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Development and use of rock mass damage thresholds for high-stress stoping mines

James Smith [a,*], Rob Bewick [a]

[a] *WSP, Canada*

Abstract

This paper describes an assessment methodology that uses performance monitoring and geotechnical data to benchmark rock mass damage thresholds against stress changes induced by mining activity in underground high-stress stoping mines. The benchmark damage thresholds are established by interpreting 3D numerical elastic stress modelling results and comparing them with performance monitoring data. The developed benchmark thresholds enable the mine to forecast when (relative to mining sequence) and where areas of high-stress concentration will occur and relate these areas to ground support and stope performance for different proposed stope sequences and geometries.

Using the developed benchmark, the paper describes the interpretation of numerical modelling results required to forecast when and where ground support elements or concepts may need to be adjusted in response to induced stress. Examples are discussed where the method is applied to identify areas that may experience or are already experiencing stress-induced damage, such as spalling and strainbursts. Lastly, the paper describes the reliability of this methodology when considering the influence of rock mass structure.

Keywords: *induced stress, support performance, stoping, forecasting damage, rock mass response*

1 Introduction

Estimation of changing induced stress conditions and associated stress damage potential is an important process for operating underground mines in high-stress conditions. As mining progresses, the induced stress changes can lead to increasing damage and seismicity that can hinder operations unless this is anticipated and incorporated into the mine sequencing, mine layout and ground support design. Anticipating when induced stress will become a hinderance to operations is a site-specific problem and can be complicated, time consuming and impractical for site personnel to adequately address without third-party support.

This paper outlines a relatively simple methodology that uses a common software tool and site-specific geotechnical and performance data to benchmark rock mass damage thresholds against induced stress changes (referred to as 'benchmarked damage thresholds' in this paper). The benchmarked damage thresholds can then be used to interpret numerical modelling estimates of changing stress conditions to estimate if the site's current mine layout, sequencing or ground support design are likely to maintain safe and productive mining operations through the life of mine (LOM). Once the benchmarked damage thresholds are developed, the operation can then iterate the process in subsequent years to improve the benchmark and revise the interpretation of LOM-induced stress hazards.

The methodology contained in this paper is presented with a case study for a longhole stoping mine located in hard rock and relatively highly stressed ground. The case study example selected for this paper follows the site-specific benchmarking of the damage threshold, the initial interpretation of stress damage through to LOM and one iteration, performed the following year, to review the benchmarked damage thresholds and

* Corresponding author. Email address: james.smith@wsp.com

LOM interpretation of induced stress hazards. Limitations associated with this approach are presented at the end of this document.

2 Methodology set-up

2.1 Assessment software and data requirements

The methodology involves the assessment of induced stress changes in response to mining activity to develop the benchmarked damage thresholds and then progress the LOM interpretation of induced stress hazards. A 3D numerical modelling software tool considering elastic rock mass behaviour was selected to perform the assessments. Elastic behaviour was used to simplify the assessment and provide an estimate of differential stress concentrations without the influence of plastic rock mass behaviour, which could complicate interpretation and increase the time commitment and difficulty of using this methodology. Elastic modelling approaches for the assessment of brittle failure around excavations have been used successfully and are accepted approaches; the development and discussion of brittle failure assessments is contained elsewhere and not repeated here (e.g. Wiles et al. 1998; Martin et al. 1999; Diederichs 1999; Kaiser et al. 2000, among others).

In addition to the numerical modelling software, the following geotechnical and performance monitoring data are necessary to complete the assessments:

- Intact uniaxial compressive strength (UCS) for the rock masses of interest.
  - These are high-quality UCS tests that would be similar to the unconfined compressive strength (σci) determined from triaxial data.
- Rock mass elastic parameters.
- Lithology wireframe solids including wireframes of major features (e.g. dykes and faults).
- Structural fabric (e.g. joints, foliation, etc.) for each rock mass domain.
- In situ stress estimate.
- Mine design solids and design sequence.
- As-built stope cavity monitoring survey (CMS) results formatted as individual wireframes for each stope.
  - Good CMS resolution is important to identify the location and shape of overbreak for comparison with the induced stress estimates and the available structural characteristics of the rock masses.
- Drift and ground support performance observations.
  - This data is critical and it is important to correlate drift observations with induced stress changes estimated by the numerical modelling.

For the case study, two main rock masses were considered and they were strong to very strong (~100 MPa for the ore and >150 MPa for the host rock). No major faults were present in the area being assessed and three major structural sets were mapped. The orientation of σ_3 is known to be vertical and σ_1 is parallel to the orebody with a stress gradient above $2*\sigma_3$. The mine is opening transverse stopes in a primary-secondary sequence and had only completed a few transverse stopes prior to the initial benchmark assessment.

2.2 Initial damage threshold assumption

Model-obtained deviatoric stress (σ_1-σ_3) divided by the average UCS of the intact rock is used as a basis to relate rock damage to induced stress changes. This metric applies to rock with high intact strength, which tends to behave brittlely when under high stress. Rock exhibiting brittle behaviour does not deform gradually but instead builds up stress until a breaking point is reached and the rock begins to fracture. This fracturing can initially be as mild as popping or cracking noises heard in drifts to more intensive damage manifesting as spalling or larger scale stope dilution.

When interpreting elastic numerical stress models, a controlling parameter for rock damage estimates is deviatoric stress/UCS (which is typically represented as a fraction from near 0 to above 1), which can be related to the depth of stress fracturing and estimates of stress damage. Typically, rock begins to exhibit stress damage (fracture propagation) at the spalling strength, which is typically in the range of 0.3 to 0.5 deviatoric stress/UCS (e.g. Nicksiar & Martin 2013); however, heterogeneities such as veining can have the influence of reducing the spalling strength into a lower range of 0.2 to 0.3 (e.g. Bewick et al. 2019). When the deviatoric stress/UCS ratio is above the spalling strength of the rock mass, increasing stress damage occurs. Rock mass damage thresholds can be related to the deviatoric stress/UCS ratio; for example, the following damage thresholds related to deviatoric stress/UCS are often found in literature (e.g. Wilson 1971; Barton et al. 1974, Chamber of Mines South Africa 1978, 1979; Hoek & Brown 1980; Stacey & Page 1984; Jager et al. 1990; Castro 1996; Kaiser et al. 1996; Brummer 1998; Martin et al. 1999; Diederichs 1999; Kaiser et al. 2000; Bewick et al. 2019; Bewick 2021) and can be used as a good baseline:

- Spalling initiates at deviatoric stress/UCS = 0.3–0.5 (which corresponds with the unconfined rock mass strength near an excavation wall).
- Notch formation with deep spalling (>20% of tunnel radius) and potentially minor strainbursting (spitting and popping) is to be expected for deviatoric stress/UCS > 0.5 to 0.6.
- Moderate strainbursting and/or deep spalling at deviatoric stress/UCS > 0.6 to 0.8.
- Major strainbursting and/or deep spalling at deviatoric stress/UCS > 0.8.

3 Case study example

The case study example outlines the process that was followed for a mine to develop benchmarked damage thresholds and then estimate induced stress hazards through to LOM. The examples in this paper are split by induced stress influence on stopes and development as the information required to benchmark and forecast impacts of stress damage is different for each excavation (e.g. overbreak/dilution for stopes versus ground support damage and performance for drifts).

3.1 Benchmarking

The case study mine had only excavated three transverse primary stopes and no secondary stopes at the time of benchmark development. Two of the primary stopes were excavated on the lowest development level, with one stope on the next development level immediately above a primary stope on the lowest development level. The LOM layout for the case study mine extended vertically for a total of four development levels, with each development level consisting of eight to 12 primary and secondary stopes. The layout of the as-built and LOM mine is simplified and sanitised for this paper (Figure 1).

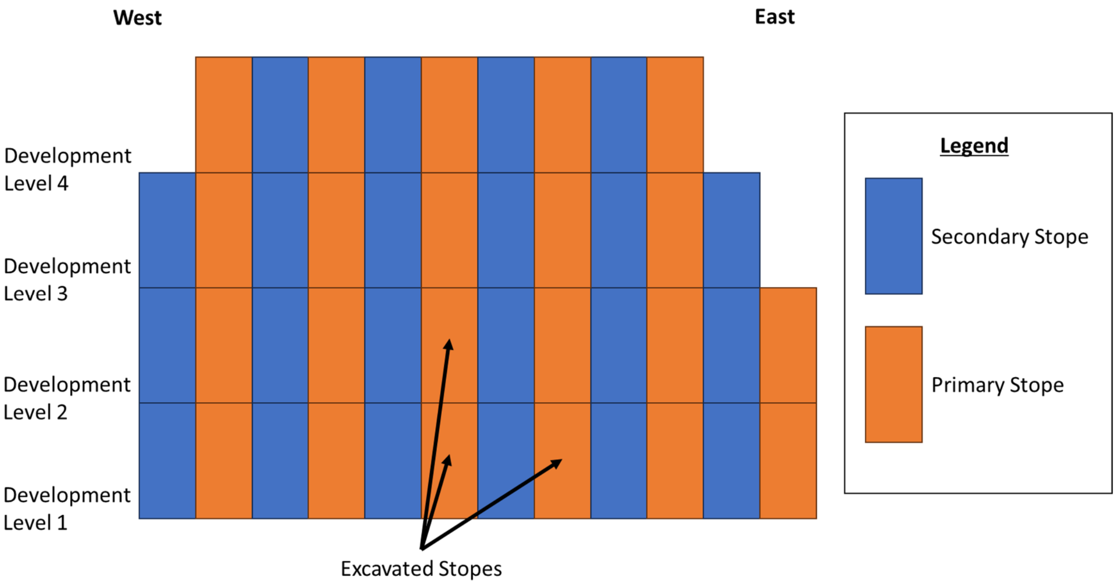


Figure 1 Simplified case study mine layout showing stopes excavated at the time of the initial benchmark

3.1.1 Stope benchmarking

To benchmark stope overbreak to modelled deviatoric stress/UCS contouring, the user must have confidence that the overbreak observed in CMS data is not caused by other mechanisms (structural failure, poor blasting, design changes, etc.). CMS data from the stopes must be of high resolution to be reviewed for overbreak potentially caused by stress-related damage; damage that may be influenced by improper blasting practices or structural kinematic failure cannot be properly assessed with an elastic stress model.

In the case study mine, a primary stope on development level 1 was influenced by structure (Figure 2) where most of the overbreak was caused by a wedge fallout. The remaining two as-built stopes did not appear to be influenced by blasting or structure and were then compared against the design shape to estimate the depth of overbreak and develop a relationship between the contouring of deviatoric stress/UCS and overbreak. The primary as-built stope on level 2 has been used as an example to explain benchmark development (Figure 3).

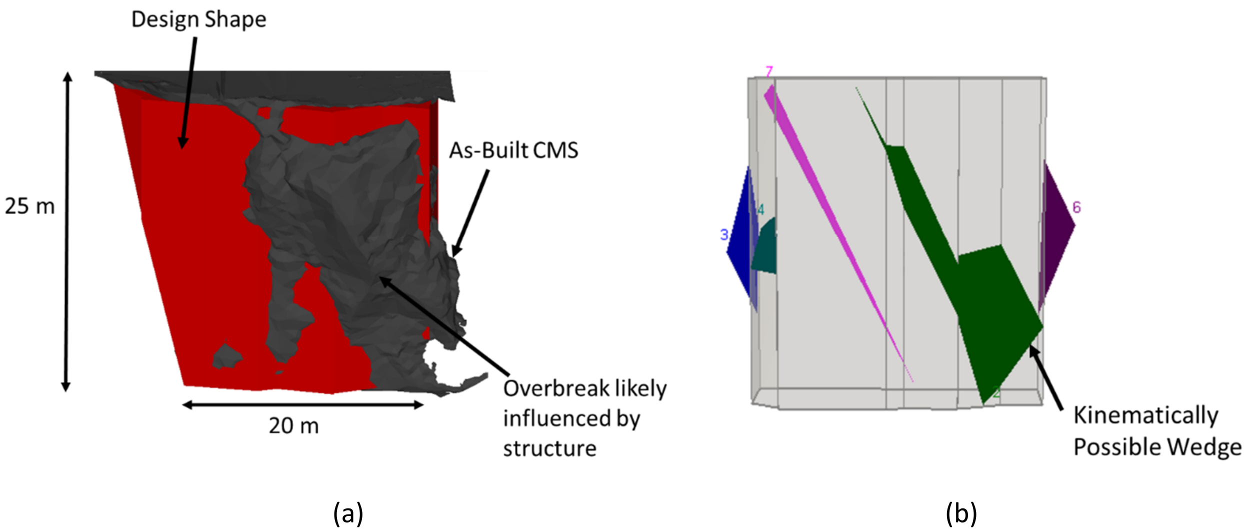


Figure 2 Structure influencing overbreak in a primary stope on development level 1: (a) Cavity monitoring survey (CMS) compared with the stope design shape; (b) Kinematic wedge assessment of the design stope shape showing agreement between a theoretical wedge and the overbreak identified in the CMS

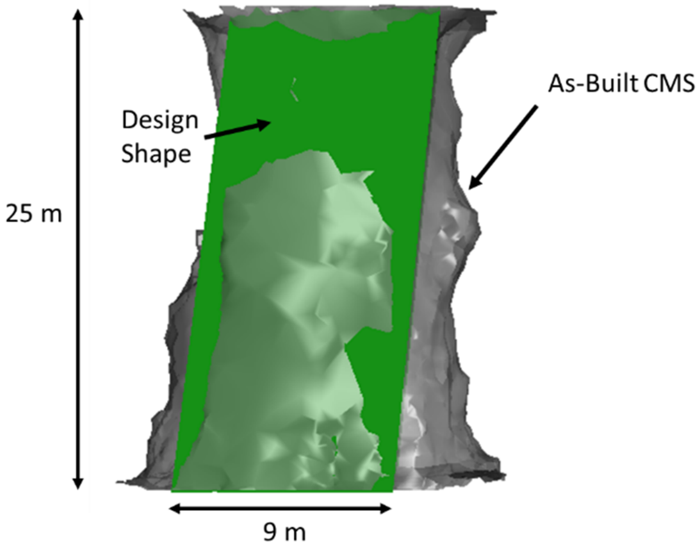


Figure 3 As-built cavity monitoring survey and design shape for the as-built primary stope on development level 2

An elastic stress model was built which assessed the as-built mining sequence, considering both the design and as-built stope geometries. The elastic stress model would first excavate the design shape for the stope and then would excavate the as-built shape in the next model stage. The results from the design shape would be used to compare with the as-built CMS while the inclusion of the as-built excavation would allow the model to incorporate the induced stress influence of the as-built shape on future mining steps.

The results of the elastic stress model for the excavation of the design shape for each as-built stope were viewed with deviatoric stress/UCS contouring and compared with the areas of overbreak identified from the CMS. For the primary stope on development level 2, the deviatoric stress/UCS contour that was found to be relatively consistent with the depth of overbreak was between 0.6 and 0.7 (Figure 4). The only other as-built stope applicable for this benchmark assessment, located on development level 1, was also assessed and found to have a similar overbreak threshold of 0.6 to 0.7 deviatoric stress/UCS. This overbreak threshold was carried forward for interpretation of the overbreak hazard through to LOM.

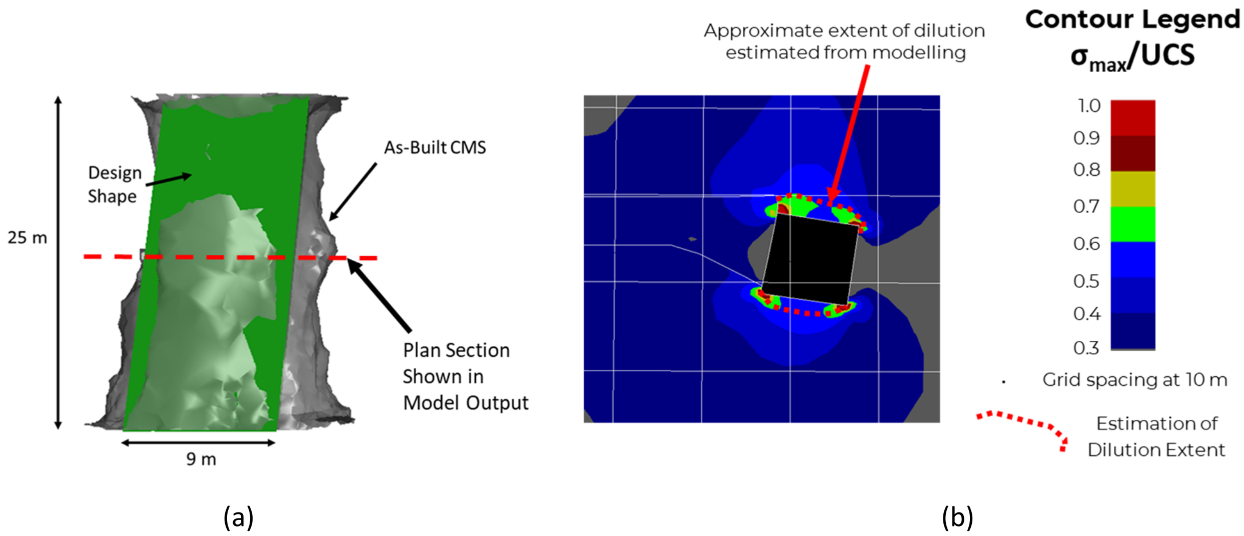


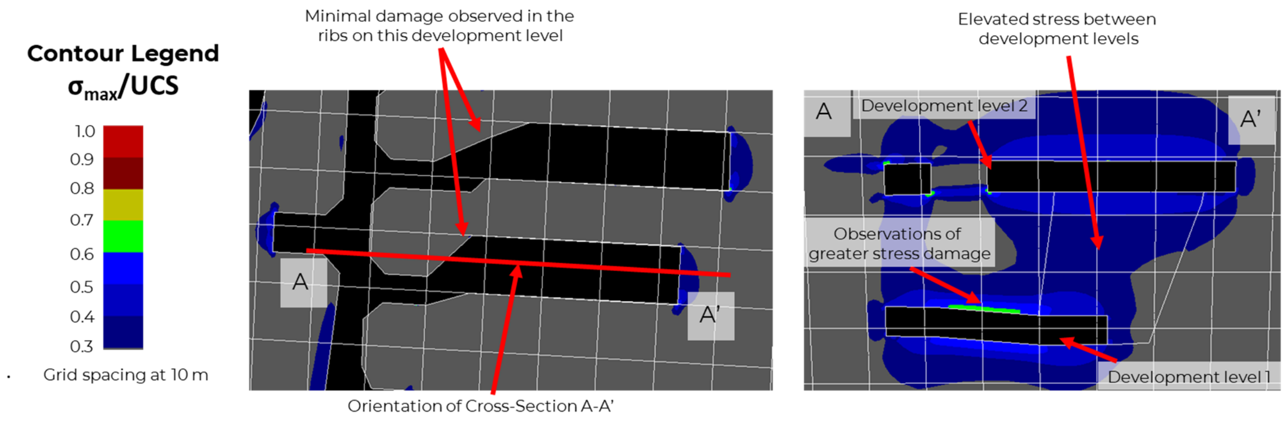
Figure 4 Benchmark assessment for the as-built primary stope on development level 2: (a) Perspective view of the stope showing the design and cavity monitoring survey geometries; (b) Plan view of the elastic model results with deviatoric stress/uniaxial compressive strength contouring and notes regarding the interpreted depth of overbreak

3.1.2 Drift development benchmarking

Unlike the stope overbreak benchmarking methods, the benchmarking for as-built drifting compares the elastic stress model results against the damage mapping collected at the case study mine. The damage mapping on each as-built drift level was reviewed against the dates of the stope blasts to identify possible correlations between ground support damage, fallout or loading in response to induced stress changes caused by stope blasts. At the case study mine some ground support damage was observed in sill drives adjacent to blasted stopes within two weeks of the blast date; this damage was characterised by bulging in the ribs, bolt plate deformation and shotcrete spalling.

The sill crosscuts drifts had spans varying from 5 to 10 m; some of the sill crosscuts on development levels 1 and 2 had 10 m spans while other drifts had 5 m spans. During drift development and prior to blasting the first primary stope, the 10 m span drifts on level 1 exhibited some limited stress damage, block detachment and noise; these events were mostly isolated to shortly after the blasting of adjacent stopes. The drifts on development level 2 with 5 m spans showed less noise and damage during development. A review of the elastic stress model results for the drifts on development levels 1 and 2 suggests the minor damage and noise in the drift back on development level 2 benchmarked well against a deviatoric stress/UCS of 0.3 to 0.5, while the greater stress damage seen in the back of the drifts on development level 1 benchmarked well against the 0.5 to 0.7 range (Figure 5).

The model results also suggested that there was stress interaction between the different sill levels (Figure 5) which indicated potential for larger stress changes (increasing the risk of a seismic event) when blasting the stope; no observations of seismicity during blasting were available for this benchmarking assessment. Additional damage observations were checked against the deviatoric stress/UCS contouring as the elastic model progressed through the as-built mining stages; however, most observations indicated minor damage and noise. Based on the damage observations and comparisons with the modelled deviatoric stress/UCS contouring, a damage threshold benchmark was developed for the case study site that relates deviatoric stress/UCS to potential drift and rock mass damage (Figure 6). The benchmark threshold used for the case study site is similar to previous thresholds presented in literature (e.g. Wilson 1971; Barton et al. 1974; and among others initially referenced in Section 2.2).



(a) (b)

Figure 5 (a) Plan view of as-built development drifting on development level 1 showing deviatoric stress/uniaxial compressive strength contouring; (b) Cross-section A-A' showing as-built drifting on development levels 1 and 2

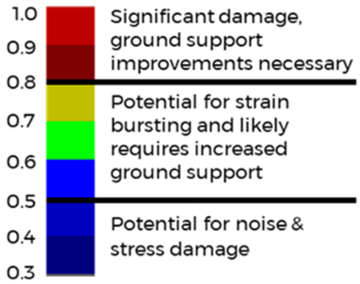


Figure 6 Benchmarked damage threshold comparing deviatoric stress/uniaxial compressive strength to rock mass damage and ground support performance observations

3.2 Interpretation of damage through to life of mine

For the case study mine, the benchmarked rock mass damage and stope overbreak estimate developed in relation to deviatoric stress/UCS was applied to future stope and drift excavations through to LOM. The results of the assessment indicated that drifting along development level 1 would likely experience increasing stress damage, the secondary stopes on the eastern edge of the orebody would have elevated stress which may influence seismicity and overbreak, and that approximately eight primary stopes showed >3 m overbreak potential and elevated induced stress changes which may cause seismicity and ground support damage in adjacent developments. Two specific examples of forecast findings from the case study in relation to the benchmarked damage threshold are in the subsections below.

3.2.1 Drift damage estimate

The benchmarked damage thresholds were used to interpret potential areas of increasing stress damage for drift development which may indicate that adjustments to the ground support design or excavation practices are necessary. For one location in the case study mine, sill drift development on development level 1 was examined towards the eastern edge of the mine layout. With four stopes remaining on the eastern edge of development level 1, the rock mass adjacent to as-built drifts was interpreted as having potential for stress damage ranging from minor damage and noise up to strainbursting with significant damage (Figure 7). Additionally, elevated stress was interpreted within the rock mass where the sill drifts were to be excavated. The interpretation of elevated stress suggested that excavation of the remaining sill drifts may result in stress damage during development or indicate that the rock mass is already damaged; either option necessitates a review of the ground support design, installation practices and excavation processes for development in this area.

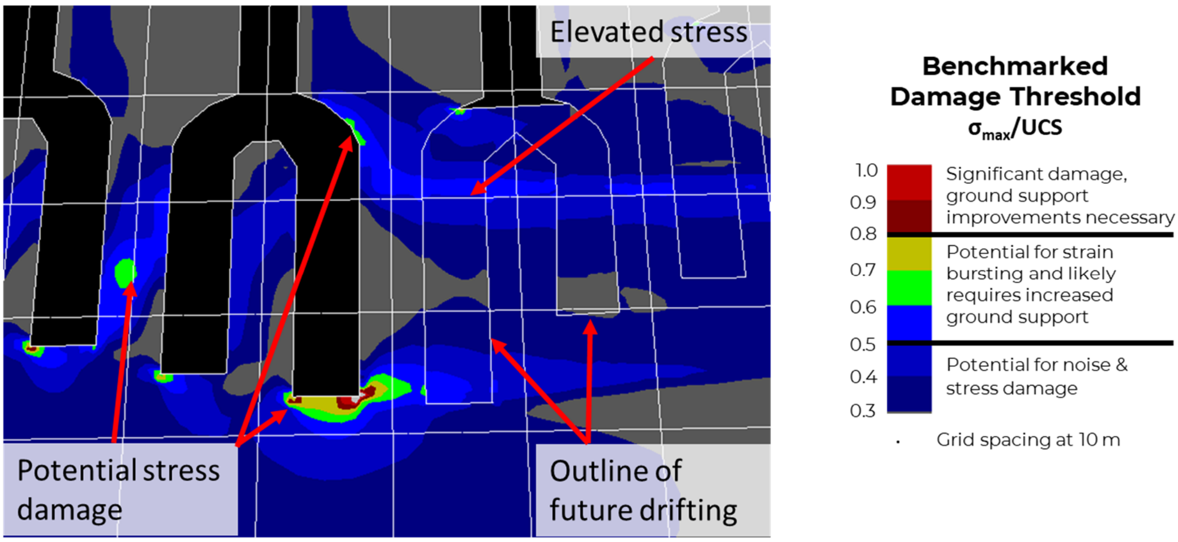


Figure 7 Plan view of the eastern edge of development level 1 prior to excavation of the last four stopes

Assuming the appropriate adjustments to drift development are made and the drifts are excavated and remain stable, the induced stress influence on the last set of sill drifts increased further (Figure 8) over the LOM. This elevated stress hazard suggests it is possible that strainbursting could occur in the ribs and at deeper locations behind the ribs. The rock mass damage potential interpreted to impact the case study mine likely necessitates a ground support design review for this area or a modification to the development sequence; perhaps limiting drift development to just-in-time development could help mitigate interpretation of the stress hazard.

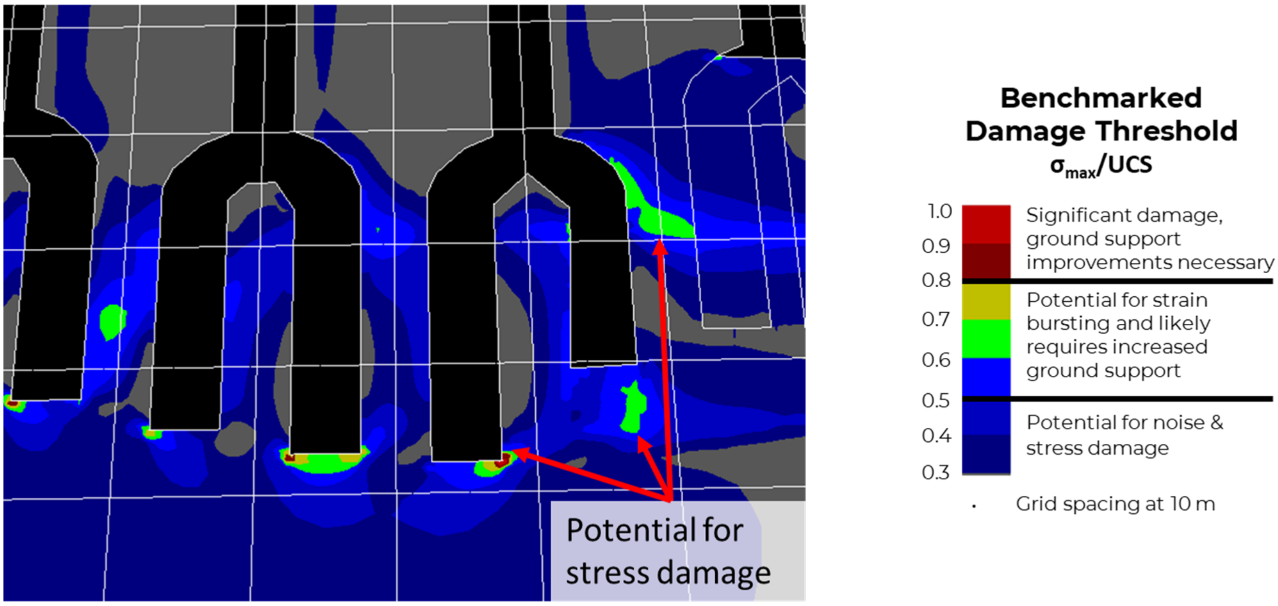


Figure 8 Plan view of the eastern edge of development level 1 prior to excavation of the last two stopes

3.2.2 Stope behaviour estimate

The deviatoric stress/UCS contouring was also used to estimate the impacts of overbreak and seismicity from blasting stopes throughout the LOM for the case study mine. In general, the interpretation of induced stress hazard for the case study mine indicates that most primary stopes, prior to blasting, have a deviatoric stress/UCS contouring of around 0.3 to 0.4, suggesting a lower seismicity hazard associated with stope blasting, while the secondary stopes were typically below 0.3, suggesting the rock mass within the secondary stopes holds reduced stress prior to blasting. After blasting, most of these stopes experienced 1–2 m of overbreak potential, in line with what was observed in the benchmarking assessment; however, certain primary stopes on the upper development levels 3 and 4 and the secondary stopes on the eastern edge of development level 1 were interpreted to have elevated stress hazards.

Eight primary stopes on development levels 3 and 4 had elevated deviatoric stress/UCS contouring (>0.5) prior to blasting and had large overbreak potential (>3 m) after the blast was completed; it was recommended for the case study mine that these stopes be panelled to reduce the induced stress transfer and thus reduce the seismic hazard and mitigate the scale of overbreak. Two of the secondary stopes near the eastern abutment on development level 1 experienced elevated stress (Figure 9a). The deviatoric stress/UCS ratio suggested that the rock mass within these secondary stopes was close to, or had already experienced, rock mass damage, suggesting that there was elevated potential for seismicity associated with blasting these stopes. Additionally, the redistribution of induced stress from the secondary stope would likely result in high-stress damage and ground support issues in the upper sill (Figure 9b) which could impact production activities on development level 2. Based on these results a recommendation was made for the case study mine to work this area (of approximately four stopes) in a primary-primary sequence to mitigate potential for seismicity and rock mass stress damage.

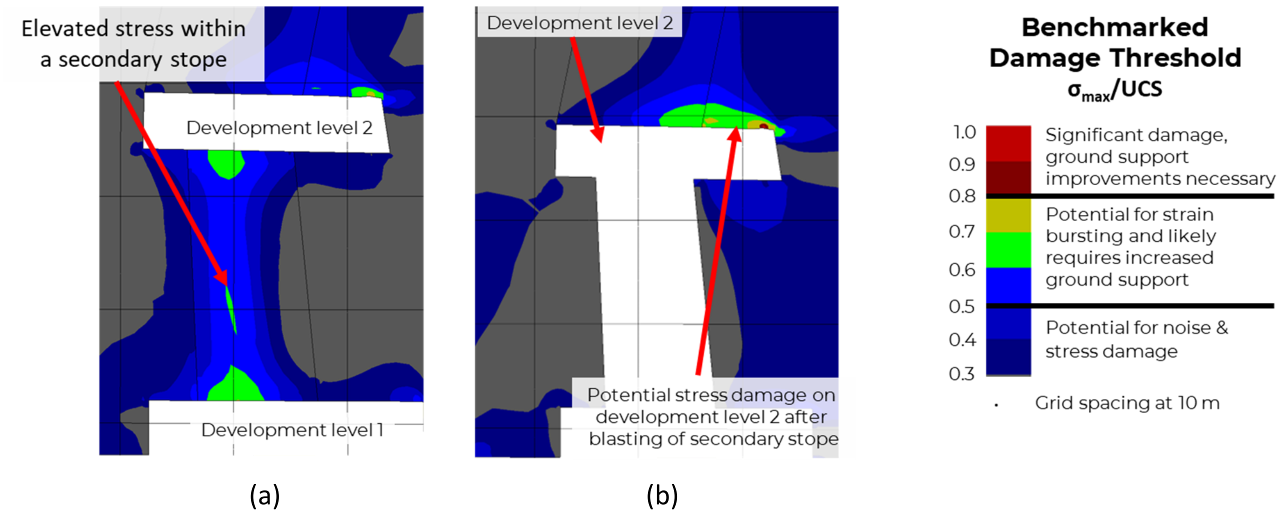


Figure 9 (a) Deviatoric stress/uniaxial compressive strength contouring through the last secondary stope prior to blasting on development level 1; (b) Deviatoric stress/uniaxial compressive strength contouring through the upper sill crosscut above the secondary stope after blasting

3.3 Assessment iteration one year later

A key part of this methodology is that the benchmarked damage thresholds should be periodically updated to increase confidence in the interpretation resulting from this process. The interval of review is not prescribed in this document and should be determined based upon the mining rate, the stress hazard, the site's risk tolerance and the mining plan; however, for the case study example, the benchmark was able to be revised after one year of mining. In that one year of mining, eight additional stopes were blasted and development had progressed to mining level 4.

3.3.1 Review of the benchmarked damage thresholds

The review of the benchmarked damage thresholds followed the same process defined in Section 3.1: first stope CMS data was compared with the elastic model result interpretations, and then damage observed in drifting was compared with the interpretation of elastic model results. Only two stope CMS were found to be candidates for review of benchmarked damage thresholds as the other six stopes were evidently influenced by structure or changes in the blast design, or did not result in overbreak. The review of the two stopes resulted in a similar interpretation; as such, only one is provided as an example in this paper.

One of the stopes that could be reasonably used to review the benchmarked damage thresholds was one of two primary stopes on development level 3. For the primary stope, overbreak was measured from the CMS and design solids as being 1 to 2 m on the footwall side while the other as-built stope dimensions reasonably agreed with the design shape (Figure 10). The deviatoric stress/UCS contouring resulting from the elastic model indicates that a 0.6 to 0.7 contour partially aligns with the as-built overbreak. The interpretation of deviatoric stress/UCS in the footwall suggests overbreak would start in the top of the footwall (where the deviatoric stress/UCS is highest) and propagate downwards to approximate the as-built overbreak. The interpretation suggests that the initial benchmark of 0.6 to 0.7 deviatoric stress/UCS equating to overbreak initiation remains reasonable for the assessment of stoping at the case study mine.

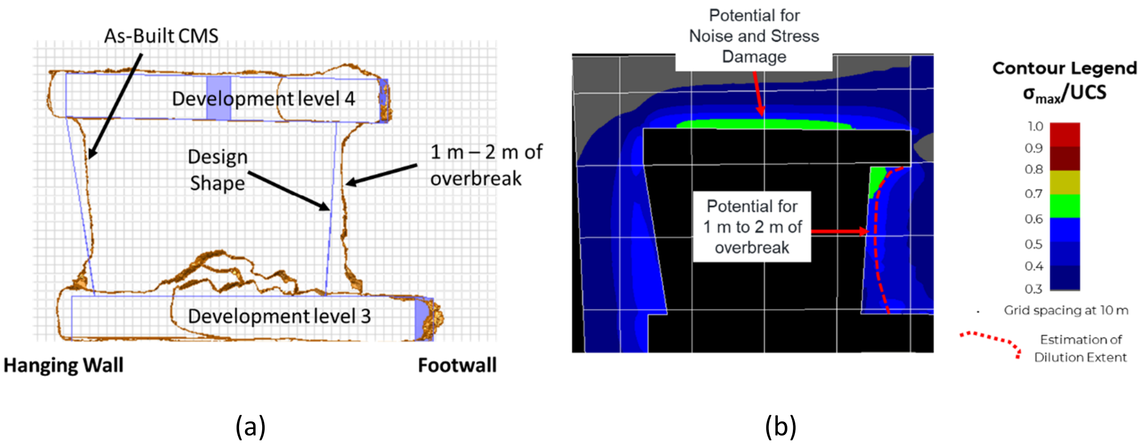


Figure 10 (a) A cross-section from hanging wall to footwall showing the stope design shape with the cavity monitoring survey geometry; (b) Elastic model results with deviatoric stress/uniaxial compressive strength contouring and notes regarding interpretation of the overbreak

Reviewing the benchmarked damage thresholds for drift development in the case study mine used damage observation notes from the four development levels. Generally the damage appears to be increasing in intensity and frequency. During the initial benchmarking assessment the damage observations were mainly limited to the drift backs and unsupported faces (during development); for the review, damage has been observed in the ribs and backs. The process of benchmark review is the same as was done for the initial benchmark described in Section 3.1, except for the addition of microseismic data. The case study mine had about six to eight months of microseismic data to compare with damage observations and interpretations developed from the elastic model results. A single example is provided in this section to convey the results of the review.

Using the initial benchmarked damage thresholds, the damage observations in the middle of development levels 1 and 2 were compared with the updated elastic model results. Areas of minor stress damage observed in the ribs generally align with deviatoric stress/UCS contours of 0.3 to 0.5 (Figure 11). Areas in the back and shoulders which correlate with microseismic crush events and damage observations suggesting bolt strain, bulking and some light ground support damage typically reflect deviatoric stress/UCS contours of 0.5 to 0.7.

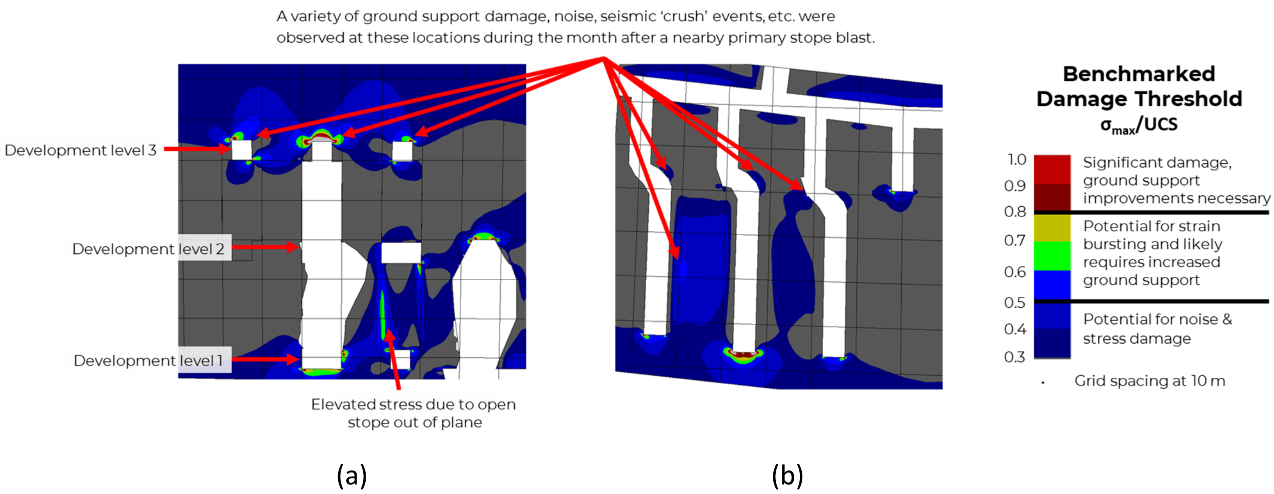


Figure 11 Correlation between deviatoric stress/uniaxial compressive strength contouring from the elastic stress model and observed rock mass damage or microseismic events: (a) East to west cross-section showing as-built stope shapes, deviatoric stress/ uniaxial compressive strength contouring and notes on observed rock mass damage in the drift backs; (b) Plan section on development level 3 showing deviatoric stress/ uniaxial compressive strength contouring and notes on observed rock mass damage in the ribs of the drifts

Based on the review, the benchmarked damage thresholds were not altered from the initial estimate. It was observed from as-built damage mapping, stope CMS and microseismic data that the interpretation of an increasing stress hazard was reasonable and recommendations around ground support review, stope sequence modifications and stope panelling were appropriate. The case study mine used the results of the study to prepare for increasing stress hazards and plan for expansion of their monitoring capabilities.

4 Limitations

The user of this method should be aware of the associated limitations. As the methodology relies on elastic induced stress assessment and only examines a rock mass damage failure mechanism considering brittle behaviour, the impacts of preferentially orientated structure and operational considerations (e.g. blasting) cannot be directly assessed with this methodology. Also, there have been some limited instances of observed rock mass damage that could not be reconciled with the deviatoric stress/UCS contouring but could still be interpreted based on other parameters resulting from the elastic stress model. These limitations are described in the following subsections.

4.1 Structure

Consistent structural sets can cause kinematically driven failure in development and stopes. While the induced stress profile can influence the movement of potential structural wedges (e.g. reduction of clamping stresses), the elastic stress model cannot meaningfully forecast where structure is located and could be meaningfully impacted by induced stress. It is important that the user of this method also examines the potential for kinematically driven structural failure using other methods and removes such failure types from datasets used to benchmark the deviatoric stress/UCS contouring to rock mass damage (Figure 1).

4.2 Operational considerations

Excessive blast damage in the stope or drift walls can cause overbreak or rock mass failure that may appear to be stress-related. Additionally, poor ground support installation practices (e.g. not fully grouting the length of a cable bolt) could result in ground support performance observations that may be misleading regarding the scale of stress damage and bulking actually occurring in a drift. It is important that the mine has a robust quality control and review process to collect data on these practices so they can be ruled out when benchmarking for stress damage and stope overbreak.

4.3 Use of other parameters in benchmarking

During the benchmark assessment for the case study mine, one sill drift with a 10 m span was noted to have moderate stress damage; however, the deviatoric stress/UCS contouring from the numerical model did not align with the observed damage. The stress damage observations were mostly defined by bulking in the ribs with some loading in the back. Additional parameters (aside from deviatoric stress/UCS) were reviewed to better interpret the observed damage. Contouring of vertical strain, σ_3, and σ_1 were reviewed to understand the changes in stress and their impact on the rock mass (Figure 12). The interpretation suggests an increase in vertical strain and a corresponding decrease of σ_3 in the pillar between an as-built primary stope and the adjacent as-built sill drift. This change in the pillar stress and strain suggests a relaxation of confining stress at the drift rib, while σ_1 retains a similar magnitude; this essentially will bulge the rock mass into the adjacent excavation as the rib rock mass is vertically loaded. The model also showed a decrease in σ_1 stress across the back of the drift, which allowed some relaxation to occur in the yielded rock mass (identified in the vertical strain contours) which caused increased vertical loading (due to the relaxed weight) on the bolt plates in the back. This example suggests that there are some damages and loading observations that may not be appropriately interpreted by using only deviatoric stress/UCS contouring and the benchmarked damage thresholds. It is important that the user of this methodology identify these exceptions when they occur and document what parameters are feasible to interpret from the observed rock mass behaviour.

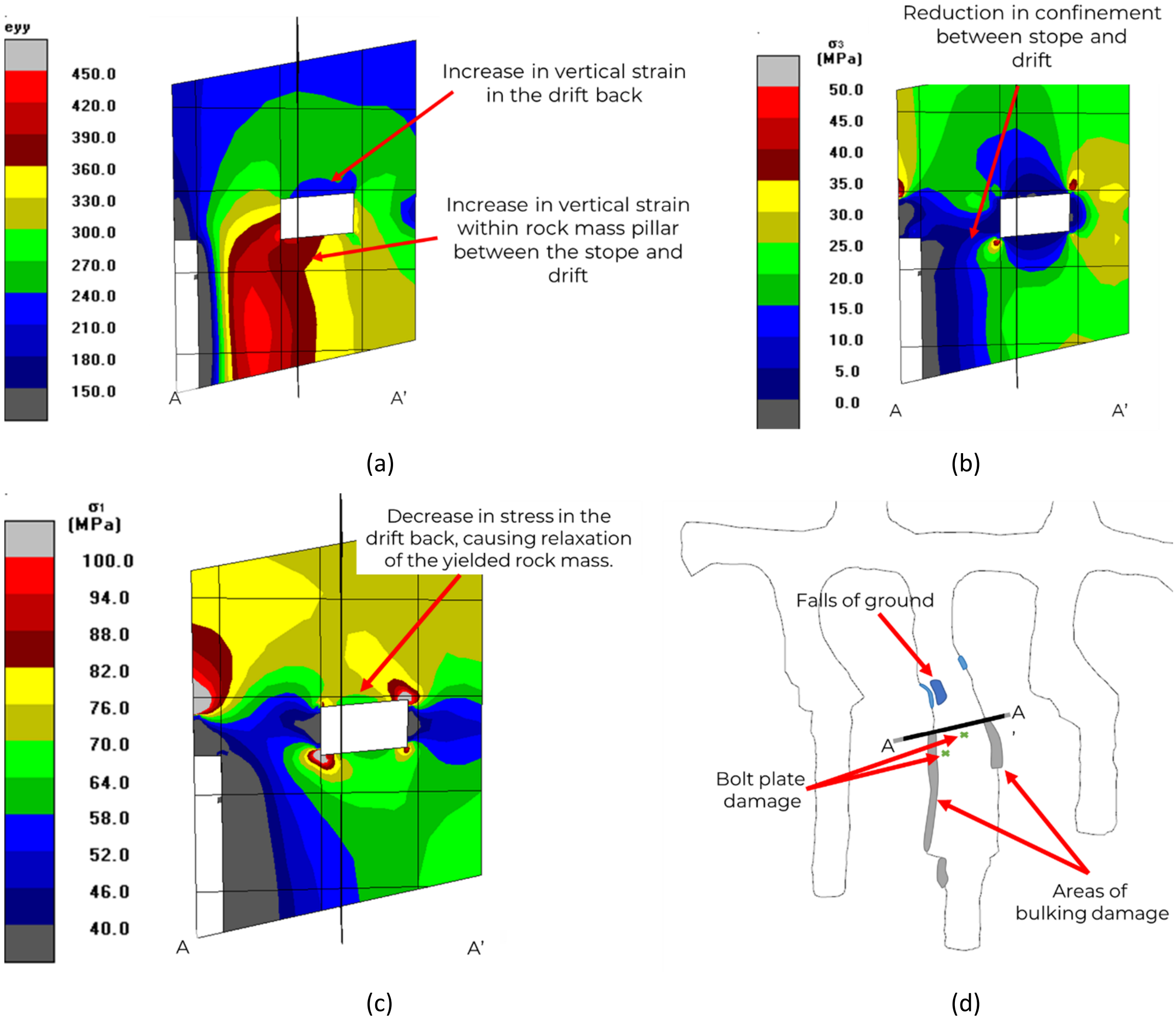


Figure 12 Elastic model results showing the influence of primary stope excavation on drifting in development level 2: (a) Vertical strain results; (b) σ_3 results; (c) σ_1 results; (d) Plan view of the drifting showing the model cross-section and areas of damage observation

5 Conclusion

A methodology was used to enable development of a site-specific relationship which relates damage thresholds to induced stress changes using common software assessment tools, typical geotechnical and performance monitoring data, and well-defined relationships that use elastic modelling to interpret brittle failure around openings. The methodology was defined using a case study example of a longhole stoping mine in hard rock with high-stress conditions. The development of this methodology enabled the case study mine to interpret future stress hazards and review their operational procedures to adapt to the changing conditions.

Once the benchmarked damage thresholds are in place, periodic review is important to maintain confidence in the interpretation of the LOM stress hazards. The methodology also has some limitations related to alternative failure mechanisms which cannot be confidently assessed in an elastic modelling approach. As such, it is important that mine sites continue to assess the potential for other failure mechanisms using existing practices (e.g. wedge kinematics).

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