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A case study – from operation to closure, transient slope supplementation measures for the northern batters of the Hazelwood mine, using the MGRI approach

S Narendranathan *GHD Pty Ltd, Australia*

J Faithful *ENGIE (Hazelwood Power), Australia*

N Patel *GHD Pty Ltd, Australia*

J Stipcevich *GHD Pty Ltd, Australia*

Abstract

In the mining industry risk is conventionally applied under absolute conditions (e.g., operational scenarios or say a rehabilitated scenario); However, challenges arise when applying these methods to a mine that is in a transient state (i.e., transitioning from operational to final rehabilitated conditions). The closure of Hazelwood Mine, Victoria, Australia, presents a number of unique challenges in this regard.

The Mine is considering a full pit lake as part of their rehabilitation and closure plan. Extensive batter stability analyses have indicated that partial lake fill options can lead to a sub optimal outcome for long term mine batter stability. The Northern Batters of the Hazelwood Mine are within close proximity to the Princes Freeway and Morwell township and have been identified as a 'critical' mine batter within the Ground Control Management Plan (GCMP).

As such, more stringent design acceptance criteria have been nominated for the Northern Batters during the transient state. It has been determined that during lake filling some sections of the Northern Batters would require slope supplementation measures to be installed to further improve the stability outcome.

The design of temporary slope supplementation measures in such transient scenarios (lake filling) need to be carefully considered as there can be an elevated risk profile where adequate treatment is not applied. The Mine Geotechnical Risk Index (MGRI) was developed by Narendranathan et al. (2019) to propose a methodology for quantifying risk under such transient states with specific consideration to mining and geological conditions in the Latrobe Valley.

This paper presents a case study on the design of transient state slope supplementation measures for the Northern Batters of the Hazelwood Mine using the MGRI approach. This ultimately resulted in the identification of critical slope sections which required supplementation.

The slope supplementation measures identified through the MGRI process and the method by which these slope supplementation measures are to be installed will be outlined in the paper.

Keywords: *rehabilitation and closure, batter stability, supplementation, mine risk, open-cut, brown coal*

1 Introduction

The Hazelwood Mine (Latrobe Valley, Victoria) is currently in the process of closure and rehabilitation, which precede relinquishment. A critical aspect of this journey is maintaining batter stability through the transient stage (i.e., the period between cessation of operation and the establishment of the final rehabilitated landform). The rehabilitation concept of the Hazelwood Mine involves filling of the current void to full pit lake, which provides optimal outcomes in relation to batter slope stability.

Over many years, the authors have worked closely with the mine operators and have carried out studies and extensive modelling assessments to understand mine batter stability, groundwater characteristics, associated mechanical behaviour, and inherent variability of the geological units encountered at the mine. A number of these batter stability assessments included geotechnical analyses of batter stability under a number of loading scenarios from the operational stage through to completion of the final rehabilitation design. These assessments enabled the identification of critical slopes areas which would require supplementation during mine rehabilitation, prior to the commencement of lake filling.

This paper presents a case study on the design of transient state slope supplementation measures, using the Mine Geotechnical Risk Index (MGRI) approach (Narendranathan et al., 2019), for the Northern Batters of the Hazelwood Mine. These batters are located within close proximity to the Princes Freeway and Morwell township, and as such, these batters have been identified as a 'critical' mine domain with respect to public infrastructure (see Figure 1 below).

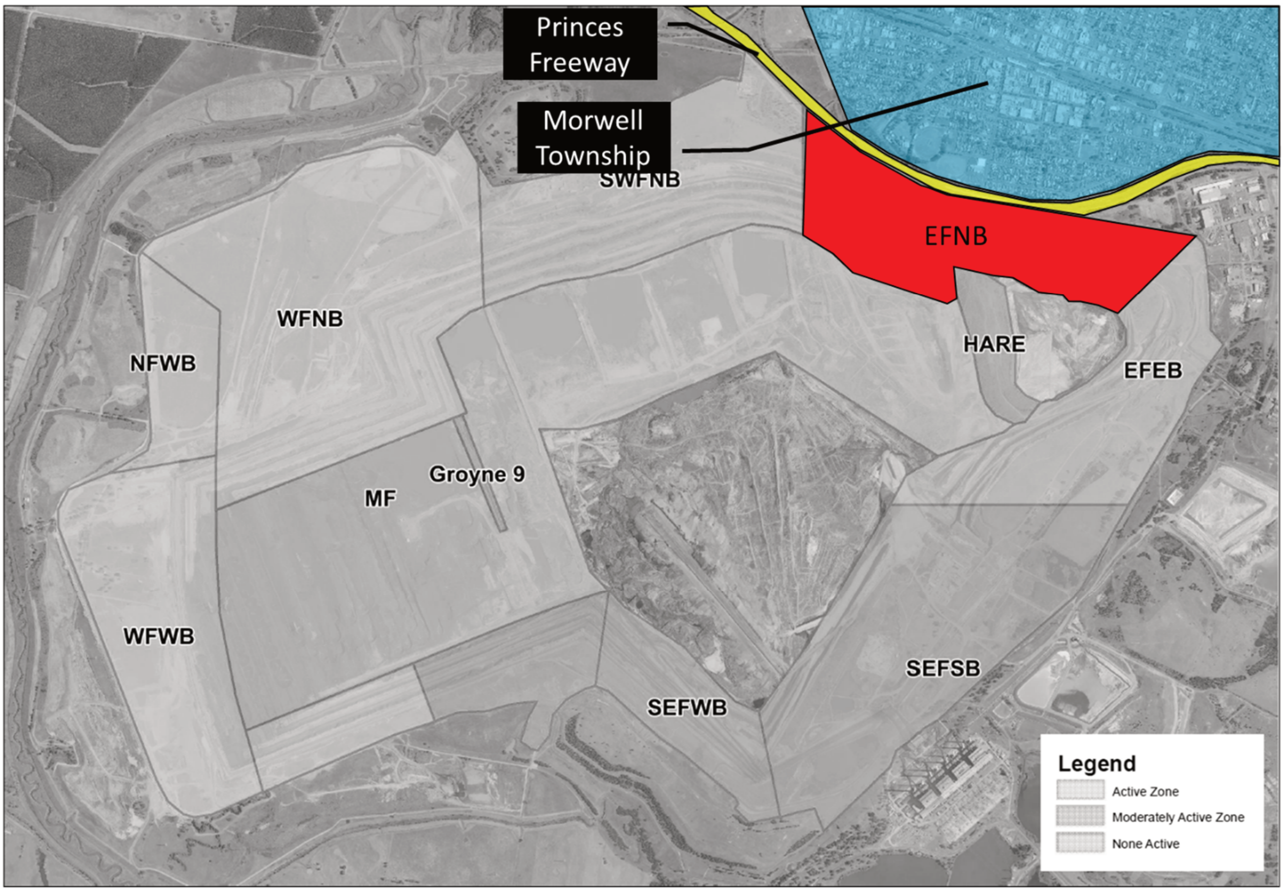

Figure 1 East Field Northern Batters domain location plan

2 Background

The Hazelwood Mine began operation in the 1950s (then referred to as the Morwell Open Cut) and was originally operated by the State Electricity Commission of Victoria (SECV). Over the ensuing decades subsequent to the privatisation, the mine was operated by a number of different companies. The contemporary owners of the Hazelwood Mine, ENGIE, made the decision in early 2017 to cease operations.

This decision led to the subsequent need to develop and implement a robust mine closure proposal for submission to the Victorian Mining Regulator (Earth Resources Regulation). This proposal would have to include all aspects of the site, (i.e., the mine void, the power plant, ash ponds and other mine infrastructure). As outlined earlier, the focus of this paper is to present how the stability of the batter slopes were assessed as a result of the rehabilitation outcomes.

There were a number of challenges faced by the authors in developing these assessments for the mine batters as follows:

- A mine of this scale in such close proximity to public infrastructure arrangements.
- In Victoria (at the time) there was no published precedence for the design acceptance criteria for the stability serviceability criteria for the closure of a mine of this scale. Noting that the serviceable life of the final landform is essentially 'in perpetuity'.
- There is significant mechanical variability of the geological materials that comprise of the mine batter slopes. Accordingly, it was challenging to characterise the materials using 'singular' parameters as there were rapid variations over small distances.
- Additionally, as the final rehabilitation concept involved a full pit lake, the assessments had to consider the stability effects of a rising pit lake. (I.e., as the pit lake rises it changes the 'equilibrium' stress regime around the batter slopes and at times can adversely affect batter stability.)

As a result of all of the above considerations and challenges, it was deemed appropriate to apply a risk-based design approach to assessing batter stability considerations associated with lake filling and rehabilitation. The probabilistic modelling approach applied by the authors was after Narendranathan (2009) and is described in further detail below.

The intent of the probabilistic stability modelling was to determine the risk and consequence of batter instability for the critical Hazelwood Mine domain at various stages associated with lake filling levels. The results of which would assist in attributing suitable supplementation measures to improve the batter stability outcomes, using the newly developed (Mine Geotechnical Risk Index) approach after Narendranathan (2019).

2.1 Introduction to the Mine Geotechnical Risk Index

Conventionally, geotechnical risk evaluation is typically conducted on particular scenarios such as operational mine conditions (i.e., current conditions) or closed and rehabilitated conditions (i.e., long term conditions) which may need to satisfy different acceptance criteria than during the transient stages. Narendranathan et al. (2019) proposed that to evaluate stability during the transitional phases using the Mine Geotechnical Risk Index approach can be employed to attribute 'acceptable' increases of tolerable risk thresholds based on research conducted by Bell et al. (2005) on landslides. Narendranathan et al. (2019) noted that the approach should not be extended to the post-closure phase, without the benefit of dedicated risk assessments.

Narendranathan et al. (2019) defined the MGRI thus:

$$MGRI = (PC_t \times C_f \times I_f \times S_f) \tag{1}$$

where:

MGRI = Mine Geotechnical Risk Index.

PC_t = Annual probability of primary instability load or scenario occurring.

C_f = Consequence Factor – Probability of Failure (PF) x Volume of Failure (VF).

I_f = Impact factor.

S_f = Seasonal factor.

NB – The probability of failure (PF) is determined by the number of occurrences where the factor of safety (FoS) is less than 1.0 (i.e., FoS < 1).

In applying Equation 1 to calculate the resulting risk, the authors provide the following guidance in selecting/calculating the respective factors above.

- Cf – consequence factor.

  PF x VF, after Lilly (2000) and Narendranathan (2009), as per the calculation process above.

- PCt – annual probability of the primary instability load or scenario occurring.

  This factor is best applied where there is documented history of a particular loading scenario or event occurring that leads to instability, without which it is contingent upon a clear understanding of site instability mechanisms and causative factors.

- I_f – Impact factor.

  The impact factor is attributed based on the potential for a single 'event' to impact multiple individuals. The following criteria is proposed:

  - Single event impacting 1 individual, If = 0.15
  - Single event impacting > 1 < 3 individuals, If = 0.5
  - Single event impacting >33 <6 individuals, If = 0.7
  - Single event impacting > 6 individuals, If = 1.0.

- S_f – Seasonal factor.

  This is a factor attributed in proportion to the likelihood of a nominated seasonal event occurring in the nominated period. For example, say the proposed period of mine rehabilitation is 20 years and let's assume the critical event that might trigger an instability by elevating the phreatic gradient within a slope is a 1 in 50 year event. This factor would be calculated thus, 20/50 = 0.4.

2.2.1 Definition of tolerable risk increase

Narendranathan et al (2019) defined the following range of tolerable risk increase thresholds based on Bell et al. (2005), but were refined with the benefit of guidance provided by a number of authors (Ammann 2005; Agustsson et al. 2003; Borter 1999; Geotechnical Engineering Office 1997; Jonasson et al. 1999; Johannesson & Agustsson 2002; Malone 2005; The ministry of the Environment 2000), on the topic of 'acceptable levels of risk' when considering landslide areas that are subjected to public access.

Table 1 Risk increase thresholds

Risk level	Threshold of variation
Very low	≤ 0 %
Low	0–13 %
Medium	13–29 %
High	>29 %

The case study outlined in the subsequent section demonstrates how the MGRI approach was utilised in concert with the above thresholds to develop a 'risk and consequence map' for the Northern Batters of the Hazelwood Mine to identify key areas that required supplementation during lake filling, prior to establishing the final rehabilitation landform.

3 Case study

3.1 Introduction

The case study presented herein portrays the northern batters of the Hazelwood Mine. It demonstrates how the MGRI approach was successfully utilised by the authors to assess the stability outcomes at various stages of mine rehabilitation for the northern batters of the mine as shown in Figure 1.

The critical mechanism that can lead to a large-scale instability is referred to as the 'Coal Block Sliding' mechanism, See Figure 2). It occurs where there are excessive destabilising forces as a result of:

- Hydrostatic pressures within the coal joints / tension cracks.
- Elevated phreatic gradient within the coal unit.
- Upthrust from underlying aquifers.

These forces are typically counteracted by the following stabilising forces:

- The strength of the underlying interseam, the unit upon which the overlying coal block could 'slide'.
- Resisting forces afforded by the pit lake.

NB - measures such as aquifer depressurisation and or suitably designed slope supplementation measures can be used to further mitigate the initiation of the block sliding mechanism.

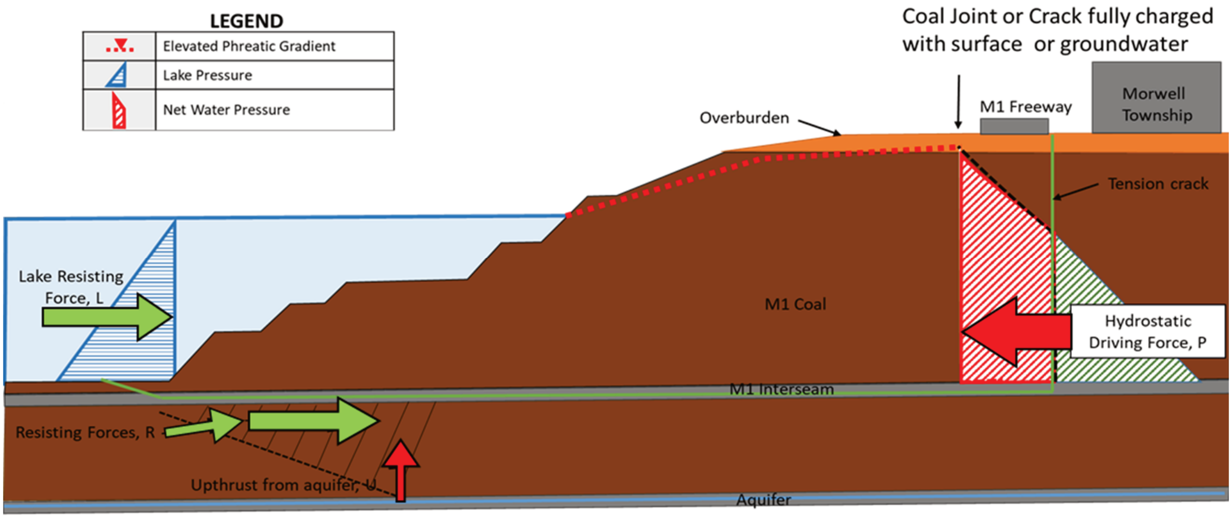

Figure 2 Coal Block Sliding Mechanism

3.1 Investigation Methodology

The following approach was employed in assessing the requirements for the batter stability supplementation for the northern batters of the Hazelwood Mine:

- A dedicated an extensive intrusive and analytical geotechnical investigation was employed across the mine. This investigation was utilised to supplement the already present geotechnical information base to amass a robust geotechnical database of information.
- Upon compilation of the newly acquired data with the existing data a probabilistic geotechnical model was developed utilising the process developed by Narendranathan (2009). This model consisted of the following features:
  - Material strengths and associated variability (i.e., distributions) for the key geological units, coal, interseam and the overburden.
  - Joint strength and orientation variability.
  - Fluctuations in groundwater gradients.
- These geotechnical models were subsequently subjected to stability calculations.
- The results of the stability calculations were incorporated into the MGRI calculation process to develop a consequence based risk map of the untreated mine batters during rehabilitation.
- This risk map was utilised to identify untreated areas of the northern batters which fell outside the tolerable thresholds as outlined in Table 1.

- These areas of the mine batters (i.e., those outside the 'tolerable' thresholds) were subjected to further investigation to identify suitable slope supplementation measures.
- The preceding steps were repeated until the resultant risk thresholds were within the 'tolerable' range. This signified a suitable slope supplementation outcome.

3.2 Investigation and Geotechnical Model Development

An extensive campaign of investigation, laboratory characterisation and associated analytical interpretation of the main lithological units at the Hazelwood Mine (i.e., the M1 Interseam, M1 Coal and the overburden unit) was undertaken.

The following approach was employed in the statistical characterisation of the above units along the northern batters of the Hazelwood Mine to assess the variability of its properties relevant to batter stability (i.e., coal block sliding movement):

- The data from the contemporary borehole investigation campaign was reduced and combined with historic material strength information, which consisted of direct shear test information obtained by the State Energy Commission Victoria (SECV) from circa 1970 onwards.
- A statistical interrogation was performed to assess the 'validity' of the combined dataset, whereby a data set needs to have a certain number of minimum 'sample points' and statistical 'confidence' in relation to its variability to be considered 'valid'. This assessment was undertaken using the criteria stipulated by Harr (1984).
- This test involved the following steps and considerations:
  - It should be appreciated that most conventional statistical 'validity' tests have been devised for assessing the variability / tolerance of 'engineered' materials, (i.e., say the Student's t-test).
  - Such tests involve 'testing' each 'sample' point against a predefined 'acceptance' value (or mean).
  - It also presupposes 'independence' between the individual data points as well as a Gaussian distribution.
  - This process is difficult to apply in the context of 'naturally' occurring materials (i.e., say the three main geological units at the Hazelwood Mine), as they do not conform to the criteria set out in the points above.
  - Accordingly, Harr (1984) and others, have studied the variance of 'naturally' occurring materials and have put forward an alternate approach that looks at a collective set of data points, and comparing the 'variance' of the set with their studied (compiled) thresholds (Refer to Table 1).
  - This process involves calculating a 'dispersion' metric for the data set in question, specifically the relative standard deviation or coefficient of variation (CoV).
  - The CoV is defined as the ratio of the standard deviation to the mean, expressed thus:

    $$c_v = \frac{\sigma}{\mu}.$$

  - It shows the extent of variability in relation to the mean of the population.

With the above in mind for the context of the Northern Batters:

- Progressive strength measurements for the respective lithological units were initially sourced from a single borehole drilled as part of the contemporary investigation, and then 'combined' progressively with the strength measurements from the historical campaigns, and the resulting mean value was calculated.

- The recalculated mean was utilised to compute a revised CoV, which was then compared to the criteria put forward by Harr et al. (1984).
- Steps (i) and (ii) were repeated until the CoV fell 'outside' the criteria stipulated by Harr et al. (1984), this was deemed to be the point at which the combined data set ceased to be 'valid'.

Implementing the above approach enabled the formulation of a statistically valid distribution of material parameters for each of the geological units. These distributions were subsequently utilised to develop shear strength envelopes that replicated the behaviour of the geological units under various stress conditions; thereby enabling the effecting replication of batter stability at different lake levels. Shown below in Figure 3 is the distribution of material properties strength envelopes and for the critical coal interseam unit.

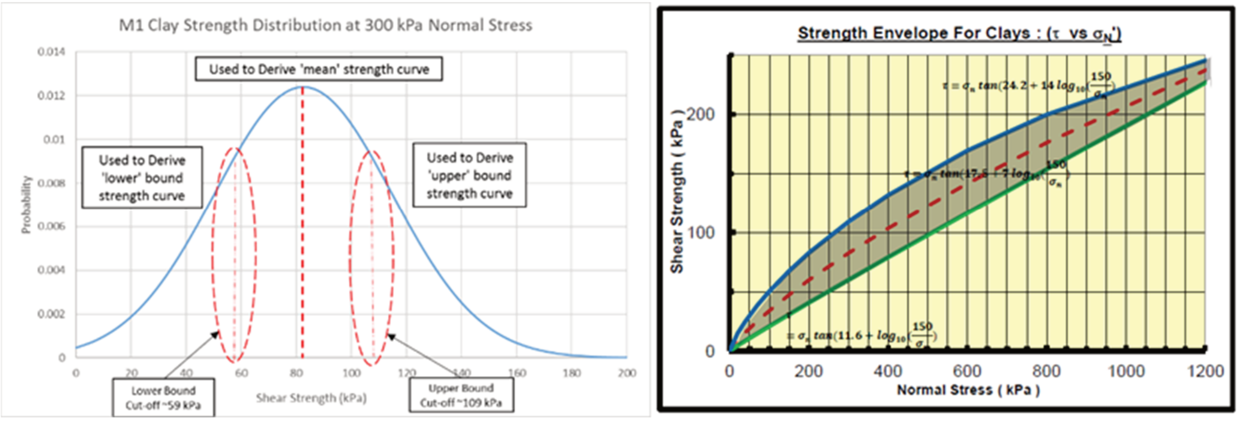

Figure 3 M1 Clay (coal interseam) strength distribution

3.3 Stability Calculations

Upon developing the probabilistic geotechnical model as outlined above, limit equilibrium stability calculations were undertaken to calculate the following parameters:

- Factor of safety - is a ratio of the resisting forces against the destabilising forces. A FoS of less than 1.0 indicates that the sum of the driving forces is greater than the sum of the resisting forces. This implies that the slope is continually displacing, i.e., moving.
- Probability of Failure – The probability of failure is defined as the likelihood of the FoS falling below 1.0.

As part of the calculation process, eight stability sections were defined across the northern batters, each of which were subjected to analyses to assess the outcomes as a result of a filling mine void. Figure 4 depicts the results of the PF variations during lake filling. There is an increase in the probability of failure during the interim lake fill stages, which substantially reduces upon reaching the full lake at the +45 mRL.

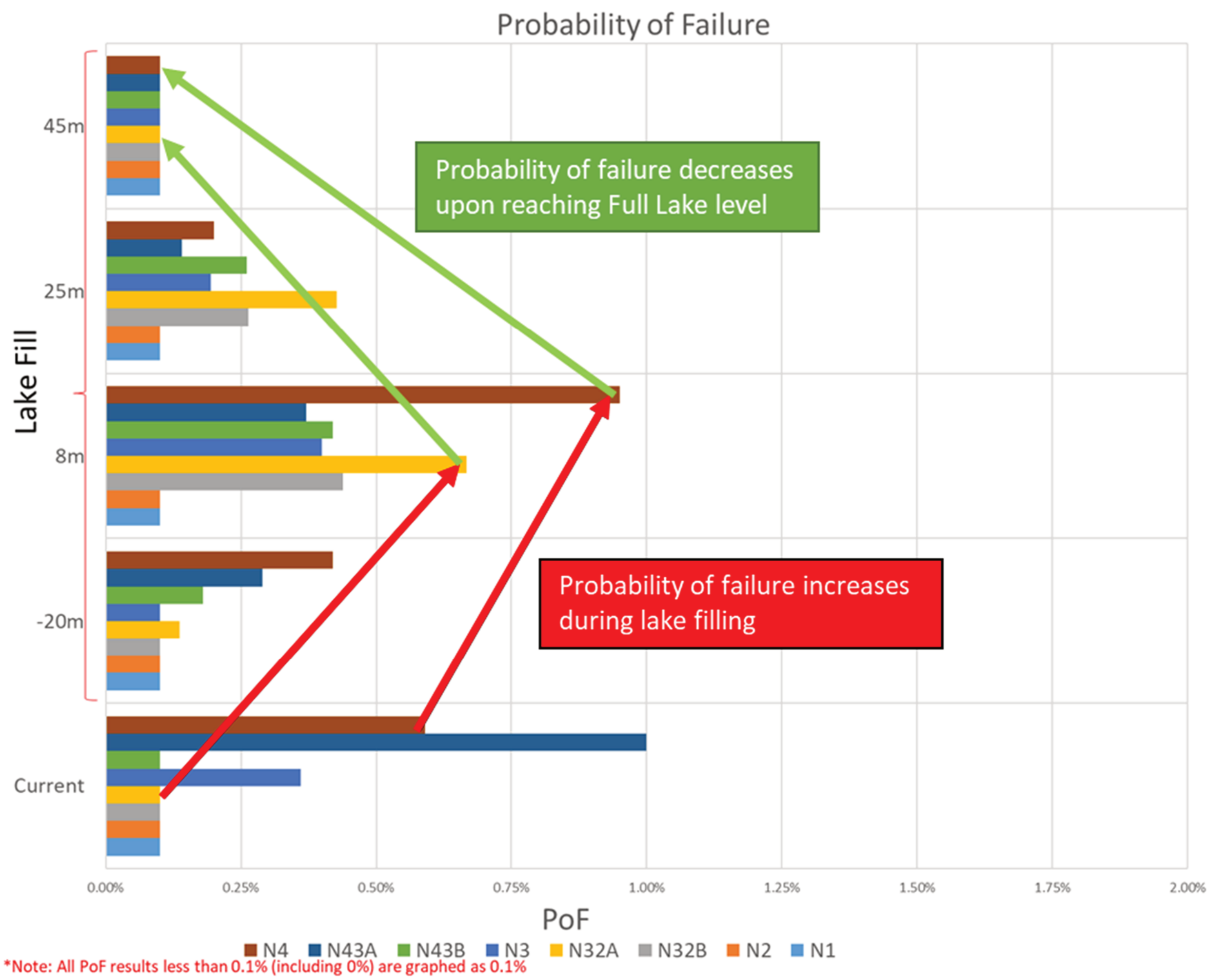

Figure 4 Probability of failure for northern batters

From Figure 4 it can be seen that there is a comparative increase the probability of failure prior to achieving the ‘full lake’ at the +45 mRL. A similar trend is also noted when examining the distribution of FoS for the respective stability sections, as shown in Figure 5.

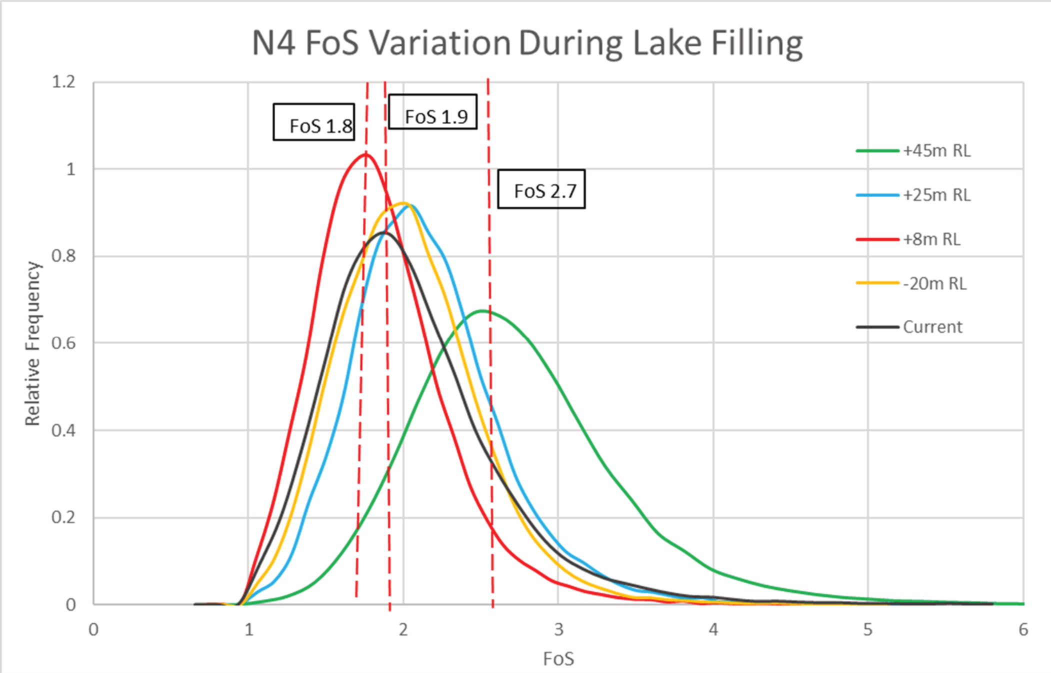

Figure 5 Factor of safety variation during lake filling

From Figure 5 above, it can be seen that the mean FoS for this section drops from approximately 1.9 to 1.8, as the lake level rises from the current state to the +8 mRL. Once the pit lake reaches +45 mRL the FoS increases to approximately 2.7. This demonstrates that a long-term lake option at +45 mRL is the optimal outcome from stability perspective at the Hazelwood Mine.

From the stability results above it can be seen that there is definitely an increase in the likelihood of instability during lake filling. The question that arises now, is whether or not this is 'tolerable' and what additional and redundant supplementation measure may need to be designed to manage these outcomes.

3.4 Mine Geotechnical Risk Index Assessment

As noted in Section 3.3 above, an increased likelihood of instability has been calculated for during lake filling. In order to assess a tolerable FoS range, and to assist with the design of any additional slope supplementation measures, the authors have adopted the MGRI approach to quantify risk during the transient phase.

For the purposes of demonstrating the manner by which the MGRI calculations are undertaken, the following two-dimensional cross section from the Hazelwood Mine, as depicted in Figure 6 below, has been selected.

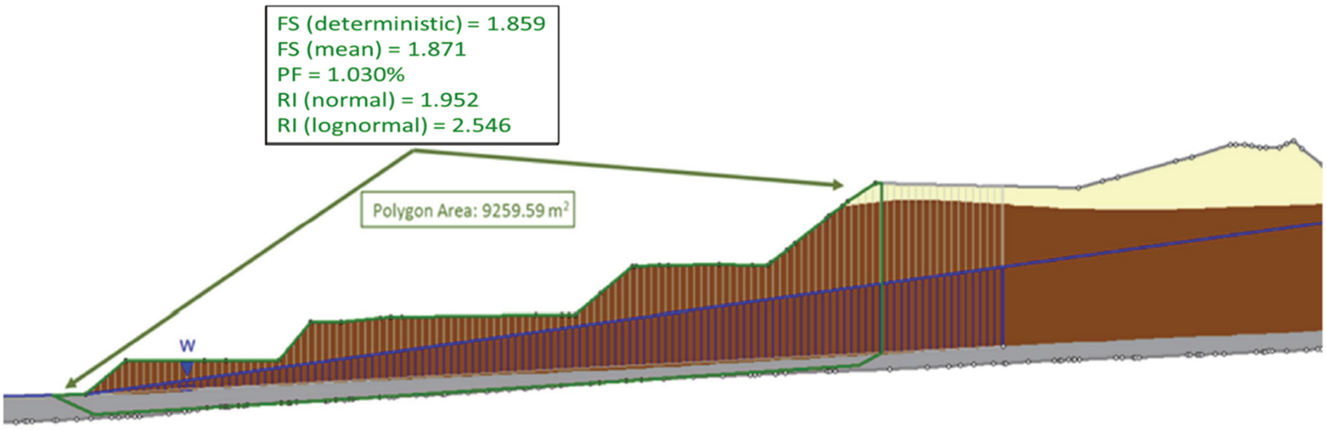

Figure 6 Stability calculations

Table 2 Calculation of the Mine Geotechnical Risk Index at closure assuming geotechnical risk management continues

Parameters	Value	Explanatory notes
PF	1.03%	Calculated PF (Figure 6)
Area (m^3/m)	9,259.59	Cross-sectional area of critical failure (Figure 6)
C_f	186.12	Consequence factor (PF x area)
PC_t	0.25	Based on an annualised probability of malfunctioning of the dewatering infrastructure
I_f	1.00	Assumption was that if the infrastructure arrangement became unserviceable it could result in 6+ fatalities
S_f	0.05	Annualised probability, designs based on 1 in 20 year event
MGRI	1.19	Calculated as PC_t x C_f x I_f x S_f

Based on the calculations in Table 2, an MGRI of 1.19 has been calculated for this section, which can be considered the base case scenario. This value will serve as the metric against which comparative risk elevations will be assessed for the respective geotechnical domains within this risk.

Table 3 below presents the calculated MGRI value for the same geotechnical section assuming the termination of active geotechnical management.

Table 3 Calculation of the Mine Geotechnical Risk Index at closure assuming geotechnical risk management ceases

Parameters	Value	Explanatory notes
PF	1.03%	Factors as Table 2
Area (m^3/m)	9,259.59	
C_f	186.12	
PC_t	0.25	
I_f	1.00	+
S_f	0.5	Annualised likelihood of drainage malfunction increases as no maintenance is undertaken during the closure phase
MGRI	11.92	
Delta	1000% increase in risk rating	

Based on the calculations undertaken in Table 3, it is expected that upon cessation of regular mine maintenance measures, in particular the maintenance of the drainage system, there will be a theoretical (absolute) increase in the overall risk profile of approximately 1000%. This increase in overall risk is well beyond acceptable tolerances put forward by Narendranathan et al (2019) as outlined in Table 1 of this paper. This demonstrates that leaving this sector of the slope untreated during the closure period could result in risks in excess of a tolerable threshold.

Table 4 presents the results of the MRGI assessments for the eight stability sections across the northern batters for the Hazelwood Mine, where no treatment is applied and assuming an unlikely and hypothetical 'failure' of all active stability management protocols.

Table 4 Untreated MGRI risk map of untreated batters

Geotechnical Stability Section	Starting pit lake (year 0)	25% pit lake (0<year<7)	50% pit lake (7<year<15)	75% pit lake (15<year<20)	Full pit lake (>year 20)
1	Base case	≤0%	>29%	>29%	≤0%
2		≤0%	>29%	>29%	≤0%
3		≤0%	>29%	>29%	≤0%
4		≤0%	>29%	>29%	≤0%
5		≤0%	≤0%	>29%	≤0%
6		>29%	>29%	>29%	≤0%
7		14%	≤0%	>29%	≤0%
8		≤0%	>29%	≤0%	≤0%

Based on the map above it can be seen that there are a number of sections within the northern batter domain of the mine that require additional treatment during the lake filling phase to remain within the 'tolerable' threshold as defined by Narendranathan et al (2019), as outlined in Table 1.

3.4.1 Using the MGRI Approach to Determine Batter Supplementation Measures

The previous section outlined that the cessation of geotechnical management results in an unacceptable increase in risk, which requires the implementation of supplementary slope management measures. The measures under consideration were the installation of surcharges (i.e., buttresses) and additional slope drainage measures to manage the coal water gradient and joint water levels. Various iterations were considered and calculated (i.e., buttress design dimensions and drainage considerations).

Presented in Figure 7 are the updated results of the stability calculations incorporating slope supplementation measures (i.e., buttress), which result in an increase in the FoS and a reduction in failure volume relative to the base case scenario presented in Figure 6. Table 5 presents the revised calculation of the MGRI for this section incorporating the slope stabilisation measures.

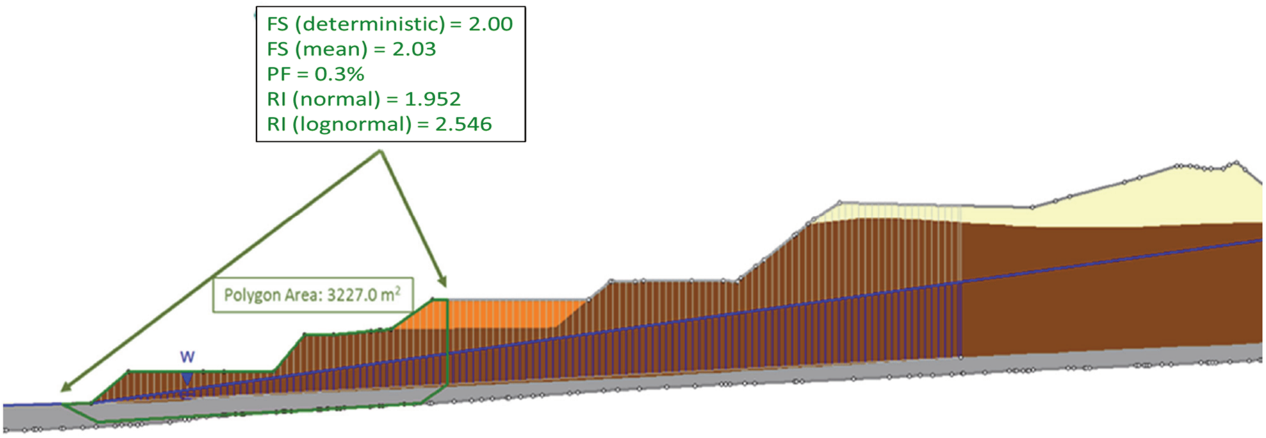

Figure 7 Derived slope stabilisation measures

Table 5 Calculation of the MGRI incorporating slope stabilisation measures

Parameters	Value	Explanatory notes
PF	0.30%	Calculated PF (Figure 7)
Area (m^3/m)	3,227.0	Cross-sectional area of critical failure (Figure 7)
C_f	9.68	Consequence factor (PF x area)
PC_t	0.25	Based on an annualised probability of malfunctioning of the dewatering infrastructure
I_f	0.15	Revised, based on the reduction in volume of failure and C_f
S_f	0.5	Annualised likelihood of drainage malfunction increases as no maintenance is undertaken during closure phase
MGRI	0.18	
Delta	<0% increase	

The MGRI approach was applied across the remainder of the eight sections used in stability analysis and the resultant values were calculated as presented in Table 6.

Table 6 MGRI risk map of treated batters

Geotechnical Stability Section	Starting pit lake (year 0)	25% pit lake (0<year<7)	50% pit lake (7<year<15)	75% pit lake (15<year<20)	Full pit lake (>year 20)
1	Base case	≤0%	10%	9%	≤0%
2		≤0%	9%	7%	≤0%
3		≤0%	8%	8%	≤0%
4		≤0%	10%	8%	≤0%
5		≤0%	2%	≤0%	≤0%
6		>17%	15%	11%	≤0%
7		14%	≤0%	2%	≤0%
8		≤0%	10%	≤0%	≤0%

Results indicate that the application of surcharges across critical areas of the mine benches during lake filling can bring all of the resultant rick ratings to a 'tolerable' threshold.

4 Conclusions and Stability Considerations During Lake Filling and Mine Rehabilitation

The authors would like to highlight that in this particular context at the Hazelwood Mine, the designed supplementation measures (surcharges) are only intended to provide supplementation prior to the lake recovering to a coincident level. Whereby the surcharges become superfluous at this point as lake forces provide an equivalent stabilising effect, see Figure 8.

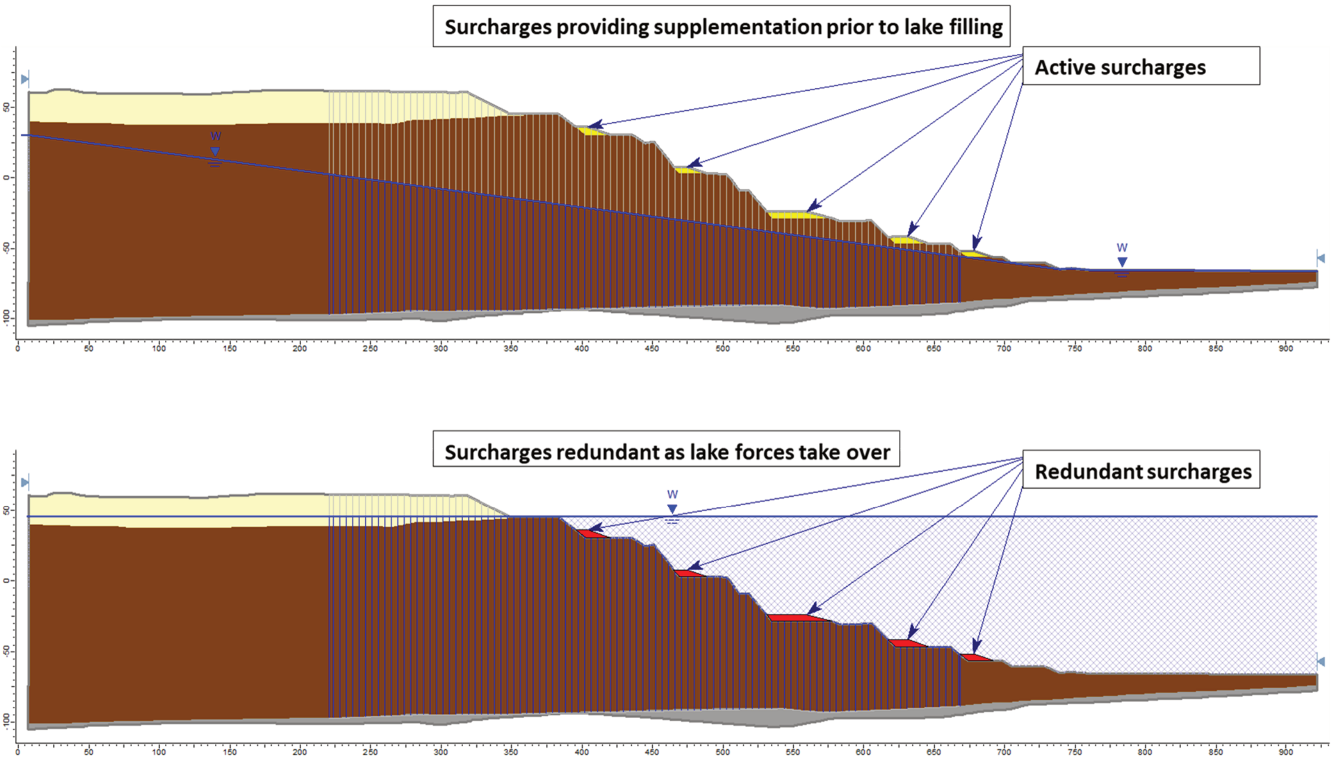

Figure 8 Interaction of Surcharge and Lake Forces

This case study demonstrates how the MGRI approach was successfully employed in the development of batter slope supplementation measures during the transient phase of mine rehabilitation, prior to the establishment of the final mine landform.

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References

Ammann, WJ 2005, 'Natural hazards: risk concept and integral risk management', in WJ Ammann, S Dannenmann & L Vulliet (eds), *Proceedings of RISK21 – Coping with Risks due to Natural Hazards in the 21st Century*, A.A. Balkema, Rotterdam.

Ágústsson, K, Jóhanneson, T, Sauermoser, S, Sigurðsson, Hó & Jensen, EH 2003, Hazard Zoning for Bíldudalur, Vesturbyggð, Report 03034, Icelandic Meteorological Office, Reykjavík, viewed 6 February 2019, http://www.vedur.is/snjoflod/haettumat/bi/bi_tech.pdf

Borter, P 1999, 'Risikoanalyse bei gravitativen naturgefahren: methode', Umwelt-Materialien, no. 107/I.

Bell R, Glade, T & Danscheid M 2005, Risks in Defining Acceptable Risk Levels, University of Bonn, Bonn.

Harr 1984, Reliability-Based Design in Civil Engineering, Department of Civil Engineering, School of Engineering, North Carolina State University, 1984.

Jónasson, K, Sigurdsson, SP & Arnalds, P 1999, Estimation of Avalanche Risk, report VÍ-R99001-ÚR01, Icelandic Meteorological Office, Reykjavík.

Jóhannesson, T & Ágústsson, K 2002, Hazard Zoning for Debris Flows, Rockfall, Slushflows and Torrents and Slushflows Mixed with Soil in Steep Slopes, report TóJ/Kri-2002/01, Icelandic Meteorological Office, Reykjavík, in Icelandic

Latrobe Valley Regional Rehabilitation Strategy 2019, Preliminary assessment of mine scale pit lake rehabilitation geotechnical risks for the Latrobe Valley Mines, Version 2, Department of Jobs, Precincts and Regions, August 2019.

Lilly, PA 2000, The minimum total cost approach to optimise pit slope design, Western Australia School of Mines, Kalgoorlie.

Malone, AW 2005, 'The story of quantified risk and its place in slope safety policy in Hong Kong', in T Glade, MG Anderson & M Crozier (eds), Landslide Hazard and Risk, John Wiley & Sons, Chichester.

Narendranathan, S 2009, 'Fundamentals of probabilistic slope design and its use in pit optimization', *Proceedings of the 43rd US Rock Mechanics Symposium & 4th US - Canada Rock Mechanics Symposium*, American Rock Mechanics Association, Alexandria.

Narendranathan, S & Cheng, M 2019, 'Development of the Mine Geotechnical Risk Index', in J Wesseloo (ed.), *Proceedings of the First International Conference on Mining Geomechanical Risk*, Australian Centre for Geomechanics, Perth, pp. 461-474.

The Ministry of the Environment 2000, Reglugerð nr. 505/2000, Reglugerð um Hættumat Vegna Ofanflóða, Flokkun og Nýtingu Hættusvæða og gerð Bráðabirgðahættumats (Regulation on hazard zoning for avalanches, debris flows and rockfall, the usage of hazard zones, and the making of preliminary hazard zoning), viewed 16 August 2018, https://www.reglugerd.is/reglugerdir/allar/nr/505-2000