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A performance-based approach for the calibration and prediction of fine tailings settlement for closure design

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Abstract

The International Council on Mining and Metals (ICMM) recommends the performance-based design method, an increasingly popular approach among tailings engineers, to manage uncertainty in design. This method involves using surveillance data collected during the facility lifecycle to adjust the existing design parameters and estimate future performance. Its significance is particularly pronounced in the post-closure phase of tailings facilities, which are designed to have an unlimited design life (i.e. annual exceedance probability 1/10,000).

This paper shows a performance-based application. The approach was used to tune the settlement design parameters of a fine, high-plasticity tailings material to predict the closure landform performance. The method used data from different instruments installed during the facility lifetime, settlement plates and topographic survey. A large strain deformation model incorporated the laboratory test results from particle size distribution, specific gravity, Atterberg limits, and Rowe cell and oedometric compression testing. The model was developed using FSCA software; a 1D finite strain consolidation analysis program used to determine the rate and amount of settlement for tailings, slurry and soft soils. The model predicted the settlements at specific locations within the tailings storage facilities (TSF) over the monitoring periods and compared them to the corresponding survey and instrumentation data results. Using the predicted settlements to inform the final design surface, the calibrated model was then used to predict the landform evolution of the fine tailings facility over the closure construction and post-closure periods. The contours mapped for different periods can indicate the future risks associated with excessive settlement and help with risk-informed decision-making in the early stages of closure design.

Keywords: *performance-based design, fine tailings, calibration, closure*

1 Introduction

Performance-based design is an engineering design approach that focuses on achieving desired performance outcomes rather than simply meeting minimum standard/guideline requirements (precautionary-based design) and is recommended by the Global Industry Standard on Tailings Management (International Council on Mining & Metals [ICMM] 2020). This approach typically involves iterative evaluations of tailings storage facilities (TSFs) design performance using analysis and simulation results from the anticipated performance parameters calibrated by surveillance data throughout the facility life. The evaluation outcomes are compared against the prescribed performance objectives to validate or further optimise the design solution.

The approach presented in this paper follows the ICMM framework (ICMM 2021) for performance-based design and is schematically shown in Figure 1. During the design phase, site characterisation data (i.e. geotechnical, hydrogeological, geological, etc.) are used to develop performance objectives for the TSF. The facility's behaviour is predicted to inform the final design and meet performance objectives. As part of the design, a surveillance program was developed to allow monitoring of key performance metrics. Throughout the construction, operations, closure and post-closure phases, surveillance data was collected,

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analysed and assessed against the performance criteria developed during the design phase. When the current performance did not meet the predicted performance, the design model was recalibrated using the surveillance data and then repredicted. The design changed when the repredicted performance did not meet the objectives. This is an iterative process completed throughout the lifecycle of the TSF, with robust design as a goal.

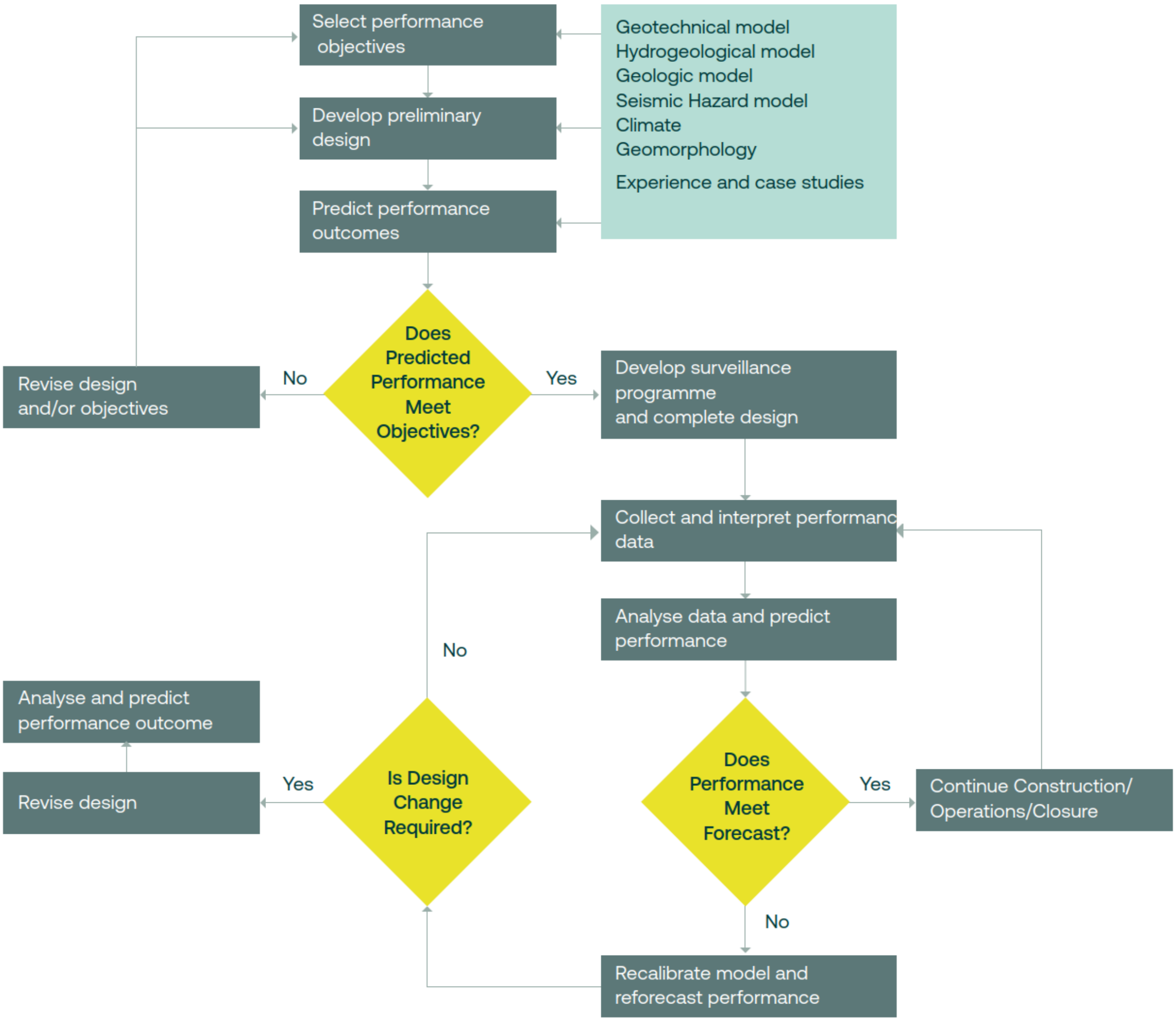


Figure 1 **Performance-based approach to design, construction, operations and closure (ICMM 2021)**

Alternate definitions of performance-based design are set out in the International Commission on Large Dams (ICOLD) Bulletin 194 Section 7.5.3 (ICOLD 2023), which recommends that performance objectives and design criteria be informed by failure modes. This key component highlighted by ICOLD is not included in the ICMM framework but is an important step in the performance-based approach. Failure modes have been incorporated into the selection of performance objectives and design criteria.

This paper presents an application of performance-based design. It was used to calibrate the settlement design parameters of a fine, high-plasticity tailings material and predict the closure landform performance for a site in northern Australia.

2 Failure modes

The performance objectives were developed with consideration of the following failure modes identified in terms of tailings consolidation:

- Tailings beach settles more than predicted, resulting in a landform below the final design levels that can compromise long-term surface water drainage.
- Tailings beach settles less than predicted, resulting in a landform above the final design levels that can compromise long-term surface water drainage.
- Isolated settlements in the capping material/tailings (i.e. collapse-settlement) result in repeated remediation work being required during and after construction of the closure cover. This failure mode has been seen in other TSF closure projects at the same mine where a prescriptive design approach was adopted (see Figure 2). These isolated collapse-settlement events occurred in thick loose-fill materials following rainfall events and required reactive measures to remediate. An improvement for future works will be to design mitigation measures to address potential failure mode occurrences ahead of executing the design as recommended by Peck (1969).
- Differential settlement results in isolated low points across the facility, which may impact water surface management and thus impact vegetation growth and development.
- Differential settlement resulting in the development of a crack in the cap can provide a path for water ingress to the tailings material. Geochemical characterisation was carried out for the studied TSF tailings and it was concluded that the tailings have a low acid-generating and metal-leaching potential.

Figure 2 Localised collapse-settlement in the cover 'reshaping fill' after the first rainy season

3 Performance objectives

The performance objectives for the settlement prediction considered a maximum incremental settlement of 0.5 m, which is considered within an acceptable range for closure performance based on the identified failure modes. This incremental settlement is interpreted as an 80% degree of consolidation in the consolidation model.

4 Preliminary cover and landform design

The mine site closure strategy for TSFs comprises encapsulation through the placement of an earthen cover system. The cover system design is a concave 'store and release' type cap cover system that limits deep drainage into the tailings material and supports the growth of the selected vegetation community. During periods of high rainfall this system allows the infiltration of some water, which is then stored within the cover until atmospheric and biotic demands remove the water through evaporation and transpiration. The low permeability of the tailings material limits infiltration and allows water to be stored in the cover layers. Surface runoff is directed off the facility via internal and external drainage networks.

The closure design comprises a concave landform developed using the following key design parameters:

- minimum capping gradient of 0.5% based on the observed performance of a rehabilitation trial completed on a different TSF and compatibility with natural landscapes at the site
- maximum excavation into tailings of 1.5 m, based on the outcomes of a geotechnical investigation and assessment of the tailings 'crust' thickness
- minimum drain longitudinal gradient of 0.5%, based on the observed performance of drains across the site.

The outlet drains' locations govern the landform's shape and subsequent cover thickness. The inverts of the drains are selected based on the maximum excavation into tailings with a 1.5 m parameter, and the landform is developed off the drain. The landform contours parallel the outlet drains to align with a natural contour look and allow flow from the cover over the drain batter. The outlet drains are aligned over existing internal embankments to reduce excavation in tailings and improve drain stability. The cover design is not related to tailings thickness. The closure design study of the TSF considered an options assessment for selecting the optimal outlet drain location for the closure design. The options assessment was undertaken through multi-criteria analysis (MCA) to simultaneously assess the options under various criteria. The key risk assessment categories used in the MCA included:

- stakeholder risk — Traditional Owner and regulator perception and acceptance
- geotechnical risk — the performance of each option from a geotechnical perspective, including potential impacts on the embankment's stability, settlement, seismicity and erosional performance
- surface water risk — catchment delineation, integration with surrounding overland flows, sediment transportation, surface water quality and potential for an overtopping event
- groundwater risk — potential for excess infiltration, contaminant transportation, phreatic level changes and potential to trigger geochemical changes
- environmental risk — vegetation disturbance and potential for ecological alteration
- social risk — human health consideration from plant uptake
- constructability risk — the level of effort required to implement the option, including working on tailings beach and trimming into tailings
- operational risk — minimising impacts on operational infrastructure or potential mine pit inundation risks
- maintenance risk — providing access to undertake maintenance regimes during establishment.

Based on the results of the MCA, the cover design comprises a northwestern drain and a southwestern drain aligned along natural pre-mining flow paths and existing internal embankments. The design incorporates a northern catchment which diverts runoff into the northwestern drain, and a southern catchment which diverts runoff into the southwestern drain. A contour plan of the closure design is shown in Figure 3.

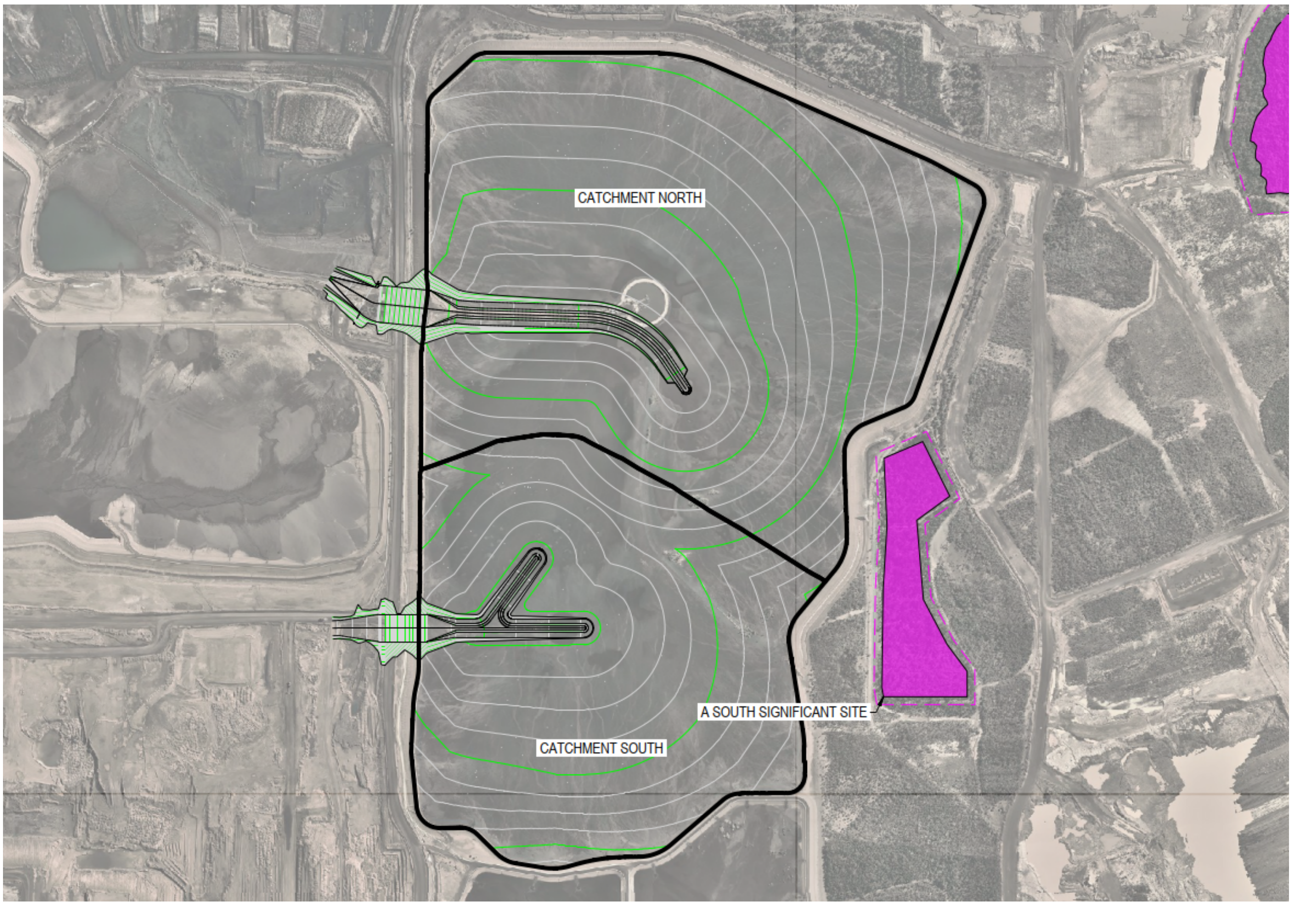
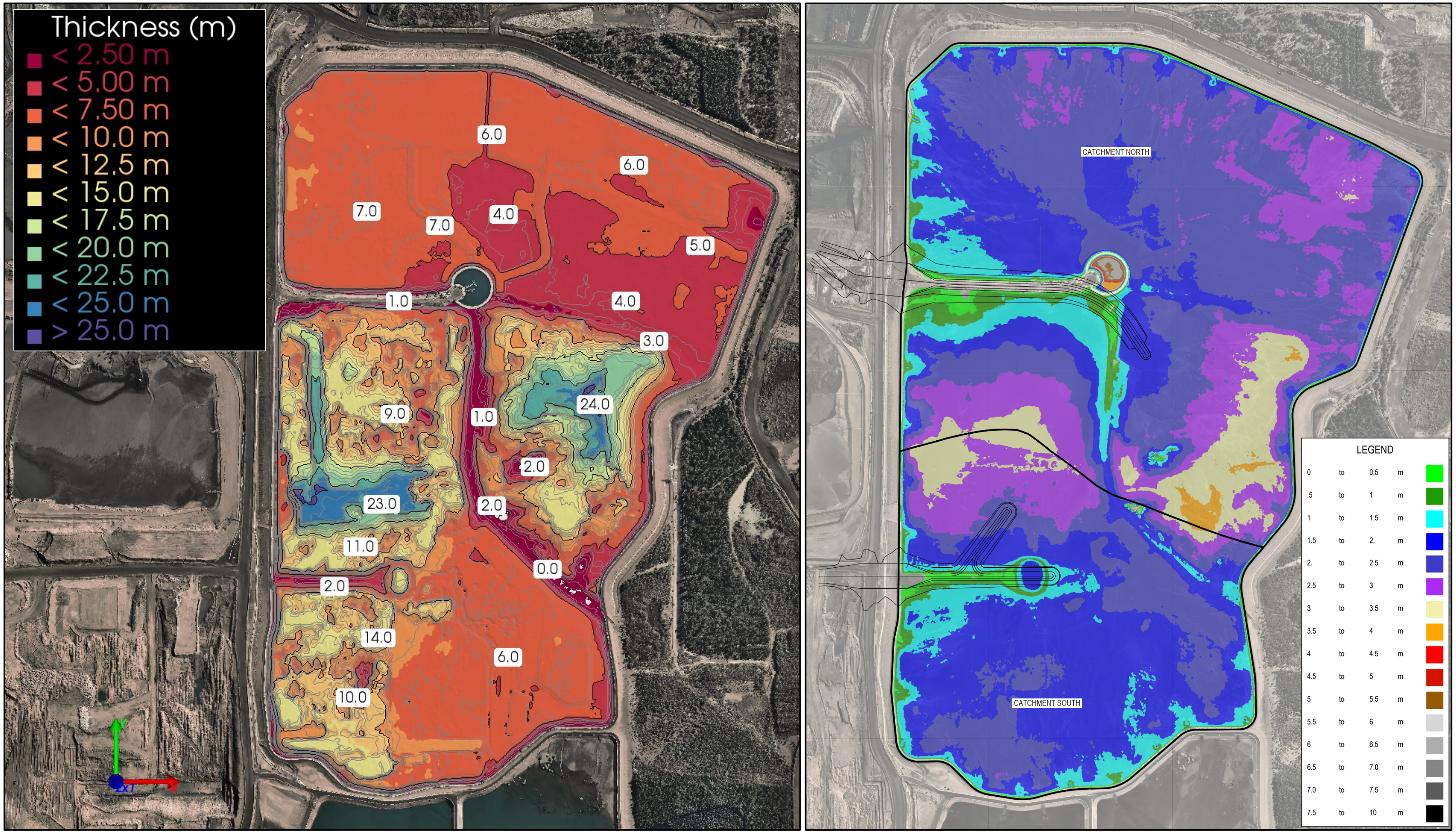


Figure 3 Tailings storage facility closure landform and outlet drain arrangement

The design of the cover system for the TSF landform comprises three material layers:

- reshaping fill — coarse borrow or overburden materials of varying thickness to achieve the design landform shape
- subsoil — 1.0 m-thick subsoil to provide growth medium for vegetation
- topsoil — 0.3 m-thick topsoil layer to provide a nutrient-rich growth medium for vegetation.

The tailings thickness within the TSF is well understood due to accurate ‘as-built’ impoundment surface information. Tailings typically range from approximately 4 to 7 m, with two notable deep tailings areas of 20–24 m thickness. The tailings thickness heatmap is shown in Figure 4a. The thickness of the reshaping fill layer varies, based on the closure design to achieve the desired landform shape (see Figure 4b). Due to the variability of tailings thickness, in particular areas of deep tailings, and corresponding cap fill thickness, large differential settlements are expected to occur following closure activities.



(a) (b)

Figure 4 (a) Tailings storage facility thickness; (b) Design cap fill thickness

5 Geotechnical model

5.1 Material characterisation

A fieldwork and sampling program was conducted on the tailings beach to characterise the tailings' physical properties and provide input parameters for the consolidation model. The fieldwork program consisted of three piezocone penetrometer tests (CPTu) on the tailings beach adjacent to the embankment crest, with collection of Shelby tube and bag samples at depths ranging from surface level to 8 m. The laboratory program comprised particle size distribution, specific gravity, Atterberg limits, and Rowe cell and oedometric compression testing.

Test results were compared with the ICOLD (2023) classification framework with the following acronyms: coarse tailings (CT), hard rock tailings (HRT), altered rock tailings (ART), fine tailings (FT) and ultra-fine tailings (UFT). The classifications are detailed in the following sections.

5.1.1 Physical characterisation

Wet sieve gradation testing and Atterberg limits were completed on the bulk tailings samples taken during the geotechnical investigation. The gradation and index tests are shown in Figures 5 and 6. The characterisation tests indicate that the tailings are silts and clays with sand. The plasticity ranges from 12 to 37%, typical of medium- to high-plastic clays and silts. The gradation and index testing indicates that tailings are classified as altered FT to UFT, with the occasional grading containing a higher sand content.

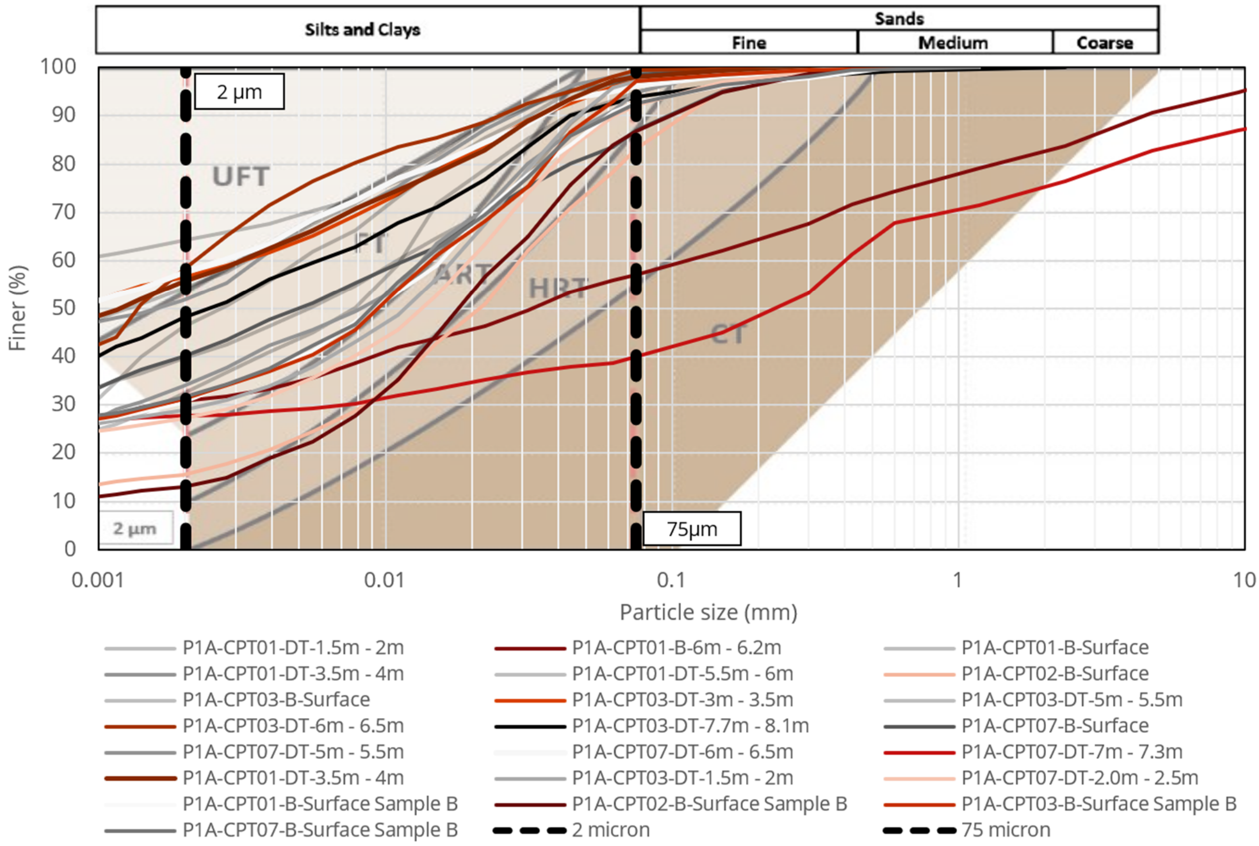


Figure 5 Tailings particle size distribution compared with the International Commission on Large Dams classification system (ICOLD 2021)

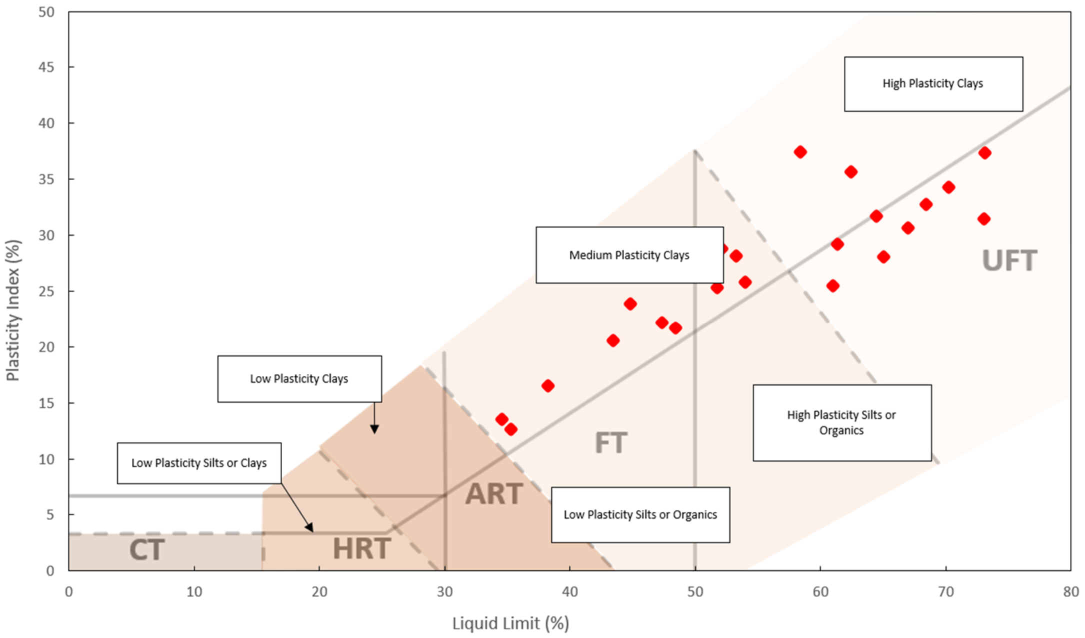


Figure 6 **Plasticity chart compared with the International Commission on Large Dams classification system (ICOLD 2021)**

The solids content of the tailings was determined from the moisture content testing through a simple relationship between moisture content and solids content. The solids content ranged from 51 to 81%, averaging 59%. The specific gravity of the three samples was determined, with the average being 3.0.

5.1.2 *Consolidation tests*

Oedometric compression and Rowe cell testing were completed on reconstituted samples from the geotechnical investigation. Four oedometric compression (AS1289.6.6.1) and three Rowe cell tests were completed on reconstituted samples. The hydraulic conductivity of the tailings measured from back-calculated consolidation is shown in Figure 7 and confirms the behaviour of FT to UFT.

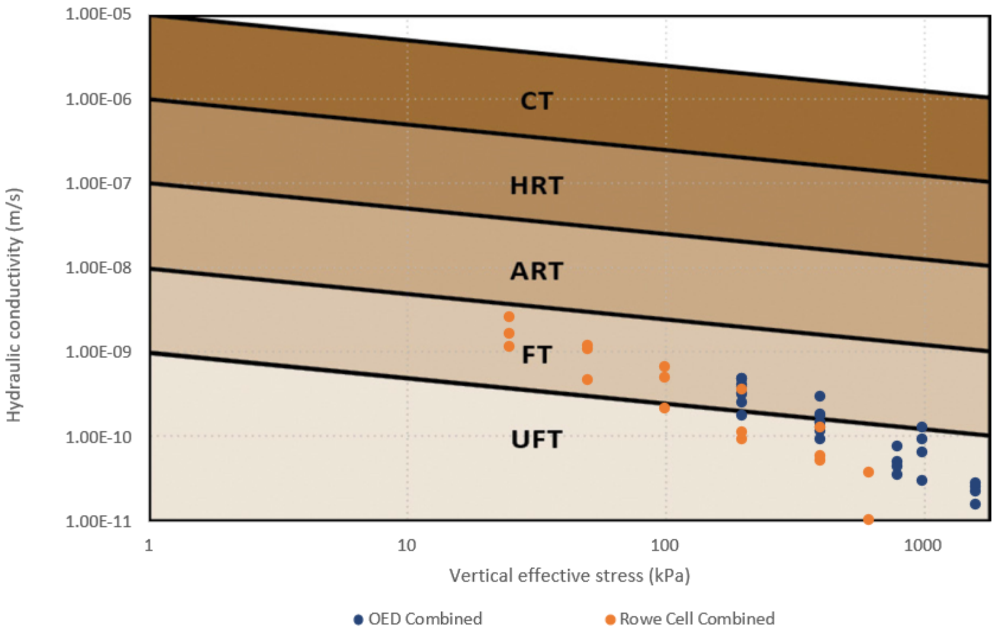


Figure 7 **Tailings hydraulic conductivity compared with the International Commission on Large Dams classification system (ICOLD 2021)**

5.2 Model configuration

Due to how the tailings beach was formed (i.e. deposited as a slurry in thick layers of high void ratios susceptible to large vertical displacements), conventional small-strain consolidation theory, which assumes that hydraulic conductivity and compressibility remain constant during consolidation, becomes less reliable for this type of material. As such, the consolidation assessment of the studied TSF tailings beach was undertaken using non-linear 1D large strain consolidation theory, which considers the non-linear relationship between vertical effective stress (σ'_v), the void ratio (e) and hydraulic conductivity (k). This approach is recommended by Fourie et al. (2022) for tailings slurry typically deposited in an under-consolidated condition.

The theoretical relationship between the vertical effective stress (σ'_v), the void ratio (e) and hydraulic conductivity (k) is expressed by the following equations, where A, B, C and D are empirical constants derived from testing. The original theory was postulated by Gibson et al. (1967). The following relationships are adopted:

$$e = A\,\sigma'^{B}_{v} \tag{1}$$

$$k = C\,e^{D} \tag{2}$$

The relationships between effective stress, void ratio and hydraulic conductivity were obtained from the consolidation testing (oedometer and Rowe cell testing) to approximate the coefficients in Equations 1 and 2. The numerical regression for the relationship between effective stress and void ratio to fit the A and B coefficients in Equation (1) is presented in Figure 8. The numerical regression for the relationship between hydraulic conductivity and void ratio to fit the C and D coefficients in Equation (2) is presented in Figure 9. Oedometer tests are represented as dots, and Rowe cell tests as crosses. Due to the testing limitations of the oedometer test, the samples had to be prepared at the liquid limit to test inside the oedometer apparatus. As a result, the initial portion (i.e. vertical effective stress less than 40 kPa) of the compressibility plot from Rowe cell tests was adopted for model calibration. A summary of the fitted Gibson parameters is shown in Table 1.

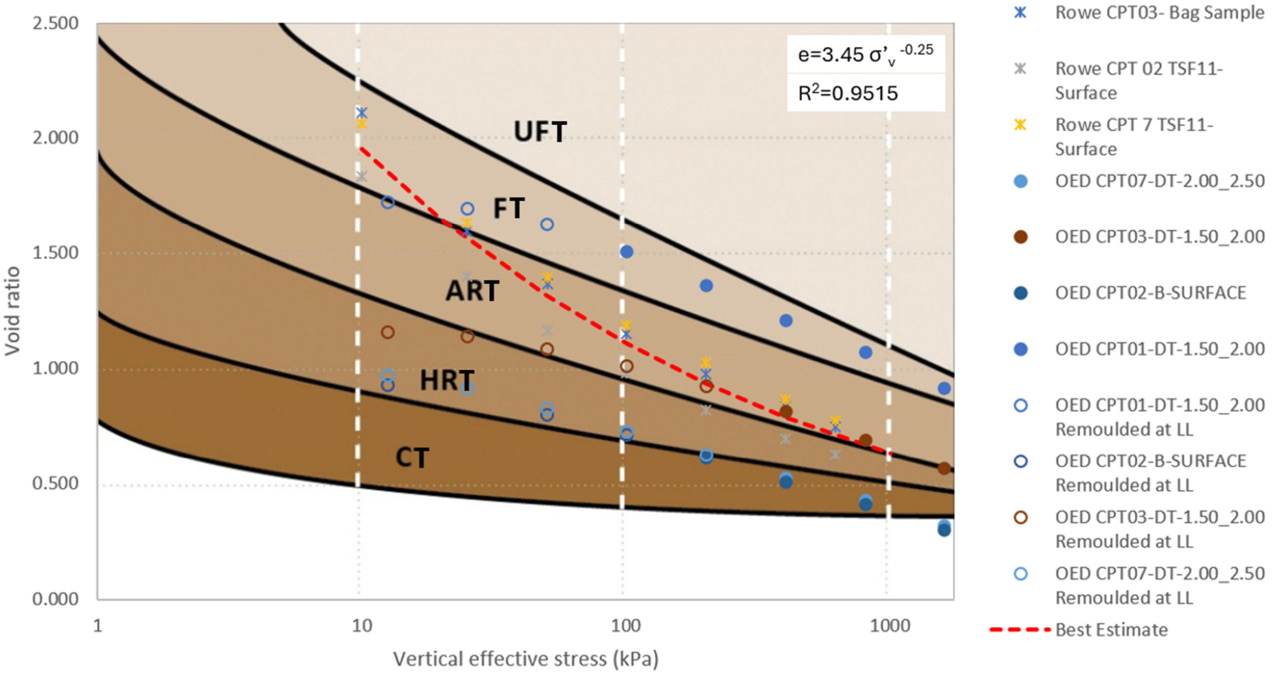


Figure 8 Tailings compressibility compared with the International Commission on Large Dams classification system (ICOLD 2023)

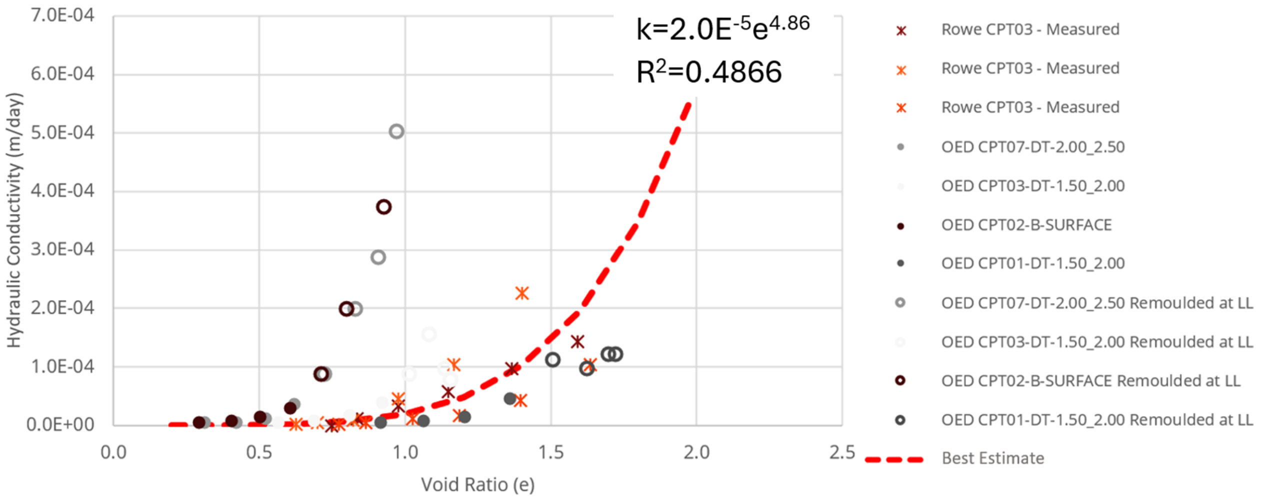


Figure 9 Hydraulic conductivity change with void ratio changes

Table 1 Summary of consolidation modelling parameters

Specific gravity (Gs)	Solids content (%)	A	B	C	D
3.0	59	3.45	–0.25	2.0E-5	4.86

6 Surveillance program

The study considered existing surveillance data to carry out the performance-based design and performance verification. A historic lidar survey of the studied TSF and a nearby similar TSF from 2013 to the present, typically at a quarterly frequency, and settlement plate readings installed on the tailings surface from a recent capping trial on the studied TSF, were available. The following sections present how the surveillance information was used to validate the model.

7 Performance verification

A series of performance verification cases were undertaken using site surveillance data to validate the model against the performance objectives. The key inputs into the FSCA consolidation model are the tailings thickness and loading (capping material). To ensure the reliability of the comparison between the model and the surveillance information, the model and survey points compared areas of equal tailings thickness. Settlement is defined herein as the difference between the initial tailings thickness and the tailings thickness at any point in time.

7.1.1 Rowe cell testing

The first verification was a simulation of a Rowe cell test completed as part of the geotechnical investigation. The FSCA model was prepared using the loading increments, sample thickness and solid content as per the Rowe cell test and the best estimate consolidation parameters in Table 1. The FSCA consolidation model provided a good match with the Rowe cell results, as shown in Figure 10. The model did not predict the exact values from the Rowe cell test as the consolidation parameters adopted for the model are the best estimates from all of the Rowe cell tests.

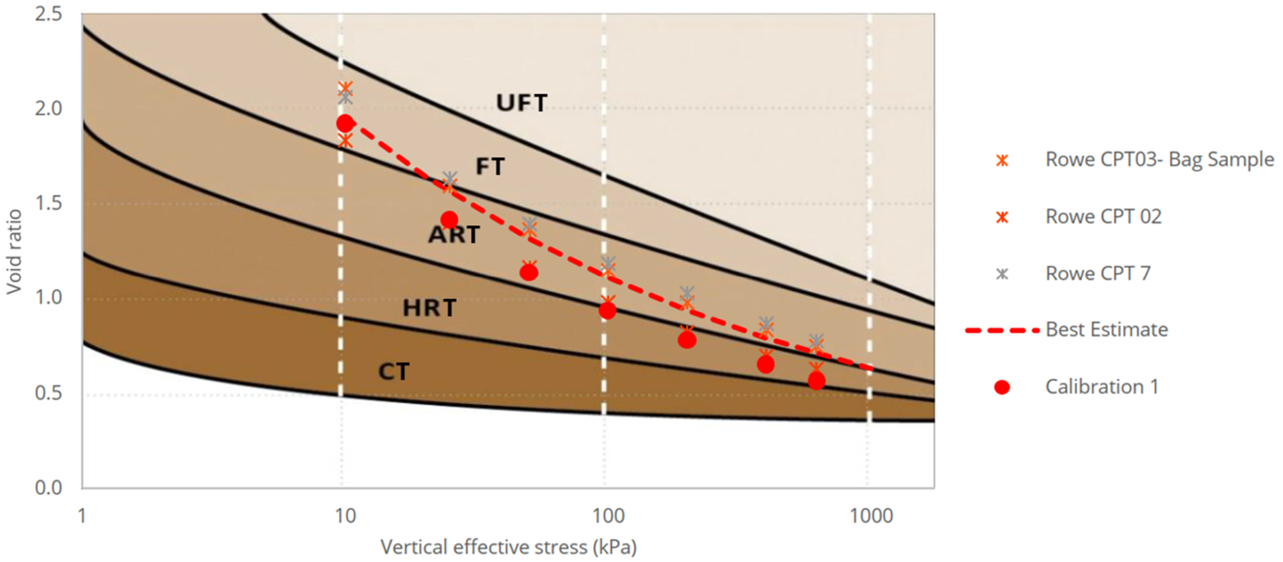


Figure 10 Verification 1 showing the consolidation model against Rowe cell data

7.1.2 Performance of modelling historical survey data for a similar tailings storage facility

The second validation aimed to verify the performance of the actual observed tailings consolidation against the model forecast by comparing modelled data against the historical lidar survey. The verification was completed for a nearby similar TSF which ceased deposition in late 2008 and commenced closure in 2021. Tailings thickness was inferred from historic CPTu testing. Using site imagery, initial tailings elevations were inferred from field observations on the upstream embankment slope. The FSCA consolidation model considered both before closure and following placement of the closure capping layer. The FSCA consolidation model successfully predicted the actual observed settlements for both the pre-closure and post-closure stages, as shown in Figures 11 and 12.

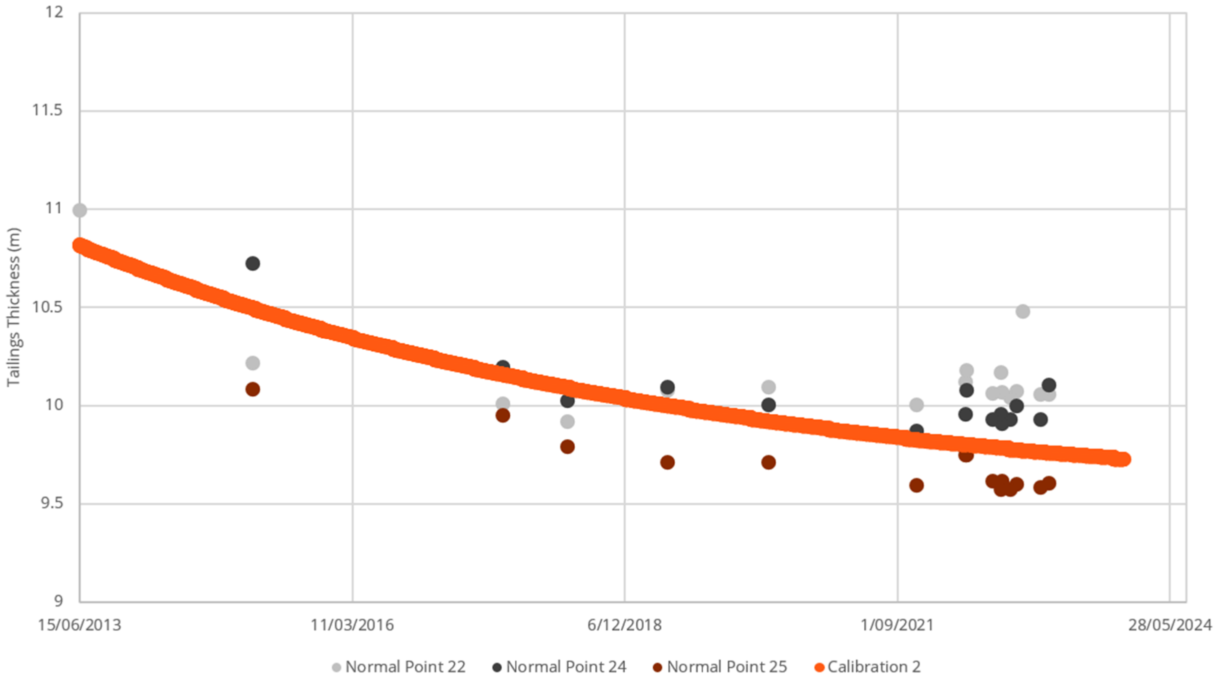


Figure 11 Second validation showing the consolidation model pre-closure against tailings storage facility historical survey data

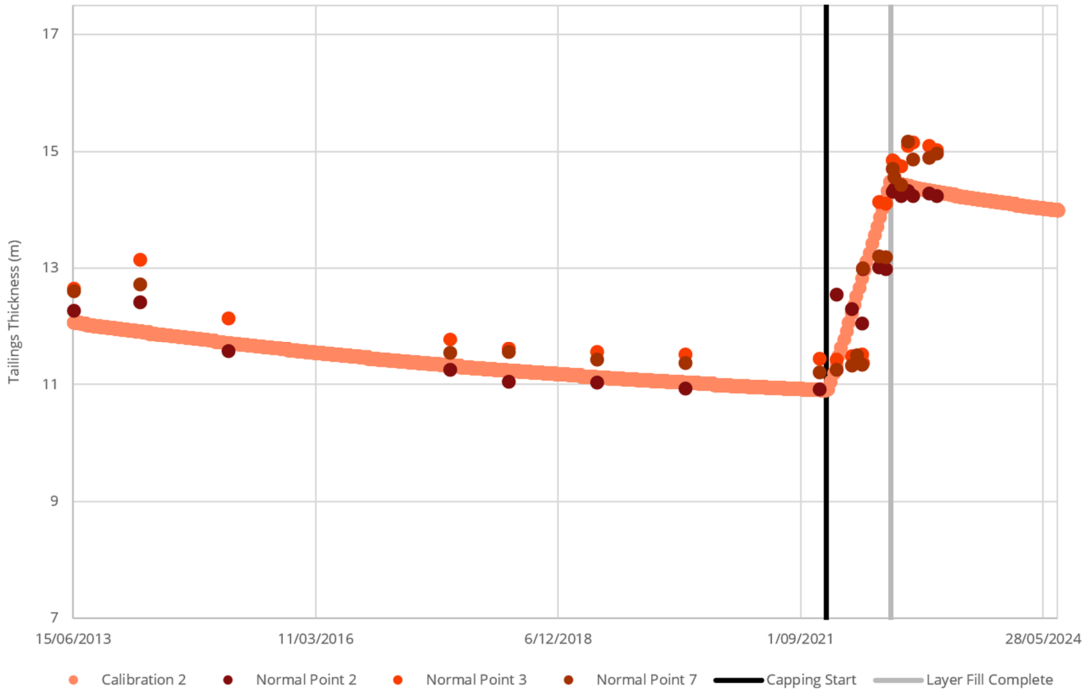


Figure 12 Second validation showing the consolidation model pre-, during and after closure against tailings storage facility historic survey data and time for placement of the capping layer

7.1.3 Performance of modelling historical survey data for the studied tailings storage facility

The third verification simulates the consolidation of the studied TSF from 2019 to 2022 and compares it with the historical survey. The studied TSF initially ceased deposition in October 2019 and restarted deposition in September 2020. It continued for approximately one year, with the final deposition ending in September 2021. The FSCA consolidation model was set up to simulate the initial settling period from October 2019 to September 2020, redeposition from September 2020 to September 2021 and, finally, the most recent survey date (December 2022). The FSCA consolidation model successfully predicted the actual observed settlements of the studied TSF (see the results in Figure 13).

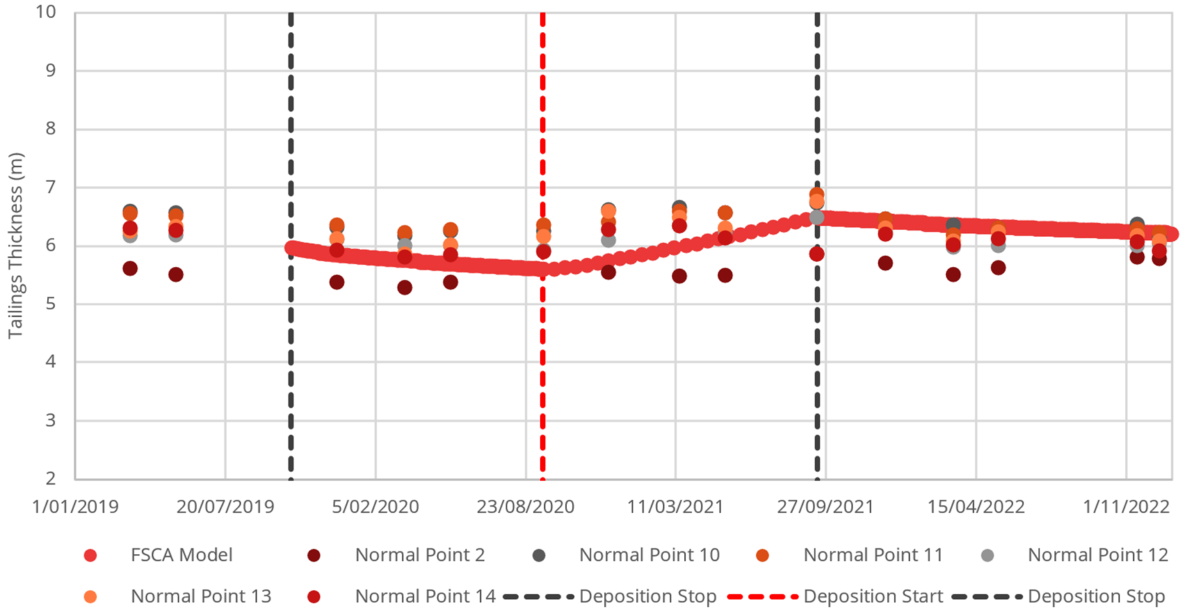


Figure 13 Third validation showing the consolidation model against tailings storage facility historical survey data

7.1.4 Performance of modelling a capping trial at the site

The fourth validation simulated the consolidation following a TSF capping trial completed in 2020 within the studied TSF adjacent to the western embankment. The trial consisted of placing fill material onto the tailings beach via truck and shovel to assess the performance of the tailings beach in terms of geotechnical stability. Part of the trial included installing settlement plates to monitor and record settlements during and after the trial. Refer to Han et al. (2023) for the trial details. Tailings and capping thickness were determined at settlement plate locations and compared against settlement plate readings. Loading was applied to the model based on the trial cap thickness and a unit weight applicable to the fill material. Figure 14 shows a good match between the consolidation model and the settlement observed during the TSF capping trial, indicating that the FSCA model successfully simulates observed settlements.

As part of the TSF capping trial, a consolidation model using Optum G2 (Krabbenhoft et al. 2021) was undertaken by Han et al. (2023) to assess the expected short-term settlements from the placement of the capping material. The Optum G2 model is presented in Figure 14 as well, and the settlements predicted using the Optum G2 (i.e. small-strain consolidation theory) were consistent with measured data for small settlements becoming less accurate and reliable at large settlements, whereas the FSCA model (i.e. large strain consolidation theory) better predicted the larger settlements. The Optum model did not consider creep settlement, which might explain some of the differences. However, it offers the advantage of 2D modelling and allows the assessment of stress/strain compatibility (i.e. potential arching effects). This mechanism is a limitation of the models presented in this study and is not replicated by the FSCA 1D modelling.

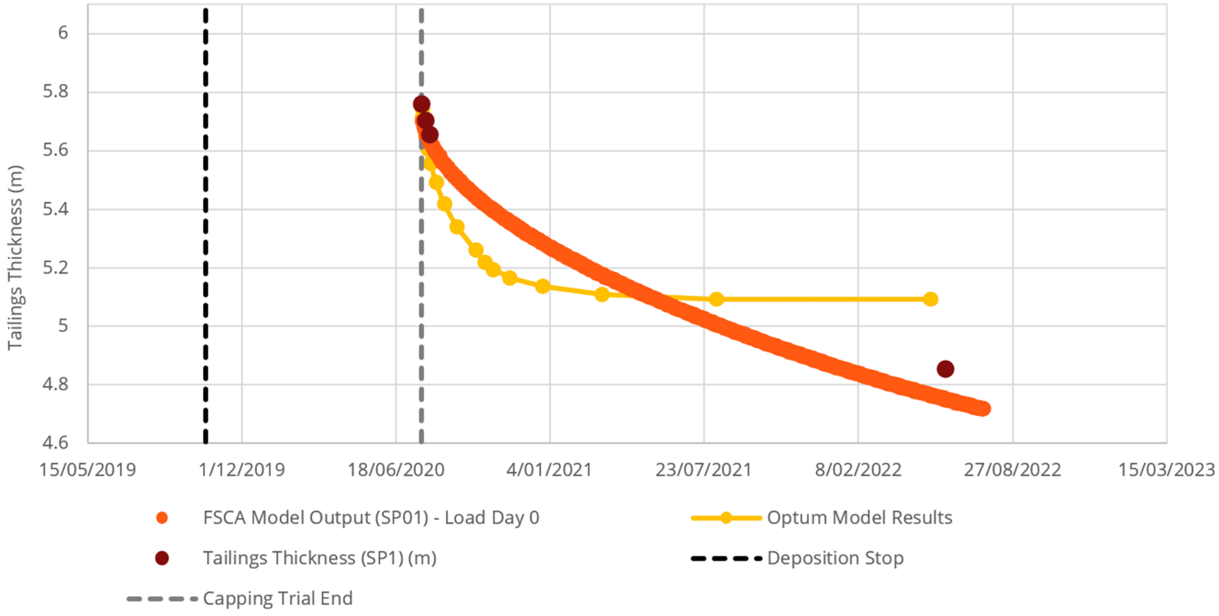


Figure 14 Fourth validation showing consolidation models against the TSF capping trial

8 Model prediction

Based on the historical survey and closure design, the consolidation modelling for the studied TSF was undertaken using a range of tailings depth and capping fill thickness combinations. Each model was run until a maximum of 0.5 m incremental settlement was achieved (i.e. 80% degree of consolidation) as per defined performance objectives. The predicted settlements from the consolidation modelling are provided in Table 2. The duration needed to achieve the maximum 0.5 m incremental settlement, which can be used to inform construction sequencing, is provided in Table 3. A settlement heatmap of the facility showing settlements at 80% degree of consolidation is shown in Figure 15.

Table 2 Predicted settlements at 80% degree of consolidation

Tailings thickness (m)	Predicted settlement (m)			
	1 m capping	2 m capping	3 m capping	4 m capping
1	0.18	0.24	0.21	0.29
5	1.07	1.29	1.42	1.53
10	2.44	2.77	3.00	3.17
15	3.98	4.39	4.68	4.90
20	5.63	6.09	6.44	6.71
25	7.36	7.87	8.26	8.56

Table 3 Predicted durations to 0.5 m incremental settlement (80% degree of consolidation)

Tailings thickness (m)	Duration to maximum 0.5 m incremental settlement (80% degree of consolidation) (years)			
	1 m capping	2 m capping	3 m capping	4 m capping
1	0.12	0.13	0.136	0.14
5	1.75	2.34	2.61	2.78
10	8.46	9.96	10.8	11.3
15	20.81	23.5	25.3	26.4
20	37.04	41.3	44.2	46.3
25	56.2	62.3	66.6	74.9

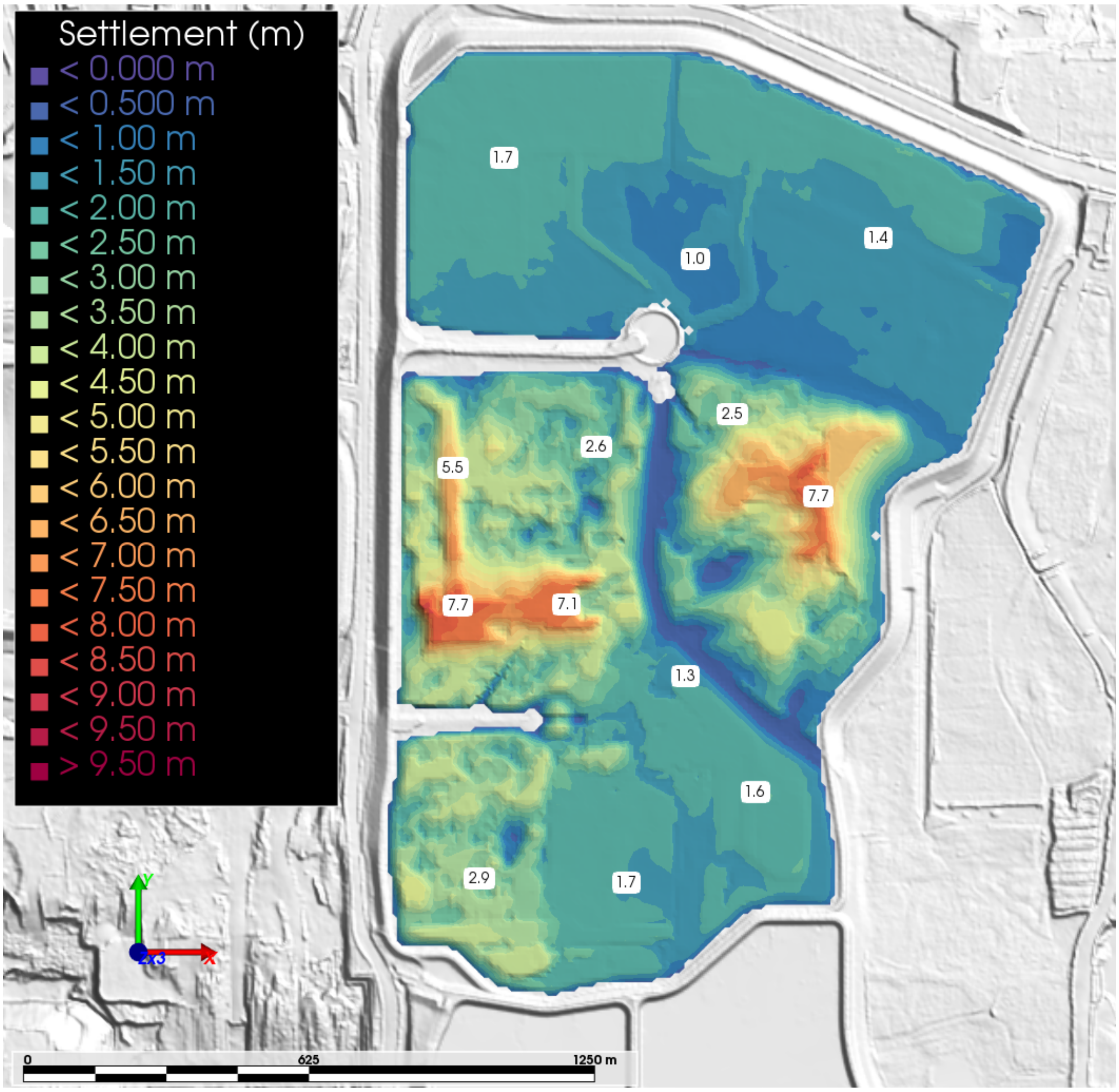


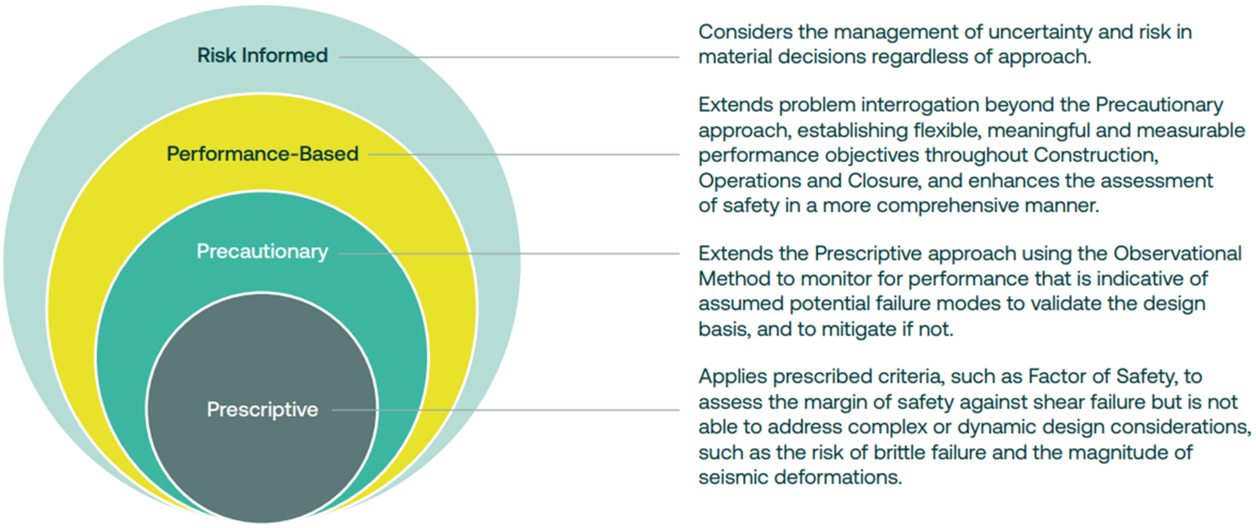
Figure 15 Heatmap showing predicted settlement values for 80% consolidation

9 Analysis and prediction of performance outcomes

The performance verification demonstrated acceptable consistency between the predicted settlement of the tailings beach and the actual observed settlement, based on the surveillance data. The ongoing collection of surveillance data through closure and post-closure and the validation of the consolidation model are vital components of the performance-based design approach to ensure the predicted performance outcomes are achieved. The following section proposes and describes additional measures to enhance the quality and accuracy of the model.

10 Path forward

The path forward for this study is to elevate the design approach from performance-based to risk-informed (see Figure 16). We expect to achieve this by assessing the variabilities of the consolidation parameters.



Considers the management of uncertainty and risk in material decisions regardless of approach.

Extends problem interrogation beyond the Precautionary approach, establishing flexible, meaningful and measurable performance objectives throughout Construction, Operations and Closure, and enhances the assessment of safety in a more comprehensive manner.

Extends the Prescriptive approach using the Observational Method to monitor for performance that is indicative of assumed potential failure modes to validate the design basis, and to mitigate if not.

Applies prescribed criteria, such as Factor of Safety, to assess the margin of safety against shear failure but is not able to address complex or dynamic design considerations, such as the risk of brittle failure and the magnitude of seismic deformations.

Figure 16 Management of uncertainty in design approaches (ICMM 2021)

To achieve risk-informed management it is recommended that the variability of the consolidation model be improved in future study phases by inferring parameters and performance using, for example, a Bayesian approach. A Bayesian analysis provides an estimation of the more likely consolidation outcome given three elements: (1) a model, (2) the data input from laboratory and field observations to the model, and (3) any prior information on the parameter values. Such approaches have been completed successfully by Llano & Contreras (2023) and Llano et al. (2022).

11 Conclusion

This paper presents a performance-based approach to predict and validate the settlement of an FT TSF and inform closure design. Performance objectives were chosen based on an acceptable incremental settlement which the authors believe would limit the need for ongoing maintenance of the closure landform due to settlement. The geotechnical model was developed using non-linear 1D large strain consolidation theory. Large strain theory is considered good practice for thick slurry deposits of high void ratios with consolidation parameters determined from material characterisation testing. The geotechnical model underwent verification by simulating various scenarios and field trials, and comparing them against the existing site surveillance data, including the lidar survey and settlement plates. The performance verification demonstrated consistency between the predicted and measured settlements, providing confidence in subsequent closure design inputs.

The assessment outcomes indicated settlement between 0.18 m for 1 m-thick tailings with a 1 m-thick cap fill and 8.56 m for 25 m-thick tailings with a 4 m-thick cap fill. Two low spots that will likely be developed in the area of deep tailings will impact the cap's ability to shed water. Predicted durations to achieve an 80% degree of consolidation within the tailing beach are between 0.12 years for 1 m-thick tailings with a 1 m-thick cap fill and 75 years for 25 m-thick tailings with a 4 m-thick cap fill. A large area of the facility will see an 80% degree of consolidation over the construction period, which is typically five years.

The capping process is unlikely to be achieved in a single phase (i.e. construction to the final design levels using the appropriate capping materials) due to the high settlement and settlement durations, particularly in the areas of deep tailings. As such, staging in the closure capping may be necessary. Possible staging may include a topping-up process in the locations of significant settlements to maintain water shedding or placement of additional fill to allow for future settlement in these locations. Additional material means that more load is applied to the tailings. In such cases the modelled predictions need to be revisited to account for the new condition. The current closure design is in the feasibility phase. Future closure design phases will detail how the settlement will be accommodated into the design.

Further work is required to elevate the current model to a risk-informed design, including additional contingency measures from a precautionary approach and further measures to improve performance versus design intent. As recommended by the ICMM (2021), the more defensive layers that are applied to the design, the better risk-informed the approach becomes.

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