The role of creep deformation in pit lake slope stability

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Abstract Large-scale open-pit mining activities have profound impacts on the surrounding landscape and environment. At the cessation of open-pit mining, the rehabilitation of large void spaces can be achieved by pit-lake filling, where the water body provides a confining pressure on surrounding mine surfaces, reducing both the likelihood of slope failure and the need for ongoing slope maintenance. Although pit-lakes present a range of long-term benefits, the geotechnical performance of mines containing soft soils that are susceptible to creep under increasing loads due to pit-lake filling is seldom considered. From a geotechnical standpoint, creep induced failure is commonly associated with slow, downslope movements, prior to critical slope failure events. In this research, time-dependent slope stability analyses based on creep-sensitive materials are presented for an open-cut mine undergoing pit-lake filling. Numerical simulation provides a mechanism for the assessment of materials exhibiting soft soil creep constitutive behaviour under various loading conditions due to pit-lake filling. The response of mine surfaces is investigated for various filling regimes, highlighting location-dependent deformation rates, pore pressures and slope Factors of Safety for a large Australian open-pit brown coal mine. Results are presented for two separate creep-sensitive materials, identifying the ability to achieve final, stable landforms for a range of long-term pit-lake conditions.

Article Highlights

- Time-dependent creep deformation behaviour is investigated for a large Victorian open-pit brown coal mine undergoing pit-lake rehabilitation.
- The soft soil creep model is implemented for a large open-pit rehabilitation model, to assess long-lasting creep movements of a specific mine slope.
- Mine void filling rates are simulated for a range of rehabilitation scenarios over a 5 to 40 year period, identifying the excess pore water pressure distributions in addition to vertical and horizontal deformations rates.
- The long-term behaviour of 8 cross-section profiles is presented, identifying the effect of pit-lake filling for silt and clay interseam materials.

Keywords Soft soil creep · Mine rehabilitation · Pit-lake · Slope stability
1 Introduction

Pit-lake filling continues to gain attention as a strategy for long-term open-pit mine rehabilitation. To ensure stability, pit-lakes are formed at the conclusion of mining operations by flooding void spaces, decreasing the risk of slope failure by providing a confining pressure on slopes and mine walls. Filling is commonly controlled by a combination of precipitation, cessation of groundwater depressurisation and runoff from drainage basins (Castro and Moore 2000). In addition to geotechnical advantages, pit-lakes exhibit a range of long-term beneficial environmental qualities, including the creation of aquatic habitats, active and passive recreation areas, and community assets. Although such structures are deemed to reduce the long-term slope stability risk through the restoration of weight-balance, pit-lakes continue to present ongoing challenges (McCullough et al. 2020). Common risks include erosion to the shoreline (McCullough et al. 2019), a reduction in water quality due to acidification (Geller et al. xxx) and slope failure (McCullough and Lund 2006; Nestler and Stoll 2001), while factors influencing pit-lake performance include climate, regional geology vegetation and regional groundwater flow (Schultze 2012). During active mining, groundwater pressures are often controlled through slope drainage and aquifer depressurisation. Contrastingly, during and after pit-lake filling, dewatering and depressurisation are not used to control groundwater pressures. Instead, capping layers of overburden minimise the infiltration of surface water (Wells et al. 2013).

Pit-lake rehabilitation can achieve mine stability by providing a counterweight to upward pressures from aquifers below the mine surface, preventing floor heave, while also increasing the lateral pressure on mine slopes (Precincts and Regions 2020). During the period of filling prior to achieving the final pit-lake design, drainage boreholes above surface waters may be required for groundwater pressure control and to minimise the risk of ground movements. Further hydrogeological factors impacting stability include surface rebound as aquifers repressurise, scouring and erosion of mine surfaces due to wave effects and increased seismic risks due to pit-lake filling (Schultze et al. 2010).

The presence of soft, rate-sensitive creeping soils can have profound implications for the stability of natural and mined slopes. Soils experiencing unrecoverable, continuous creep deformation can lead to an eventual loss of shear strength (Tran et al. 2018). In soil slopes, creep shear strain causes a redistribution of stresses that may lead to near-failure states that are sensitive to additional disturbance (Pusch et al. 2016). Creep often results in a slow and steady downhill movement that results in permanent deformation insufficient to cause shear failure (Ziemer 1977). Contrastingly, many slopes undergo continuous deformation due to creep, causing gradual geometric changes that can lead to a reduction in shear strength, eventually triggering slope failure (Vermeer and Neher 2000a). As a phenomenon, creep has been observed at both the near-surface, exhibiting shallow movement (Asch et al. 1989) and at the deep-seated level (Tran et al. 2018). Long-term time-dependent creep strength was first investigated by Goldstein and Babitskaya (1959), considering the creep failure in response to the application of long-term loads. More recently, a number of soil models have been developed to assess the stability of soft soil slopes and embankments through numerical slope stability analysis. Although numerous slopes containing soft soils exhibiting creep have been investigated (Ghadrdan et al. 2020a, b; Long et al. 2020; Wongchana et al. 2020), the performance of pit-lakes containing soft soils undergoing reloading due to the filling of void spaces has seldom been considered. As soft, creeping soils may be susceptible to further disturbance, the rate of reloading due to the weight of pit-lake water has the potential to bring forth additional deformation and induce failure.

In this research, an open-pit lignite mine within the state of Victoria, Australia, containing a soft inter-seam susceptible to creep is considered for various potential loading scenarios due to the rate of pit-lake filling. Building on the results of studies characterising the properties of mine soils in the region (Karami and Tolooiyan 2020; Tolooiyan et al. 2020; Tolooiyan et al. 2021; Wen et al. 2020), coupled with previous numerical slope stability analyses of recent open-pit mine batter geometries (Ghadrdan et al. 2020a, b; Dyson and Tolooiyan 2019), this research investigates the response of mine batters to a range of pit-lake filling scenarios based on potential filling rates. As a result, progressive changes in deformation, pore water pressures, plasticity and Factor of Safety (FoS) are investigated to determine the likelihood of soft
soil creep mechanisms to impact the stability of large-scale rehabilitated mine slopes under pit-lake filling.

2 Pit lakes and final landforms

Pit-lakes require careful design, especially in relation to long-term stability for periods often in excess of 100 years (Graaf et al. 2019). Predicting future modes of slope instability is a non-trivial task. McCullough and Lund determined that a rebound in groundwater pressures can increase the likelihood of slope failure due to a decrease in the effective stress of mine slope walls (McCullough and Lund 2006). Slopes exposed to fluctuations in the waterfront level induce external water loading, changes in pore pressures and erosion, as can be seen in many embankment dam failures (Johansson 2014), and in some cases, slope failure (Jian et al. 2014; Moregenstern 1963). Sources of natural water level fluctuation include tidal water level changes (Li et al. 1997; Raubenheimer et al. 1999) and wind-induced waves (Bakhtyar et al. 2009). Carter (Carter 2014) noted a range of factors that control the degradation of stability over time, including changes to groundwater pressures, stress conditions and geometry. Erosion and rilling have the potential to damage slope covers and create preferential surface flows, which can negatively impact groundwater pressures, while also allowing surface water to pond.

In many cases, a loss of stability can be linked with rapid drawdown, with an associated reduction in water level. However, a rising level of water, as seen with pit-lake filling, can also be cause for concern. Increases in the water level have been shown to cause stress redistributions due to external loads, which can lead to a loss of shear strength and overall stability, such was the case with the initial filling of the Panama Canal and the Three Gorges Reservoir (Jian et al. 2014; Lane 1966). In assessing slope failure mechanisms, the Finite Element Method (FEM) has been extensively implemented to investigate the influence of water level changes (Lane and Griffiths 2000; Rinaldi et al. 2004; Zhan et al. 2006).

Several types of pit-lake structures exist based on the desired properties of the final landform, each with a unique set of geotechnical and hydrological characteristics. The design of lake structures is often based on their susceptibility to failure mechanisms (such as rockfalls and slides), hydrological conditions (such as the interaction with ground and surface waters) and water availability. Six viable rehabilitated pit-lake landforms for open-cut mines are presented below:

Fig. 1 Commonly implemented mine filling scenarios a full pit-lake, filled close to the crest b pit backfilled with overburden c partial pit-lake filled to a level significantly below the crest d empty void space
2.1 Full level pit-lake

Requiring minimal overburden above the water level, a deep lake is formed by filling the pit to the crest of the mine. In this scenario, groundwater is often allowed to recover to the natural level without the requirement of continual dewatering. Mine slopes below the final water level do not require reshaping and are permitted to remain steep. Slopes above the water level are often reshaped to produce shallow slopes, allowing for access and maintenance. Figure 1a indicates the prominent features of a full level pit-lake.

2.2 Full backfilling

Under exceptional circumstances, the mine pit is fully filled with overburden and non-polluting waste material (Fig. 1b). The full backfilling option requires sufficient overburden to fill the void and is rarely an option for deep pits. Groundwater is allowed to recover to natural levels, with landforms surrounding the pit reshaped to control the drainage of surface water.

2.3 Partial pit-lake

In cases where there is insufficient water resources to fill the pit, a partially filled pit provides a final land-use scenario creating a dry landform significantly lower than the mine crest (Fig. 1c). As such, groundwater pumping and mine drainage are required above the water table. Mine slopes above the water surface are reshaped to meet land use requirements.

2.4 Empty void

The mine is partially filled with an engineered impermeable (often clay) liner to inhibit the flow of water into the pit (Fig. 1d). As a result, ongoing groundwater dewatering is required.

3 Soft soil creep constitutive behaviour

Soft clay deposits are complex in nature, often displaying significant signs of anisotropy and rate sensitivity due to underlying sedimentary processes and consolidation history (Burland 1990). In recent years, the time-dependent behaviour of soft soils has been represented using constitutive models such as Soft Soil Creep (SSC) (Vermeer and Neher 2000a). As the name indicates, the model is used to simulate the behaviour of creep (i.e., secondary consolidation) for soft soils such as clay and silt. SSC discerns between primary loading and unloading/reloading behaviour, similar to the Soft Soil (SS) model, however, the SS model does not consider time dependency, as is required when investigating rate-dependent pit-lake filling regimes.

The primary assumption of SSC behaviour is the instantaneous development of elastic strains, while viscoplastic strains are defined by

\[ e_{ij} = e_{ij}^e + e_{ij}^c \]  

where \( e_{ij}^e \) and \( e_{ij}^c \) are the elastic and creep components, respectively. The creep volumetric strain \( e_v^c \) is calculated by

\[ e_v^c = \frac{\mu}{\tau} \left( \frac{p_{eq}}{p_p} \right)^{\frac{\lambda^* - \kappa^*}{\mu^*}} \]  

where \( \lambda^*, \kappa^* \) and \( \mu^* \) are defined as the modified compression, swelling and creep indices, respectively; \( \tau \) is time; \( p_{eq} \) is the stress state, as given in Eq. 3; and \( p_{eq}^c \) is the generalised equivalent pre-consolidation pressure, as given in Eq. 4.

\[ p_{eq} = p + \frac{p^2}{M^2(p + c \cot \phi)} \]  

\[ p_{eq}^c = p_{eq0}^c \exp \left( \frac{e_v^c}{\lambda^* - \kappa^*} \right) \]

where \( p \) and \( q \) are stress invariants defined by the current stress state; \( M \) is the critical state gradient; \( p_0 \) is the initial conditions when the creep volumetric strain and time are equal to zero; and \( c \) and \( \phi \) are the cohesion and friction angle shear strength parameters, respectively.

In the case of the modified compression and swelling indices \( \lambda^* \) and \( \kappa^* \), parameters are determined based on isotropic compression tests for loading and unloading. The slope of the normal consolidation curve yields
the modified compression index, while the slope of the unloading curve provides the modified swelling index. The creep index is obtained by calculating the long-term volumetric strain with respect to log time. The relationship between $\lambda^*$, $\kappa^*$, and $\mu^*$, Cam-Clay parameters and normalised parameters are detailed in Table 1.

The creep strain tensor is defined by Eq. 5, with the critical state line $M$ calculated using the lateral earth pressure $K_{nc}^0$ from oedometer testing, as shown in Eq. 6. As such, similar to the Modified Cam Clay constitutive model, the bulk modulus is a function of the confinement and modified swelling index (Eq. 7).

$$K = \frac{p}{\kappa^*} = \frac{E_{ur}}{3(1-2v_{ur})}$$

where $E_{ur}$ and $v_{ur}$ are the unloading/reloading modulus and Poisson’s ratio, respectively.

Creep-induced slope instability usually occurs when the stress levels are above the critical state line but less than the peak strength. Instability develops as a result of the accumulation of plastic volumetric dilation which leads to a slow softening, finally resulting in failure (Tavenas et al. 1978). There are a range of alternative methods capable of capturing the creep behaviour of soils. A popular method for capturing plasticity inside the yield surface is the bounding surface plasticity method due to its simplicity (Dafalias and Popov 1975). A bounding surface viscoplasticity method has been implemented in several cases to

### Table 1 Relationship between SSC indices, Cam-Clay and normalised parameters (after (Vermeer and Neher 2000b))

| Parameter                   | Relationship to cam-clay parameters | Relationship to normalised parameters |
|-----------------------------|-------------------------------------|---------------------------------------|
| Modified compression index  | $\lambda^* = \frac{\lambda}{1+e}$  | $\lambda^* = \frac{C}{2.3(1+e)}$     |
| Modified swelling index     | $\kappa^* = \frac{\kappa}{1+e}$    | $\kappa \approx \frac{3}{2.3} \frac{1}{v_{ur}} \frac{C}{1+e}$ |
| Modified creep index        | $\mu^* = \frac{C}{2.3(1+e)}$       | $\mu^* = \frac{C}{2.3(1+e)}$         |

$$\varepsilon_{ij}^c = \left(\frac{\partial \varepsilon_{ij}^{eq}}{\partial p}\right) \mu^* \left(\frac{p^{eq}}{p_p}\right) \left(\frac{\partial \sigma_{ij}}{\partial \varepsilon_{ij}}\right)$$

$$M = \sqrt{\frac{(1 - K_{nc}^0)^2}{(1 + 2K_{nc}^0)^2} + \frac{(1 - K_{nc}^0)(1 - 2v)(\frac{\lambda^*}{\kappa^*} - 1)}{(1 + 2K_{nc}^0)(1 - 2v)(1 - K_{nc}^0)(1 + 2v)}}$$

![Fig. 2 Location of the Latrobe valley and Yallourn open-cut brown coal mine, Victoria, Australia](image-url)
model time-dependent soil behaviour for drained and undrained behaviour during both primary and tertiary creep (Higgins et al. 2013; Mac et al. 2020; Xu and Zhang 2015), nevertheless, the research presented in this study focuses on the use of the Soft Soil Creep model.

### 4 Site condition and case study

#### 4.1 Location and background

The Latrobe Valley, located in the state of Victoria (Fig. 2), Australia, contains one of the largest brown coal deposits in the world, encompassing more than $43 \times 10^{10}$ tonnes of brown coal (Spurrier 1986). Three large open-cut mines exist in the region— the Hazelwood, Loy Yang and Yallourn mines, with Yallourn and Loy Yang currently in active use. The Yallourn mine is Australia’s second-largest open pit, containing continuous seams extending in excess of 100 m in

#### Table 2 Material properties, after (Ghadrdan et al. 2020a)

| Parameter          | Overburden | VBC  | Clay Interseam | Silt Interseam |
|--------------------|------------|------|----------------|----------------|
| Unit weight (kN/m³)| 21         | 11.5 | 20.2           | 20.2           |
| Cohesion (kPa)     | 20         | 155  | 16.5           | 8.67           |
| Friction angle (°) | 24         | 31.4 | 16.7           | 26.2           |
| Permeability (m/day)| 0.4       | 0.0605 | 0.0467     | 0.0467         |
| Elastic modulus (MPa)| 45     | 35   | 45             | 45             |
| Tensile strength (kPa)| 0  | 80   | 0              | 0              |

![Cross-sectional stratigraphy of the north-east batter and the presence of the major vertical joint at the crest of the better](image)

**Fig. 3** Cross-sectional stratigraphy of the north-east batter and the presence of the major vertical joint at the crest of the better
depth. The coal seams of the region are particularly sensitive to changes in water content and undergo rapid moisture loss and oxidation (Wen et al. 2020). Victorian Brown Coal (VBC), is a relatively lightweight Intermediate Geotechnical Material (IGM), with a specific gravity of approximately 1.1 g/cm and a moisture content of up to 60% (Moein et al. 2016). Geotechnical parameters demonstrated in several previous studies (Ghadrdan et al. 2020a, b; Karami and Tolooiyan 2020) highlight the necessary properties to simulate the constitutive behaviour of overburden, VBC and interseam materials (Table 2) as found within the mine, with Fig. 3 denoting the stratigraphy of the Yallourn north-east batter. Similarly, parameters necessary for the Soft Soil Creep constitutive model are presented in Table 3. The Creep Ratio $CR$ (Eq. 8) produces values of 2.7 and 5 for clay and silt, respectively. Values equal to 5 or less are often considered to be creep sensitive.

VBC permeability is highly variable due to the jointed nature of the material in situ. Tolooiyan et al. [2020] observed VBC permeabilities through Lugeon packer tests which vary significantly from permeability tests conducted on small-scale samples within the laboratory (Tolooiyan et al. 2020). A range of large coal joints have been observed within the region, through geotechnical and geophysical exploration methods, with one of the primary joints identified in the vicinity included at the crest of the slope geometry provided in Fig. 3 (Tolooiyan et al. 2019). Further

### Table 3 Proposed pit filling timelines and scenarios for the Latrobe Valley, after (Precincts and Regions 2020)

| Scenario                                                        | Hazelwood Fill duration (years) | End date for filling | Yallourn Fill duration (years) | End date for filling | Loy Yang Fill duration (years) | End date for filling |
|-----------------------------------------------------------------|---------------------------------|----------------------|--------------------------------|----------------------|--------------------------------|----------------------|
| Sensitivity to different assumed supply volumes                 | 20                              | 2041                 | 24                             | 2056                 | 22                             | 2070                 |
| Groundwater and surface water supply at licence and entitlement volumes rather than historic use | 15                              | 2036                 | 14                             | 2046                 | 14                             | 2062                 |
| Sensitivity to different assumed supply volumes                 | 19                              | 2040                 | 22                             | 2054                 | 28                             | 2076                 |
| Sensitivity to different assumed supply volumes                 | 19                              | 2040                 | 25                             | 2057                 | 32                             | 2080                 |
| Sensitivity to different assumed supply volumes                 | 19                              | 2040                 | 29                             | 2061                 | 37                             | 2085                 |
| No supply from power generator bulk entitlements                | 25                              | 2046                 | 34                             | 2080                 | 70                             | 2118                 |
| Groundwater supply 15 GL/yr to Loy Yang only, none to other mine sites | 25                              | 2050                 | 35                             | 2067                 | 58                             | 2106                 |

*Fig. 4 Variability of cored Yallourn interseam samples consisting of clay and silt (5 m core)*
details regarding joint interface properties, in addition to the joint characterisation and performance of the joint are found in Ghadrdan et al. (2020c) and Shagghazi et al. (2020a, b), respectively. The interseam layer underlying the primary layer of excavated coal contains a mixture of localised bands of clay and silt, which can be observed from a range of core samples extracted from the region (Fig. 4). The modified compression index ($\lambda^*$), swelling index ($\kappa^*$) and creep index ($\mu^*$) for a clay interseam were observed as 0.06, 0.006 and 0.02, respectively, while the values for silt were observed as 0.045, 0.01 and 0.007, respectively.

$$CR = \frac{\lambda^* - \kappa^*}{\mu^*} \quad (8)$$

4.2 Latrobe valley mine filling and water availability

Recent estimates place the volume of water necessary to partially fill the Yallourn mine void, attaining counterweight balance at approximately 1600 GL, with 2800 GL required to completely fill the pit, equivalent to five times the volume of Sydney harbour (Precincts and Regions 2020). Despite such a large magnitude of water, current progressive rehabilitation plans suggest that filling would likely take place over a period of decades, dependent on a number of external factors, including water availability as a function of dam storage, climate change, etc. Table 3 presents a range of filling times for each of the three Latrobe Valley mines, based on various constraints, suggesting a timeline for Yallourn pit filling between 14 and 35 years, as considered by the Victorian Government’s Regional Rehabilitation Strategy (Precincts and Regions 2020).

5 Numerical analysis

To consider the behaviour of the North-East batter for a range of potential filling scenarios, Finite Element (FE) models were initially developed, implementing the Hardening Soil (HS) model for VBC and the SSC constitutive model for interseam (Ghadrdan et al. 2020b) within the PLAXIS 2D FE environment (Version 21) (Brinkgreve et al. 2016). Due to the variability of the interseam, two simulation categories were considered – those consisting of a predominantly clay interseam material and those with a predominantly silt interseam. A staged construction procedure was implemented to investigate the time-dependent nature of the filling process consisting of ten filling stages, uniformly distributed between RL -44 and RL -4.

![Filling Stage 10: RL -4](image1)

![Filling Stage 1: RL -40](image2)

Fig. 5 Model groundwater levels at the commencement (RL -40) and conclusion (RL -4) of filling

![Finite element mesh distribution](image3)

Fig. 6 Finite element mesh distribution of the unexcavated model geometry
To investigate filling times, a total of ten pit-lake filling stages were used to model the filling process to the crest of the batter. Total filling times range from 5 to 40 years, at increments of 5 years. Each model stage consisted of Fully Coupled Flow Deformation (FCFD) calculations, followed by a Factor of Safety (FoS) stage, to determine the stability and associated failure of the slope at each filling level. For the purposes of the research, a full pit-lake scenario was considered, based on a set of “what if” scenarios for the potential filling rates, commencing from an initial slope excavation surface reached at the end of 2007. The initial study of creep-induced deformations does not incorporate overburden capping layers or reshaping of batters above the water level, due to the lack of public-access data regarding final pit-lake plans.

Fig. 7 Cross-section locations 1–8 used to assess model deformations and pore water pressures

Fig. 8 Deformation and pore water pressure profiles for location 1, modelled with a silt interseam, for a 5 year filling scenario
Groundwater levels for the FE model at the commencement and conclusion of filling are shown in Fig. 5.

The FE mesh contains 6243 triangular elements and 50,348 nodes (Fig. 6). To ensure that stress concentrations in the slope do not develop due to the

Fig. 9  Deformation and pore water pressure profiles for location 5, modelled with a silt interseam, for a 5 year filling scenario

Fig. 10  Total displacement contours at the conclusion of a 5 year filling scenario
location of the model boundary conditions, the geometry was sufficiently extended from the toe and crest of the slope. Left and right boundaries were horizontally fixed, with the bottom boundary fully fixed. Pore water pressures were controlled such that seepage can occur at vertical boundaries, with no seepage at the bottom of the geometry. To assess depth-dependent trends in deformation and pore water pressures, eight cross-section locations in the mine floor as well as close to the slope toe and crest were chosen, as shown in Fig. 7.

Figures 8, 9, 10 indicate the horizontal ($U_x$) and vertical deformation ($U_y$), and excess pore water pressures ($P_{\text{excess}}$) for Locations 1 and 5, indicating the behaviour at the toe and bench of the slope when considering a silt interseam and a filling regime of 5 years. The deformation profile for each case is given with respect to the initial deformation of the slope, prior to excavation (as indicated in Ghadrdan et al. 2020b). In each case, continual deformation is observed for each of the ten filling stages, particularly within the upper coal and interseam layers. The slope deformation, and excess porewater pressure profile at the conclusion of the 5 year filling period are given in Figs. 10 and 11. The level of total deformation at the conclusion of filling for each of the eight filling time scenarios (Figs. 12, 13) demonstrates that the rate of deformation is dependent on the rate of filling, with the rate of creep slowing as a result of the time required to reach the final water level. Deformation levels are presented with respect to the excavation stage, such that the filling time can be chosen based on the level of acceptable deformation. The level of creep is location dependent, with vertical deformation dominating in all cases.

To understand the predominant creep behaviour and the rate dependencies due to the filling process, the deformation and pore water pressure was assessed along cross-Sect. 6, slightly below the interseam boundary at an RL of −42 m. The results for the horizontal and vertical deformation along with their time derivatives, in addition to the excess pore water pressure for each of the filling regimes considered (5–40 years) are shown in Figs. 14 and 15. It is evident that the rate of filling impacts the level of deformation, for both silt and clay interseams. While a longer filling period results in an extended period of creep, inducing larger deformations (Figs. 14a and 15a), it is also evident that the horizontal and vertical deformation rates of change diminish rapidly over short filling periods (Figs. 14b and 15b). In the case of the less creep-sensitive silt interseam, a small rebound in deformations towards the initial slope geometry is most discernable at the conclusion of
the 5, 10 and 15 year filling scenarios (Fig. 14c and e). This can be attributed to the negative excess pore water pressure generation close to the crest of the mine, over shorter pit filling periods. This negative pore water pressure acts to keep the slope in tension, reduce the rate of deformation towards the pit void and produce a minor level of deformation towards the initial slope positioning. While this is the case when considering a silt interseam, the behaviour is absent for a clay interseam due to the lack of negative excess pore water pressure (Fig. 15c and e). The salient feature of both analyses is the ongoing (yet diminishing) deformation with time, despite the confining pressure applied to the batter by the pit-lake.

Figure 16 presents the FoS distributions for both materials. Although both materials exhibit continual deformation, due to the rate of movement coupled with the confining pressure of the pit-lake, an increase in the FoS is observed for both cases. Only minimal changes in the shape of the failure are observed throughout the filling process, with the typical slope failure surface given in Fig. 17.

Fig. 12 Comparison of deformation profiles at location 1 for a silt interseam scenario
6 Conclusion

Creeping and rate-sensitive soft soils are challenging materials for large-scale slope design. In the case of mine pit rehabilitation, the rate of filling is often constrained by a number of factors such as water availability. Although this is a primary factor in current pit-lake rehabilitation, the rate at which soft soils are loaded can also impact the behaviour of the mine slope. Results of numerical analyses using the Soft Soil Creep constitutive model present a set of scenarios based on mine filling rates for an Australian open-pit mine. Although continual deformation is noted throughout the filling period, with the rate of creep controlled by the speed of filling, the Factor of Safety remained unhindered by the loading process, indicating that based on the limited factors considered in this study, large-scale slope failure mechanisms as a result of changes to the water level are unlikely. Although the results highlight the behaviour of sensitive clays within pit-lakes, a number of additional factors for future consideration may provide further insight into their performance for mine rehabilitation scenarios. The angle of mine slopes above the final water level are commonly reduced to minimise failure and allow for long-term access and maintenance. Impermeable liners are also commonly implemented to

![Deformation profiles at location 5 for a silt interseam](image)
Fig. 14  Pit-lake deformation and excess pore water profiles at RL -40 for a silt interseam.  
(a) horizontal deformation  
(b) rate of horizontal deformation  
(c) vertical deformation  
(d) rate of vertical deformation  
(e) excess pore water pressure generation
Fig. 15 Pit-lake deformation and excess pore water profiles at RL -40 for a clay interseam a horizontal deformation b rate of horizontal deformation c vertical deformation d rate of vertical deformation e excess pore water pressure generation
produce a barrier inhibiting the infiltration of water, controlling groundwater pressures. Given the interplay between soft soil rate creep and rate sensitivity with respect to mine rehabilitation, the performance of partial pit-lake scenarios and final water levels, when combined with rate sensitive materials, presents a compelling case for future investigation.

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Data availability Specific data can be provided on request by the corresponding author.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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