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A first-principles approach to mine closure and risk in a complex system: Yallourn Mine

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Abstract

In mines with complex systems, it is difficult to capture key technical elements for successful closure planning and design using conventional geotechnical approaches. These conventional approaches typically rely on prescriptive processes, heuristics and reasoning by analogy derived from sites where the conditions that govern stability are often more predictable. This paper presents a first-principles approach to mine closure, demonstrated through a case study at Yallourn Mine in the Latrobe Valley, Australia. The Yallourn Mine constitutes a complex system with many mutually interacting components where stability is fundamentally sensitive to water loading. Substantial topographic relief surrounds the site, with large areas well above free-spilling lake level, presenting a potential destabilising water load risk to mine batters. Successful rehabilitation involves the effective capture and controlled discharge of peripheral catchment water into the void, achieved through a pit lake and peripheral catchment drain system.

A first-principles approach derives the design solution from the basic facts of the system rather than from convention or analogy. Nonetheless, a logical risk-based framework is followed: a 2-tier risk evaluation, combining domain-specific technical risk ratings with a conventional consequence assessment to produce design criteria for each domain. Those criteria directly inform the peripheral drainage design, through targeted block sliding stability analyses along peripheral catchment alignments, from which drain requirement, extent and sizing are systematically derived. The process links the probability of hydrologic exceedance, geotechnical stability and consequence class into a coherent design framework. The integrated assessment produces practical drainage outcomes based on analytical results and validated by decades of empirical monitoring data.

Keywords: *first-principles thinking, risk-based design, design acceptance criteria, DAC, slope stability, peripheral catchment drainage, mine rehabilitation, complex geotechnical system*

1 Introduction

Yallourn Mine is one of the largest open pits in Australia and is located in the Latrobe Valley in Eastern Victoria. The mine has been in operation for over 100 years and will continue extraction of brown coal until the planned end of mining (EOM) in 2028 when it will enter the rehabilitation phase. The Latrobe Valley and the brown coal mines it contains constitutes a system with many mutually interacting components that have evolved and become more complex over a long time. Geotechnical stability is related to that history. Significant stability incidents have historically occurred over short time intervals compared to the period of their development. Sudden transitions to instability are typical of the dynamics of complex systems; this has the potential for the system to become self-organising in its internal structure.

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Risks can be difficult to recognise in complex systems where conditions may lie outside the experience base of conventional design approaches, and even with detailed investigation and analysis, engineering judgment is key (Sullivan 2006). It is therefore difficult to capture key technical elements for successful closure planning and design using conventional geotechnical approaches. Early mine rehabilitation studies across the industry attempt to specify design criteria that apply in all circumstances. More recent guidelines have increasingly adopted risk-based frameworks, but these still typically rely on prescriptive processes, heuristics and reasoning by analogy, which assume historical precedent from sites where the conditions that govern stability are more predictable. In doing so, these approaches can often result in broad objectives that may conceal the assumptions embedded within them.

This paper presents a first-principles approach to mine rehabilitation demonstrated through a case study at Yallourn Mine. First-principles thinking derives the design solution from the basic truths rather than using convention or analogy. This process begins with a clearly defined goal, establishes the fundamental facts of the specific system, and derives the design solution from those facts alone. The case study demonstrates how first-principles thinking defines the primary objective more precisely, in this case study is: how to achieve long-term batter stability through passive water management in a system fundamentally sensitive to surface water loading from peripheral catchments. Through this first-principles approach, using a logical risk-based framework, the design criteria are the technical answers derived from the basic facts of the system.

2 Yallourn Mine and rehabilitation approach

2.1 Site setting and key characteristics

Several governing characteristics control stability and rehabilitation outcomes at Yallourn. The Latrobe Valley mines are different to other mines in that they comprise very large open pits with very thick, very low density coal seams. The mine comprises 2 very large excavations: the Yallourn Township Field (YTF) pit in the west, and the Yallourn East Field (YEF) and Maryvale Field (MVF) pits in the east (Figure 1). The 2 voids are separated by the Morwell River Diversion (MRD) – an elevated man-made structure tens of metres above the adjacent mine floors.

The coal sequence contains sub-vertical joints that allow direct access for water into the batter profile and is underlain by soil-strength interseam clays of very low residual strength. The coal density is only slightly greater than water, and because the coal seams are very thick, coal makes up a large proportion of the batter profiles. This means that stability of the batter slopes is highly sensitive to any water loading (Sullivan 2007). Given the fundamental sensitivity of these mines to water loading and defining the rehabilitation challenge, several significant stability incidents have occurred in the region; these range from large-scale failure and deformations to local cracking in critical areas (Sullivan 2008; Jones et al. 2024).

Several additional characteristics further compound this challenge, as shown in Figure 1:

1. Large areas of the mine were floodplains of the Latrobe and Morwell rivers, both of which have been diverted to various extents throughout mining operations.
2. Substantial topographic relief surrounds the mine, with large parts well above the planned pit lake level of RL 37 m. The peripheral catchments present a source of potential destabilising water load risk to the mine batters.
3. The mine was deliberately sited to avoid complex large-scale geological structures, enabling safe and efficient mining. However, these structures remain close to (but outside) the mine crests as a legacy rehabilitation issue.
4. The mine batters are old, sensitive to loading events, with extensive historical cracking and a history of significant stability events some of which are linked to legacy decisions made during previous ownership by the State Electricity Commission of Victoria.

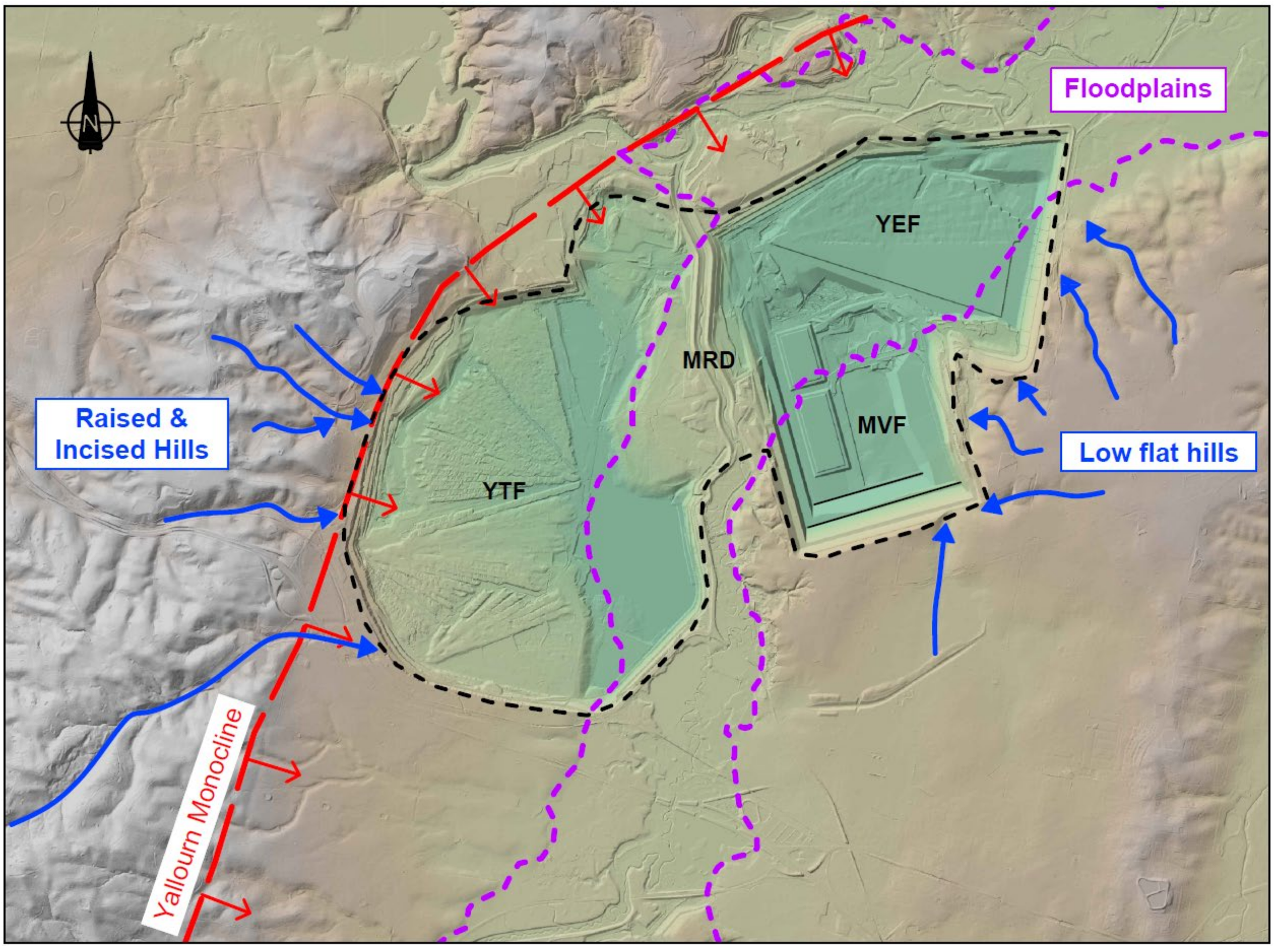

Figure 1 Mine setting and key elements

2.2 Summary model for rehabilitation

The interaction between these key site characteristics that impact on stability and rehabilitation is illustrated in the schematic model in Figure 2. The model illustrates 4 principal factors that govern long-term stability and rehabilitation outcomes:

- rising topography and peripheral catchments outside the mine, which represent pre-existing surface catchments of variable sizes and run-off characteristics, truncated by mining and with old man-made diversion systems
- a deformed zone of old coal batters, characterised by increased cracking, open joints, deteriorated rock mass properties, and heightened sensitivity to water loading from the catchment above
- in-pit support to stop large-scale batter movements provided by either lake filling or pit floor buttressing or a combination of both
- bedding dip relative to the mine batters and the presence of major folding.

General and Latrobe Valley experience has demonstrated that adverse water pressures and failure of man-made diversions have played a role in all significant stability incidents in the region. The model therefore establishes the conceptual basis from which the rehabilitation strategy is derived.

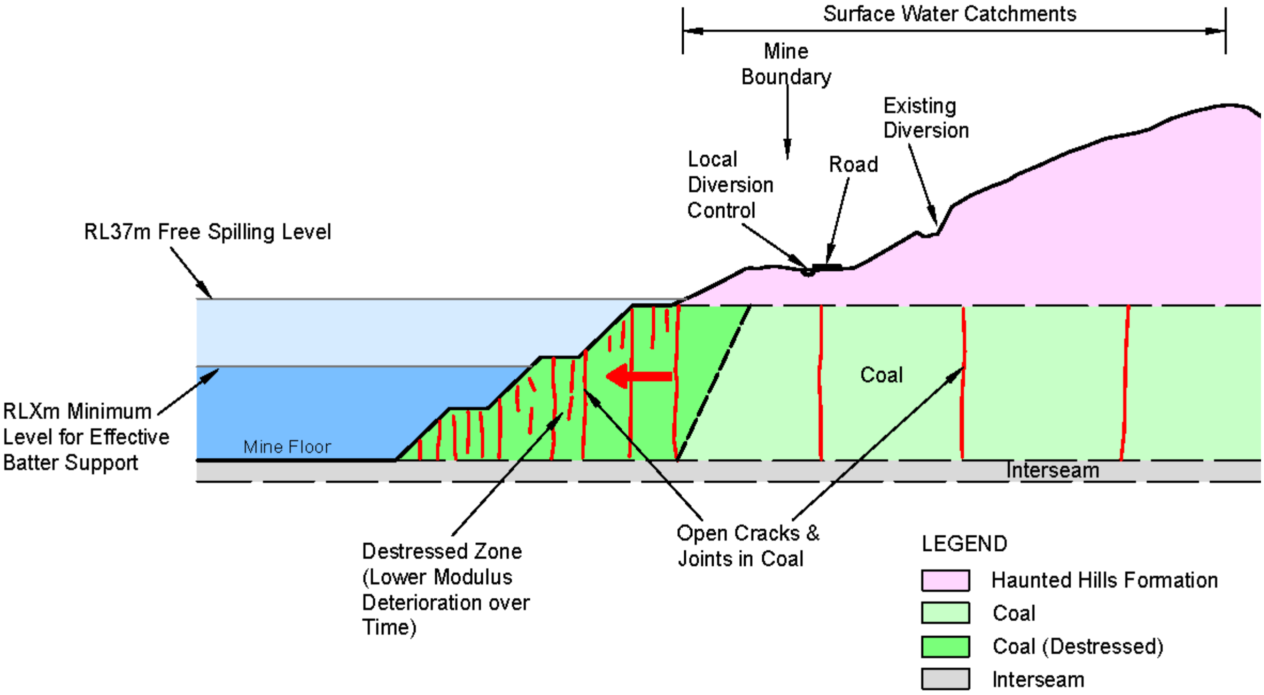

Figure 2 Summary model of principal factors and considerations for rehabilitation

2.3 Rehabilitation strategy

The fundamental site facts established in the preceding sections define what the rehabilitation design must achieve. Firstly, stability is sensitive to water loading from multiple sources, including the surrounding rivers, peripheral surface water catchments and groundwater. Secondly, passive management is necessary because active intervention cannot be guaranteed in perpetuity. Finally, because the system is large, variable and complex, no single uniform response will be adequate across all domains.

The rehabilitation strategy therefore focuses on 3 key elements: batter stability, effective control of surface water, and the potential beneficial use of water for stability control where possible. Engineering geomorphology also forms an important input, since the historical behaviour of the pre-mining landforms informs the design of stable rehabilitated slopes (see Chan et al. 2026).

Understanding the main factors that could undermine these elements is essential to the strategy. There are 3 types of natural factors that could shape or destabilise future rehabilitation landforms:

1. Preparatory factors, including long-term creep movements and crack development of the old batters, and adverse changes in the groundwater system.
2. Controlling factors, including bedding dip in coal and its direction relative to the mine, the presence of major geological structures, and the catchment drainage pattern.
3. Triggering factors, including intense rainfall in peripheral catchments and flooding, which could lead to failure of a diversion system, direct large uncontrolled flows over sensitive mine batters, or cause large-scale movement or failure of the batters.

The rehabilitation strategy is aimed at understanding and accounting for the preparatory and controlling factors in design, and at eliminating or controlling the triggering factors. Of these, the peripheral catchment rainfall contribution is the one most amenable to engineering control, and its elimination is the basis of the rehabilitation strategy.

The rehabilitation approach is therefore to drain the peripheral catchments into the mine in a controlled manner, returning the surface water environment somewhat to the pre-mining condition and favouring soft engineering approaches within a total catchment framework. This simultaneously manages the destabilising water load risk and contributes to the beneficial filling of the pit lake. Within this first-principles based strategy, the design of the peripheral drainage structures required to achieve this is thus inherently linked to and inseparable from the geotechnical rehabilitation design.

2.4 Rehabilitation domains

The mine has been divided into discrete rehabilitation domains. The domains are mostly based on the mine batter alignments, but also reflect the physical conditions of the ground, including geology, geotechnical characteristics, groundwater conditions and surface water catchment boundaries. They also consider internal infrastructure such as the MRD, external infrastructure, and future mining. Some of the domain boundaries as a result extend well beyond the mining licence.

These domains collectively form the basis for the risk-based domain classifications, which were assessed against the historical understanding of the factors controlling batter movements and stability in the Latrobe Valley, as described in Section 2.1. The domains therefore represent distinct technical areas from which specific design criteria are developed based on the main constraints of each area. This ensures that the design accounts for the spatial variability across the mine and that the outcomes are formulated based on the unique domain-specific conditions.

3 Risk evaluation

3.1 Overview of framework

The rehabilitation strategy requires a framework to systematically capture the variability of conditions across the domains. Given the mine’s large scale and the range and variability of settings around the mine, there are many complex technical factors and inter-relationships between the technical factors to be assessed. To capture all the elements needed for effective rehabilitation, a 2-tier risk evaluation has been adopted, combining technical and conventional consequence evaluations:

1. Tier 1 uses separate evaluations of the geotechnical and surface water technical risk ratings.
2. Tier 2 uses a conventional failure consequence rating and ensures the designs effectively deal with the potential consequence issues related to safety, environment, land and property, and cultural heritage.

3.2 Technical risk ratings

3.2.1 Geotechnical risk assessment

A geotechnical risk assessment framework is formulated from first principles to qualitatively define and classify the rehabilitation domains. The relative risk has been qualitatively assessed for each domain by evaluating all the important technical areas that contribute to instability, grouped into 2 elements: base conditions and system responses.

The base conditions have been assessed semi-quantitively to represent the inherent constraints of the system that dictate the basic risk setting, recognising that surface water bodies and geological structure are the major drivers of instability at Yallourn. Numerical ratings are assigned to each element, for example whether a domain catchment comprises a floodplain or an external catchment, and whether geological structure is favourable (bedding dipping out of the pit) or adverse (bedding dipping into the pit and/or major structures in the slope).

The system responses identify whether other factors have exacerbated the underlying risk setting over time to capture the temporal evolution of the domain. Numerical ratings are assigned on elements such as groundwater responses observed in piezometer data, pin monitoring data indicating slope movement, and observed physical deformations ranging from minor cracking to major cracking and significant slope deformation.

The base conditions score and system responses score for each domain are plotted against each other as shown in Figure 3a. The assessment results in 3 risk rating groups: 'lower', 'medium' and 'higher'.

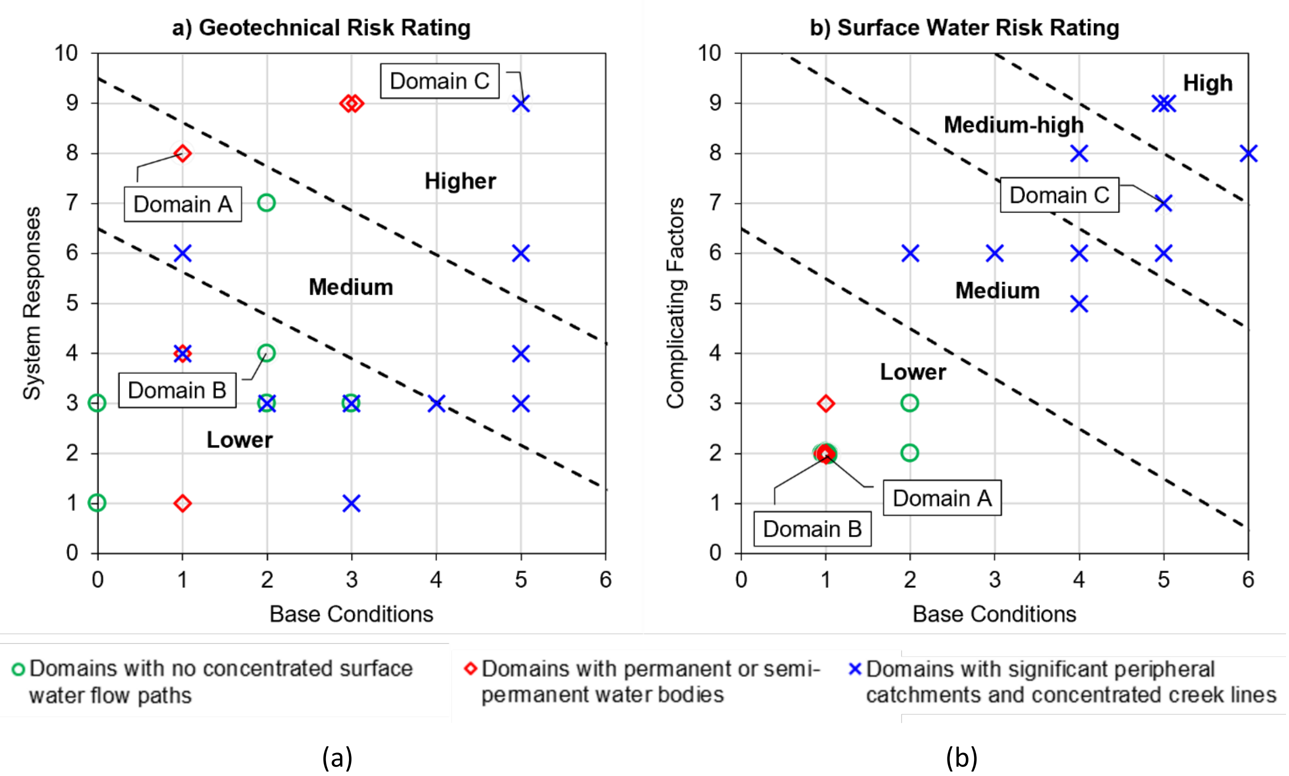

Figure 3 Teir 1 technical risk assessment for rehabilitation domains grouped by landform type; (a) Geotechnical risk rating; (b) Surface water risk rating

3.2.2 Surface water risk assessment

The surface water risk assessment framework, developed from first principles, assesses the important factors for control of potential adverse surface water loading events on mine stability. The assessment groups the relevant technical areas into base conditions and complicating factors.

The base conditions are the inherent factors that categorise the domain, i.e. catchment size and the nature of the peripheral catchment. These range from no substantial catchment in low-lying flat terrain, which is considered a more easily controllable situation, to multiple large catchments in steep rising terrain, which presents greater engineering and design difficulty.

The complicating factors are those elements that would increase future design complexity. These include the complexity of existing surface water diversion infrastructure, the simplicity of the future surface water control system required, and the ability to control surface water in the future, which is a function of land ownership and catchment extent relative to the mine crest.

The base conditions and complicating factors scores are also plotted against each other as shown in Figure 3b, and result in 4 risk rating groups ('low', 'medium', 'medium–high' and 'high').

3.3 Consequence classification and post-mining land use

The Teir 2 risk assessment uses the mine's conventional risk assessment system, developed as part of the Declared Mine Rehabilitation Plan (DMRP) and closely aligned with the Victorian Government Department of Energy, Environment and Climate Action system. The intended post-mining land use (PMLU) affects the potential consequence of failures. Five consequence categories have been developed based on infrastructure and proposed PMLU, summarised in Table 1. Higher consequence domains ('major' and 'critical') are related to the presence of the highway and railway lines, and major rivers. The PMLU is preliminary and subject to change in subsequent design stages, and where domain-scale assessment over-predicts geotechnical impact on distant infrastructure, consequence or likelihood may be reduced. Consequence ratings change between rehabilitation periods as the PMLU evolves for some domains. For example, a domain that carries active mining infrastructure at EOM may transition to a lower consequence land use once rehabilitation is complete.

Table 1 Summary of the EnergyAustralia Declared Mine Rehabilitation Plan consequence classifications and post-mining land use

Rating, category & principal risk elements	Safety & health	Environment (impact years)	Land & property	Cultural heritage
5 – Critical Highways, major roads and railway lines	Loss of life	>20	Significant damage, permanent loss	Permanent loss
4 – Major Rivers	Permanent injury, public health impact	10–20	Damage resulting in temporary losses	Significant impact
3 – Moderate Secondary public roads, mining infrastructure or private land	Recoverable injury or health impact	5–10	Moderate damage, short-term and recoverable	Limited impact
2 – Minor Picnic spots or areas of temporary human occupation (for a few hours)	Negligible	1–5	Minor damage or impact	Negligible
1 – Insignificant Farmland or areas with no extended or permanent human occupation	None	Minimal	Not discernible	None

3.4 Consolidated risk assessment outcome and design application

The 3 risk assessment systems are applied together for each domain, and their combined outcomes form the basis for the rehabilitation design, preceding the stability analyses and other detailed design factors. It is an input to the design process, not a replacement for it.

The Tier 1 technical risk ratings define where, when and how particular design measures need to be addressed. The geotechnical risk rating identifies domains where adverse technical behaviour is more likely. The surface water risk rating informs decisions on drain location and type, and whether interim or permanent structures are needed.

The Tier 1 ratings subsequently group the domains into 3 landform classifications with similar rehabilitation characteristics, colour-coded in Figure 3:

1. Domains with no concentrated surface water flow paths and flatter topography, generally those with 'lower' to 'medium' geotechnical risk ratings and 'low' surface water risk ratings.

2. Domains with permanent or semi-permanent water bodies, generally those with 'medium' to 'higher' geotechnical risk ratings and 'low' surface water risk ratings, such as those along the Morwell and Latrobe rivers.
3. Domains with significant peripheral catchments and concentrated creek lines are those with 'medium' to 'higher' surface water risk ratings. These are either coupled with 'medium' to 'higher' geotechnical risk ratings where adverse geological structure is present, or otherwise with 'lower' to 'medium' geotechnical risk ratings.

The spatial distribution of domain and stability section landform classifications across the mine is shown in Figure 4.

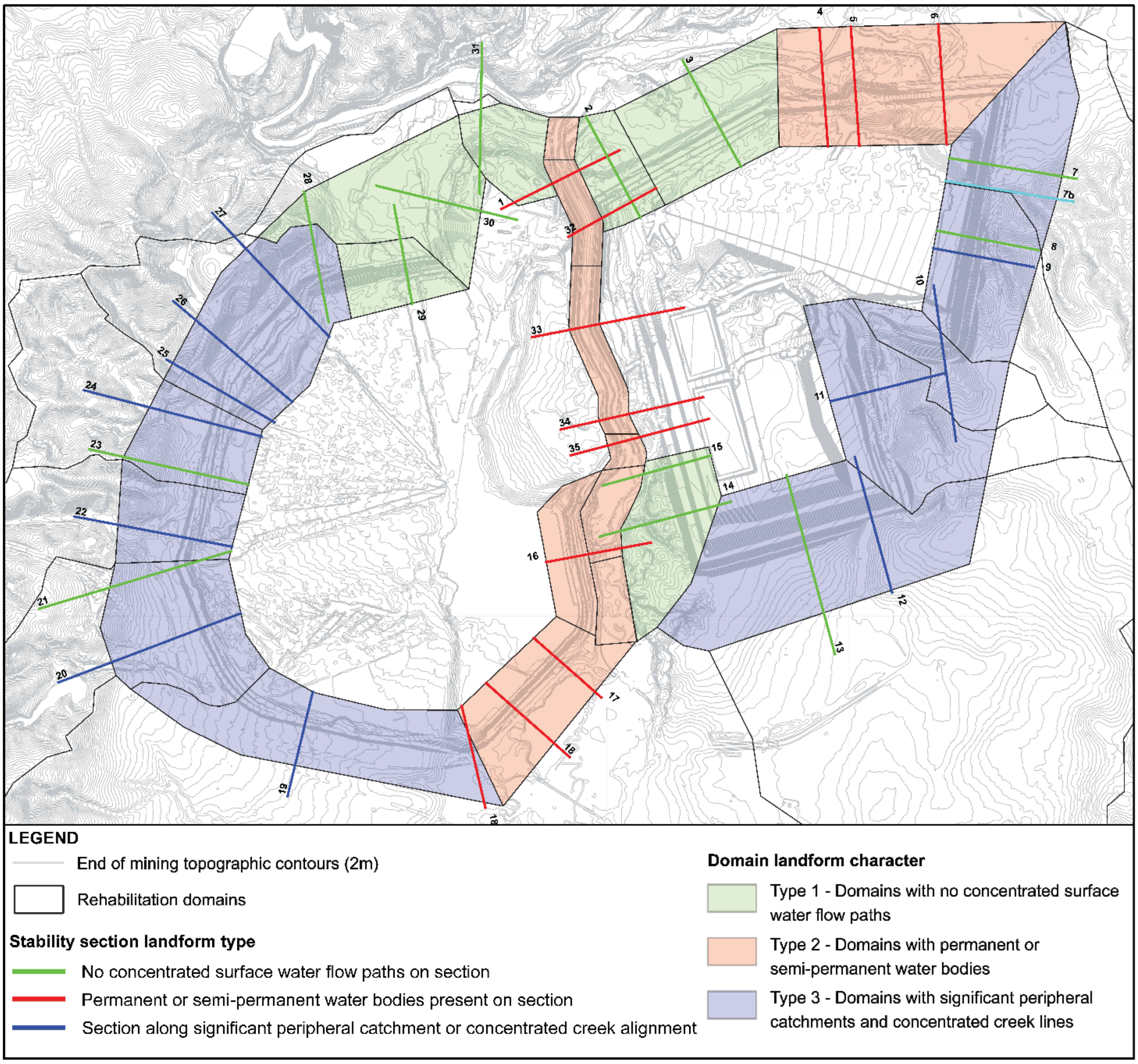

Figure 4 Distribution of domain landform classification and stability section landform type

The Tier 1 ratings inform the domain-scale landform classification and then are applied at the individual section scale, recognising that within a domain, individual stability sections may have a different landform type to the overall domain. The domain-scale classification provides the broad rehabilitation context, while the section-specific landform type determines the credible design failure modes across the 3 principal design periods (EOM, lake filling, and post-rehabilitation). Of these landform types, domains with significant peripheral catchments are the principal focus, as control of adverse surface water loading is the primary engineering challenge for long-term rehabilitation.

The Tier 2 consequence classification then informs the design acceptance criteria (DAC), including required Factor of Safety (FoS) and drain design criteria. The tiers are complementary: Tier 1 assesses technical exposure and sensitivity, while Tier 2 reflects the severity of impact should failure occur, irrespective of the technical conditions driving it. In practical terms, lower consequence domains can adopt lower design annual exceedance probabilities (AEPs) for drainage structures, while domains with 'major' or 'critical' consequence require more stringent designs. The framework therefore produces DAC as an outcome of the combined assessment that reflects the true variability of conditions across the mine.

Three domain examples, one from each landform classification, are summarised in Table 2 and described in this paper to illustrate how the consolidated assessment produces different design outcomes depending on the combination of technical risk and consequence ratings.

Table 2 Risk evaluation domain examples

Domain	Landform classification	Technical risk ratings		Consequence category	
		Geotechnical	Surface water	EOM & lake filling	Post rehabilitation
Domain A	1 – Permanent or semi-permanent water bodies	Higher	Low	4 (Major)	4 (Major)
Domain B	2 – No concentrated surface water flow paths	Low	Low	3 (Moderate)	1 (Insignificant)
Domain C	3 – Significant peripheral catchments & creek lines	Higher	Medium-high	3 (Moderate)	3 (Moderate)

Domain A is located adjacent to a major river and was the site of a significant historical stability incident, resulting in extensive cracking and ongoing groundwater responses linked to river levels. The geotechnical risk rating is 'higher', reflecting the history of instability and adverse base conditions, while the surface water risk rating is 'low', due to the flat terrain and absence of significant peripheral catchments. The consequence rating is 'major' (Category 4) due to the adjacent major river. This domain illustrates the complementary nature of the 3 assessments, whereby the Tier 1 ratings point in opposite directions, and the Tier 2 consequence is independently elevated by the river irrespective of the technical conditions. Running the assessments independently ensures these distinct drivers are not obscured.

Domain B is located on generally flat, high-lying terrain with no considerable peripheral catchments. Both Tier 1 risk ratings are 'low'. The consequence rating is 'moderate' (Category 3) at EOM due to the presence of mine infrastructure, reducing to 'insignificant' (Category 1) at the post-rehabilitation stage once that infrastructure is removed, illustrating how the Tier 2 consequence rating can change between rehabilitation periods as the PMLU evolves.

Domain C has a long history of instability, characterised by steep rising topography, a complex existing drainage system, and a major adverse geological structure close to the mine crest. The geotechnical risk rating is 'higher', reflecting the adverse geological structure and considerable historical deformations and movements. The surface water risk rating is 'medium–high', due to the complex peripheral catchment conditions and existing drainage infrastructure. The consequence rating is 'moderate' (Category 3), owing to the presence of a secondary public road as the primary infrastructure at risk. Domain C is discussed in detail as the worked example in Section 5.5, demonstrating how the integrated risk assessment translates into a practical peripheral drain design outcome.

4 Design principles and acceptance criteria

4.1 Guiding principles for long-term stability

The rehabilitation strategy established in Section 2 translates into 3 guiding design principles for long-term stability:

- Control the potential for large-scale block movement through pit lake filling and targeted construction of overburden buttresses to improve long-term slope stability.
- Minimise surface water loading by constructing peripheral catchment drainage structures to remove the risk of adverse water loading on the mine batters.
- Reduce the potential for long-term progressive deterioration of the coal batters through lake filling, and of the overburden batters through reprofiling in accordance with the engineering geomorphology principles (Chan et al. 2026).

Together, these principles define what the design must achieve. The DAC that translate these principles into design outcomes are derived in the following sections as an outcome of the risk evaluation framework, not as predetermined inputs.

4.2 Derivation of the design acceptance criteria

The risk evaluation framework produces domain-specific DAC informed by 4 main factors:

1. Landform type – which of the 3 defined types for both the overall domain and individual stability section apply
2. Design failure mode – prescribed based on the domain and section landform type and the potential for adverse water loading
3. Design period – which of the 3 rehabilitation phases applies, namely, EOM, lake filling, or post-rehabilitation (lake full)
4. Consequence category – the Tier 2 rating reflecting infrastructure at risk and PMLU, which is the primary driver of design stringency.

Model confidence is also an important consideration in the derivation of the DAC. At Yallourn, model confidence is established at a uniformly high level across all domains throughout the assessment for the following reasons:

- With over 100 years of operational experience at Yallourn, there is a well-established knowledge base of the geotechnical models, material parameters, controls on slope stability and credible failure modes. Model confidence is therefore based on an extensively validated body of site knowledge.
- The absolute lower bound residual shear strength has been adopted for the interseam, which is the principal parameter resisting instability. This value is the minimum derived from a validated dataset and historical stability event back-analyses. The design strength is therefore considered to represent the lowest credible value for the interseam material.
- The assumed maximum credible water pressure loading is commensurate with each respective failure mechanism. For the block sliding mechanism, which is the critical failure mode directly relevant to peripheral catchment design, a full-depth tension crack filled to the ground surface with water is assumed, ensuring the principal adverse loading factor cannot in practice be any higher than assumed.

Together, these establish a uniformly high level of analytical conservatism across all domains. Confidence therefore does not vary by domain and does not become an additional variable in the DAC.

The critical failure mechanism is block sliding, involving a persistent sub-vertical joint (modelled numerically as a tension crack) filled with water from a surface source such as a river, floodplain or concentrated rainfall run-off along peripheral catchments and creek lines, which mobilises instability along the underlying very low strength interseam clays. Where this mechanism is not credible because the topographic setting or design solution cannot sustain a water-filled tension crack, a secondary multilinear mechanism governs. This remains fundamentally a block sliding mechanism along the interseam, but with a progressively developing back-scarp from the rock structure rather than a single discrete water-filled tension crack, representing deformation under modified groundwater conditions rather than full hydrostatic loading.

The section-specific landform type informs the credible mechanism and therefore the governing DAC. Table 3 summarises the 3 landform types and the corresponding credible failure modes across the 3 rehabilitation design periods. The adopted DAC for each respective failure mode are presented in Figure 5.

Table 3 Summary of domain landform types and applicable design failure modes

Design period	Domain landform classification and stability section type		
	1 – No concentrated surface water flow paths	**2 – Permanent or semi-permanent water bodies**	**3 – Significant peripheral catchments & creek lines**
EOM & lake filling	Multilinear governs. No concentrated flows to facilitate large-scale block sliding.	Multilinear or block sliding, whichever gives the lower FoS.	Block sliding governs. Full tension crack water loading is credible. Peripheral catchment drainage structures not yet constructed.
Post-rehabilitation (lake full)	Multilinear governs. Topographic setting unchanged.	Multilinear or block sliding, whichever gives the lower FoS.	Multilinear governs. Peripheral catchment drainage structures constructed, eliminating the credible block sliding trigger.

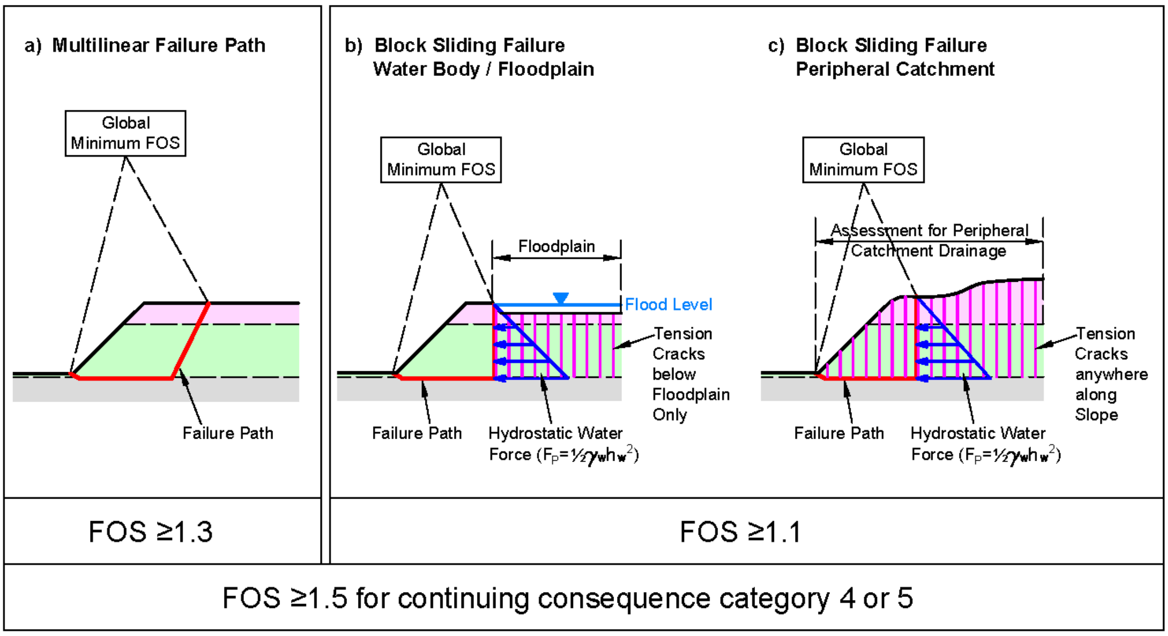

Figure 5 Design acceptance criteria for prescribed failure mode based on landform type

The shift in the governing failure mode from block sliding to multilinear in Type 3 domains at the conclusion of rehabilitation (at the conclusion of lake filling) is a direct consequence of the rehabilitation drainage strategy. It is the successful implementation of the peripheral drain system that changes the DAC, not a change in the underlying geotechnical conditions. This is an important illustration of how the drainage design and geotechnical DAC are intrinsically linked.

4.3 Design acceptance criteria outcomes and stability analyses

The adopted DAC are deterministic rather than probabilistic, which is considered appropriate given the uniformly high level of analytical conservatism established in Section 4.2. For comparison purposes, the same criteria have been applied consistently across all 3 design periods, noting that criteria during EOM and lake filling could justifiably be lower given active management is in place during those periods.

The DAC provide the design thresholds for stability assessment. For each domain, stability analyses were undertaken on representative sections, which were selected on the basis of critical geological conditions and peripheral catchment or flood-prone alignments. For Type 1 and Type 2 domains, general mine batter stability analyses assess whether the DAC are achieved, or if not, what buttressing or remediation measures may be needed (not covered in this paper).

For Type 3 domains with significant peripheral catchments, additional targeted block sliding analyses are undertaken to define where peripheral drains are required and to what extent from the mine crest. Once drains are constructed to that extent, the block sliding mechanism is no longer applicable and the governing failure mode reverts to multilinear, at which point the general stability analyses confirm that the DAC are achieved. Section 5 describes this sequential process.

5 Peripheral catchment drainage design

5.1 Drain design process

The stability analyses for peripheral catchment sections described in Section 4.3 produce FoS profiles behind the mine crest, showing changes in stability with distance from crest. These profiles are a direct input to the peripheral drain design criteria and inform the 3 sequential drainage design steps described in this section. The design process follows 3 sequential steps:

1. Requirement – whether a peripheral catchment drain needed. This is determined by the minimum block sliding FoS across the full length behind the crest. If the FoS falls below the applicable stability threshold, a drain is required.
2. Extent – the required drain length from the mine crest. This is defined by the distance at which the FoS profile increases to the applicable stability threshold.
3. Sizing – the required drain capacity. This is determined by a qualitative risk category derived from the FoS profile, which directly informs the design hydrologic likelihood, see Section 5.2.

Together, these steps translate the geotechnical stability assessment directly into a practical drain design outcome for each domain and section.

5.2 Qualitative risk category for drain design

A qualitative risk category for peripheral drain design is determined from the block sliding FoS profile behind the mine crest, as summarised in Table 4. This directly informs the appropriate hydrologic likelihood over the design intent period that the drain needs to be designed for. Noting the FoS criteria in this table are indicative and need to be developed specific to each mine rehabilitation situation.

Table 4 indicates that if the minimum block sliding FoS across the slope behind the crest exceeds 1.3 (or 1.5 for consequence category 4 or 5), then the domain is assessed as being ‘very low’ risk and no peripheral drains are required.

Table 4 Qualitative risk category and drain sizing criteria (100-year design intent period)

Risk category	Min. block sliding FoS from peripheral catchment analyses	Peripheral drain design hydrologic likelihood	Equivalent AEP
Very Low	>1.3 (>1.5 for consequence category 4/5)	Drains may not be required, otherwise >99%	>1 in 10
Low	1.2–1.3 (1.2–1.5 for consequence category 4/5)	>99%	~1 in 10
Medium	1.1–1.2	30%	~1 in 300
High	<1.1	2–5%	~1 in 2,000 to 1 in 5,000

The risk category determined from Table 4 may be modified in the following circumstances:

1. Where the infrastructure at risk lies beyond the FoS threshold applicable to its consequence category, the incident likelihood or consequence may be reduced, resulting in a lower risk category and less stringent sizing criteria. This is illustrated in the example presented in Section 5.5.
2. For 'high' consequence domains, the drain design incorporates a well-lined channel with overflow capacity to accommodate events exceeding the design flow.

It is important to understand what the risk categories represent, as the framing is counterintuitive relative to conventional geotechnical thinking. In conventional practice, higher risk is associated with a requirement for a higher FoS. In this case, the FoS values are directly informed from the targeted stability analyses and describe the domain's stability condition under a worst-case water loading scenario, being a full-depth tension crack filled to the ground surface with water. A domain returning a block sliding FoS below 1.1 is a 'high' risk domain precisely because stability is so marginal under that loading scenario that any uncontrolled water ingress could trigger instability. This means the drain should be designed for a higher event, because the consequence of overtopping is potentially more severe. Conversely, a domain returning an FoS above 1.3 is 'very low' risk; even if the drain overtops, the slope has sufficient stability margin to remain stable.

5.3 Criteria for defining drain requirement and extent

The zone where a peripheral catchment drainage structure is required is defined by the block sliding FoS profile and the risk category established in Section 5.2. Where the block sliding FoS is less than 1.3 (or less than 1.5 in category 4 or 5 domains) a peripheral catchment drain is required across that zone. The distance from the crest at which the FoS profile crosses the applicable threshold defines the required drain extent. With the construction of the peripheral drain within this zone, block sliding under water-filled tension crack conditions is no longer credible and the governing failure mode reverts to multilinear. Where the block sliding FoS falls below 1.0, the instability risk is such that a peripheral catchment drain alone is not sufficient to control the surface water risk, and second-order drains, such as swales or herringbone drains positioned closer to the pit crest, are also necessary to remove surface water from within the local catchment.

Figure 6 illustrates these criteria for 2 examples for a peripheral catchment section from a category 3 consequence domain. In Example 1, the block sliding FoS profile returns a minimum FoS of 1.13 at the mine crest, falling within the 'medium' risk category. The peripheral catchment drain is required to extend 70 m back to the point where the FoS reaches 1.3, as shown. Beyond the drain extent, the FoS is above 1.0 throughout, meaning no second-order drains are needed and surface run-off can be managed as distributed flow across the rehabilitated slope. The drain is sized to a hydrologic likelihood of 30%. In Example 2, the minimum FoS at the crest is 0.86, falling within the 'high' risk category. The peripheral catchment drain extent is again defined by the FoS = 1.3 threshold and is required to extend 140 m behind the crest. However, the FoS also falls below 1.0 over a large zone between the crest and the drain extent. Second-order drains are therefore also required in this zone. The peripheral catchment drain is sized to a hydrologic likelihood of 2–5%.

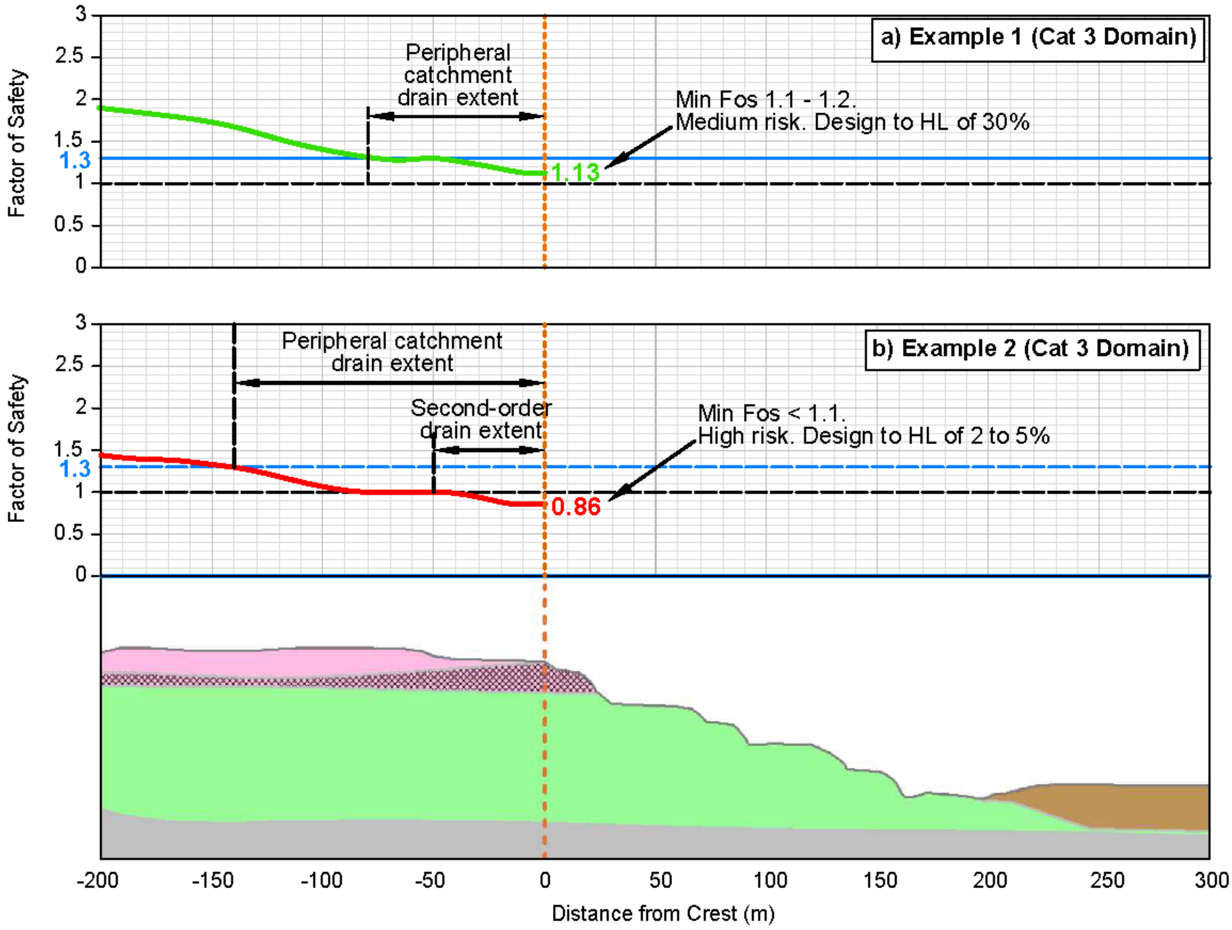

Figure 6 FoS profiles for 2 examples illustrating the criteria for drain requirement, extent and sizing

5.4 Drain sizing criteria and design approach

The peripheral drain sizing criteria are based directly on the qualitative risk category through selection of an appropriate hydrologic likelihood over the design intent period, summarised in Table 4. The hydrologic likelihood describes the probability of the design event being exceeded over a defined design intent period rather than in any single year; it is a more meaningful measure for rehabilitation structures than AEP alone as it accounts for the full exposure period over which the structure must perform. A design intent period of 100 years has been adopted for this rehabilitation design, representing the post-relinquishment period over which the rehabilitated landform is expected to perform without active intervention. For ease of comparison with other standards, an equivalent stationary AEP is also provided.

The design hydrologic likelihood is selected based on the consequence of a hydrologic exceedance event and whether it leads to geotechnical instability, and if so, what the consequence of that instability is. These 3 elements – the probability of hydrologic exceedance, the geotechnical stability consequence, and the rehabilitation consequence class – are intrinsically linked and must be selected carefully for a coherent drainage design. This is the mechanism by which the Tier 2 consequence classification directly informs drain sizing.

The drain design incorporates a high overflow capacity approach where possible, particularly for high-risk drains. The intention is to design a durable, deformation-tolerant well-lined drain to accommodate a medium-size flood event, while also including a wider flange area that is less intensively protected, for example grass lined, for higher flood loads. In this way, the full drain capacity handles the design flow while the drain design is optimised.

The drain design considers both EOM and post-relinquishment time periods to determine whether peripheral drains are required as interim or permanent structures. A detailed discussion of the hydrologic design criteria including non-stationary climate effects is presented in Rogan et al. (2026).

5.5 Integrated assessment outcome for drainage, stability and risk

The integrated peripheral drain design for each domain considers topographic and geometric factors, the existing surface water network, the Tier 1 and Tier 2 risk ratings, geotechnical and groundwater conditions, and recorded historical deformation and pin movement data. These inputs inform the stability analyses, from which the block sliding FoS profile behind the mine crest is derived and compared against the empirical deformation evidence. Where the stability analyses confirm that infrastructure at risk lies outside the zone of geotechnical influence, or where consequence ratings are time-limited, the consequence or likelihood assigned to the domain can be modified accordingly.

Domain C is presented as an example to demonstrate how the integrated design process translates into a practical drainage solution for a domain with significant peripheral catchments. The domain has a long history of instability and movement, characterised by steep rising topography, presence of a historical stabilising buttress at the toe of the slope, and a complex existing drainage system that has presented ongoing management challenges. A major adverse geological structure lies close to the mine crest in this domain, and the limit of deformations and significant movements is very well defined by the effective Yallourn Coal seam subcrop, located 150–250 m from the mine crest, providing a well-defined boundary that directly constrains the required extent of surface drainage protection.

The Tier 1 risk ratings are 'high' for geotechnical risk and 'medium–high' for surface water risk, reflecting the adverse geological structure and complex peripheral catchment conditions. The Tier 2 consequence rating is 'moderate' (Category 3), owning to the presence of a secondary public road as the primary infrastructure at risk.

Stability analyses along a representative critical section, aligned with the axis of the main peripheral catchment valley, give a block sliding FoS of 1.06 at EOM, increasing to 1.26 at completion of rehabilitation due to the stabilisation effects of the pit lake. The FoS profile at EOM increases to over 1.3 approximately 200 m beyond the mine crest, defining the required peripheral catchment drain extent. There is a small reduction in FoS during lake fill but the FoS remains above 1.0 throughout pit filling.

Figure 7 shows the geotechnical base conditions and the system responses for this domain; much of it reflects proximity to the adverse geological structure. The performance data, i.e. total horizontal surface pin movements and recorded deformations, show a very well-defined limit of the at-risk geotechnical zone, defined by the effective Yallourn Coal seam subcrop. The concentration of large historical movements (>500 mm) and cracking within this limit defines the at-risk zone. The stability results are in good agreement with the empirical deformation and pin movement data, which independently define the same zone of instability risk and therefore validate both the analytical approach and the empirically observed limit of the geotechnical zone.

Figure 8 presents the integrated drainage, stability and risk outcome for the domain. The minimum block sliding FoS of 1.06 along the critical section would ordinarily place this domain in the 'high' risk category, requiring a drain sized to a hydrologic likelihood of 2–5%. However, the secondary public road lies beyond the FoS 1.5 contour, well outside the DAC threshold of FoS 1.3 applicable to Category 3 infrastructure, confirming it falls outside the zone of geotechnical influence. The risk category is therefore moderated from 'high' to 'medium'. In this case, the Tier 2 consequence classification does not penalise the drain sizing outcome, because the infrastructure at risk cannot in practice be affected by the instability mechanism being designed for. The drain is sized to a hydrologic likelihood of 30% over the 100-year design intent period.

The drainage solution comprises a single peripheral catchment drain sized to a hydrologic likelihood of 30% along the main valley axis extending approximately 200 m beyond the mine crest, with a series of simple down-batter drains incorporated into the general regrading of the batters for the remaining area. With the peripheral catchment drain in place along the critical section, the block sliding trigger is controlled and stability is governed by the multilinear mechanism. The multilinear FoS exceeds 1.3 at completion of rehabilitation, confirming the DAC are achieved for this section.

Across the remainder of the domain, stability is also governed by the multilinear mechanism for all sections. The multilinear FoS exceeds 1.4 at EOM and 1.3 at completion of rehabilitation for all sections, meeting the DAC, except for one section at the northern end of the domain where the FoS falls below the DAC at completion of rehabilitation. Given the history of instability in this area, extension of the existing in-pit buttress to achieve the DAC at that location is recommended. This demonstrates that where the drainage strategy alone is insufficient, the framework identifies the need for an additional stabilisation measure and the design can respond appropriately.

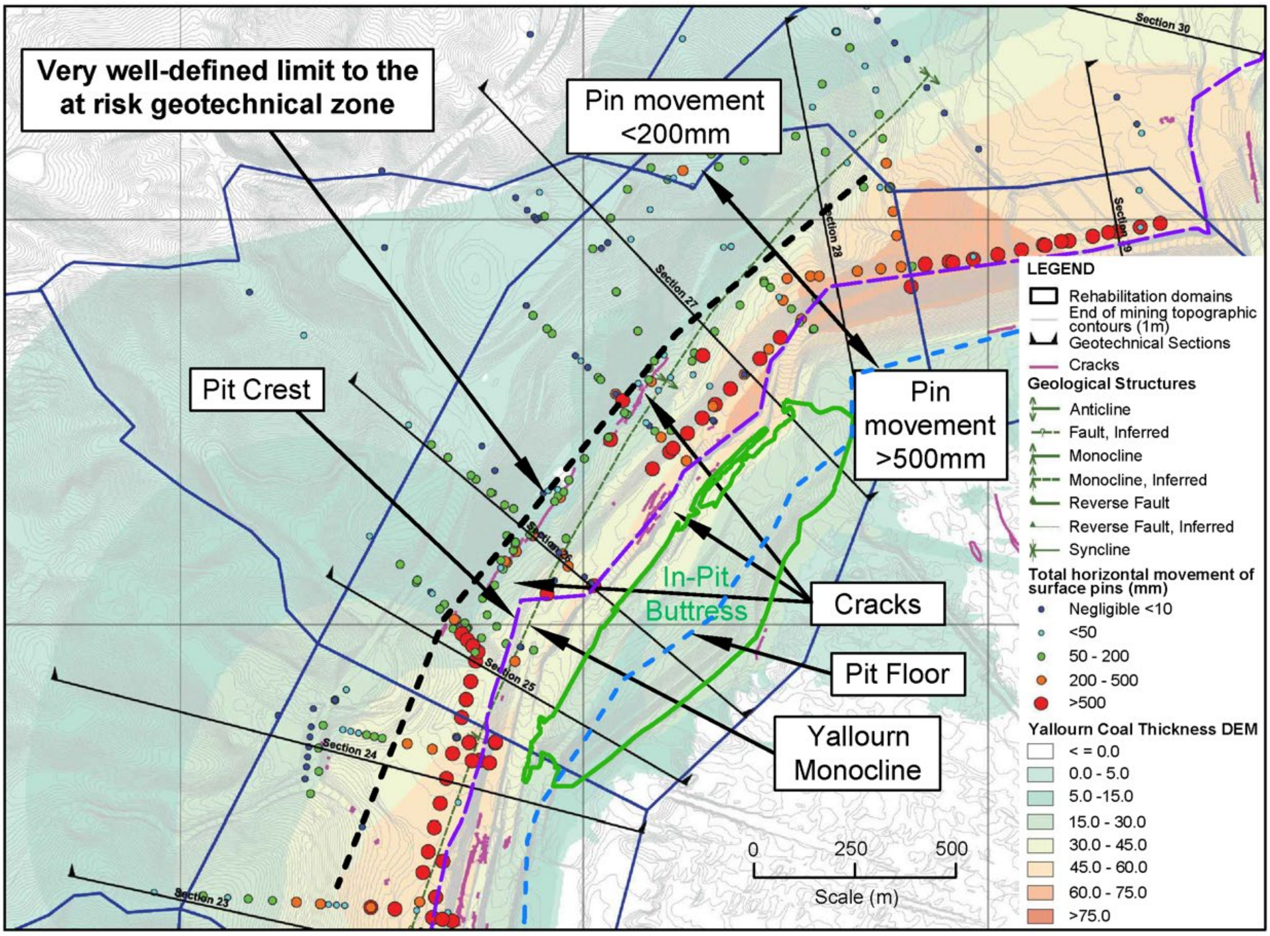

Figure 7 Well-defined limit of the at-risk geotechnical zone for Domain C, defined by total horizontal surface pin movements and historical cracks

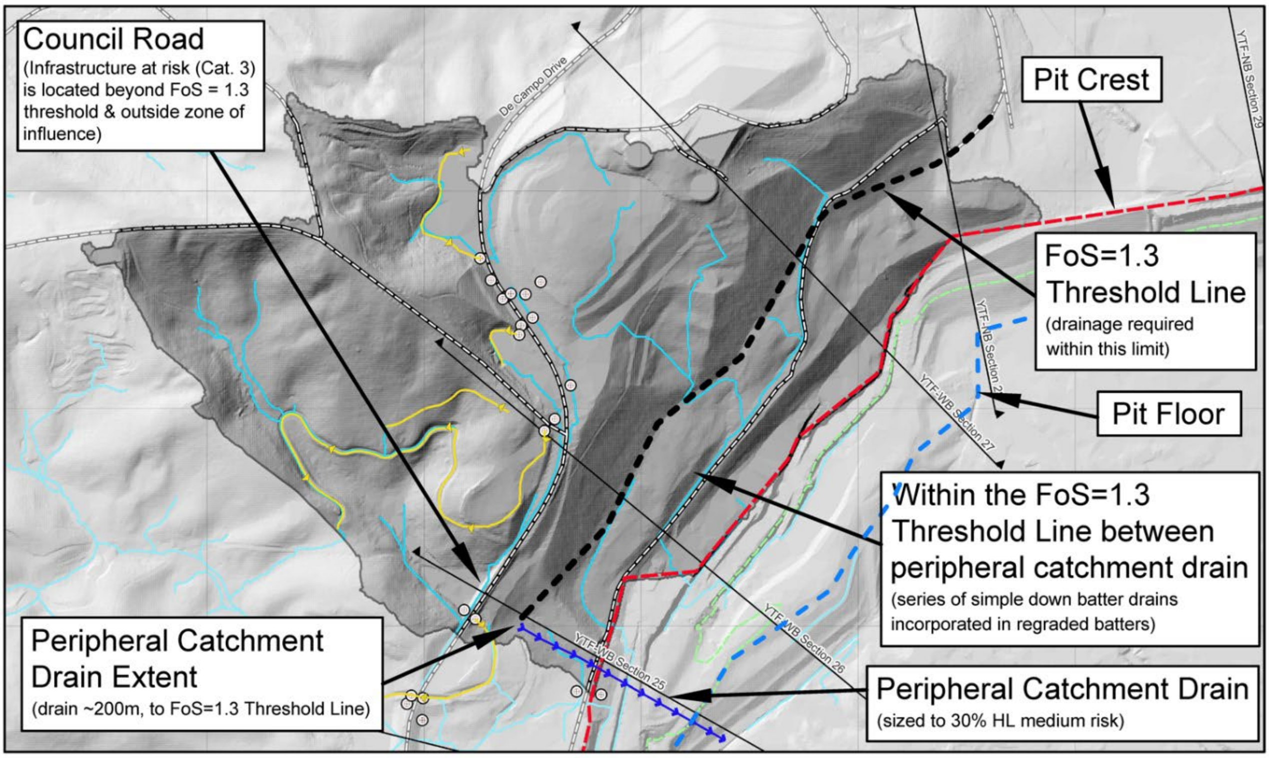

Figure 8 Integrated drainage, stability and risk outcome for Domain C

6 Conclusion

This paper has presented a first-principles approach to mine rehabilitation design at Yallourn Mine and demonstrated how that approach directly informs peripheral catchment drainage design. Conventional approaches to mine closure in complex systems rely on prescriptive processes, heuristics and analogy that may fail to capture the key technical elements needed for successful rehabilitation. Typical mine closure objectives are broadly stated as achieving safe and stable rehabilitation. Such statements can be satisfied by almost any approach, provide no meaningful design constraint, and conceal the assumptions embedded within them. A first-principles approach instead demands a precisely defined objective, deriving the design solution from the basic facts of the specific system rather than from assumptions.

Applied to the Yallourn Mine case study, the basic facts of a complex geotechnical system sensitive to surface water loading demand a risk-based framework as the logical and inevitable outcome. A 2-tier risk evaluation combining domain-specific technical risk ratings with a conventional consequence assessment produces design criteria that vary by domain rather than being uniformly prescribed. Those criteria directly inform the peripheral drainage design through the block sliding stability criterion, linking the probability of hydrologic exceedance, geotechnical stability and consequence class into a coherent design framework. The integrated assessment produces practical drainage outcomes based on analytical results and validated by empirical monitoring data. The case study demonstrates that for complex mine systems where conventional approaches are insufficient, first-principles thinking produces a risk-based framework that is both technically defensible and adaptable to the variable conditions encountered across the mine.

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