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Simulation of cover stability on a slope containing a sub-layer of low hydraulic permeability

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Abstract

The intention of covers is to control water flow by reducing erosion risk through increasing infiltration, increasing water storage, but also minimising deep drainage. In conditions where an underlying sub-layer has very low permeability (e.g. brown coal) and where the landform is primarily sloped, soil stability may be reduced during events of high rainfall and exceedance of the storage capacity of the cover. When water accumulates in a cover on a low-permeability interface, hydrostatic stresses will increase, leading to a decrease in the Factor of Safety and potentially causing slope failure.

The objective of the study was to investigate the hydrologic performance of a sloped cover including a low-permeability sub-layer and quantify the Factor of Safety under a typical rainfall regime of the Latrobe Valley, Australia. Hydrologic parameters were measured and calibrated from glasshouse-controlled column experiments using HYDRUS-1D. The model's HYDRUS-2D and add-on module SLOPE CUBE were then used to simulate the hydrologic performance and slope stability.

The results showed that under current climatic conditions relatively high amounts of rainfall affected the stress distribution, mainly at the interface between cover material and coal. The calculated Factor of Safety was reduced but remained above the generally acceptable minimum design values (1.5~2.0). The column experiments showed that despite the very low permeability of coal, fractures through the coal matrix allow bimodal water flow and hence reduce the risk of water ponding on coal, reducing the risk of slope failure. However, predicted change in the regional rainfall regime may lead to situations of reduced stability during extreme events.

The concept of this study and pathway to quantify water flow and slope stability is transferable to similar cover designs, where a sub-layer of very low permeability, like geotextile, underlies the functional cover.

Keywords: *cover design, numerical mechanical–hydrological modelling, preferential flow, cracking*

1 Introduction

Coal slope coverage is a critical element of long-term mine pit rehabilitation in Gippsland's Latrobe Valley. Cover systems applied to mine slopes provide several key benefits, including reducing surface water infiltration and lowering the risk of fire associated with coal combustion. The design of rehabilitated mine slopes is typically guided by acceptable erosion rates and the accessibility requirements of maintenance machinery. While these factors are essential, the structural integrity of coal cover systems is equally significant.

Previous research conducted by Federation University's Geotechnical and Hydrogeological Engineering Research Group (GHERG) has shown that the shear behaviour of clay soils governs the performance of

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clay–coal interfaces on slopes. However, the influence of cover degradation, although observed, has not yet been examined. Compromised cover integrity can result in tensile cracking, erosion and increased water infiltration, leading to changes in pore pressures and soil mechanical properties that may trigger ground movements.

A pit lake rehabilitation option is currently preferred, and results in covers being required on pit slopes of varying lengths above the water level. To ensure the long-term integrity of a typical mine cover system supporting vegetation, a sufficiently thick substrate layer underlain by a low-permeability cover to prevent deep drainage is often considered to be required. Disturbance of the substrate layer can subsequently result in the failure of the cover layer due to erosion and desiccation. When considering the slope stability of the cover design including a low-permeability (water flow barrier) layer, there are additional drawbacks. In wet periods, a significant amount of water can build up on top of the sealing/low-permeability layer, reducing the available shear resistance. Furthermore, infiltration of water and the development of saturated conditions within the cover system can reduce the interface strength of the cover–underlying material, creating the potential for a critical slip surface (Deissmann et al. 2003). Cracking can be the result of differential settlement and change in moisture conditions of the cover system. Cracking is often considered the most significant feature affecting cover integrity and slope instability. Cracks can form in the cover system due to a critical level of suction which exceeds the tensile strength of the material, in combination with gravitational downslope forces. Previous studies have indicated that cracking of cover systems can occur when the water content of the cover dips below the plastic limit (Harison & Hardin 1994). Infiltration of water within the cover system, especially through vertical cracks, then has the potential to reduce the shear strength of the cover–coal interface due to water saturation. The flow of water through the substrate layer of the cover can sufficiently impact the magnitude of hydrostatic pressures building up within a slope material layer, with the risk of triggering failure events.

An example of a potential cover system that is typical for the Latrobe Valley is shown in Figure 1. The system comprises a topsoil layer placed over a clay capping layer that functions as the cover substrate. An optional drainage layer may be installed between the cover system and the underlying coal to facilitate downslope drainage of infiltrating water and to reduce the risk of water pressure build-up above or within the coal (Allen 2018).

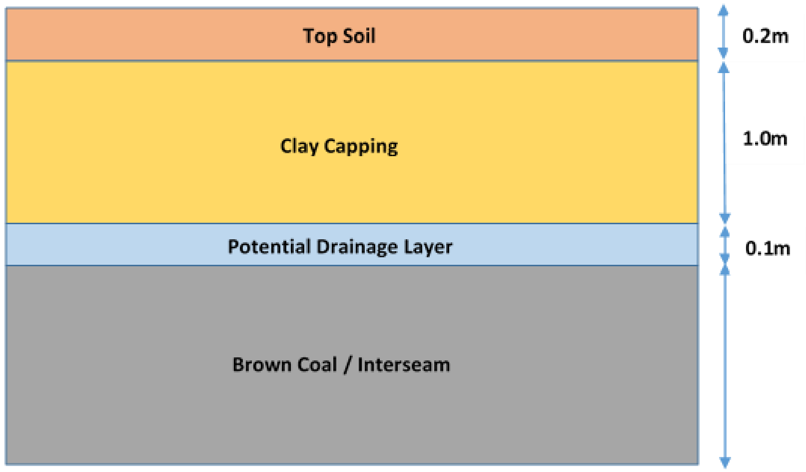

Figure 1 Illustration of a possible Latrobe Valley batter cover system

Water infiltration and wetting of the clay at the coal interface can subsequently affect mechanical properties by reducing the shear strength at this interface. For this specific cover design, an intact brown coal can act as an almost impermeable layer.

To reduce the risk of sliding, cover–coal interfaces are often shaped by creating a ‘keyed’, roughened surface between the 2 materials. These saw-toothed undulations significantly impact the shear strength of the interface as the roughness of the surface increases (Barton & Choubey 1977).

Patton introduced a relationship between surface roughness and shear strength as follows:

$$\tau = \sigma_n \tan(\varphi_b + i) \quad (1)$$

where:

τ = the interface shear strength

σ_n = the normal stress

φ_b = the basic friction angle of the surface and

i = the angle of the saw-tooth face.

Patton's equation is important for modelling the shear strength of material interfaces with numerical modelling software packages. The interface strength of materials is commonly measured in the laboratory using the direct shear test through the calculation of the interface shear strength (ASTM International 2011).

The objective of the project was to investigate the fundamental hydrological and mechanical processes occurring within coal cover slopes and their implications for slope stability by employing numerical simulations. Material properties determined through laboratory testing are used as input parameters for the simulations. The effects of cracking in both the cover material and the underlying coal are represented through bimodal hydraulic properties that characterise matrix–crack dual-porosity systems.

2 Material and methods

2.1 Laboratory analysis

Laboratory investigations involved establishing water retention curves for both coal and clay cover materials, as well as determining material strength parameters through unconfined compressive strength (UCS) testing. All testing was carried out using advanced soil and rock laboratory equipment at the GHERG at Federation University. The resulting data were then used as input parameters for numerical modelling to evaluate the hydrological and mechanical behaviour of coal cover systems.

2.1.1 Water retention curves

A water retention curve refers to the relationship between the water content and the soil water potential. This curve is characteristic for different types of soil, and is also called the soil moisture characteristic. It is used to predict the soil water storage, water supply to the plants (field capacity) and soil aggregate stability. In this project, water retention curves of coal and clay samples were measured in the laboratory using a combination of the dewpoint potentiometer WP4C and HYPROP instrument (both manufactured by METER Group, Inc., USA).

2.1.2 Unconfined compressive strength

The primary purpose of the UCS test is to obtain an approximate compressive strength value of the material. Results of this test will provide understanding of both strength and elasticity of materials.

UCS tests were performed on core samples of disturbed clay used to construct covers at Loy Yang Mine. Cylindrical samples with diameter of 38 mm and height of 76 mm were cored for UCS tests. After saturation, UCS and shear tests were conducted using a stiff-frame compression machine with a top bearing platen. From the UCS and shear test results, the material mechanical parameters, including cohesion, friction angle, Poisson's ratio and Young's modulus, were derived.

2.2 Numerical analysis

In this project, numerical simulations have been performed with HYDRUS-2D and associated SLOPE CUBE module (Simunek at al. 2008, 2012, 2020) to assess the hydrological and mechanical behaviour of coal cover slope models.

SLOPE CUBE represents a Slope Stress and Stability module for HYDRUS. It is a physically based hydro-mechanical framework focusing on assessment and prediction of the initiation and locations of landslide occurrences under rainfall conditions (Lu et al. 2010, 2012, 2013). It allows simulation of transient fields of soil moisture, soil suction, suction stress, total and effective stresses, slope displacement and local Factor of Safety. The module is intended to predict spatially and temporally infiltration-induced landslide initiation and to carry out the slope stability analysis under variably saturated soil conditions. Transient moisture and suction fields are directly obtained using HYDRUS, and are used to compute the effective stress field and displacement field in hillslopes. Furthermore, instead of the methodology of a single Factor of Safety for the entire slope in the classical slope stability analysis, the SLOPE CUBE module computes the field of Factor of Safety in the entire domain within hillslopes, allowing identification of the development of potential failure surface zone or surface.

The water balance and slope stability were analysed for different climate conditions. The impacts of cracking in coal and cover on water flow and slope performance were also investigated using HYDRUS-2D with HYDRUS-2D supporting dual-porosity models that can be used to simulate water flow in matrix-fracture systems.

2.3 Slope model configuration

A reference slope, chosen from the *Hazelwood Mine Fire Inquiry Report: Expert Report on Rehabilitation Relevant to Loy Yang Mine*, published in 2015 (Sullivan 2015), has been used for constructing the slope model for numerical simulations. This slope is chosen because it is representative for mine pit batter slopes for rehabilitation at Latrobe Valley brown coal mines. Figure 2 shows that a 3H:1 V coal slope, lying between 2 flat benches, is rehabilitated with a cover system consisting of a clay capping layer and a topsoil layer. The slope length is not specified but should be limited to less than 100 m, according to the report. The thickness of the cover system is not specified either. In a rehabilitation trial conducted on the western slopes in the open pit of one of the mines in the early 2000s, a 0.6 m clay layer and a 0.1 m topsoil layer have been placed over the exposed coal (Rienerts 2015). The in-pit lake water level in Figure 2 is set to above the lower bench. However, as pointed out by the original author, the major uncertainty relates to the final pit lake level and needs to be incorporated in rehabilitation designs; it is currently not defined or approved.

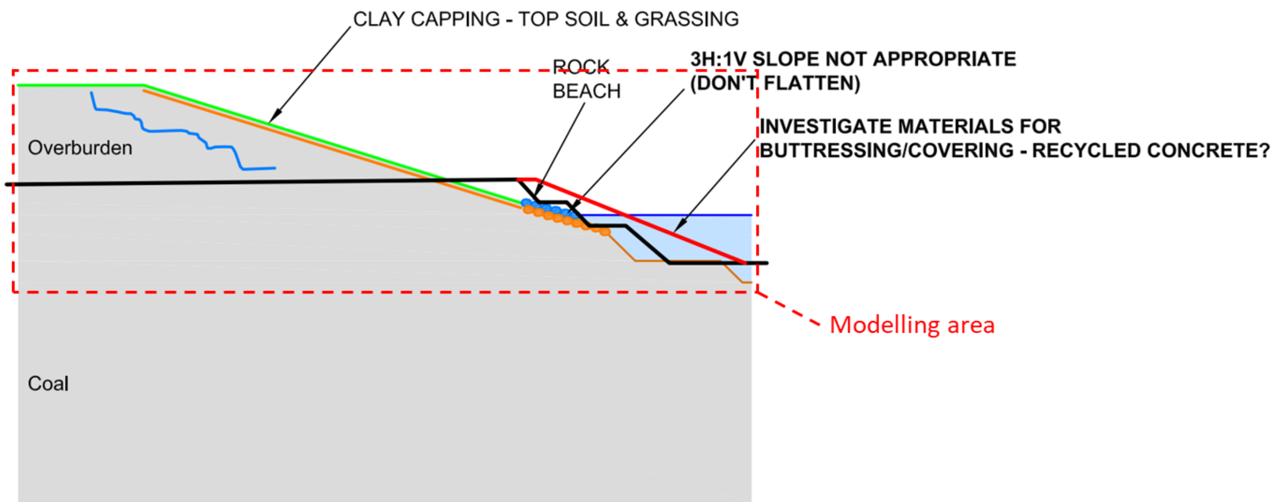

Figure 2 Reference slope showing planned rehabilitation for section of northern batters at Loy Yang Mine, Victoria, Australia (modified from Figure 15 in Sullivan 2015)

2.4 Geometry of slope model for simulation

Based on the reference slope (Figure 2), a 2D slope model for numerical simulations has been created. The 3H:1 V slope has a height of 30 m and a width of 90 m, resulting in a slope length of 94.87 m. The slope lies between a higher bench and a lower bench, both 20 m wide. A cover design with a clay capping layer thickness of 1 m and a 0.2 m-thick topsoil layer has been chosen. For this example, the in-pit water level is set to 26.2 m.

2.5 Slope model mesh and initial and boundary conditions

The simulation requires knowledge of the initial distribution of pressure head or the water content within the computational domain. In the slope model of interest for which a mesh has been generated as shown in Figure 3, a hydrostatic equilibrium pressure head initial condition is applied. The initial condition defines a depth-dependent distribution that is in hydrostatic equilibrium with the pressure head at the lowest point of the model domain. The pressure head at the bottom boundary is set to 39.35 m, with a slope of 7.88° applied in the X direction. This produces an inclined watertable located 11.85 m below the ground surface at the left side of the slope, rising to intersect the slope surface at the in-pit water level. Pressure head values are positive below the watertable and increase with depth, while negative values occur above the watertable and decrease towards the ground surface. The domain below the watertable is fully saturated, whereas the zone above is partially saturated, with water content decreasing towards the surface.

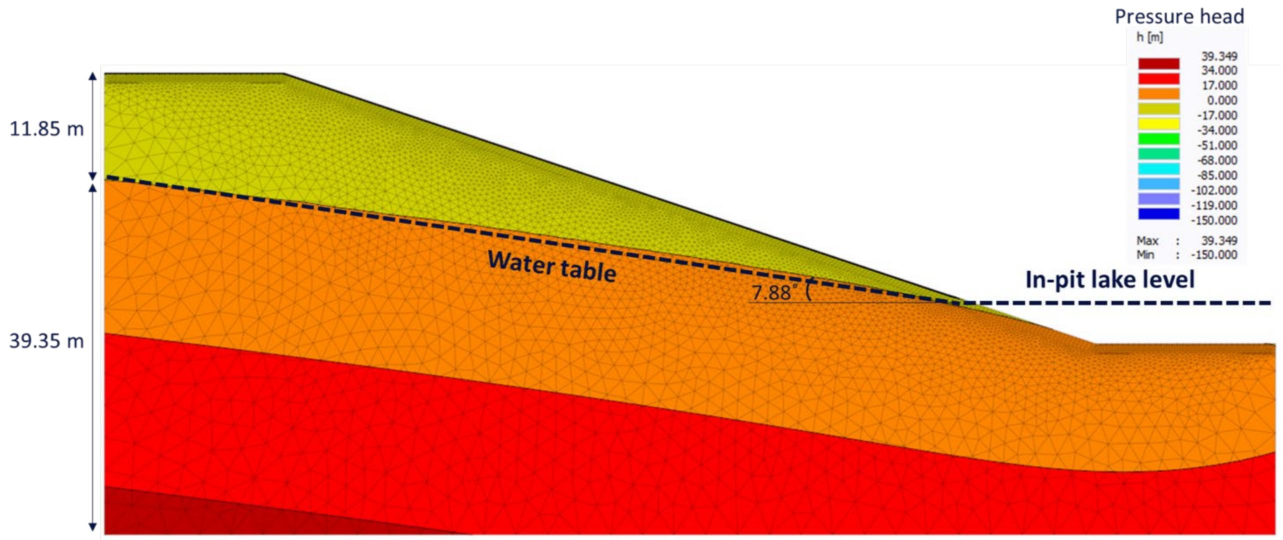

Figure 3 Geometric mesh and initial pressure head condition in hydrostatic equilibrium with an inclined watertable

Boundary conditions:

- **Atmospheric boundary condition**, assigned to top bench surface. With this boundary condition, time-dependent precipitation rate and evaporation rate must be specified.
- **Atmospheric–seepage face boundary condition**, assigned to slope surface and bottom bench surface. With this combined boundary condition, water leaves the saturated part of the flow domain through a seepage face. On the unsaturated part of the boundary, the atmospheric boundary condition is applied to account for precipitation and evaporation.
- **Constant pressure head boundary**, assigned to side boundary sections below the watertable. With the boundary condition, pressure heads are fixed at corresponding boundary nodes.
- **No flow boundary conditions**, assigned to left boundary section above the watertable. This boundary condition implies an impermeable boundary where the flux is zero perpendicular to the boundary.

2.6 Material properties

2.6.1 Hydraulic properties

Water retention curves of coal samples have been measured in the laboratory using a combination of a dewpoint potentiometer WP4C and HYPROP (Meter Inc., USA). The van Genuchten parameters used in numerical simulations are derived through a fitting process from the measured curves and summarised in Table 1.

The hydraulic parameters for the matrix of topsoil and cover (Table 1) were derived from a combination of laboratory measurement and values suggested values by the HYDRUS program for loam and clay. The laboratory measurements were validated by cover column experiments carried out in the glasshouse with a comparable cover design. The van Genuchten parameters were refined by inverse parameter fitting for a cover design not affected by shrinkage cracks within the clay cover substrate (see also final report: CRC TiME, 2024).

Table 1 Input hydraulic properties (van Genuchten parameters) for the matrix of topsoil, cover and coal

	$\boldsymbol{\theta_r}$	$\boldsymbol{\theta_s}$	$\boldsymbol{\alpha}$ (1/cm)	n	$\boldsymbol{K_s}$(cm/day)
Topsoil matrix	0.078	0.43	0.016	1.56	24.96
Cover matrix	0.068	0.38	0.008	1.23	4.8
Coal matrix	0	0.728	0.00037	3.38	0.03
Cracks/macropores	0	1.0	0.3	6	–

The investigated slope cover systems is susceptible to crack formation, leading to an alteration of hydraulic properties which can be explained by a bimodal pore size distribution. Cracks and fractures are also found in coal on which the cover system is built. Cracking is often considered the most significant feature affecting cover integrity and slope stability, by enhancing the infiltration of rainwater and potentially increasing porewater pressure and reducing values of soil mechanical properties describing mechanical stability.

To include the effect of cracking on slope hydrological and mechanical behaviour in numerical simulations, a dual-porosity system of matrix and fracture has been simulated. Bimodal hydraulic properties are determined for topsoil, cover and coal using an extended van Genuchten–Mualem model to dual-porosity systems by Durner (1994), based on the weighting of cracks/fractures/macropores in the system. Weighting factors of cracks ranging from 0% to 20% are applied to topsoil and cover, and those ranging from 0% to 10% are applied to the coal. The resultant saturated hydraulic conductivity values for these matrix-fracture dual-porosity systems are summarised in Table 2. Figure 4 shows an example of the impact on the shape of the water retention curve. Cracks/macropores only play a role close to the saturated state in increasing hydraulic conductivity when the water suctions are small.

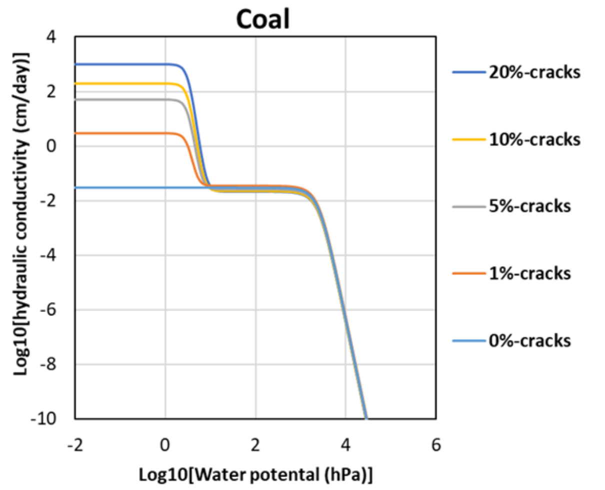

Figure 4 Hydraulic conductivity curves for matrix-fracture dual-porosity systems of coal with varying weighting of cracks/macropores

Table 2 Saturated hydraulic conductivity values for matrix-fracture dual-porosity systems of coal, cover and topsoil, with varying weighting of cracks/macropores

Weighting of cracks	Coal	Cover	Topsoil
0%	0.03	4.8	24.96
1%	3	10	40
5%	50	48	99.84
10%	200	144	249.6
20%	1,000	480	998.4

2.6.2 Mechanical properties

Mechanical properties were determined from laboratory UCS tests conducted on core samples of disturbed clay used in cover construction at Loy Yang Mine. The resulting strength parameters for the 3 substrate groups (topsoil, clay cover and coal) are summarised in Table 3. In general, the topsoil exhibits higher strength than the underlying clay, largely due to reinforcement from plant root systems. Accordingly, the topsoil was assigned doubled values of cohesion, friction angle and Young's modulus, as presented in Table 3. In addition, mechanical properties for the coal were obtained from a review of relevant literature (Karami & Tolooiyan 2020; Shaghaghi et al. 2020). Although coal has a lower specific gravity than the cover and topsoil materials, its strength parameters are considerably higher.

Table 3 Input mechanical properties (SLOPE CUBE parameters) of topsoil, cover and coal

	Topsoil	Cover	Coal
Specific gravity (–)	2.72	2.72	1.174
Cohesion (kPa)	48	24	150
Friction angle (°)	32	16	32
Poisson’s ratio (–)	0.3	0.3	0.3
Young’s modulus at dry state (kPa)	10,200	5,100	35,000
Young’s modulus at wet state (kPa)	3,800	1,900	7,000
Power law parameter m (–)	0.56	0.56	0.25

3 Results and discussion

3.1 Set-up of simulation, data reference

Numerical simulations have been performed using HYDRUS-2D and SLOPE CUBE on the slope model (Figure 3) with 5% crack weighting for coal and 10% crack weighting for both topsoil and cover, under various rainfall conditions. These weighting factors were adopted as the resultant hydraulic parameters and are considered to have the most realistic values. Before the application of natural rainfall during 3 years from 2018 to 2020, an initial synthetic rainfall event was applied to allow the slope to reach a state of equilibrium.

For interpretation of results, 8 observation points along the slope were introduced in 2 depths of the cover (4 observation points for each depth).

A synthetic rainfall event was initially applied to allow the slope to identify its typical equilibrium and to verify this state as initial condition for the real rainfall simulation scenarios. The synthetic event comprised 10 days of continuous rainfall at 15 mm/day, followed by 720 days of dry conditions, with a constant evaporation rate of 3 mm/day. Over the 2-year period, total rainfall was 150 mm and total evaporation was 2,190 mm.

Following the establishment of equilibrium conditions using the synthetic rainfall event, 3 years of observed rainfall were subsequently simulated in the slope model. Daily rainfall and evaporation data for the period 2018–2020 were obtained from Bureau of Meteorology weather station at Latrobe Valley Airport (Morwell), Victoria. Rainfall occurred throughout the 3-year period but exhibited substantial day-to-day variability. The highest recorded daily rainfall was 40 mm, occurring in 2020 (Figure 5).

Rainfall characteristics varied notably between years. The year 2018 was comparatively dry, with a total annual rainfall of 499.4 mm, representing only 68.1% of the local mean annual rainfall of 733.3 mm. The maximum daily rainfall in 2018 was 20 mm, and no significant rainfall events were observed. In 2019, total rainfall increased to 668.8 mm, remaining below the long-term average, though 3 major rainfall events in the latter half of the year led to sharp increases in cumulative rainfall. The maximum daily rainfall recorded in 2019 was 32 mm. The wettest year was 2020, with a total rainfall of 766 mm, exceeding the long-term mean. The largest rainfall event across the 3-year period occurred in 2020, with a peak daily rainfall of 40 mm, along with several smaller events throughout the year.

In contrast, potential evaporation exhibited relatively minor seasonal and interannual variability. Daily evaporation rates ranged from 0.5 mm/day to 13 mm/day and were generally lower between April and September, likely due to reduced temperatures and shorter daylight hours. Total annual potential evaporation amounted to 1,201.3 mm in 2018, 1,260.8 mm in 2019, and 1,045.6 mm in 2020, exceeding annual rainfall in all cases. Consequently, the net water balance was negative for each year, with values of −701.9 mm, −592.0 mm, and −276.6 mm, respectively.

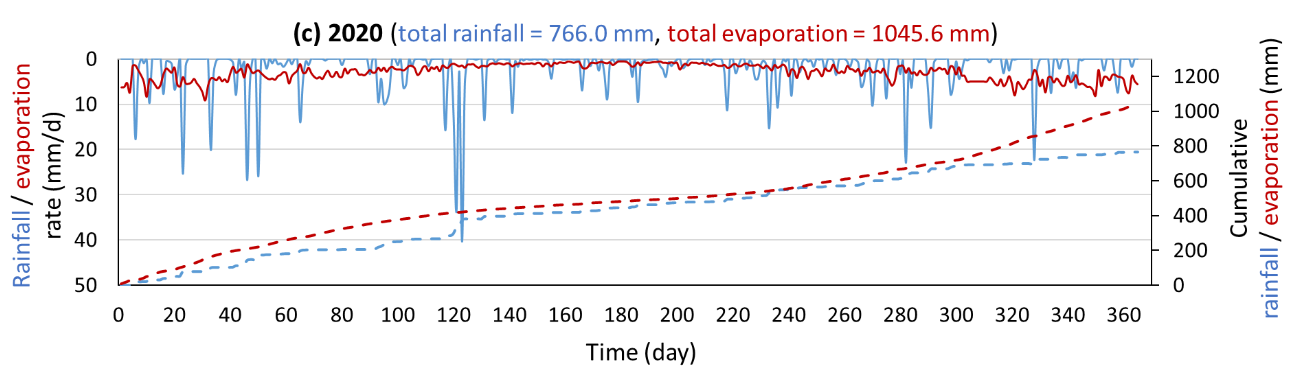

Figure 5 Daily rainfall and evaporation data for exemplary year 2020 recorded at Latrobe Valley Airport (Morwell), Victoria (source: Bureau of Meteorology website). Blue and red curves show the rainfall and evaporation, respectively. Solid and dashed curves show the rate and cumulative values, respectively

3.2 Simulation results

3.2.1 Fluxes across atmospheric boundary

Simulated fluxes across atmospheric boundaries from 2018 to 2020 show that infiltration rates closely followed rainfall patterns, while actual evaporation rates were consistently lower than potential evaporation due to limited soil water availability (Figure 6). As a result, total infiltration exceeded evaporation in all 3 years, producing net inward fluxes to the slope domain despite annual precipitation being less than potential evaporation. The amount of water entering the slope was influenced not only by total rainfall but also by rainfall intensity, frequency and duration.

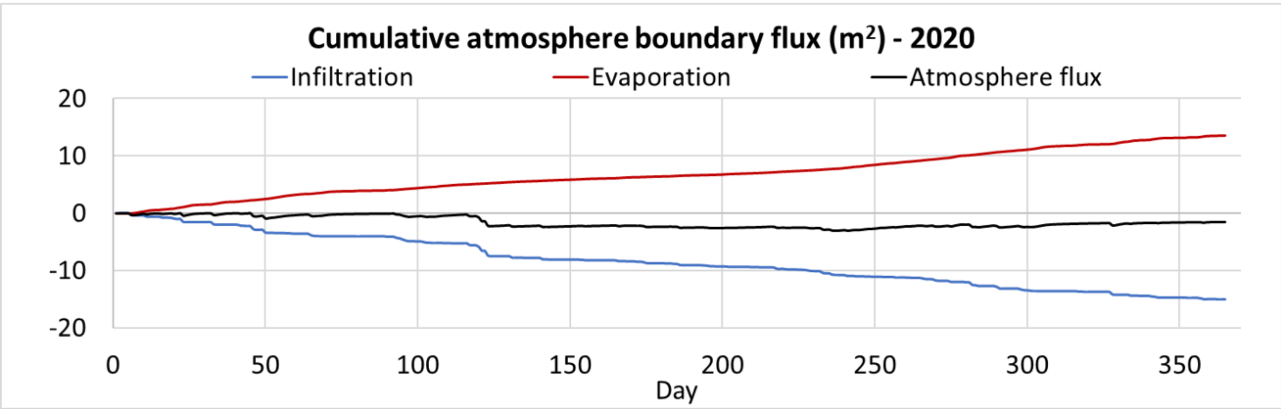

Figure 6 Example of data for cumulative flux across atmosphere boundaries in 2020. Blue, red and black curves show infiltration, evaporation and net flux, respectively

3.2.2 Fluxes across coal–cover interface

Flux across the coal–cover interface was monitored at 4 locations to assess flow behaviour during 2018–2020. Flow direction and magnitude varied by interface position and rainfall conditions. At the top bench, flow shifted from upward to downward as rainfall increased cover pressures, but cumulative flux remained small. At the upper slope, predominantly upward flow was observed, though intense rainfall events in wetter years caused temporary downward flow; cumulative fluxes there were substantially larger than at the top bench. Interfaces below the watertable exhibited consistently upward flow from coal to cover across all years, with large and nearly constant cumulative fluxes unaffected by rainfall variability. Water exiting the cover at these lower interfaces ultimately discharged through seepage boundaries into the in-pit lake.

3.2.3 Pressure head, water content and suction stress

For interpretation of simulation results in the slope domain, time-series of hydrological data were recorded at the selected observation points. Pressure head and water content change with time at these points following wetting or drying events. At the shallower observation points lying along the topsoil–cover interface, which is 0.2 m below the land surface, the hydrological properties showed large sensitivity to the rainfall/infiltration rates. In all 3 years (2018–2020), pressure head and water content both increased quickly during rainfall events, and decreased gradually in subsequent dry periods. Close to zero pressure heads and close to full saturation water contents were observed at times, suggesting that large rainfall events caused almost full saturated conditions.

The deeper observation points located along the coal–cover interface at a depth of 1.2 m from the land surface showed slower and more moderate responses to the variations of rainfall than the shallower points. Close to zero pressure heads were identified for the wetter years 2019 and 2020. These close to zero pressure head and close to full saturation water content values indicate that a sufficient amount of water had infiltrated, primarily through the crack flow paths, the cover during large rainfall events to cause nearly full saturation at the coal–cover interface.

HYDRUS and SLOPE CUBE assess slope stability using the concept of suction stress rather than porewater pressure. Suction stress integrates various interparticle forces in unsaturated soils and depends on soil moisture conditions through the suction stress characteristic curve. This approach effectively represents soil failure behaviour and provides a practical measure of stress in unsaturated soils, equating to porewater pressure under saturated conditions but being smaller when soils are partially saturated. In SLOPE CUBE, suction stress is calculated using van Genuchten soil water characteristic parameters.

The analysis of the suction stress data at all observation points shows that at the beginning of the simulation (early 2018), suction stress follows a pattern similar to that of pressure head: values are positive below the watertable and increase with depth, while remaining negative above the watertable and decreasing toward the ground surface. By the end of the simulation period (late 2020), suction stress in the unsaturated zone – encompassing both the cover and coal layers above the watertable – had increased to values close to zero because of higher degrees of saturation (Figure 7). This increase in suction stress leads to a reduction in effective stress, which consequently decreases the soil shear strength.

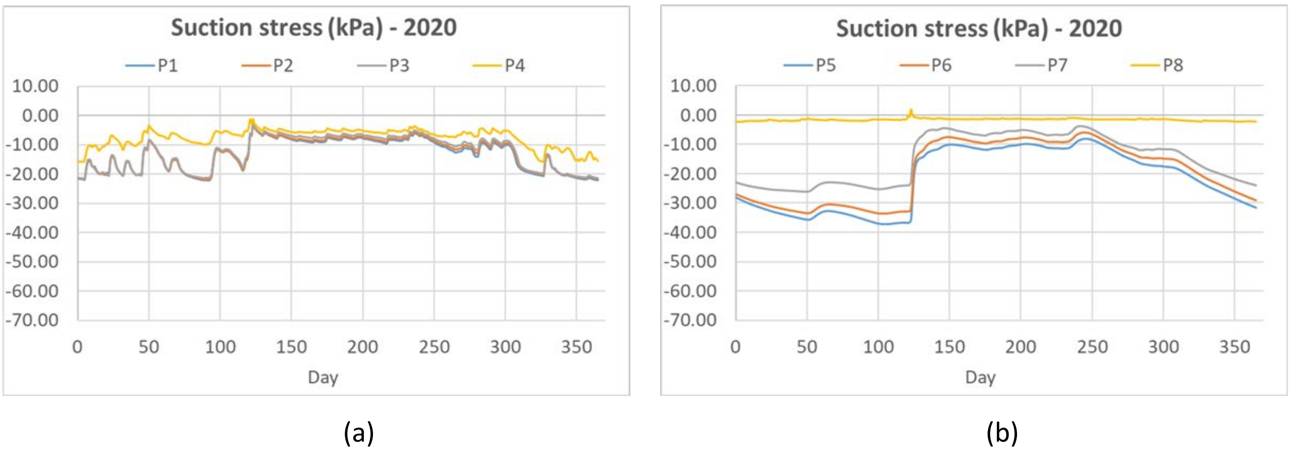

Figure 7 (a) Change of suction stress at observation points along the topsoil–cover interface (P1–P4); (b) Coal–cover interface (P5–P8) – 2020

3.2.4 Local Factor of Safety

The modelling approach used in HYDRUS and SLOPE CUBE allows slope stability to be assessed locally across different parts of a slope rather than using a single overall safety value. Results show that slope stability varies with depth and moisture conditions, with shallow layers near the surface being more sensitive to rainfall, while deeper zones are less affected (Figure 8). Although stability generally remains well within acceptable design limits, periods of intense and prolonged rainfall can significantly reduce local stability, indicating a higher risk of slope failure under extreme wet conditions.

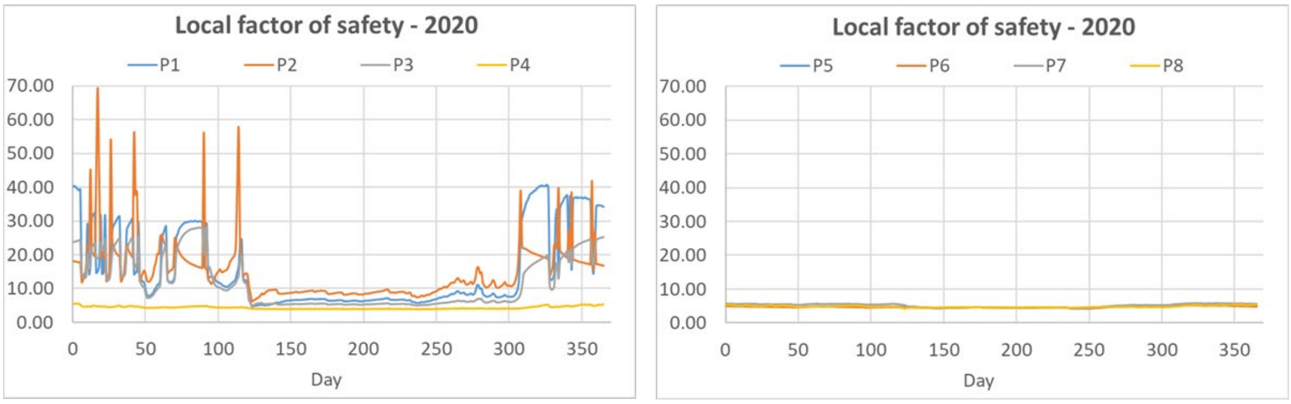

Figure 8 (a) Change of local Factor of Safety at observation points along the topsoil–cover interface; (b) Coal–cover interface – 2020

4 Conclusion

This project used numerical modelling, supported by laboratory testing, to investigate the hydrological behaviour and stability of rehabilitated coal cover slopes in Latrobe Valley brown coal mines. Laboratory measurements provided key hydraulic and mechanical properties for coal and soil materials, which were incorporated into a slope model based on a reference rehabilitation design, with Loy Yang Mine used as an example based on information provided by the Hazelwood mine fire inquiry. The model accounted for the effects of cracks on water flow, recognising their role in increasing hydraulic conductivity near saturation.

Simulations were carried out using HYDRUS-1D, HYDRUS-2D and the SLOPE CUBE module, beginning with a synthetic rainfall period to establish equilibrium, followed by simulations using observed climate data from 2018–2020. Results showed that water infiltration into the slope generally exceeded actual evaporation, despite higher potential evaporation rates. Shallow layers near the surface were found to be more sensitive to rainfall, showing greater changes in moisture conditions, stress and stability, while deeper layers were less responsive except during extreme rainfall events.

Overall, wetter conditions led to increased saturation, reduced soil strength, lower local Factors of Safety, and increased slope displacement. However, even under extreme rainfall, stability remained within acceptable design limits and predicted displacements were small.

The study provides a sound base case understanding of slope behaviour, which can be used to assess alternative scenarios, designs including scenarios of climate change and support future optimisation of rehabilitation designs.

Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used Microsoft Copilot to improve language. The authors have reviewed the content and edited it where required and take full responsibility for said content.

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