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What I wish I knew earlier about rock engineering for deep mines

Rob Bewick [a,*], **Justin Roy** [a]

[a] *WSP, Canada*

Abstract

This paper presents some valuable lessons learned about rock engineering in deep mines: namely the misapplication of jointed rock mass models and classification systems, the relevant brittle rock mass damage mechanisms, the importance of understanding the intact rock strength, and management of stress and deformation.

Keywords: *rock engineering, brittle rock masses, spalling, deep mining*

1 Introduction

The goal of this paper is to highlight important lessons learned from rock engineering in deep and high stress mines. The lessons fall under the following themes:

- Hoek–Brown geological strength index (GSI)-based rock mass strengths – not universally applicable
- rock mass classification systems – diminishing value with increasing depth
- brittle rock mass strength – dependent on damage mechanism not scale
- cohesive defects matter – joints are less dominant in many deep mine settings
- estimation of depth of spalling – they are maximums not averages
- elastic modelling – can be of great value
- rock mass damage – not always failure but always deformation
- ground management – the story doesn't end once the ground support is installed.

The themes discussed are contained throughout the high stress rock engineering literature but not in a consolidated format, which is therefore the value of this paper.

2 Lessons learned

2.1 Hoek–Brown GSI-based rock mass strengths – not universally applicable

The GSI coupled with the Hoek–Brown (HB) failure criterion for the estimation of rock mass strength assumes the rock mass is heavily jointed. This is a fundamental assumption that underpins the rock mass strength scaling from intact rock to the rock mass. The heavily jointed rock mass conditions drove the assumptions by HB to consider a specific mechanism of rock block rotation and shear along discontinuities and the rock mass being of low to zero tensile strength. The approach does not consider fracturing of the rock blocks themselves (Hoek & Brown 2019) or a situation where no blocks exist (i.e. the rock mass is massive). HB-GSI is thus mechanism-dependent and generally not suited for material parameter estimation in most deep mining applications. Many (e.g. Wagner 1987; Pelli et al. 1991; Martin 1997; Castro 1996; Grimstad & Bhasin 1997)

* Corresponding author.

have also shown that the HB-GSI rock mass strength estimation approach does not reliably forecast stress-induced brittle rock mass damage around excavations. Other approaches to rock mass strength estimation need to be applied in the deep mining context such as those outlined by Diederichs (1999), Kaiser et al. (2000) and Bewick et al. (2019).

As initial guidance, when GSI is greater than (approximately) 65, the dominance of block rotation and shearing in the rock mass damage mechanism diminishes, and rock and infilled/healed discontinuity fracturing takes over. These rock masses are commonly referred to as ‘moderately jointed to massive’ based on their low intensity of jointing or as ‘brittle rock masses’ based on the dominance of brittle stress fracturing in the damage mechanism.

2.2 Rock mass classification systems – diminishing value with increasing depth

There is industry comfort and familiarity with rock mass classification systems (e.g. rock quality designation [RQD], rock mass rating [RMR], iRMR and Q) that have been widely applied in shallow underground mining and surface mining. However, increasing depth of mining has consistently shown that rock mass conditions and damage mechanisms are not well captured by the existing engineering classification systems.

Rock masses at increasing depth have fewer open discontinuities, typically with reduced continuity. This is a generality and not a rule but has been confirmed by many mines that have had brittle rock mass response at depth (i.e. rock mass damage through stress fracturing opposed to block rotation). The traditional rock mass classification approaches were predominately developed for rock masses with open discontinuities. While rock mass classification is not discouraged, the value of the systems in rock masses at depth is diminished due to the reduced structural conditions leading to consistently high rock mass quality numbers. This is especially true for systems such as the RQD and RMR (Bieniawski 1976). The Q-system (Barton et al. 1974) does have adjustments for stress-induced failure but when using the system for ground quality (i.e. Q’ where strength reduction factor and Jw are set to 1) and not support requirements, the system also suffers in a similar way as RMR (i.e. high values and low variability of rock mass quality numbers).

2.3 Brittle rock mass strength – dependent on damage mechanism not scale

The rock mass strength for a mechanism of stress-induced fracturing (i.e. fracture initiation and propagation) is consistent across many scales, rock types and intact rock strengths. Stress fracturing has been observed around raises (1–5 m span), mine drifts (3–7 m span), large mine chambers that house infrastructure (7–20 m span), stopes (10–30 m span), power caverns (20–35 m span), narrow unconfined pillars of various sizes (3–50 m) and cave boundaries (> 50 m span). Figure 1 summarises back-analysed near excavation (up to ~55 m span) rock mass strengths normalised to their mean uniaxial compressive strength (UCS). These show a consistent range of rock mass strength from 0.3 to 0.5 UCS_{lab}.

At low confinement, brittle rock masses fail in compression by dominantly extensional fracturing and the development of slabs/spalls. This process is commonly referred to as spalling. If rock mass structures such as joints start to control the strength of the rock mass, spalling will not dominate but can still contribute to, and typically initiates, the failure process unless the intact rock is weak or ductile. Based on the back-analysis compiled in Figure 1, spalling strength appears to be scale-invariant and spalling will occur at any scale unless a different damage mechanism occurs (e.g. stress fracturing of a rock bridge leading to the release of a kinematic block).

What also needs to be understood for spalling assessments, or the assessment of brittle rock mass strength, is that there is no scaling of the intact rock strength for size. This is because the rock mass strength of brittle rock is related to the crack initiation threshold, and it has been shown that the crack initiation threshold is scale-invariant for many rocks (Figure 2). Thus fundamentally, the rock mass strength in rock that deforms through the development of induced fractures is not, or only minimally, influenced by the excavation scale.

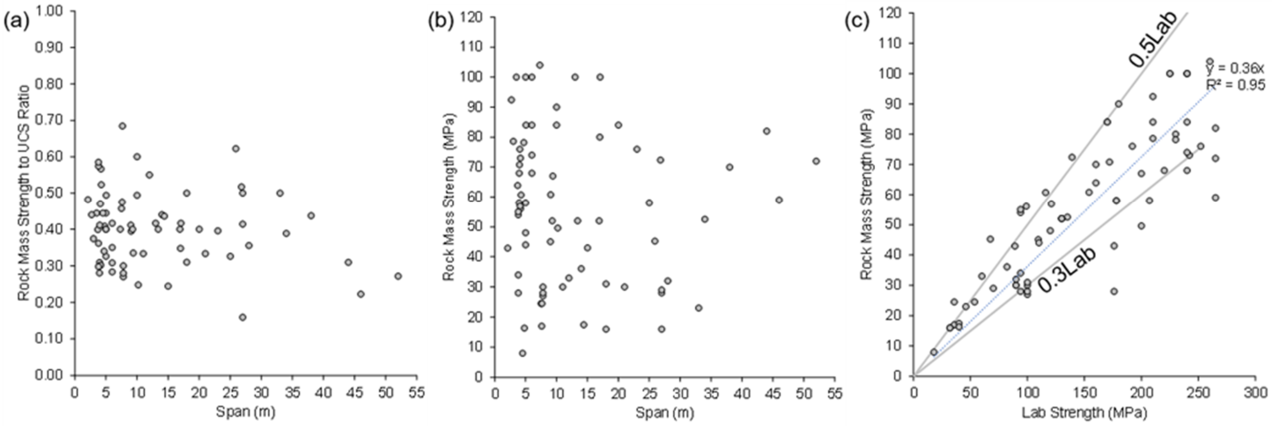

Figure 1 Rock mass strength database developed for built and back-analysed excavations including mine stopes, narrow pillars, tunnels, drifts, crusher chambers, power stations, porphyry/veined rock masses, etc. The back-analysis approach for these cases was consistent for about 90% of the data. (a) Excavation span versus back-analysed rock mass strength normalised to laboratory UCS; (b) Excavation span versus back-analysed rock mass strength not normalised; (c) Relationship between lab strength and back-analysed rock mass strength showing a best fit of 0.36 UCS_{lab}

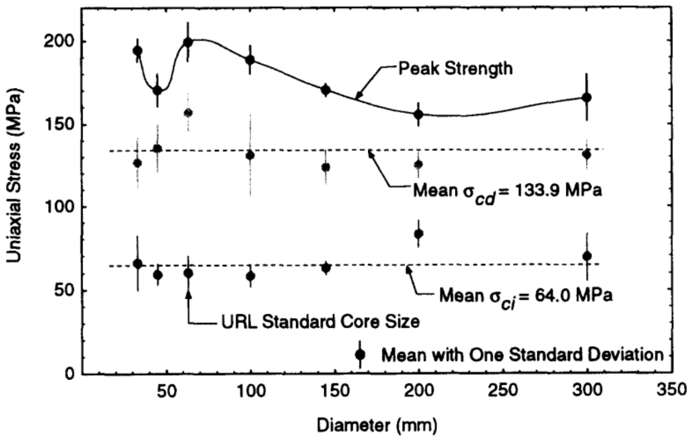

Figure 2 Summary of uniaxial compressive strength testing with different rock core diameters showing a general reduction in peak strength with increasing diameter but consistent crack initiation and crack damage thresholds (Martin & Chandler 1994)

2.4 Cohesive defects matter – joints are less dominant

At depth, open discontinuities are less frequent (and typically have reduced continuity) and focus needs to be placed on understanding the spatial distributions of intact rock strength, locations of small-scale faulting, local rock mass volumes of increased discontinuity intensity and the distributions of various healed discontinuities such as veins. Approaches need to be adopted that allow for a more informed understanding of the cohesive nature of the rock mass. These include a more rigorous approach to measuring intact strength and strength variability through increased uniaxial and triaxial compressive strength testing to assess failure types and modes (e.g. Bewick et al. 2015), and regular/systematic point load testing (with failure type recording) to better assess rock mass strength variability. An example of a jointed rock mass from a surface excavation versus a veined rock mass in a deep mine heading is shown in Figure 3.

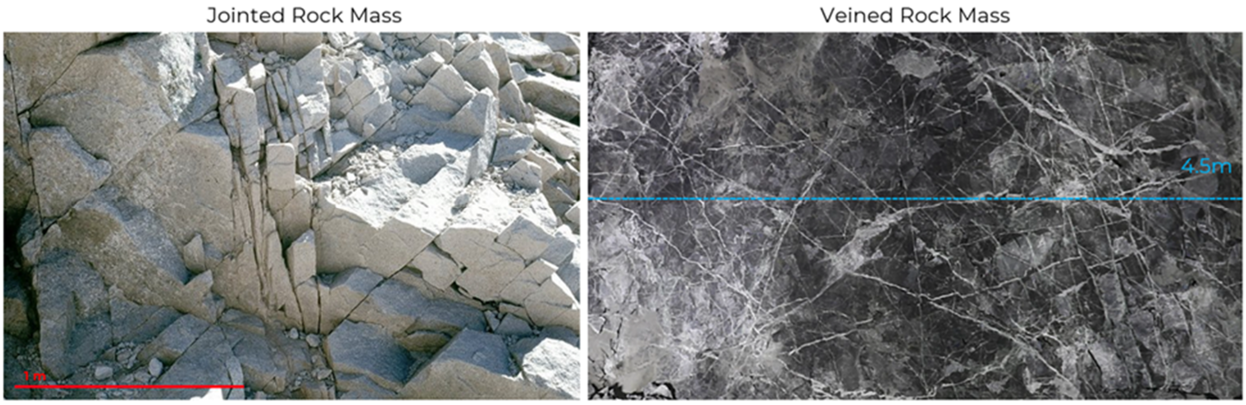

Figure 3 Left plate shows a rock mass from a surface excavation that is jointed and blocky. Right plate shows a heading in a deep mine with a veined rock mass, with no visible jointing

The critical factors that need to be recorded during strength characterisation have been identified as follows (e.g. Bewick 2021; Bewick et al. 2022):

- Failure type and defect intensity (Figure 4) – describe how the specimen fails and what influences the failure of the specimen. Failure types are a symptom of different factors influencing the strength of a defected rock and must not be combined during interpretation. Failure type should not be confused with failure mode, which is the mechanism of specimen failure (e.g. axial splitting, single shear, etc.) and is also important to record. At a minimum, the following failure types need to be considered:
  - Homogeneous failure – failure through the homogeneous rock matrix by extension or shear at low confinement or shear rupture at high confining stress
  - Combined failure – failure that includes partial failure on a discrete cohesive feature(s) and extension or shear failure through the otherwise homogeneous rock matrix
  - Weakness or defect network failure – mostly failure along or around multiple veins, clasts or other cohesive defects
  - Discrete failure – failure along one discrete pre-existing cohesive feature. This failure type cannot be processed in the principal stress space and must first be fitted in shear-normal stress space and transformed into principal stress space. Guidance for this can be found in Hoek & Brown (1980), Goodman (1989) and Bewick et al. (2019).

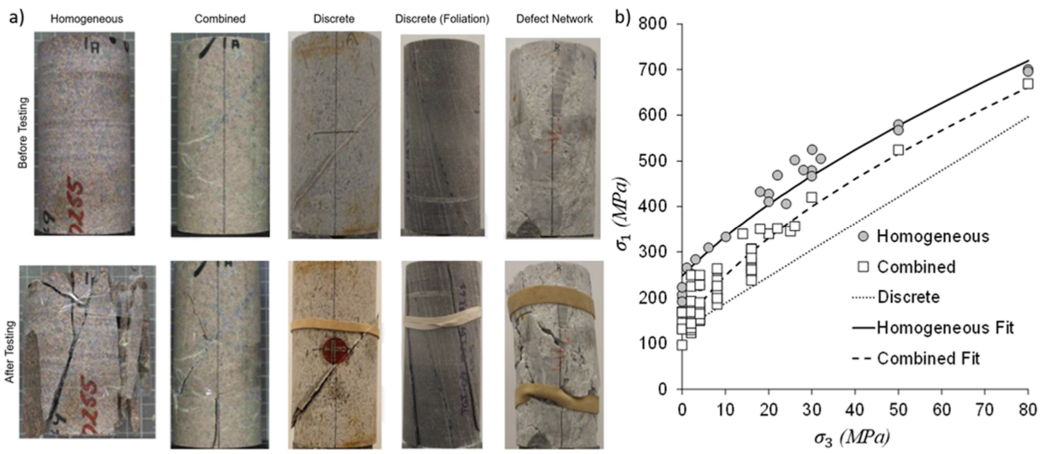

Figure 4 (a) Failure type examples and (b) impact of failure type on intact rock strength showing progressive reduction from homogeneous to discrete (modified from Bewick et al. 2019). From Bewick (2021)

The failure types outlined above also represent the influence of vein or defect intensity on rock strength. As defects become more dominantly involved in the specimen failure the strength is reduced. This is reflected in the progression from homogeneous to combined to defect network to discrete failures (Figure 4b). One key point to note is that not all veins or defects impact the rock strength. A rock may contain a weak and a strong vein set. While the overall vein intensity in the rock would be the sum of the two vein sets, only the weak vein set may be impacting the rock strength; thus only the weak vein type and intensity should be considered.

Identification of the vein or defect type is critically important. Figure 5 shows an example of the relative point load index strengths of different veins, classified by their primary infill mineralogy. For the failure types involving veins (i.e. combined, discrete and weakness network), the specific vein type involved in the failure must be recorded. For example, a rock unit may contain vein networks of pyrite and calcite. These two vein types have different strengths and will impact rock strength differently. Thus within the testing data set of a single rock type where combined failures are being recorded it is important to identify the vein types involved in the failure process to better understand the testing data and scatter.

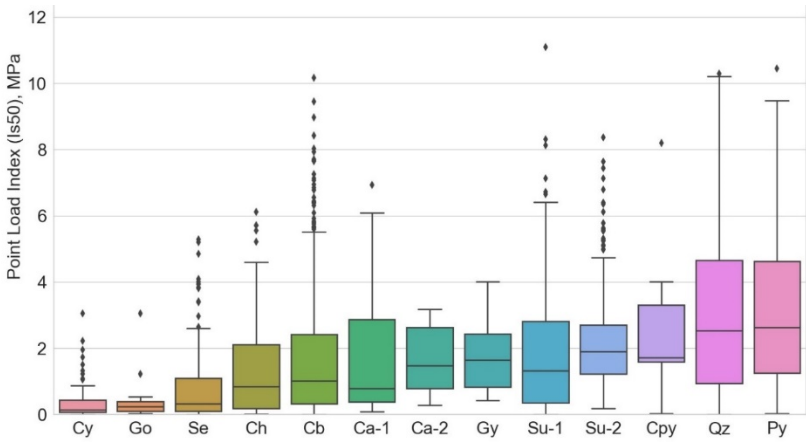

Figure 5 Box plot of > 3,600 point load index test data points showing the primary vein infilling mineralogy influence on the strength of discrete veins (Bewick et al. 2022)

Alteration of the host rock can also weaken (e.g. argillic alteration) or strengthen (e.g. silicification) a rock and must be considered during strength interpretation. In some cases rock strength data can be used to help inform alteration models.

2.5 Estimation of depth of spalling – they are maximums not averages

A relationship based upon observations and measurements in the field from tunnels (both mining and civil) around the world failing in a progressive brittle manner and by rockbursts (Kaiser et al. 1996) was developed, as shown in Figure 6. This figure shows the relationship between the deepest measured depth of spalling (damage) along the length of an excavation or tunnel and the stress level index (SLI) (Kaiser et al. 2000). This relationship shows that spalling starts around 0.4 UCS. As the SLI increases so does the depth of spalling. The importance of the depth of failure forecast being the deepest (i.e. maximum) cannot be over emphasised. Since the deepest or maximum depth of failure is being estimated and the UCS used in the SLI is the mean of very high-quality testing data, a range or distribution of UCS should either not be considered or the variability considered very carefully. Note that when the relationship was developed there were limited veined rock cases and thus the UCS is for homogeneous failure types. Essentially, the depth of failure lines in Figure 6 provides a range in the depth of damage without the need to consider a range of UCS. If a range or lower-bound UCS was considered in the forecasting of the depth of failure around an excavation, the forecasted depth of failure would be unrealistic and unrelated to the database used to develop the relationship.

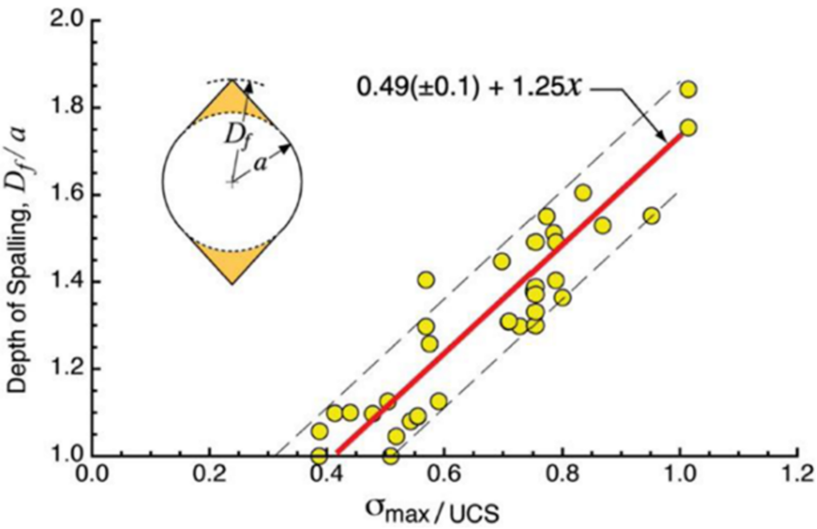

Figure 6 The maximum depth of failure and stress level index relates the mining-induced maximum stress (*σ_{max}*) around an equivalent circular excavation in elastic rock to the rock's intact compressive strength, in this case the UCS (Martin et al. 1999)

2.6 Elastic modelling – simple, fast and valuable

Brittle stress damage thresholds of 0.3 UCS, 0.4 UCS and 0.5 UCS (note that UCS is based on high quality and very reliable testing data) relate to stages of progressive and the speed of brittle stress damage development. When considered in this way, simple numerical stress models can be used for hazard forecasting in an effective method. While elastic stress models cannot always be successful, thoughtful interpretation often results in the ability to use elastic models to forecast spalling and strainbursting rock mass response.

Elastic models are also simple to construct and fast to run, improving the modeller's ability to evaluate different excavation sequences and geometries. Understanding how the mining sequence induces stress and how the mine layout and geometries concentrate stress, and then making modifications to improve stress conditions, is an effective strategy for mitigating deep mining ground hazards.

Overall case history data from civil and mining measurements (Wilson 1971; Barton et al. 1974; Wiseman 1978, 1979; Hoek & Brown 1980; Stacey & Page 1984; Jager et al. 1990; Kaiser et al. 1996; Board & Brummer 1997; Brummer 1998; Martin et al. 1999; Castro 1996; Diederichs 1999; Kaiser et al. 2000; Bewick et al. 2019; Bewick 2021; and Xiao et al. 2023, amongst many others) support the following damage thresholds, which are also confirmed by application to projects by the authors:

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

These are very consistent damage thresholds in brittle rock masses. If observations differ from the above the stress state or strength data are questionable. Departure from the above should not be used to justify a unique rock mass behaviour that is not obeying currently understood rock fracture physics.

When the above are also benchmarked to a mine they can be used with 3D or 2D elastic numerical stress models to assess where and when (relative to a mining sequence) different rock mass responses may occur (Figure 7). The elastic modelling approach for the assessment of stress damage and strainbursting has been adopted by many including Wiles et al. (1998), Martin et al. (1999), Diederichs (1999) and Kaiser et al. (2000).

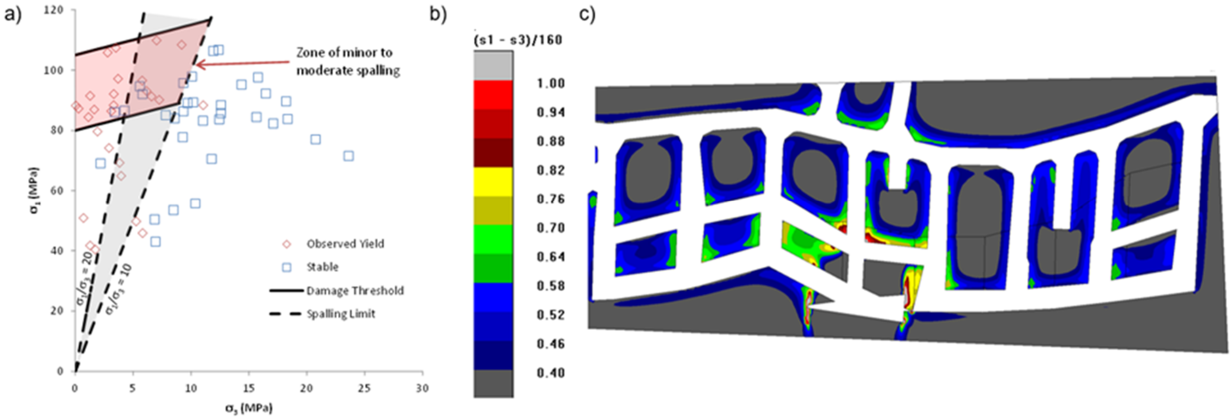

Figure 7 (a) Elastic modelling results at damage locations to benchmark a brittle failure criterion; (b) Deviatoric stress normalised to UCS for stress damage threshold plotting in (c); (c) Plan view of a mine level in a stoping operation, identifying areas of concern and depth of stress damage for ground support selection considerations

2.7 Rock mass damage – not always failure but always deformation

The occurrence of rock mass damage does not mean that the rock mass, the ground support or the excavation have failed. Stress-induced damage to the rock masses in deep and high stress mines is inevitable. When the correct damage mechanisms are identified and planned for, rock mass damage and deformation can be effectively managed to reduce the likelihood of failure occurrence and maintain serviceability of the excavation.

Rock mass damage in deep mines results in bulking displacements (Figure 8). These displacements occur within the narrow zone of damaged rock around an excavation, which contrasts from weaker rock masses where deep-seated deformation is possible. The bulking displacements occur initially due to dilation of new fractures, followed by shearing and rotation along the newly created slabs. Low confinement allows the slabs to separate from each other and be forced out into the excavation as they move (shear and rotate), relative to one another. The geometric incompatibility of the stress-fractured rock and slabs means that the bulking deformation is not reversible. Cai & Kaiser (2018) summarise how bulking (single wall) is generally 2 to 10% for supported ground and up to 20% for unsupported and extremely strained broken ground. This is consistent with the measurements reported by Hepworth (1985).

When support capacity is consumed and then lost due to progressive bulking, bulking factors can also increase, even for strong support with rock mass reinforcement. Bulking factors need to be considered relative to the change in support capacity over time as it is lost due to mining-induced stress changes causing increased bulking displacements.

In many cases the rock immediately surrounding the excavations is not relied upon for 'structural' support of the mine and therefore the main function of the rock and ground support is to maintain the original excavation profile or some tolerable deformation. Deformation-based failure criterion can be defined to maintain serviceability of the excavation (e.g. when mining equipment can no longer fit) and to identify when bolts start to break due to displacement capacity being reached.

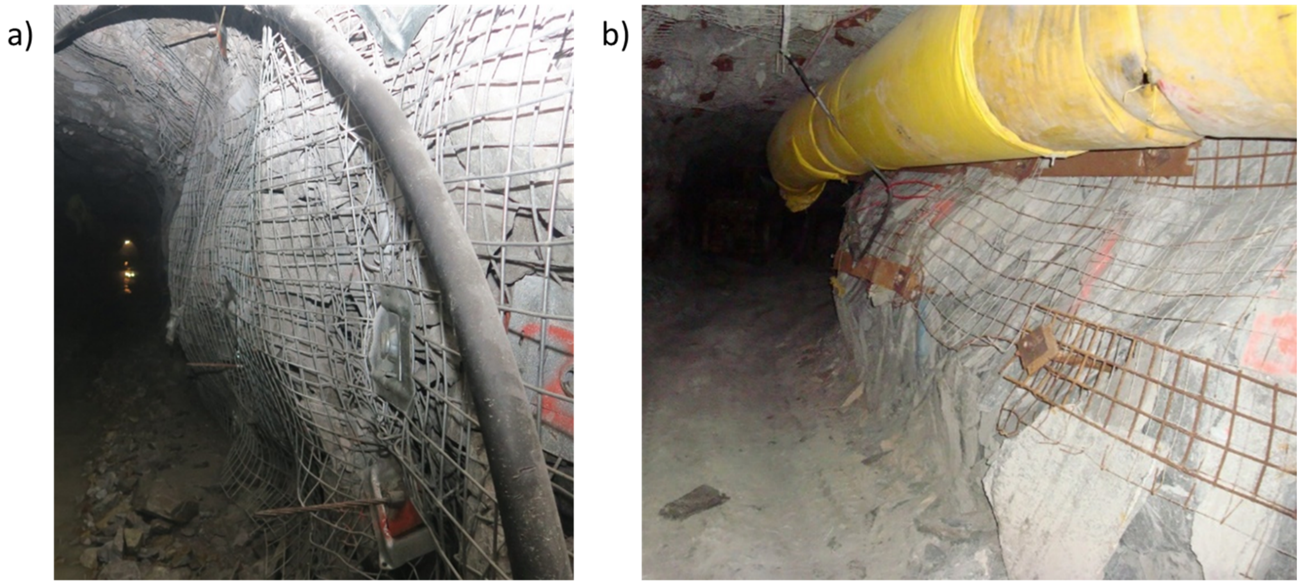

Figure 8 (a) Spalling leading to rock mass bulking around a drift and reducing the effective service dimensions of the excavation; (b) Foliation buckling leading to a reduced drift cross-section and the potential for earlier-than-planned equipment or personnel access restrictions

2.8 Ground management – the story doesn't end when the ground support is installed

Ground support is the last line of defence in deep mines. The capacity of ground support is also consumed over time and needs replacement. Preventative support maintenance programs are critical and require adequate consideration in ground support designs.

Excavations must be treated similarly to fixed and mobile equipment in mines, where the objective is to have a reliable system based on a robust regime of performance monitoring and planned maintenance. The objective is to reduce the number of production interruptions due to unplanned repairs by implementing a program of measurement and planned excavation maintenance.

The first step in such a change is to measure key performance indicators including:

- quality – how well the drift is initially constructed. Quality is important since it will impact the drift's reliability and the mean time for repair
- availability – the proportion of the time the drift is available for its intended purpose
- utilisation – the proportion of the time the drift is available and used for its intended purpose
- reliability – how often the drift does not fulfil its intended purpose, usually measured by mean time between failures
- mean time to repair – average time required to repair a drift to a safe and/or productive state.

When excavations are considered this way it becomes clear that excavation performance will strongly influence production reliability and form an integral component of material movement assessments.

3 Conclusion

Some items of importance for rock engineering in deep mines have been summarised in this paper. The goal of the paper is to outline helpful aspects of practical importance that may not be known in detail. The items covered are contained throughout the knowledge corpus of high stress rock engineering but not in a consolidated format. The authors hope that readers find this paper and reference list of use.

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