Investigating drainage boundary effects in multi-lift tailings consolidation using geotechnical centrifuge physical modelling

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ABSTRACT: The extraction and processing of oil sands produce significant volumes of fluid fine tailings, which are stored in tailings facilities requiring management for long-term stability and closure. The consolidation behaviour of tailings plays a crucial role in predicting settlement, excess pore pressure dissipation, and strength gain over time. Centrifuge physical modelling provides an effective method for studying this behaviour under field-representative stress-strain conditions. Physical models of tailings typically consider only one-way drainage to the surface. This study investigates the influence of drainage boundary conditions on tailings consolidation using geotechnical beam centrifuge testing. A customized setup was designed and added to a cylindrical consolidation cell to simulate double drainage by enabling flow from both the top and bottom boundaries of the tailings deposit. Two different tailing types were co-deposited using a multi-lift strategy in two identical cells—one with double drainage and the other with single drainage. Each lift was spun for the equivalent of one year under 100g, and spinning the final deposit was continued for an equivalent of about 100 years. Settlement was monitored using a high-speed camera and pore pressure was measured using embedded sensors. At the end of the test, the strength profile was determined in-flight using a miniature T-bar probe. Results indicated that double drainage conditions primarily affected early-stage consolidation compared to the single drainage. In addition to experiment, the settlement and compressibility data were used for back-analysis of permeability parameters. This study provides insight into tailings management and closure by considering the effects of drainage boundary conditions on tailings consolidation.

1 INTRODUCTION

Oil sands production in northern Alberta, Canada generates substantial volumes of fluid fine tailings as by-products of bitumen extraction. These tailings consist primarily of fine clay, silt, and water, and are stored in large tailings ponds that pose significant challenges for long-term management, stability, and reclamation. The slow consolidation and high-water content of fluid tailings hinder surface reclamation, necessitating decades to achieve trafficable strength (Jeeravipoolvarn, 2004, 2010). Consequently, improving the rate of dewatering and consolidation of tailings deposits remains a key focus in advancing sustainable oil sands operations.

In recent years, various treatment strategies—such as thickening, in-line flocculation, and co-deposition of tailings—have been developed to investigate tailings dewatering (Daliri et al., 2016; Gowan et al., 2010; Grabinsky et al., 2002). These treatments can produce deposits with enhanced permeability which gain stength faster, thereby facilitating reclamation process.

Despite advances in treatment methods, understanding the influence of drainage boundary conditions on the long-term consolidation behaviour of treated tailings remains limited. In most tailings impoundments, drainage is assumed to occur only upward toward the surface; however, engineered drainage systems at the base of a deposit can provide an additional pathway for water removal. The presence of double drainage conditions can change drainage paths, the rate of pore pressure dissipation, and consolidation (Carrier et al., 2018). Ma et al., (2023) conducted 1.2 m-high column tests to evaluate the combined effects of drainage conditions and cement addition on the consolidation of tailings slurry. Their results revealed that increasing drainage boundaries (from bottom-only to full lateral drainage) promoted faster pore pressure dissipation compared to adding cement (Ma et al., 2023). While laboratory tests provide valuable insight, they are limited by scale effects and the difficulty of reproducing realistic in-situ stress fields. Experimental validation of drainage mechanisms under realistic stress conditions is essential for optimizing tailings design and closure strategies. Although classical one-dimensional consolidation theory predicts that reducing drainage path length decreases consolidation time, this framework assumes small strains and constant material properties. In contrast, oil sands fine tailings undergo large-strain self-weight consolidation, with evolving void ratio and permeability(Been and Sills, 1981; Gibson et al., 1981). Therefore, the influence of drainage boundaries cannot be directly inferred from classical theory and requires experimental validation under realistic stress conditions.

Geotechnical centrifuge modelling offers a powerful tool to investigate the response of tailings under field-representative stress states and time scaling. The scaling relationships govern the relationship between model and prototype parameters—for example, length scales as 1/N, stress remains constant, and the consolidation time scales as $1/N^2$ (N is the multiple of earth gravity) (Madabhushi, 2017; Taylor, 2018). By subjecting small-scale models to high gravity fields, centrifuge tests can replicate prototype-scale self-weight consolidation within days, providing valuable insight into long-term performance(Antonaki et al., 2018; Beckett et al., 2016; Sorta, 2015; Zambrano-Narvaez et al., 2018, 2021, 2022) . Previous centrifuge studies on tailings have focused mainly on single-drainage configurations, leaving the comparative influence of bottom drainage unexplored.

This study investigates the effect of drainage boundary conditions on the consolidation behaviour of co-deposited oil sands fine tailings using centrifuge physical modelling. Tests were conducted under Single Drainage (SD) and Double Drainage (DD) conditions. The experimental setup was designed to simulate multi-lift deposition and long-term consolidation equivalent to about 100 years of prototype time. Settlement, pore pressure, and strength evolution were monitored throughout testing, and the results were analyzed to evaluate the impact of drainage configuration on consolidation rate. The findings provide insight into the bottom drainage systems for tailings dewatering.

2 EXPERIMENTAL SETUP AND DATA ACQUISITION

The experiments were conducted at the Geotechnical Centrifuge Research Facility (GeoCERF) at the University of Alberta, which houses a 2-m radius beam centrifuge capable of generating accelerations up to 150 g (Zambrano-Narvaez and Chalaturnyk, 2014).

2.1 Consolidation cells

The custom cylindrical consolidation cell was fabricated from transparent Plexiglas with an internal diameter of 177.8 mm, height of 568.6 mm, and wall thickness of 13 mm, reinforced by an aluminium support structure as shown in Figure 1. The transparent wall enabled continuous visual observation of the solids–water interface (mudline) during centrifuge testing. Possible radial deformation under elevated stresses at 100g was assessed during early commissioning of the GeoCERF consolidation cells, which indicated very small (maximum values 200 μm) radial deformation. This deformation is not important for this class of material with very low undrain shear strength.

Two drainage configurations were examined. One cell was tested under one-way drainage conditions (SD), with drainage directed toward the top of the model. The other, a DD cell, was tested under two-way drainage boundary conditions, allowing water to drain from both the top and bottom surfaces. A standpipe system was connected to the DD cell to maintain a constant hydraulic head. The height of the standpipe was adjusted to match the sample surface and allow controlled removal of any overflow to drain cell. The complete cell setup is illustrated in Figures 1 (a) and (b). In addition, to facilitate drainage at the base, a 3 cm sand layer covered with filter paper and a fine mesh screen was installed, as shown in Figure 2.

2.2 Instrumentation and monitoring

During centrifuge operation, pore pressure was continuously recorded by different pore pressure transducers (EPRB1-NU33-3-35B) at different elevations. The data acquisition system transmitted signals through the centrifuge slip rings to a ground-based computer for real-time logging. Simultaneously, the high-speed in-flight camera system (IDS uEye RE, 2448 × 2048 pixels) equipped with a CINEGON 1.8/4.8 Ruggedized lens camera recorded images of the mudline to evaluate settlement-time behaviour. Millimetre-graduated rulers were affixed vertically to the inner wall of the cell using epoxy, allowing quantitative measurement of settlement throughout the test.

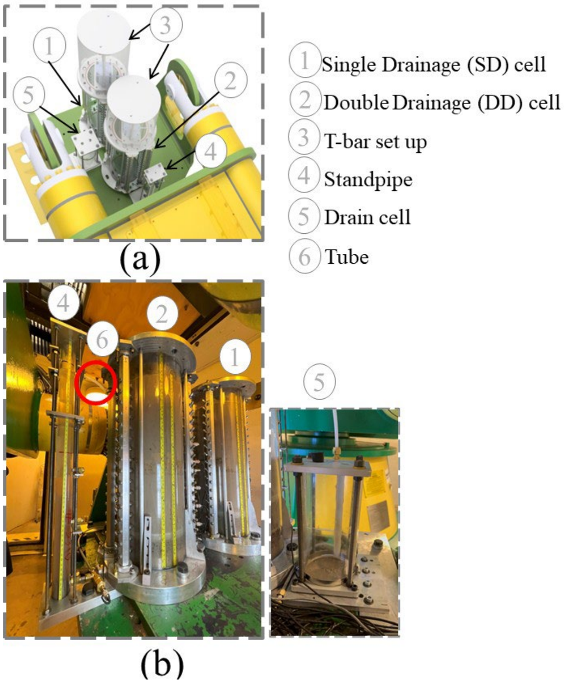

Figure 1. (a) Setup of consolidation cells on the centrifuge platform, (b) details of consolidation cells

Based on the image resolution, the settlement measurement resolution was approximately ±0.5 mm in model scale. The complete instrumentation arrangement is presented in Figure 2.

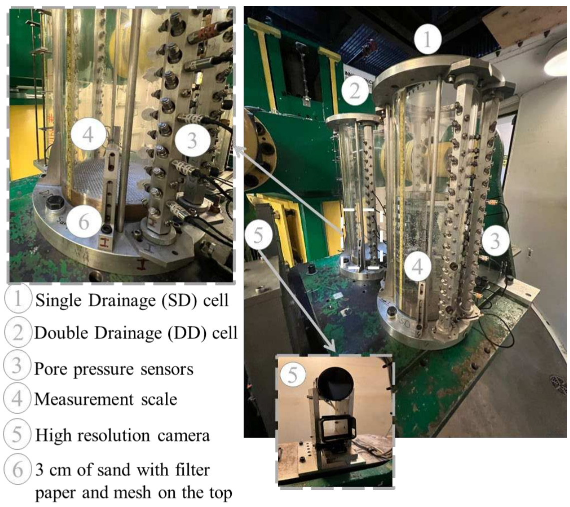

Figure 2. Instrumentation and setup of consolidation cells.

2.3 Strength measurement

Upon completion of centrifuge spinning, the undrained shear strength of the consolidated tailings was measured in-flight using a miniature T-bar penetration device mounted above the consolidation cell. The T-bar, equipped with strain gauge, was driven vertically into the specimen at a constant penetration rate by a stepper motor. The undrained shear strength, s_u , was computed following (Randolph and Houlsby, 1984):

$$s_u = \frac{Pd}{N_b} \quad (1)$$

where P is the force per unit length acting on the bar, d is the diameter of the bar, and N_b is the bar factor. An intermediate value of 10.5 for N_b was adopted based on established T-bar penetration theory for slender bars (Length/diameter ≥ 4) in normally consolidated soft soils (Randolph and Houlsby, 1984) .

3 MATERIALS AND TESTING PROCEDURE

3.1 Tailings material

Two treated oil-sands fine tailings were used. Table 1 summarizes the pre-mixture properties of the materials.

Table 1. Pre-mixture properties of tested tailings.

Tailings type	Average solid contents (%)	Specific gravity (G_s)	Sand Fines Ratio (SFR)
Type 1	54.8	2.58	1.45
Type 2	24.4	2.40	0.01

3.2 Sample preparation and deposition

A co-deposited mixture consisting of 80% Type 1 and 20% Type 2 by dry mass ratio was prepared for each lift and for each drainage configuration. The materials were prepared separately and pre-mixed to a uniform slurry state before being introduced simultaneously into the consolidation cell to replicate staged co-deposition of the field. Deposition was performed at controlled and matched pour rates to minimize preferential segregation during filling. Each lift of the model had a total mass of approximately 4 kg, corresponding to a prototype-equivalent tailings thickness of about 13 m.

The multi-lift sequence was designed to represent staged filling of a tailings deposit, where material is placed incrementally and allowed to consolidate between deposition events. After placement of each lift, the centrifuge was accelerated to 100 g and maintained for one hour (1.2–1.3 years of prototype time per lift). The decant water that accumulated at the surface was carefully removed prior to adding the subsequent lift. Following placement of the final (fourth) lift, the model was spun for 3.8 days, corresponding to an additional ~102 years of prototype time, to simulate the long-term post-deposition (closure) phase under self-weight loading. Both SD and DD tests followed identical deposition and spinning procedures to ensure direct comparability of results.

4 NUMERICAL ANALYSIS OF MULTI-LIFT TAILINGS

The consolidation of tailings deposits can also be addressed through a finite-strain consolidation model, which accounts for large deformations that occur under self-weight loading. The continuum framework developed by Gibson et al., (1981) provides the governing equations for one-dimensional large-strain consolidation by combining fluid-solid continuity equations, Darcy's law for pore-fluid flow, and effective stress theory (Gibson et al., 1981). In this context, consolidation is defined as a time-dependent volume reduction driven by the increase in effective stress as excess pore-water pressures are dissipated. The magnitude and rate of settlement are thus principally controlled by the material's compressibility and hydraulic conductivity, which themselves evolve during deformation.

In this study, a one-dimensional finite strain consolidation analysis was performed using the Finite Strain Consolidation Analysis (FSCA) software (FSCA, 2025). The governing equations of large-strain consolidation were solved based on two fundamental non-linear constitutive relationships: compressibility (e–σ′) and hydraulic conductivity (k–e). These relationships account for the continuous variation of soil properties during the consolidation process.

The void ratio–effective stress relationship, derived from one-dimensional consolidation tests, one form was expressed following (Liu and Znidarčić, 1991) as:

$$e = A\sigma'^{B} \quad (2)$$

Similarly, the hydraulic conductivity–void ratio relationship, obtained from saturated hydraulic conductivity tests conducted at varying void ratios, was described as (Gjerapic et al., 2008):

$$k = Ce^{D} \quad (3)$$

where A, B, C, and D are fitting parameters.

5 RESULTS AND DISCUSSION

5.1 Settlement behaviour

Each cell was constructed in four sequential lifts, representing cumulative prototype timeframes of up to 105 years. The final (fourth) lift reached a prototype-equivalent initial height of approximately 44 m, which subsequently consolidated to 28.1 m for the DD model and 28.8 m for the SD model after 105 years (Figure 3). The detailed settlement data for each lift and corresponding prototype time are summarized in Table 2.

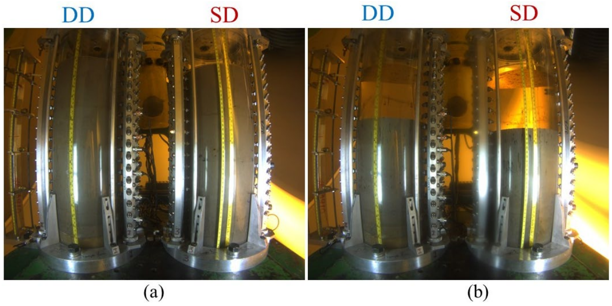

Figure 3. Tailings deposits (a) year 3 (b) year 105.

During the early stages of the test, corresponding to the first 3 years of prototype time, the three lifts were placed sequentially, during which the DD cell exhibited a faster reduction in height indicating faster pore pressure dissipation through the bottom drainage layer. This trend is quantitatively reflected in the settlement–time curves shown in Figure 4. After completion of the multi-lift phase, the settlement curves for both configurations began to converge, with the rate of settlement becoming similar after approximately 5 years of prototype time indicating that while bottom drainage enhances early-stage consolidation, its effect on the long-term settlement magnitude remains limited and overall consolidation becomes governed by the material's compressibility and permeability.

Table 2. Settlement data for each lift DD and Single SD conditions.

Time	**Thickness Tailings (m)**	
	DD	**SD**
Year 0	13.1	13.1
Year 1	10.1	10.6
Year 1 with second lift	23.5	23.2
Year 2	20.2	20.7
Year 2 with third lift	33.6	33.5
Year 3	30.1	31.5
Year 3 with fourth lift	43.7	44.7
Year 100	28.1	28.8

5.2 Index properties after consolidation

Post-test subsampling of the consolidated specimens performed immediately after spin-down to measure distributions of solids content, water content, dry density, and void ratio along the sample as plotted in Figure 5. Given the normally consolidated condition and low swelling potential of the tailings, elastic rebound during unloading from 100 g to 1 g is expected to be minimal.

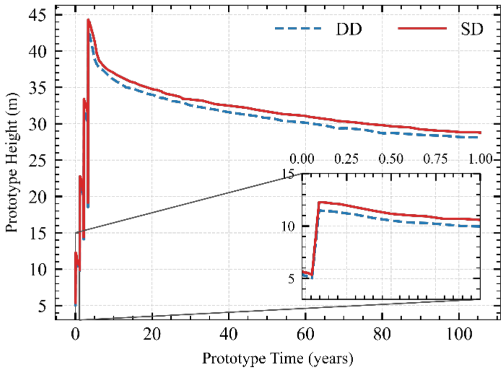

Figure 4. Settlement curve for DD and SD with a zoom for early time.

Both the SD and DD specimens exhibited clear vertical gradients in index properties, indicating progressive compaction with depth as a result of self-weight–induced consolidation (Figure 5). In both configurations, the solids content increased from approximately 25–30% near the surface to ~82% at the base. The Sand Fines Ratio (SFR) also increased systematically with depth, reaching values of up to ~2.5 at the bottom of the deposit for both specimens. Correspondingly, the void ratio (e) decreased from approximately 7–8 near the surface to ~0.5 at the base, consistent with the observed increase in solids content and fines concentration. Although SFR increases with depth, the profile is smooth and continuous rather than abrupt. This trend is consistent with stress-driven redistribution during large-strain consolidation rather than placement-induced segregation. In flocculated tailings systems, particles settle as aggregated structures under hindered settling conditions, limiting hydraulic sorting during deposition. The similar SFR gradients observed in both SD and DD specimens further indicate that the variation is governed primarily by consolidation processes rather than by segregation during placement. No visible stratification or particle banding was observed during testing.

5.3 Pore pressure dissipation

The evolution of pore pressure was continuously monitored at multiple elevations within each cell. Figure 6 and Figure 7 present the excess pore pressure profiles at different prototype times for the DD and SD configurations, respectively. In both models, the initial excess pore pressures were highest near the mid- to lower section of the deposit, corresponding to zones of maximum self-weight stress and limited drainage.

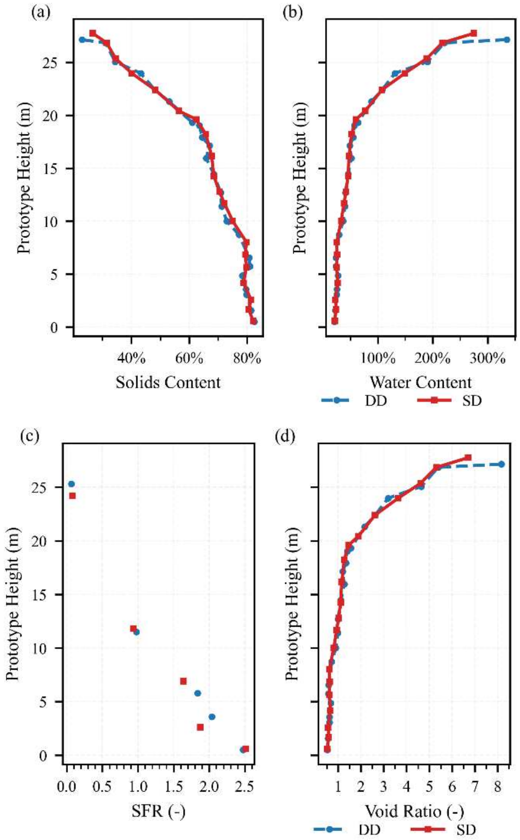

Figure 5. Index profiles after consolidation (a) solid contents, (b) water content, (c) SFR and (d) void ratio.

In the DD model (Figure 6), pore pressure dissipation occurred rapidly during the early stages of consolidation and by 50 years, excess pore pressures decreased substantially throughout the profile. By contrast, the SD model (Figure 7) retained higher excess pore pressures near the base even after 50 years, with gradual dissipation continuing until approximately 80–100 years. The slower response under single drainage reflects the longer drainage path and reduced pore water escape. No evidence of underdrain clogging was observed in the DD configuration. Pore-pressure dissipation near the base remained continuous, and post-test index profiles showed no localized fines accumulation at the drainage boundary. The isochrones exhibit local curvature rather than perfectly monotonic profiles. This behaviour is attributed to staged multi-lift deposition under large-strain conditions, where each lift develops slightly different consolidation states and permeability. The inflection elevations correspond with subtle variations in solids content, and are further influenced by interpolation between discrete sensor measurements.

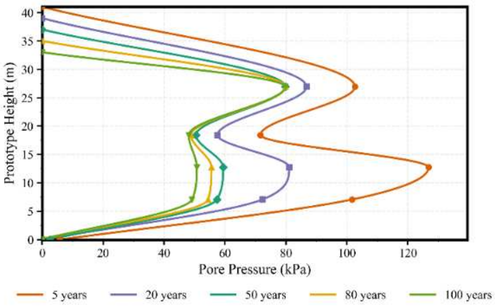

Figure 6. Excess pore pressure isochrones in DD.

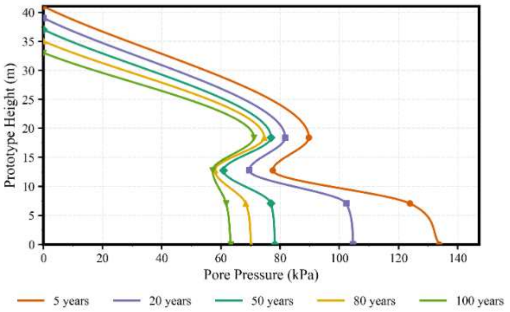

Figure 7. Excess pore pressure isochrones in SD.

5.4 Stress distribution

The distributions of total stress, pore-water pressure, and effective stress at the end of the test for both drainage configurations are shown in Figure 8. As expected, the total stress (σ) increased approximately linearly with depth, consistent with the overburden load of the tailing's column. The pore-water pressure (u), decreased with time as consolidation progressed, resulting in a gradual increase in the effective stress (σ′ = σ – u). After 105 years, the maximum effective stress near the base reached approximately to ~200 kPa in the SD and DD cells.

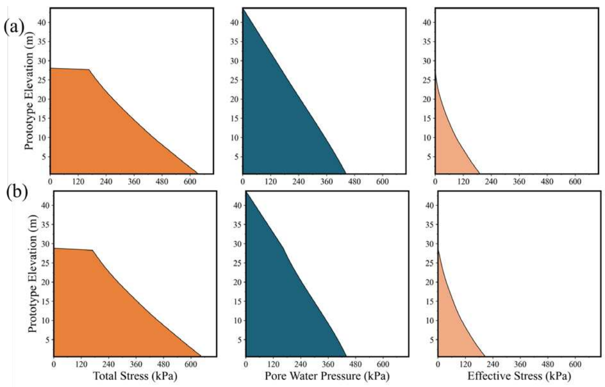

Figure 8. Stress profiles after 105 years (a) DD and (b) SD.

5.5 Compressibility behaviour

Void ratio–effective stress relationships derived from post-test sampling are presented in Figure 9. The compression index for both drainage conditions follows a power-law relationship of the form Equation (2). Fitted correlations were:

$$e = 6.13\,(\sigma')^{-0.445} \text{ for DD} \quad (4)$$

$$e = 5.37\,(\sigma')^{-0.453} \text{ for SD} \quad (5)$$

The similarity between the DD and SD curves ($b \approx 0.45$) indicates similar compressibility behaviour between tests, consistent with both being derived from identical material mixtures. The drainage condition could influence the rate but not the fundamental compressibility of the material. Both systems exhibit comparable e–σ′ behaviour, governed primarily by the intrinsic compressibility of the tailings matrix. It should be mentioned that despite the presence of residual excess pore pressure, the e–σ′ curves were derived from measured in-flight effective stresses from measured pore pressures at the final time step at 100 g and therefore reflect the actual stress state rather than an assumed equilibrium condition.

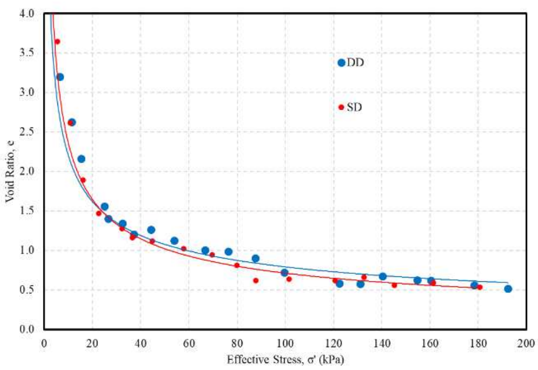

Figure 9. Compressibility curves in DD and SD.

5.6 Undrained shear strength

The in-flight T-bar penetration tests provided the undrained shear strength (s_u) profiles for both drainage configurations, as shown in Figure 10.

The measured strength values increase consistently with depth, following the trend of increasing solids content. Near the surface, both SD and DD specimens exhibited low strength (<1 kPa), corresponding to the high-water content and low solids fraction.

With increasing depth, the s_u values increased, reaching approximately 16 kPa near the middle of the DD specimen after the equivalent of 105 years of prototype time. The DD profile displayed slightly higher strength throughout the mid-depth region (15–20 m). The increase in solids content and undrained shear strength confirms the direct relationship between consolidation state and mechanical resistance.

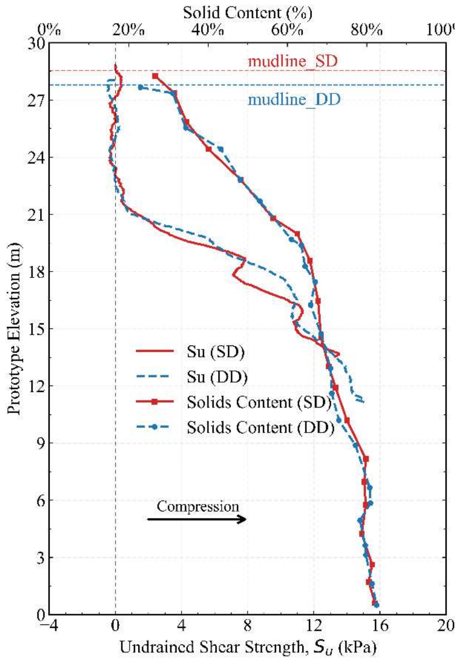

Figure 10. Profiles of s_u and solids content for SD and DD.

5.7 Numerical Modelling Results

A back-analysis was performed using the FSCA software to estimate the hydraulic conductivity–void ratio (k–e) relationship for the tested tailings. Because direct permeability measurement under large-strain centrifuge conditions is not feasible, history matching provides a physically consistent method to estimate k(e). The analysis utilized the Pond Filling feature in FSCA, which allows simulation of sequential deposition and consolidation for a multi-layered deposit with varying material properties and periods of loading and quiescence (FSCA, 2025).

The workflow for this back-analysis employed the experimentally derived compressibility relationship (Figure 9) and iteratively adjusted the empirical parameters C and D in the hydraulic conductivity equation (Equation 3) to achieve agreement between the numerical settlement predictions and the measured centrifuge settlement–time response. (Zambrano-Narvaez et al., 2022). For both SD and DD tests, the best fit was obtained using average of $C = 8 \times 10^{-6}$ and $D = 8$, which produced close match between the simulated and experimental settlement curves, as shown in Figure 11. The calibrated relationship between hydraulic conductivity and void ratio is illustrated in Figure 12, demonstrating the expected exponential decrease in permeability with decreasing void ratio during consolidation.

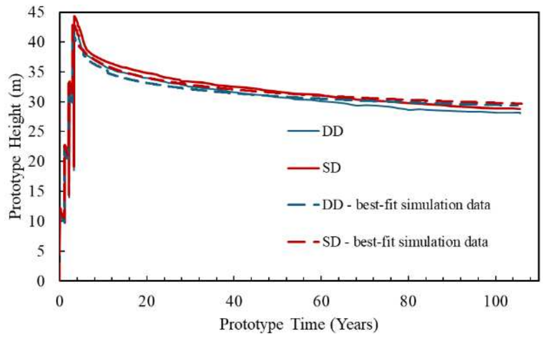

Figure 11. Best fitted for DD and SD results.

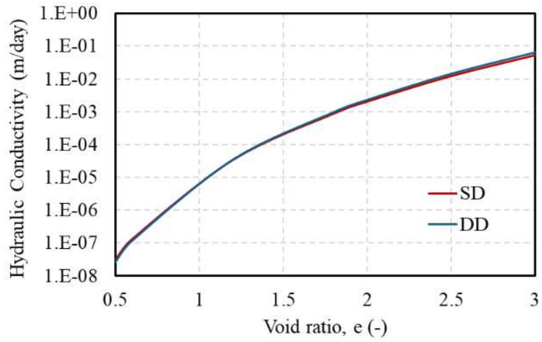

Figure 12. k-e relationship curve.

6 CONCLUSIONS

Centrifuge modelling was used to investigate the effect of drainage boundaries on multi-lift tailings consolidation. Both single drainage (SD) and double drainage (DD) cells reached similar final heights after ~105 years, though DD showed faster early-stage settlement and pore-pressure dissipation. Post-test profiles showed solids content increasing to ~82% and void ratio decreasing to ~0.5 at the base. Compressibility curves for both conditions followed a similar power, indicating comparable intrinsic behaviour. In this study, the long-term settlement magnitude was primarily governed by evolving compressibility and permeability under large-strain conditions. As void ratio decreased, hydraulic conductivity reduced nonlinearly, limiting drainage efficiency. Overall, bottom drainage enhanced early consolidation but had limited influence on long-term performance.

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