Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_153

A pseudo 3D approach to predicting post-closure settlement in a tailings storage facility

Joel Eadie [a,*], Minh Bui [a], Georgia Greening [a]

[a] *ATC Williams, Australia*

Abstract

A key design consideration for tailings storage facility (TSF) rehabilitation is long-term settlement and consolidation. Long-term settlement can alter surface gradients and disrupt post-closure drainage networks. The magnitude of settlement is impacted by a range of factors including age, depth and tailings rate of rise, water management during operations, and foundation drainage conditions.

This paper presents a case study of a consolidation assessment for a TSF including the data used to undertake the assessment, methodology, outcomes and proposed monitoring to calibrate the model. The methodology comprised a staged approach, coupling one-dimensional (1D) consolidation modelling with geospatial analysis of tailings thickness to approximate 3-dimensional (3D) settlement behaviour. This cross-valley TSF was commissioned in around 2000 and has been incrementally raised since then. Several factors are expected to lead to differential settlement across the facility, including the range of tailings depths (from less than 1 m to 70 m), co-disposal of waste rock in tailings at depths up to 20 m, and the presence of a rockfill decant causeway. The range of tailings depths and varying age of tailings present a challenge when assessing the final landform for the facility following settlement.

To quantify settlement, 1D consolidation columns (ranging from 20 m to 70 m) were initially modelled, capturing the rate of rise for the 26 years of operation, and the age of tailings through the modelled profile. Input parameters were derived from site-specific Rowe Cell laboratory testing, with the results benchmarked against literature values for gold tailings. Outputs from the model comprised estimated settlement depth as a function of time based on the range of tailings thickness across the facility. Geospatial analysis was then undertaken to spatially integrate consolidation outputs with the mapped tailings thickness and internal rockfill geometry to predict the settlement depths and generate a final surface representative of conditions post settlement.

This case study reinforces that robust operational record-keeping and early consideration of long-term settlement in landform design are essential to achieving reliable, sustainable post-closure outcomes for TSFs.

Keywords: *consolidation modelling, long-term settlement, landform design*

1 Introduction

Long-term settlement and consolidation is a key consideration for the design, operation and closure of tailings storage facilities (TSFs) as it can alter surface gradients with potential consequences for drainage performance, erosion control and long-term stability of the closure landforms. The prediction of settlement and consolidation is important for informed planning and risk management as regulatory and stakeholder expectations are for no or low maintenance post-closure outcomes.

Assessing settlement is complex due to the nature of tailings deposits. Settlement behaviour is influenced by factors such as tailings thickness, age and rate of rise, operational water management practices, material properties and foundation drainage conditions. These factors often have spatial and temporal variability,

---

[*] Corresponding author. Email address: JoelE@atcwilliams.com.au

particularly in TSFs that have been constructed and raised incrementally over multiple decades. The presence of internal structures or co-disposed materials, such as waste rock or rockfill causeways, further increases the potential for differential settlement and non-uniform deformation of the tailings surface.

The impacts of consolidation are often considered late in the life of the TSF, when closure designs are already constrained and operational records may not fully capture operational deposition. This highlights the value of operational record-keeping and early consideration of long-term settlement for TSFs with variable deposition strategies, tailings properties and tailings thickness.

This paper presents a case study of a TSF commissioned around the year 2000 and progressively raised over approximately 26 years of operation. The TSF contains varying tailings thickness – from less than 1 m to approximately 70 m – and includes zones of waste rock co-disposed within the tailings and a rockfill decant causeway.

The objective of this paper is to demonstrate a practical, pseudo 3-dimensional (3D) approach for evaluating long-term consolidation settlement across a TSF with significant variability in tailings thickness and material composition. The approach combines one-dimensional (1D) consolidation modelling with spatial mapping of tailings and internal rockfill structures to illustrate how settlement predictions can be integrated into spatial analyses to inform post-closure surface and drainage assessments. The outcomes of the case study provide insight into the importance of early and data-driven consideration of settlement processes in supporting reliable and sustainable TSF closure designs.

2 Tailings storage facility

2.1 Description and historical development

The TSF was commissioned in around 2000 and has been developed progressively through a series of staged embankment raises. The TSF is located within a creek valley and comprises the following 3 embankments that provide storage capacity of approximately 61 Mm^3 and a surface area of approximately 1.22 km^2 at full supply level:

- Northern Embankment, which forms the primary embankment around the northern and eastern extents, with a maximum height of approximately 70 m
- Western Saddle Embankment, which joins the Northern Embankment
- Southern Embankment.

Throughout the operational phase of the TSF, the rate of rise has varied, impacted by internal geometry and tailings production rates. The natural pre-mining topography within the TSF footprint is highly undulating. Consequently, tailings thickness varies from less than 1 m around the outer edges, to approximately 70 m in the centre of the TSF. The cumulative tailings thickness since commissioning is shown in Figure 1.

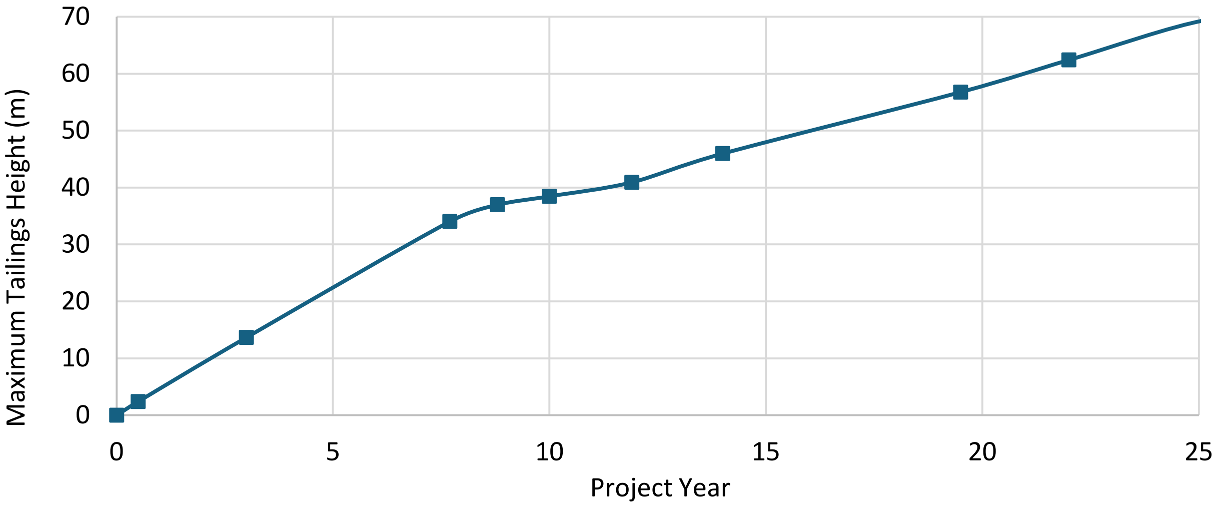


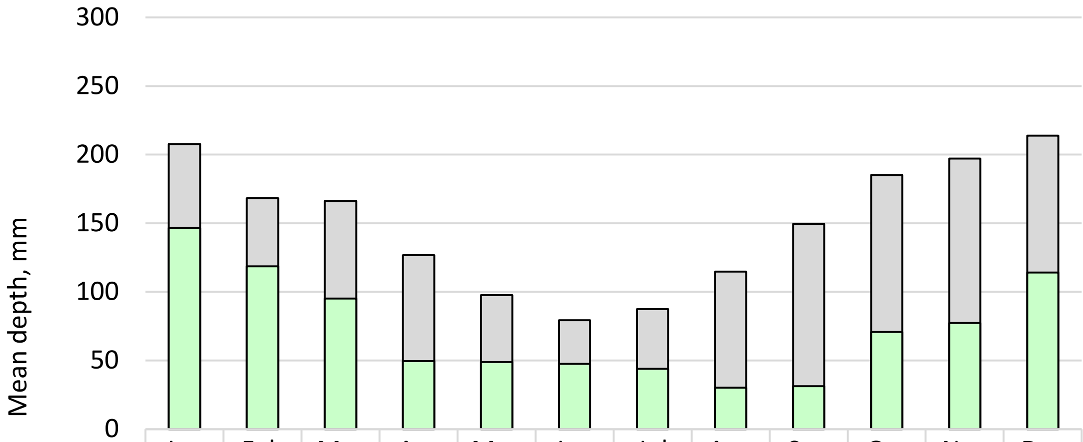
Figure 1 Tailings depth since 2000

The closure intent is to achieve a stable landform which is not impacted by long-term consolidation settlement and requires minimal post-closure maintenance. The general closure strategy is to create a free-draining landform comprising low gradient rehabilitated surfaces directing run-off to a defined discharge channel. A cover system will be constructed over the tailings beach to support closure objectives. The TSF embankment does not require modification, being constructed out of material which will meet closure performance objectives.

2.2 Climate

The TSF is located within a sub-tropical climate, characterised by hot, humid summers and mild, predominantly dry winters. Mean annual rainfall is approximately 874 mm, with a distinct wet season occurring between October and March that accounts for approximately 71% of total annual rainfall. Mean annual potential evaporation is approximately 1,857 mm, resulting in an evaporation to rainfall ratio of approximately 2:1.

The net moisture deficit influences tailings behaviour, particularly with respect to near-surface drying, seasonal desiccation and consolidation processes. The mean monthly distributions of rainfall and evaporation are illustrated in Figure 2.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation, mm	207.7	168.2	166.2	126.8	97.5	79.3	87.4	114.8	149.6	185.1	197.2	213.8
Rainfall, mm	146.5	118.7	95.2	49.5	48.8	47.4	44	30.2	31.2	70.8	77.3	114

Figure 2 Mean monthly rainfall and evaporation

3 Tailings geotechnical characteristics

The assessment was aided by 20 years of geotechnical studies, including field investigations, laboratory testing and operational observations. A summary of the tailings characteristics for the case study is provided in Table 1.

Table 1 Summary of tailings behaviour

Tailings characteristic	Description
Geotechnical classification	SANDY SILT/SILTY SAND (SM-ML), Non-plastic
Particle density	2.6–2.7 t/m^3
Particle size distribution	P_{80} 106 µm
Atterberg limits	Non-plastic
Permeability	10^{-6} to 10^{-8} m/s, kx/ky ratio = 0.1
Tailings density (undrained breaching or low-permeability foundation)	~1.2 t/m^3
Tailings density (drained beaching or dried foundation)	~1.6 t/m^3
Rate of rise	~2.5 m/year (mean); overall mean bulk density ~1.6 t/m^3
Typical beach slopes (subject to sub-aerial deposition methods)	0.5–1.2%

The tailings is generally classified as sandy silts to silty sands (SM-ML), with a fines content between 28% and 60%, and is non-plastic. Characterisation of the in situ state was informed by piezocone penetration testing (CPTu), which provided continuous profiles of tailings variability and consolidation condition. Laboratory Rowe Cell consolidation testing was undertaken on representative fine and coarse tailings samples to determine compressibility and consolidation parameters, including coefficients of consolidation and compression indices.

4 Literature review

A literature review was undertaken to benchmark site-specific tailings characteristics and consolidation behaviour against published gold case studies. Of particular note, there is very little literature regarding settlement and consolidation estimates for TSFs, particularly with observations over long time periods. Notwithstanding, available literature comprising both laboratory-based consolidation studies and field-scale settlement assessments from comparable TSFs is summarised below.

Key references informing consolidation behaviour and modelling approaches include McDonald and Lane (2010), Fredlund et al. (2013), Stone et al. (1994) and Tripathi et al. (2020).

A comparison of tailings properties derived from this case study and selected published case studies is summarised in Table 2. The comparison includes particle size distribution, initial void ratio at the time of deposition, plasticity, dry density and permeability ranges. Predicted settlement magnitudes from published consolidation assessments for gold tailings are summarised in Table 3.

Table 2 Summary of tailings characteristics of selected published case studies

Description	Unit	Case study (subject of this paper)	Gold case study 1	Gold case study 2	Gold case study 3	Gold case study 4
Tailings commodity	–	Gold	Gold	Inferred gold	Gold	Gold
Solids content	%	~50%	~43%	–	–	38.0% initial, 64.5% average
Specific gravity	t/m³	2.6-2.7	–	2.74	–	–
Soil classification	–	Silty SAND/ Sandy SILT, P_{80} 106 µm	Sandy SILT, P_{80} 75 µm	SILT with Sand	Sandy SILT/CLAY $P_{80–100}$ passing No. 200 sieve	Silty SAND/ Sandy SILT
Initial void ratio, e_{init}	–	0.99	3.00	1.52	~3.00–4.00	~1.60–2.30
Plasticity	–	Non-plastic	–	Non-plastic	–	–
Dry density	t/m³	1.2–1.6	1.0–1.6	1.16–1.46	–	–
Vertical permeability	m/s	1×10^{-6} to 1×10^{-8}	1×10^{-8}	1.56×10^{-6} to 4.06×10^{-7}	1×10^{-7} to 1×10^{-8}	1×10^{-9} to 4×10^{-8}

Source: Gold Case Study 1 (McDonald and Lane, 2010), Gold Case Study 2 (Tripathi et al. 2020), Gold Case Study 3 (Fredlund et al. 2013), Gold Case Study 4 (Stone et al. 1994).

Table 3 Summary of predicted settlement of selected published case studies

Published case study	Total tailings thickness (m)	Predicted consolidation settlement (m)	Settlement as a percentage of tailings thickness (%)	Rate of rise (m/yr)	Years active	Climate
Gold case study 1	48.0	~4.0 (actual) ~7.1 (predicted)	8.3	25.0	~2.0	Hot, desert climate, characterised by hot and humid conditions with little rainfall
Gold case study 2	16.7–170.1	2.0–8.9	12.0–5.2	25.9	6.6	–
Gold case study 3	29.5–30.0	1.7–2.5	5.7–8.5	Unknown; assessment was undertaken after deposition		Mediterranean climate with distinct wet and dry seasons
Gold case study 4	27.0	5.4	20.0	4.6	4.3	Mediterranean style (hot, dry summers and cold, wet winters)

Source: Published Case Study 1 (McDonald and Lane, 2010), Published Case Study 2 (Tripathi et al. 2020), Published Case Study 3 (Fredlund et al. 2013), Published Case Study 4 (Stone et al. 1994).

Figures 3 and 4 compare the relationship between effective stress, void ratio and permeability against published gold tailings behaviour. The fine tailings from this case study generally plots within the median range of published gold tailings data, indicating comparable compressibility (Figure 3) and permeability behaviour (Figure 4). Coarser tailings fractions exhibit lower compressibility (Figure 3) and higher permeability (Figure 4) than both the fine tailings and majority of the published gold tailings behaviour.

The literature review indicates that the geotechnical properties adopted for the fine tailings are generally consistent with published gold tailings behaviour and are considered suitable for use in initial consolidation modelling.

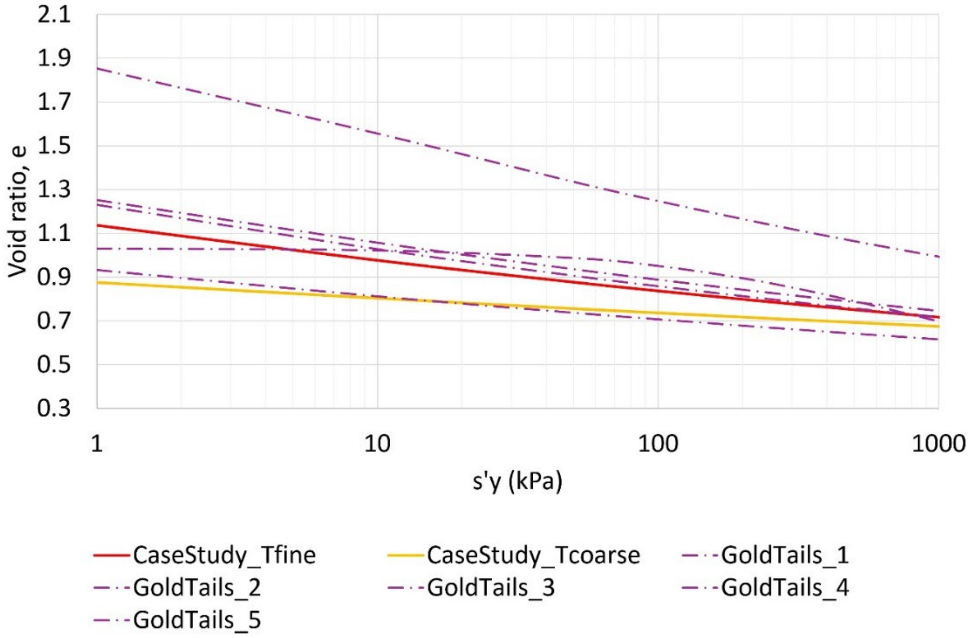


Figure 3 Tailings characteristics comparison – effective stress versus void ratio

Source: GoldTails_1 (Tripathi et al. 2020), GoldTails_2, GoldTails_3 & GoldTails_4 (Priestley, 2011), GoldTails_5 (Bonnin et al. 2019))

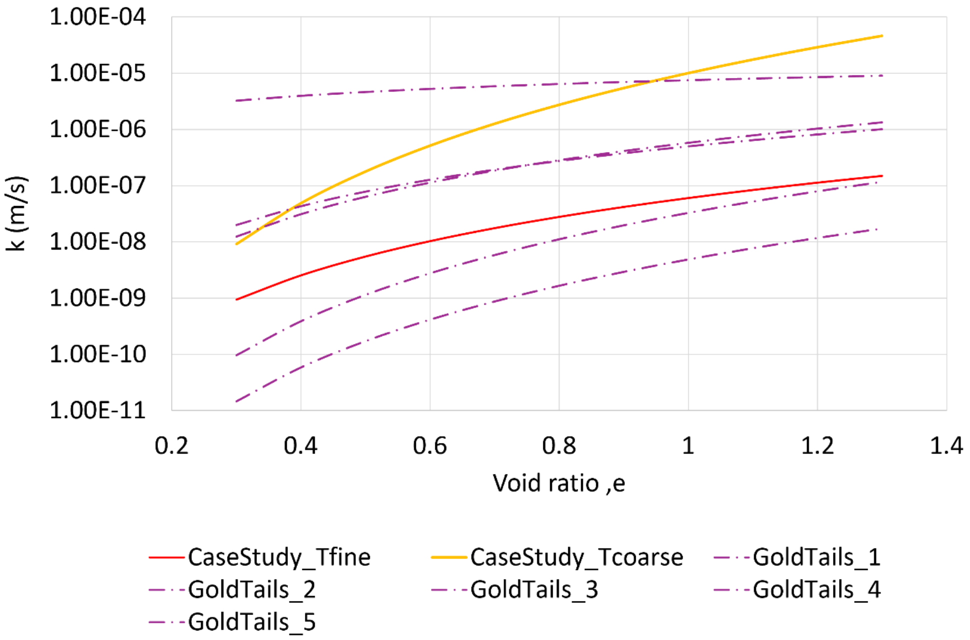


Figure 4 Tailings characteristics comparison – void ratio versus vertical permeability

Source: GoldTails_1 (Tripathi et al. 2020), GoldTails_2, GoldTails_3 & GoldTails_4 (Priestley, 2011), GoldTails_5 (Bonnin et al. 2019)

5 Consolidation modelling

5.1 Overview

Consolidation settlement is the time-dependent compression of saturated fine-grained soils resulting from dissipation of excess porewater pressures under applied loading, including self-weight loading. As excess pore pressures dissipate, effective stress within the tailings increases, leading to volumetric strain and surface settlement.

The consolidation estimate needed to consider the range of tailings thickness, variability in tailings age and presence of rockfill zones within the tailings. Therefore, a pseudo 3D approach was adopted, whereby consolidation behaviour was simulated using a series of representative 1D models for the range of tailings thickness observed, and coupled with a geospatial analysis to apply the 1D estimates to the 3D final landform model.

Consolidation analyses were undertaken using the finite element software SIGMA/W (GeoStudio; GeoSlope International Ltd). Initial in situ conditions were established using gravity loading, followed by time-dependent consolidation analyses to estimate settlement magnitude and rate.

5.2 Modelling approach and assumptions

The consolidation modelling was based on the following assumptions and limitations:

- Tailings within each modelled column was assumed to be homogeneous with depth, such that segregation and layering associated with depositional processes are not explicitly represented. While layering may influence local behaviour, this simplification is not considered to have a material effect on the outcomes of the assessment.
- Drainage conditions were represented as 1D vertical flow paths, with lateral and multidirectional drainage mechanisms not explicitly simulated.
- Consolidation parameters were derived from laboratory Rowe Cell testing and considered to represent worst-case conditions within the TSF, through deliberately selecting material close to the decant. The segregation of fine and coarse rejects was not considered.

These assumptions reflect a deliberate balance between modelling complexity and the level of accuracy required to inform long-term settlement and closure drainage assessment.

5.3 Model geometry and staging

A series of 1D consolidation models was developed to represent tailings columns with thickness ranging from 10 m to 70 m, analysed at 10 m vertical intervals. This range captures a spectrum of tailings thicknesses present across the TSF.

Staged tailings deposition was simulated to reflect the historical rate of rise and deposition history of the TSF. Consolidation analyses were progressed to the date of the most recent site survey (March 2025) to approximate current conditions, followed by post-closure simulations extending to 100 years after closure.

5.4 Analysis cases

Two bounding drainage scenarios were assessed to capture the range of plausible foundation and drainage conditions:

- Scenario 1 – very low permeability foundation: Tailings is assumed to be deposited on a very low permeability foundation, with excess porewater pressures dissipating only through upward drainage. This scenario represents a conservative case, permitting the accumulation of excess pore pressures during deposition and slow subsequent consolidation.

- Scenario 2 – drained foundation: Partial drainage is permitted at the base of the tailings profile, with the basal pore pressure boundary condition set to 50% of that assumed in Scenario 1. This scenario represents improved drainage conditions, resulting in reduced excess pore pressures and accelerated consolidation.

5.5 Material parameters

The effective stress parameters adopted for the consolidation modelling are summarised in Table 4. The elastic modulus was varied as a function of effective stress to replicate the non-linear compressibility behaviour observed in laboratory Rowe Cell testing.

Table 4 Consolidation modelling parameters

Material	Initial void ratio, e_{init}	Unit weight (kN/m³)	Effective elastic modulus, E (kPa)	Effective Poisson's ratio	Effective cohesion, c' (kPa)	Effective friction angle, (ϕ) (°)
Fines tailings (varied modulus)	0.95	19.5	Function (Y-effective stress versus effective elastic modulus)	0.25	0	25

5.6 Settlement as a function of tailings depths

The output from modelling undertaken was the expected settlement for tailings depths ranging from 0 m to 70 m. Figures 5 and 6 show most of the settlement occurs in the initial 20–50 years. Minimal settlement occurs between 50 and 100 years. Furthermore, the magnitude and rate of settlement is highly dependent on the drainage conditions within the TSF. A drained foundation results in a higher rate of settlement, with around 90% of consolidation occurring after 20 years. In the case of low-permeability foundations, after 20 years some 55% of the total settlement has occurred, and it takes ~50 years before >90% of the total consolidation has occurred. For drained foundations, the total settlement depth (around 1 m at 70 m tailings depth) is around 40% less than the scenario with low-permeability foundations (1.6 m at 70 m tailings depth).

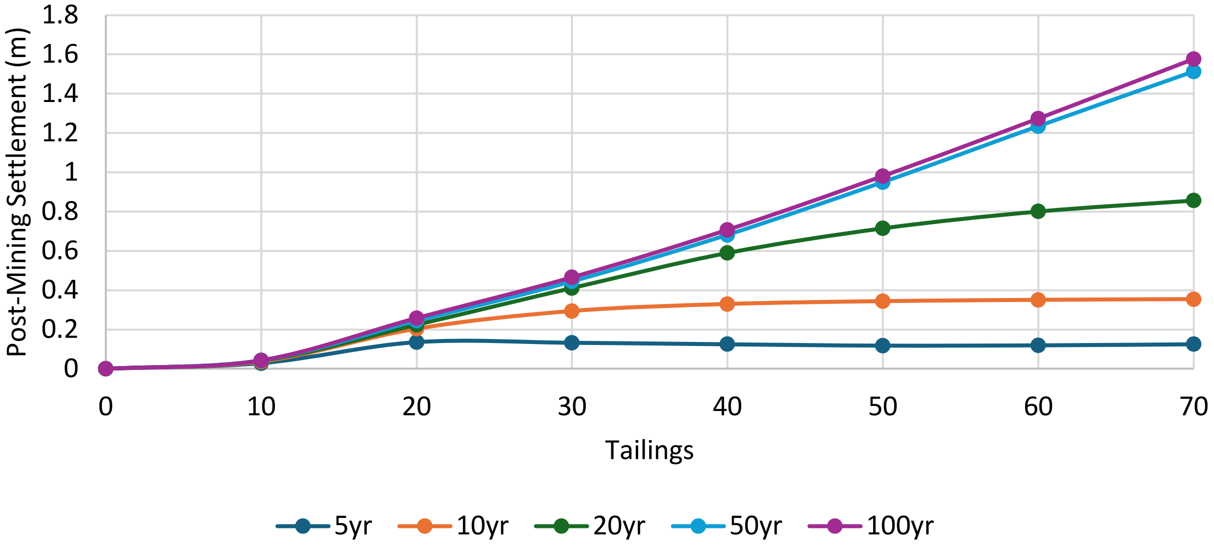


Figure 5 Low-permeability foundation – settlement versus time

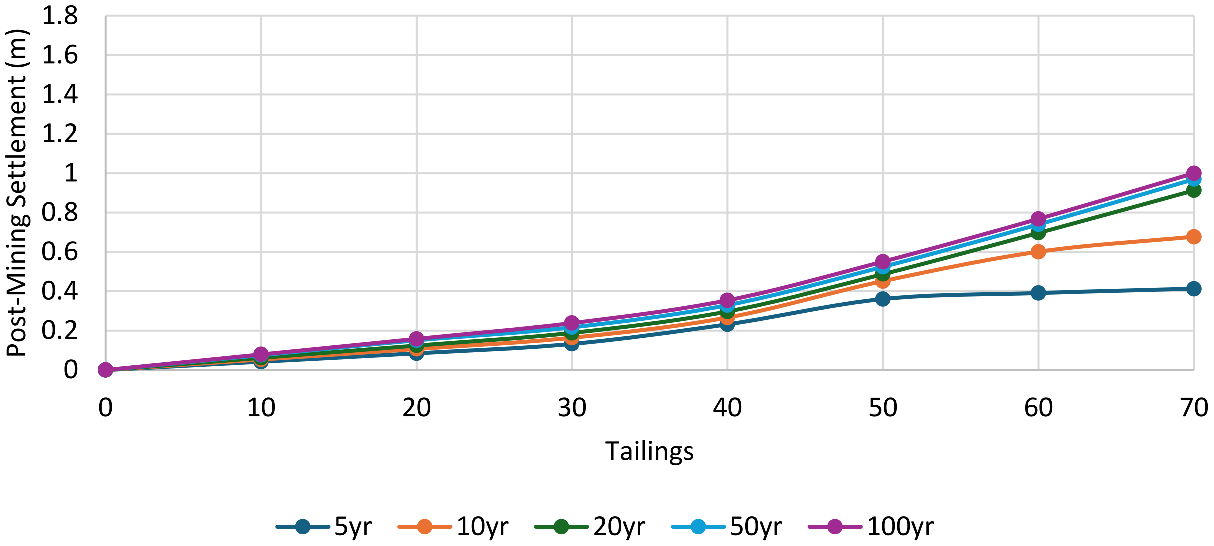


Figure 6 Drained foundation – settlement versus time

6 Geospatial analysis (rockfill mapping)

To quantify differential settlement caused by the range of factors described above, and its implications for the final landform and drainage performance, a geospatial analysis was undertaken to integrate 1D consolidation results with the 3D geometry of the facility.

A series of digital terrain models were developed to represent key structural and depositional components of the TSF. These included:

- the pre-mining natural surface
- the rockfill surfaces, derived from historical surveys which were taken at least annually over ~20 years
- the current facility surface, based on the most recent survey available at the time of the assessment (January 2025)
- the final closure landform, based on the approved rehabilitation design.

Using these surfaces, the spatial distribution of tailings and rockfill thicknesses was mapped throughout the tailings mass. The resulting model was the rock mass 'floating' in the tailings mass as depicted in Figure 7. Figure 8 depicts the depth of tailings in two-dimensional (2D) space.

It is important to note that most of the rockfill was submerged at the time of this case study. Without local knowledge and detailed record-keeping of the facility, the rock mass location and magnitude would be unknown. If comparing the natural surface to the most recent surface, tailings would appear to be 70 m deep and relatively uniform across the facility. When considering the rockfill, the actual tailings depth in areas was reduced to less than 3 m, which has a major impact on the expected consolidation depth in that area.

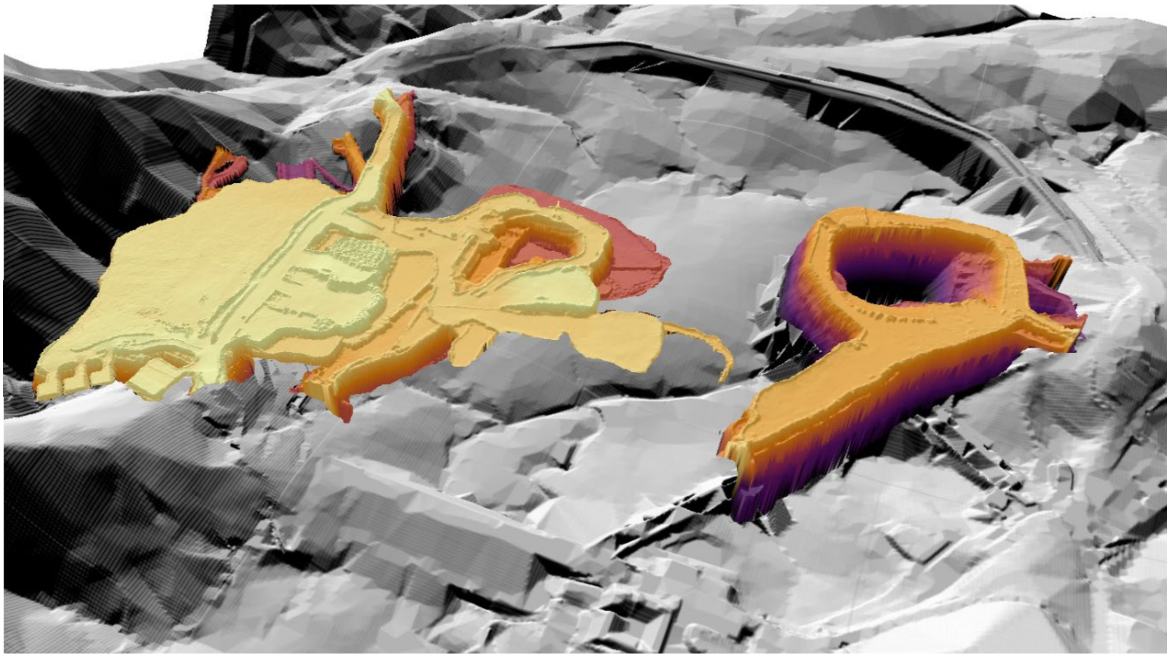


Figure 7 Mapped rock mass, submerged in tailings

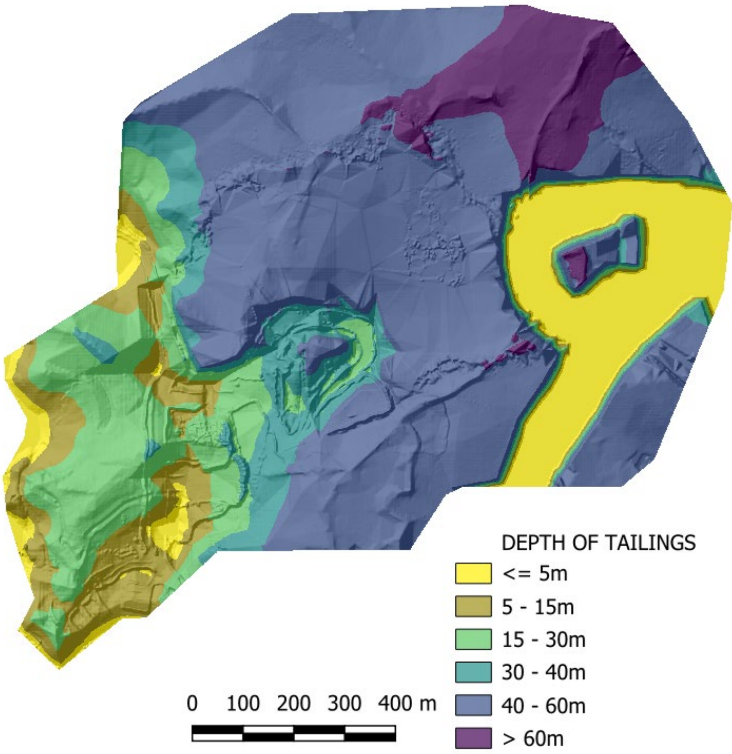


Figure 8 Depth of tailings

7 Predicted long-term settlement

Using the settlement curves generated as discussed in Section 5, and reduced tailings thickness as discussed in Section 6, the settlement was estimated as discrete time periods of 5, 20, 50 and 100 years.

The consolidation modelling and geospatial analysis indicate that both linear and differential settlement will occur across the TSF over the long term, with the magnitude primarily governed by tailings thickness, rockfill presence and post-closure drainage conditions. Predicted settlements across the facility range from negligible in areas where the tailings depth is thin to a maximum of ~1.6 m in the deepest sections of the tailings.

The overall beach geometry is not expected to be materially affected by consolidation settlement. The final rehabilitated beach slopes, predicted to be approximately 0.60% at closure, are expected to flatten marginally to approximately 0.54% over time. This change is not considered sufficient to adversely impact surface drainage performance, and overland flow paths are expected to continue to report to the designated discharge channel.

Localised differential settlement is predicted in areas where thick tailings deposits abut rockfill structures, particularly along the original decant causeway located in the eastern portion of the facility. The decant causeway comprises rockfill over the full height of the TSF, whereas adjacent areas comprise tailings of equivalent thickness. Consolidation analyses indicate that differential settlement of up to approximately 1 m over a horizontal distance of 50 m may occur in these transition zones.

Figures 9 and 10 show 2 localised areas where settlement had the potential to inhibit drainage and cause ponding on the final landform:

- Area 1: located near the centre of the original decant causeway, encompassing approximately 19,200 m². Settlement in this area is predicted to be up to 1.3 m greater than in adjacent sections of the causeway, creating the potential for localised ponding if not addressed.
- Area 2: located immediately east of the decant causeway, encompassing approximately 51,000 m², where settlement may isolate the area from the intended surface drainage network and prevent run-off from reporting to the discharge channel.

Overfilling these areas during closure was the recommended solution to ensure long-term drainage performance.

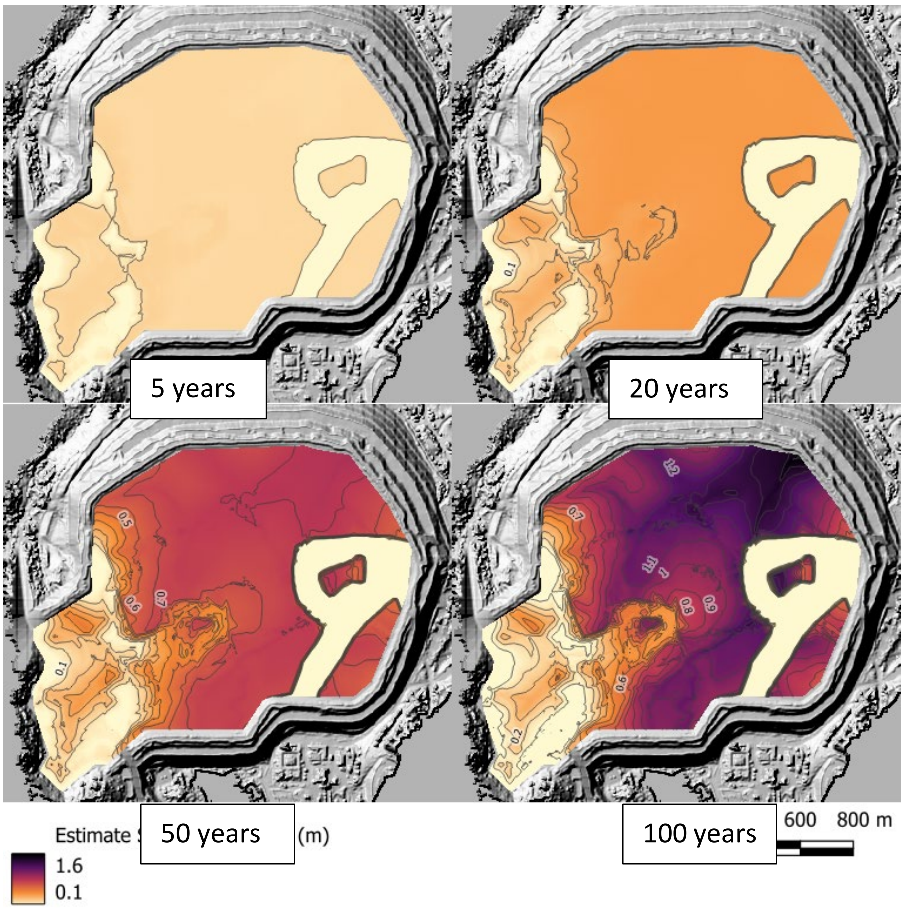
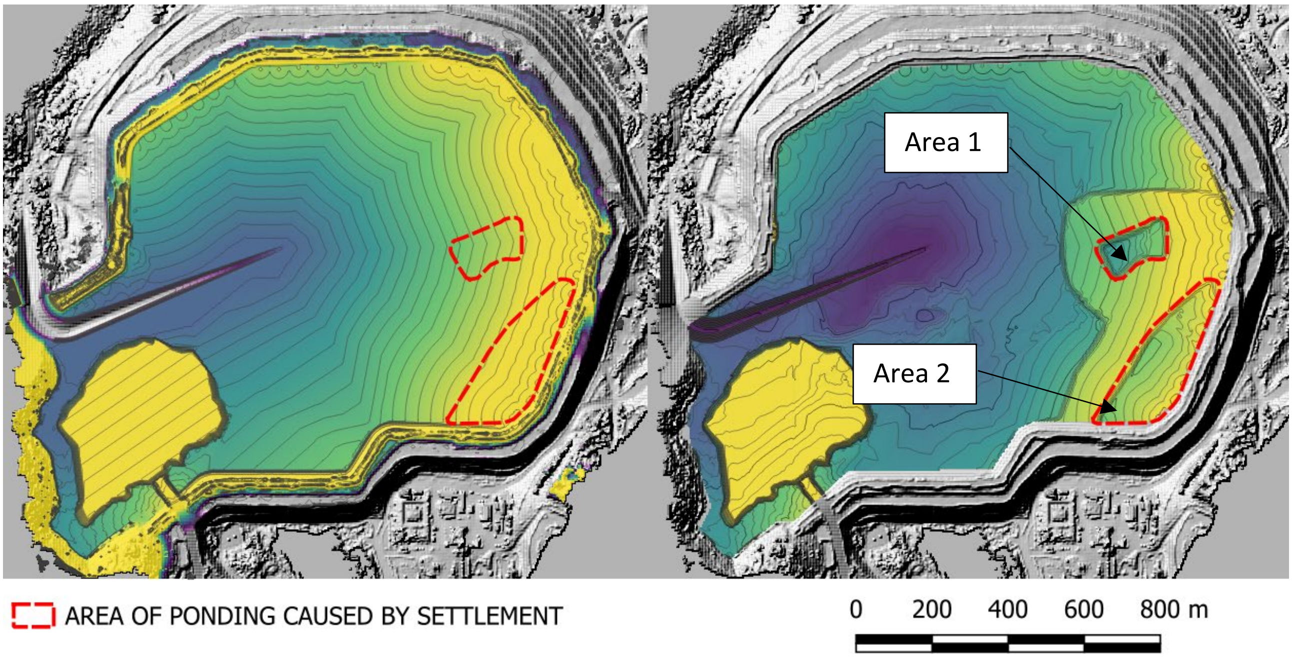


Figure 9 Magnitude of predicted settlement



(a) (b)

Figure 10 (a) Final surface before settlement; (b) Final surface after settlement

8 Conclusion

This paper has presented a consolidation and settlement assessment for a TSF with highly variable tailings thickness, internal waste rock and rockfill structures, and an operational life spanning more than 20 years. The assessment integrated site-specific geotechnical characterisation, 1D consolidation modelling and geospatial analysis to evaluate long-term settlement and its implications for closure landform performance.

Consolidation modelling indicates that total settlement across the TSF is predicted to range from less than 0.1 m to approximately 1.6 m, depending primarily on tailings thickness, drainage conditions and the presence of waste rock and rockfill. The majority of settlement is expected to occur within the first 50 years following closure.

Geospatial analysis identified that, while overall beach slopes and drainage performance are not materially impacted at a large scale, localised areas near the original decant causeway are susceptible to differential settlement that could affect surface drainage, if not addressed. Targeted mitigation measures, including strategic overfilling of tailings or placement of inert fill during rehabilitation, were identified as practical and effective means of managing these localised risks.

The assessment demonstrates the value of long-term local knowledge and record-keeping, with historical laboratory testing, field investigations, survey and imagery instrumental to the assessment. Without this information, highly detailed investigations would have been required. Alternately, with the assumption of homogeneity in the tailings profile, settlement occurring years after closure could have led to areas of ponding and closure targets not met.

Several factors were identified, which could not be incorporated into this case study. These factors include:

- Lateral and multidirectional drainage mechanisms are difficult to characterise with variability tailings depths, embankment profiles, saturation throughout the tailings profile, etc.
- Segregation of fines and coarse tailings particles may lead to areas of the beach settling at different rates and/or magnitude. It would be difficult to account for this, particularly where the decant pond and deposition strategy has varied throughout the facility's life cycle.

- Monitoring of settlement during active deposition is difficult – both to inform the drainage conditions within the TSF due to constant recharge from tailings bleed water and to monitor settlement with a beach that is consistently changing.

In the context of this case study, these factors were determined as not material to the final closure design; however in other instances, may require further consideration.

The outcomes of this case study indicate that predicted consolidation settlement can be accommodated within the proposed closure design and that post-closure drainage objectives can be achieved with manageable and well-defined mitigation measures.

References

Bonnin, M, Cabral A & Nuth, M 2019, 'Examination of the effects of solids content on thickened gold mine tailings sedimentation and self-weight consolidation', *Geotechnical Testing Journal*, vol. 42, no. 6, pp. 1493–1617.

Fredlund, MD, Lu, H, Shelbourn, M & Zhan, J 2013, 'Modelling field-scale multi-dimensional tailings consolidation', *Proceedings of the 10th International Conference on Tailings and Mine Waste*, University of Alberta, Banff.

McDonald, L & Lane, JC 2010, 'Consolidation of in-pit tailings', in R Jewell & AB Fourie (eds), *Mine Waste 2010: Proceedings of the First International Seminar on the Reduction of Risk in the Management of Tailings and Mine Waste*, Australian Centre for Geomechanics, Perth, pp. 49–62, https://doi.org/10.36487/ACG_rep/1008_05_McDonald

Priestley, D 2011, *Modelling Multidimensional Large Strain Consolidation of Tailings*, MS thesis, The Faculty of Graduate Studies, Mining Engineering, The University of British Columbia, Vancouver.

Stone, KJL, Randolph, MF, Toh, S & Sales, AA 1994, 'Evaluation of consolidation behaviour of mine tailings', *Journal of Geotechnical Engineering*, vol. 120, no. 3, pp. 473–490.

Tripathi, S, Scheremeta, J, Coffin, J & Reiva, J 2020, 'Consolidation modelling for design of complex in-pit tailings storage facility', *Proceedings Tailings and Mine Waste 2020*, Department of Civil and Environmental Engineering, Colorado State University, Fort Collins.