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Slope stability design acceptance criteria for closure of the Victorian Latrobe Valley coal mines

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Abstract

Design acceptance criteria (DAC) for the stability of open pit mines are often based on widely accepted industry standards, such as those quoted in renowned literature like Read & Stacey (2009) or Hawley & Cunning (2017). However, these standards are only applicable to the operational phase of the mine life cycle and may not reflect the increased long-term uncertainty and lower degree of operator management associated with the closure phase. They also may not be applicable for complex geological environments, namely lignite mines. A desktop review of timely and relevant technical guidance was undertaken to examine the feasibility of developing stability DAC for open pit mine closure, with a focus on the Victorian Latrobe Valley coal mines. After consideration of critical issues during and after closure, as well as published literature around design confidence during the mine lifecycle, the concept of data reliability was included as a measure for determining appropriate DAC. This paper proposes a set of stability DAC, in terms of Factor of Safety and/or Probability of Failure, which is contingent upon the level of data reliability, in terms of coefficient of variation that can be achieved for open pit mine closure. It is recommended that these criteria, if adopted, are reviewed and adjusted so that they are made site-specific to the project of interest.

This paper is designed to address the aforementioned issue via the use of conventional and published metrics. It is acknowledged that further work has recently been published, such as CSIRO's Guidelines for Open Pit and Waste Dump Closure (eds de Graaf et al. 2025), which establishes new means of quantifying closure objectives and performance. This paper does not aim to supersede or contest those works but presents a potential solution as an alternative approach while uptake by industry is underway.

Keywords: *mine closure, design acceptance criteria, Latrobe Valley coal mines, data reliability, coefficient of variation*

1 Background

1.1 Brief history of Latrobe Valley brown coal mines

The Latrobe Valley in south-east Victoria, Australia, spans from Moe in the west to Traralgon in the east. The Valley derives from and was shaped by the Latrobe River, which flows from west to east, between the Baw Baw Ranges to the north and the Strzelecki Ranges to the south. The Valley therefore is linear and broader from east to west than it is from north to south.

Three brown coal mines are situated in the Latrobe Valley: Hazelwood Mine, Loy Yang Mine and Yallourn Mine. All three coal mines have previously been defined by the Victorian Minister for Resources as "declared mines" under the *Mineral Sources (Sustainable Development) Act 1990* (MRSDA) (Government of Victoria 1990). A declared mine is one that has geotechnical, hydrogeological, water quality or hydrogeological factors that may be deemed to pose significant risk to public safety, the environment or infrastructure.

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For almost 100 years the three brown coal mines located in the Latrobe Valley (shown in Figure 1) have provided the raw material to generate most of the state's electricity. Following the closure of ENGIE's Hazelwood Mine in 2017, both Energy Australia (Yallourn Mine) and AGL (Loy Yang Mine) have announced their intentions to cease coal production in 2028 and 2035, respectively.

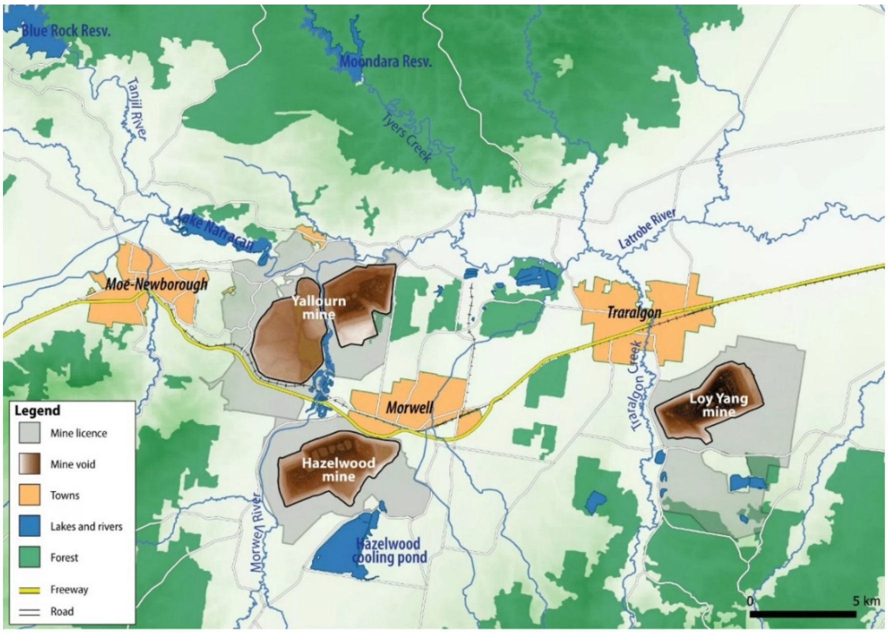

Figure 1 Map of the Latrobe Valley coal mines (courtesy of Mine Land Rehabilitation Authority)

The Victorian State Government is in the process of developing guidance material to assist the coal mine owners to prepare declared mine rehabilitation plans (DMRPs). Licensees of declared mine land are required under section 84AZU of the MRSDA (Government of Victoria 1990) to prepare DMRPs which include (in summary):

- an assessment of the risks posed by the declared mine land
- a rehabilitation plan to address the risks posed by the mined land
- closure criteria to measure achievement of the rehabilitation objectives and land use outcomes
- a post-closure plan that identifies any risks that may continue in post-closure and sets out the monitoring and maintenance to be carried out following rehabilitation of the land.

Geotechnical design criteria for the final rehabilitated slopes are required in order to design the slopes. This paper considers a proposed framework for incorporating design reliability in a risk-based approach to the design acceptance criteria (DAC).

1.2 Some geotechnical considerations

Latrobe Valley brown coal mine slopes can present a number of challenges when compared to hard rock slopes (PSM 2022, 2024):

- the presence of very thick seams of coal
- brown coal has a density only slightly greater than the density of water
- the coal is of very low strength and only marginally above the strength of soil
- the coal seams are separated by interburden soil units that also contain groundwater aquifers
- the groundwater has naturally elevated temperatures
- these aquifers can be at high pressure within the slopes and require depressurisation for stability control

- the mines are quite deep (up to 200 m) given the geotechnical nature of the brown coal and interseam materials.

These factors mean that subsequent deformation occurs in areas within and surrounding the mines. The stability of the slopes is very sensitive to water from any source, both groundwater and surface water. All of these factors, together with data reliability and uncertainty, need to be considered for closure DAC.

2 Design for closure

The dilemma for closure designers is how to transition the planning focus from an operations approach to a focus on public safety, infrastructure, environment, land and property (Carter et al. 2022). For open pit closure design, which must consider low-recurrence hazards with potential high-consequence outcomes, appreciation of control mechanisms is critical to minimise expenditure on ineffective mitigation measures. Data reliability and the level of understanding of underlying site-specific geotechnical information must therefore be commensurate with the level of identified risk, and this should then dictate the extent of engineering analysis needed. At relinquishment, final slope geometries must be in harmony with long-term material strengths and pore pressure conditions to not only ensure sufficient stability but also to achieve as much reduced risk as practicable, consistent with legislation requirements as set out in the *Mineral Resources (Sustainable Development) Act 1990* (Government of Victoria 1990). The interpreted long-term profiles adopted in the design should allow for the flexibility to be upgraded in the future if performance is not meeting the design.

2.1 Data uncertainty

When developing a geotechnical model, various uncertainties[†] need to be considered in the context of the project life cycle and the required level of confidence and reliability. The following questions need to be addressed in an attempt to minimise uncertainty (Dunn 2015):

- Is there sufficient data to capture natural variations in the rock mass?
- Is the spread of the data adequate to adequately define boundaries between different lithological units and identify critical structures or zones that could be problematic?
- Is the data collection consistent using industry accepted practices?
- How good is the quality of data collection and what quality assurance and quality control processes are used?
- Is there a bias in the data such as the direction of drilling or sampling of stronger materials?
- How good is the laboratory testing program, both in the quantity and quality of testing?
- How is the data managed and interpreted?

Another complexity is introduced in that the quality and quantity of collected geotechnical data may have significant implications on the slope design, especially in terms of maintaining safety, stability and sustainability in the long term. For example, the International Society for Rock Mechanics and Rock Engineering (Bieniawski & Bernede 1979) has guidelines which specify the minimum number of specimens to be tested for the determination of uniaxial compressive strength, with at least five specimens being preferred. Other authors (Gill et al. 2005; Rufollo & Shakoor 2009; Fillion & Hadjigeorgiou 2013) have explored the minimum sample size required for a given rock type and targeted precision index. The slope

[†] Different types of uncertainty can exist, such as: (a) natural variability uncertainty within the rock mass since it is not homogeneous; (b) knowledge/epistemic uncertainty due to data gaps, approximations; (c) decision model uncertainty due to models or design techniques not accurately representing a system's true behaviour; (d) operational uncertainties associated with mining and human factors and (e) decision uncertainties, for example, in relation to social objectives or social aversion to risk (Baecher & Christian 2003).

designer is encouraged to refer to those studies for further guidance on sample size and data reliability and uncertainty in the various geotechnical parameters applied in the slope design. It is considered that the concept of 'Factor of Safety' (FoS) itself includes uncertainty and error as perfect knowledge of the parameters is never reached (Bleiker 2024).

Long-term effects of weathering (whether atmospheric air, water, snow or chemical degradation) can result in shear strength reduction of the soil/rock mass over many years, dependant on the severity and extremity of the weathering agents. It is also acknowledged that closure criteria need to consider impacts from climate change, which introduce uncertainty and non-stationary aspects. For example, increased rainfall and rising temperatures can increase the likelihood of slope failure. Increased rainfall can lead to higher pore water pressures in slopes, thus reducing the soil strength. Rising temperatures can also impact placed vegetation by altering root systems, which can lead to a loss in soil binding and therefore an increased likelihood of slope instability. It is noted that this science is not mature and there is a high level of uncertainty regarding these impacts.

Pit slope DAC typically comprise a FoS, which is simply defined as the ratio of the geotechnical capacity of the slope to the geometric and external demand imposed on the slope. Geotechnical uncertainty is accommodated either via adjusting the FoS or using a stochastic approach deriving a Probability of Failure (PoF). Typical operational DAC for open pits outlined in Read & Stacey (2009) are built around FoS and PoF criteria based on operational experience and each operator's risk profile, framed within typical regulatory requirements. Furthermore, they are generally predicated on active risk management, thus allowing mining to be undertaken to the steepest slopes possible. By contrast, a more conservative approach is taken in *Guidelines for Mine Waste Dump and Stockpile Design* by Hawley & Cunning (2017), reflecting a heightened degree of failure consequence and lower achievable risk management for dumps compared with pit slopes.

2.2 Design reliability

Another issue of concern for directly applying typical FoS criteria recommended for operations to mine closure is that such FoS limits, particularly where data uncertainty is high, cannot be reliably interpreted as an indication of PoF. Data reliability for rehabilitated open pit DAC will be higher than for operating conditions because greater longevity is required and thus more extreme value statistics become a necessity. There is also a dilemma from a risk exposure viewpoint as risk during operations can be actively managed, while for full pit relinquishment after closure, the opportunity for active management is greatly minimised. As such, demonstration that the risk will be sufficiently (passively) mitigated such that public exposure is reduced to tolerable limits is required. This dilemma may be addressed by the identification of risks related to various milestone phases of rehabilitation, which then informs the various management plans and procedures.

3 Relationship between Factor of Safety, Probability of Failure and coefficient of variation

Coefficient of variation (CoV) is often used in geotechnical engineering to define uncertainty in geotechnical parameters. CoV is the measure of relative distance between the standard deviation and the mean; in other words, the degree to which parameters vary from the average value.

Silva et al. (2008), Wesseloo & Read (2009), Dunn (2019), Macciotta et al. (2020) and others have described the relationship between DAC and design confidence in terms of CoV ranges. Bleiker et al. (2024) are of the opinion that more than 60% of the level of engineering judgement considered in Silva et al. (2008) relates to the designer's judgement in selecting adequate conservatism in design parameters.

Christian & Urzua (2009) recognised that "engineering experience and judgement in effect assume a standard deviation of approximately 0.3 in those cases that can be achieved mathematically". It should be noted that for a lognormally distributed FoS, a standard deviation of 0.3 is equivalent to a CoV of 0.3. Typically, a CoV value of less than 0.1 is considered as having high certainty in the geotechnical parameters, while CoV values greater than 0.3 are considered as having high uncertainty in the geotechnical parameters. The evidence available from the batter stability assessments for Hazelwood suggests that the relationship between PoF and FoS applicable to Latrobe Valley's brown coal mines is approximately equivalent to a CoV for FoS of 0.25 (MLRA 2022).

This paper focuses on the relationship between FoS and CoV in more detail as the majority of the three coal mines have been applying the FoS approach with their slope designs. To have a reliable FoS value that can be maintained in a safe, stable and sustainable manner in the longer term (i.e. after closure, following relinquishment of the mining licence), input variables to the geotechnical model need to meet a minimum value of certainty, namely the CoV. As there may be uncertainty in how input parameters are weighted or quantified (Moffitt 2023), a considered methodology which applies, for example, lower bound values for those parameters used in the development of the geotechnical model and other engineering models which inform the slope design process, needs to be implemented. This process or methodology must be evidence based and well documented so the decision maker can understand the data uncertainty and data reliability in the slope design proposed for closure.

4 Proposed reliability-based design acceptance criteria for inter-ramp and overall slopes (closure conditions)

The geotechnical design approach is informed by the risk-based design process as outlined in the Declared Mine Rehabilitation Plan Guideline (Department of Energy, Environment and Climate Action 2025, unpublished at the time of this paper's submission).

The slope DAC proposed for inter-ramp and overall slopes require defining the consequence categories (Table 1), with a focus on public safety and environmental impacts.

Table 1 Consequence categorisation approach and proposed descriptions (modified from the International Council on Mining and Metals 2025)

Consequence category	Description
Insignificant	Environmental impacts lasting days or less Receiving environment altered with no sensitive habitats and no biodiversity value (e.g. urban/industrial areas) Public safety impacted by the need for first aid treatment
Minor	Environmental impacts lasting weeks, affecting a limited area (hundreds of metres) Public safety impacted by the need for medical treatment in the short term
Moderate	Environmental impacts lasting months, affecting an extended area (kilometres) Receiving environment comprising largely natural habitat and moderate biodiversity value Public safety impacted by the need for medical treatment in the long term or extensively
High	Environmental impacts lasting years, affecting area on a sub-basin scale Receiving environment classified as having a sensitive natural habitat with high biodiversity value Public safety impacted by permanent disability or a single fatality
Major	Permanent impact on environmental receptors, affecting the area on a whole basin or regional scale Receiving environment classified as a highly sensitive natural habitat with very high biodiversity value Public safety impacted by numerous permanent disabilities or multiple fatalities

Once the consequence category for each rehabilitation or slope domain is selected, the CoV and corresponding DAC values are selected and applied in the geotechnical closure design for the slopes (refer to Table 2). Note that high-consequence scenarios with very low design confidence and major consequence scenarios with low to very low design confidence are not considered acceptable for closure of the brown coal mines.

Table 2 Proposed slope design acceptance criteria (DAC) for inter-ramp and overall open pits slopes (modified from Macciotta et al. 2020)

DAC	Consequence category				
	Insignificant	Minor	Moderate	High	Major
Coefficient of Variation	≤0.20 (low confidence)	≤0.15 (high confidence)		≤0.10 (very high confidence)	
Probability of Failure	≤30%	≤20%		≤10%	
Factor of Safety	≥1.3	≥1.4		≥1.6	

Note that the listed values for PoF and FoS in Table 2 are based on numerical modelling results for the Latrobe Valley coal mines. The complex geology and unique material parameters limit the achievement of higher standards that are typically prescribed for closure scenarios at other sites (e.g. FoS > 2.0). Where possible, the DAC values should be tailored to site-specific conditions such that a reasonable estimate for that site is made.

5 Conclusion

The proposed criteria as outlined in Table 2 link FoS and PoF and quantify the confidence indirectly using CoV. Within the ranges of the proposed CoV values, the selection of the appropriate FoS and PoF is left to be demonstrated by the closure designer.

Uncertainty in geotechnical closure design of brown coal slopes can have a major negative impact on the regulator’s confidence in the proposed geotechnical closure model. The coal mine licensees are encouraged to increase slope stability understanding through robust investigations and monitoring during operations. This may lead to the benefit that at closure, sensible measures can be implemented to assist with reducing the extent of engineered works required to achieve acceptable closure.

It is also acknowledged that site-specific conditions and characteristics will inform the design approach and derived criteria. These should be assessed on their own merit, with demonstrated justification of the derived site-specific criteria.

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