computed during advancement of the sand cap.

3.1.1.1.1 Void Ratio vs. Effective Stress [$e = f(\sigma')$]

To ensure that the model was in static equilibrium before the start of sand cap advancement, a void ratio vs. effective stress relationship was developed for each initial solids content (and undrained shear strength) profile and each cap thickness (the cap thickness governed the thickness of the underlying fine tailings used in the modelling of that case). A typical example is shown in **Figure 1**. The curvature is consistent with the shape that has been observed for other flocculated MFT materials.

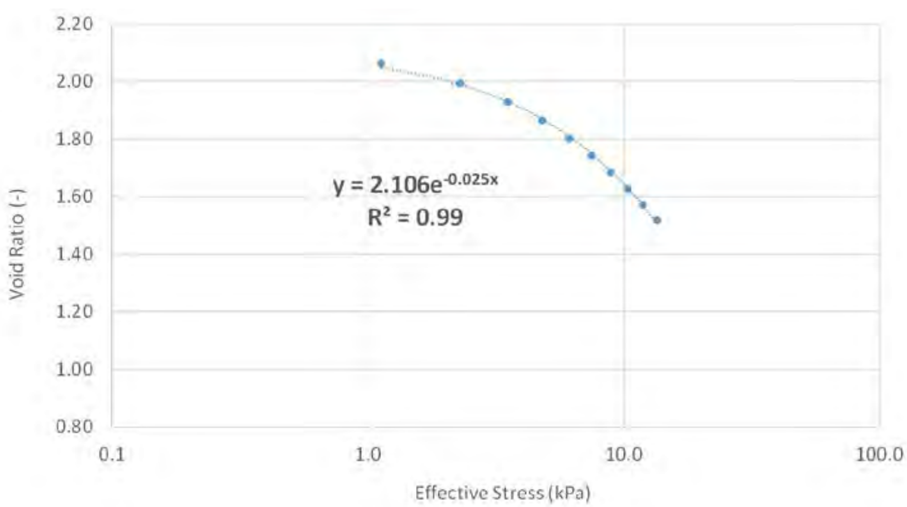

Figure 1 Typical Void Ratio vs. Effective Stress Relationship from FLAC Initial Equilibrium Run

3.1.1.1.2 Undrained Shear Strength vs. Liquidity Index [$s_u = f(LI)$]

An Atterberg limits-based undrained shear strength relationship using liquidity index was used for the modelling. The liquidity index (LI) is defined as:

$$LI = \frac{\frac{e}{G_s}*100-PL}{LL-PL} \qquad \text{Eq. 1}$$

where e = void ratio, and the rest of the parameters are as defined in the Tailings Parameters section, above.

The flocculated MFT relationship between undrained shear strength and liquidity index is shown on **Figure 2**, adapted from Beier et al., 2013, using a LL of 60% and PL of 30%.

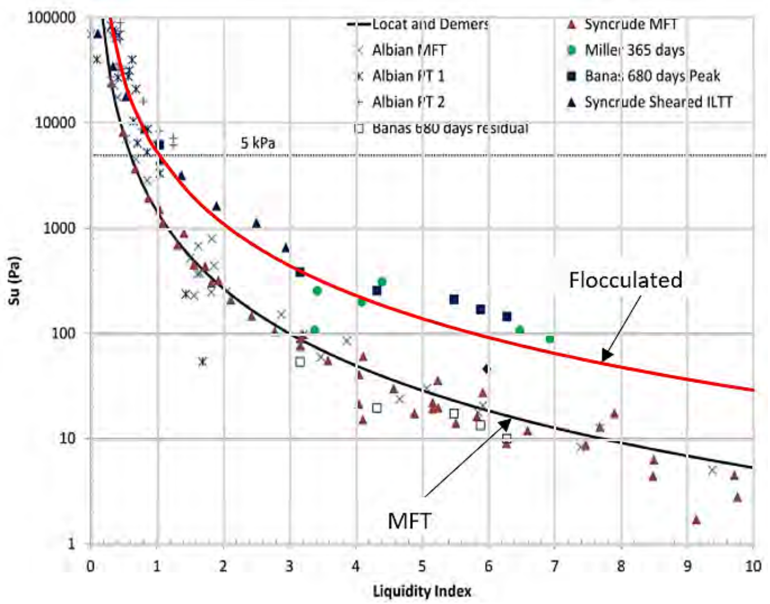

Figure 2 Undrained Shear Strength of Oil Sand Fine Tailings as a Function of Liquidity Index (after Beier et al., 2013)

The area of interest for this study is primarily in the liquidity index range of 1 to 3, where the curve is not at its steepest. Note the clear distinction between MFT and Flocculated MFT in the range of interest.

Although the PL and LL for flocculated fines-rich tailings can range widely, the difference is often around 30 to 35, and thus 30 was considered a representative value for the plasticity index (LL-PL).

The resulting relationship used for modelling is as follows:

$$s_u = (45/LI)^{2.25} \qquad \text{Eq. 2}$$

where the undrained shear strength, s_u, is in Pa.

3.1.1.2 Fines Void Ratio vs. Solids Content [$e_f = f(s)$]

The relationship between fines void ratio and solids content is defined as:

$$e_f = \frac{\left(\frac{1}{s}-1\right)\cdot G_f}{(S_r \cdot G_w \cdot f)} \qquad \text{Eq. 3}$$

where the parameters are as defined in the Tailings Parameters section, above.

3.1.1.2.1 Hydraulic Conductivity vs. Fines Void Ratio [k = f(e_f)]

As described in Hockley (2017), the hydraulic conductivity of fines-dominated deposits can be represented as a function of the fines void ratio. This modelling effort adapted the flocculated tailings hydraulic conductivity reported in Dunmola, et al. (2013) as a function of fines void ratio as shown in **Figure 3**.

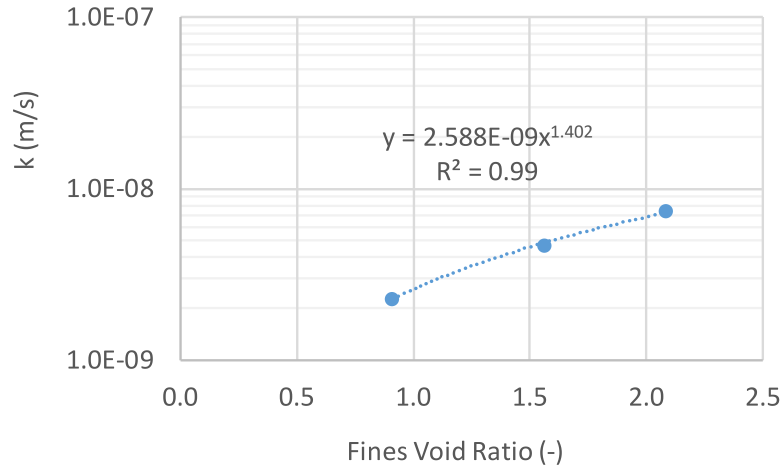

Figure 3 Hydraulic Conductivity of Oil Sand Fine Tailings as a Function of Fines Void Ratio (after Dunmola, et al., 2013)

The resulting relationship used in the modelling is as follows:

$$k = 5.704 \cdot 10^{-11} \cdot e_f^{3.776} \qquad \text{Eq. 4}$$

where k = hydraulic conductivity in m/s and e_f is the fines void ratio.

3.1.2 Cap Profiles and Cap Advancement

Cap profiles were separated into subaqueous and subaerial cases.

For the subaqueous model runs, the cap advance rate was based on the concept of a barge depositing about a 10-m-wide swath of cap through a 3-metre water cover over the tailings. Itasca developed a FISH function for use in the FLAC modelling to represent the cap advance. The cap thickness, front slope, and cap/barge advance rate were varied. For each run, the cap exhibited a uniform thickness (horizontal surface) with a front slope. Cap thicknesses modelled were 20, 50, and 100 cm. The three front slopes shown in **Figure 4** were considered for each cap thickness.

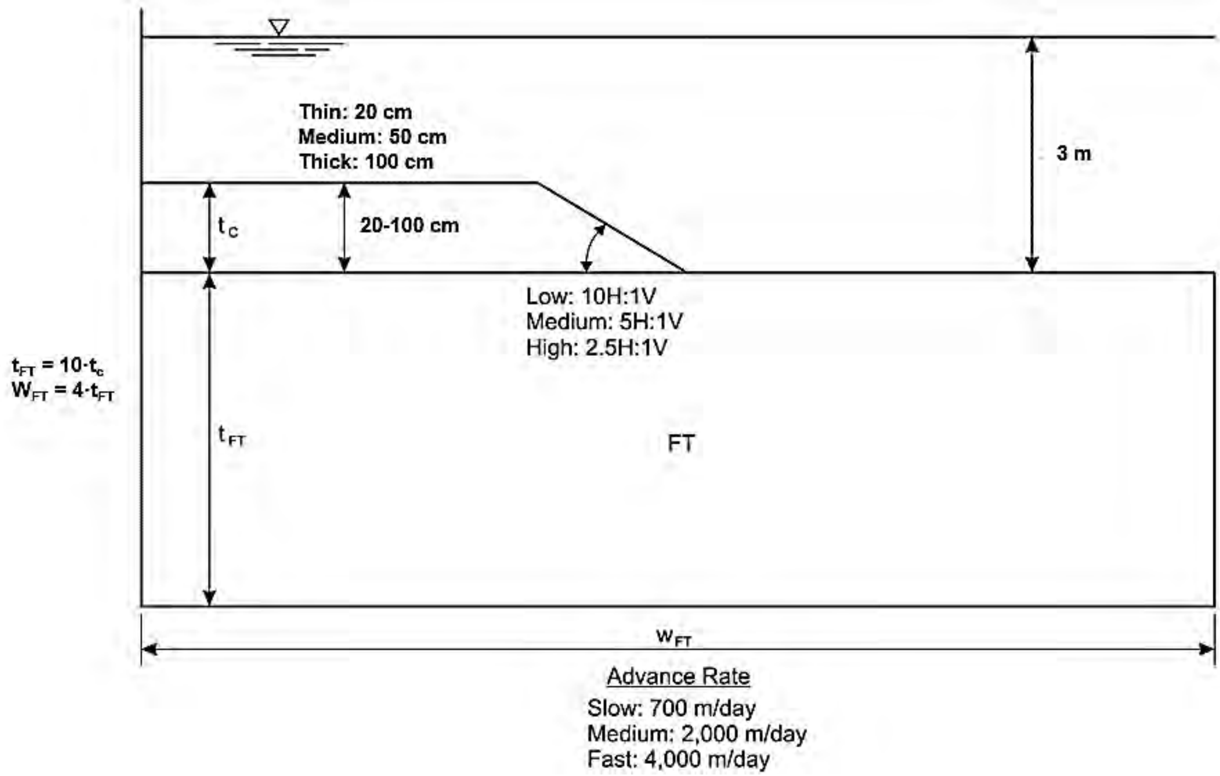

Figure 4 Subaqueous FLAC Runs: Geometry and Input Parameters

For the subaerial model runs, the cap advance rate was based on anticipated rates of granular cap advance assuming material was hydraulically discharged. The cap thickness, front slope, and cap advance rate were varied. For each run, the front slope and beach slope were fixed, which meant that the cap became thicker at a given location as the cap advanced. The point at which the front slope and the beach slope intersected (cap thickness) was determined by the depth of clear water, i.e. the front slope was underwater while the beach slope was above water. In consequence, the portion of the cap below water adds only the submerged weight of the sand to the loading. Cap thicknesses modelled were 50, 100, and 200 cm. The three front slopes (with phi =30^o, these correspond to 1.7H:1V, 3.7H:1V, and 7.6H:1V) and three beach slopes shown in **Figure 5** were considered for each cap thickness.

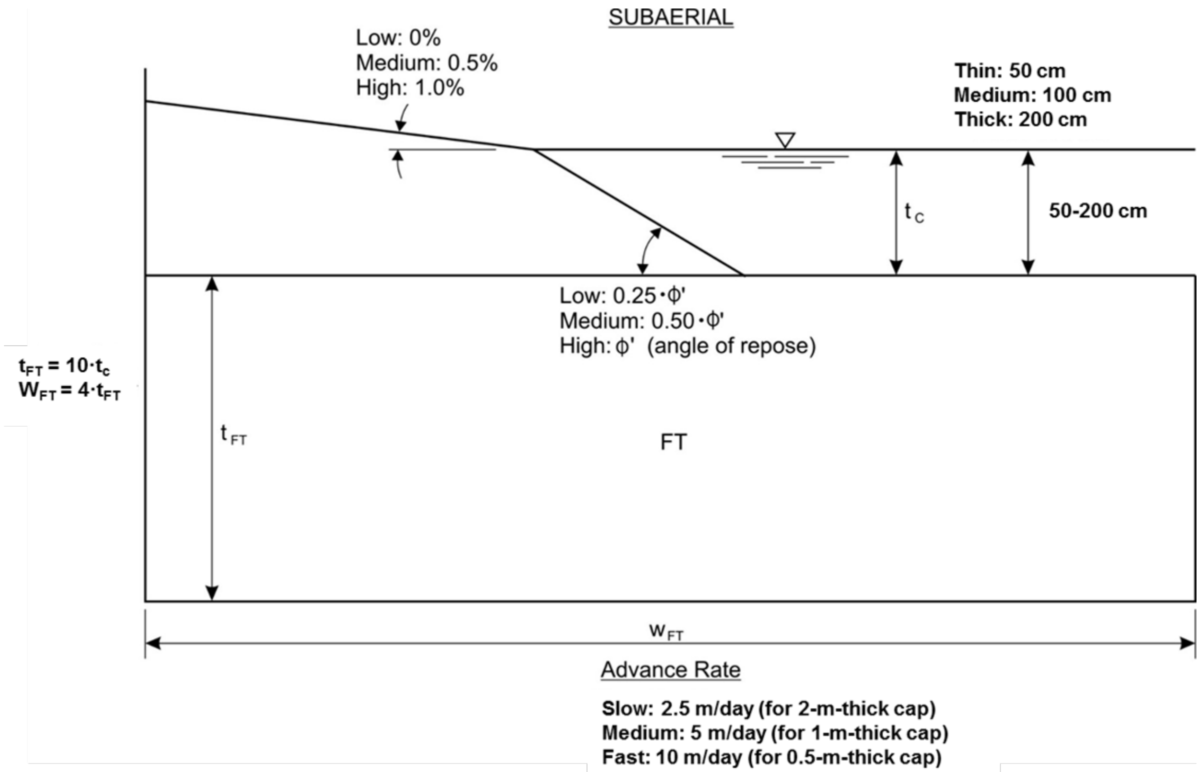

Figure 5 Subaerial FLAC Runs: Geometry and Input Parameters

3.1.2.1 Cap Material Parameters

The cap material modelled for this work consists of sand or coke. The following properties were used for sand material based on the authors' experience.

- Dry density: 1,485 kg/m^3
- Saturated density: 1,935 kg/m^3
- Porosity: 0.45
- Specific gravity: 2.70
- Shear modulus (small-strain): 10,000 kPa
- Drained Poisson's ratio: 0.30
- Peak friction angle: 30°
- Hydraulic conductivity: 8.0x10^{-4} cm/s (assumed)

Coke is assumed to consist of round and smooth particles (fine granular material) with a relatively low friction angle. Coke is a very lightweight material with a specific gravity generally in the range of 1.2 to 1.8. The following properties are assumed for coke material based on the team's experience.

- Dry density: 860 kg/m^3
- Saturated density: 1,385 kg/m^3

- Porosity: 0.46
- Specific Gravity: 1.60
- Shear modulus (small-strain): 6,000 kPa
- Drained Poisson's ratio: 0.20
- Peak friction angle: 28°
- Hydraulic conductivity: 8.0x10^{-4} cm/s

Coke is assumed to consist of round and smooth particles (fine granular material) with a relatively low friction angle. Coke is a very lightweight material with a specific gravity generally in the range of 1.2 to 1.8. The following properties are assumed for coke material based on the team's experience.

- Dry density: 860 kg/m^3
- Saturated density: 1,385 kg/m^3
- Porosity: 0.46
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- Shear modulus (small-strain): 6,000 kPa
- Drained Poisson's ratio: 0.20
- Peak friction angle: 28°
- Hydraulic conductivity: 8.0x10^{-4} cm/s

3.1.3 Methodology

As stated above, the modelling was carried out using FLAC. This section describes the software, modelling procedure, definition of failure, and the simplifications and assumptions.

3.1.3.1 Software

Analysis of the cap advance was performed using the deformation analysis approach. The deformation analyses were conducted using FLAC (Fast Lagrangian Analysis of Continua), a computer-modelling program for engineering mechanics computation. FLAC simulates the behaviour of soil, rock, or other geotechnical materials that may undergo plastic flow when their yield limits are reached. Materials are represented by zones, which form a grid to fit the shape of the geometry modelled. Each element behaves according to a prescribed linear or nonlinear stress-strain law in response to the applied forces or boundary restraints. The material can yield and flow, and the grid can deform (in large-strain mode) and move with the material that is represented.

FLAC is capable of modelling deformations and computing the factor of safety of a slope while analyzing complex geometry, stratigraphy, and loading conditions. FLAC also models the groundwater flow through soil, thus the model accounts for fluid-mechanical interaction (i.e., solves equations of equilibrium and groundwater flow). The flow modelling may be done by itself, independent of the mechanical calculation of FLAC, or it may be done in parallel with the mechanical modelling to capture the effects of fluid-soil interaction.

Another advantage of FLAC is its ability to accept user-defined inputs in the form of FISH functions. This means that complex parameter distributions and loading conditions can be applied, and the results are more realistic than can be achieved using other modelling packages.

3.1.3.2 Modelling Procedure, Assumptions, and Simplifications

Modelling was performed to show the response of the tailings to a cap advancing across a submerged tailings surface of a defined strength. The surface strength defined the solids content at the mudline, as summarized in Table 2. The model used a fixed, initial solids content profile for the tailings. Based on the solids content profile and the relationships defined above, the other elastic, hydraulic conductivity parameters and profile of undrained shear strength with depth were calculated.

While it is recognized that the moisture content of the tailings modelled for this work was often above the liquid limit, the modelling effort assumed that effective stresses had been developed within the fine tailings. A related assumption is that the shear modulus of the material was not zero, indicating that the material is in the "soil mechanics regime" and not the fluid mechanics/sedimentation regime. These assumptions are reasonable for the range of solids contents modelled.

Prior to initiating cap advance, the model was brought to initial equilibrium. Generally more than one iteration of equilibrium calculations were needed to establish internal consistency of the parameters. After deposit equilibration, the cap was advanced across the tailings.

As a simplifying assumption for this initial evaluation of cap advancement, the FLAC model mesh for the fine tailings was not allowed to deform, which means that the gridpoints remained fixed as the cap advanced across the surface of the fine tailings. Deformation of the tailings was computed but the mesh itself was not allowed to distort in order to match the computed deformations. Thus, the model calculations were performed in small-strain mode, but deformation of the tailings, even large strain deformation, was nonetheless computed by FLAC. Using FLAC in small-strain mode simplified the modelling of the cap in this preliminary assessment in that the cap thickness did not change in response to tailings deformation (settlement). A future project will address cap thickness change in response to tailings deformation.

The primary time dependent processes accounted for in these analyses were consolidation and the advance of the cap. Another modelling simplification was that tailings behavior did not account for strain softening, viscosity (creep) or other possible time-dependent or fluid behaviour (potentially relevant for tailings above the liquid limit) processes.

The model advanced the cap across the fine tailings at a constant pre-defined advance rate using a FISH function. During the advancement process, the undrained shear strength and hydraulic conductivity parameters were updated based on the relationships defined above. The cap continued to advance until either the cap had moved across the entire deposit domain, or the tailings and cap had failed.

This procedure was carried out to cover the range of parameters shown in **Figure 4** and **Figure 5**. Modelling indicated which conditions induced failure of the cap for the various initial undrained shear strength profiles (solids content profiles).

3.1.3.3 Initial Model State

Figure 6 illustrates the initial state for a subaqueous model run. It shows the following parameters as a function of depth below mudline for an initial undrained shear strength of 0.75 kPa (at mudline), just before the cap began to advance:

- Total vertical stress
- Pore pressure (hydrostatic, note 3 m of clear water)
- Pore pressure (including excess pore pressure, also note 3 m of clear water)
- Effective vertical stress
- Undrained shear strength

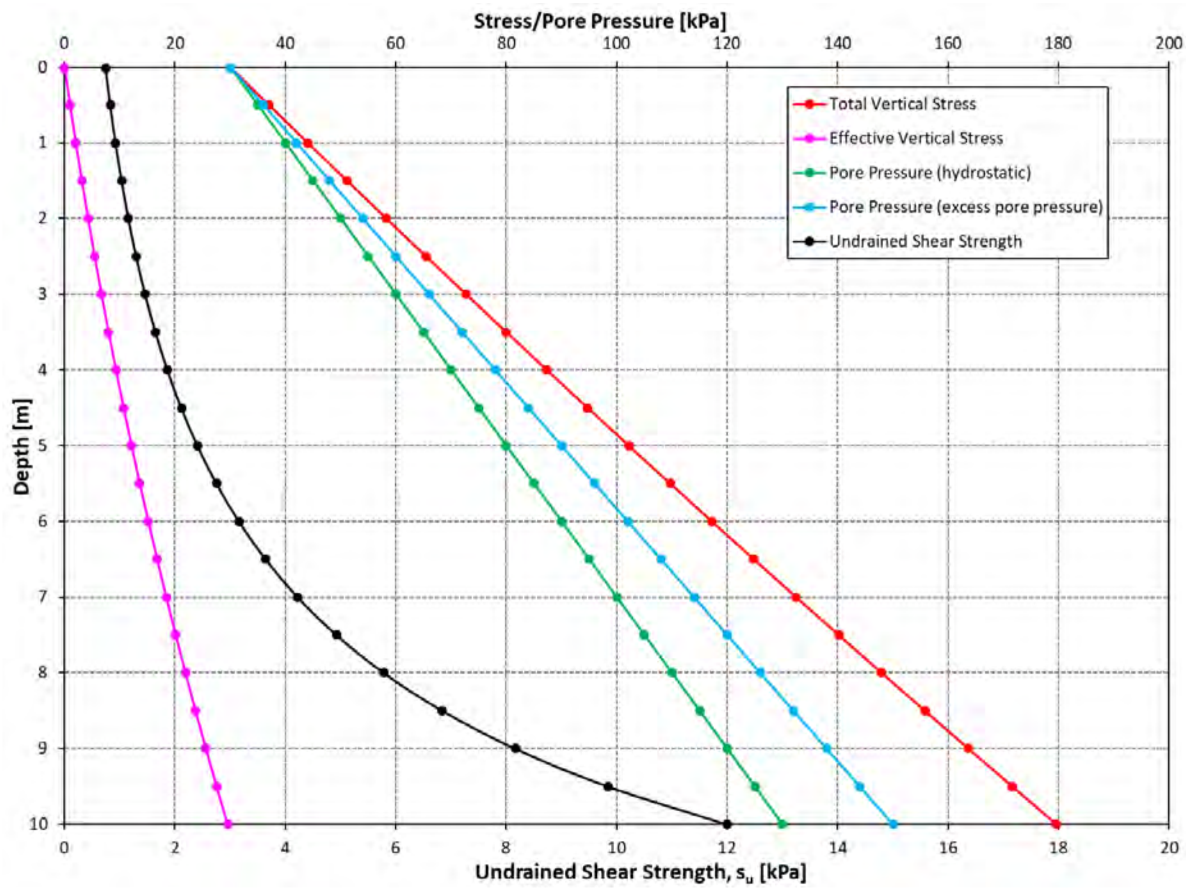

Figure 6 Initial Conditions for a Typical Subaqueous FLAC Run (su=0.75 kPa)

3.1.3.4 Definition of Failure

The definition of failure is an important consideration for this modelling effort. In general terms, it is defined as failure of the cap. It is known that deformation of the cap will occur due to instantaneous deformation and consolidation of the underlying fine tailings in response to the imposition of the cap. However, failure would not be considered to have occurred if the cap layer remains continuous even if it deforms somewhat.

Failure is defined as follows:

- Slope instability (plastic shear deformation) of the cap and underlying fine tailings in which the failure surface extends as far into the fine tailings vertically as the thickness of the cap.

- Punching failure in which the vertical shear deformation in the cap is greater than the thickness of the cap. In other words, the cap would be sheared through and no longer be continuous. This failure mode was not observed in the modelling.

- Other failure mechanisms in which the integrity of the cap is compromised and the continuity of the cap is broken. One of these could be squeezing in which the fine tailings squeeze out faster than the cap advances, leading to sinking of the cap and causing difficulties for practical capping of the deposit. However, the squeezing mechanism requires a “hard” bottom and the bottom of the model has been established deep enough that this particular failure mechanism was not observed.

From a modelling standpoint, success or failure of cap advancement was determined based on model convergence. For example, in cases where cap failure occurred, displacements could become very high, far exceeding the cap dimensions, and subsequently the model did not converge. Given that these are obviously erroneous displacements and the model would not converge, these were flagged as failing cases. On the other hand, displacements (especially vertical displacements) were less than the cap thickness for the successful cases in which the model converged throughout the cap advancement process.

3.1.4 Subaqueous Results

The subaqueous capping model results for a sand cap and for a coke cap are shown in **Table 3**. The cap thickness, front slope, and advance rate were varied for various initial undrained shear strengths. The green sections of the table indicate successful capping (Pass) while red areas of the table indicate unsuccessful capping (Fail). The success or failure of a cap advance was determined based on model convergence – excessive horizontal displacements (far exceeding the model mesh or cap dimensions) indicated cap failure. A second criterion was excessive vertical deformation – deformation greater than the cap thickness was defined as failure, however, this criterion was not triggered in the subaqueous modelling. It should be noted that some cases were inferred by extrapolation and not by a specific model run, for which the P_e and F_e symbols were used.

Table 3 Results of FLAC Simulations for Subaqueous Cap Advancement

SAND																											
Cap Thickness [m]	1.0									0.5									0.2								
Front Slope	2.5H:1V			5H:1V			10H:1V			2.5H:1V			5H:1V			10H:1V			2.5H:1V			5H:1V			10H:1V		
Advance Rate [m/day]	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700
s_u [kPa]																											
2.0	P	P	P	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
1.0	F	F_e	F	P	P_e	P	P	P_e	P	P	P	P	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.75	F_e	F_e	F_e	F_e	F_e	F	P	P_e	P	P	P	P	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.50	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F	F_e	F_e	F_e	F_e	F	P	P_e	P_e	P	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.25	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F	F	F	F_e	F_e	F_e	F	F	F
0.10	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F	F	F
COKE																											
Cap Thickness [m]	1.0									0.5									0.2								
Front Slope	2.5H:1V			5H:1V			10H:1V			2.5H:1V			5H:1V			10H:1V			2.5H:1V			5H:1V			10H:1V		
Advance Rate [m/day]	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700	4000	2000	700
s_u [kPa]																											
2.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
1.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.75	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.50	P_e	P_e	P	P_e	P_e	P_e	P_e	P_e	P	P	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.25	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F	P_e	P_e	P	P_e	P_e	P_e	P	P_e	P_e
0.10	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F	F_e	F_e	F_e	F_e	F_e	F

***P- Pass, F- Fail, P_e - Pass Extrapolation, F_e- Fail Extrapolation**

The modelling results are broadly consistent with reported capping of soft deposits. For instance, the Ijburg project (De Leeuw, 2002) successfully placed a 0.5 m subaqueous sand cap on clay-rich sediments of 0.7 to 1 kPa undrained shear strength. The Ijburg cap was placed with 5H:1V slopes on the front and edges. This is consistent with the sand cap modelling summarized in **Table 3** that shows successful subaqueous capping for a 0.5 m cap on tailings of 0.75 kPa undrained shear strength.

Another check on the reasonableness of the modelling results was calculation of the expected outcome of capping based on a bearing capacity evaluation. For sand capping, the bearing capacity showed expected cap success and failure cases summarized in **Table 4**.

Table 4 Bearing Capacity Estimation of Maximum Cap Thickness

Undrained Shear Strength (kPa)	Bearing Capacity (kPa)	Estimated Maximum Sand Cap Thickness (m)
0.10	0.67	0.07
0.20	1.34	0.15
0.50	3.34	0.4
0.75	5.01	0.6
1.00	6.68	0.7
1.50	10.02	1.1
2.00	13.36	1.5

As can be seen comparing the **Table 3** sand cap results and the bearing capacity table, they predict substantially identical success and failure limits. This was taken as confirmation that the model is producing reasonable results for the conditions evaluated. The bearing capacity evaluation, unlike the modelled cases, has several weaknesses compared to the FLAC modelling. Bearing capacity calculations did not provide information on deformations, and are not suitable for assessing consolidation, readiness for placement of additional lifts of capping material, or the acceptable thickness of those additional lifts.

The influence of the solids content/undrained shear strength (S_u) profile increasing with depth was tested to understand the importance of this parameter. Three representative cases along the Pass/Fail boundary shown in **Table 3** were selected and modelled with a solids content increase over a depth of 15 m of 5% (0.33%/m) rather than 25% (1.67%/m). The cases modeled were ones that had passed under the original conditions:

- 1-m sand cap thickness, 10H:1V front slope, and S_u of 0.75 kPa at mudline
- 0.5-m sand cap thickness, 2.5H:1V front slope, and S_u of 0.75 kPa at mudline
- 0.2-m sand cap thickness, 2.5H:1V front slope, and S_u of 0.50 kPa at mudline

The 1 m and 0.5 m thick caps that with the original solids content profile (i.e., 1.67%/m) were stable (see **Table 3**), failed with a solids content profile of 0.33%/m. The 0.2 m cap did not fail, even with the lower solids content increase.

Results of this sensitivity analysis confirms that the success or failure of cap placement on marginal materials depends on the initial solids content profile and associated undrained shear strength profile, in addition to a number of other factors such as cap thickness, cap front slope, cap material density, and excess pore pressure.

The following observations can be made from the modelling and the results in **Table 3**:

1. The model is providing reasonable results - the overall pattern of success and failure is consistent with experience and expectations; stronger tailings are required to support thicker caps.
2. Capping tailings weaker than 0.5 kPa with a 0.2 m sand cap does not appear practical, even using subaqueous placement methods. To cap such tailings, lighter-weight granular materials or sand lifts thinner than 0.2 m should be explored.
3. The front slope can be a very important factor near the cap thickness limits that a tailings strength can support.
4. The tailings strength/solids content profile is an important factor in the success of a cap, and should be accounted for in the planning and design process.
5. Cap advance rate is a very small factor for success. The advance rate would have to be very slow in order for there to be any benefit from consolidation and strength gain under the leading slope of the cap. The reason for this is the low hydraulic conductivity of the fine tailings. The inconsequential consolidation and strength gain during cap advancement results in very little difference in the performance of the various advance rates.

3.1.4.1 Example Subaqueous Model Results: Successful Cap

A typical successful case is shown in **Figure 7**. This is the case with the following geometry and material strength:

- Cap thickness: 1 m
- Front slope: 10H:1V
- Advance rate: 4,000 m/day
- Undrained shear strength: 0.75 kPa

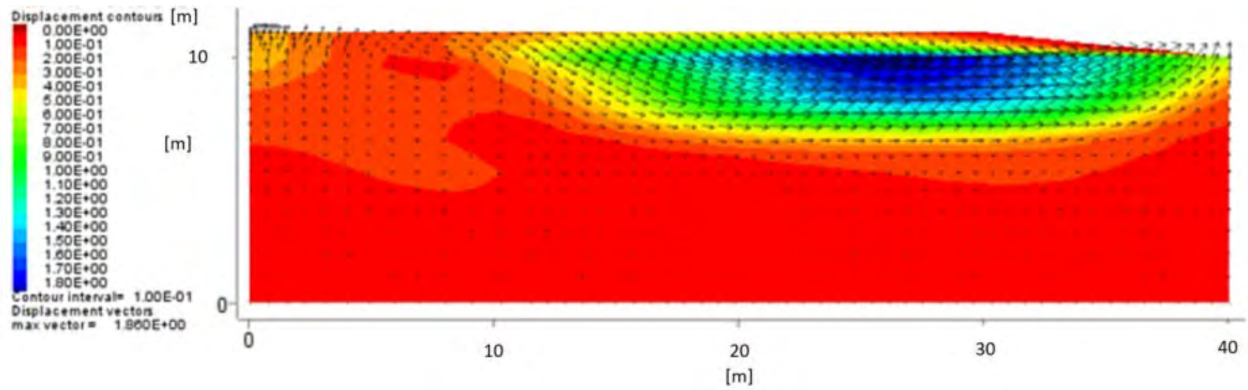

Figure 7 Total Displacement Contours and Displacement Vectors for a Typical Successful FLAC Run

Figure 7 shows the cap as a trapezoidal shape above 10 m while the fine tailings occupy the lower 10 m of the geometry. In this illustration, the cap has advanced all the way across the fine tailings from left to right and the toe of the front slope has touched the right boundary. The color contours are total cumulative displacement (resultant of horizontal and vertical displacements) in units of metres and the arrows are displacement vectors. Most of the deformation is horizontal out in front of the cap advance; as the cap is placed, the tailings in the vicinity of the front of the cap deform forward and upward. As the cap overruns that “bulge,” the tailings deform back downward, and are even displaced downward some centimetres below their original elevation due to the loading from the cap. The details of how the model tracks displacement account for apparent differences in displacement between the cap and the tailings.

Figure 8 and **Figure 9** depict results from the same run but show only horizontal and vertical displacements, respectively. The only other difference is that the mesh is shown instead of displacement vectors.

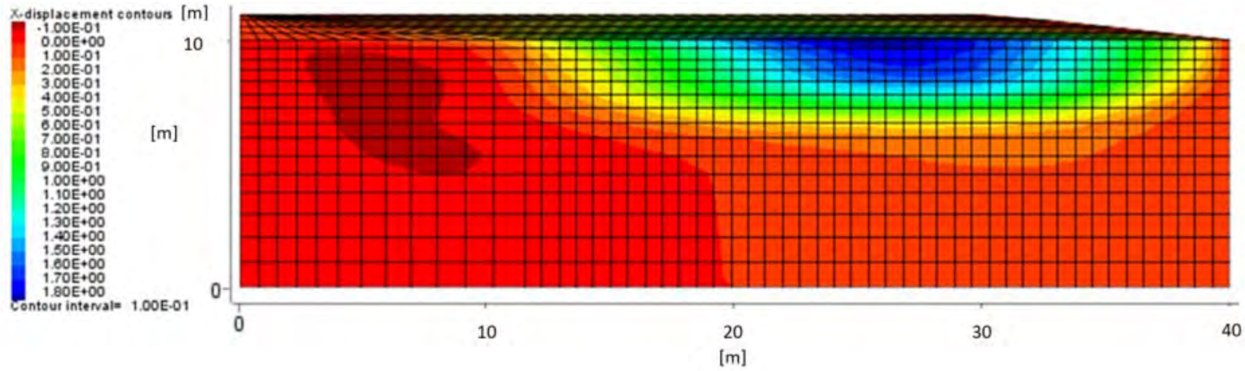

Figure 8 Horizontal Displacement Contours and Mesh for a Typical Successful FLAC Run

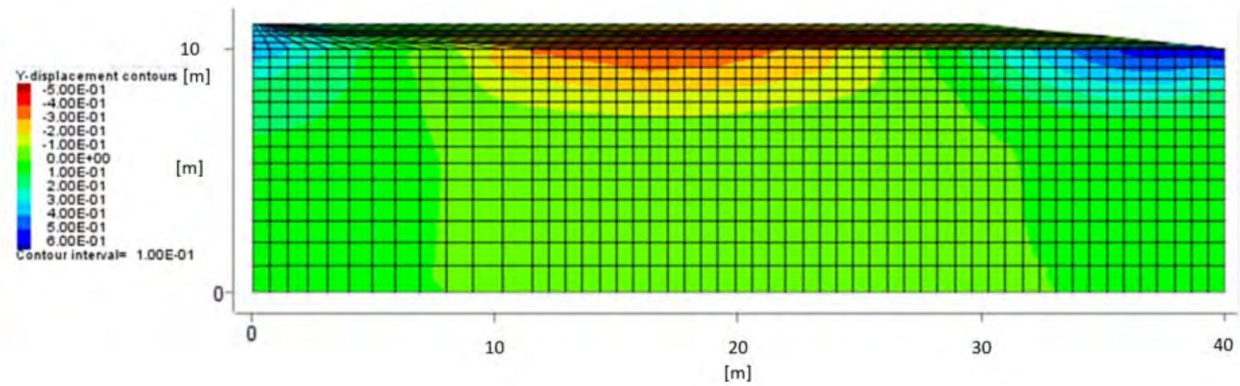

Figure 9 Vertical Displacement Contours and Mesh for a Typical Successful FLAC Run

FLAC modelling outputs for the successful case example shown in **Figure 7** to **Figure 9** represent expected kinematics of a physically stable capping process where both vertical and horizontal deformations are within a reasonable range (e.g., vertical displacements in cap are less than cap thickness, upward movement of tailings in front of cap advancement are not excessive).

3.1.4.2 Example Subaqueous Model Results: Cap Failure

A typical unsuccessful case is shown in **Figure 10**. This case had the following inputs:

- Cap thickness: 1 m
- Front slope: 5H:1V
- Advance rate: 4,000 m/day
- Undrained shear strength: 0.75 kPa

Note this case is identical to the successful case described above except that the front slope is 5H:1V rather than 10H:1V.

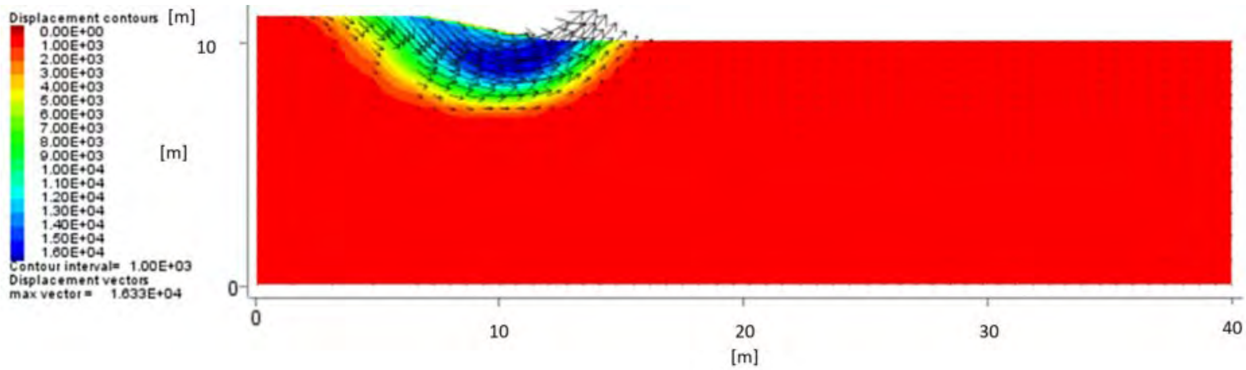

Figure 10 Total Displacement Contours for a typical Unsuccessful FLAC Run

As in the previous figures, the total displacements are in units of metres. Of note is the model-computed displacement of 1.60 x 10^4 m, indicating that the deformations are unrealistically large (i.e., kinematics of an unstable capping process). Furthermore, the model stopped running shortly after this total displacement output, indicating non-convergence, and failure of the tailings and cap.

3.1.5 Subaerial Results

The subaerial capping model results are shown in **Table 5** to **Table 7**. The cap thickness, front slope, beach slope, and advance rate were varied for various initial undrained shear strengths. The green sections of the table indicate successful capping (Pass, shown as P) while red areas of the table indicate unsuccessful capping (Fail, shown as F). As stated above, the success or failure of a cap advance was generally determined based on model convergence. However, another failure criterion was observed in the subaerial runs – the criterion based on excessive vertical deformation (orange sections), which was defined as vertical deformation greater than the cap thickness. This phenomenon is designated by FD (failure by excessive deformation). It should be noted that, as for the subaqueous runs, some cases were inferred by extrapolation and not by a specific model run, for which the P_e, F_e, and FD_e symbols were used.

Table 5 Results of FLAC Simulations for Subaerial Cap Advancement (2-m cap thickness)

SAND																											
Cap Thickness [m]	2.0																										
Front Slope	ϕ									0.5*ϕ									0.25*ϕ								
Beach Slope (%)	1			0.5			0			1			0.5			0			1			0.5			0		
Advance Rate [m/day]	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5
s_u [kPa]																											
25.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
10.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
5.00	P	P_e	P	P_e	P_e	P_e	P	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
2.00	P	P_e	P	P_e	P_e	P_e	P	P_e	P	P	P_e	P	P_e	P_e	P_e	P	P_e	P_e	P	P_e	P	P_e	P_e	P_e	P_e	P_e	P
1.00	F	F_e	F-e	F_e	F_e	F-e	F_e	F_e	F	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F
0.50	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e
0.25	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e
COKE																											
Cap Thickness [m]	2.0																										
Front Slope	ϕ									0.5*ϕ									0.25*ϕ								
Beach Slope (%)	1			0.5			0			1			0.5			0			1			0.5			0		
Advance Rate [m/day]	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5
s_u [kPa]																											
25.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
10.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
5.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
2.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
1.00	P	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P
0.50	F	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F
0.25	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e

***P- Pass, F- Fail, P_e - Pass Extrapolation, F_e- Fail Extrapolation, FD- Failed under Displacement, FD_e-Failed under Displacement, Extrapolation**

Table 6 Results of FLAC Simulations for Subaerial Cap Advancement (1-m cap thickness)

SAND																											
Cap Thickness [m]	1.0																										
Front Slope	ϕ									0.5*ϕ									0.25*ϕ								
Beach Slope (%)	1			0.5			0			1			0.5			0			1			0.5			0		
Advance Rate [m/day]	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5
s_u [kPa]																											
25.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
10.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
5.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
2.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
1.00	F	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F	F_e	F_e	F_e	F_e	F_e	F	F_e	FD	P	P_e	P_e	P_e	P_e	P_e	P	P_e	P
0.50	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F
0.25	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e
COKE																											
Cap Thickness [m]	1.0																										
Front Slope	ϕ									0.5*ϕ									0.25*ϕ								
Beach Slope (%)	1			0.5			0			1			0.5			0			1			0.5			0		
Advance Rate [m/day]	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5
s_u [kPa]																											
25.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
10.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
5.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
2.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
1.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.50	P	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.25	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e

***P- Pass, F- Fail, P_e - Pass Extrapolation, F_e- Fail Extrapolation, FD- Failed under Displacement, FD_e-Failed under Displacement, Extrapolation**

Table 7 Results of FLAC Simulations for Subaerial Cap Advancement (0.5-m cap thickness)

SAND																											
Cap Thickness [m]	0.5																										
Front Slope	ϕ									0.5*ϕ									0.25*ϕ								
Beach Slope (%)	1			0.5			0			1			0.5			0			1			0.5			0		
Advance Rate [m/day]	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5
s_u [kPa]																											
25.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
10.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
5.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
2.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
1.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.50	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F	F_e	F_e	F
0.25	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F_e	F-e	F_e	F_e	F_e	F_e	F_e	F_e
COKE																											
Cap Thickness [m]	0.5																										
Front Slope	ϕ									0.5*ϕ									0.25*ϕ								
Beach Slope (%)	1			0.5			0			1			0.5			0			1			0.5			0		
Advance Rate [m/day]	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5	10.0	5.0	2.5
s_u [kPa]																											
25.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
10.0	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
5.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
2.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
1.00	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.50	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e
0.25	FD	FD_e	FD_e	FD_e	FD_e	FD_e	FD_e	FD_e	FD_e	FD	FD_e	FD_e	FD	FD	P	P	P_e	P	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P_e	P

***P- Pass, F- Fail, P_e - Pass Extrapolation, F_e- Fail Extrapolation, FD- Failed under Displacement, FD_e-Failed under Displacement, Extrapolation**

The subaerial table is three times the size of the subaqueous table because an additional factor was added – the beach slope, which ranged from flat (0%) to 1%, to represent the effect of the slope on the top surface of the advancing subaerial cap. All of the cap below the water level – whose depth is the same as the nominal cap thickness – is considered to be at the submerged unit weight for the sand. Consequently, the outcomes for both the subaerial cap and the subaqueous cap are quite similar; for instance, in both cases, a 1 m cap requires 2 kPa undrained shear strength tailings to succeed unless there is a flat front slope on the cap, in which case 1 kPa could be sufficient.

As would be expected, capping with coke can be successful on tailings of much lower strength than is required for successful sand capping – for coke, success of a 1-m cap can be expected on 0.5 kPa tailings, but for a sand cap, 1 to 2 kPa tailings would be needed (see **Table 6**). A logical extension of this result is to use a lightweight material such as coke for the initial cap lift(s) on weak tailings before switching to sand after the tailings gain sufficient strength to support the greater load of subsequent lifts.

The following observations can be made from the modelling and the results in **Table 5** to **Table 7**:

1. The model is providing reasonable results - the overall pattern of success and failure is consistent with the subaqueous modelling results in addition to the authors' experience, i.e. stronger tailings are required to support thicker caps.

2. Capping tailings weaker than 0.5 kPa with a 0.5 m sand cap does not appear practical. To cap such tailings, lighter-weight granular materials or sand lifts thinner than 0.5 m should be explored.

3. Similar to the subaqueous method, the front slope can be a very important factor near the cap thickness limits that a given tailings strength can support.

4. The tailings strength/solids content profile is an important factor in the success of a cap, and should be accounted for in the planning and design process.

5. The cap advance rate had an inconsequential effect on the deformation-based failure criterion. The advance rate would have to be impractically slow in order to gain any benefit of strength gain of the tailings during cap advancement.

3.1.5.1 Example Subaerial Model Results: Successful Cap

A typical successful case is shown in **Figure 11**. This is the case with the following geometry and material strength:

- Cap thickness: 1 m
- Front slope: 7.6H:1V (0.25ϕ)
- Beach Slope: 1%
- Advance rate: 10 m/day
- Undrained shear strength: 1.0 kPa

There are scale differences to note between the plots of subaqueous and subaerial examples. The thickness of the modeled deposit for subaerial was 20 m, but only 10 m for subaqueous. The horizontal extent of the model was 80 m for subaerial, but only 40 m for subaqueous. **Figure 11** shows that the subaerial deformation profile is broadly similar to what was observed for the subaqueous case, despite the subaerial case having a 1% beach slope that created a linearly increasing pressure extending from the front of the cap back through its entire horizontal extent.

Most of the deformation during cap placement is horizontal out in front of the cap; as the cap advances, the tailings in front of the leading edge of the cap deform forward and upward. When the cap advances, it rides over the upward-deformed tailings and they settle to somewhat below their original elevation. As a result of the beach slope, more settlement occurs at the back of the cap where the cap is at its greatest thickness as shown in **Figure 12**. **Figure 13** depicts results from the same run for the horizontal component only of the displacements.

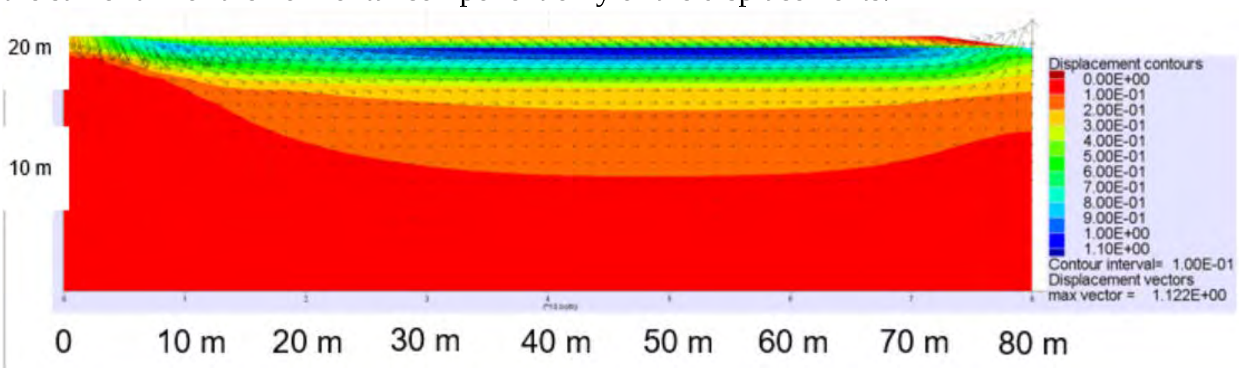

Figure 11 Total Displacement Contours for a Typical Successful FLAC Run

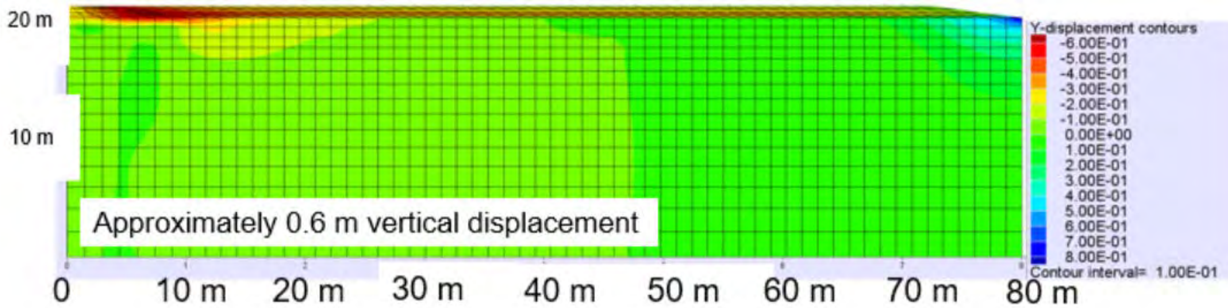

Figure 12 Vertical Displacement Contours and Mesh for a Typical Successful FLAC Run

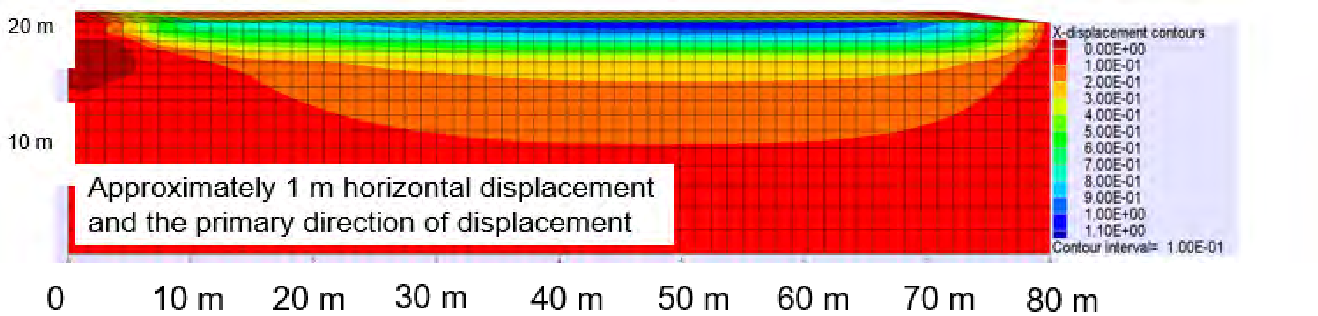

Figure 13 Horizontal Displacement Contours and Mesh for a Typical Successful FLAC Run

FLAC modelling outputs for the successful case example shown in **Figure 11** to **Figure 13** represent expected kinematics of a physically stable capping process where both vertical and horizontal deformations are within a reasonable range (e.g., vertical displacements in cap are less than cap thickness, upward movement of tailings in front of cap advancement are not excessive). The unsuccessful capping cases (an example is depicted in **Figure 14**) failed under the same mode as subaqueous cap placement showing similar behaviour. The unsuccessful cap had a cap thickness of 1 meter, front slope equal to friction angle of sand (ϕ), beach slope of 1%, advance rate of 10 m/day and undrained shear strength of 1 kPa on top.

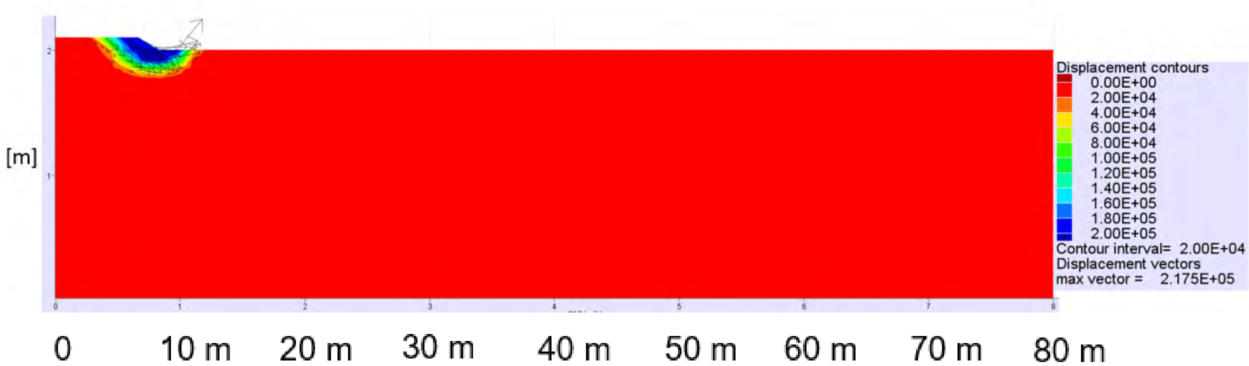

Figure 14 Total Displacement Contours for a Typical Unsuccessful FLAC Run

An electronic copy of the FLAC input files for all the runs and a copy of the FISH functions used for the cap advance over the tailings has been supplied as part of this project. There may be limitations on use or distribution of these materials, as for instance the FISH functions are the intellectual property of IOSI.

3.1.6 Conclusions

The cap advance modelling provided an initial assessment of the required conditions for the stable advancement of a granular cap over soft treated tailings. Advanced numerical modelling using FLAC 2D showed the influence of a number of factors affecting deposit stability in response to granular capping.

Among the conclusions regarding the modelling outcomes and the factors varied in the modelling:

- A flatter front slope is more stable than a steeper front slope, reducing the magnitude of the shear at the cap edge, and possibly acting as a "counter balance" to minimize upward displacement at front of cap
- The tailings strength is a key factor in the allowable thickness for the cap, with 1 kPa tailings strength as apparent lower limit for practical (0.5 to 1 m thickness) sand capping
- Cap advance rate and beach slope appear to have a minor effect on the failure potential during initial placement of cap
- Consolidation during cap advance is inconsequential for practical cap advance rates
- Weaker tailings can be capped using light-weight materials, such as coke, where the same thickness of sand would cause failure
- Water table location - cap submerged, and water level at cap front slope - produced generally similar results, but a submerged cap can be placed on somewhat weaker tailings as long as the slope on the face is flat (e.g., 10H:1V).
- The deposit solids content / strength profile, in addition to the strength at the surface, is an important consideration in cap success

Several observations about the FLAC model itself and using it in small-strain mode were noted:

- The model predicts failure by displacement:
  - Excessive displacement indicates failure (the model fails to converge)
  - Failure was defined as vertical displacement exceeding cap thickness, and several boundary cases failed in this mode
  - The failure mechanism for most cases appeared to be rotational failure at the leading edge of the cap

- o Squeezing failure was not observed, though the model is capable of representing it, because the deposit depth was sufficient and the bottom was horizontal, so that squeezing was not a relevant failure mechanism

- Horizontal displacement was the dominant displacement, for both successful and unsuccessful capping cases, with the small strain model

- Small strain models may not capture excessive vertical displacements for assessing failure mechanics; large strain models appear to be necessary to assess the interaction between deltaic cap advance and tailings settlement. Thus modelling in small-strain may predict successful capping in cases that would fail in practice.

The choice to use FLAC in small-strain mode for this work was deliberate, as this was a first assessment of cap advance modelling to see what conditions promoted success or failure. In small-strain mode, the thickness of the cap remained constant, regardless of the tailings deformation beneath the cap. However, in practical applications, as the tailings deform, additional cap material can fill in, increasing the cap thickness and promoting further deformation of the deposit, possibly leading to failure. Precisely this circumstance is the topic of the 2019 IOSI project "Modeling the Cap Placement with Tailings Deformation and Consolidation."

A number of other important considerations that can address uncertainties and gaps in understanding for modelling are presented in Section 6.0.

3.2 Physical Testing (Laboratory Bench Test)

The physical testing (laboratory bench-scale test, bench test, or aquarium test) was included in the program to cost-effectively evaluate the potential for treated oil sands tailings to support a sand cap, and to corroborate the suitability of FLAC modelling for representing tailings behaviour in response to capping.

A second aspect of the rationale for the physical testing was to illustrate a critical consideration in designing a bench-scale testing program of geotechnical behaviour – the experimental facility must be large enough to allow the relevant failure mechanisms to occur. A preliminary analysis showed that in order to have a test allowing all relevant failure modes to be expressed for subaqueous capping of tailings of 1 kPa strength, the size of the test vessel should be more than 1.5 metres tall, 3 metres long, and preferably as wide as it was tall. The preliminary analysis demonstrated the importance of understanding the scale needed for bench- and pilot-scale tests in order to produce meaningful, scalable results. As a result, the aims of the physical test work were:

1. Demonstrating the feasibility of sand capping treated fine tailings by doing so at bench scale
2. Accounting for the scale requirements for expression of the primary geotechnical failure mechanisms for tailings of various strengths
3. Collecting enough information to support assessment of critical factors for scaling corrections and strategies for prediction and testing at larger scales

3.2.1 Preliminary Studies and Numerical Modelling

Preliminary work was conducted to plan the physical test. The team:

1. Modelled failure dimensions using PLAXIS (a geotechnical code);
2. Performed energy balance calculations
3. Ran a small capping trial and
4. Modeled the physical test using FLAC 2D in large-strain mode

The main objective of the PLAXIS modelling was to determine suitable scale (i.e. size of physical model) or acceptable strength of the tailings for the bench test. The PLAXIS modelling showed a minimum depth of about 0.5 m of tailings would be needed to accommodate rotational failures for tailings of 250 Pa strength (see Appendix A).

The energy balance calculations were used to estimate the thickness of the sand layer that could be supported by the tailings, accounting for wall effects. The calculations suggested that the wall effects could add at least 30% to the resistance to failure (see Appendix A for the calculations sheet and Section 6.0 for a post-physical test evaluation of factors that affected resistance to failure and the magnitudes of their effects).

The small capping trial used a 10-cm cap placed on 20 cm of tailings in a 10-gallon (38 L) glass-walled aquarium (dimensions approximately 51 cm length x 30 cm height x 25 cm width). The tailings strength was measured at approximately 180 Pa. The trial tested the functionality of the vibrating wire piezometers, lateral displacement discs, and settlement plates, in addition to showing the general character of tailings response to loading as a cap was placed.

The FLAC model was used to 1) investigate the likely behaviour of tailings; 2) estimate the sand capping conditions (e.g. load) that should cause failure; 3) select instrument locations to monitor major effects during the test; and 4) assess the approximate magnitude of the effects to be sure the instruments had appropriate sensitivity and measurement range. The team had already performed the small (10-gallon aquarium) capping trial before the modelling was started, and so knew that large vertical deformations could be expected in the experiment. In addition, since the aquarium tests did not use a moving cap (a transient condition that may be challenging to model using FLAC 2D in large-strain mode), the team concluded that a simplified FLAC 2D model in large-strain mode would be a good choice for helping plan the test.

One of the primary advantages of using the large-strain version of FLAC 2D for an application that involves staged lift placement (such as in the physical test modelling) is that the entire mesh deforms during computation. When a coupled analysis is performed such that mechanical and water behaviour calculations are being carried out simultaneously at a real time scale, the settlement of the lift is taken into consideration as the next lift is placed. For example, if a lift is placed on a very compressible foundation and significant settlement occurs because of the induced load from that lift, the next lift will be thicker and excess pore pressures in the foundation will be higher, assuming the lift is being constructed according to a “top of lift” elevation vs time schedule. This is exactly how the physical test was run. Having large-strain capabilities in the modelling software allowed FLAC to reasonably predict cap settlement as observed in the physical test.

Two FLAC 2D model scenarios were run during the planning for the physical test: one scenario that placed four nominal 5-cm lifts that, including settlement, resulted in a 30 cm thick cap, and a second scenario that placed twelve lifts that, including settlement, resulted in a 55 cm thick cap. In both cases, the tailings deposit was 60 cm deep with a uniform 180 Pa undrained shear strength. The FLAC 2D large-strain mode modelling showed that the sand cap was likely to fail in a bearing capacity mode, progressively displacing the tailings but not sinking to the bottom of the test vessel, and also suggested the beginnings of a rotational failure mode by the time the total cap thickness had been added. Figures showing selected outputs from the two model runs are in Appendix A.

3.2.2 Physical Testing

The bench-scale physical testing, including set-up, placing the cap, and decommissioning, took place between January 28 and February 2, 2019, at Barr's Fort McMurray Field Office (FMFO). Section 5.2 summarizes the materials, instruments, methods, and decommissioning of the test. The Execution Plan describing the test plan and measurement program in detail can be found in Appendix B.

The placement was conducted subaerially rather than subaqueously in order to provide a cap surface that could be accurately measured and photographed in real time and also to allow for the adjacent non-capped CFFT to be observed.

3.2.2.1 Test Material

The materials utilized in the testing consisted of CFFT and CST collected from Albian Sands (JPM Sand Cell 2) and transported to the FMFO. The preliminary properties of the CFFT can be seen below in **Table 8**. Additional testing was conducted on both materials and the results of the testing can be found in Appendix C.

Table 8 Summary of Preliminary Index Testing on Centrifuge Cake

Test	Result
Bulk Dry Density	1,520 kg/m^3 (at 45% porosity)
Wet Density	1,330 kg/m^3
Specific Gravity by Pycnometer	2.60
Particle Size Distribution – Laser Diffraction for <44 μm	See Appendix C Sand: 3.0% Silt: 86.9% Clay: 10.1%
pH	8.02
Water Chemistry	See Appendix C
Dean Stark (by closure)	Bitumen: 2.26% Water: 54.57% Mineral: 42.97%

Test	Result
Particle Size Distribution – Wet Sieve	See Appendix C Sand: 3.8% Silt: 86.8% Clay: 9.4%
Atterberg Limits	See Appendix C Plastic Limit: 20 Liquid Limit: 62 Plasticity Index: 42
Methylene Blue Index	MBI: 9.12 meg/ 100 g Clay: 65.43%[1]

[1] Calculated using the Amar Sethi method found in Appendix C

The tank utilized in the testing was a glass-walled aquarium nominally 6 feet long, 2 feet wide, and 3 feet tall, with a glass brace across the top to minimize wall deflection as the tank was filled. The tank wall was 3/4" (1.9 cm) glass, so the inner dimensions of the tank were 178.5 cm long, 57.0 cm wide, and 90 cm tall. This gave the tank a maximum capacity of 916 L.

Figure 15 Physical Test Tank (Aquarium)

3.2.2.2 Testing Instrumentation

Various instruments were placed throughout the tank to provide real-time measurements over the course of the testing. These included:

- VW Earth Pressure Cells (4)
- Low Pressure VW Piezometers (7)
- Atmospheric Pressure VW Piezometer (1, outside the tank)
- Settlement Plates (3)
- Lateral Displacement Disks (8)

- Thermocouples (5)

The layout of the instruments can be seen in **Figure 16** below, while details and locations of these instruments can be found in **Table 9**. Additional information regarding the location and installation methods as well as the purposes of these instruments can be found in the Execution Plan in Appendix B.

The coordinate system used for measurements and instrumentation was referenced from X = 0+00, Y = 0, and Z = 0, at the lower left corner along the front side of the aquarium (the CST being placed from the left side of the tank). The form of notation selected in an effort to make clear what dimension was being reported was as follows: X measured the horizontal distance for the length of the tank in stationing format 1+79.5; Y measured the horizontal distance for the width of the tank, with Y as the lead character, as in Y57; and Z measured the vertical height above the inside bottom of the tank, with an H as the lead character, as in H90. All measurements were in centimetres. The instrument positions shown in the figures use this format. Location information is sometimes presented in other formats, such as in **Table 9**, where the x, y, and z dimensions are in metres, but still use the same origin point for the coordinates.

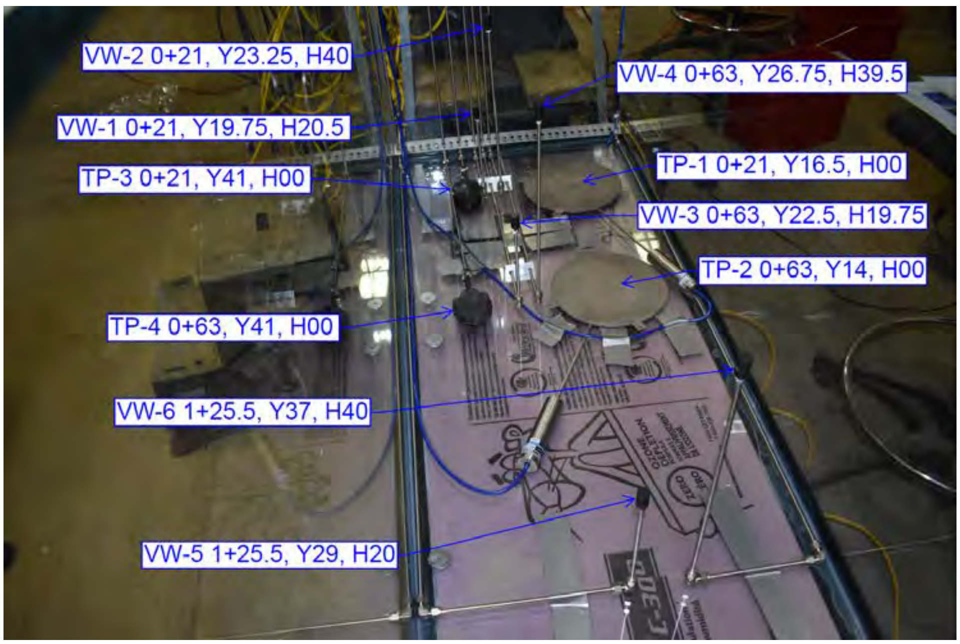

Figure 16 Inner Aquarium Instrumentation As-built View

Table 9 Instrumentation Details and Locations

Instrument Type	Instrument Tag Number/SN	X (m)	Y (m)	Z (m)
Low Pressure VW Piezometer (Pore Pressure)	VW-1 1843520	0.20	0.29	0.20
Low Pressure VW Piezometer (Pore Pressure)	VW-2 1843521	0.20	0.29	0.40
Low Pressure VW Piezometer (Pore Pressure)	VW-3 1843522	0.60	0.29	0.20
Low Pressure VW Piezometer (Pore Pressure)	VW-4 1843523	0.60	0.29	0.40
Low Pressure VW Piezometer (Pore Pressure)	VW-5 1843524	1.20	0.29	0.20
Low Pressure VW Piezometer (Pore Pressure)	VW-6 1843525	1.20	0.29	0.40
Low Pressure VW Piezometer (Pore Pressure)	VW-7 184326	0.20	0.17	0.40
Low Pressure VW Piezometer (Total Pressure)	TP-1 1843527	0.20	0.15	0.00
Low Pressure VW Piezometer (Total Pressure)	TP-2 1843528	0.60	0.15	0.00
Settlement Plate	SP-1	0.20	0.24	0.60
Settlement Plate	SP-2	0.20	0.292	0.40
Settlement Plate	SP-3	1.10	0.29	0.40
Lateral Displacement Disc	LD-1	0.20	0.48	0.40
Lateral Displacement Disc	LD-2	0.60	0.38	0.10
Lateral Displacement Disc	LD-3	0.60	0.27	0.20
Lateral Displacement Disc	LD-4	0.60	0.44	0.40
Lateral Displacement Disc	LD-5	1.06	0.18	0.15
Lateral Displacement Disc	LD-6	1.06	0.21	0.40
Lateral Displacement Disc	LD-7	1.50	0.32	0.20
Lateral Displacement Disc	LD-8	1.50	0.24	0.40

Instrumentation was also placed outside of the aquarium, which consisted of web-accessible, live-feed Vivotek cameras, time-lapse Nikon D5600 cameras, and a Leica P20 scanner which can be seen in **Figure 17**. This setup enabled the team and project stewards to remotely observe both the experiment and the associated instrumentation readings live as the experiment was being carried out.

Figure 17 Leica P20 Scanner and Vivotek Camera Installation

3.2.2.3 Material Placement

The initial plan called for alternating lifts to be mixed with pink Rhodamine fluorescent dye such that displacement could be observed across the tank edges as can be seen below in **Figure 18** and **Figure 19**.

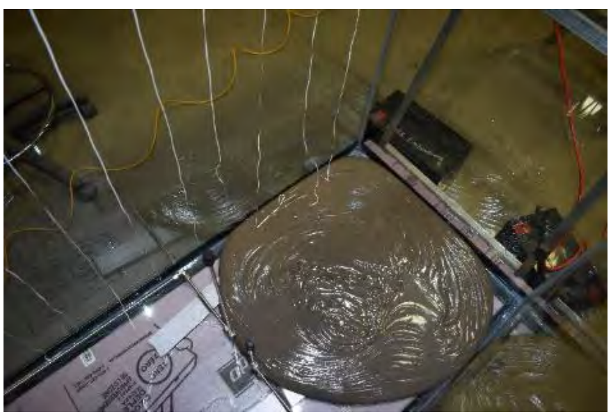

Figure 18 Regular CFFT

Figure 19 Dyed CFFT

Unfortunately, the CFFTs behaviour was more fluid than expected, resulting the pink CFFT simply displacing and mixing with the prior lift rather than resting on top to form distinct bands, as can be seen in **Figure 20** below. This resulted in most CFFT appearing as a greyish purple and release water collecting on the surface or in the CST appearing bright pink. Once the CFFT filling was complete, vane shear tests were taken near the corners distal from the cap zone.

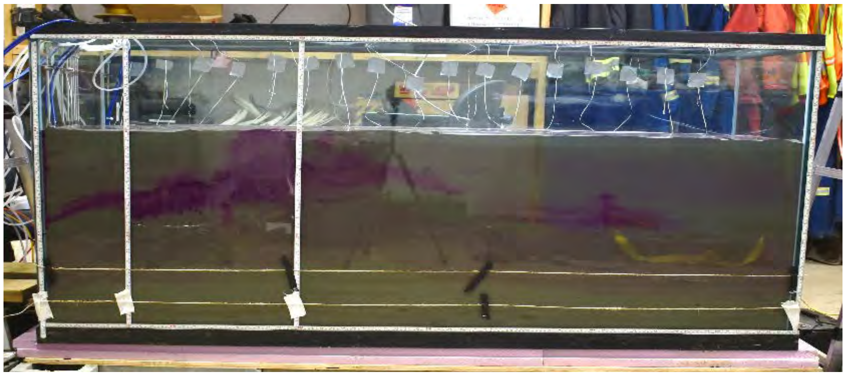

Figure 20 CFFT Filled the Tank to a height of 60 to 61 cm, Ready for Capping

The lateral displacement disks and settlement plates were installed as the tank was filled, as illustrated in **Figure 21** and **Figure 22**.

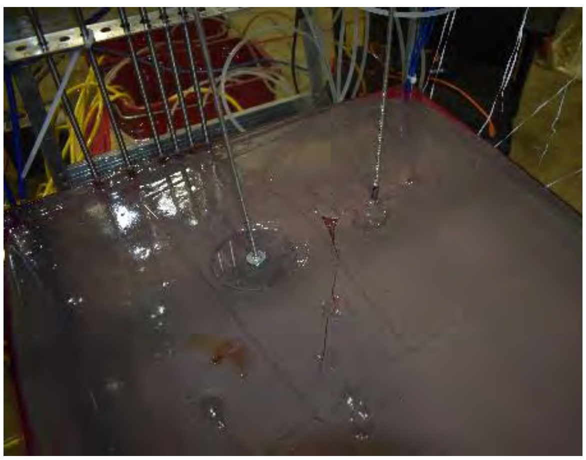

Figure 21 Settlement Plate SP-1 at Surface, SP-2 Immersed

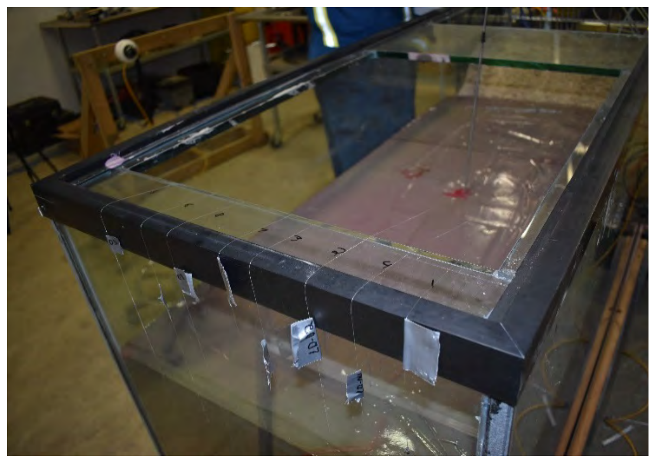

Figure 22 Lateral Displacement Disk Measuring Station

The CST sand cap was placed above the CFFT by hand, gently distributing the sand in a controlled manner using a small scoop to sprinkle the sand, and smoothing the top with a paint brush. No intentional compaction was applied to the CST during placement.

CST placement began with two 2.5-cm-thick lifts followed by seven 5.0-cm-thick lifts. Just before placing a lift, a target lift height was marked on the side of the tank and sand was added until even with the mark. The lifts covered the full 57 cm width of the tank for a length of 40 cm. The slope on the front face was allowed to develop naturally.

The Nikon D5600 time lapse cameras captured each lift and the associated effects on the CFFT. Additional photos were taken of the interface (contact) between the CFFT and the CST. During the capping process, the following instrument measurements were collected:

- Total stress (pressure) at the base of the CFFT (4 VW earth pressure cells)
- Pore pressure in the CFFT (7 low pressure VW piezometers)

- Atmospheric pressure (1 low pressure VW piezometer)
- Deformation of the CFFT (3 settlement plates and 8 lateral displacement disks)
- Temperature in the tailings and the experimental facility (5 thermocouples)
- Shape of the cap surface and CFFT at the start and end of each CST lift (measured with Leica P20 scanner).

The following physical measurements were collected with each lift:

- CST mass placed in the cap lift
- CST cap surface height
- CST cap top of slope and toe of slope location and height
- CFFT deformation under the cap, as seen by the CST-CFFT interface at the tank walls
- CFFT rise outside the CST lift
- Settlement plate height
- Lateral displacement disk movement

Tables of the measurements collected during the test are in Appendix D.

3.2.2.4 Test Decommissioning

Upon completion of the ninth and final lift, final measurements were taken. Vane shear measurements of the undrained shear strength of the CFFT material were taken at multiple locations along the length and width of the tank. The final locations of the lateral displacement disks were measured before being removed from the tank. Final measurements were taken of the settlement plates but they were left in place so as not to disturb nearby instruments. The majority of the CST was excavated from the aquarium carefully in an attempt to obtain final instrument locations such as VW-6, which can be seen below in **Figure 23**. Unfortunately, the final location of VW-7 and LD-1 were compromised during vane testing, thus only a final elevation was estimated for these two instruments. All CST not contaminated with CFFT was returned to its original tote while the CFFT and contaminated CST were removed into the CFFT tote.

Figure 23 VW-6 Excavation during Decommissioning

3.2.3 Results

The capping portion of the experiment was run from January 31 to February 1 at Barr's FMFO facility, a climate-controlled warehouse. Approximately 620 litres of CFFT with a mass of 820 kg (at the measured density of 1325 kg/m^3 were placed in the tank. The CFFT surface was approximately level at 60 to 61 cm above the bottom of the tank before cap placement began. The CFFT had a vane shear strength of approximately 100 Pa.

Five lifts of sand cap – two lifts of a nominal 2.5 cm thickness and three lifts of a nominal 5-cm thickness – were placed on the afternoon of January 31. Another four sand cap lifts were placed on February 1, three lifts of a nominal 5-cm thickness, and 1 lift of nominal 4 cm thickness. The total mass of the nine lifts was 193.3 kg, or approximately 152 litres at a density of 1270 kg/m^3. The nominal cap thickness placed was 39 cm, but the cap never reached 39 cm height, and displaced CFFT as it was built, pushing 20 to 30 cm into the CFFT, so that the total CST thickness placed to build the cap was 50 to 60 cm.

The balance of Section 5.3 presents and summarizes the measurements collected during the test. Physical measurements and Leica P20 scans were used to document the evolution of the cap and tailings surface throughout the test. **Figure 24** below shows the Leica scan results for a cross-section along the centerline of the tank of the initial tailings surface and the 9 cap lifts. The scans are of the surface just prior to placing the next lift, except lift 9, which is just after placing the lift. The glass brace at the top of the tank obscured a portion of the surface (from about X=0+70 to 1+15), but this area was generally uniform and hand measurements were taken in this zone, so the loss of scan measurement in that area was deemed of small importance.

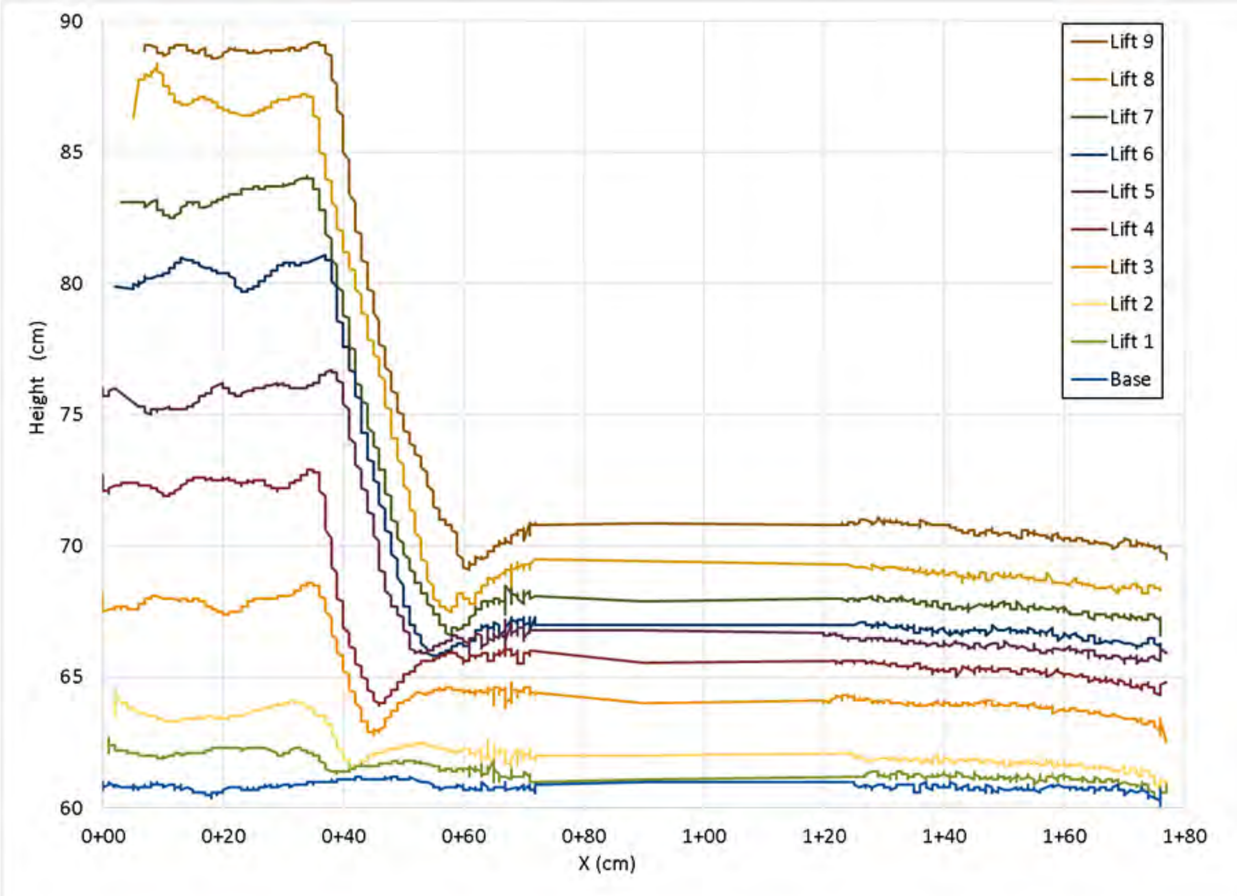

Figure 24 Profile of Tailings and Cap from Laser Scans

As the cap was placed, the tailings were displaced downward beneath the cap, causing the rest of the tailings to rise. Measurements of the tailings surface taken at the sides of the tank are summarized in **Table 10** and plotted in **Figure 25**.

Table 10 CFFT Surface Measurements by Lift at Tank Wall

Height of CFFT (cm)											
Front Wall (Y = Y00)											
Sand Lift #	**x = 0+00**	**x = 0+20**	**x = 0+40**	**Even with Top of CST Slope**		**Toe of CST Slope**		**x = 0+90**	**x = 1+20**	**x = 1 + 50**	**x = end (1+ 79)**
				x =	**z =**	**x =**	**z =**				
1	61	61	61	40	61	43.5	61	61	61	61.2	60
2	61.5	61	61.5	40	61.6	44	61.2	62	61.5	61.4	60.5
3	61	53	61	40	61	48	62	64	63.5	63.5	62
4	61	49.4	52.5	40	52.5	50.5	64.3	65.6	65.5	65	64
5	60	47.5	50.8	40	50.8	55	66	66.4	66	65.7	65
5	60	47.2	49.4	40	49.4	55.2	66.5	66.7	66.1	65.7	65.2
6	60	45.5	47	40	47	56	68	67.9	67	66.9	66.2
7	60	45	46	40	46	60	65.5	67.8	67.5	67.1	66.5
8	59	42.3	42.5	40	42.5	63	68	69.8	69.4	69	68
9	58.5	40.5	40.5	41	40.5	65	69	70.8	70.4	70	69.3
Back Wall (Y = Y57.1)											
1	61	60.5	61	40	61.5	40.5	61.5	61.2	61	60.5	60.5
2	59	60.5	60.7	40	60.7	43	60.7	62	61.6	61	60.5
3	60	54	56.5	40	56.5	48	62.8	64	63.8	63.5	62
4	59.2	50.5	53	40	53	50	64	65.5	65.5	65	63.5
5	58.9	48	49.4	40	49.4	56	65.7	66.7	66	66	65.5
5	59.5	48.2	49	40	49	56	65.5	66.9	66.2	66	65.5
6	59	44.7	45.5	40	45.5	57.5	65.4	67.7	67.3	67	66
7	58.8	44.2	44.4	40	44.4	60	66	67.9	67.7	67.4	66.4
8	59.4	41.5	42	40	42	64	68.9	70	70	69.1	69
9	58.5	39.5	39.7	42	39.7	64	69.5	70.9	71	70.4	70

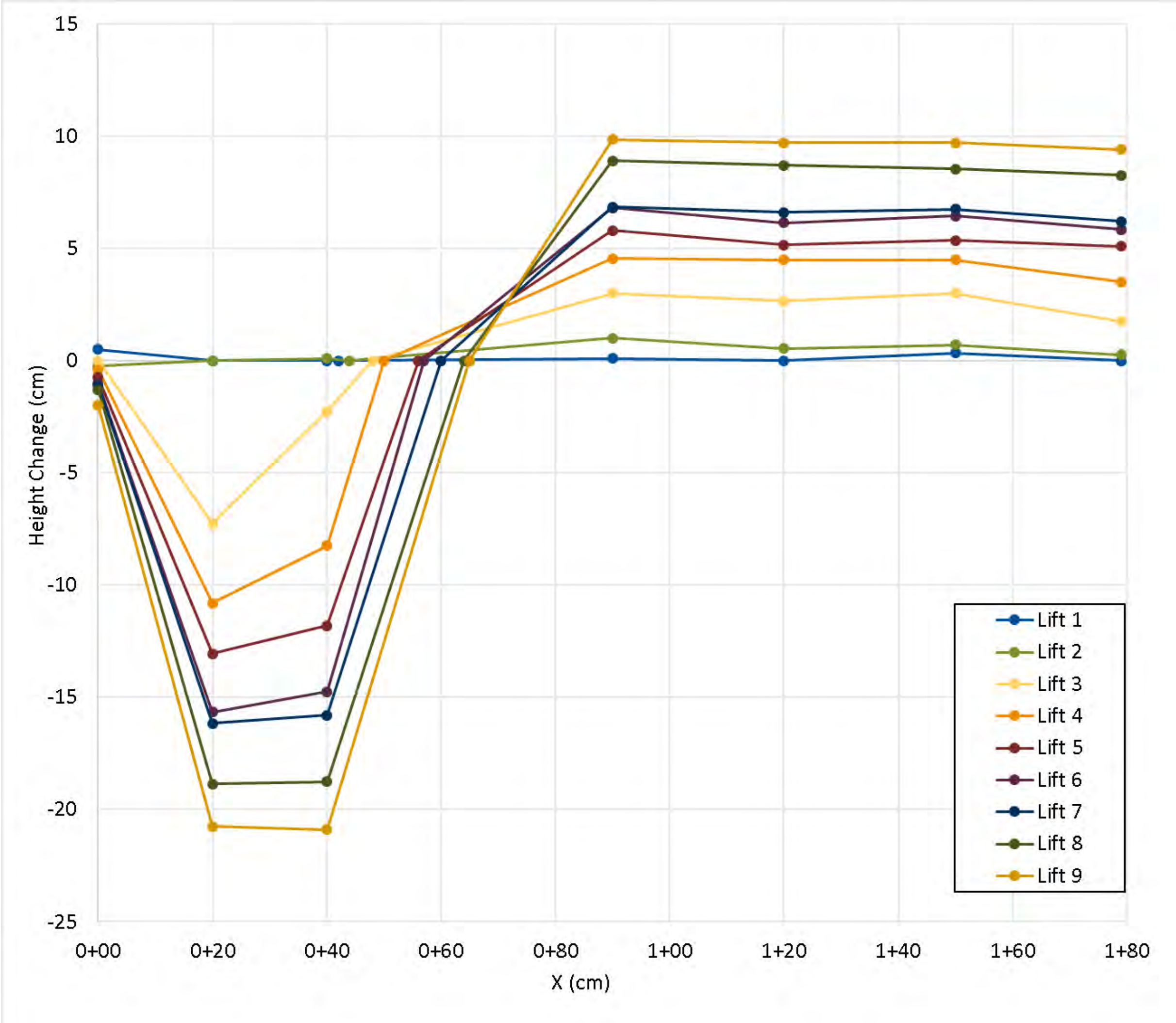

Figure 25 CFFT Surface at Wall: Averaged Front and Back Wall Measurements

The displacement of the tailings beneath the cap is very evident starting with lift 3. For ease of viewing, the measured points for each lift are connected in **Figure 25**. The actual shape of the tailings surface was as seen in **Figure 26** and **Figure 27**, showing lift 5 and lift 9, the final lift (see Appendix E for more photos). The tape measures on the wall are at X=0+00 cm, 0+20 cm, and 0+60 cm. The blue vertical line is at X=0+40 cm and marks the target for the top of the cap slope.

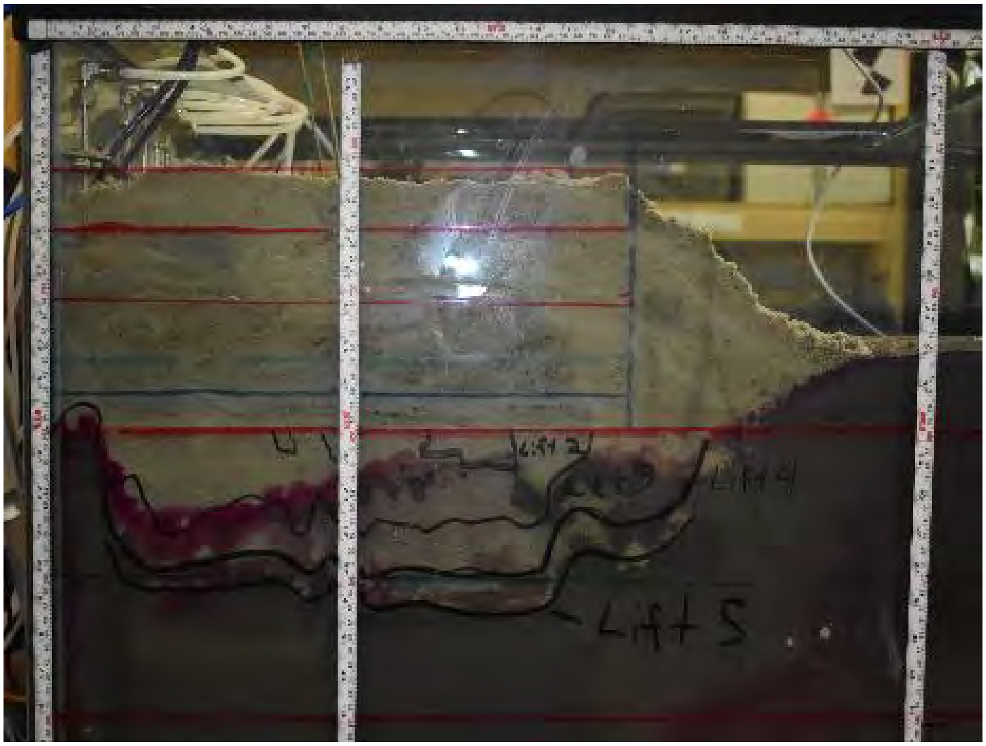

Figure 26 Lift 5 Cap and CFFT-CST Interface

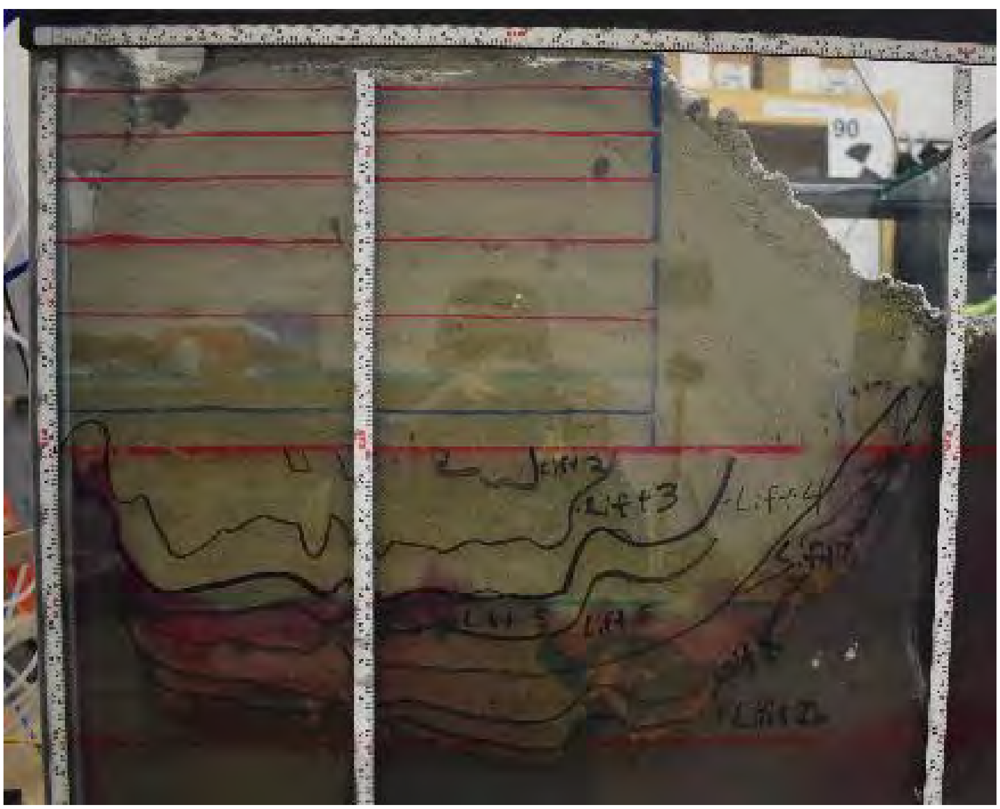

Figure 27 Lift 9 Cap and CFFT-CST Interface

A few points to note: 1) Measurements collected at X=0+00 m suffered from edge effects and end effects (corner of the aquarium) and interference from instrument tubing structures, so tailings at that location stayed at about their original height throughout the test. 2) More generally, the CFFT-CST interface did not settle uniformly, as is evident from the traces of the interface for each lift seen on **Figure 27**). The wall effect was expected to somewhat inhibit cap settlement, so a settlement plate (SP-1) was deployed at the CFFT-CST interface (under the cap) about 12 cm from the wall and 20 cm from the end to monitor settlement of the base of the cap. 4) There was settlement of the cap during lift placement and between completion of one lift and placement of the next lift. Settlement during lift placement had the effect of increasing the amount of sand needed to build the cap to the designated height marked on the side of the tank. The between-lift settlement can be discerned on the photos of lifts in Appendix E. It is also evident on **Figure 27**, where the “target” lift height lines on the tank wall for the upper lifts are less than 5 cm apart. This is a result of marking the new lift height 5 cm above the current cap surface just before placing the next lift. The surface had settled between completion of the prior lift and starting the current lift. Lifts 8 and 9 added only one to two centimetres height to the cap – the cap settled 7 to 8 cm, nearly equal to the 9 cm cumulative added with those two lifts, which was considered to indicate the cap was in failure.

3.2.3.1 Settlement Plate Measurements

Settlement plate measurements for the trial are summarized in **Table 11**. SP-1 measured the interface between CFFT and CST under the cap. The total downward displacement was 28.1 cm, 8 cm more than the 20.8 cm observed at the wall. SP-1 made it evident that there was 2 to 3 cm of downward displacement of the cap into the CFFT for each of lifts 1 and 2, whereas at the wall no downward displacement was seen until lift 3 (see **Figure 25** and **Table 10**).

Table 11 Settlement Plate Displacement Measurements

Lift	**SP-1 Increment (cm)**	**SP-2 Increment (cm)**	**SP-3 Increment (cm)**	**SP-1 Cumulative (cm)**	**SP-2 Cumulative (cm)**	**SP-3 Cumulative (cm)**
0	0.0	0.0	0.0	0.0	0.0	0.0
1	-3.0	-2.0	0.5	-3.0	-2.0	0.5
2	-2.5	-2.0	0.5	-5.5	-4.0	1.0
3	-7.5	-6.5	1.8	-13.0	-10.5	2.8
4	-9.0	-8.5	1.8	-22.0	-19.0	4.6
5 (pm)	-0.5	-1.5	0.5	-22.5	-20.5	5.1
5 (am)	0.0	-0.5	-0.8	-22.5	-21.0	4.3
6	-1.4	-2.0	0.2	-23.9	-23.0	4.5
7	-0.1	-0.2	0.8	-24.0	-23.2	5.3
8	-2.8	-3.5	1.1	-26.8	-26.7	6.4
9	-1.3	-1.0	1.6	-28.1	-27.7	8.0

Settlement plate, SP-2 was placed 20 cm below the cap, and was intended to help with interpretation of model results. The difference between the two under-cap settlement plates (SP-1 and SP-2) is displayed in **Figure 28**, as is the settlement observed mid-way along the cap at the wall (X= 0+20). There is an extra 0.5 cm settlement of SP-2 overnight (lift 5), which was not seen at SP-1 and may not reflect tailings settlement.

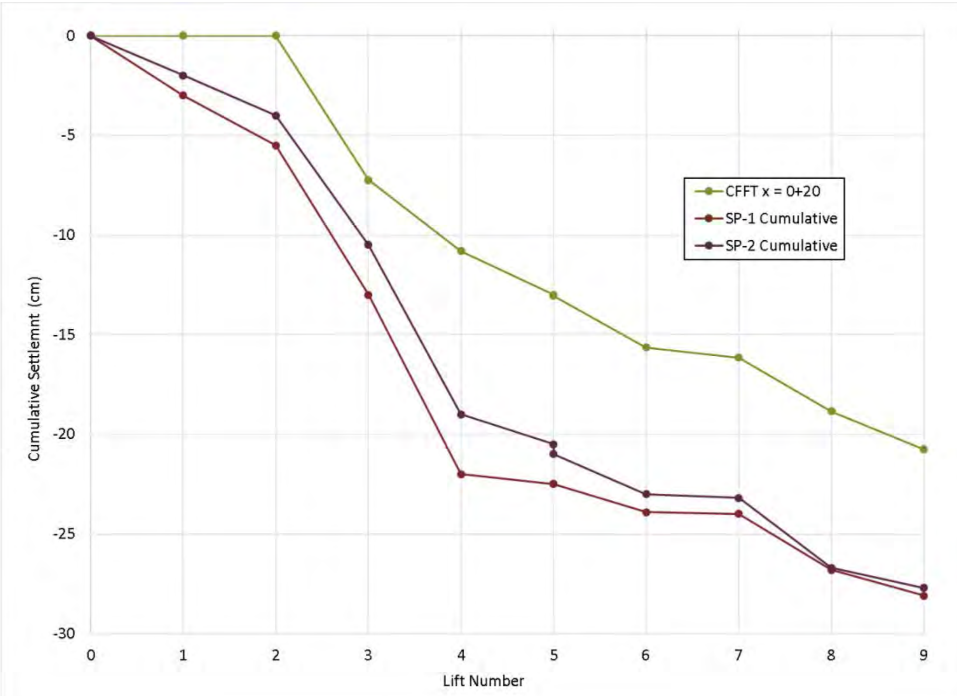

Figure 28 Settlement under Cap X=0+20: Settlement Plates and CFFT at Front Wall

Outside of the CST cap (X=0+60 cm and greater), the CFFT surface rose progressively, at lift 9 reaching an average of 9.7 cm above the original tailings level. The settlement plate SP-3, deployed to monitor expected uplift in the tailings, matched the rise at the wall until lift 6. Following the placement of Lift 5, the experiment was halted for a period of 12 hours and resumed the next morning. Upon resuming the experiment, SP-3 (placed at X=1+10) measured a -0.8 cm (downward) vertical displacement despite experiencing positive (upward) displacement during each lift as can be seen in **Figure 29**. Applying the 12-hour overnight rate of settlement to the 30 hours the settlement plates were present in the tank, SP-3 may have experienced an additional 2.0 cm of uplift as compared to the recorded values. That would put the SP-3 total uplift at 10 cm, slightly greater than the 9.7 cm uplift measured at the wall. SP-3 moved 10 cm laterally over the course of the capping experiment, ending up at X = 1+20 cm.

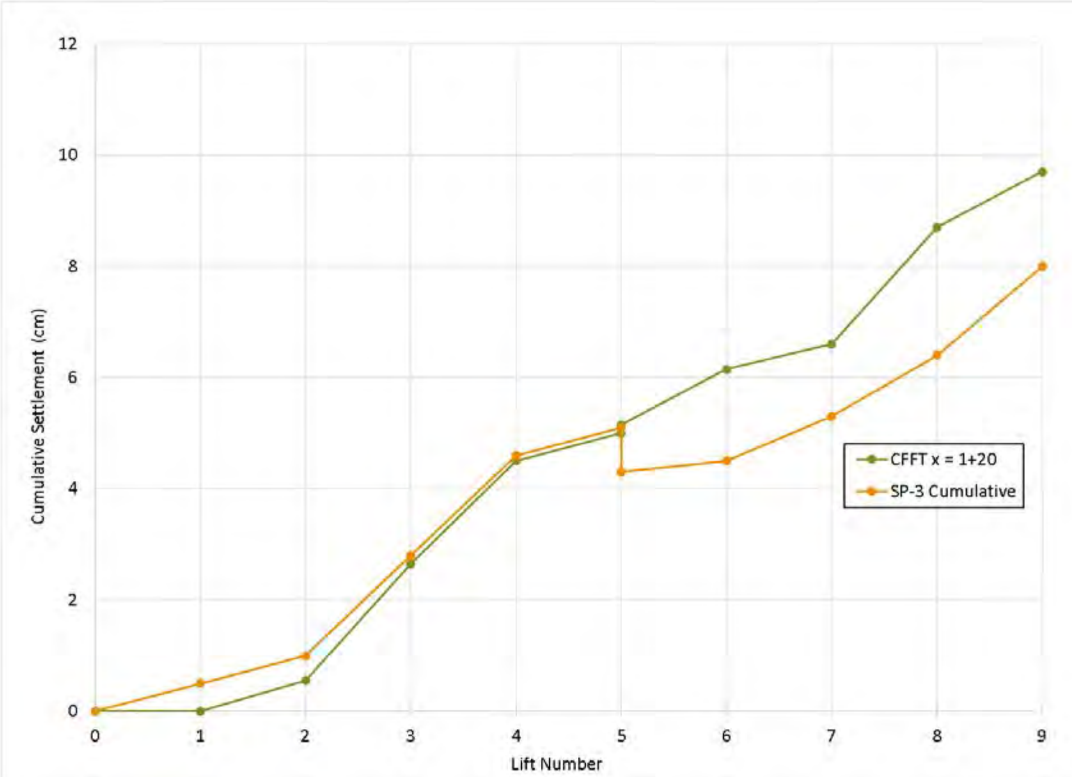

Figure 29 CFFT Uplift X=1+20

3.2.3.2 Vertical Displacement Summary

Figure 30 compares the sidewall and settlement plate measures of vertical tailings displacement shown at their locations along the length of the tank, and includes the cap height as well. The "CST cap crest" is the final height of the cap at the end of the test. The sidewall measured displacements are very uniform, except the one at X=0+00, at the end of the tank where tubes for instruments also interfered with settlement. As can be seen in photos, like **Figure 26** and **Figure 27**, the end effect does not extend more than 5 to 10 cm into the tank.

In addition to the end effect, **Figure 30** illustrates the wall effect. The two settlement plates under the cap had about 1/3 greater vertical displacement than the tailings at the wall (28 vs 21 cm).

The net cap height after lift 9 was approximately 25 cm above the original tailings surface. Based on the settlement plates, the tailings displaced approximately 28 cm downward below the cap. That is 53 cm of cap material placed to build a nominal 39 cm thick cap (two 2.5 cm lifts, six 5 cm lifts, and one 4 cm lift), but that rose only about 25 cm above the tailings surface. The cap was considered to be in failure with placement of lifts 8 and 9, as the height of the cap rose only one to two centimetres as a result of placement of the additional 9 cm of sand. Photos of the experiment show that after lift 8 the cap sank to within 1 cm of its starting level, and lift 9 settlement was highly variable, with most of the cap 0 to 2 cm above the lift 8 starting level.

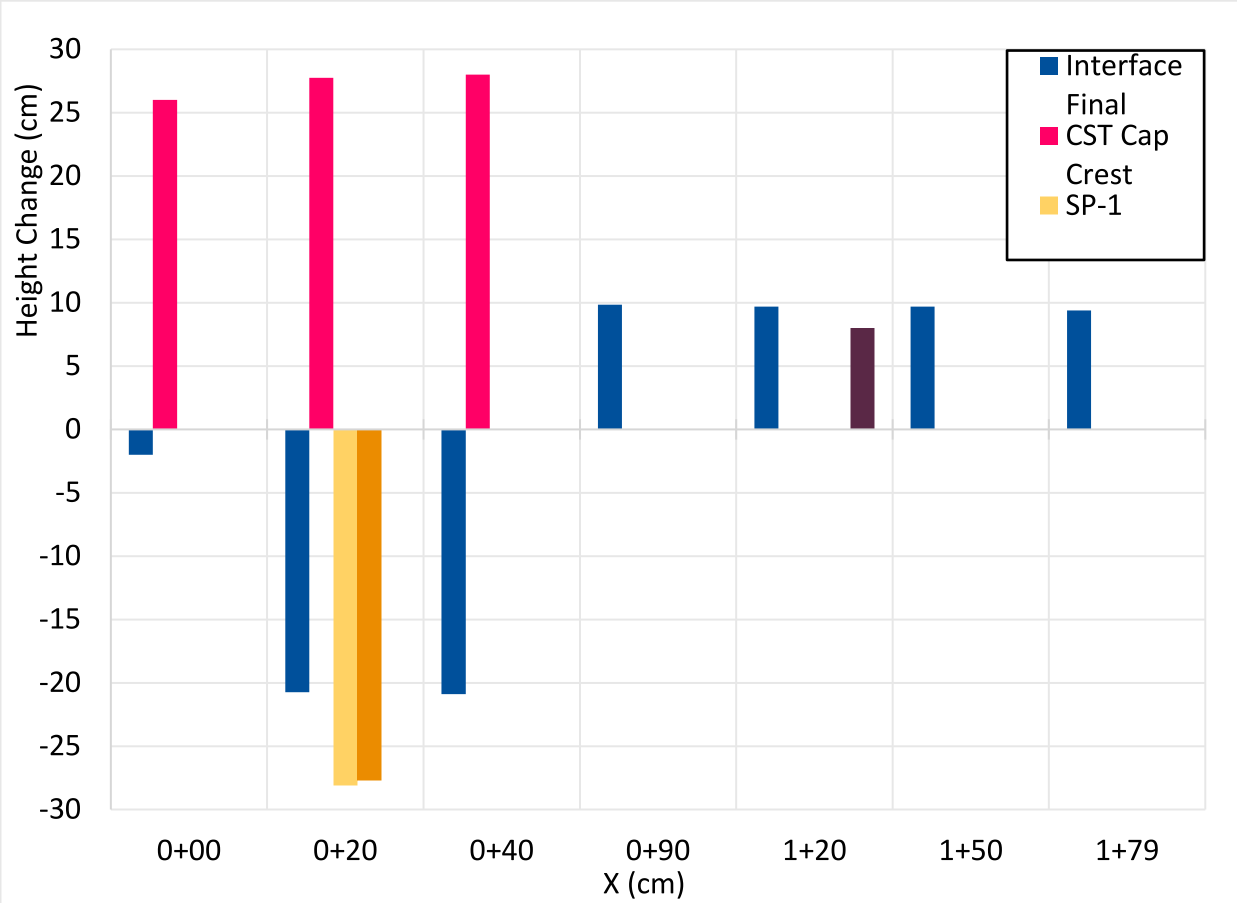

Figure 30 Final Cap Height and CFFT Vertical Displacement across Tank

3.2.3.3 Lateral motion of the tailings

Lateral displacement disks were placed to measure horizontal movement of the tailings, which was expected based on the geometry of the capping trial and the FLAC model results. The lateral displacement disks consisted of a stainless steel washer affixed to fishing line. Once the disks were installed at the correct locations, the fishing line was hung lengthwise over the edge of the tank (1+79) using small weights to keep the line tight. The lengthening or shortening of the line hanging over the end of the tank was recorded with each lift placed. Before decommissioning, the final locations (specifically the elevation) of the disks was determined. The total displacement measured was the hypotenuse of a right triangle for a disk that could be moving both vertically and horizontally with each lift. Applying basic trigonometry, and assuming proportional horizontal and vertical movement, the paths of the disks were estimated as shown in **Figure 31**. The movement, by lift, of the three settlement plates is also shown on the figure for comparison, and the approximate final positions of the CST and CFFT as seen at the sidewall are shown for context.

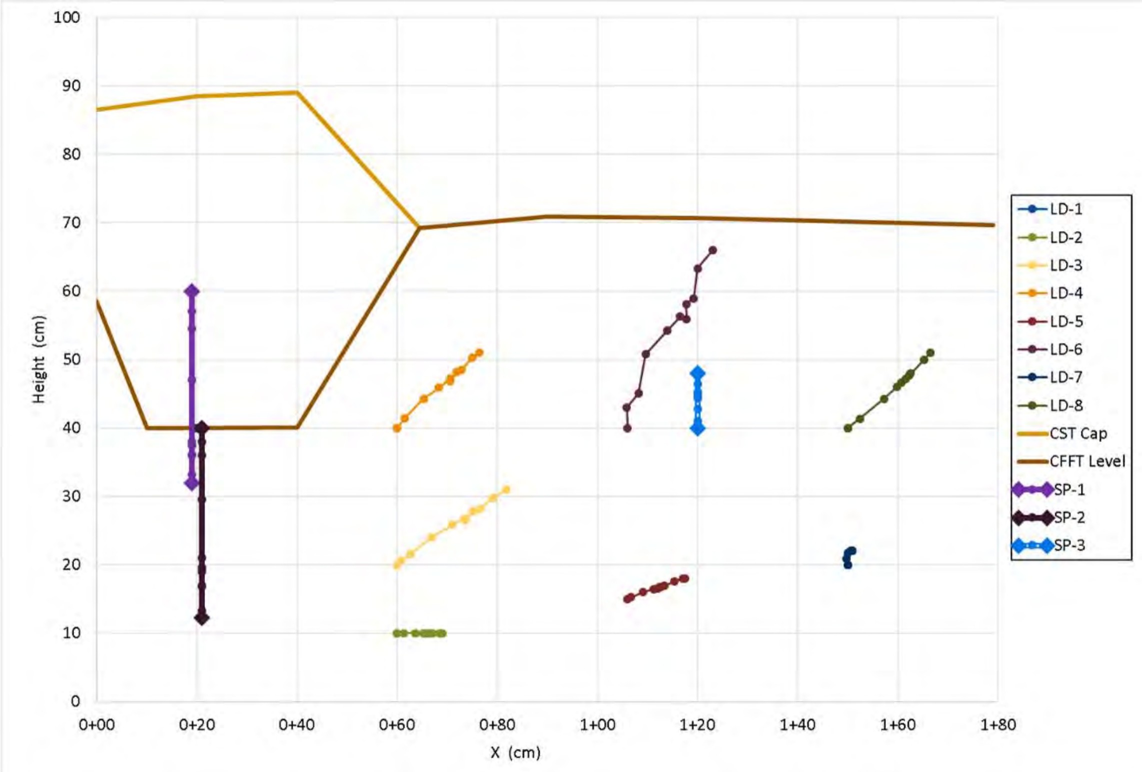

Figure 31 Lateral Displacement Disks and Settlement Plates

The data appear to be internally consistent, with the exception of LD-6 (at X = 1+06 and starting at Z = 40 cm) where the rise is disproportionate with the SP-3 rise, and is consequently suspect. The movement of the lateral displacement disks was always to the right and/or upward. Settlement plates SP-1 and SP-2 moved downward. The lateral displacement disc and settlement plate motions conform to the directions expected as a result of tailings displacement from settlement of the cap into the CFFT.

3.2.3.4 Pressure Measurements

As stated above, a series of vibrating wire piezometers were installed to measure pore pressures at seven points throughout the tailings, along with "total pressures" (total vertical stress) at four locations on the bottom of the aquarium. Data from all instruments were measured during initial filling of CFFT in addition to the various stages of filling with CST.

Table 12 below summarizes the date and time for each task related to filling along with the measured "total pressure" in each instrument. Note that TP1 and TP3 were installed at the same distance from the back wall (0+20), centered under the cap, while TP2 and TP4 were installed at a distance selected to place them under the cap slope (0+60). Four TP cells were installed because of the possibility of exceeding the maximum capacity of the two connected to the VW sensors. Further, all instruments were corrected to the same starting point (7.35 kPa, average of all four TP measurements) after the CFFT had reached a depth of 60 cm and just before the first lift of sand was placed.

Table 12 Total Pressure Measurements vs Time at Various Stages during CFFT and CST Filling

Date/Time	**Task**	**Total Pressure [kPa]**			
		TP1_0+20.H00.y14	**TP2_0+60.H00.y14**	**TP3_0+20.H00.y38**	**TP4_0+60.H00.y38**
1/30/2019 18:07	Start placing fine tailings	-0.03	-0.05	-0.08	-0.04
1/30/2019 20:30	Finish placing fine tailings	6.86	6.84	7.52	7.66
1/31/2019 13:28	Start placing sand Lift 1	7.35	7.35	7.35	7.35
1/31/2019 13:48	Finish placing sand Lift 1	7.50	7.49	7.52	7.47
1/31/2019 14:42	Start placing sand Lift 2	7.49	7.47	7.51	7.47
1/31/2019 15:04	Finish placing sand Lift 2	7.60	7.59	7.66	7.59
1/31/2019 15:57	Start placing sand Lift 3	7.57	7.57	7.70	7.64
1/31/2019 16:22	Finish placing sand Lift 3	7.92	7.97	8.14	7.98
1/31/2019 17:30	Start placing sand Lift 4	7.84	7.92	8.11	8.02
1/31/2019 17:45	Finish placing sand Lift 4	8.09	8.20	8.41	8.25
2/1/2019 9:10	Start placing sand Lift 5	7.97	8.05	9.21	9.14
2/1/2019 9:22	Finish placing sand Lift 5	8.18	8.31	9.51	9.34
2/1/2019 9:39	Start placing sand Lift 6	8.17	8.28	9.49	9.37
2/1/2019 9:40	Finish placing sand Lift 6	8.34	8.47	9.73	9.49
2/1/2019 10:34	Start placing sand Lift 7	8.23	8.32	9.54	9.44
2/1/2019 10:44	Finish placing sand Lift 7	8.29	8.43	9.68	9.52
2/1/2019 11:46	Start placing sand Lift 8	8.24	8.38	9.66	9.54
2/1/2019 12:02	Finish placing sand Lift 8	8.58	8.72	10.03	9.81
2/1/2019 13:46	Start placing sand Lift 9	8.51	8.58	9.87	9.75
2/1/2019 13:58	Finish placing sand Lift 9	8.66	8.81	10.13	9.92
2/1/2019 16:08	Start tearing down experiment	8.60	8.71	9.99	9.86

Table 13 below summarizes the date and time for each task related to filling along with the measured pore pressure in each piezometer. As with the total pressure cells, all piezometers were corrected to the same theoretical starting value for a given depth based on a water unit weight of 10 kPa and the instrument's respective depth below the top of the CFFT. These starting values were 4.00 kPa for the instruments at a height of 20 cm above the bottom of the aquarium (40 cm below the top of the 60 cm deep CFFT) and 2.00 kPa for the instruments at a height of 40 cm above the bottom of the aquarium (20 cm below the top of the 60 cm deep CFFT).

Table 13 Pore Pressure Measurements vs Time at Various Stages during CFFT and CST Filling

Date/Time	Task	Total Pressure [kPa]						
		VW1_0+20.H20.y28	**VW2_0+20.H40.y28**	**VW3_0+60.H20.y28**	**VW4_0+60.H40.y28**	**VW5_1+20.H20.y28**	**VW6_1+20.H40.y28**	**VW7m_0+20.H40.y38**
1/30/2019 18:07	Start placing fine tailings	-0.45	-0.24	-0.23	0.69	-0.24	1.62	-0.01
1/30/2019 20:30	Finish placing fine tailings	3.04	1.28	0.44	1.95	1.51	3.48	-0.02
1/31/2019 13:28	Start placing sand Lift 1	4.00	2.00	4.00	2.00	4.00	2.00	2.00
1/31/2019 13:48	Finish placing sand Lift 1	3.90	2.10	4.07	1.93	3.95	2.00	2.18
1/31/2019 14:42	Start placing sand Lift 2	4.44	2.10	4.13	2.25	3.74	2.11	2.17
1/31/2019 15:04	Finish placing sand Lift 2	4.53	2.20	4.16	2.23	3.69	2.10	2.33
1/31/2019 15:57	Start placing sand Lift 3	4.63	2.27	4.22	2.31	3.69	2.14	2.31
1/31/2019 16:22	Finish placing sand Lift 3	4.91	2.58	4.37	2.36	3.77	2.27	2.69
1/31/2019 17:30	Start placing sand Lift 4	5.00	2.61	4.53	2.61	3.85	2.42	2.59
1/31/2019 17:45	Finish placing sand Lift 4	5.07	2.84	4.44	2.61	3.83	2.45	2.71
2/1/2019 9:10	Start placing sand Lift 5	5.94	2.93	5.31	2.97	3.95	2.74	2.78
2/1/2019 9:22	Finish placing sand Lift 5	5.99	3.11	5.29	2.96	3.92	2.73	2.89
2/1/2019 9:39	Start placing sand Lift 6	6.13	3.09	5.24	3.00	3.94	2.88	2.95
2/1/2019 9:40	Finish placing sand Lift 6	6.13	2.68	5.25	3.00	3.95	2.88	2.99
2/1/2019 10:34	Start placing sand Lift 7	6.24	3.24	5.49	3.11	4.03	2.96	2.97
2/1/2019 10:44	Finish placing sand Lift 7	6.25	3.25	5.49	3.16	4.01	2.97	3.02
2/1/2019 11:46	Start placing sand Lift 8	6.31	3.20	5.70	3.28	4.00	2.98	3.01
2/1/2019 12:02	Finish placing sand Lift 8	6.52	2.53	5.67	3.19	4.00	3.02	3.21
2/1/2019 13:46	Start placing sand Lift 9	6.63	2.43	5.97	3.32	4.14	3.24	3.20
2/1/2019 13:58	Finish placing sand Lift 9	6.70	2.46	6.07	3.36	4.12	3.19	3.24
2/1/2019 16:08	Start tearing down experiment	6.81	2.39	6.21	3.54	4.20	3.39	3.26

The data from all four total pressure sensors throughout the aquarium testing are plotted below in **Figure 32**.

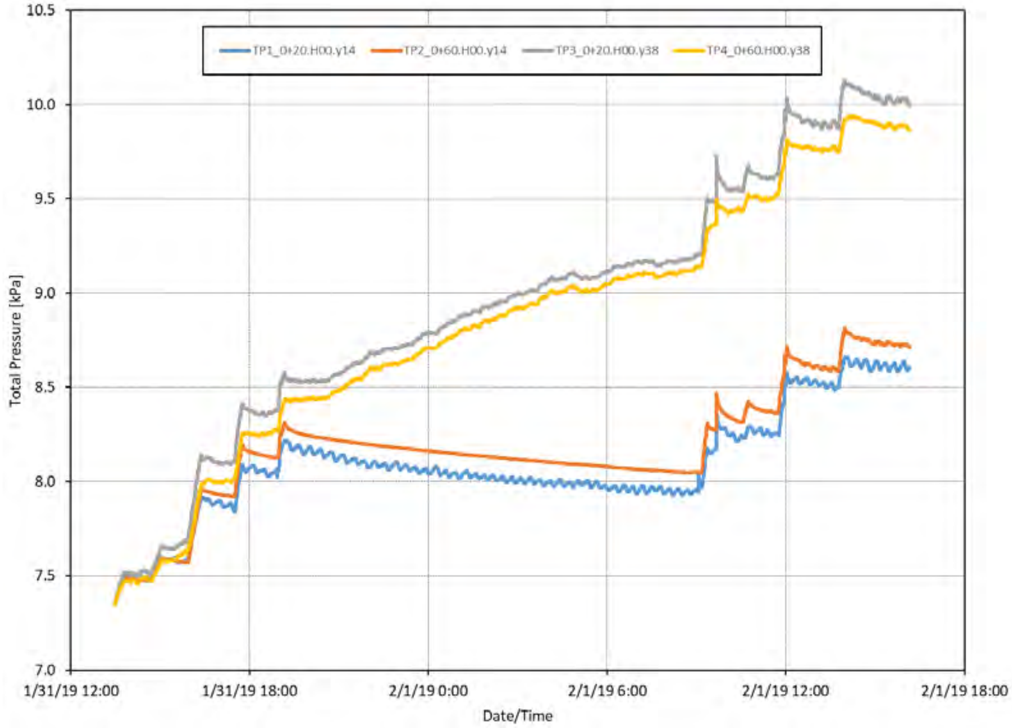

Figure 32 Total Pressure vs Time (Corrected to Average Initial Value)

The data from all seven piezometers throughout the aquarium testing are plotted below in **Figure 33**. The pressure in VW-2 abruptly dropped during placement of lift 8, presumably because the cap engulfed it, so it was no longer measuring pressure in the CFFT.

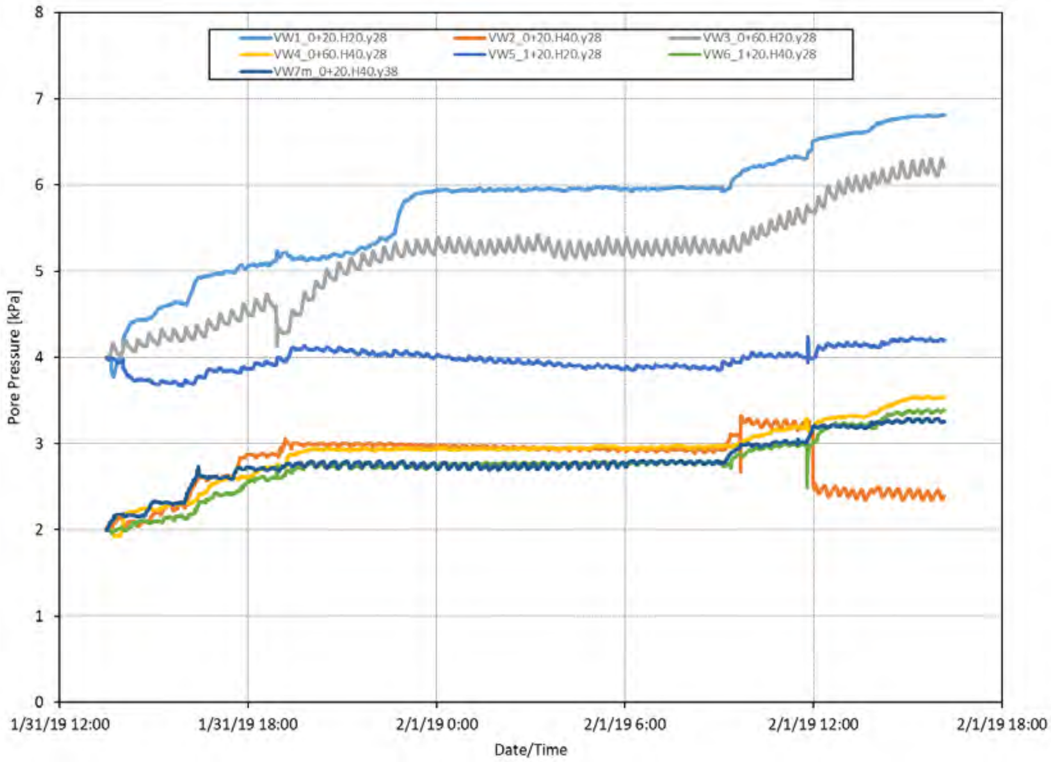

Figure 33 Pore Pressure vs Time (Corrected to Theoretical Initial Value)

3.2.4 Discussion

While the primary purpose of the physical test portion of this report is to provide a factual account of the work done and the data collected, some work was done as a preliminary interpretation of some of the data. This work helps cross-check aspects of the data and illuminate the potential value of further interpretive work in a future follow-on project.

In this section, preliminary assessments are provided of the mass and volume of sand added, to check the reasonableness of the placed CST density. Observations are made regarding measured displacements as compared to those from the FLAC model used to plan the work.

The measured pore pressures and total pressures are compared in a preliminary way to those from the FLAC model, pointing to the potential for additional value from follow-on work to model the test as actually run.

3.2.4.1 Mass, Volume, and Density of the Cap

The measured mass and estimated volume of sand placed with each lift were used to calculate the bulk density of the sand cap. Mass of sand was collected prior to lift placement and is shown both by lift and cumulatively in **Table 14** below. The cumulative mass and estimated volume of CST placed is shown in **Figure 34**. As the sand was lightly spread and not compacted, the density likely varied over the course of the test, including from densification as the cap got thicker. The estimated volume, by lift and cumulatively, is summarized in the table, and the calculation method is described in Appendix F. The volume estimates took into account the difference in settlement at the wall as compared to the settlement plate measurements, but some uncertainty remains, as explained below regarding the "actual thickness" of cap layers placed. The combination of volume estimate uncertainty, density differentials between sand on the slope and sand in the flat portion of the cap, and possible densification as the cap thickness increased introduced multiple uncertainties in the density calculation. The magnitude of the uncertainty can be seen in the fluctuations in the calculated density values by lift in **Table 14** and **Figure 35** below.

Table 14 CST Lift Measurements

Lift	Lift Mass (kg)	Cumulative Mass (kg)	Lift Volume (cm^3)	Cumulative Volume (cm^3)	Lift Density (kg/m^3)	Cumulative Density (kg/m^3)
0	0.0	0.0	0	0	0	0
1	10.4	10.4	10600	10600	978	978
2	11.5	21.9	6767	17367	1698	1259
3	36.2	58.1	24186	41553	1498	1398
4	26.3	84.4	30311	71864	869	1175
5	25.2	109.6	18238	90102	1379	1216
6	23.4	133.0	12780	102882	1834	1293
7	14.4	147.5	17560	120442	822	1224
8	23.9	171.3	15672	136114	1523	1259
9	22.0	193.3	16873	152987	1302	1264

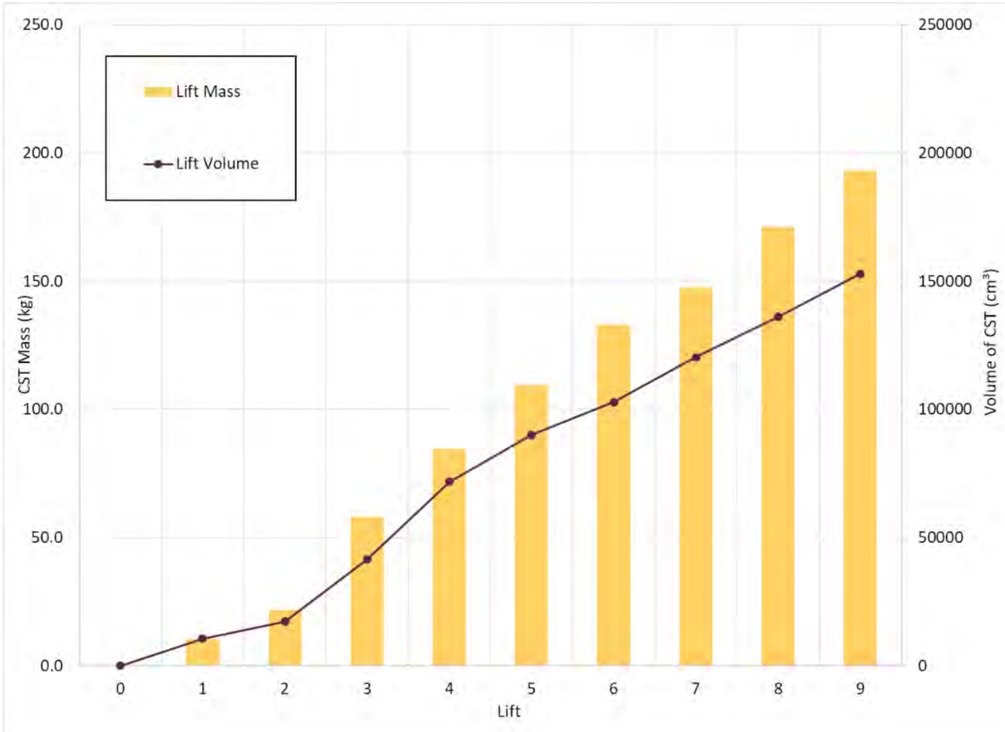

Figure 34 Quantities of CST, Cumulative

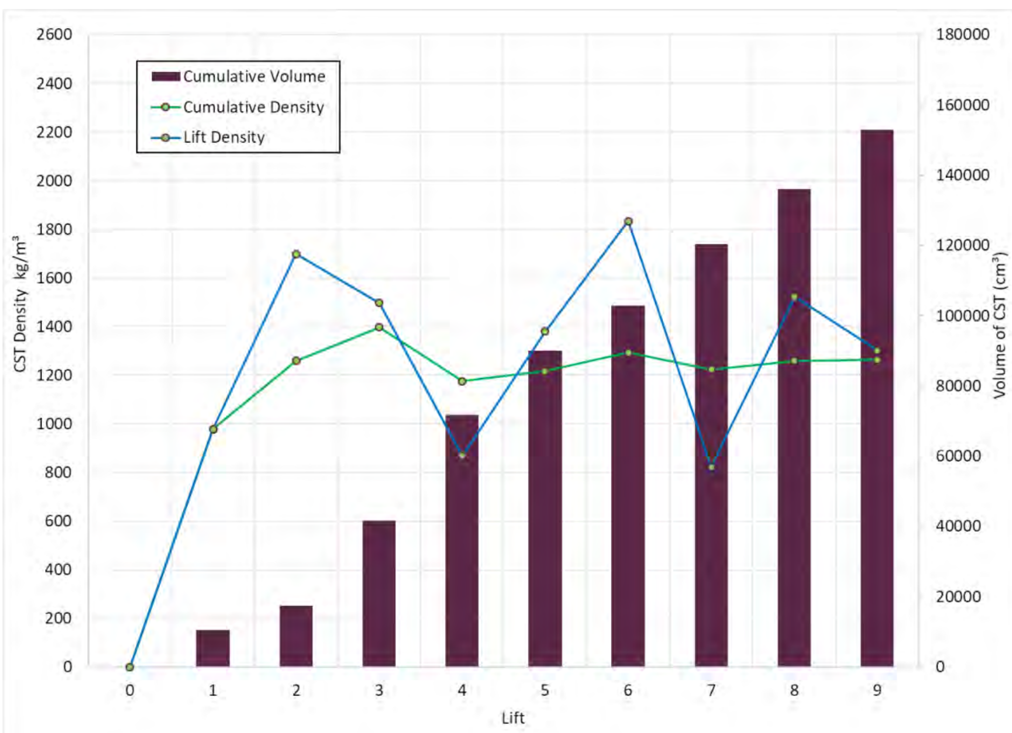

Figure 35 CST Density and Volume

The fluctuations in calculated density are taken as an indication of the accuracy of the cap volume estimates. As the total volume of added sand grew with additional lifts, the relative magnitude of the uncertainties diminished, and the final cumulative density calculation, 1264 kg/m^3, suggests the correct value is likely in the neighborhood of 1230 to 1300 kg/m^3. This range is consistent with small-scale CST density measurements performed by the team on the CST.

The actual thickness of lifts placed was somewhat different than the nominal planned thickness. This was largely a result of the settling of the lift as it was placed. One way to estimate the net lift thickness is to take the height of each lift, as marked on the side of the tank, and add the settlement of plate SP-1 at the CST-CFFT interface under the cap. The resultant estimates by lift and total are shown in **Table 15**, below.

Table 15 Net Lift Height Accounting for Settlement

Lift	Nominal Lift Thickness (cm)	Net Cap Rise (cm)	Settlement at SP-1 (cm)	Total Lift Thickness (cm)
1	2.5	2.5	3.0	5.5
2	2.5	2.3	2.5	4.8
3	5.0	3.9	7.5	11.4
4	5.0	4.9	9.0	13.9
5	5.0	4.1	0.5	4.6
6	5.0	3.0	1.4	4.4
7	5.0	3.0	0.1	3.1
8	5.0	0.8	2.8	3.6
9	4.0	0.0	1.3	1.3
Total	39.0	24.5	28.1	52.6

The actual thickness of lifts was likely somewhat different than the “total thickness” in **Table 15**. As can be seen in the traces of settlement at the wall for each lift (**Figure 27**), the settlement for any lift was variable, and the SP-1 plate may not have measured the “average” settlement for any single lift. Also, this table could have been constructed using the average of the measured heights of the lifts, which would give a total net cap rise of 27.2 cm rather than the 24.5 cm in Table 5-8. The difference is largely that the measured lift 9 rise averaged 3.2 cm, taken before it had settled much after placement (which may comport better with the SP-1 reading). It is reasonable to conclude that multiple lines of evidence must be used to produce a best estimate of the conditions for any lift. As the number of lifts increase, the incremental effect of errors (measurement, time delays, and variable surfaces) from any single lift diminishes, and the estimates for the cap as a whole become more consistent. This was also seen in the density estimates for the sand cap. Thus the conclusion that the total cap thickness placed was 50 to 60 cm is considered a more reliable estimate than the calculated thickness for any single lift.

3.2.4.2 Observed and Modeled Displacement of CFFT

The lateral displacement disks and settlement plates were located to help show whether model-predicted displacements would be observed during the test. **Figure 36** is an overlay of the measured displacements with those predicted by the model for a nominal 40-cm cap. The modeled cap and actual cap were not identical in shape, so the model results are shifted in the figure to align the top of the cap slope. In general, the experiment and model showed large displacements in the same general areas: significant downward motion below the cap, turning more horizontal beneath the cap slope, and becoming upward motion to the right. The model also identified areas where very little displacement was expected. Lateral displacement disk LD-7 was placed in a zone modelled to have little deformation, and the experiment corroborated that expectation.

The predicted and measured direction of CFFT displacement are remarkably similar in the right half of the tank (right of station 1+00, shown in **Figure 36**). The displacement vectors from the model align with the movement measured by the lateral displacement disks.

In the middle of the tank (between about stations 0+60 and 1+00, shown in **Figure 36**), the comparison is not as favorable. Between these stations, the predicted displacement is downward and to the right, whereas the measured displacement is upward and to the right. Reasons for the mismatch may be in part because the cap slope extends further to the right in the model than in the experiment, because the model did not account for side wall effects and end wall and bottom wall interface effects, and possibly because of the difference in tailings strength between experiment and model (100 Pa measured vs. 180 Pa modelled). For more details on the modelled displacements, shear zones, other model predictions, see Appendix A.

The modelling shown in Appendix A suggests a progressive bearing capacity failure, starting as elastic distortion and leading to local shear (shear zones). Later in the process, general bearing failure was observed, after which a more classic rotational failure was observed as the cap load increased. The model shows that the progression of bearing capacity to a general shear mode may be impacted by the bottom of the aquarium and the general shear may have developed differently with a deeper deposit. Most importantly, however, the end wall under the cap appears to have led to one half of a Prandtl wedge commonly observed in a bearing failure. It is also noted that during the aquarium testing, lifts 3 and 4 appear to represent when local shear bands first developed. Further, the last lift of sand could not be sustained, as the cap settled to the elevation it started at, suggesting that failure was occurring at the end of testing, as predicted by the model.

Modelling is recommended in the future to match the cap placement program of the experiment, applying scale corrections for the tank and experimental set-up as explained in Section 6. This will allow validation of the model's application and help explain the potential significant differences between bench and pilot scale tests, differences that must be accounted for to successfully apply bench scale work to larger scales. A project that includes the major aspects of this recommended modelling has been approved by IOSI for 2020: "Tailings constitutive models for capping assessment and scale-up."

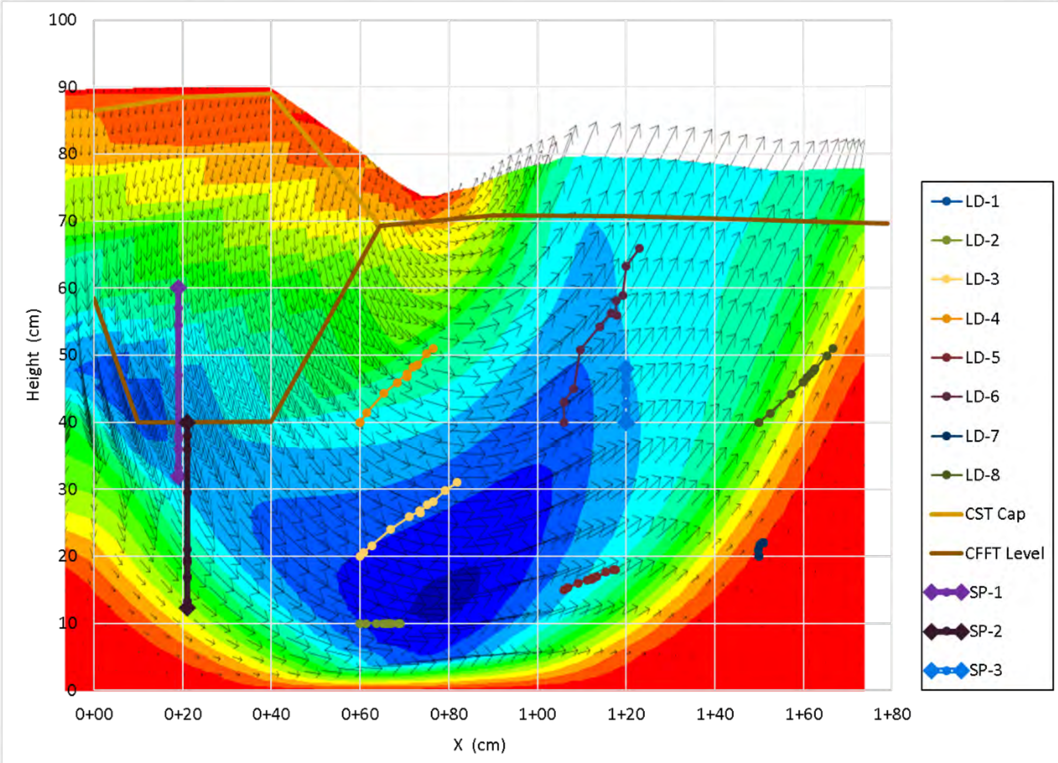

Figure 36 Comparison to FLAC 2D with Matching Crest

3.2.4.3 Measured and Modelled Pore Pressures and Total Pressures

As stated above, a series of vibrating wire piezometers were installed to measure pore pressures at various points throughout the tailings, along with "total pressures" (total vertical stress) at two horizontal locations on the bottom of the aquarium. The coordinates for these instruments in the FLAC model and in the aquarium are shown in **Table 16** below. It should be noted that the vertical datum was different between the FLAC model and the aquarium, with the FLAC model datum being located at the top of the tailings because various relationships were based on depth rather than elevation. Furthermore, the history numbers are shown in this table, as these are the locations at which various parameters are tracked with calculation step in FLAC.

Table 16 Piezometer and Total Pressure Cell Positions in Tank

History	Instrument Type	Instrument Tag Number/SN	X (m)	Y (m)	Z (m), FLAC Coordinates	Z (m), Aquarium Coordinates
1	Low Pressure VW Piezometer (Pore Pressure)	VW-1 1843520	0.20	0.29	-0.40	0.20
2	Low Pressure VW Piezometer (Pore Pressure)	VW-2 1843521	0.20	0.29	-0.20	0.40
3	Low Pressure VW Piezometer (Pore Pressure)	VW-3 1843522	0.60	0.29	-0.40	0.20
4	Low Pressure VW Piezometer (Pore Pressure)	VW-4 1843523	0.60	0.29	-0.20	0.40
5	Low Pressure VW Piezometer (Pore Pressure)	VW-5 1843524	1.20	0.29	-0.40	0.20
6	Low Pressure VW Piezometer (Pore Pressure)	VW-6 1843525	1.20	0.29	-0.20	0.40
7	Low Pressure VW Piezometer (Total Pressure)	TP-1 1843527	0.20	0.15	-0.60	0.00
8	Low Pressure VW Piezometer (Total Pressure)	TP-2 1843528	0.60	0.15	-0.60	0.00

Figure 37 below shows the pore pressures measured by the VW piezometers installed in the aquarium throughout the test. Along with these data, the FLAC results are shown for comparison. Note that the aquarium testing uses a true time scale while the FLAC modeling is shown as a function of calculation steps. The FLAC modeling exercise used a decoupled approach, meaning that a true time scale was not used and the model was brought to equilibrium for each lift without fully coupled consolidation occurring as a function of time. Thus, the horizontal scales were adjusted to show the full duration of the aquarium testing along with the FLAC modeling, but the number and timing of individual lifts do not match.

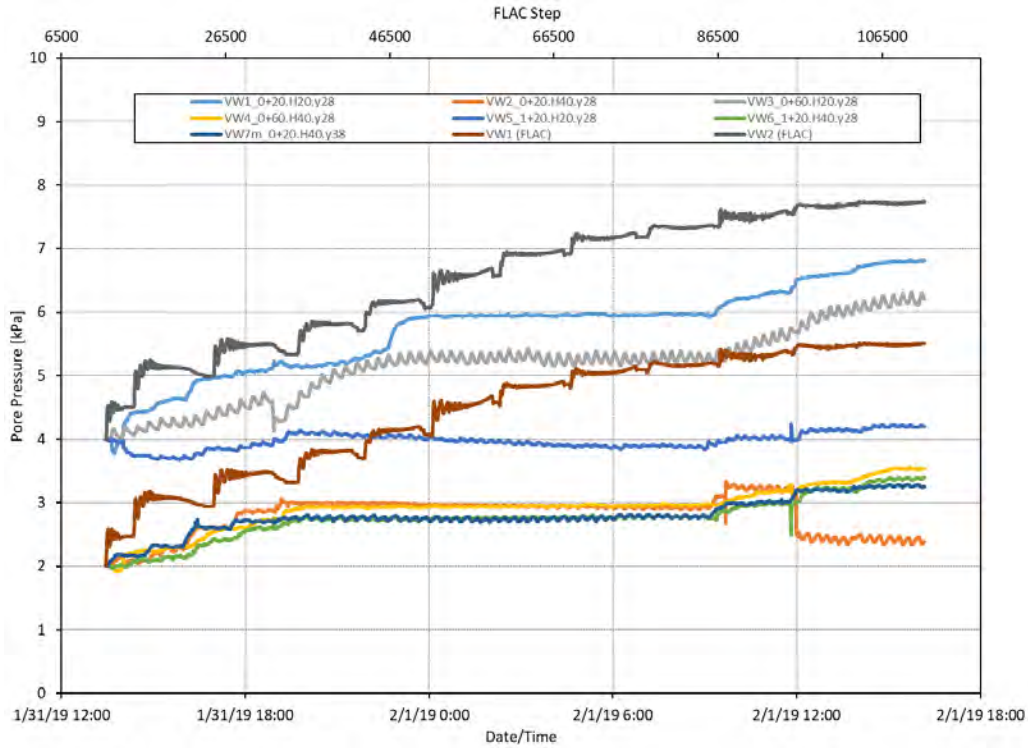

Figure 37 Pore Pressure vs Time (Corrected to Theoretical Initial Value) with FLAC Results (Adjusted for Settlement of Piezometer Tips in Model)

It should be noted in **Figure 37** that individual lift thicknesses are not consistent between FLAC and the aquarium testing, though the typical lift thickness was a nominal 5 cm. The details of the lift thicknesses can be shown in **Table 17** below. This table also summarizes the increase in total vertical stress $\Delta\sigma_v$ and pore pressure Δu for each lift in the FLAC modeling and aquarium testing. With these parameters summarized for each lift, the ratio $\Delta u/\Delta\sigma_v$, which is often called Skempton's "B parameter", can be computed.

Table 17 Comparison of Increases in Total Vertical Stress and Pore Pressure with Lift Details

Lift No.	Lift Thickness [m]		Increase in Total Vertical Stress, $\Delta\sigma_v$ [kPa]		Increase in Pore Pressure, Δu [kPa]		B Parameter ($\Delta u/\Delta\sigma_v$))	
	Aquarium [1]	FLAC	Aquarium [2]	FLAC [3]	Aquarium [4]	FLAC [4]	Aquarium	FLAC
1	0.025	0.050	0.16	0.73	--	0.51	--	0.70
2	0.025	0.050	0.13	0.73	0.09	0.63	0.74	0.87
3	0.050	0.056	0.40	0.81	0.27	0.34	0.69	0.42
4	0.050	0.048	0.28	0.70	0.08	0.33	0.28	0.47
5	0.050	0.042	0.25	0.61	0.05	0.36	0.20	0.58
6	0.050	0.066	0.20	0.96	0.00	0.43	0.01	0.45
7	0.050	0.048	0.10	0.71	0.00	0.32	0.03	0.45
8	0.050	0.053	0.35	0.77	0.21	0.25	0.59	0.32
9	0.050	0.040	0.20	0.58	0.08	0.16	0.39	0.28
10	--	0.041	--	0.60	--	0.18	--	0.29
11	--	0.038	--	0.55	--	0.17	--	0.31
12	--	0.022	--	0.32	--	0.05	--	0.15

Notes

1- Nominal lift thickness

2- Average of TP1_0+20.H00.y14 and TP3_0+20.H00.y38 (total pressure cells nearest the back wall, bottom of aquarium at X=0+20 m)

3- At piezometer location

4- Piezometer VW1_0+20.H20.y28 (back piezometer, 20 cm above aquarium bottom at X=0+20 m)

A plot of the B parameter as a function of lift number is shown in **Figure 38** below.

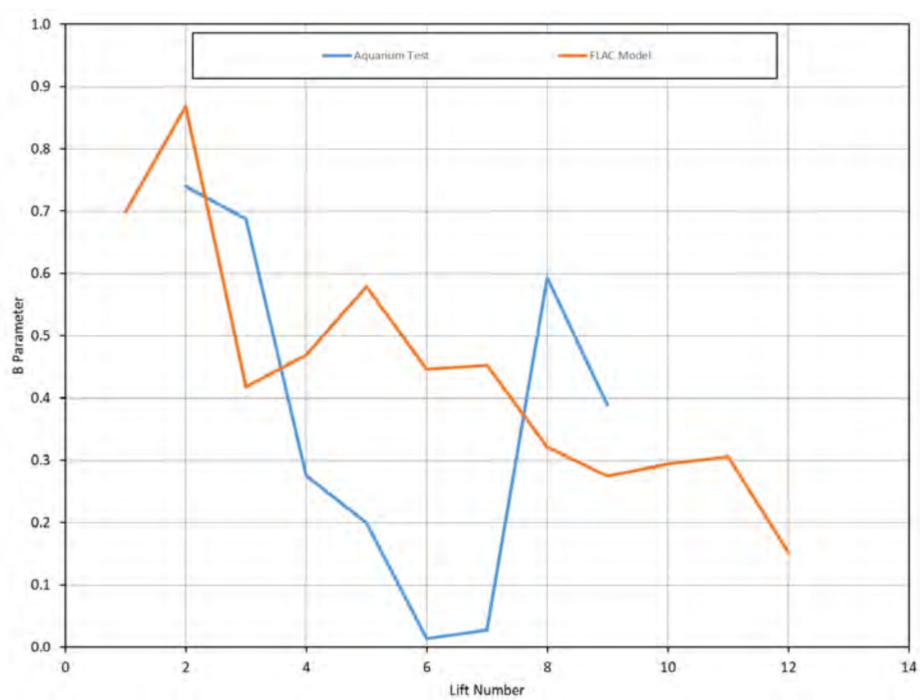

Figure 38 Comparison of B Parameter vs Lift Number

It can be seen in this figure that the B parameter was very low for Lifts 6 and 7. However, when these two lifts are neglected, the B parameters for the aquarium test and the FLAC model are generally similar, indicating that the instrumentation in the aquarium is generally capturing the excess pore pressure generation computed on a theoretical basis in the FLAC model.

Also, the increases in total vertical stress and pore pressure are generally significantly higher in the FLAC model than in the aquarium. The reason for this phenomenon is likely the increased friction from the wall effects in the aquarium as additional CST is placed for each lift. This would, in effect, mask the increase in load being imparted to the CFFT.

3.2.4.4 Conclusions from Bench-Scale Physical Test

The bench-scale physical test was successful in a number of ways. Some of the conclusions drawn from the data presentation and preliminary analysis above include:

- Modelling prior to Physical Testing was valuable for instrument and monitoring planning
- A sand cap was successfully placed subaerially on tailings of about 100 Pa undrained shear strength
- The test was run until failure, indicated by no further rise in the cap with placement of additional sand
- Deformation modelling (FLAC in large-strain mode) is promising as a tool to reasonably represent tailings response to capping, even for tailings above the liquid limit
- The test generated a significant and valuable data set. Follow-up work is needed to:
    - Mine the data
    - Model the actual cap placement

As regards follow-up modelling, it is recommended that modelling of the bench test be performed to represent the sequence and quantities of sand placed and to better calibrate the model, in addition to representing scale effects (more on that in Section 3.3). This will stengthen confidence that the model reasonably represents tailings behaviour. In turn, this will support use of this tool in planning pilot scale and commercial-scale tests. The follow-up modelling should explicitly discuss the significant differences between bench and pilot scale work, differences that must be accounted for to successfully apply bench scale work to larger scales. A project that includes the major aspects of this recommended modelling has been approved by IOSI for 2020: “Tailings constitutive models for capping assessment and scale-up.”

As regards mining the data from the bench-scale test, getting the best representation of the data from the bench test will help with the recommended modelling of the bench test. Data that can be mined includes the displacement data from the scans of the CST/tailings surface. This can provide a cross-check on the sand quantities and tailings displacement reported in this section. Using an internally consistent data set for use in the FLAC model will increase confidence that the conditions being modelled are representative, and will support effective comparisons between the measured data and modelled results.

3.3 Scale-Up Effects

3.3.1 Introduction

This evaluation of scale-up effects uses the findings of the bench test and the literature to present considerations for upscaling sand capping. The objective is to provide initial guidance on accounting for the differences that exist between a small-scale lab test and a larger scale capping trial such as a pilot test or practical full-scale application.

The assessment addresses various types of differences:

- Reduced Scale Geometry Effects
- Time Effects
    - Shear Softening and Thixotropic Hardening
    - Strength Profile Development
- Environmental Exposure effects
- Heterogeneity
    - Tailings
    - Cap
- Gas Production
- Temperature
- Water Table Level
- Deposition Method and Dynamics

This section first illustrates the application of geometry scale effects on the bench test, then addresses each of the above effects with a description and commentary on the effect on the bench scale test and more generally on the sand capping process.

3.3.2 Bench Scale Test

3.3.2.1 Introduction

The interpretation of the bench test, as required to derive conclusions for the upscaling of the sand capping methodology, must account for the differences that exist between the small-scale lab test and a larger scale capping like in a pilot test or practical full-scale application.

There are various types of differences, of which the reduced scale of the aquarium capping test is one of the most obvious: the proximity of the sides and bottom of the aquarium and the presence of different types of sensors which are at fixed points in the aquarium reduces the freedom with which the tailings can deform. This section steps through a critical assessment that must be done to account for the geometry and scale effects on a bench-scale capping test. This sort of analysis is essential in order to be able to draw legitimate conclusions and avoid seriously faulty conclusions from bench-scale work.

Other differences between bench and larger scale trials are described below.

3.3.2.2 Reduced Scale Geometry Effects

In an earlier phase of the project, a simple spreadsheet was used to assess potential boundary effects. The ultimate geometry of the bench test deviates in some respects from the earlier assumptions, which led to a different failure mode, whereby the placed sand cap slid vertically along the back of the aquarium. The top of **Figure 39** shows the initially anticipated load and deformation pattern in the bench test, while the bottom depicts the implemented deposition pattern.

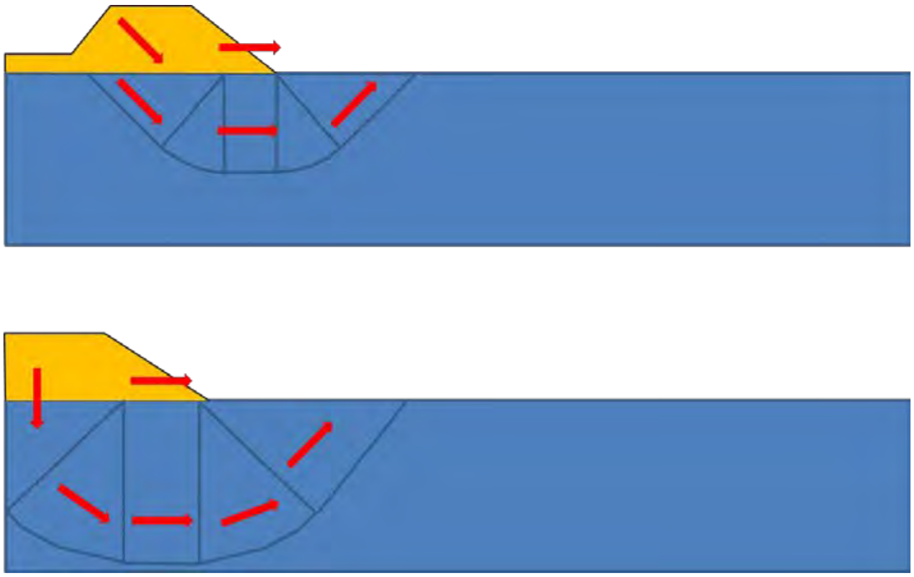

Figure 39 Sand Cap Free Failing (Top) and Sand Cap Sliding along Aquarium Back Wall (Bottom)

The actual geometry (which could not readily be predicted using the original design spreadsheet) is shown in **Figure 40**.

Figure 40 Sand Cap Penetrating Deep into the Tailings

The lateral displacement of the tailings under the sand cap, which necessarily occurs when the cap penetrates, as shown in **Figure 40**, is sometimes referred to as a squeezing mechanism. This can lead to confusion: the classic squeezing mechanism occurs when two "solid" bodies approach each other and the material between them is forced out in a lateral direction. In case of a sand cap, the top body (the cap) is not solid and will tend to move laterally with the underlying tailings. Formulas that give an allowable surcharge for a squeezing mechanism can therefore be underrepresent by a factor two and are not to be applied without accounting for that effect.

The FLAC modelling performed for the bench test indicated the presence of a sloping shear zone within the tailings under the sand cap near the toe (see Appendix A). This shear zone indicates that half of a Prandtl wedge is developing within the tailings as sand lifts are placed progressively. The Prandtl wedge signifies that a punching mechanism develops early in the process, as evidenced by very little upward deformation of the tailings surface out in front of the toe. As more sand is placed, the deformation mode transitions to general bearing failure as the tailings surface begins to rise. This failure mode is shown in **Figure 40**. An important distinction is that the Prandtl wedge is likely developing because the back wall constrains the deformation of the sand cap and underlying tailings to occur in the vertical direction, in essence creating a vertical plane, or boundary, that does not allow horizontal deformation. The fully developed general bearing failure with the complete Prandtl wedge in addition to shearing/deformation in both horizontal directions would be observed if another identical aquarium were placed as a mirror image against the back wall. This exercise would show a typical bearing capacity failure of a trapezoidal embankment prism rather than the slope with a flat crest against the back wall as carried out in the bench test.

It is important to realise that a stable cap will not lead to significant (plastic) shearing in the tailings. All failure mechanisms require shear zones in the tailings. Whether a failure mechanism is more the "plunging" (vertically penetrating) type or the "Prandtl" or rotational type will depend on the shear strength distribution in the tailings and the geometry of the sand cap as being constructed. A vertical "plunging" failure mechanism will tend to stop once stronger and denser layers are approached. The ultimate strong layer is of course the hard boundary of the aquarium in this test or older deposits or even the bottom of the tailings pond in field trial test and full-scale applications.

When the ideal 2D case is analysed, the Prandtl solution for a surcharge on a cohesive material yields a bearing capacity of $(2+\pi)s_u$, which, for a sand layer 0.45 m high having an effective weight of 14.3 kN/m^3 predicts a required s_u value of 1.25 kPa.

When one adds the effect of the slope of the sand cap (assumed to be 1V:1H) the required shear strength further reduces to 956 Pa. This represents still a "perfect" two-dimensional case, without part of the sand cap embedding (sinking) into the tailings.

To get insight in the effect of the boundaries of the bench test the energy dissipated by shearing along the sides of the aquarium can be added to the equation. It is assumed that the tailings have an adhesion that is equal to the cohesion (s_u) of the tailings and that the sand has an internal friction of 32 degrees and a sand-glass interface friction of 0.7*32 = 22.4 degrees. In addition, it must be assumed that the sand, being not perfectly dry, but moist, will have a capillary cohesion of approximately 300 Pa. When this is taken into account one finds that the tailings only need to have a shear strength of 411 Pa in order to carry the sand cap.

When an approximate assessment is made of the effect of vertical downwards sliding along the back wall of the aquarium and the effect of interaction between the mounts of the various instruments that were pre-installed in the bench test, the required strength further reduces to 282 Pa. The effect of interaction between the instrument mounts and the moving tailings represent a relatively small part (an estimated 2%) of the total energy dissipation. The total breakdown of energy dissipation now amounts to (rounded values):

- 30% internal shearing in the tailings

- 11% sliding of the tailings along the aquarium sides
- 41% sliding of the sand cap along the aquarium sides
- 17% sliding of the sand cap along the back-wall of the aquarium
- 2% interaction between the instrument and the moving tailings

This implies that the side effects amount to 70% of the total resistance.

The effect of the sand sinking into the tailings further reduces the required tailings strength. In view of the fact that the dry weight of the sand is in the same order of magnitude as the total weight of the tailings, the result is that the driving force by the sand cap is approximately halved, while the energy dissipation by tailings and sand sliding along the sides of the aquarium remains unchanged. The rough assessment would then be that the required shear strength needed to carry the partially embedded sand cap is in the order of 50% of 282 Pa, i.e. approximately 140 Pa.

One finds therefore that the geometric effects of a bench-scale test can be large. From the "ideal" 2D case, where a strength of 956 Pa is needed to support the cap on top of the tailings, to a strength of only approximately 140 Pa that is needed to support a 0.45 m cap that is 50% embedded and where boundary effects and interaction between instrumentation lead to extra plastic energy dissipation.

In view of this finding, it is essential to analyse the failure pattern in the 2D FLAC calculations in detail in order to make a more precise assessment of the magnitude of the dissipated energy along the sides of the aquarium and to account properly for the embedment of the sand into the tailings. Since the effect of the instruments and their mountings is relatively small as long as they do not become embedded in the sand cap the execution of 3D finite elements analyses has limited added value at this stage.

3.3.3 Time Effects

Commercial tailings will have been in place for much longer than in bench-scale tests before construction of a sand cap. Additionally, the sand cap will be resting on the tailings for a very long time in a commercial setting and phenomena like delayed (tertiary creep) failure therefore come into play.

Consolidation effects that concern the total depth of the tailings happen much faster in the bench test than in full scale. This is in contrast to consolidation effects at the interface between soft tailings and cap that happen at equal speed in bench and larger scales.

3.3.3.1 Shear Softening and Thixotropic Hardening

Geotechnical engineers worldwide widely generally utilize the concept of “effective stress” to approximate geotechnical parameters (such as strength) through correlating these parameters with effective stress; assuming these parameters are independent of time. However, there are some time dependent behaviour characteristics such as shear softening and thixotropic hardening that are recognized and cannot be solely described by this concept. Soil-like materials such as tailings under shear tend to lose strength with shear deformation over time due to break down of the micro-structures (so-called shear softening) but recover their strength with time at rest without any change in water content thanks to attractive forces at micro-scale levels (so-called thixotropic hardening, structuration, or "setting"). The thixotropic hardening effect has a time scale of from several hours to days, even months, during which the strength of tailings may increase by approximately a couple of hundred Pascal in yield stress. Thixotropic hardening is likely to be more relevant for the (interpretation of) the aquarium test than for the understanding of larger scale tests or applications since it is not expected that tailings are capped immediately after their deposition. In larger scale applications thixotropic hardening can be relevant after a cap failure whereby strain softening occurred. The thixotropic hardening will then cause the factor of safety to increase (somewhat) above 1.0 and possibly enable easier continuation of the capping process after a failure.

Hence, in the current aquarium test, the initial strength of tailings was lowered to a value of about 100 Pa in yield stress due to the pre-test mixing. This may have led to a lower bearing capacity of tailings in the beginning of test (e.g. the first day of deposition) while after this initial stage, thanks to thixotropic hardening, the tailings recovered part of their strength resulting in a higher bearing capacity. This difference in bearing capacity during the sand capping process, however, will not exist in pilot and full commercial scale sand capping as the tailings will have been at rest for a much longer time.

3.3.3.2 Strength (Vertical) Profile Development

Soil-like materials such as tailings, at rest and under self-weight consolidation tend to form a strength profile in which the tailings strength increases with depth. In the current aquarium test, however, such strength profile did not exist due to the initial mixing. Moreover, as the initial density of tailings in the aquarium was relatively high, formation of a density and strength profile by sedimentation and hindered settling processes would not occur. What remains is the self-weight consolidation of the material that was placed in the aquarium. However, within the relatively short time between the placement of tailings in the aquarium and the start of sand cap construction significant strengthening under self-weight consolidation could not occur.

3.3.3.2.1 Self-weight strength profile of the tailings

The time scale for self-weight consolidation can be weeks to months, even years. The self-weight consolidation in a pilot test is expected to have more effect as it is expected that in a pilot test a tailings deposit would be capped that is much more like realistic, undisturbed, tailings that have been in place for a significant time. In that case, a strength differentiation over the depth of the deposit is expected. This is an important factor to be considered while scaling up the result of aquarium test, since such a self-weight strength profile can act as a mitigating factor against failure of sand cap by limiting the depth of failure.

3.3.3.2.2 Cap-induced extra strength at depth

Apart from the (long term) strength increase due to the self-weight consolidation of the tailings,, a (long term) strength increase will also result from the weight of the sand cap. The influence of the sand cap weight deep in the tailings is not different from the influence of the weight of the upper layers of the tailings on the layers at greater depth. However, since this long-term effect only starts after placement of the first layer of the sand cap, the initial cap thickness that may be placed has no benefit from this strength increase deeper in the deposit.

3.3.3.2.3 Cap-induced extra strength near the tailing-sand interface

In the top of the tailings, near the interface with the sand cap, extra strength may develop more quickly than the rest of the deposit, during and after the (initial) sand cap placement. The time scale for this effect is in the order of hours for the first centimetre, but the influence depth increases in proportion with the square root of the elapsed time: if one centimetre is consolidated in say two hours, it will take two hundred hours to consolidate a layer of 10 centimetres.

In the current aquarium test, the time interval was about a day. Therefore, while the strength near the interface with the cap may have increased, the increase of strength deeper down in the test bed did not have enough time to occur.

Note that formation of a strength profile due to either self-weight consolidation or surcharge load(s) is associated with the out-migration of water from the tailings. The expelled water typically migrates upwards and is added to any water layer that already covers the tailings. The effect of a water layer overlaying the tailings is discussed separately.

3.3.4 Environmental Exposure Effects

Due to exposure of tailings to ambient climate, a temperature profile will develop in the tailings, and surficial changes in properties of tailings may occur such as cracks and crust formation, freeze and thaw. These surficial changes generally increase the strength of the top layer of tailings in the order of magnitude of several thousand Pascal. Plant growth on the surface enhances and deepens the drying out effect of the environment, and root-reinforcement effects in the top layer of the deposit can strengthen the upper portions of the tailings. The plant stems, if they lay flat in response to subaerial hydraulic capping, can supplement the erosion resistance provided by the roots, and help distribute the cap load on the tailings.

The time scale for significant drying effects is months, and typically years where freezing and thawing or plant growth are concerned. Crust formation and top layer strength increase can prevent penetration of sand into the tailings during sand cap placement and will increase the bearing capacity of tailings to some extent. However, this increase in the bearing capacity of tailings is limited to the layers near the surface and in the presence of high load cannot avoid a deeper seated failure.

In the executed aquarium test, these exposed top layer strengthening effects were not present, though they can be designed into bench-scale tests. As may be evident from this review, it could be a challenge to translate their effect at bench scale to pilot or commercial scale.

Note that in full scale sand capping projects remnants of earlier crusts may be present at depth for a variety of reasons. For example, operational practices may have moved the tailings discharge point in the pond over time and left part of the tailing surface exposed drying/freezing/thawing, only to be covered by new tailing deposits at a later stage. These buried crusts can have beneficial (e.g., deposit strength) and detrimental (e.g., lower hydraulic conductivity) effects.

3.3.5 Heterogeneity

The material "structure" at bench scale is generally different because of the way the tailings were deposited. In the bench test, the tailings were homogenized before placement aiming to achieve an equal undrained shear strength throughout the aquarium. Scale-up should account for tailings heterogeneity.

The sand cap “structure” is also normally different between bench and larger scale trials. In the bench test, the sand cap was deposited by sprinkling repeated layers of a few centimetres thickness of slightly moist coarse sand tailings (CST). As long as the slightly moist sand remains above the water table the sand will exhibit an extra strength component due to capillary suction effects. As discussed in Section 6.2, adjusting for this effect would be an important step in scaling up bench to pilot-scale or commercial-scale capping.

3.3.5.1 In the Tailings

In pilot and commercial scale deposits, tailings are delivered at different times and presumably with somewhat different qualities (e.g. in composition). This leads to formation of a heterogeneous tailings pond in which the strength of the tailings vary over the extent of the tailings pond. For instance, the older a tailings deposit, generally the more time it has had for self-weight consolidation and as a result the higher its strength and bearing capacity, and vice versa. Because of the heterogeneity in strength throughout the tailings pond, the tailings might be prone to local failures or local compaction differences during and after sand cap placement, leading to heterogeneity in the sand cap thickness itself. In the current aquarium tests this effect was not present. Local heterogeneity may or may not lead to longer term (delayed) failures. This aspect requires further investigation. Heterogeneity and delayed failures might affect the geometry of the final landscape and thus its suitability or usability. Hence, depending on the desired/targeted landscape, these local failures or settlement differences could be important.

3.3.5.2 In the Sand Cap (Local Differences in Thickness/Density)

Change in the quality of sand cap production and its placement/deposition (i.e. rate and geometry of sand cap deposition) may result in a variable sand cap thickness. Just like the effect of variable stiffness and strength in the supporting tailings, the variation in sand cap thickness may lead to local failures and uneven settlement. This could lead to an unfavourable landscape topography. This effect was not present in the current aquarium test.

Another aspect that becomes relevant when the sand capping process is scaled up is the consequence of interruption of the sand capping (intentionally or unintentionally): If a sand layer covers only part of the tailings surface, the edge stability of the sand cap can be critical. At this stage it is not established whether the criticality decreases or increases during the interruption of the sand placement process. Under a sand cap (and also under its edge) the weight of the sand will lead to an increase in the effective stresses in the tailings when the consolidation process continues and excess pore pressures dissipate. This causes an increase of the strength of the tailings. Consolidation is however not the only process that is going on. Near the sand cap edge, by definition, shear stresses are also imposed on the tailings because a sand cap load is present next to exposed tailings. These shear stresses lead to shear deformation. If the tailings behave as a non-Newtonian fluid and, apart from plastic shear deformation, a viscous shear deformation is occurring; the shearing may lead to a strength loss in the tailings if the strength increase due to consolidation and setting (structuration, thixotropy) is outpaced by the strain softening process.

3.3.6 Gas Production

The rate of production of CH_4 and CO_2 depends strongly on the quantity of organic matter (in particular residual solvents) present in tailings and its availability for decomposition. In addition, the age of the organic material has an important influence. In general, the rate of gas production in an oil sands tailings deposit can be expected to exceed the rate at which gas can be transported in the dissolved phase by diffusion and advection. As a result, nucleation of gas bubbles will occur over time as gas production exceeds solubility. Gas accumulation continues as gas production exceeds the outflow. Accumulation takes place in gas bubbles, which therefore increase in size and cause expansion of the tailings deposit layer. If the bubbles reach sufficient size, they may start to rise owing to the density difference with the surrounding material. The average bubble size remains limited to a few centimetres because of the large number of bubbles per m^3 and the total volume of gas that can be produced. During bubble growth the amount of deformation energy stored in the tailings matrix increases. When the matrix fracture energy is exceeded, cracks will be generated in areas where the stress condition enables this. As soon as cracks are propagated so that a system is created that communicates with the tailings - water interface, channel formation will occur from this interface. Channels spread downwards by the erosive action of outflowing gas and consolidation water. Channel formation is possible up to a depth at which the sediment shear strength is just large enough to keep the channel stable. In deeper parts a system of plain, closed cracks exists where further growth of bubbles and lenses occurs.

The time scale for gas production in a biologically-active zone is about several weeks to months, longer if the biological community is not fully established. This effect was not significant in the current aquarium test. Channel formation due to gas release may lead to heterogeneity in the strength of tailings and therefore local failures.

If further consolidation is needed, extra gas in the sediment will increase the compressibility of the water-gas mixture in the pores and therefore delay consolidation strengthening. To some extent, this may be counteracted by channels formed by escaping gas, as these channels may act as drains as well.

3.3.7 Temperature

Apart from the surficial effects of temperature (freezing/thawing), the temperature in the bench-scale test will differ from that in a pilot or full-scale test. While some effects of temperature are undisputed (with higher temperatures the viscosity of the pore fluids (and bitumen) will decrease, creep rates will increase with temperature and chemical processes will unfold faster (decomposition and gas formation) the overall effect of temperature differences seem to be relatively small. A brief scan through literature revealed the following:

- Short- and long-term consolidation (i.e. creep) properties of solid-like material (such as tailings) may alter due to temperature variation. Typically, the consolidation rate increases as the temperature increases. This is related to an increase in the permeability as the temperature increases. The reduced viscosity of pore water at high temperatures causes an increase in the hydraulic conductivity. Indeed, the intrinsic permeability is independent of temperature.

- The literature also showed the following effects of temperature: the excess pore pressure increased with temperature decrease. The hydraulic conductivity (k) and coefficient of consolidation (c_v) increased with temperature increase. The stress-strain behaviour was slightly affected by temperature variations. The compression (c_c) and swelling (c_s) indexes could be considered slightly temperature dependent. The (apparent) pre-consolidation pressure (p_c) decreased with temperature increase, while the creep index (c_α) slightly increased with temperature increase (Nidal, 2016).

3.3.8 Water Table Level

Water table level ties in with the environment, but deserves a special mention. On an initially dry tailings surface, subaerial hydraulic placement of a sand cap on weak tailings will always involve the presence of water as transport medium, over, in and at the toe of the beaching sand. In the case of sand raining and subaqueous deposition, a water layer is present to provide the platform on which a spraying vessel will move.

There was no water on top of the aquarium test while the sand layers were placed on top of the tailings, and the cap was placed smooth and level so that it exerted a relatively uniform load on the tailings. In contrast, at pilot or commercial scale, a subaerial sand cap placed hydraulically will exert a load that differs spatially due to the water in the sand slurry, movement of the flow channel, water draining from the deposited sand, the surface slope of the growing delta, and the control of the water level in the basin being filled. This includes the effect of sand under the water table having a lower effective weight than sand above the water table.

In the bench-scale test, there was water present in the sand cap only in a portion of the sand cap that displaced tailings. The rest of the sand remained moist but not saturated, and consequently the sand in the bench test had an effective weight that was not significantly reduced by the buoyancy of the sand grains below the water table. The cap also therefore retained its capillary cohesion strength. In an actual (pilot or full-scale) deltaic beaching deposit the water flow required to transport the sand will first of all saturate most of the sand, with the exception of the uppermost parts of the deltaic cap, and second will maintain a high groundwater level in the sand cap. **Figure 41** depicts the three different conditions: Bench test with lowest water table, the deltaic deposition case with an intermediate water table and the subaqueous deposition case with the highest water level.

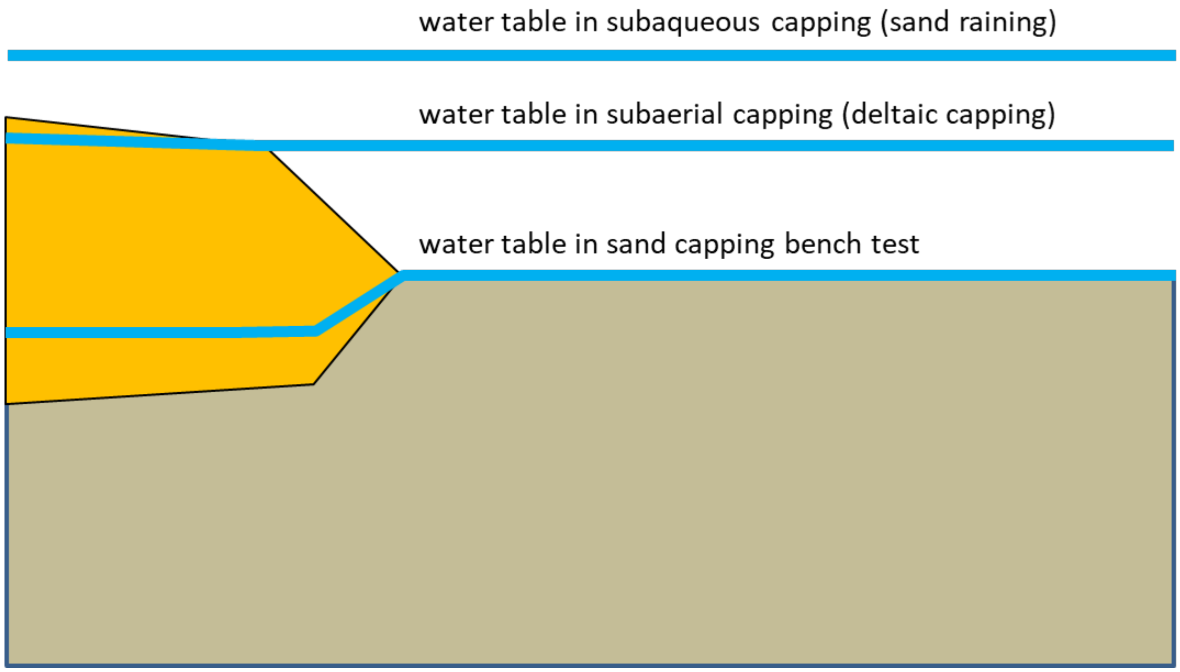

Figure 41 Different Water Table Positions for Bench-Scale Deposition, Deltaic Deposition, and Sand Raining

The importance of the water table location should not be underestimated. Some of the consequences of the different levels illustrated in **Figure 41** include:

- Subaqueous capping imposes inherently lower loading than subaerial capping on the tailings for the same cap thickness. In consequence, subaqueous capping has greater potential for successful cap placement on weaker tailings than subaerial capping.

- The net load imposed on tailings by subaerial hydraulic capping (deltaic capping) will depend in part on the water level maintained in the basin during capping.

    - If the water level at the capping front is low (the tailings surface), the load will be greatest, and the concern about erosion of the tailings surface will be highest.

    - If the water level is high, the load imposed on the tailings may be little more than for subaqueous placement, and care may need to be exercised in drawing the water table down after cap placement. A high water level at the capping front can determine the cap thickness and rate of cap advance, necessitating conscious control of the water level in order to balance slurry feed rate and cap advance rate, and to avoid excessively variable cap thickness.

- Bench scale tests can provide important information to help assess effects of loading, water table level, potential for erosion, and many other factors. In order to be able to isolate the effect of interest from other influences, bench tests need to be carefully designed, likely need to be run with and without the factor under study, and should not be expected to provide scalable information for too many factors in a single test.

3.3.9 Deposition Method and Dynamics

The sand placement methodology used in the bench test (dry sprinkling by hand) differs greatly from what would likely be used for larger-scale tests or commercial application. Some of the larger-scale considerations worth noting are:

- Beach flow deposition is characterised by mainly horizontal velocities in the water-sand mixture, exerting limited pressures on the tailing surface.

- Underwater sand raining generates a vertical water flow, dragged along with the settling/sedimenting sand particles. The rate of deposition, the density of the mixture and the free water depth above the tailing surface determine what extra pressures are exerted on the tailings and how these vary over the tailing surface.

- Employment of rainbowing through air as a deposition method has inherently larger dynamic aspects, and the effects depend on parameters like the flow rate, the spraying nozzle characteristics, the rainbowing trajectory and the receiving water depth.

Differences between deposition methods can lead to (temporary) excess pore pressures in the deposited sand cap and may give rise to different deposition (sedimentation and erosion) patterns. Erosion processes may very well extend beyond the sand cap itself, into the underlying tailings.

3.3.10 Recommendations for Study of Processes Critical to Subaerial Capping Success

The table below provides an assessment of the relative importance of the various processes and effects mentioned in this upscaling memo and suggestions regarding the degree to which each of these items requires further investigation. The symbols used in the summary table have the following meaning:

Potential relevance (estimated magnitude of the effect of the aspect on the safety factor of the sand cap stability and thereby the capping success):

*	Not, or only slightly relevant	(likely less than 10% influence on safety factor)
**	Relevant for design	(10% - 100% influence on safety factor)
***	Highly relevant	(potentially more than 200% influence on safety factor)

Degree of understanding (current state of engineering practice and science):

A Well understood, quantifiable
B Reasonable understanding and quantification
C Only qualitative understanding and approximate quantification

Prioritisation for upscaling studies:

1 High priority, essential research for proof of full-scale feasibility
2 Intermediate priority, research for optimisation
3 Low priority, research for increased understanding and academic advancement

It should be noted that the ranking system is simply an attempt to organise the recommendations in an understandable and logical manner. The ratings given to "relevance" and "understanding" are based on our subjective engineering judgment.

Table 18 Applied Ranking System for Research Priority

Understanding (right) and relevance (below)	A	B	C
*	3	3	2
**	3	2	1
***	2	1	1

Table 19 Research Priority for Subaerial Hydraulic Capping of Tailings

Phenomenon	Potential relevance	Degree of understanding	Research priority
Bench test boundary effects	***	A-B	1-2
Time dependent behaviour - viscosity (creep)	**	C	1
Strain dependent behaviour - strain softening	**	C	1
Tailings self-weight strength development	***	B	1
Cap induced strength development at depth	*	B	3
Cap induced strength development at surface	*	B	3
Tailings surficial strength - crust formation	**	C	1
Tailings heterogeneity	**	C	1
Sand cap heterogeneity	**	B	2
Gas production	* to **	C	1-2
Effect of temperature	*	C	2
Effect of water table position	**	A	3
Deposition method and dynamics	***	B	1

The conclusion from the **Table 19** prioritization and from the analysis in this Section is that there are a number of high priority areas to study for subaerial hydraulic capping.

Deposition method and dynamics are of great importance. The dynamics of cap placement methods can lead to (temporary) excess pore pressures in the deposited sand cap and may give rise to difference deposition (sedimentation and erosion) patterns. Another dynamic to consider is the effect of the advance of a cap on tailings deformation ahead of and under the leading portions of the cap. The deformations near the leading edge of a cap may tend to destabilize the cap. Strain-dependent and time-dependent behaviour of tailings needs to be better understood, both at the constitutive model level and for practical (e.g., numerical) applications. When capping soft tailings, this effect could cause progressive failure. Therefore, this should be well understood to manage reasonable margins of safety in cap design. IOSI has approved two projects that are intended to advance knowledge in these areas: the 2019 project "Modeling the Cap Placement with

Tailings Deformation and Consolidation“ and the 2020 project “Tailings constitutive models for capping assessment and scale up.“

It is likely that practical hydraulic capping of soft treated tailings will include some surface strengthening of the tailings beforehand. Work is urgently needed to better understand the potential surface strengthening that can be practically achieved, and to estimate the benefits of a strengthened surface for cap success. IOSI has approved a project that is intended to take the next step in analysing cap advance over soft tailings with a strengthened surface: the 2019 project “Geotechnical Modeling of Surface Strengthening for Soft Tailings Capping.“ Other work on potential surface strengthening options, such as vegetative cover, has been in progress for some time at Canadian Natural Resources Limited (Smith, 2018), and other operators have been examining aspects of this topic as well.

The bench test boundary effects merit additional study to use that data more rigorously for scale-up of bench-level work. It is essential to analyse the failure pattern seen in the physical test done for this project. A powerful geotechnical model such as FLAC 2D could be used to make a more precise quantitative assessment of the magnitude of the dissipated energy along the sides of the aquarium and to account properly for the embedment of the sand into the tailings. Since the effect of the instruments and their mountings is relatively small as long as they do not become embedded in the sand cap, the execution of 3D finite element analysis has limited benefit at this stage. IOSI has approved a project that is intended to take the next step in this analysis: the 2020 project “Tailings constitutive models for capping assessment and scale up.“

A major consideration in successful capping of soft tailings will be the tailings self-weight strength development, in particular for treated tailings, where the behaviours at commercial scale are still being observed and tested. Advances in understanding and representing this phenomenon will underpin the design of programs to cap soft tailings.

Tailings heterogeneity is another high priority research field for capping of treated soft tailings. While not an issue at bench or perhaps some pilot scale tests, it is almost certain to become a dominant consideration for commercial-scale capping applications.

Gas production and release or retention in the tailings can have a dramatic effect on consolidation. The physical processes governing gas behaviour and its effects remain an area that merits much more attention for tailings such as those considered here.

Other study areas are identified in **Table 19**, but are at lower priority than the topics discussed above. The list is not exhaustive, e.g. it did not attempt to consider many important aspects of placing a cap using a hydraulic slurry. Those will need to be identified when that particular topic is more closely examined.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Overall, the project delivered on the objectives of developing the first steps of a model (FLAC 2D) useful for predicting success or failure of cap advance on soft tailings, and identification of potential failure mechanisms. Physical testing was also conducted to compare cap success and failure conditions to expectations based on model predictions. Finally, critical factors were identified that should be considered when assessing how to bridge the gap between small-scale tests and eventual implementation in the field.

4.1.1 FLAC 2D Modelling

The intent of the modelling work was to provide an initial assessment of the required conditions for the stable advancement of a granular cap over soft treated tailings. Advanced numerical modelling of the capping advancement process was performed to evaluate the main factors affecting deposit stability in response to granular capping.

The cap advance modelling provided an initial assessment of the required conditions for the stable advancement of a granular cap over soft treated tailings. Advanced numerical modelling using FLAC 2D showed the influence of a number of factors affecting deposit stability in response to granular capping. Subaqueous and subaerial conditions were modelled. In one critical respect, the subaerial condition modelled was very similar to the subaqueous – the cap material below the waterline imposed only the buoyant weight load to the tailings. The following observations can be made from the modelling results:

4.1.1.1 Subaqueous Capping

- The model is providing reasonable results - the overall pattern of success and failure is consistent with experience and expectations; stronger tailings are required to support thicker caps.

- Capping tailings weaker than 0.5 kPa with a 0.2-m sand cap does not appear practical, even using subaqueous placement methods. To cap such tailings, lighter-weight granular materials or sand lifts thinner than 0.2 m should be explored.

- The front slope can be a very important factor near the cap thickness limits that a tailings strength can support.

- The tailings strength/solids content profile is an important factor in the success of a cap, and should be accounted for in the planning and design process.

- Cap advance rate is a very small factor for success. The advance rate would have to be impractically slow in order for there to be any benefit from consolidation and strength gain under the leading slope of the cap. The reason for this is the low hydraulic conductivity of the fine tailings. The inconsequential consolidation and strength gain during cap advancement results in very little difference in the performance of the various advance rates.

4.1.1.2 Subaerial Capping

- A flatter front slope is more stable than a steeper front slope, reducing the magnitude of the shear at the cap edge, and possibly acting as a "counter balance" to minimize upward displacement at front of cap (this is a critical feature for developing a delta slope model).

- The tailings strength is a key factor in the allowable thickness for the cap, with 1 kPa tailings strength as an apparent lower limit for practical (0.5 to 1 m thickness) subaerial sand capping.

- Cap advance rate and beach slope appear to have a minor effect on the failure potential during initial placement of cap.

- Consolidation during cap advance is inconsequential for practical cap advance rates.

- Weaker tailings can be capped using light-weight materials, such as coke, where the same thickness of sand would cause failure.

- Water table location - cap submerged, and water level at cap front slope - produced generally similar results, but a submerged cap can be placed on somewhat weaker tailings as long as the slope on the face is flat (e.g., 10H:1V).

- The deposit solids content / strength profile, in addition to the strength at the surface, is an important consideration in cap success.

Several observations about the FLAC model itself and using it in small-strain mode were noted:

- The model predicts failure by displacement:

    - Excessive displacement indicates failure (the model fails to converge)

    - Failure was defined as vertical displacement exceeding cap thickness, and several boundary cases failed in this mode

    - The failure mechanism for most cases appeared to be rotational failure at the leading edge of the cap

    - Squeezing failure was not observed, though the model is capable of representing it, because the deposit depth was sufficient and the bottom was horizontal, so that squeezing was not a relevant failure mechanism

- Horizontal displacement was the dominant displacement, for both successful and unsuccessful capping cases, with the small strain model.

- Small strain models may not capture excessive vertical displacements for assessing failure mechanics; large strain models appear to be necessary to assess the interaction between deltaic cap advance and tailings settlement. Thus modelling in small-strain may predict successful capping in cases that would fail in practice.

4.1.2 Physical Testing (Laboratory Bench Test)

The physical testing (laboratory bench-scale test) was included in the program to cost-effectively evaluate the potential for treated oil sands tailings to support a sand cap, and to corroborate the suitability of FLAC modelling for representing tailings behaviour in response to capping.

The bench-scale physical test was successful in a number of ways. Some of the conclusions drawn from the data presentation and preliminary analysis include:

- Modelling prior to Physical Testing was valuable for instrument and monitoring planning

- A sand cap was successfully placed subaerially on tailings of about 100 Pa undrained shear strength

- The test was run until failure, indicated by no further rise in the cap with placement of additional sand

- Deformation modelling (FLAC in large-strain mode) is promising as a tool to reasonably represent tailings response to capping, even for tailings above the liquid limit

- The test generated a significant and valuable data set. Follow-up work is needed to:
    - Mine the data
    - Model the actual cap placement

4.1.3 Scale-Up Effects and Considerations

Relevant scale-up effects were identified and described through use of the literature and the findings of the bench tests. The assessment addressed various types of differences:

- Reduced Scale Geometry Effects
- Time Effects
    - Shear Softening and Thixotropic Hardening
    - Strength Profile Development
- Environmental Exposure effects
- Heterogeneity
    - Tailings
    - Cap
- Gas Production
- Temperature
- Water Table Level
- Deposition Methods and Dynamics

Priority areas identified for further research from this analysis are discussed in Section 5.2 below.

4.2 Recommendations for Future Work

4.2.1 Future Studies

The current project has contributed significantly to understanding the potential for hydraulic capping of treated fine tailings deposits in the oil sands. There however remain a number of high priority areas to study in order to establish the conceptual foundation for understanding the success and failure potential for this technology.

The bench test boundary effects merit additional study to use that data more rigorously for scale-up of bench-level work. It is essential to analyse the failure pattern seen in the bench-scale test using a powerful geotechnical model such as FLAC 2D. This will provide a more precise quantitative assessment of the magnitude of the dissipated energy along the sides of the aquarium and account properly for the embedment of the sand into the tailings. Since the effect of the instruments and their mountings is relatively small as long as they do not become embedded in the sand cap, the execution of 3D finite element analysis has limited benefit at this stage. The FLAC model that has been updated to capture the most significant experimental results should then be used to evaluate the stability of capping tailings at larger scales, accounting for the changes in boundary effects and environment. Note that the results of scaled-up modelling cannot be verified until measured data is acquired from a pilot test (rather than just a bench test). IOSI has approved a project that is intended to take the next step in this analysis: the 2020 project "Tailings constitutive models for capping assessment and scale up." Notwithstanding the conclusion that FLAC 2D is sufficient for modelling the aquarium test, 3D analysis may be preferred for field pilot or commercial scale tests, as the deformations at those scales tend to be inherently 3D, and may be misrepresented in a 2D analysis.

Deposition method and dynamics are of great importance. The dynamics of cap placement methods can lead to (temporary) excess pore pressures in the deposited sand cap and may give rise to difference deposition (sedimentation and erosion) patterns. Another dynamic to consider is the effect of the advance of a cap on tailings deformation ahead of and under the leading portions of the cap. The deformations near the leading edge of a cap may tend to destabilize the cap. Strain-dependent and time-dependent behaviour of tailings needs to be better understood, both at the constitutive model level and for practical (e.g., numerical) applications. When capping soft tailings, this effect could cause progressive failure. Therefore, this should be well understood to manage reasonable margins of safety in cap design. IOSI has approved two projects that are intended to advance knowledge in these areas: the 2019 project "Modeling the Cap Placement with Tailings Deformation and Consolidation" and the 2020 project "Tailings constitutive models for capping assessment and scale up."

It is likely that practical hydraulic capping of soft treated tailings will include some surface strengthening of the tailings. Work is urgently needed to better understand the potential surface strengthening that can be practically achieved, and to estimate the benefits of a strengthened surface for cap success. IOSI has approved a project that is intended to take the next step in analysing cap advance over soft tailings with a strengthened surface: the 2019 project "Geotechnical Modeling of Surface Strengthening for Soft Tailings Capping." Other work on potential surface strengthening options, such as vegetative cover, has been in progress for some time at Canadian Natural Resources Limited (Smith, 2018), and other operators have been examining aspects of this topic as well.

A major consideration in successful capping of soft tailings will be the tailings self-weight strength development, in particular for treated tailings, where the behaviours at commercial scale are still being observed and tested. Advances in understanding and representing this phenomenon will underpin the design of programs to cap soft tailings.

Tailings heterogeneity is another high priority research field for capping of treated soft tailings. While not an issue at bench or perhaps some pilot scale tests, it is almost certain to become a dominant consideration for commercial-scale capping applications.

Gas production and release or retention in the tailings can have a dramatic effect on consolidation. The physical processes governing gas behaviour and its effects remain an area that merits much more attention for tailings such as those considered here.

Other high priority work needed for development of the subaerial hydraulic capping approach is to model cap build-up to support reclamation construction. This will involve placement of successive layers of cap to bring the cap thickness and deposit strength to a level that would support construction activity and the differential loads associated with landforms. The analysis should include an estimate of the time to achieve deposit conditions to support successive lifts, how thick those lifts can be, and what total thickness of cap is needed to produce a workable reclamation construction surface. Operators have been examining aspects of this topic, and the remaining gaps in understanding need to be addressed in order to know this technology has the potential to achieve the most basic of objectives for cap placement.

Significant benefit could be derived from modelling operator data or data from research institutions that have performed relevant experiments and comparing model results with the observations and data. This can help illuminate the failure conditions observed in past work, and strengthen confidence that the tool (FLAC) can represent the range of conditions that already have been tested.

The above summary includes study areas not identified in **Table 19**, and that table identifies a number of lower priority study topics than those above. The list is not exhaustive, e.g. it did not attempt to consider many important aspects of placing a cap using a hydraulic slurry. Those will need to be identified when that particular topic is more closely examined.

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APPENDIX: LIST OF PUBLICATIONS AND PATENT FILING/APPLICATION

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