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Case study: an assessment of integrated geotechnical considerations during the Hazelwood mine lake filling for mine closure using a reliability-based approach

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Abstract

The Hazelwood mine (Latrobe Valley, Victoria, Australia) is currently in the process of being rehabilitated following mine closure. The planned final landform concept incorporates a full pit lake. As the mine transitions from the 'empty' void scenario to the full pit lake, a number of geotechnical considerations need to be taken into account. These considerations include the assessment of mechanisms such as coal block sliding along critical interseams (basal geological units), kinematic (structural) considerations, ground movement (rebound) and weight balance, against floor heave. This paper presents the reliability-based assessment approach the authors undertook to understand the critical considerations during the planned lake-filling phase of the Hazelwood mine for closure, and the manner in which these were assessed using reliability-based metrics.

Keywords: *Latrobe Valley, brown coal, mine, geotechnical, batter, stability, reliability, index, floor heave*

1 Introduction

Since the closure of Hazelwood mine in March 2017 a significant body of work has been undertaken by the authors in concert with the mine operator (Hazelwood Power) and other consultants in relation to planning the various activities associated with site rehabilitation. The overall objective is to relinquish the site as a safe, stable and sustainable landform capable of supporting productive end land use. The studies undertaken during this period have considered:

- The geotechnical performance of the site during and post rehabilitation, including the
  - stability of the interim and final landforms
  - stability of the associated pit slope batters
  - rate and magnitude of potential ground movement
- The hydrogeological performance of the rehabilitated site, including the
  - behaviour of groundwater in response to altered pumping regimes
  - potential implications to aquifer pressures and risk of mine floor heave
- The hydrological performance of the final landform and connected waterways
- The lasting environmental impact of the final landform.

As appreciation for the long-term performance of the site matured in line with outcomes of the various studies undertaken by the authors and Hazelwood Power, a number of rehabilitation concepts were developed which involved the establishment of a pit lake within the Hazelwood mine void. This process has

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progressively led to the formalisation of the Hazelwood Rehabilitation Project, which consists of the following components:

- filling the mine void to a final level of RL +45 m AHD using a combination of groundwater, surface water and other approved water sources
- re-profiling the exposed upper mine batters to construct slopes which are geotechnically stable, and erosion- and fire-resistant
- construction of infrastructure necessary to maintain lake depth and potential connectivity with external waterways
- restoration of surrounding disturbed land to pre-mining conditions, including aspects such as public amenity i.e. recreational and public use.

This paper presents the findings of the reliability-based stability assessments undertaken by the authors that present the technical justification which demonstrates that RL +45 m AHD is the only feasible lake level that enables the site to meet the desired closure criteria while also reducing the risk of ongoing mine and batter instability to the lowest achievable level of risk.

2 Background to the case study — Hazelwood mine

Mining of brown coal in Victoria's Latrobe Valley commenced in the late 19th century through the extraction of shallow surface deposits, leading to the development of the Yallourn mine. The then-Morwell open cut (now Hazelwood mine) and accompanying power station were constructed and incorporated into the state energy grid in 1964 by the State Electricity Commission Victoria (SECV). This was followed by the Loy Yang mine and power station in 1984, at which point the Latrobe Valley was generating over 80% of Victoria's energy requirements. Figure 1 depicts the relative location of the three Latrobe Valley coal mines.

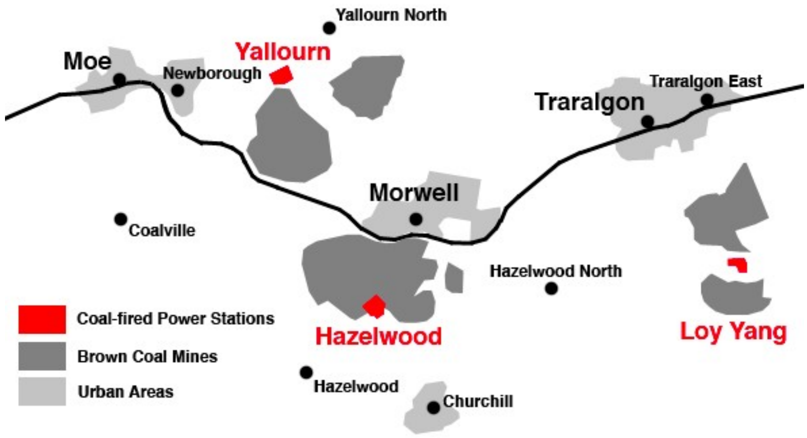

Figure 1 Location of Hazelwood mine

The Latrobe Valley coal mines have not operated without incident; with fires, flooding and batter failures occurring infrequently but consistently throughout operations. Historically this has involved a lack of appreciation for the complex geotechnical conditions which affect the Latrobe Valley, coupled with a previously increased tolerance for risk through now-outdated mining practices. More recently Latrobe Valley mine-related incidents have come about due, in part, to the sheer scale of the mines and the associated stress conditions induced as a result of the operations. Appreciation and due consideration of these factors are particularly critical in the context of mine closure and relinquishment. The manner in which key stability aspects have been assessed for Hazelwood mine will be presented in subsequent sections of this paper.

2.1 Geology

Hazelwood mine is located in the Latrobe Valley Depression within the Gippsland Basin. The region contains Victoria's main deposits of brown coal, which is split into the Yallourn, Morwell and Traralgon Formations (Barton et al. 1993). Each formation consists of one or many coal seams, separated by material known as interseam. These interseam bands typically range from 1 to 25 m in thickness and comprise clays, sands and gravels. The coal is overlain with a variably thick overburden named the Haunted Hills Formation (HHF). The HHF ranges up to 30 m in thickness and comprises clays, sands and gravels. Summarised below are the defining properties of the Latrobe Valley geological units which contribute to stability within the Latrobe Valley mines. See Figure 2 for a geological cross-section.

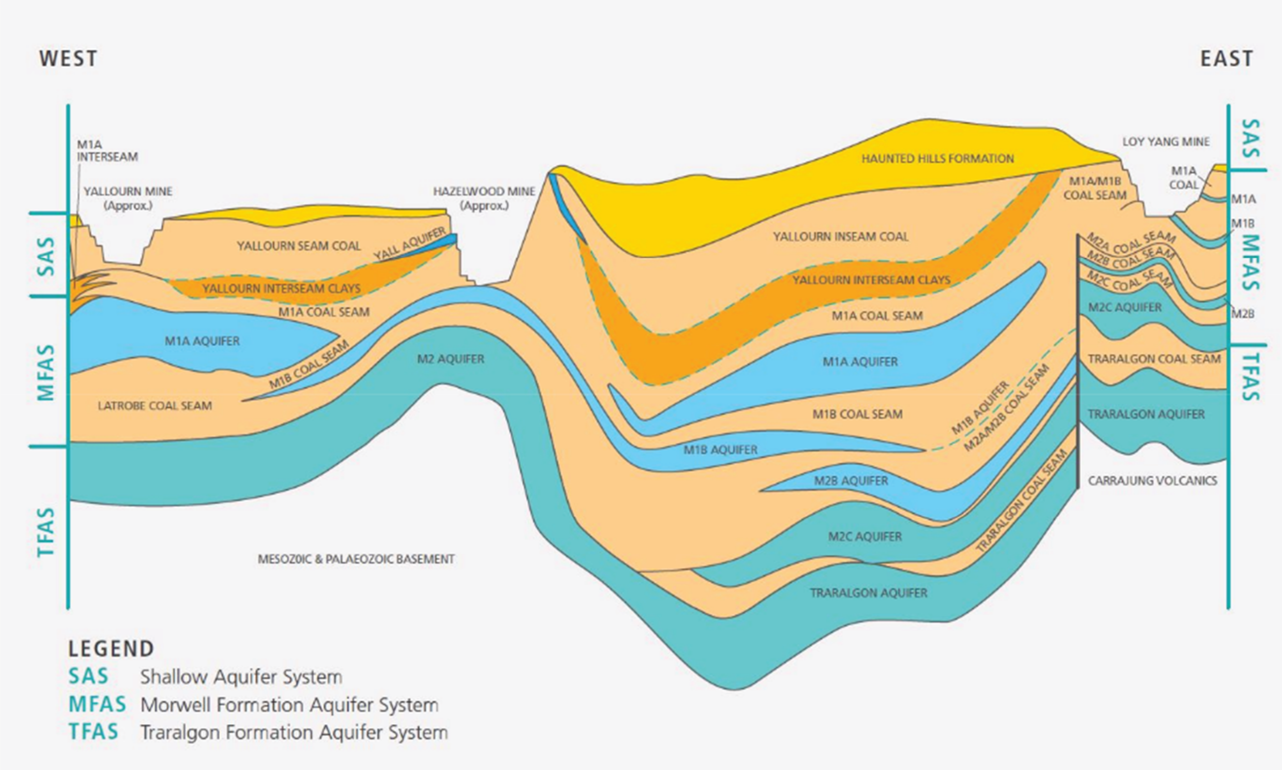

Figure 2 Geological and hydrogeological cross-section of Latrobe Valley mines

2.1.1 Haunted Hills Formation

The HHF is a thick overburden layer in all three open cuts, and is characterised by varying compositions of clays, sands and gravels. The material is generally firm and strong when in situ or compacted, however, it is prone to erosion when exposed.

2.1.2 Brown coal

The brown coal at Hazelwood mine is a brittle material of relatively low strength compared to stone. Owing to its brittle nature, the brown coal is generally highly fractured as a result of tectonic forces, with pervasive sub-vertical jointing encountered throughout the coal mass. Fractures within the coal gives rise to coal joint water as seepage transmits through the void spaces. It is the build-up of water within the coal joints that can lead to movement within the coal through a mechanism known as coal block sliding. Brown coal is susceptible to environmental weathering, eventually crumbling to a fine-grained material following long periods of exposure.

2.1.3 Interseams

The interseams are clayey, sandy bands of material which separate adjacent coal seams. In comparison to brown coal, interseams exhibit ductile behaviour when deforming due to a high clay proportion. The strength of the interseam variably ranges from that of a soft malleable clay up to a firm hard clay. Notably, however, interseam strength is understood to reduce significantly following episodes of past ground movement, due to a loss of the intact clay bond. Interseams act as aquifers that transmit water around the coal deposits.

2.2 Hydrogeology

Two major aquifers, named the M1 and M2 aquifers, extend regionally across the Latrobe Valley and therefore Hazelwood mine. These systems transmit groundwater through the relatively permeable interseam layers which separate coal seams of relatively low permeability. These aquifers are understood to be confined and necessitate depressurisation as part of mining to mitigate the effects of potential floor heave and slope instability. This is discussed further in subsequent sections of this paper. The M1 aquifer is a sub-regional confined aquifer system of moderate permeability comprised of between 15 to 25 m of interbedded clay, silt and sands units. The system is rarely continuous throughout the region, resulting in subset aquifers of various thickness, lateral extent and interconnectivity. The M1 aquifer sands are found at between 5 and 35 m below Hazelwood mine. The M2 aquifer is a confined high-permeability aquifer comprised of interbedded clay, sands, gravel and basalts between 120 to 200 m in thickness.

2.3 History of slope performance at Hazelwood mine

There is a well-documented history of slope performance/movement at Hazelwood mine over the past 70 years. Understanding the catalysts for these slope movements is crucial in designing a final landform that is to remain ‘stable’ into perpetuity. This landform needs to remain stable during the transitional phase of mine rehabilitation and pit lake recovery.

Following are summaries of some key features of Hazelwood mine slope performance:

- Mine floor heave of up to 2.5 m in height was first recorded at Hazelwood mine in 1965 as mining first developed below RL +10 m AHD. This was understood to be a result of cracking forming between the M1 and M2 aquifers, causing pressures within the upper M1 aquifer to exceed the mine floor weight balance. Floor heave of up to 3.3 m in height and aquifer flow through the floor surface was reported from 1969 to mid-1970 as mining development occurred below RL –30 m AHD. By 1972 cumulative heave was estimated to be in the order of 6 m. These events have since been mitigated by reducing M2 aquifer pressures through aquifer depressurisation below weight balance pressures. Note that the mechanics of floor heave and weight balance are discussed in the next section of this paper.
- In 2011 intense rainfall resulted in small but widespread movement along Hazelwood mine’s northern batters, causing cracking to appear across the adjacent Princes Freeway and nearby roads in the Morwell township. The incident caused significant disruption to the area, with the Princes Freeway closed for a number of months while the area was remediated.
- In 2014 spotting bushfire embers caused exposed coal batters to ignite at the mine in what became known as the Hazelwood mine fire. The fire burnt for 45 days and resulted in significant impact on the local community. As part of the effort to suppress the fire, water was sprayed to douse the burning slopes. This caused movement along the northern batters.
- As a result of aquifer depressurisation activities, ongoing subsidence and horizontal translation towards the mine have been noted. Cumulative settlements and horizontal movements of 2.6 m and 2.0 m, respectively, have been noted as at 2015.

3 Mechanics of slope movement and final landform considerations

The two primary mechanisms of slope movement that impact Hazelwood mine are coal block sliding and floor heave. There are secondary mechanisms such as kinematically controlled ones, which typically affect single benches, as well as circular failure mechanisms that affect the overburden unit (HHF). While these secondary mechanisms are important and have been considered by the authors, this paper focuses on the coal block sliding and floor heave mechanisms.

3.1 Coal block sliding

Coal block sliding is identified as the primary mechanism which governs batter stability at Hazelwood mine. Figure 3 depicts a typical cross-section of a Hazelwood mine coal batter under stable operating conditions. Key figure annotations include:

- the overburden, coal, and interseam strata
- a groundwater table controlled by mine depressurisation and drainage through horizontal drain holes
- sub-vertical jointing that occurs ubiquitously throughout the coal, some of which extends through to the interseam.

When a temporary elevation of the coal joint water level occurs due to surface water infiltration following intense rainfall event:

- A hydrostatic force (red triangle in Figure 3) is induced, which acts to drive the coal block along the underlying interseam. The interseam shear strength acts to resist the movement of the coal block (green arrow).
- Uplift force caused by the buoyancy of the coal beneath the groundwater table and any contribution from the underlying aquifers will result in a further destabilising effect (Figure 3 blue arrow and triangle). Where there is a pit lake within the void, a further 'resisting lake force' will be imparted to stabilise the block.

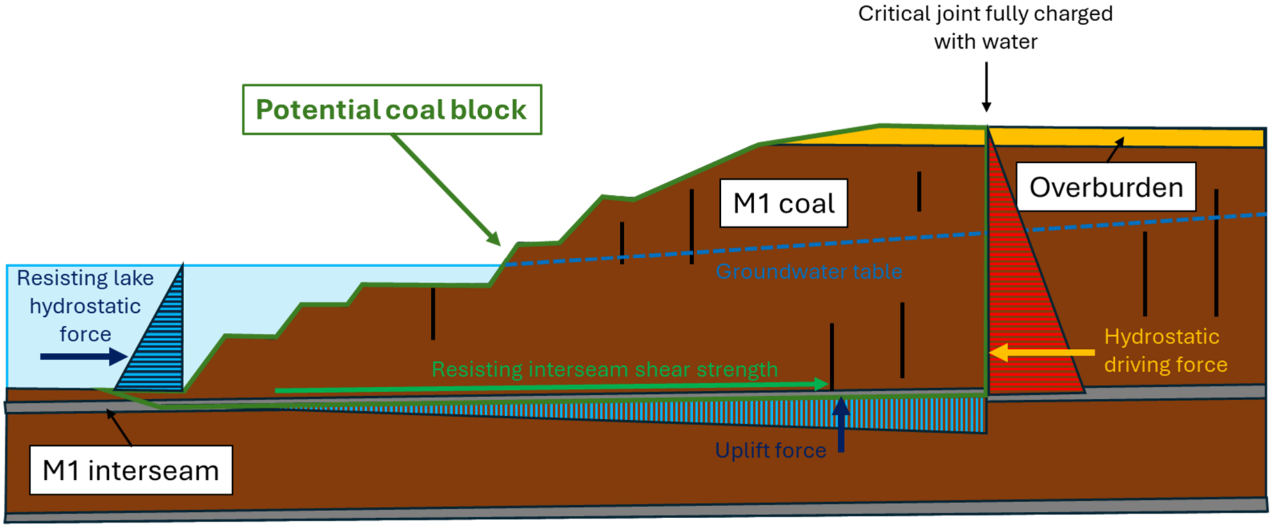

Figure 3 The mechanics of coal block sliding

Typically, coal block sliding is controlled at Hazelwood mine through a network of horizontal drains, which minimise the magnitude of destabilising hydrostatic (driving) forces.

3.2 Floor heave

Like coal block sliding, floor heave is considered a primary failure mechanism that governs mine stability. Floor heave occurs when the underlying aquifer pressures exceed the weight of overlying earthen cover and vertical forces from a pit lake; conditions which denote a negative weight balance (Figure 4). To date, aquifer depressurisation through groundwater pumping at Hazelwood mine has been employed to control aquifer uplift in parallel with mining development to maintain a positive weight balance.

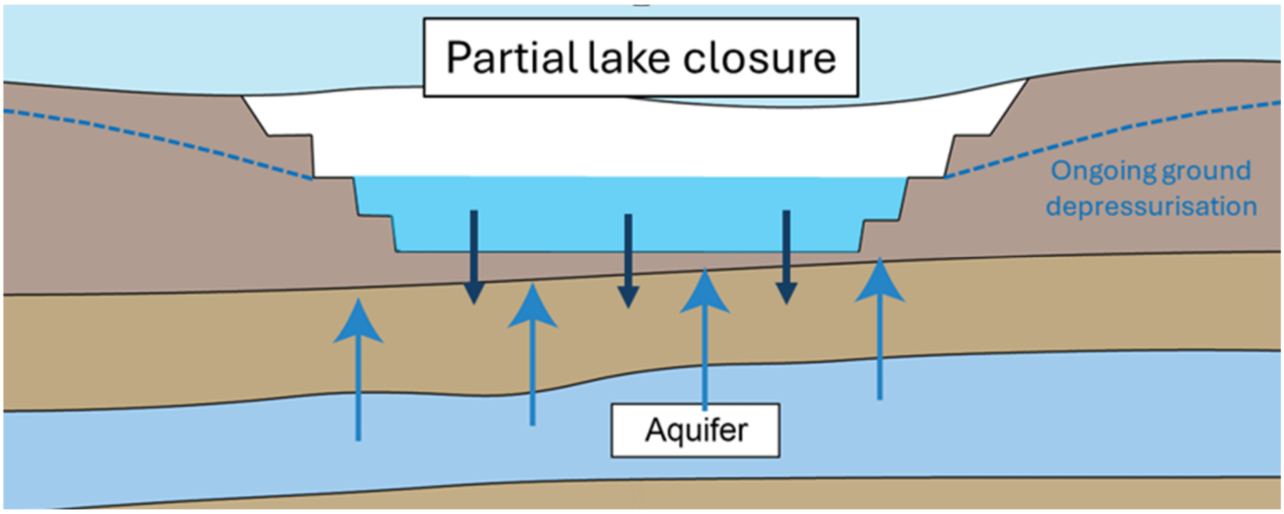

Figure 4 The mechanics of floor heave – partial lake

3.3 Landform design considerations

The final landform must satisfy myriad requirements, including technical, regulatory, public perception and access. While all these aspects are crucial in achieving the final landform, this paper focuses on the technical considerations pertaining to batter slope stability, with due consideration to the coal block sliding and floor heave mechanisms. As outlined in the preceding sections pertaining to the mechanics of deleterious slope movements, much of the currently applied management protocols require active intervention and management (i.e. horizontal drains and aquifer depressurisation pumps). Such active management measures are not feasible in the long term as these systems have a finite serviceable life. Accordingly, the final landform will need to incorporate a profile, pit slope geometry and lake level that facilitate a passive stabilisation premise. A key aspect of passive stabilisation is the effect imparted from the horizontal and vertical pit lake forces, respectively. These pit lake forces act to counteract deleterious movements that act to destabilise the landform. Noting this, it can be appreciated that there will a 'minimum pit lake' level that affords the final landform the requisite passive support to be self-sustaining and at a natural equilibrium. A reliability-based approach has been applied by the authors to calculate this minimum pit lake.

4 Reliability-based assessments of Hazelwood mine pit lake and landform

The concept of uncertainty, reliability and risk as it relates to geotechnical engineering has been conceived by many practitioners to date, and has best been simplified by Baecher & Christian (2003). Typically, the uncertainties that are encountered in geotechnical engineering fall into three major categories:

- natural variability — associated with the 'inherent' randomness of natural processes (i.e. geological deposition, manifesting as variability over time for phenomena that take place at a single location [temporal variability], or as variability over space for phenomena that take place at different locations at a single time [spatial variability], or as variability over both time and space)
- knowledge/data uncertainty — attributed to a lack of data, information about events and processes, or understanding of physical laws that limit our ability to model a real-world system or process

- model uncertainty — the degree to which a chosen mathematical model accurately portrays reality. Model uncertainty reflects the inability of a model or design technique to precisely represent a system's true physical behaviour, or our inability to identify the best model, or a model that may be changing in time.

The manner in which each of the above processes has been handled within the context of mine batter stability analyses has a direct bearing on the reliability of the final calculated outcomes (i.e. the confidence associated with the calculated factors of safety (FoS) and the associated probability of failure (PoF). The approach applied by the authors to assess and quantify the uncertainty associated with each of the three primary components above is outlined in subsequent sub-sections.

4.1 Quantifying data uncertainty

Given that Hazelwood mine has been in operation for well over half a century, it has been the subject of numerous investigation campaigns over the course of its operation. This information base, which dates back the early 1970s, has been further supplemented with ongoing targeted investigation programs aimed at investigating particular areas/units as slope performance behaviours manifested. Owing to the extensive history of data collection there was a clear understanding of the data 'gaps' that were present within the revised mine domains at the onset of closure. This process revealed the following information:

- The geotechnical properties of coal within the mine are based on over 50 years of sampling and data collection which occurred during mine development, and as such are generally well understood. Accordingly, all stability models incorporating coal strength had a relatively high reliability.
- Gaps in information were primarily related to interseam strengths, and were subsequently addressed and successfully supplemented in a further campaign of testing undertaken in early 2017, shortly after closure of the mine. This campaign was performed with the intent of reducing data uncertainty surrounding the interseam properties and strength behaviours. Multiple samples were collected within each of the mine batter domains, with investigation sites designed to maximise spatial coverage.

The question still arises as to whether the contemporary investigation program has satisfactorily 'filled in the gaps' associated with the 'uncertainty' within the knowledge base. Subsequent to the data collection phase of the 2017 campaign, a process of statistical interrogation was performed to assess the 'validity' of the data. This enabled representative strength distribution relationships to be developed for the purpose of coal block sliding stability analyses. The following notes summarise the steps undertaken to ensure data gaps pertaining to knowledge uncertainty were suitably bridged:

- Contemporary data was combined with that from historic SECV records and all available sampling campaigns. This was 'tested' for statistical conformance to the dataset based on a pre-defined acceptance tolerance (Harr 1984). These statistical validity tolerances are defined by a parameter referred to as the coefficient of variability (CoV).
- Specifically, individual sample points were compared against the expected 'natural' distribution of data to highlight potential anomalies which would otherwise skew the dataset.
- This process was undertaken for all key material properties including strength (cohesion and friction angle) and plasticity of the interseam clays.

The above process of statistical testing and validation provides confidence in the verification of the knowledge uncertainties being suitably bridged as the resultant values sit within acceptable norms as defined by Harr (1984).

4.2 Calculating model uncertainty

Model uncertainty pertains to the degree to which a chosen mathematical model accurately reflects reality and therefore reliably predicts future behaviours. In the context of Hazelwood mine's geological strength models, uncertainty can be reduced by gathering adequate data which is considered reflective of natural conditions and employing a statistical approach to estimate foundational model parameters which addresses:

- the representative statistical distribution fitted to each of the critical geological units
- the strength model derived and fitted to the respective geological units
- Derivation of statistical distribution.

Upon segregating and plotting the constituent strength data in a histogram format (i.e. the friction angle and the cohesion) for a given domain at Hazelwood mine, one can arrive at a chart as illustrated in Figure 5. It can be observed that this chart represents a skewed Gaussian (normal) distribution.

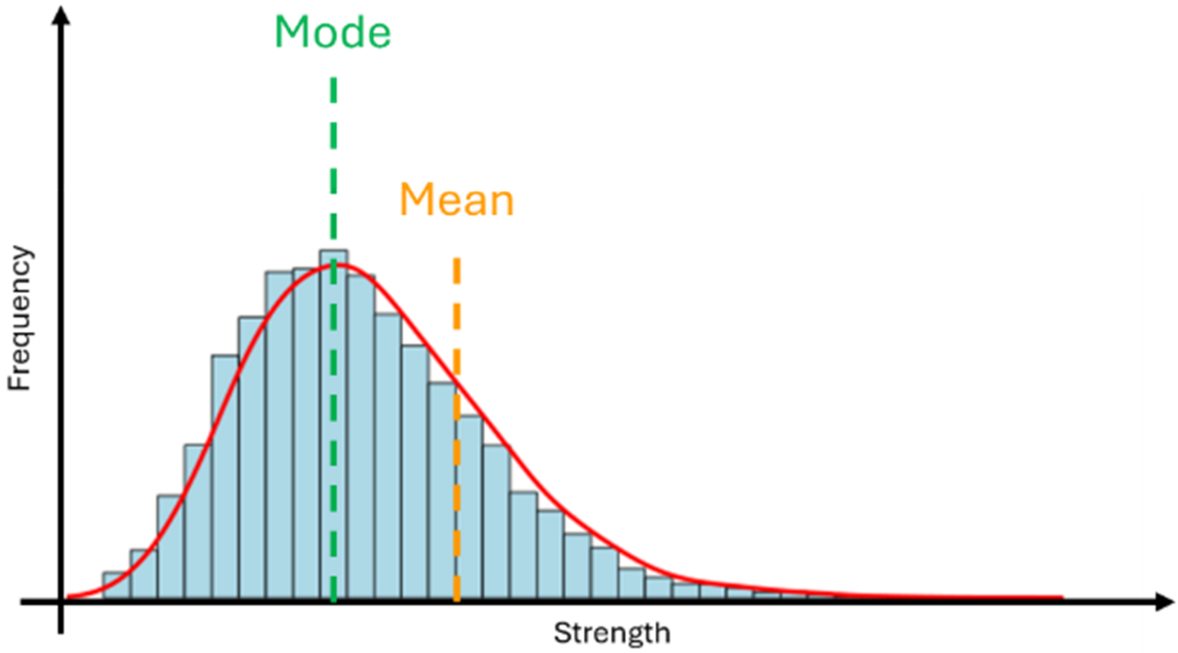

Figure 5 Strength distribution skewed towards lower bound values

Noting the above and acknowledging that there can be a high degree of complexity associated with the definition of a statistical (strength) distribution, two key parameters are relied upon: the characteristic value and the CoV, which defines how much above and below this characteristic value we are likely to 'encounter' a data point.

Accordingly, the premise applied when defining the statistical distributions of material strengths for the critical geological units is as follows (Figure 6):

- The nature of the distribution was observed (i.e. normal, lognormal, skewed, multi-modal, etc).
- A characteristic value was selected based on the nature of the distribution. For instance, this value may be the mean for a purely Gaussian (normal) distribution or potentially a modal or lower bound value for a lognormal distribution.
- Subsequent to the above, conservative cut-offs were applied to the upper bound strengths to ensure that the resultant CoVs were within the criteria noted by Harr (1984). All lower bound tail values are commensurate with residual values obtained from laboratory testing.

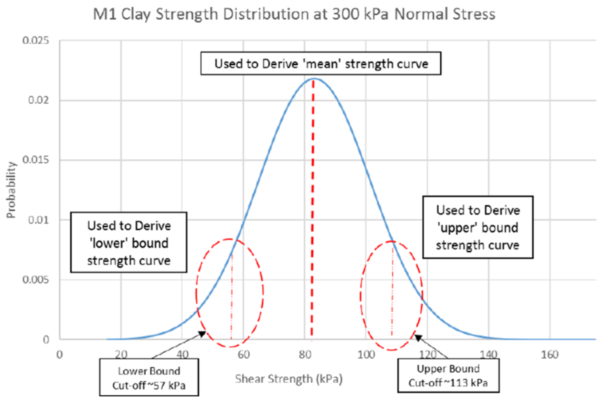

Figure 6 M1 clay interseam strength distribution (GHD 2018a)

The above process ensures that the resultant distributions for the critical material strengths have a calculable CoV that can be directly taken forward for further analyses and probabilistic stability calculations. The way the above strength distributions were defined in stability modelling software was to derive non-linear curves commensurate with the lower bound and (conservative) upper bound cut-offs, respectively. Figure 7 is an example of the East Field Eastern Batters (EFEB). The halo shaded in grey represents the assessed variability in the strength of the material(s) for that given domain. This process ensures that the subsequent stability calculations that result in the FoS and PoF metrics have an associated reliability. The manner in which these reliability indices have been employed by the authors is outlined in the subsequent section.

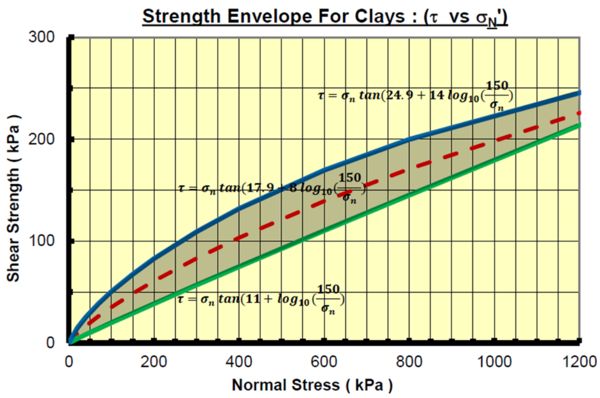

Figure 7 M1 clay strength envelope (GHD 2018a)

4.3 Reliability-based analyses

As part of the Hazelwood mine rehabilitation process, model reliability was measured using two methods to evaluate the confidence with which long-term slope stability could be determined. The methods are as follows:

- A reliability index (RI) as defined by Lilley (2000)
- An RI automatically calculated using slope stability modelling software.

Further description on each approach is presented below.

4.3.1 Reliability index after Lilley (2000)

Lilley (2000) derived the RI based on the simple equation:

$$Reliability\ index\ (\%) = 100 - PoF\ (\%) \tag{1}$$

As per the above, RI is inversely proportional to the PoF for any one model. For example, a maximum of RI of 100% relies on a PoF of 0%, indicating there is a no calculated likelihood of a batter instability occurring.

Conversely, a minimum RI of 0% is calculated when the PoF equals 100%, indicative of certain slope failure. Given the RI is dependent on the PoF of a model, which itself is based on the uncertainty attributed to input parameters through respective data availability and suitability, the RI established by Lilley (2000) is considered the most effective means of quantifying the reliability of the model system as a whole. This approach implicitly incorporates the variability of the entire system. Therefore, reliability associated with the calculated outcomes can be considered representative of the overall system being assessed.

4.3.2 Modelling software reliability index

In addition to calculating the output FoS and PoF, slope stability modelling software will compute an RI when probabilistic modelling is undertaken. In this case, the RI represents the distribution of calculated FoS; specifically, the number of standard deviations which separate the mean FoS from the critical FoS of 1.0. This is calculated through a number of approaches, depending on the distribution type of FoS data (i.e. normal or lognormal) as follows:

Normal distribution —

$$\beta = \frac{\mu - 1}{\sigma} \tag{2}$$

Lognormal distribution —

$$\beta_{LN} = \frac{\ln\left(\frac{\mu}{\sqrt{1+V^2}}\right)}{\sqrt{\ln(1+V^2)}} \tag{3}$$

where:

β = reliability index (RI)

μ = mean FoS

σ = standard deviation

V = FoS coefficient of variation (CoV).

The intent of the RI in this example is to quantify the 'spread' of data away from the critical FoS. A low data spread indicates that the model output RI is high, given that the respective input parameters have resulted in the relative alignment of model calculations. A high data spread indicates a low RI, given high variability in the input parameters. The next section presents the outcomes of reliability-based calculations undertaken using both methods for batter stability analyses, with particular consideration given to the coal block sliding undertaken as part of the Hazelwood mine rehabilitation and landform planning. This process lands at a given pit lake level that can be attributed to the highest reliability, thereby objectively demonstrating the minimum lake level required to maintain mine batter stability in the long term.

5 Outcomes of analyses

The reliability-based stability analyses conducted by the authors using the approached outlined in the previous section were based on distributions of input parameters; in particular, material strengths. Critically, the residual interseam strengths for each domain as derived (GHD 2017, 2018a) were considered. Table 1 presents a summary of residual interseam strength data as per the information presented in the assessments. The CoV values for each domain fell within natural tolerances as defined by Harr (1984), supporting the validity of the distributions.

Table 1 Hazelwood mine interseam shear strength (GHD 2018a, 2018b, 2019a, 2019b, 2019c)

Domain	Interseam shear strength at 400 kPa confining pressure			Shear strength CoV (%)	Distribution type
	Lower bound	Characteristic	Upper bound		
NFNB	70	127	178	14	Normal
SWFNB	80	121	167	19	Bi-modal
EFNB	79	104	132	29	Lognormal
EFEB	75	104	137	29	Lognormal
SEFSB	69	116	178	27	Normal
SEFWB	69	116	178	27	Normal
WFSB	103	142	207	22	Lognormal
WFWB	70	127	178	14	Normal

The data to evaluate the precise model reliability index (Riβ) in accordance with the formulas presented in the previous section were derived from the stability analyses and associated calculations. Notably, material variability is implicitly captured within this process. Table 2 describes the RI based on the calculated PoF.

Table 2 Reliability index based on the calculated probability of failure

Reliability index (RIβ)	Probability of failure	Approx. performance reliability
1.0	16%	Hazardous
1.5	7%	Unsatisfactory
2.0	2.3%	Below average
2.5	0.6%	Minimum acceptability
3.0	0.1%	Above average
4.0	0.003%	Good
5.0	0.0003%	High

As per Table 2, a minimum RIβ of between 2.5 and 3.0, corresponding with an approximate PoF of 0.5%, is required to satisfy the nominated Hazelwood mine closure criteria. While the analyses were undertaken for a multitude of critical stability sections, for the purposes of this paper the authors are presenting the results for three key stability lines: namely S5, S6 and N4 (Figure 8). These sections were selected based on the criticality of their past performance as well as their proximity to key external public infrastructure.

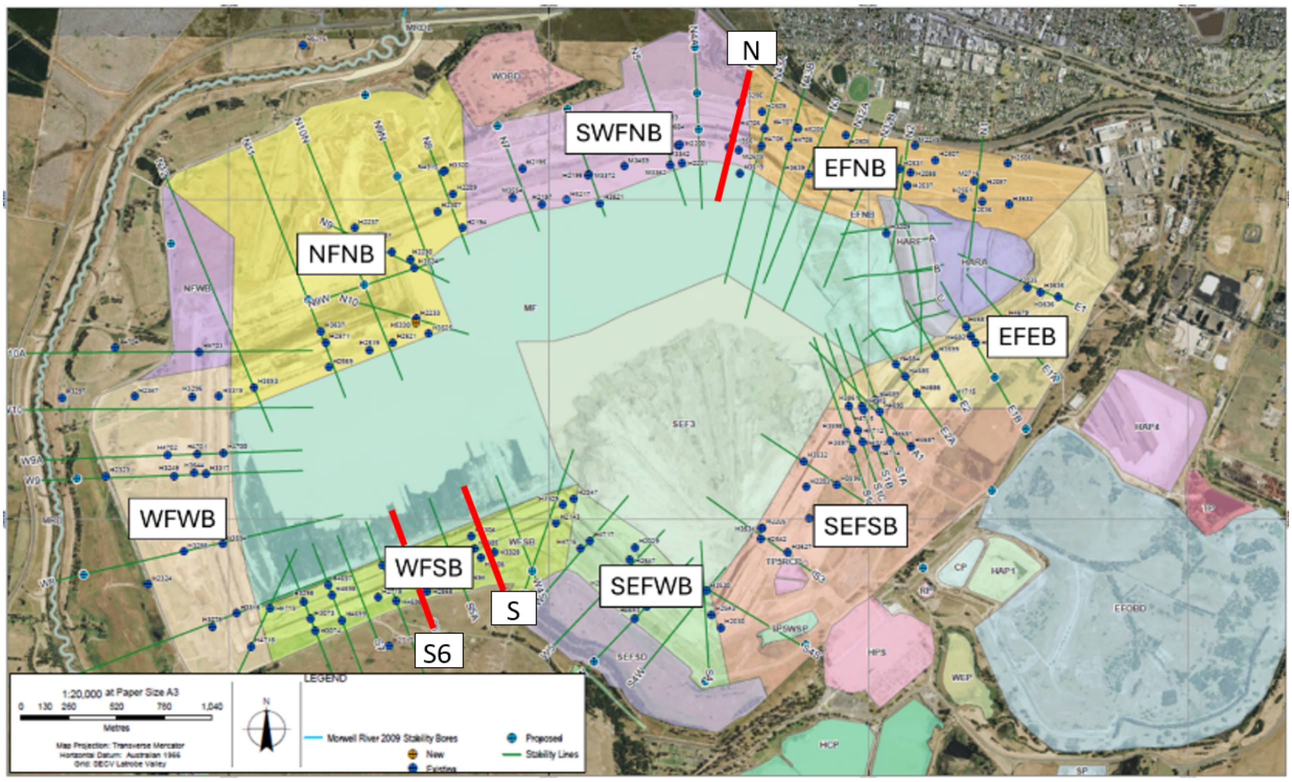

Figure 8 Hazelwood mine geotechnical domains and critical sections (GHD 2023)

The following convention has been adopted to denote conformance to the respective RI criteria:

- green
  - Lilly (2000) RI greater than 99.5%
  - RIβ between 2.5 and 3.0
- amber
  - Lilly (2000) RI between 98% and 99.5%
  - RIβ between 2.0 and 2.5
- red
  - Lilly (2000) RI less than 8%
  - RIβ less than 2.0.

Summarised in Table 3 are the outcomes of the reliability based stability calculations.

Table 3 Reliability index based on select GHD (2024) stability analyses results

Lake level (m AHD)	Stability section S5		Stability section S6		Stability section N4	
	Lilly (2000) RI (%)	Approx. RIβ	Lilly (2000) RI (%)	Approx. RIβ	Lilly (2000) RI (%)	Approx. RIβ
0	84.3%	1.0–1.5	97.8%	2.0–2.5	98.8%	2.0–2.5
1	86.3%	1.0–1.5	Not assessed		Not assessed	
2	88.3%	1.0–1.5	Not assessed		Not assessed	
3	89.0%	1.0–1.5	Not assessed		Not assessed	
4	89.5%	1.0–1.5	Not assessed		Not assessed	
5	90.6%	1.0–1.5	96.1%	1.5–2.0	99.5%	2.5–3.0
10	90.6%	1.0–1.5	98.0%	2.0–2.5	99.9%	2.5–3.0
11	88.8%	1.0–1.5	97.0%	1.5–2.0	94.3%	1.5–2.0
12	87.0%	1.0–1.5	96.1%	1.5–2.0	95.1%	1.5–2.0
13	85.0%	1.0–1.5	95.4%	1.5–2.0	92.8%	1.5–2.0
14	82.4%	1.0–1.5	95.8%	1.5–2.0	95.1%	1.5–2.0
15	84.2%	1.0–1.5	93.9%	1.5–2.0	98.3%	2.0–2.5
16	88.2%	1.0–1.5	94.3%	1.5–2.0	98.4%	2.0–2.5
17	90.7%	1.0–1.5	94.7%	1.5–2.0	98.3%	2.0–2.5
18	92.3%	1.0–1.5	94.9%	1.5–2.0	98.4%	2.0–2.5
19	94.1%	1.5–2.0	95.7%	1.5–2.0	99.2%	2.0–2.5
20	95.1%	1.5–2.0	95.9%	1.5–2.0	99.7%	2.5–3.0
21	Not assessed		Not assessed		99.8%	2.5–3.0
22	Not assessed		Not assessed		99.8%	2.5–3.0
23	Not assessed		Not assessed		99.8%	2.5–3.0
24	Not assessed		Not assessed		99.8%	2.5–3.0
25	95.0%	1.5–2.0	97.3%	1.5–2.0	99.8%	2.5–3.0
26	Not assessed		Not assessed		99.8%	2.5–3.0
27	Not assessed		Not assessed		99.8%	2.5–3.0
28	Not assessed		Not assessed		99.8%	2.5–3.0
29	Not assessed		Not assessed		99.9%	2.5–3.0
30	92.3%	1.0–1.5	95.6%	1.5–2.0	99.9%	2.5–3.0
35	93.0%	1.0–1.5	93.9%	1.5–2.0	99.9%	2.5–3.0
36	Not assessed		95.0%	1.5–2.0	Not assessed	
37	Not assessed		95.1%	1.5–2.0	Not assessed	
38	Not assessed		96.5%	1.5–2.0	Not assessed	

Lake level (m AHD)	Stability section S5		Stability section S6		Stability section N4	
	Lilly (2000) RI (%)	Approx. RIβ	Lilly (2000) RI (%)	Approx. RIβ	Lilly (2000) RI (%)	Approx. RIβ
39	Not assessed		96.7%	1.5–2.0	Not assessed	
40	98.4%	2.0–2.5	99.7%	2.5–3.0	99.9%	2.5–3.0
41	99.3%	2.0–2.5	99.9%	2.5–3.0	Not assessed	
42	99.7%	2.5–3.0	99.5%	2.5–3.0	Not assessed	
43	99.9%	2.5–3.0	99.9%	2.5–3.0	Not assessed	
44	99.9%	2.5–3.0	99.9%	2.5–3.0	Not assessed	
45	99.9%	2.5–3.0	99.9%	2.5–3.0	99.9%	2.5–3.0

The results indicate:

- Any landform with a final lake level of RL +30 m AHD or below is considered unviable.
- The performance of the final landform associated with a level of between RL +30 and RL +40 m AHD was rated low.
- The performance of the final landform associated with a level of between RL +40 and RL +45 m AHD was rated moderate. However, this remained below the required design acceptance criteria as outlined in Figure 8.
- The performance of the final landform associated with a level of between RL +40 and RL +45 m AHD was rated acceptable for all sections.

6 Conclusion

This paper examined pertinent aspects of technical studies undertaken since the closure of Hazelwood mine which centre on the safe, stable, sustainable and non-polluting rehabilitation of the void. In doing so, the context behind and evolution of the Hazelwood mine rehabilitation approach has culminated in the development of the full pit lake closure concept. Consideration of risk in this context has been undertaken through a reliability-based approach to determine the level of confidence that can be attributed to modelled rehabilitation outcomes; in particular, the final landform and pit lake level. The analyses objectively justifies the long-term sustainability of a full pit lake closure when compared to that of a partial pit lake closure. Specifically, the findings demonstrate that a final pit lake level of between RL+42 m and RL +45 m AHD achieves critical stability metrics, including the closure criteria prescribed by the Hazelwood mine licence conditions. These conditions relate to batter stability and a positive weight balance preventing aquifer-induced mine floor heave. Table 4 demonstrates that any lake level below a full lake concept does not achieve the necessary rehabilitation design intent and thus is unsuitable for closure.

Table 4 Concluding lake level summary

Final lake level	Batter stability	Weight balance	Overall rating	Comment
<RL +30 m AHD	Unviable	Unviable	**Unviable**	Does not satisfy stability closure criteria for the majority of mine batter domains Negative weight balance Would require a high degree of ongoing active management including ground depressurisation and erosion maintenance in perpetuity Exposed coal would necessitate clay capping and present and ongoing fire risk
RL +30 to RL +40 m AHD	Low	Low	**Low**	Does not satisfy stability closure criteria for some mine batter domains Negative weight balance Ongoing ground depressurisation and landform management required Exposed coal would necessitate clay capping and a present and ongoing fire risk
RL +40 to RL +45 m AHD	Moderate	Moderate	**Moderate**	Does not satisfy stability closure criteria for select mine batter domains Weight balance achieved at RL +45 m AHD Requirement for some degree of ongoing ground depressurisation, particularly during periods of dry climate Exposed coal would be minimal and the fire risk significantly reduced
>RL +45 m AHD	High	High	**High**	Satisfies stability closure criteria for all mine batter domains Positive weight balance with some tolerance periods of dry climate Lowest level of active management achieved Natural groundwater equilibrium achieved Maximum level of regional ground rebound achieved Exposed coal would be minimal and the fire risk significantly reduced Public utility of final landform

Furthermore, requirements for ongoing active management of the site are reduced to as low as reasonably practicable for a full lake closure upon rebound of natural groundwater levels anticipated in the period following target lake level attainment. This includes the need for ongoing ground depressurisation pumping and the management and maintenance of stability supplementing earthworks which would otherwise be relied upon to support a partial lake final landform. Additionally, the fire risk associated with exposed coal is minimised at lake levels of at least RL +45 m AHD, with potentially combustible coal batters largely submerged by water. Finally, the end land use value for the community is maximised with a full pit lake and recreational activities including water sports, as well as bushwalking through rehabilitated nature reserves anticipated for public utility.

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