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Mining through historic underground workings and systematic void management processes at McArthur River Mine

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Abstract

The McArthur River Mine (MRM) is in the Northern Territory, Australia, and is the largest known stratiform sediment-hosted Zn-Pb deposit. Mining of the deposit commenced in 1995 as an underground operation before transitioning into an open cut in 2006. The primary method of underground mining was room and pillar, specifically targeting the high-grade ore. Bulk sublevel open stoping and bench stoping were also used where appropriate. The bulk stopes were taken with a stope and retreat method, leaving all stopes open on closure of the underground mine. The historic underground voids have presented a significant hazard to be managed as the open cut has progressed.

This paper presents the analysis methods used to determine a safe working crown pillar thickness for the open pit mining operations. The primary analysis methods used at MRM to determine a safe working level are the catastrophic failure analysis (CFA) and scaled span analysis (SSA). The CFA considers a progressive failure of the crown utilising a bulking factor to represent the volumetric increase between intact rock and broken rock and determines whether a failure event will progress to the surface or choke itself off. The SSA is an empirical approach based on rock mass quality and scaled span.

Failure events such as caving, ravelling, and chimneying can reduce crown pillar thickness, which in turn can lead to subsidence and collapse. Probe drilling is conducted from active open cut levels to investigate the surface crown pillar and to delineate the spatial extent of the underground void.

Probe drilling has identified several cases of failure events in most bulk stopes. These failure events, in conjunction with locations where the crown has not failed, have been used to calibrate an empirical method for estimating crown pillar thickness to the MRM site conditions.

This paper presents the systematic void management processes, analysis methods used to determine a safe working crown pillar thickness, and unique challenges faced while mining through historic underground workings.

Keywords: *void management, open pit mining, underground mining*

1 Introduction

The McArthur River Mine (MRM) is in the Northern Territory, Australia and is the largest known stratiform sediment-hosted Zn-Pb deposit. The sediments consist of varying beds of dolomitic, bituminous, pyritic shales and breccias with inter-bedded tuffaceous beds throughout. The mineralised beds are approximately 55 m thick and have been divided into eight orebodies. There are two main fold zones within the proposed pit area, the Upper Fold in the western margins and the Lower Fold or Hinge Zone in the eastern margins. Between the folds, the deposit dips from 10–30° to the southeast.

Underground mining operations at MRM began in 1995. Room and pillar mining was the primary extraction method specifically targeting the lower three closely spaced orebodies, the 2–4 orebodies. The lower orebody (2OB) was extracted first. Later, bulk open stoping and bench stoping were used to mine the 4OB using the existing room and pillar as the mining horizon. The bulk stopes were extracted using a stope and retreat method leaving all stope voids open on completion of mining. Underground mining operations ceased in early 2006, having extracted most of the high-grade ore. Figure 1 represents the plan view of the current pit outlining the historic underground mine.

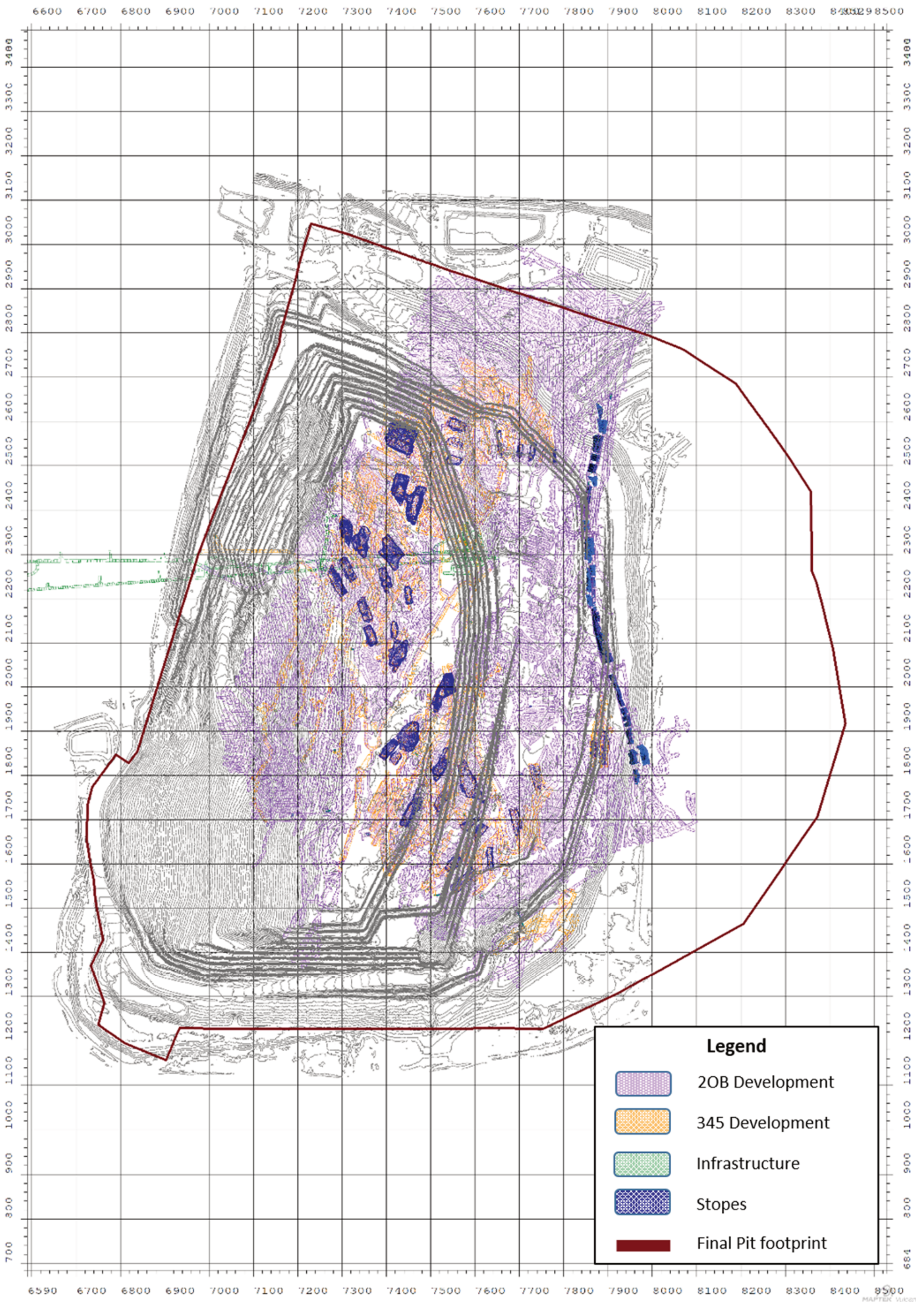


Figure 1 Plan view of open cut showing the historic underground mine and final pit footprint

MRM transitioned from underground to open cut in 2006. The transition has presented significant geotechnical hazards to the open pit such as the stability of pit walls, pit floor and the safety of mining personnel. The geological structure, rock mass properties, deterioration over time and the hydrogeological conditions must all be considered while open cut mining progresses. Failures such as caving, ravelling, and chimneying can lead to a reduced crown pillar thickness resulting in potential surface level subsidence. Also, the effects of water, blasting, and shearing on bedding planes with stress/relief cycles and the consequent redistribution of stress, rock mass deformation, and relaxation may lead to the misinterpretation of stability.

Empirical methods and numerical simulations are used to predict the potential impact that a failure of the underground voids could have on the surface. To date there have been no failures of the crown pillar that have impacted the pit floor, however, there have been instances of voids being visible post-blasting. It is assumed that these voids are present due to chimneying failure.

This paper presents the systematic void management processes, analysis methods used to determine safe working crown pillar thickness, and the unique challenges faced while mining through the historic underground workings at MRM.

2 Void management

There are hazards with a high-risk potential within MRM open pit that develop when the open pit approaches and progressively mines through the historic underground workings. These hazards present unique challenges compared to a traditional open cut operation and include:

- Sudden and unexpected collapse of the open pit floor and/or walls.
- The loss of personnel and/or equipment into unfilled or partially filled underground workings.
- Loss of explosives from charged blastholes that have broken through into the underground workings.
- Instability of the open pit walls and surrounding surface areas.

Void management systems at MRM were initially adopted from Glencore's Black Star Open Cut and tailored to suit conditions at MRM. The void management model consists of three primary stages: identification, analysis, and risk management (Bar et al. 2018). Figure 2 represents the void management model used at MRM.

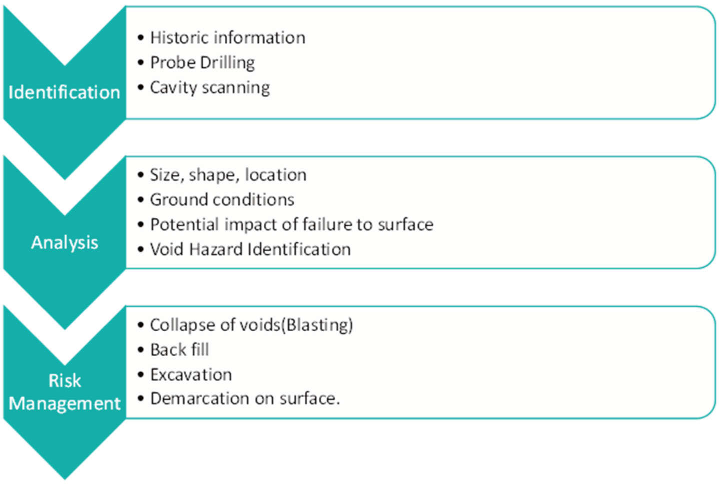


Figure 2 Void management process model

3 Identification

The underground mine was surveyed in 2006 prior to its closure. This surveyed model provides the basis for initial void identification. Considering the age of the open stopes (since 1995 to 2006), it is likely that changes in ground stress/relief, and the periods of flooding and dewatering have affected the conditions of the underground workings and crown pillars. Failures such as caving, ravelling, and chimneying can reduce crown pillar thickness, which in turn can lead to effects such as crown collapse and subsidence.

MRM therefore conducts probe drilling to verify the accuracy of the surveyed model and to delineate the spatial extent of the voids. MRM also deploys a cavity auto laser scanner (C-ALS) in the probe holes to more accurately model void geometries.

Probe drilling and scanning the voids has proven to be an effective method to identify voids.

4 Analysis

Several different methods have been used at MRM to determine crown pillar stability and minimum crown thickness. The experience gained operating a high production open cut above an expansive network of underground voids has led to the catastrophic failure analysis (CFA) and scaled span analysis (SSA) being used to determine stability, minimum pillar thickness, and to ensure the safety of mining personnel.

Every crown pillar and void are different; therefore, they are all assessed on a case-by-case basis. The CFA is the primary method of determining the minimum crown pillar thickness by using probe drilling results. These methods of analyses appear to be quite conservative as no crown failures have propagated or impacted pit operations. In some complex situations, further investigation and crown analysis are used to determine stability.

Voids are treated as individual entities at MRM, whether they are present in sequence or groupings for example room and pillar. This relies on two assumptions:

- Should the crown pillar fail, it will fall into the void beneath it.
- The bulking factor appropriately represents the swelling of the rock mass that forms the crown pillar.

4.1 Catastrophic failure analysis

The CFA was introduced to MRM in 2009 (Bar et al. 2018) to predict the progression of a crown failure and whether it will reach the surface or choke itself off. CFA assumes failure occurs and progresses up towards the surface as a series of horizontal slices. A bulking or swelling factor (*SF*) is adopted to represent the volumetric increase between broken and intact rock. As the failure progresses, the void height (x) reduces as the volume of intact rock swells to the volume of broken rock. The total volume of material required to choke the progressive caving is the sum of all the incremental volumes.

This can be written as the sum of an infinite geometric series, where each volume after the initial void volume is found by:

$$V = \sum_{k=0}^{\infty} x \left(\frac{1}{1+SF}\right)^k$$

and as the series exponentially decays, then the sum simplifies to:

$$V = \frac{x}{1-\left(\frac{1}{1+SF}\right)}$$

and hence:

$$V = x\left(1 + \frac{1}{SF}\right) \quad (1)$$

The calculated failure height is used to determine the minimum pillar thickness required. Figure 3 shows the assumed catastrophic failure model. An alternative 'choked cave' model could also be used to derive Equation 1 as shown schematically in Figure 4. The stress state is implicitly considered in the assumption that the crown rock mass fails.

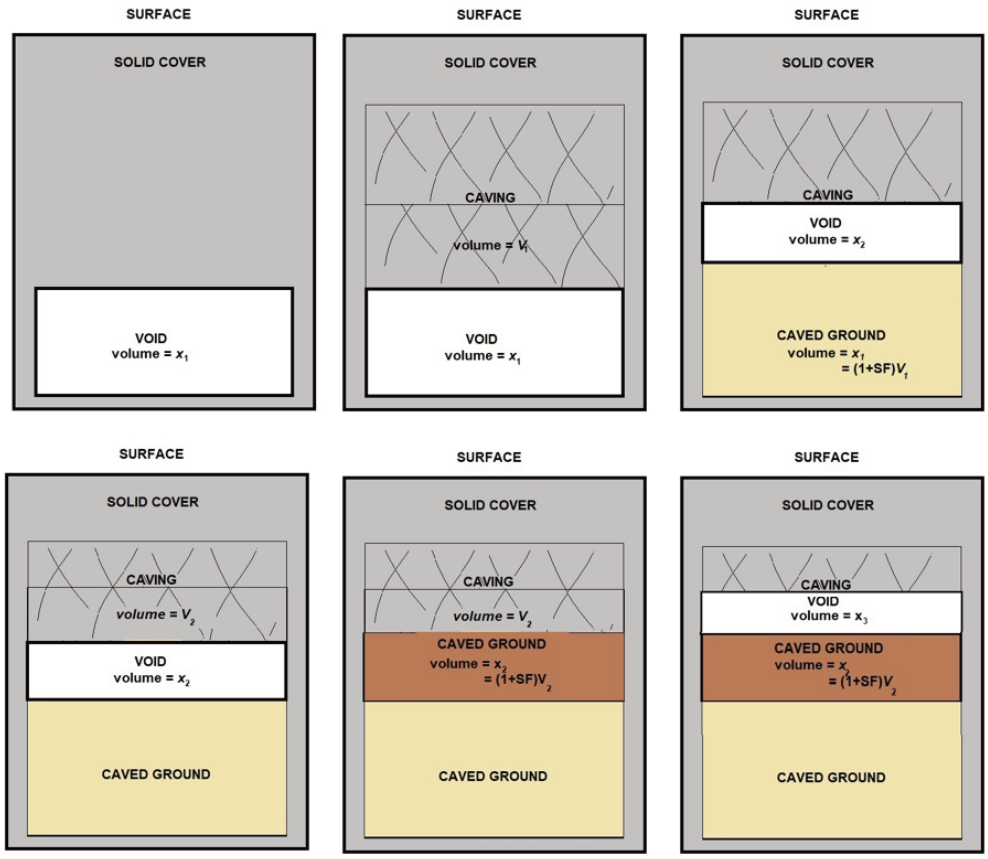


Figure 3 Catastrophic failure model

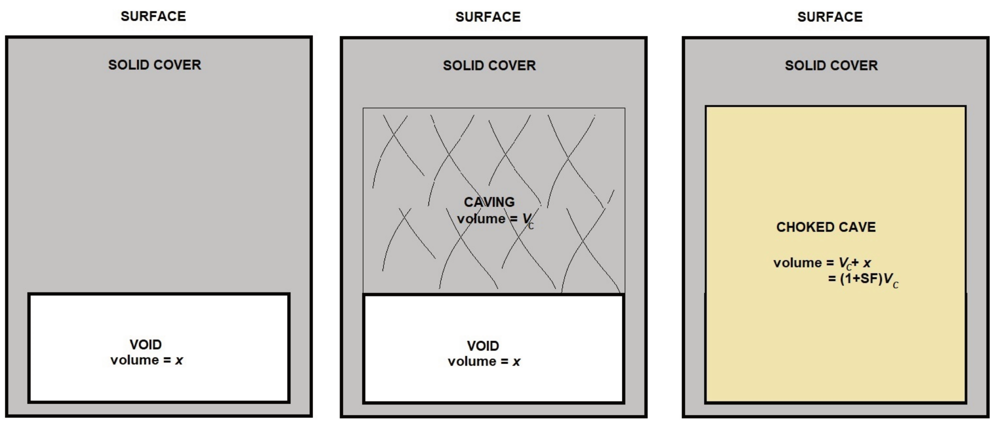


Figure 4 Catastrophic failure model: alternative

4.2 Scaled span analysis

The SSA is an empirical approach to determine the stability of crown pillars for mined openings (Carter 2014). The analysis plots the Q rock mass quality index against the scaled span of the void, which is empirically derived by considering crown pillar thickness, span and length, dip and specific gravity, to indicate the stability of the crown pillar.

4.2.1 Rock mass quality

The rock mass at MRM has been broadly grouped into typical, folded, and faulted conditions. Detailed assessments of the rock mass conditions were undertaken based on borehole logs and surface mapping to gauge the range of Q values. Figure 5 presents the result of the assessment for the typical ground conditions.

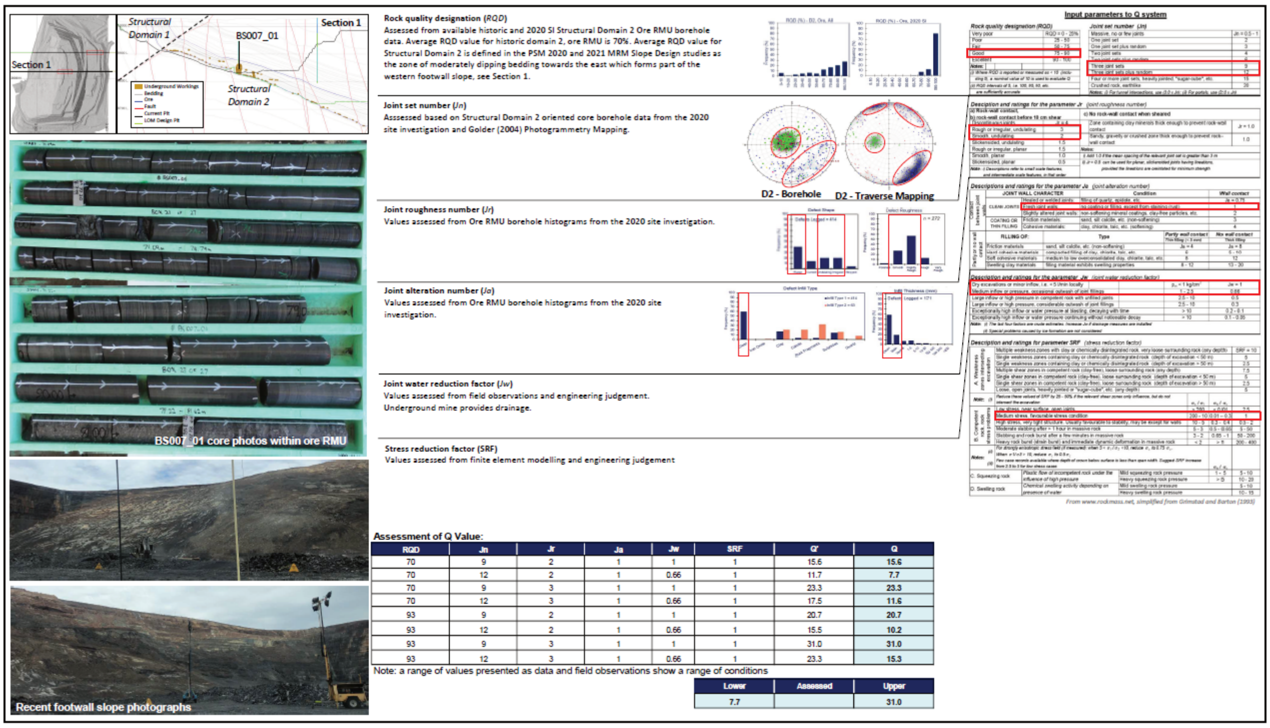


Figure 5 Assessment of Q values for typical ground conditions at McArthur River Mine

The assessments produced the following Q value ranges, as shown in Figure 6:

- Typical – 8 to 30, average 15.
- Folded – 4.6 to 30, 10.
- Faulted – ≤0.2, 0.1.

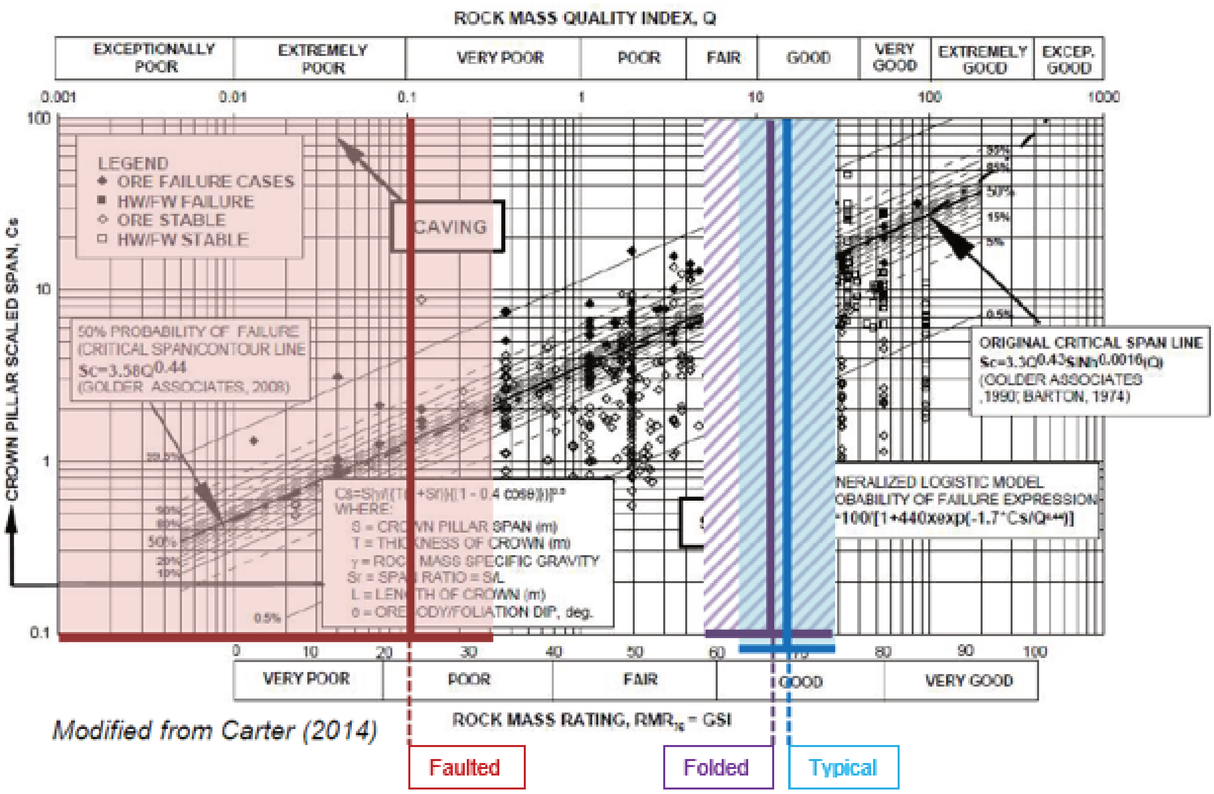


Figure 6 Q values for typical, folded and faulted ground conditions at McArthur River Mine

4.2.2 Past performance

Historic and current probe drilling data has shown cases of significant crown failures of most of the bulk stopes. The bulk stopes had spans between 5 and 30 m. The caved heights ranged up to 50 m above the mined stope crown. These cases, in conjunction with other locations where the crown has not failed, were collated to calibrate the Probability of Failure (PoF) levels to suit MRM conditions. This data is plotted over the general experience data presented in Carter (2014). This is shown in Figure 7.

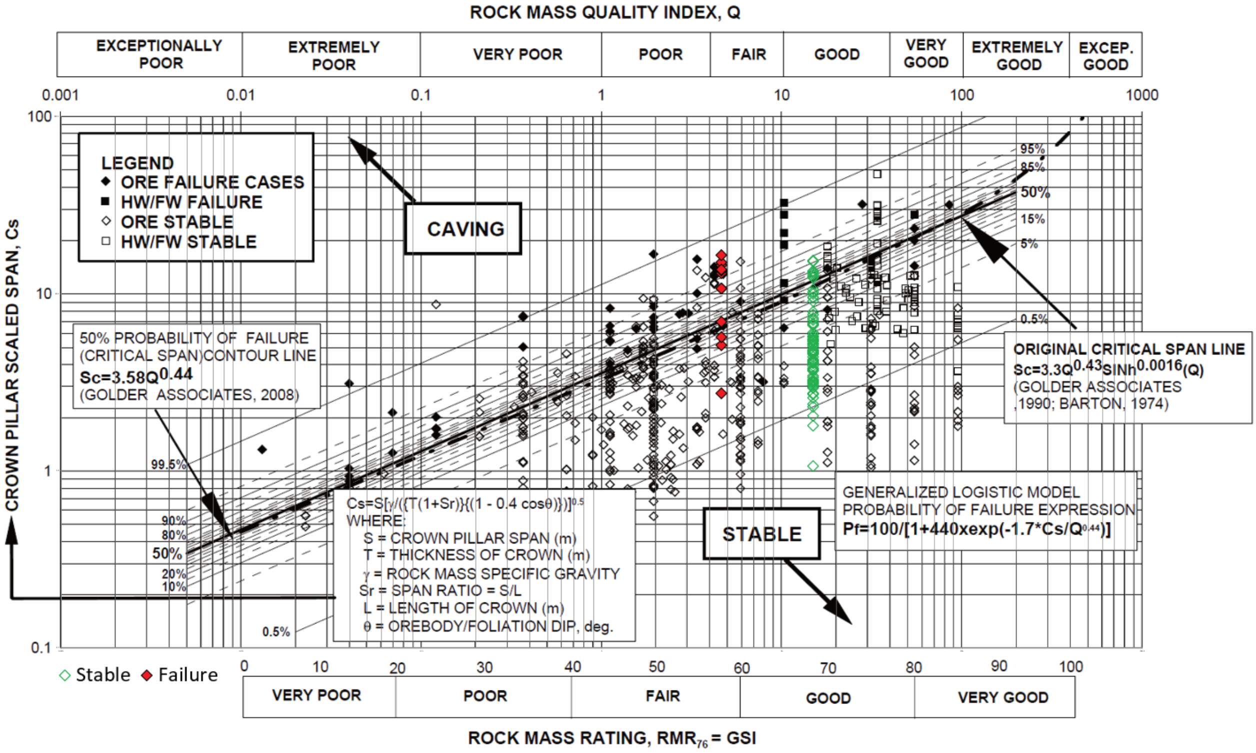


Figure 7 McArthur River Mine empirical analysis scaled span plots (modified from Carter 2014). Open green diamonds represent stable crown pillars and solid red diamonds represent failed crown pillars

4.2.3 Probability of Failure

MRM developed a relationship between the PoF suggested by the analysis and the precautions used in open pit operations, as shown in Table 1.

Table 1 Relationship between Probability of Failure and McArthur River Mine applicable precautions

Probability of Failure	Action required
Less than 5%	None under normal circumstances
Between 5 and 10%	Black and yellow (B&Y) precautions applied
Between 10 and 20%	Red and white (R&W) precautions applied
Higher than 20%	No person allowed without detailed risk assessment and mine managers permission

5 Risk management

5.1 Classification

Control measures have been developed at MRM to minimise the risk of unexpected crown collapse or failure. Voids are classified according to the potential hazard they pose to mining operations, based on factors such as:

- The type of void, i.e. development drive, stope, etc.
- Geometry.
- Fill status.
- Crown pillar thickness.
- Ground conditions.

Void hazard classifications used by MRM are black and yellow (B&Y), red and white (R&W), and exclusion zones. MRM's geotechnical department inspects the void hazard areas as part of its daily pit inspections.

The B&Y void hazard is a low-risk classification. It is assigned to voids where either the crown has been blasted, the void has been filled or the crown of a stope has been excavated, as there remains a possibility that these voids are not completed filled. B&Y void hazards prohibit access to light vehicles and personnel on foot, however, heavy vehicles fitted with rollover protection are permitted to transit and work within these areas. B&Y void hazard areas are delineated in the open pit using either black and yellow hi-vis cones or black and yellow tape or a combination of both, as shown in Figure 8a.

R&W void hazards are a high-risk classification. It is typically assigned to voids that either fail the CFA, are close to the surface, or are in areas of uncontrolled subsidence. R&W void hazard areas are delineated by red and white cones or tape, as shown in Figure 8b, and where accessible, a hard barrier placed on the boundary to prevent access. No access is allowed in R&W areas.

No stopping or exclusions zones are also implemented by MRM to suit operational requirements.

(a) (b)

Figure 8 (a) Black and yellow void hazard area delineation; (b) Red and white void hazard area delineation

5.2 Mitigation

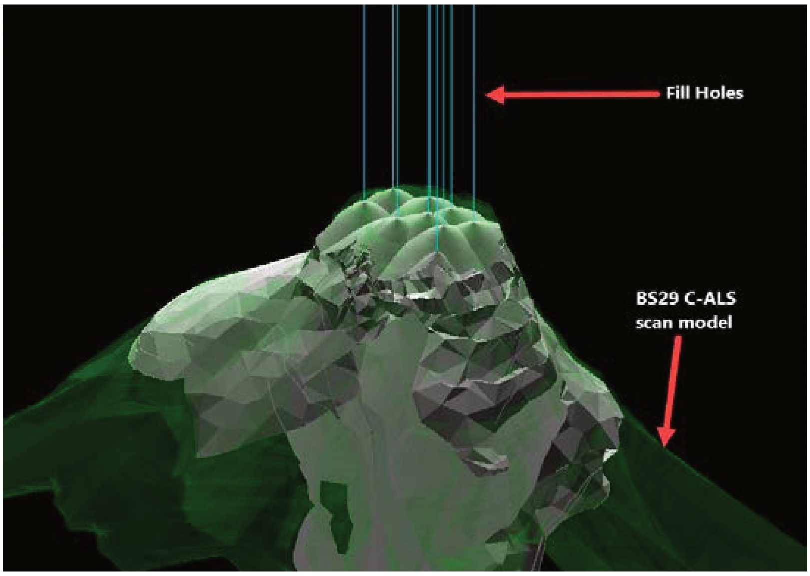
The primary methods used at MRM to mitigate void hazards are collapsing the crown pillar and backfilling the void.

The crown pillar to be collapsed is identified and incorporated into the production drill pattern.

Backfilling is predominantly used on the larger voids such as stopes and vertical openings, i.e. ore passes and vent rises. Backfill material is dumped onto drillhole collars and self-feeds under gravity, as shown in Figure 9a. MRM uses heavy medium rejects (HMR) as the backfill material. The holes are drilled in the pattern determined by a detailed cone modelling analysis, which considers the 3D shape achieved within the void when the HMR is gravity-fed into the holes. An example is shown in Figure 9b.

However, as there is potential that either the crown remains partially intact after blasting or the backfilling does not completely fill the void, a B&Y void hazard boundary is assigned in both cases.

(a)



(b)

Figure 9 (a) Fill hole collar during filling operations; (b) 3D cone modelling on bulk stope 29

A standoff distance is applied to all void boundaries as an additional precaution. The standoff distance is a minimum offset distance, measured from the external perimeter of a digitised void scan in plan view, which is applied to each void with a designated classification. The standoff distances depend on the type of underground workings as shown in Figure 10.

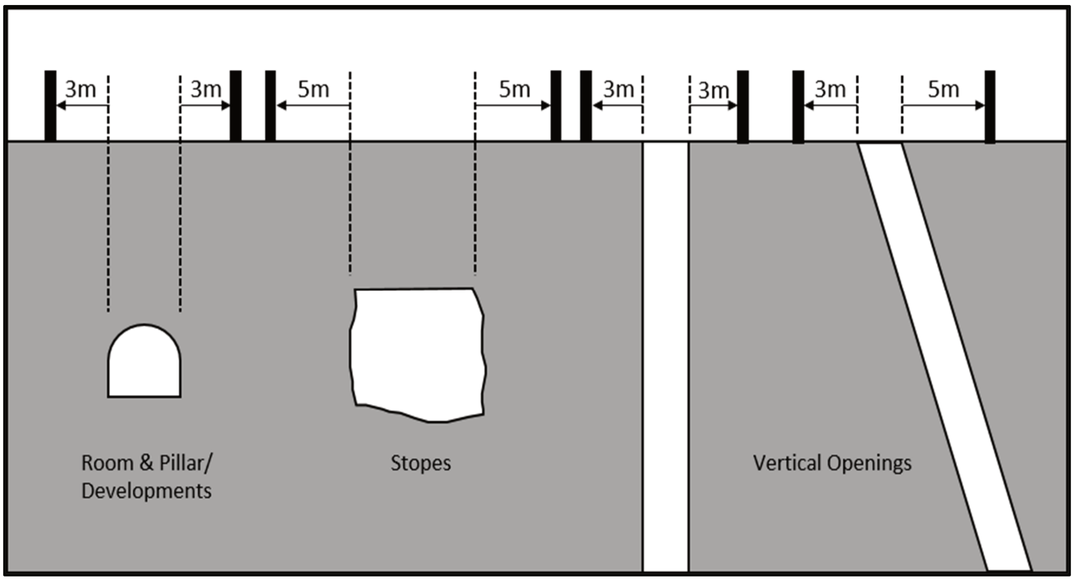


Figure 10 Application of standoff distances applied for void hazard boundaries

It is a further MRM site requirement that all mining operations personnel complete void hazard awareness training, which is developed and presented by the geotechnical department. The void hazard awareness continues as part of the operations and includes the following:

- Void hazard maps are distributed site-wide to show the void hazard delineation and exclusion zones within the pit.
- The void hazard maps are issued when changes to the boundaries or exclusion zones have been made to ensure that all operations staff are aware of the current void hazards within the pit.
- Void hazards are discussed at the shift pre-start meetings.
- The geotechnical department delivers a return-to-work presentation to all crews first shift back onsite after their break, detailing the current void hazard areas.

6 Conclusion

The methods employed at MRM to safely operate the open cut above historic underground workings are presented in this paper.

- The survey model of the historic underground workings provides the basis for initial void identification.
- Estimates of safe working crown pillar thickness are made using the CFA and SSA. The past performance of crown pillars has been collated to calibrate the PoF levels of the SSA to suit site conditions.
- Probe drilling is conducted from the open pit to investigate the crown pillar and to delineate the spatial extent of the underground void.
- Underground voids are classified according to the potential hazard they pose to mining operations: low-risk (B&Y), high-risk (R&W) and exclusion zones.
- The primary methods to mitigate void hazards are collapsing the crown pillar and backfilling the void.
- A standoff distance is applied to all void boundaries.
- MRM operates an ongoing void hazard awareness programme. The key is the assured ability for mining to occur as close and reasonably practicable to a void without impeding on the safety of mining personnel.

To date, the interaction of the underground mine and slope performance has been minor. A separate paper is being planned to discuss the impact on future proposed slopes. The authors are also considering numerical back-analysis of the caved voids to provide better estimates of rock mass properties, e.g. strength, modulus, in future studies.

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