Physical Modelling in Geotechnics

Predicting multi-lift mine tailings consolidation with centrifuge physical modelling and numerical simulation

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ABSTRACT: Oil sands production in Alberta generates large volumes of soft fine tailings, which are temporarily stored in tailings ponds. Industry is developing an alternative permanent disposal option of the soft tailings material within depleted mine pits. This type of deposit is built with the multi-lift tailings filling process. Multi-lift deposition of tailings is an effective way of maximizing the volume of dry tailings in tailings ponds. It is critical to estimate the rate and final amount of surface settlement, the movement of water in the pit, and the changes of strength through the depth of the tailings. Conventional methods such as field trials and laboratory tests are unable to duplicate the scale and cycle of in-situ multi-stage conditions. This study adopts the geotechnical centrifuge as a physical simulation tool as it offers the advantages of preserving in-situ stress similarities and completing long-term evaluation in a short period of time. A consolidation model was constructed that followed a complete development cycle of a multi-lift deposited pit lake. Following centrifuge scaling laws, it resembles a 66-m deposit with more than 10 years of multi-lift deposition, followed by 35 years of self-weight consolidation. The same model was also numerically simulated using finite strain consolidation analysis. Centrifuge modelling and the numerical simulation was cross-calibrated and cross-verified. After combining two models, a comprehensive evaluation was acquired for the multi-lift pit lake scenario. Evaluation helps tailings operators make quick and accurate predictions for the continual development of pit lakes, while offering enormous cost- and time- saving advantages.

Keywords: Oil sands tailings, Multi-lift deposition, Consolidation, Pit lake.

1 INTRODUCTION

1.1 Multi-lift deposition of tailings in pit lakes

Oil sands production in Alberta generates large volumes of fine tailings. Pit lakes are used at many mine sites for reclamation and closure. Developing a successful pit lake requires advance planning and iteration of research results. Pit lake designs have changed over time to reflect the state of knowledge of oil sands mine waters and tailings, technological advances, changing regulations, and inputs from local stakeholders and Indigenous communities. (CAPP, 2021).

Multi-lift deposition of tailings is an effective way of maximizing the volume of dry tailings in tailings ponds. The multi-lift deposition technique involves multiple subaerial placements of tailings streams. After each placement, there is an initial water discharge, followed by the long-term consolidation of the deposited material. With constant renovation of multi-lifts deposition technique and tailings treatment technology, the development of tailings ponds needs additional evaluation to maximize performance and reduce the risk of uncertainty. Quick feedback helps optimize process control.

1.2 Modelling of tailings consolidation

Tailings consolidation behavior can be physically modelled with a geotechnical beam centrifuge. This method allows for evaluation and collection of accurate and reliable feedback in a timeframe measured in hours. A geotechnical beam centrifuge can be used for modelling of large-scale nonlinear problems for which gravity is the primary driving force, including the self-weight consolidation of fine tailings (Toh, 1992; Zambrano-Narvaez et al., 2018a; Townsend et al., 1986; Dunmola et al., 2018; Zambrano-Narvaez et al., 2019; Ansah-Sam et al., 2019; Dunmola et al, 2019). The fundamental principle of centrifuge modeling is based on the stress similarity between a prototype and a centrifuge model. Scaling laws for size and time are used to design the appropriate centrifuge operation. Equations 1 and 2 illustrate the scaling laws for size and time in a geotechnical centrifuge model when modelling the self-weight consolidation of fine tailings.

$$h_p = N * h_m \qquad (1)$$

$$t_p = N^2 * t_m \qquad (2)$$

where h_p is the height of the prototype being simulated, h_m is the height of the centrifuge model and N is the multiple of earth gravity that the centrifuge model is subject to in the form of centrifugal force (N times earth gravity). Also, t_p is the prototype time and t_m is the time of the centrifuge model.

The same consolidation process can also be modelled with a finite strain consolidation model. The mechanism of large-strain self-weight consolidation of tailings can be numerically modelled with a continuum theory developed by Gibson et al. (1981). The theory is built on continuity equations for the fluid and solid phases governed by Darcy's law and Terzaghi's effective stress theory. Consolidation is a time-dependent deformation caused by change in the effective stress. The rate and amount of consolidation are controlled by the material's compressibility and hydraulic conductivity. Somogyi （1980） proposed that non-linear compressibility and hydraulic conductivity for saturated soils can be best described by a power law function as:

Compressibility: $e = A\sigma'^{B}_{v}$ (3)
Hydraulic conductivity: $k = Ce^{D}$ (4)
where A, B, C and D are the curve-fit constants.

By applying the tailings consolidation parameters, a numerical model can also provide the long-term behavior of the tailings deposit.

1.2 The Geotechnical Centrifuge Experimental Research Facility

The Geotechnical Centrifuge Experimental Research Facility (GeoCERF) at the University of Alberta, operates a 2-m radius geotechnical beam centrifuge. The facility can model a high-gravity environments up to 150 time of earth gravity (Zambrano-Narvaez and Chalaturnyk, 2014). GeoCERF has conducted centrifuge modelling on many types of treated oil sands tailings candidates for a multi-lift deposition projects. These include a mixture of flocculent and coagulant dosages, treatment techniques, and clay-water ratio (Zambrano-Narvaez et. al. 2018b).

2 CENTRIFUGE MODELLING OF MULTI-LIFT TAILINGS

2.1 Objective and test plan

The goal of the physical model is to represent a field deposition prototype in Northern Alberta, including the deposition schedule and thickness of layers.

A 30-m prototype base was deposited first and consolidated for one prototype year. The following lifts were each one year apart and had gradually reducing lift thickness. A total of 14 lifts were planned and prepared (See Table 1). After the last lift was deposited, the entire deposits consolidated for a total of 45 prototype years.

The centrifuge operation plan was designed to match the deposition schedule. 120G-level condition was chosen to scale up the model to fit the test platform. According to the centrifuge scaling laws, the model thickness for each lift was determined and test duration adjusted to meet the prototype requirement.

Table lists the centrifuge test plan for the specimen.

Table 1. Prototype lift schedule

Year	Lift thickness (m)	Volume of Tailings (m^3)
2018	30	0.38
2019	10	0.13
2020	10	0.13
2021	8	0.10
2022	8	0.10
2023	8	0.10
2024	8	0.10
2025	8	0.10
2026	8	0.10
2027	8	0.10
2028	7	0.09
2029	7	0.09
2030	7	0.09
2031	7	0.09
2032	7	0.09

Table 2. Centrifuge test plan

G	Thickness		Time	
	Prototype	Model	Prototype	Model
120	66 m	55 cm	1 yr per lift a total of 45 yrs	45 min per lift a total of 55 hrs

2.2 Test design and procedure

A consolidation cell was constructed to accommodate the sample on the centrifuge platform. The cell is 55 cm tall and 17.78 cm in diameter. The main body of the consolidation cell was a transparent acrylic cylinder of 18 cm internal diameter and a wall thickness of 1.3 cm, it allowed precise readings of the internal mudline tailings inter-face during the test. The cell also supported columns of pore pressure transducers, which can be installed in 2 cm intervals on the side. Multiple pore pressure transducers (TE Connectivity, EPRB-1, 3.5Bar) were attached to the consolidation cell. Porewater pressure was monitored during centrifuge tests. Fig. 1 shows the on-platform consolidation cell with attached pore pressure transducers.

The consolidation cell simulates a single drainage environment during consolidation. Water can move and accumulate on top of the tailings during consolidation. Decant water was removed before deposition of new lifts. Fifteen tailings dispensers were manufactured. The dispensers were used to store tailings sample after treatment and also had an acrylic body and an attached internal ruler for monitoring the settlement. The tailings material was prepared in a commercial lab and filled into the dispensers according to the prototype lift schedule (Fig. 1).

The tailings dispenser was designed to fit the quick transition time expected in the multi-stage testing environment. At the beginning of each lift, the dispenser was installed on top of the consolidation cell and shifted

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downward to reach the target cumulative lift height. A piston was inserted into the dispenser and pressed to discharge the materials uniformly to-wards the consolidation cell. The whole process took less than 10 minutes before the one prototype year of self-weight consolidation. Fig. 2 shows the action when a new lift was deposited into the consolidation cell.

Fig. 1. Left: Consolidation cell with attached pore pressure transducers. Right: Tailings dispensers with tailing lift

The tailings dispenser was designed to fit the quick transition time expected in the multi-stage testing environment. At the beginning of each lift, the dispenser was installed on top of the consolidation cell and shifted downward to reach the target cumulative lift height. A piston was inserted into the dispenser and pressed to discharge the materials uniformly to-wards the consolidation cell. The whole process took less than 10 minutes before the one prototype year of self-weight consolidation. Fig. 2 shows the action when a new lift was deposited into the consolidation cell.

Fig.2. Depositing a new lift into the consolidation cell with the dispenser

The inter-face settlement is recorded during centrifuge tests through an on-board high-resolution in-flight camera (IDS, 2448x2048 pixel, gigabit ethernet uEye RE model, CINEGON 1·8/4·8 CMPCT RUGGEDZD lenses mod-el)

After all lifts were deposited and the deposit was self-weight consolidated for 45 prototype years, the consolidation cell was removed from the centrifuge platform. The entire deposit was excavated from the surface and multiple sub-samples were taken for geotechnical measurements. The sub-samples were correlated with layers and index property profiles were constructed.

3 NUMERICAL MODELLING OF MULTI-LIFT TAILINGS

One-dimensional finite strain consolidation theory approach was conducted using FSCA software developed based on Gibson et al. (1967) inverse procedure to extract the material hydraulic conductivity parameters from geotechnical centrifuge test results. The numerical analysis is used to determine the rate and amount of settlement of tailings material.

A new version of FSCA was developed to include the actual gravity field that represents the condition in centrifuge physical modelling. The detail of this numerical model has been submitted to a journal publication. It includes the input of centrifuge rotational speed (e.g. revolution per minute) and the effective radius of the specimen. The governing equations of finite strain consolidation was solved using two important non-linear relationships: compressibility (e-σ’) and hydraulic conductivity (k-e). These relationships, account for the dynamic values of soil properties during the consolidation process.

The relationship between void ratio and effective stress is crucial as it governs the soil strain changes under self-weight loading. Mine tailings are usually deposited with very high void ratios and low effective stress, so it is important that the e-σ’ relationship covers a broad range of effective stresses.

The relationship between hydraulic conductivity and void ratio can be determined through standard laboratory tests such as large strain consolidation (LSC) tests. It can also be back analyzed though curve fitting with measured consolidation behavior such as from centrifuge tests.

In this study, the C and D empirical parameters are estimated through back analysis method**.**

4 RESULTS AND ANALYSIS

4.1 Centrifuge modelling results

The centrifuge test plan completed after the self-weight consolidation performance was obtained from the multi-filled tailings specimen. The interface settlement curve is shown in Fig. 3.

Pore pressure dissipation curves were a clear indication of the progress of consolidation. The build-up of pore pressure was captured during the lifting process. Pore pressure dissipation curves for the multi-lift model are shown in Fig. 4. Sensor locations relative to the base of the deposits are also included. Hydrostatic pressure for these sensor locations were determined by spinning the consolidation cell filled with water of the same levels, and excess pore pressure distribution was obtained at the end of the test.

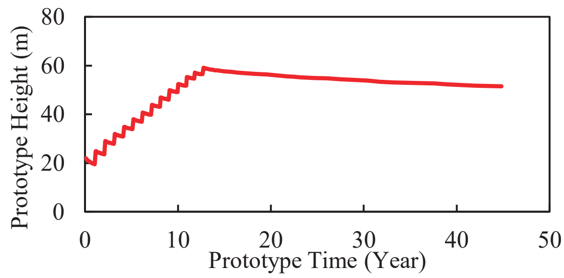

Fig.3. Interface Settlement

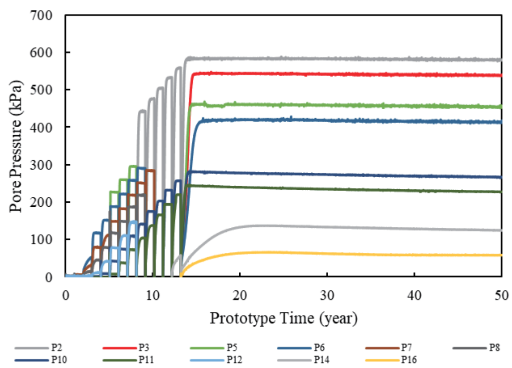

Fig.4. Pore pressure dissipation curves

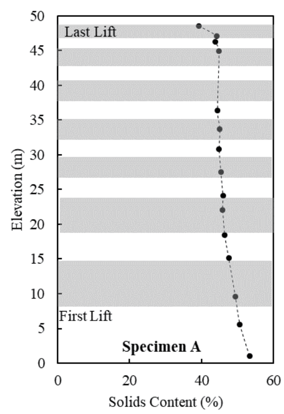

Fig.5. Solids content distribution with depth

By conducting post-mortem analysis of consolidated deposits in layers, solids content profile, void ratio profile, and density profile of the tailings model at the end of the test were obtained. With interface markers, individual layers were marked within the profiles. Figure 6 shows the solids content profiles obtained.

By combining the bulk density profile, void ratio profile and the distribution of excess pore pressure at the end of the centrifuge test, the effective stress (σ') vs void ratio (e) relationship was constructed. Consolidation parameters A and B were obtained by curve fitting the e-σ' curve using the power function shown in Equation 3. In the centrifuge model, A = 4.3828 and B = -0.113. Fig. 6 shows the void ratio vs effective stress relationship and their fitted power functions.

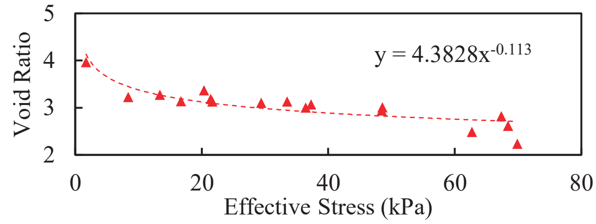

Fig.6. Obtained compressibility curve

4.2 Numerical Modelling Results

Table 3 illustrates the configuration used to construct the numerical model that represent the centrifuge physical model.

Table 3 Multi-lift configuration in model space.

Fill #	Gs	Solids content (%)	Radius to bottom of sample (m)	Layer thickness (m)	Settling period (hr)
1	2.55	32.7	1.95	0.194	0.85
2	2.55	33.1	1.79	0.056	0.87
3	2.55	33.0	1.75	0.057	0.85
4	2.55	33.2	1.71	0.045	0.85
5	2.55	33.4	1.69	0.045	0.87
6	2.55	32.4	1.66	0.046	0.85
7	2.55	32.6	1.63	0.04	0.88
8	2.55	33.0	1.61	0.05	0.85
9	2.55	33.0	1.57	0.05	0.85
10	2.55	33.0	1.55	0.04	0.88
11	2.55	33.7	1.52	0.04	0.82
12	2.55	33.3	1.49	0.04	0.87
13	2.55	32.5	1.46	0.03	0.85
14	2.55	31.8	1.44	0.03	24.65

A back-analysis procedure was used to estimate the (k-e) relationship. The workflow for this back-analysis employs the compressibility relationship shown in Fig. 6 and varies the empirical hydraulic conductivity parameters C and D of Equation 4 in the FSCA numerical analysis until the numerical results matched the time-settlement behavior measured in the centrifuge. This procedure leads to an accurate (k e) relationship because the back-analysis is very sensitive to variations of permeability. For the current test, Fig. 7 shows a history match between the numerical and the centrifuge model settlement curve based on the hydraulic conductivity parameters C = 2x10^{-6} and D = 6.12. Fig. 8 illustrates the shape of the k-e relationship for the material.

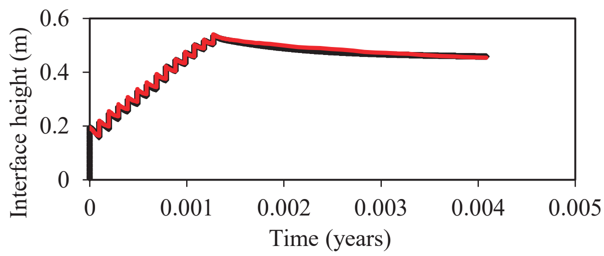

Fig.7 best fit obtained for the sample

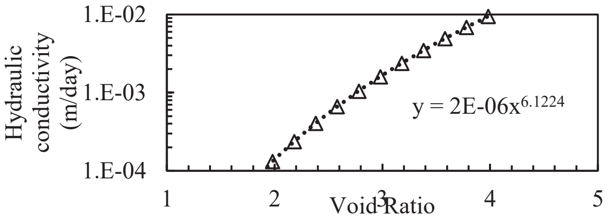

Fig.8 Hydraulic conductivity and void ratio relationship curve

6 CONCLUSIONS

As part of a commercial technical assessment of the behavior of oil sands tailings from northern Alberta, a centrifuge modelling test to simulate 45 years of multi-lift consolidation behavior was conducted in GeoCERF at the University of Alberta. The test duration was 55 hours under 120 times the Earth's gravity acceleration. The model simulates a one-way drainage, 14-layer tailings deposit. Unique test cell and tailings dispensers were developed by the GeoCERF research group that allow closely-spaced measurements of pore pressure change within tailings specimens and permit unparalleled visualization of the settlement behavior of the specimens. The geotechnical centrifuge model offers an effective method to assess tailings consolidation parameters. The void ratio and effective stress relationship were derived from the void ratio and pore-water pressure profile at the completion of the centrifuge tests. The permeability relationship was estimated by the back-analysis method, varying the relationship to obtain the best fit between numerical and predictions and the observed behavior in the centrifuge tests. The numerical model uses the compressibility parameters (void ratio – effective stress relationship) obtained from centrifuge model and the best matched hydraulic conductivity parameters were determined.

This study has shown that combining numerical simulation and centrifuge simulation through the back-analysis approach is a powerful tool in obtaining tailings consolidation parameters and predicting tailings consolidation performance. The ability to "fail fast" offers obvious cost- and time-saving benefits that appeal to both industry and consumers, but by far the greatest and most important impact of research carried out in GeoCERF is risk mitigation. Knowledge being acquired through testing performed today will shape industry's ability to implement reclamation efforts both during and upon completion of projects, with the ultimate objective being to meet or exceed the mandates by the regulator.

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