

Long-term settlement of mine voids backfills

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Abstract

Open pit mining voids can create lasting land use constraints due to physical instability, water-related hazards and permanent changes to topography. Depending on the materials present, open pit slopes have the potential to erode or fail long after mining ceases, while abandoned voids often fill with water, forming deep, stagnant lakes that may pose safety or environmental hazards that need to be mitigated. These voids can also alter groundwater flows and disrupt surface water regimes, potentially changing drainage patterns and affecting surrounding land and environment receptors.

Backfilling voids with mine waste rock is a common strategy to achieve closure completion criteria and reduce closure liabilities by improving stability, restoring a landform that achieves visual amenity requirements, and limiting adverse impacts on water systems. However, a key challenge is determining the appropriate design backfill height, as loosely dumped waste rock material can undergo significant long-term settlement that directly impacts the final closure surface profile.

This paper presents an approach for modelling and predicting void waste rock backfill settlement, demonstrated through a specific case study. The approach aimed to provide guidance to ensure that long-term backfill levels would remain above the pre-mining watertable, thereby preventing pit lake formation and meeting closure completion criteria. A conceptual settlement model was developed, accounting for both creep and saturation-induced collapse mechanisms. Historical large-scale oedometer test results were used to illustrate the application of the settlement prediction tool. The findings offered valuable insights into prediction reliability and identified opportunities to improve the capabilities of the prediction.

Keywords: waste rock, long-term settlement, backfill void, closure

1 Introduction

Open cut mining voids present significant closure challenges, particularly where permanent changes to topography create the potential for pit lake formation and altered surface water drainage regimes. Backfilling with waste rock is a common closure strategy used to improve stability and restore landform function. However, the magnitude of long-term settlement of loosely dumped waste rock is difficult to assess, representing a critical uncertainty in backfill design.

A key design consideration is the end-of-construction fill level, to ensure that after long-term settlement, the backfill surface continues to meet closure completion criteria (DMPE 2025, DMIRS 2023, Young et al. 2019). This is particularly critical where closure commitments require the backfill surface to achieve a design elevation: under-prediction may result in insufficient final levels and unintended pit lake formation, while over-prediction can lead to inefficient overfilling. Both scenarios can also impact surface water flow paths and the ability to meet associated closure commitment criteria. In either case, relinquishment may not be possible until additional post-closure rehandling or remediation works are completed. While rehandling is technically

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feasible, it is undesirable from both economic and closure performance standpoint. Accordingly, robust settlement estimates are essential for design and construction optimisation, closure risk management, and the definition of monitoring requirements to demonstrate performance.

This paper presents a practical method for modelling and predicting post-construction settlement of waste rock backfill. The method combines a simplified geotechnical model with a spatial workflow that can be implemented using readily available software. A case study is used to demonstrate how the approach can support closure design and backfill optimisation.

2 Geotechnical model for backfill post-construction settlement

Post-construction settlement refers to the gradual downward movement of the backfill surface after the final design elevation is achieved. For modelling purposes, backfill placement is assumed to occur rapidly relative to the long-term performance period, and settlement associated with self-weight during active filling is assumed to be masked by continued placement of material. Post-construction settlement is then considered to commence from a defined reference time corresponding to completion of filling.

The post-construction settlement is conceptualised as the combination of 2 primary mechanisms:

- time-dependent creep
- saturation-induced collapse.

The model is built on the following assumptions:

- Incremental compensation: settlements occurring during the backfill phase are masked by the continuous placement of additional fill to achieve a predetermined elevation.
- Reference time: the moment the predetermined elevation is achieved is established as the 'reference time' (t_0) for all subsequent post-construction settlement assessment.
- Hydrological equilibrium: full groundwater rebound, from pit floor level to pre-mining (or modelled post-closure) level, is assumed to occur entirely within the post-construction estimation period.
- Scope limitations: settlements induced by fluctuation in air moisture or material suction are considered secondary, immaterial in terms of magnitude, and are excluded from this specific settlement model.

The following 2 sections describe the primary mechanisms incorporated into the model.

2.1 Time-dependent creep settlement

Creep settlement refers to the time-dependent deformation of the loosely placed coarse waste material under a constant stress. Its occurrence is due to slow and progressive particle rearrangements, crushing and degradation within the granular skeleton.

A general description of the underlying physical mechanisms is provided below:

- Particle rearrangements: under sustained stress, particles can slowly slide past each other, reorient themselves, leading to a more stable packing configuration. This 'settling' or 'densification' leads to macroscopic deformation.
- Frictional slip and stick-slip phenomena: frictional contacts between grains can exhibit stick-slip behaviour, where periods of static friction are followed by sudden, minute slips. These micro-events contribute to the overall creep strain.
- Particle crushing/breakage: at higher stress levels, or for brittle particles, particle crushing can occur. The generation of finer particles can lead to further rearrangements and changes in the void ratio, influencing creep.

- Weathering: granular materials often exhibit time-dependent degradation or ‘ageing effects’, where their stiffness and strength decrease over time even under constant stress. This phenomenon is intricately linked to creep, as the rearrangement of particles leads to a more stable force chain network.
- Time-dependent contact behaviour: the normal and shear forces at particle contacts can evolve over time, influencing the creep rate.

A generic model for creep strain under constant mean effective stress is detailed below, capturing the characteristic log-linear progression of deformation observed in laboratory settings:

$$\varepsilon_v(t) = \lambda \log\left(\frac{t}{t_0}\right) \quad (1)$$

where:

- $\varepsilon_v(t)$ = post-construction vertical strain due to creep, at an elapsed time t in creep regime
- λ = creep rate which depends on the stress level; it represents the time dependency
- t_0 = reference time, at which the creep deformation is assumed to begin.

2.2 Saturation-induced collapse

Saturation-induced collapse refers to the sudden deformation of the loosely placed coarse backfill material due to wetting that occurs, in this case, when operational groundwater levels rebound to the pre-mining groundwater level. This phenomenon is attributed primarily to particle breakage and rearrangement triggered by wetting under stress (stress corrosion).

The concentrated stresses at particle contacts within a loosely packed granular assembly are often very high. When water is introduced (even as high relative humidity in the pore air), it significantly reduces the strength of individual rock particles by promoting the propagation of existing micro-fissures or cracks within the particles. This is a form of stress corrosion or subcritical crack growth at the particle level (Oldecop & Alonso 2001, 2004). This crushing creates finer particles and allows the remaining larger fragments to rearrange into a denser matrix, leading to a macroscopic volumetric compression (collapse).

While high relative humidity alone can initiate collapse, full saturation intensifies the effect. Water lubrication and the loss of residual matric suction further diminish inter-particle forces, accelerating particle rearrangement and crushing.

A basic model for saturation-induced collapse during post-construction is presented below:

$$\varepsilon_{v\text{collapse}} = \Delta e / (1 + e_0) = \alpha \quad (2)$$

where:

- $\varepsilon_{v\text{collapse}}$ = vertical strain due to wetting
- α = collapse coefficient that captures the reduction of pore volume due to wetting; it is related to the available pore volume and the stress level
- Δe = corresponding void ratio change
- e_0 = initial void ratio.

2.3 Settlement model

Total post-construction settlement (S_{p_total}) is determined by summing the creep and collapse contributions across discretised fill layers:

$$S_{p_total} = S_{p_creep} + S_{p_collapse} \quad (3)$$

$$S_{p_total} = \sum_{i=1}^n [\lambda_i \cdot H_i \cdot \log(t/t_0)] + \sum_{j=1}^m \alpha_j \cdot H_j \quad (4)$$

where:

S_{p_creep}	=	post-construction time-dependent settlement due to creep
$S_{p_collapse}$	=	post-construction settlement when wetting is anticipated
n	=	total number of discrete layers into which the backfill deposit is divided for the purpose of the settlement calculation
λ_i	=	creep coefficient evaluated for layer i
H_i	=	thickness of layer i
t	=	reference time plus the time eventually elapsed since start of post-construction backfill settlement
t_0	=	reference time, which refers in this case to the start of the post-construction settlement
m	=	total number of discrete layers into which the eventually submerged material thickness is divided for the purpose of the settlement calculation
α_j	=	collapse potential evaluated for layer j
H_j	=	thickness of layer j .

3 Prior estimate of model parameters

To explore the settlement model, reference values for the parameters λ and α were derived from historical large-scale laboratory data, providing a foundation for future inverse analysis and optimisation.

3.1 Laboratory data

The model parameters α and λ were estimated across varying stress levels by interpreting results from available large-scale oedometer tests. These tests, spanning multiple projects, were all conducted at the University of Chile's geotechnical laboratory, IDIEM (Instituto de Investigación y Ensayos de Materiales). Testing employed specialised equipment capable of applying vertical stresses up to 12 MPa on specimens with diameters ranging from 900 to 1,000 mm and heights ranging between 1,800 and 2,000 mm. The maximum particle size of the tested samples ranged from 150 to 200 mm. In the actual backfill material, however, the maximum particle size may be as large as 2 m, although such oversized particles are expected to represent only a minor proportion of the overall particle size distribution.

The tested materials exhibited high strength and durability and were categorised as follows:

- Loosely placed igneous rock: includes granodiorite, porphyry and granodioritic porphyry, with average unconfined compressive strength (UCS) values between 100 and 140 MPa.
- Compacted composite: a mixture of approximately 70% monzonite (UCS = 140 MPa) and 30% fine-grained carbonate sediment/micrite (UCS = 100 MPa).
- Loosely placed BIF-derived overburden: Pilbara material from banded iron formation (BIF).

The study evaluated 43 determinations of the creep parameter λ and 9 determinations of the wetting collapse parameter α . We used the full range of λ data but limited the α analysis to loosely placed materials to ensure a consistent behavioural baseline.

Despite inherent variability in material origin and sample composition, the parameters λ and α correlate clearly with effective vertical stress (σ'_v). Figures 1 and 2 illustrate these trends using power laws regressions.

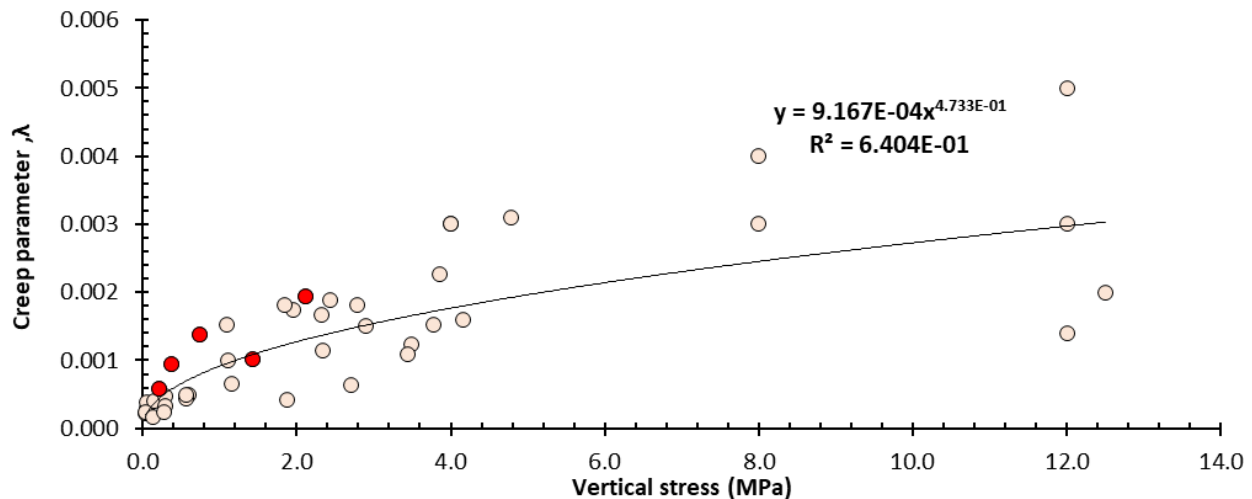


Figure 1 Derived relationship between creep parameters and vertical stress (materials from Pilbara region are shown in red dots)

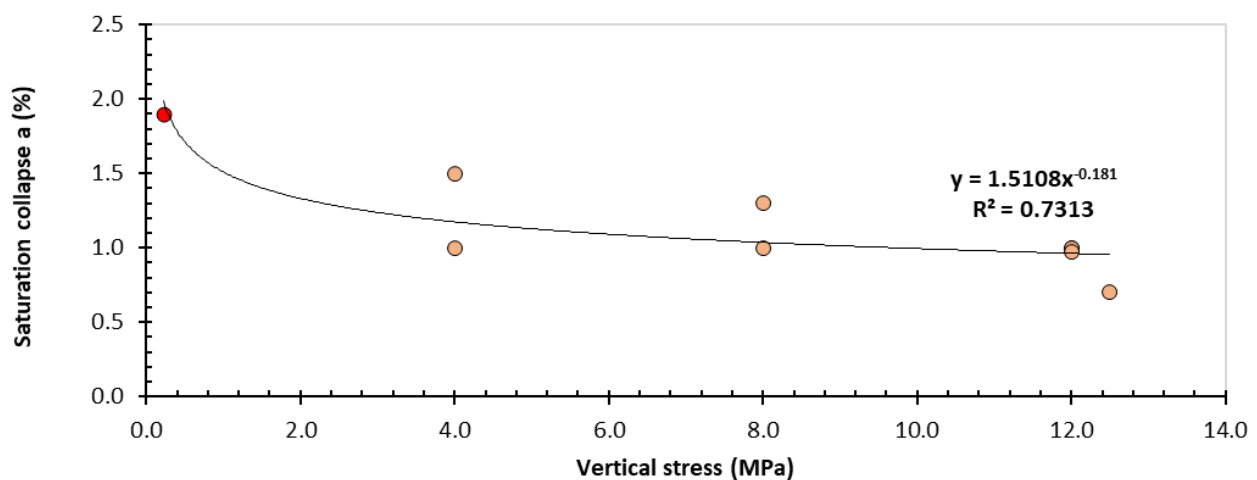


Figure 2 Derived relationship between wetting collapse potential and vertical stress (materials from Pilbara region are shown in red dots)

3.2 Estimation of model parameters within 95% confidence level

To build a margin of safety, a Bayesian regression analysis was conducted to determine 95% confidence intervals for model parameters as a function of vertical stress. Adopting a 95% confidence level allowed a transition from mean measured values to conservative estimates aiming to account for laboratory-scale effects, inherent material variability and general epistemic uncertainty in initial settlement predictions.

For the Bayesian evaluation, it was assumed that the mathematical function representing the parameters were power laws in the following form:

$$\lambda = A(\sigma_v')^n \quad (5)$$

$$\alpha = B(\sigma_v')^{-m} \quad (6)$$

where:

- λ = creep parameter in settlement model
- α = saturation-induced collapse parameter in settlement model
- σ_v' = effective vertical stress
- A; B = initial tangent slope of the power equation
- n; m = exponents that capture the stress-dependency.

The analysis was conducted to determine parameters A and n for the creep function and parameters B and m for the saturation-induced collapse function. The analysis method involves using prior distributions on the 4 parameters for inference. The prior distributions are specified with sufficiently vague values, defining uniform distributions with ample ranges to avoid constraining the result. The posterior probability distribution is evaluated by sampling the parameters using a Markov chain Monte Carlo (MCMC) algorithm. A detailed description of the methodology can be found in Contreras et al. (2018), in the context of the shear strength of intact rock strength.

Errors in Bayesian analysis can be evaluated using absolute or relative residuals. The creep parameter analysis was performed using relative residuals to address the observed heteroscedasticity in the data. Relative residuals are computed by normalising λ at the data points relative to the σ_v' provided by the model. This approach ensures that errors in λ are measured consistently, regardless of the level of effective vertical stress. Using relative residuals helps reduce bias caused by larger errors at higher stress levels. The wetting collapse analysis employed conventional absolute residuals.

The parameter values that yield the maximum probabilities with the posterior function are determined using the MCMC sampling procedure. Throughout the process of sampling parameters with the MCMC method, comprehensive probability distributions for λ and α values are established at selected σ_v' locations. These distributions facilitate the definition of prediction intervals for λ and α with the desired confidence levels. The prediction intervals constructed in this manner account for the variability of the mean and standard deviation of the parameters.

Figures 3 and 4 summarise the results of the analysis for the creep and saturation-induced collapse functions, respectively. The graphs display the data points, the mean fitted envelope, and the band of the 95% highest density interval of the λ and α coefficients. The highest density interval band represents the uncertainty of the inferred parameters A and n for creep and B and m for wetting collapse. The graphs also show the band defining the 5% and 95% prediction intervals of λ and α . The 95% prediction interval is marked in red and indicates the upper bound creep and saturation-induced collapse coefficients based on conservative values of the parameters, which are adopted for evaluating the settlement model.

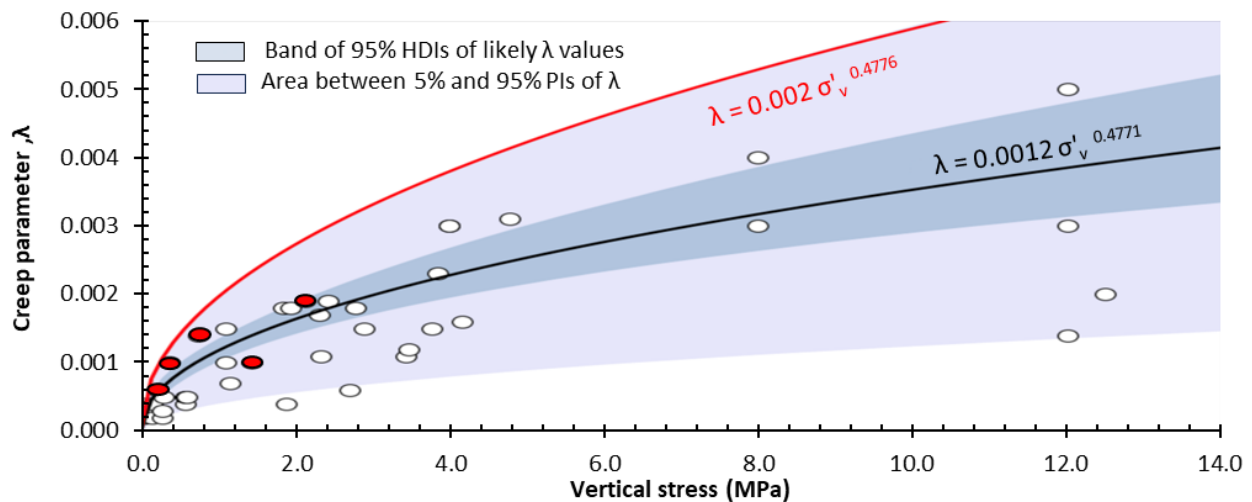


Figure 3 Data, mean fitted envelope, band of 95% highest density interval of the more likely λ values, and band between the 5 and 95% prediction interval of λ (materials from Pilbara region are shown in red dots)

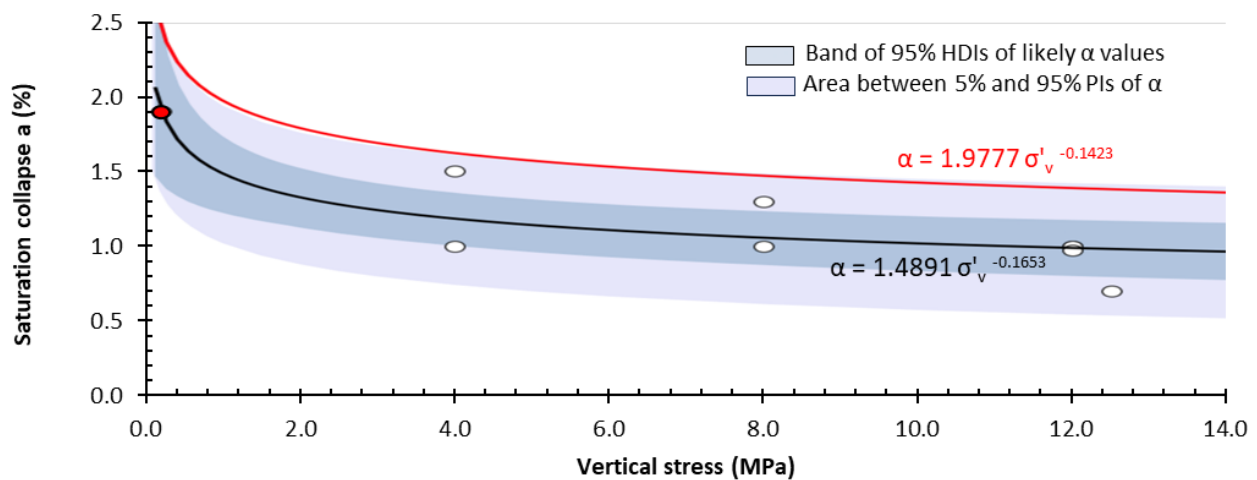


Figure 4 Data, mean fitted envelope, band of 95% highest density interval of the more likely α values, and band between the 5 and 95% prediction interval of α (materials from Pilbara region are shown in red dots)

4 Settlement prediction workflow

4.1 Proposed workflow

The workflow combines geographic information system (GIS) or computer-aided design (CAD) surface processing with a calculation engine.

The workflow starts by processing 2 topographical surface datasets: the as-mined surface, which represents the landform after mining, and the as-built surface, which represents the landform post backfilling. These surfaces are processed in CAD or GIS software to import, visualise and export the data in x, y, z coordinate format for analysis. At this stage, an appropriate grid resolution is selected to balance accuracy and processing efficiency, as finer grids provide greater spatial detail but generate more data and incur longer computation times. The exported surface data are then imported into a calculation engine, where each grid column is subdivided into multiple vertical layers to enable layer-by-layer settlement calculations. This segmentation allows settlement parameters to be evaluated at different depths using the model

relationships defined previously. Total settlement is then calculated as a function of elapsed time and rebound groundwater level, incorporating both creep and saturation-induced collapse. The resulting post-settlement surface is exported again in x, y, z format for visualisation, reporting or further geospatial analysis, and can be triangulated in CAD or GIS software to produce a digital elevation model.

4.2 Influence of input variables on settlement results

Sensitivity analyses were undertaken using an existing void to assess the influence of input variables on the settlement prediction, to identify their impact on the results and to evaluate reasonable working ranges. The parameters assessed were surface grid resolution, vertical layer segmentation and backfill unit weight. Surface data were exported at grid sizes of 1, 5, 10 and 20 m; each vertical column was discretised into between 1 and 10 layers; and unit weights of 20, 22, 24 and 28 kN/m³ were adopted to represent potential variability in the (iron-rich waste rock case) backfill. The baseline case used a 5 m grid, 6 layers and a unit weight of 22 kN/m³, with creep settlement estimated over 100 years for a representative backfilled area.

Grid resolution had a noticeable effect on the spatial character of predicted settlement. Finer grids captured local variability more clearly, whereas coarser grids smoothed settlement gradients. Within the ranges assessed, a 1 m grid was selected as the preferred resolution for improved representation of the closure surface, as shown in Figure 5. Increasing the number of layers improved vertical resolution, but within the current model structure, the effect was less significant than the effect of grid resolution. This does not mean layering is unimportant. Rather, it suggests that, at the current stage of model development, improving surface representation may yield more value than aggressively increasing the number of vertical layers. Predicted settlement increased with assumed backfill unit weight because higher unit weight increases effective vertical stress. This highlights the importance of selecting realistic density inputs and where possible relating them to material types, placement method and depth.

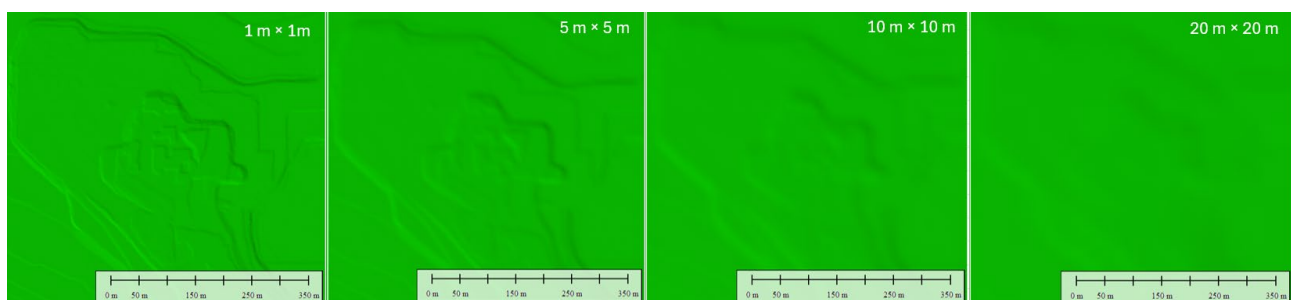


Figure 5 Estimated creep settlement over 100 years based on different grid resolutions

Note: Grid sizes are presented in the upper right hand side corner of each sub-image.

4.3 Limitations

The settlement prediction tool and its associated workflow were developed to facilitate practical implementation of the settlement model and to provide an initial assessment of its performance. Therefore, the results should be interpreted as high-level estimates of potential vertical displacement in backfilled mine voids rather than precise forecasts.

At this stage, the approach remains subject to several important limitations.

- **Data scarcity and source:** because project-specific data are currently limited, model parameters were primarily derived from datasets from other projects. These proxy values may not fully capture the unique geotechnical characteristics of the analysed site.
- **Scale effects:** parameters obtained from laboratory-scale testing may require appropriate scaling factors to accurately represent the behaviour of backfill at a project-scale.

- Material and placement variability: the inherent variability of backfill materials and the methods used for placement necessitate site-specific calibration to reflect the actual range of field performance.
- Model sensitivity: predicted settlement is sensitive to user-defined modelling choices – particularly grid resolution, vertical discretisation, and assumed unit weight – which can materially influence the predicted results.

5 Applying the workflow: a case study

This case study demonstrates the application of the settlement workflow to a typical backfilled void and illustrates how spatial variability in backfill thickness influences long-term settlements.

Figure 6a presents the pit void and as-mined topography, while Figure 6b presents the projected as-built surface following backfill operations. The design specified a final backfill surface at a target elevation of 3 m above the pre-mining groundwater level. Given that the fill thickness reaches a maximum of roughly 63 m, groundwater recovery to pre-mining levels would saturate nearly 60 m of the backfill profile in the deepest sections.

Although groundwater rebound occurs progressively over time, full groundwater rebound, from pit floor level to pre-mining level, is assumed to occur entirely within the post-construction settlement estimation period, for simplicity, as indicated in Section 2.

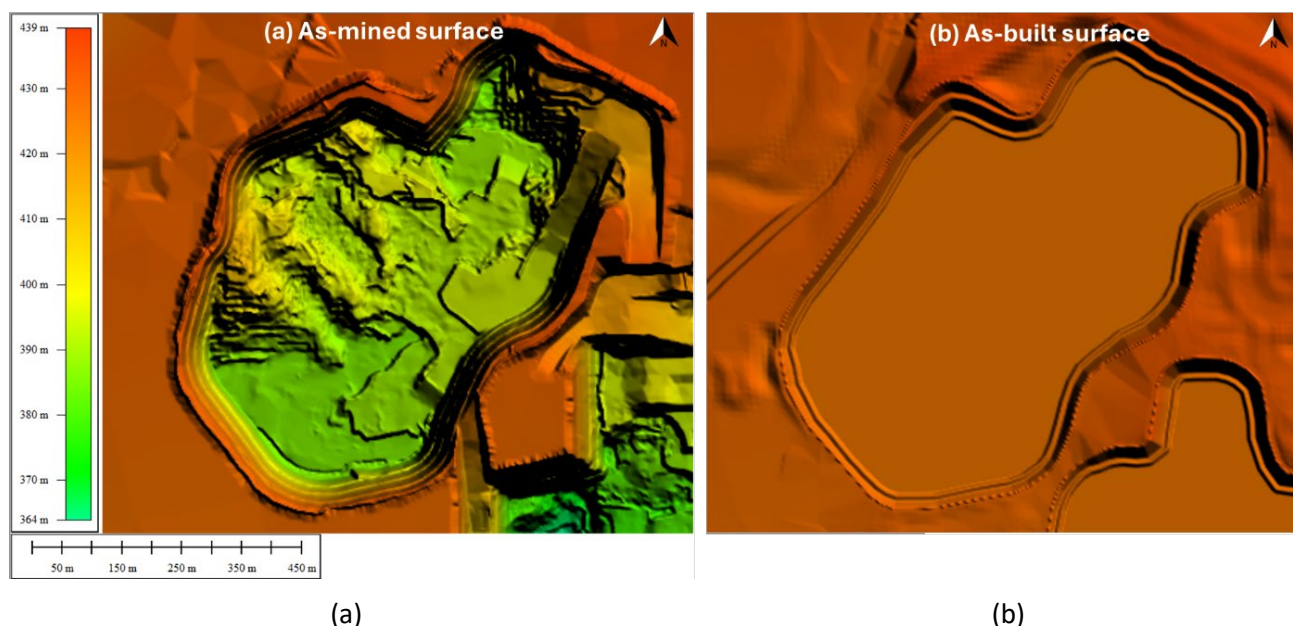


Figure 6 Comparison of surface morphologies. (a) As-mined condition; (b) Projected as-built backfill condition

The workflow was used to estimate long-term settlement across the void, which accounts for spatial variations in backfill thickness and the stress-dependent behaviour of both creep and saturation-induced collapse.

To explore the workflow, 4 scenarios were assessed:

- Scenario 1: creep settlement after 20 years (Figure 7a), representing deformation over a hypothetically remaining life of mine.
- Scenario 2: creep settlement after 100 years (Figure 7b) and 1,000 years (Figure 8a), representing longer-term closure conditions.

- Scenario 3: settlement due to groundwater rebound to the pre-mining groundwater level, isolated from creep effects (Figure 8b).
- Scenario 4: the combined impact of 1,000 years of creep and full groundwater rebound (Figure 9).

The results illustrate the occurrence of differential settlements due to the heterogeneity of the pit void floor surface. While creep deformation increases over time, its magnitude remains relatively stable across the broad temporal range from 2 decades to 1,000 years, remaining below 1% of the fill height in this specific case. Notably, saturation-induced settlement was significantly more pronounced than creep-related deformation.

Figure 9 compares the post-backfilling landform with the predicted surface after 1,000 years, accounting for the combined effect of creep and groundwater rebound. The results indicate that the nominal criterion of 3 m above the pre-mining groundwater level appears sufficient to avoid pit lake formation in this example. However, the analysis also shows that settlement is greater in the deeper sections of the void, resulting in a less uniform final surface. This suggests that a uniform backfill criterion, while potentially adequate for closure compliance in some cases, may not represent the most efficient or optimised design strategy where backfill thickness varies substantially across the void.

The evaluation indicates that the backfilling strategy must account for the variable depth of the underlying pit floor. Since settlement is directly proportional to the thickness of the material, a uniform lift height will inevitably result in an uneven surface as deeper sections settle more than shallower ones. To mitigate this and optimise material usage, a variable overfill strategy should be employed, such as placing additional 'settlement compensation' fill in areas with greater depth while maintaining lower profiles in shallower zones. This proactive approach ensures that, once settlements develop, the final landform achieves a uniform elevation, while minimising material needs.

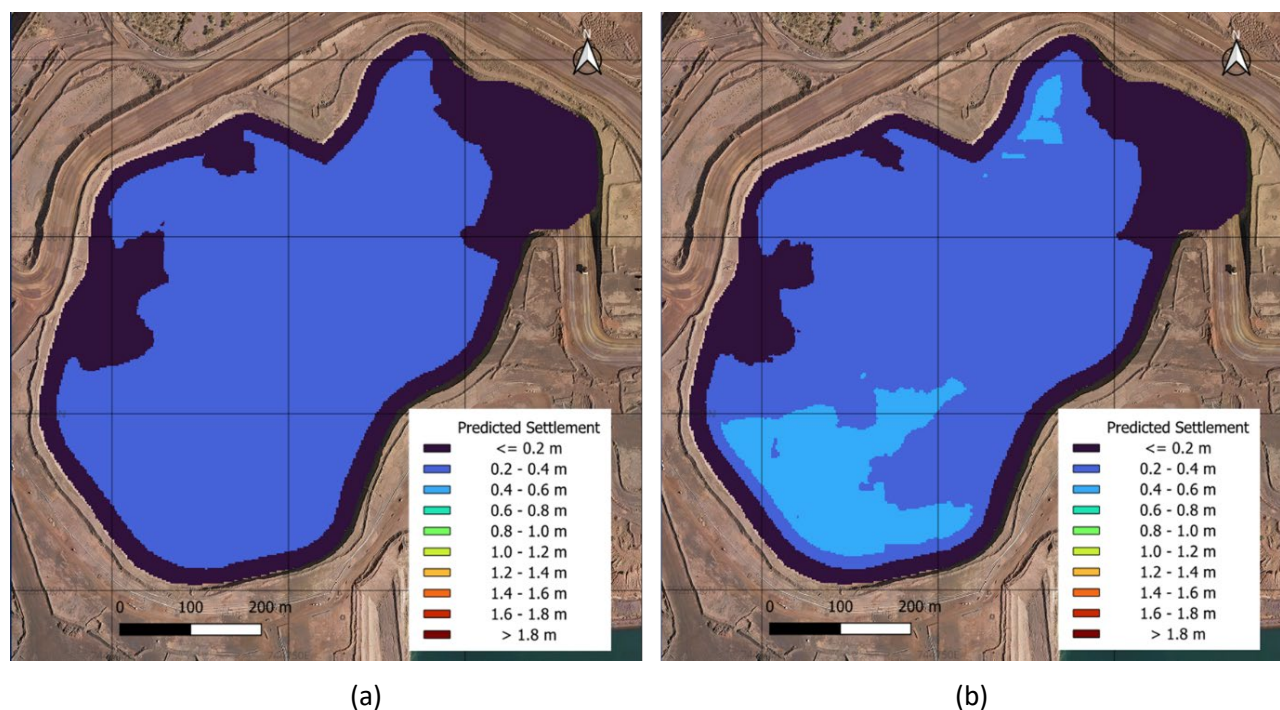


Figure 7 (a) Creep after 20 years; (b) Creep after 100 years

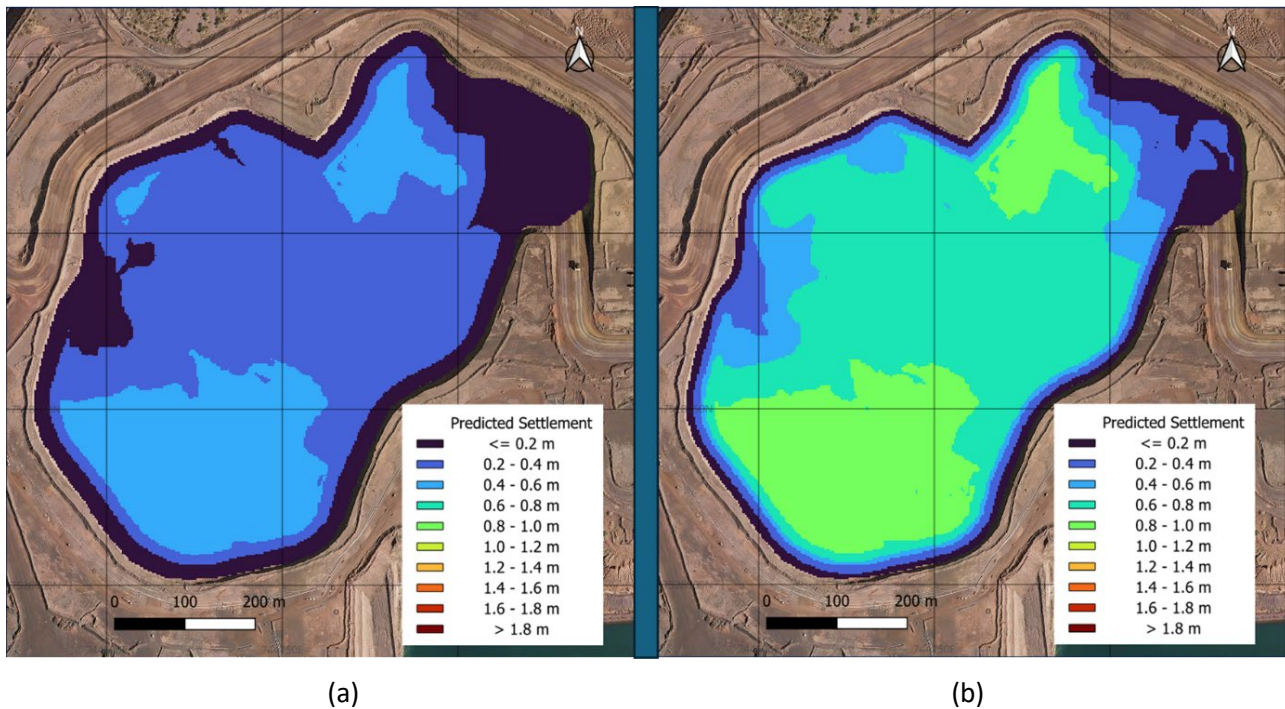


Figure 8 (a) Creep settlement after 1,000 years; (b) Total saturation-induced collapse settlement

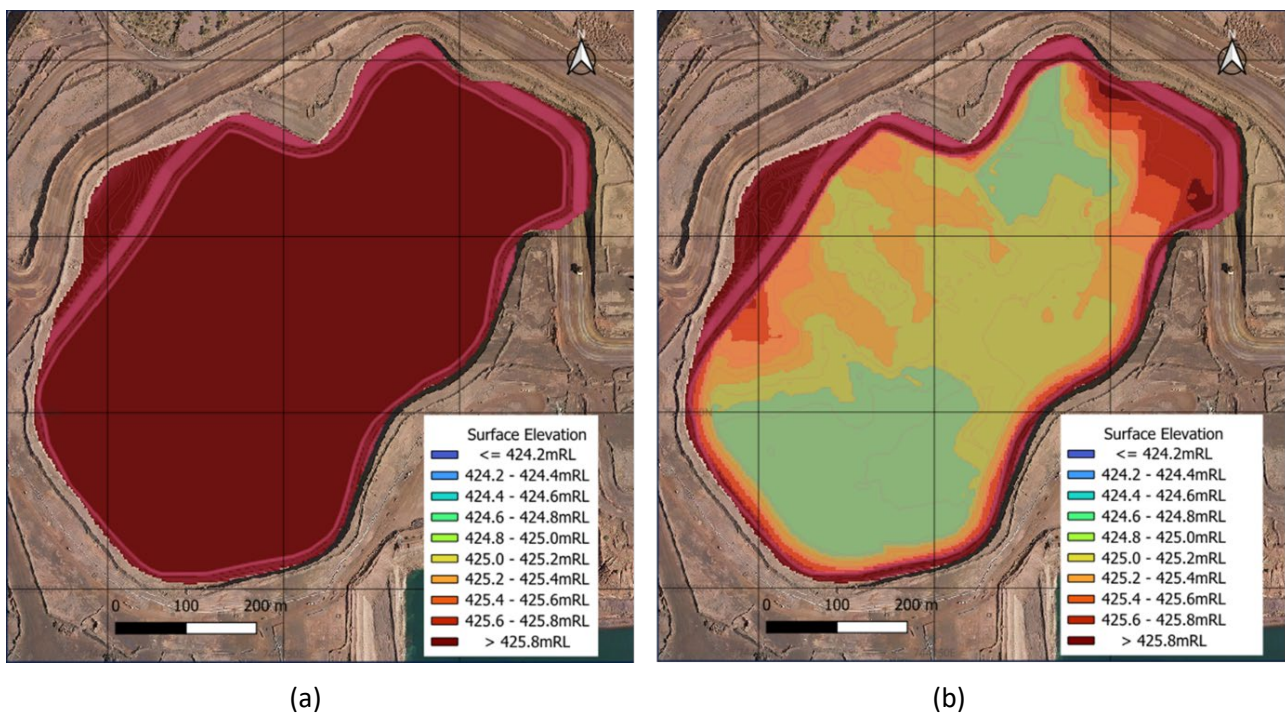


Figure 9 (a) Landform immediately after backfilling; (b) Predicted landform after 1,000 years with groundwater rebound to the pre-mining groundwater level

6 Discussion

The case study highlights the importance of spatially assessing settlement in closure design, because it reveals localised low points that may not be identified when applying a single uniform backfill criterion across the void. This is geotechnically important, as a nominally adequate lift height at the time of placement does not necessarily ensure that the final post-settlement surface will consistently remain above the required closure elevation. Differential settlement driven by variations in backfill thickness, vertical stress and the

depth of material affected by groundwater rebound can produce isolated zones that fall below the pre-mining groundwater level over time and alter surface water flow paths. The workflow therefore supports a more robust backfill strategy by identifying where variable backfill thickness or additional design fill thickness may be required to maintain compliance over the long term. It can also be used to establish a conservative backfill allowance, where operationally preferred, by quantifying predicted settlement and applying an appropriate design margin.

The workflow is also valuable from a broader landform design perspective. Closure performance is not governed solely by whether the post-settlement surface remains above groundwater level, but also by how the final landform will function and evolve over time under erosion, weathering, sediment transport and surface water runoff. While a strategy that simply places additional backfill in inverse proportion to predicted settlement may correct elevations locally over time, it may also create an irregular or geomorphically unstable landform that is inconsistent with the surrounding landscape and that adversely alters drainage behaviour. For this reason, settlement predictions should be integrated with landform and drainage design, rather than used in isolation. In practice, the workflow provides an initial basis for evaluating how settlement may influence closure landform performance and for identifying mitigation measures from the onset of backfilling through to long-term closure.

The current workflow should nevertheless be applied with caution. It remains a screening and design support tool that is still being refined through the incorporation of site-specific data and calibration against observed field performance using interferometric synthetic aperture radar (InSAR) and conventional survey measurements.

7 Conclusion

This paper presents a practical workflow for assessing the long-term settlement behaviour of waste rock backfill in open pit voids, with the aim of supporting closure planning and design.

The workflow integrates a simplified settlement model with a structured operational workflow that combines CAD or GIS-based software processing alongside calculation engines.

The settlement model incorporates time-dependent creep and saturation-induced collapse, explicitly considering the influence of the stress levels on the magnitude and progression of these processes.

Settlement prediction is critical for determining appropriate backfill fill levels to meet long-term closure criteria, particularly where the final landform is required to remain above the pre-mining groundwater level or support surface water flow paths.

The prediction capability of the workflow depends on the quality of the settlement model parameters and the adopted discretisation of the physical model within the workflow. In this study, model parameters were inferred from a general laboratory dataset and are used demonstrate the proposed framework. The discretisation of the physical model can be adjusted by the user, with the horizontal grid resolution being the more critical choice. In this work, the grid resolution was selected based on a sensitivity analysis undertaken to support the presented case study.

Application of the workflow to the case study enabled the creep and saturation-induced collapse components of settlement to be evaluated and visualised separately, and showed that the latter was the dominant mechanism in this example. It also highlighted the significance of differential settlement resulting from variability in the underlying void geometry. Overall, the workflow demonstrates practical value in supporting backfill design strategies that consider and mitigate both total settlement and differential settlement.

At its current stage, the workflow should be regarded as a decision support tool that provides high-level estimates of settlement behaviour and helps identify where additional backfill allowance or targeted monitoring may be required. Its reliability and usefulness for closure practice will improve through further refinement, particularly by incorporating site-specific data and calibrating predictions against field observations.

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