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# Managing squeezing ground in underground mines: an integrated toolbox

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## Abstract

*Underground mines with weak rock masses subjected to relatively high stress levels may experience squeezing ground conditions, which represents a major challenge for ground support performance and excavation serviceability. Rehabilitation becomes frequent, and large convergences can restrict equipment access. Conventional approaches based primarily on increasing support capacity are often insufficient to manage these conditions effectively.*

*This paper presents an integrated squeezing ground management methodology comprising a series of tools that can be used to estimate squeezing levels, appropriate support selection based on deformation demand and yielded zone characterisation, mine layout optimisation and monitoring. A practical damage mapping matrix developed specifically for squeezing ground is presented as a preliminary risk management tool to support rehabilitation prioritisation and decision-making.*

*In addition, the paper demonstrates how development profile optimisation can reduce buckling susceptibility in anisotropic rock masses and how calibrated numerical modelling can be used to evaluate alternative mine layout scenarios.*

**Keywords:** *squeezing, weak rock, convergence, damage mapping, mine layout, numerical modelling, development profile*

## 1 Introduction

Mining in weak rock and squeezing ground is one of the significant challenges of underground mines, as frequent rehabilitation requirements and reduced mine profiles can generate safety risks and affect drive serviceability.

One of the most accepted squeezing definitions comes from the International Society of Rock Mechanics:

> *"Squeezing of rock is the time dependent large deformation which occurs around the tunnel and is essentially associated with creep caused by exceeding a limiting shear stress. Deformation may terminate during construction or continue over a long time period."* (Barla 1995)

Hadjigeorgiou et al. (2013) stated that in a mining context, squeezing ground conditions are encountered when the excavation convergence, even with ground support, exceeds 2%. According to Potvin & Hadjigeorgiou (2024), in squeezing ground the drive closure will reach tens of centimetres within the life expectancy of a supported drive. Considering a stiff support system, the resulting loads tend to be greater than its capacity, and extensive rehabilitation work is required.

There are 3 main failure modes in squeezing rocks as presented in Figure 1 (Aydan et al. 1993). The first one is complete shear failure, which is common in weak and ductile rock masses. The second one is buckling

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failure, mostly present in metamorphic rocks, such as phyllite, and mica schists, and in thinly bedded ductile sedimentary rocks (i.e. mudstone, shale and siltstone). The last one is tensile splitting, shearing and sliding failure, which can occur in thickly bedded sedimentary rocks and involves sliding along bedding planes and shearing of intact rock.

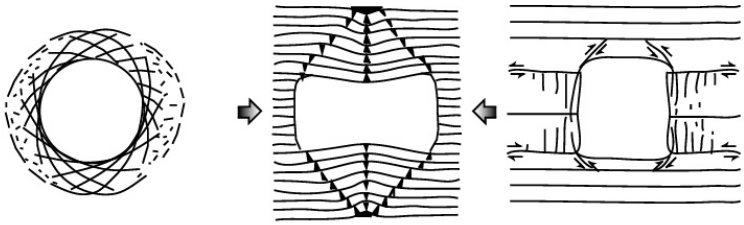


**Figure 1 Classification of failure forms of tunnels in squeezing rocks, after Aydan et al (1993). (a) Complete shear failure; (b) Buckling failure; (c) Tensile splitting, shearing and sliding**

Potvin & Hadjigeorgiou (2024) classified the level of squeezing in hard rock mining environment as per the division below:

- No or low squeezing (0% < ε <5%)
- Moderate squeezing (5% < ε <10%)
- Pronounced squeezing or rehabilitated drifts (10% < ε <35%)
- Extreme squeezing (ε > 35%).

The purpose of this paper is to present an integrated squeezing ground management methodology comprising four main stages: squeezing level estimation and failure mechanism identification (pre-design); management strategy definition, including ground support selection, development profile optimisation, and mine layout assessment (design); monitoring and risk management (implementation); and performance assessment. The information obtained during the monitoring and performance assessment stages is used as feedback to refine the pre-design and design stages, as illustrated in Figure 2.

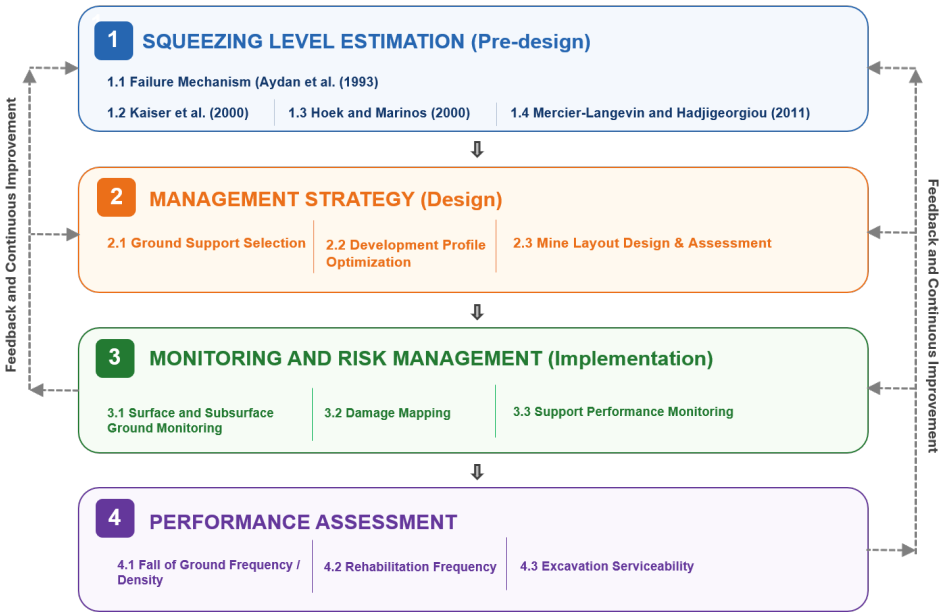



**Figure 2 Squeezing ground management strategy, comprising squeezing level estimation, management strategy definition, monitoring and risk management, and performance assessment within a continuous feedback process**

# 2 Squeezing level estimation

The first step is to identify the degree of squeezing expected around the excavations. This section discusses different techniques that can be applied to anticipate squeezing conditions and estimate deformation potential in mine drives.

As presented by Kaiser et al. (2000) in Figure 3, squeezing conditions may develop in highly fractured rock masses (RMR < 50) subjected to high in situ stress, characterised by a $\sigma_1$/UCS ratio greater than 0.4.

Terzaghi (1946) also mentions that "Prerequisite of squeeze is a high percentage of microscopic and sub-microscopic particles of micaceous minerals or of clay minerals with a low swelling capacity". Given this requirement, foliated rocks with clay minerals have potential to present high displacement when loaded with high stress.

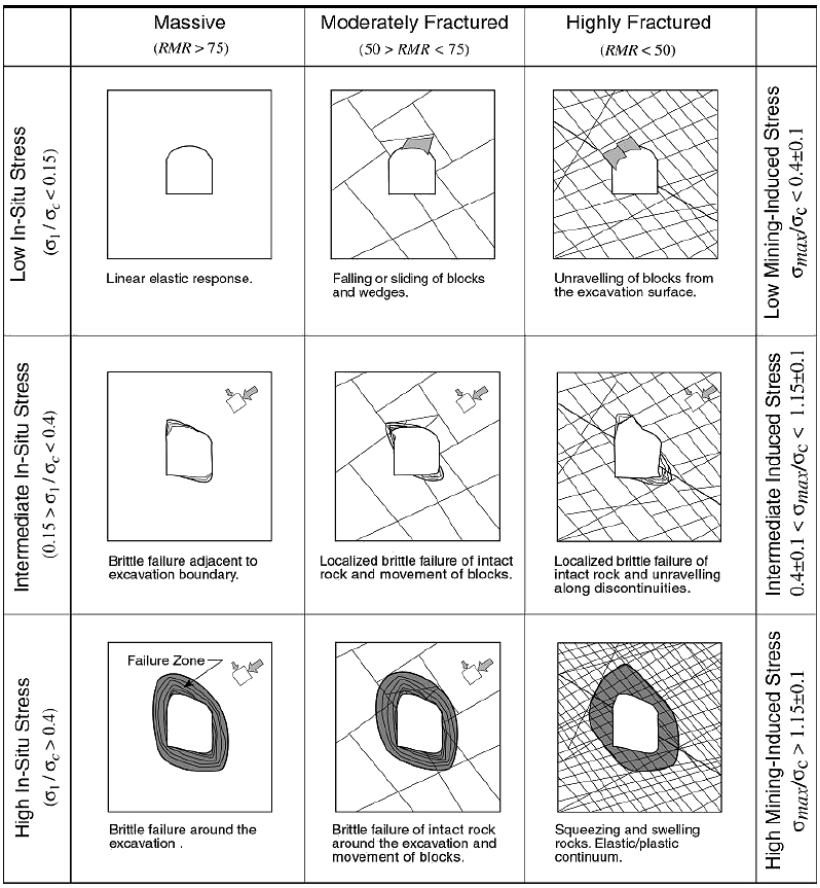



**Figure 3 Relationship between damage, increasing stress and decreasing rock mass quality (Kaiser et al. 2000)**

Hoek & Marinos (2000) also propose a methodology to obtain a first crude estimate of the tunnel strain and progressive potential tunnelling problems due to squeezing based on rock mass strength to in situ stress ratio. These problems may range from minor support issues (strain less than 1%) to extreme squeezing problems (strain greater than 10%), as illustrated in Figure 4.

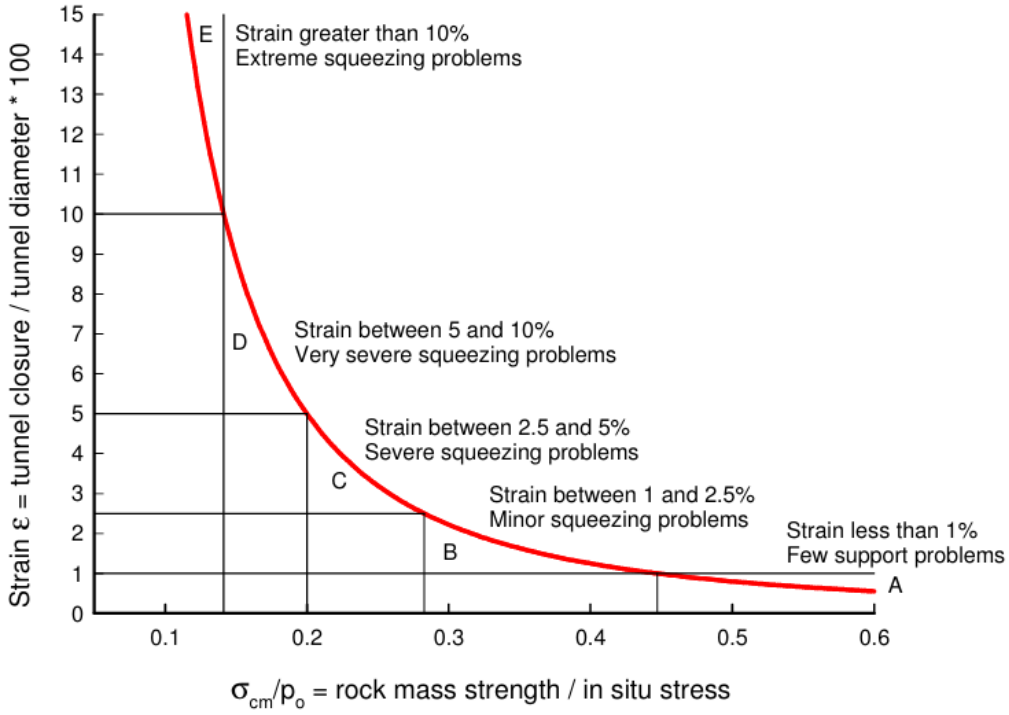



**Figure 4 Squeezing levels in tunnelling and the ratio of rock mass strength to in situ stress (Hoek & Marinos 2000)**

It is important to note that those ranges were originally defined for civil construction tunnels. In mining environments where larger displacements can generally be tolerated, the strain thresholds proposed by Potvin & Hadjigeorgiou (2024) – with extreme squeezing defined as strains greater than 35% – are considered more appropriate for this context. Their full classification, ranging from low to extreme squeezing conditions was presented in the Introduction.

Mercier-Langevin & Hadjigeorgiou (2011) advocate that the squeezing potential is a function of the foliation spacing, the angle between the wall and the foliation and the major principal stress-to-intact rock strength ratio. Relating those parameters, it is possible to obtain the hard rock squeezing index and estimate the strain amount, as presented in the matrix shown in Figure 5. This relationship of foliation spacing and wall displacement, mainly related to buckling, is also mentioned by Hutchison & Diederichs (1996), who relate the buckling initiation potential with the slenderness ratio (length-to-thickness ratio of the slabs).

The estimated squeezing level, expected deformation mechanism, and main controlling factors provide the basis for selecting the support, excavation profile, monitoring, and mine layout strategies discussed in the following sections.

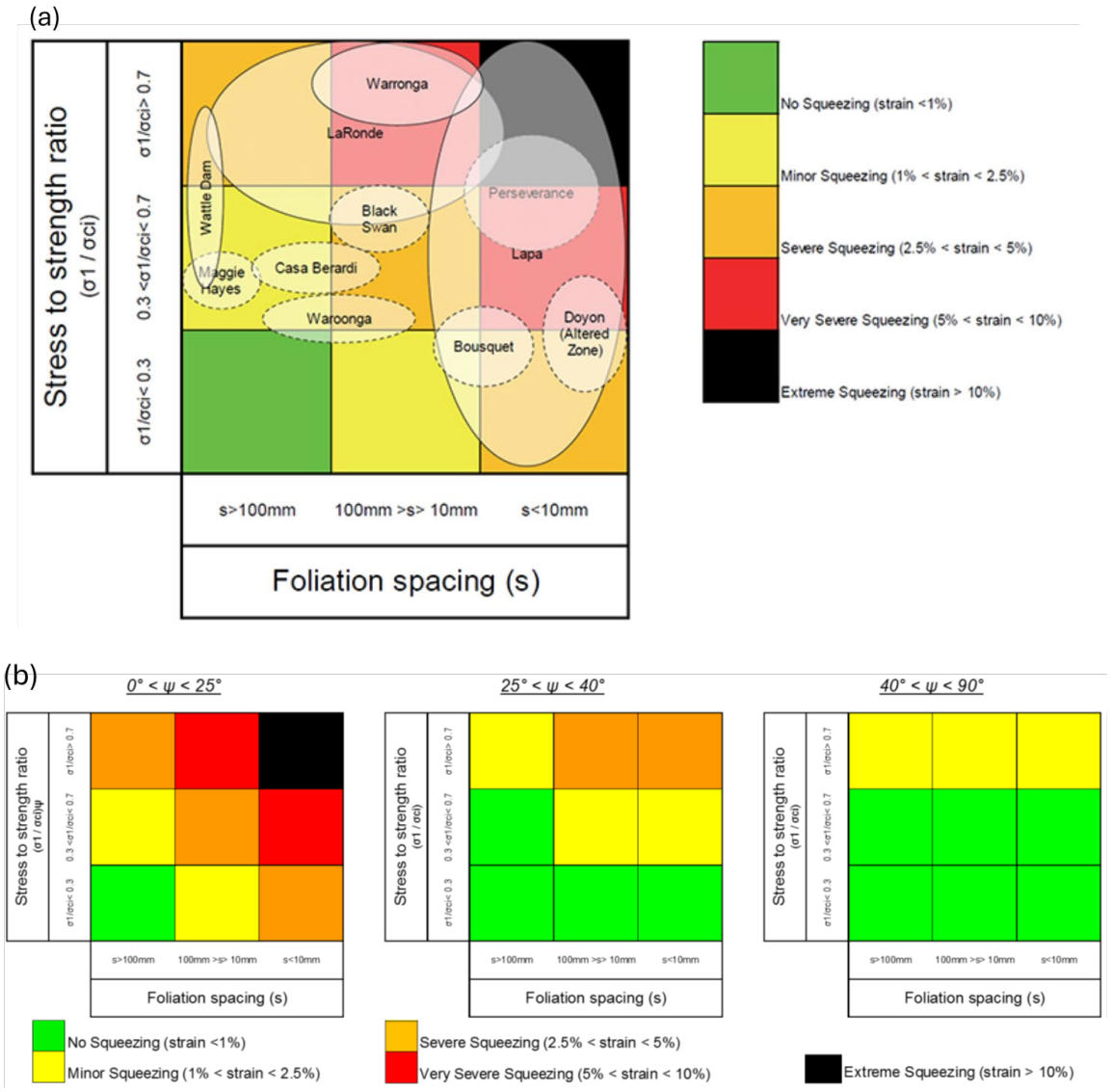



**Figure 5 Hard rock squeezing index. (a) Generic matrix; (b) Matrices for different angles between the foliation and the analysed face (Mercier-Langevin & Hadjigeorgiou 2011)**

# 3 Support selection

Following identification of the mine areas with moderate to elevated squeezing potential, an appropriate support selection must be done to ensure adequate management of large deformations.

Traditionally, the design of ground support in mining tunnels rely on analytical tools, such as the three-dimensional wedge (e.g. Unwedge software), empirical approaches like the Q-system chart (Grimstad & Barton 1993), and elastic stress-strain analysis. While these approaches remain applicable under low or no squeezing conditions, conventional ground support guidelines do not explicitly address the deformation capacity required under significant squeezing, where yielding support systems may be necessary to accommodate large displacements (Hadjigeorgiou & Potvin 2023).

In civil tunnels, squeezing ground is often managed with ductile systems – such as slots in the shotcrete or sliding steel arches (Figure 6) – which allow controlled ground deformation, maintain the excavation integrity, and reduce the stress concentrations on the ground support (Potvin & Hadjigeorgiou 2024).

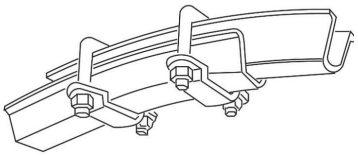


**Figure 6 Example of a sliding joint in a steel arch, which can be used in tunnels to relief the stress in the support system (Hoek 1998)**

In underground mines, larger strains can be tolerated, and tunnels generally have smaller cross-sections compared to civil tunnels. The support system typically consists of ductile bolts and mesh, installed after shotcrete application. In such conditions, when reinforced shotcrete and standard bolts are used, shotcrete scats can be generated and bolts may lose their plates, leading to frequent rehabilitation (Costa et al. 2019).

For the ground support to be effective and ensure long-term structural stability, it must function as an integrated system of retention, reinforcement, and holding (Figure 7). As explained by Charette & Bennet (2017), under static conditions, there is only a minimal requirement for the support and the reinforcement to work together. However, under dynamic conditions – whether slow (squeezing – mm/day) or rapid (rockburst – m/s) – the overall performance of the support system depends significantly on load transfer between its components.

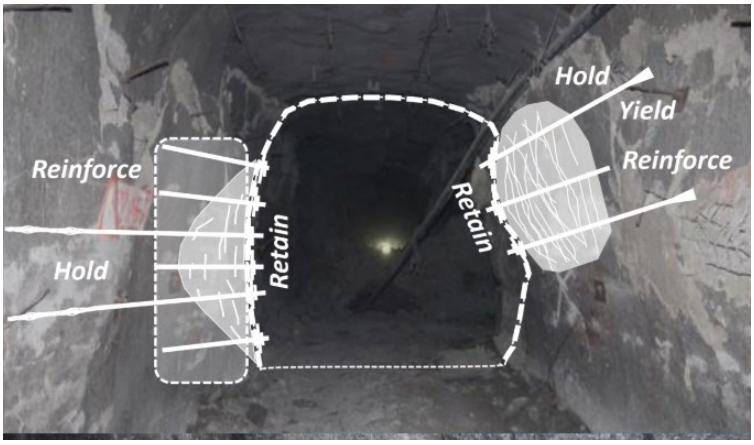



**Figure 7 Reinforcement, holding and retaining concepts (Cai & Kaiser 2018)**

For the system to function integrally and ensure an effective load transfer between components, bolts should be installed after the surface support system. Ideally, the face plate should begin to deform near the yielding capacity of the bolt and have an ultimate capacity higher than that of the bolt itself (Charette & Bennett 2017). Although this represents the minimal requirement, the authors' experience indicates that most commercially available bolts in the industry do not meet this criterion.

The surface support and reinforcement should have ductile behaviour in squeezing ground. As shown in Table 1 and Figure 8, there are a range of options for bolts and surface support schemes. The surface support options that guarantee high deformability capacity (deflection greater than 200 mm) are the ones where mesh is exposed on the surface, applied alone or after shotcrete application (Louchnikov et al. 2014). Resin-grouted rebars present stiff behaviour, which is not desired in a tunnel with a large displacement demand. Dynamic bolts, such as modern versions of the cone bolt or the Vulcan bolt are a more compatible option, since they present high displacement capacity (greater than 200 mm) and strength above 10 tonnes.

The required length of bolts in squeezing ground conditions depends on the extent of the yielded zone. To estimate the depth of fractured rock, several methodologies can be applied, including numerical modelling, borehole camera inspections and extensometer monitoring. Depending on the excavation geometry, two-dimensional stress-strain software packages, such as RS2 (Rocscience) can be used. For more complex geometries, the depth of fracturing should be simulated with three-dimensional software (e.g. Map3D, Examine3D, RS3).

**Table 1 Capacities of surface support systems based on static loading tests under 'stiff' boundary conditions (Louchnikov et al. 2014)**

| Type of surface support | Energy absorption per unit area (kJ/m²) | Peak load at failure (kN) | Maximum displacement at failure (mm) |
|---|---|---|---|
| FRS 60 mm, synthetic fibre | 0.75 | 25 | 60 |
| FRS 80 mm, synthetic fibre | 2 | 65 | 80 |
| FRS 110 mm with embedded WM | 6 | 120 | 120 |
| WM 100 × 100 × 5.6 mm | 1.3 | 45 | 210 |
| FRS 60 mm + WM over | 2 | 45 | 210 |
| FRS 80 mm + WM over | 3.3 | 65 | 210 |
| MINAX M85/2.7 | 1.7 | 55 | 185 |
| TECCO G80/4 | 6 | 110 | 250 |
| FRS 60 mm + MINAX M85/2.7 | 2 | 55 | 185 |
| FRS 60 mm + TECCO G80/4 | 6.8 | 110 | 250 |
| FRS 80 mm + MINAX M85/2.7 | 4 | 65 | 185 |
| FRS 80 mm + TECCO G80/4 | 8 | 110 | 250 |
| FRS 110 mm + TECCO G80/4 | 12 | 120 | 250 |
| HEA mesh | 2.5 | 160 | 800 |
| Strap mesh | 1.5 | 50 | 210 |

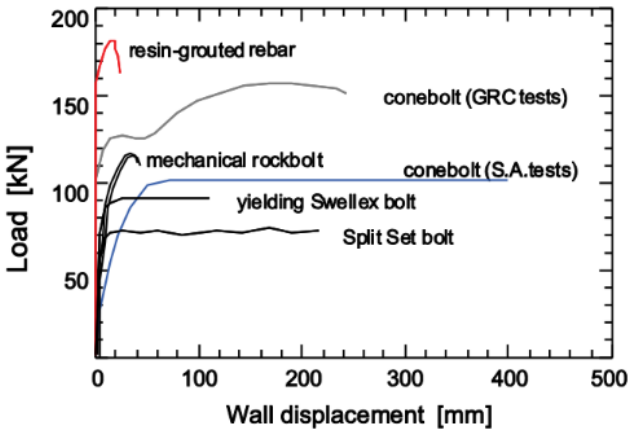



**Figure 8 Pull test performance of common bolts applied in underground mines (Kaiser et al. 1996)**

Visual assessment of the fracturing depth can also be performed using borehole cameras. Figure 9 presents an example of application of this tool. Monitoring instruments represent another valuable tool for delineating the fractured zone and identifying major structures that may extend or shear. Extensometers can be used to measure normal separation between planes parallel to the long axis of the hole, while inclinometers obtain the shearing displacement perpendicular to the hole axis. By analysing the displacement profile along the instrument length (Figure 10), the geotechnical practitioner can determine the minimum length required to cross the yielded zone and then add the critical embedment length to define the support dimension. This should be complemented with inclinometer measurements to identify any shearing displacements throughout the hole.

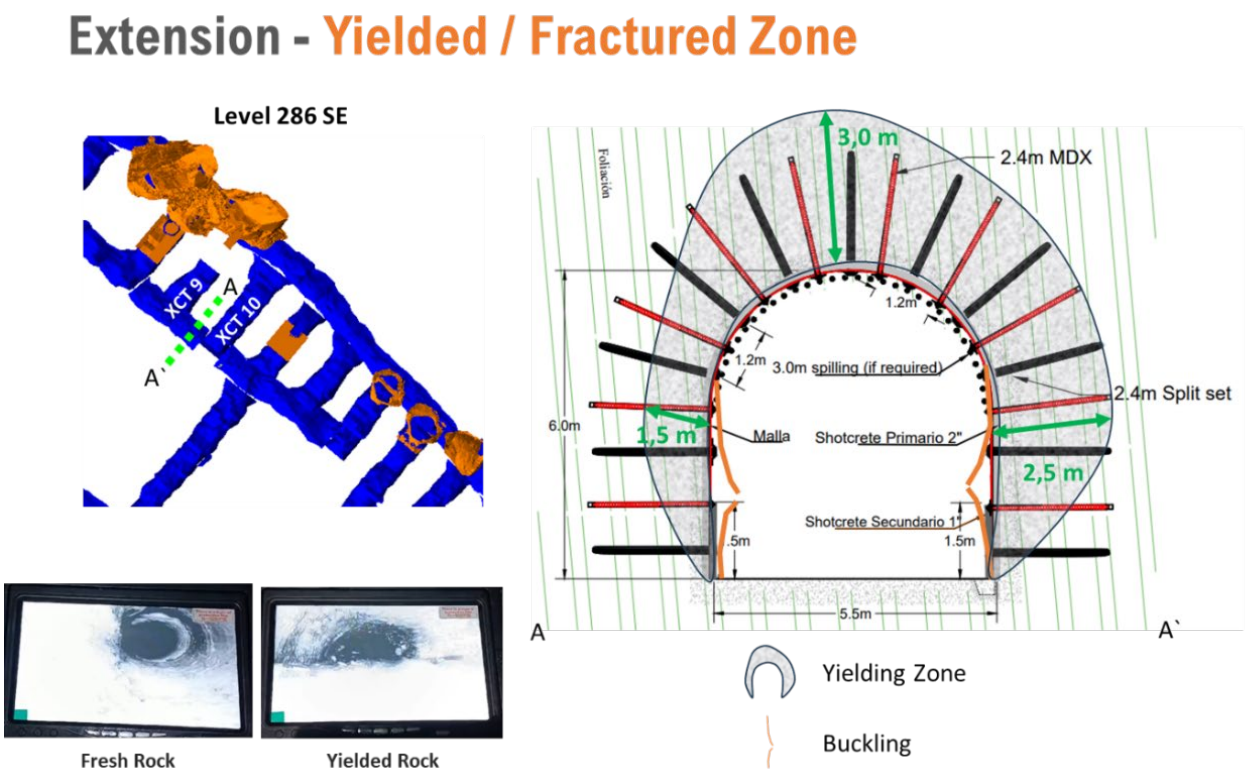



**Figure 9 Examples of borehole camera monitoring results**

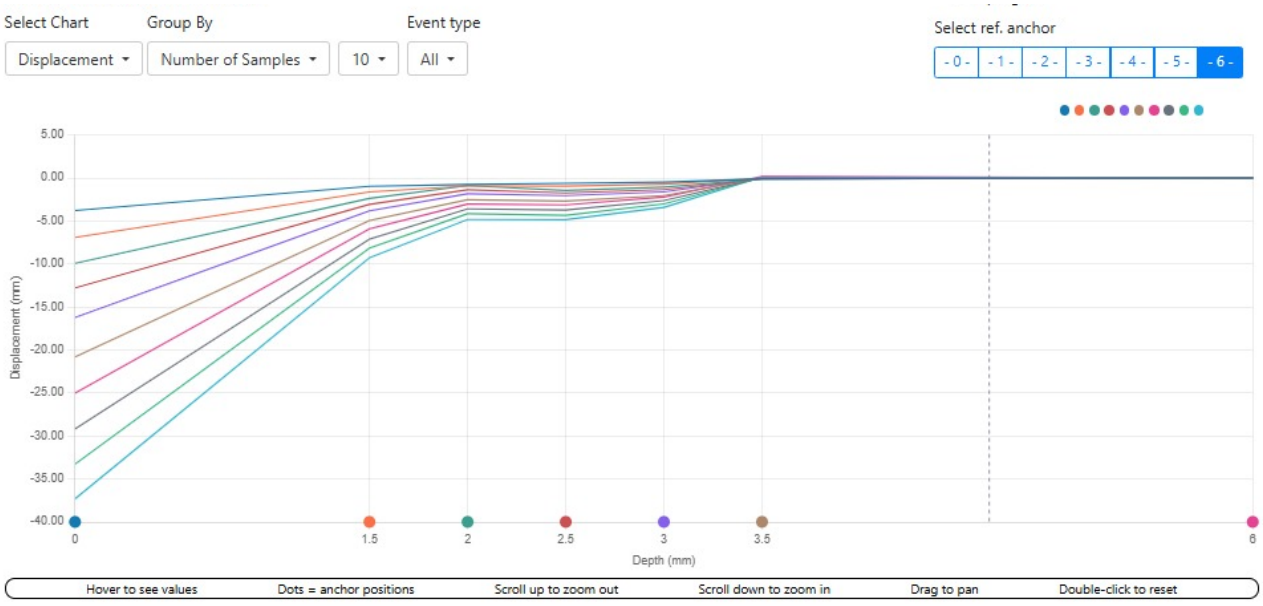



**Figure 10 Example of an extensometer monitoring in an underground mine, indicating yielding concentrated about 2 m in the excavation sidewalls. This should be complemented with inclinometer measurements to identify any shearing displacements throughout the hole**

Primary surface support refers to areal supports that cover the ground entirely, such as mesh and shotcrete. In contrast, secondary surface supports are areal supports that cover the ground partially. They serve as a means of load transfer between the rockbolts and to secure mesh overlaps (Louchnikov et al. 2014). The most common secondary supports are the Osro straps, w-straps and mesh straps.

In pronounced to extreme squeezing conditions, the ground bulking can be excessive, causing mesh overlaps to open and mesh wires can be sheared by the plates. As a result, the support system can become ineffective in preventing unravelling and ensuring ground structural stability. This leads to complete tunnel rehabilitation, safety concerns, additional costs and production impacts. To avoid such situations, secondary surface support, such as mesh straps, can be applied as a mitigation measure (Figure 11).



**Figure 11 Mesh straps applied to connect cable bolts and avoid failures through the mesh overlaps**

In addition to load and deformation capacity, the long-term durability of the support should be considered during support selection, especially in corrosive environments. Corrosion can gradually reduce the capacity of ground support elements and compromise their ability to sustain loads imposed by the squeezing ground. Where corrosive conditions are anticipated, appropriate corrosion protection should be selected according to the required excavation service life.

When dealing with squeezing tunnels where the ground deterioration is so rapid that there is a significant risk of collapse before ground support can be installed, pre-support should be applied, and blast rounds may have to be shortened (Potvin & Hadjigeorgiou 2024). One way to identify the areas where these measures are necessary is by utilising the stand-up-time graph from Bieniawski (1989). Considering that mine drives normally have a width between 5 and 6 m, for the excavation to remain stable while the primary support is not installed, the RMR should be higher than 30 and 35, respectively (Figure 12). Therefore, if the RMR is below 35 in a normal mine drift, the application of pre-support should be considered, such as spiling bolts (Figure 13).

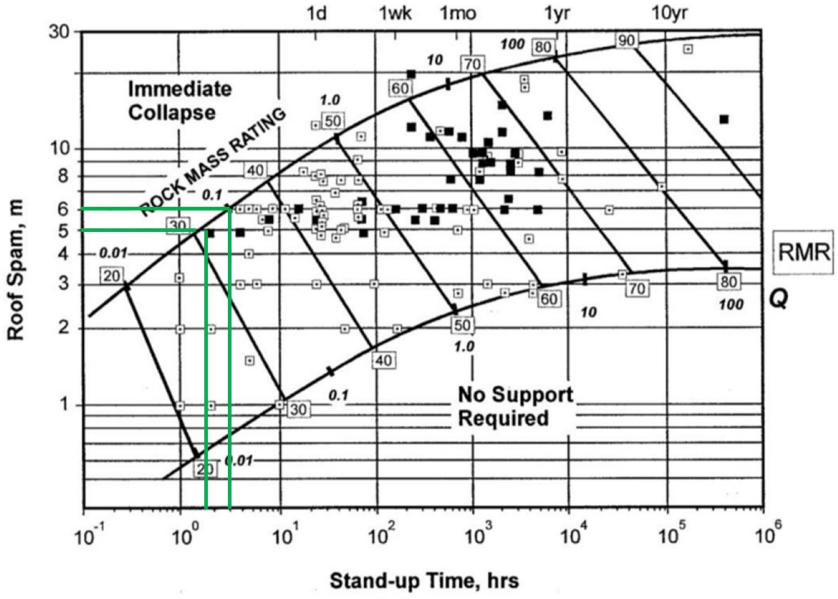



**Figure 12 Stand-up time data plotted by Bieniawski (1989). In this graph, the minimum rock mass rating (RMR) to avoid immediate collapse is plotted for drift spans of 5 and 6 m**

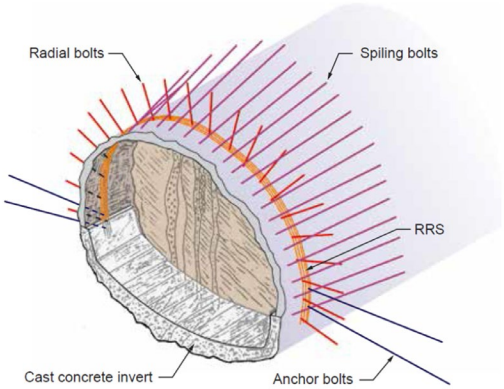



**Figure 13 Illustration of support of poor rock masses by spiling. It shows an example of the use of spiling combined with sprayed concrete ribs and concrete invert (Holmøy & Aagaard 2002)**

# 4 Development profile

An appropriate support system is not only required to manage large deformations, but also optimisations in the development profile must be analysed to promote a reduction in tunnel convergence.

Squeezing ground is often characterised by large displacements that develop in tunnels over time and are usually anisotropic. As illustrated in Figure 1, the main failure mechanisms are complete shear failure, buckling failure, and tensile splitting shearing and sliding (Aydan et al. 1993). Essentially, 2 of these mechanisms are directly related to anisotropic rock masses.

When dealing with anisotropic rock masses, one of the main observed mechanisms is buckling failure, which consists of a flexural stress that induces tensile forces in the rock slabs. This anisotropy can be caused, for example, by foliation or sedimentary bedding planes. The critical stress required to induce buckling can be estimated by Euler's approach, which is presented in Figure 14 (after Hutchison & Diederichs 1996). According to this methodology, one of the key parameters that defines the buckling potential is the slenderness ratio (length-to-thickness ratio of the slabs).

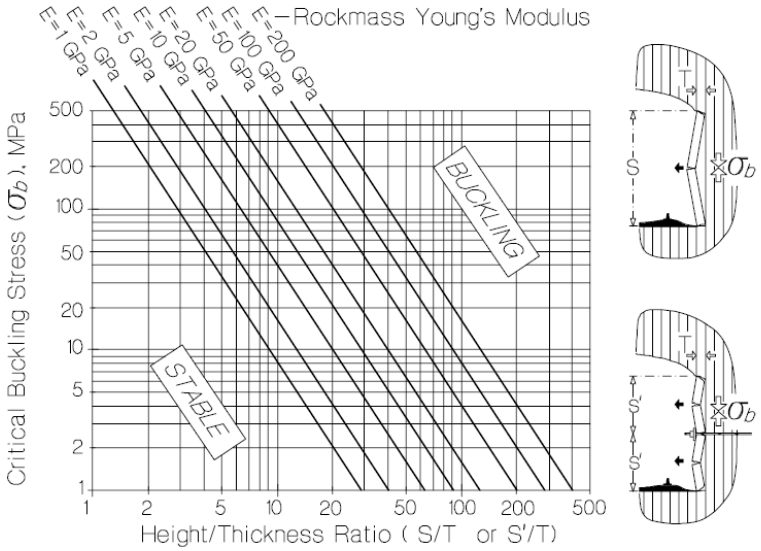



**Figure 14 Simplified representation of buckling in foliated rock (after Hutchison & Diederichs 1996)**

There are 2 main ways to reduce the slenderness ratio. The first is by reducing the height of the excavation, assuming a semi-vertical foliation or bedding plane. The second one is by modifying the geometry of the excavation. As presented in Figure 15, for a semi-vertical foliation plane, a concave sidewall generates a more

harmonic profile, since the exposed slab height can be reduced from approximately 6 m (tunnel height) to just a few tens of centimetres, depending on the degree of concavity applied.

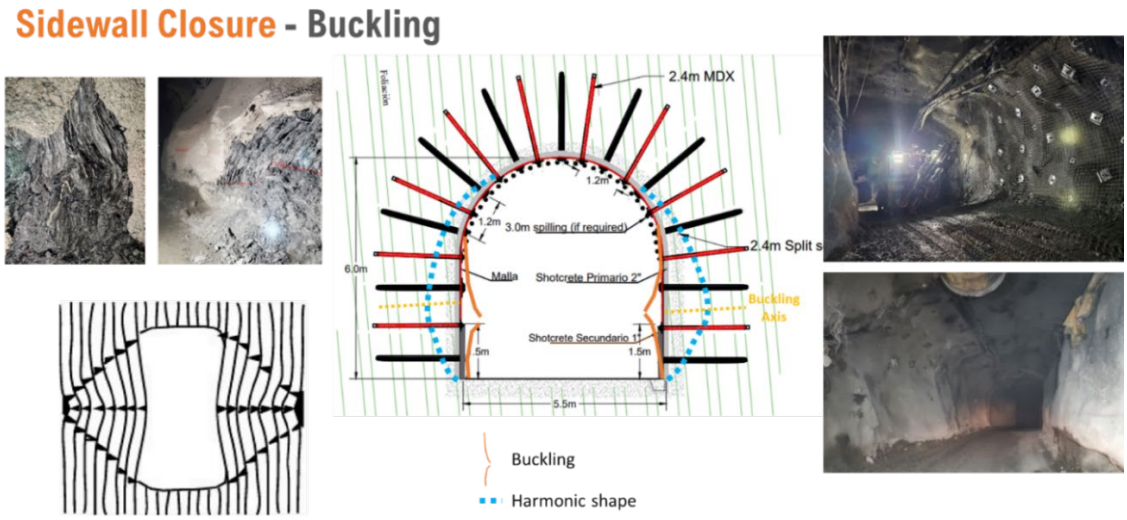



**Figure 15 Buckling failure mechanism and the effect of excavating the tunnel in a harmonic shape (concave sidewalls) compared to a vertical sidewall**

In addition to reducing the slenderness ratio of the slabs, an arched sidewall may also provide a more favourable geometry for the shotcrete, as vertical sidewalls favour flexural loading while curved profiles can promote compressive action within the liner (Potvin & Hadjigeorgiou 2024). When dealing with weak rocks, high stresses can induce a complete shearing mechanism. The main driver of this behaviour is the relationship between tangential stress and rock mass strength. Since rock mass strength is influenced by the sampling size, a reduction in tunnel dimensions tends to increase this parameter, as fewer structural features are intercepted. Similarly, the reduction of nearby excavations can potentially decrease tangential stress and result in less convergence of the drive.

# 5 Mine layout

Damage mapping, or alternatively monitoring data, can be used to evaluate alternative mine layouts. This is an important step, because adverse stress conditions surrounding the excavations can compromise all the previously established controls.

Given the rock mass properties, the anisotropy induced by the main geological structures, the in situ stress field, and the historical damage observed in the support system, different mine layout scenarios can be analysed to identify the most suitable option.

Figure 16 presents an example of a calibration workflow used to correlate observed damage levels with Map3D numerical modelling results and define a damage classification criterion based on the $\sigma_1$/UCS. First, a damage mapping classification was obtained in mine regions with varying pillar sizes. More detail on the damage mapping methodology will be provided in the following section (monitoring and risk management). The maximum principal stress ($\sigma_1$) was then obtained for these pillars using a Map3D numerical model. Those outputs were finally compared to establish a relationship between the observed damage level and the corresponding $\sigma_1$ to UCS ratio.

Subsequently, the calibrated criterion was applied to evaluate future excavation scenarios and define the most suitable crosscut layout (Figure 17). As shown in this figure, a crosscut spacing of 12 m was recommended over the 7 m spacing, as the latter could result in elevated damage levels.

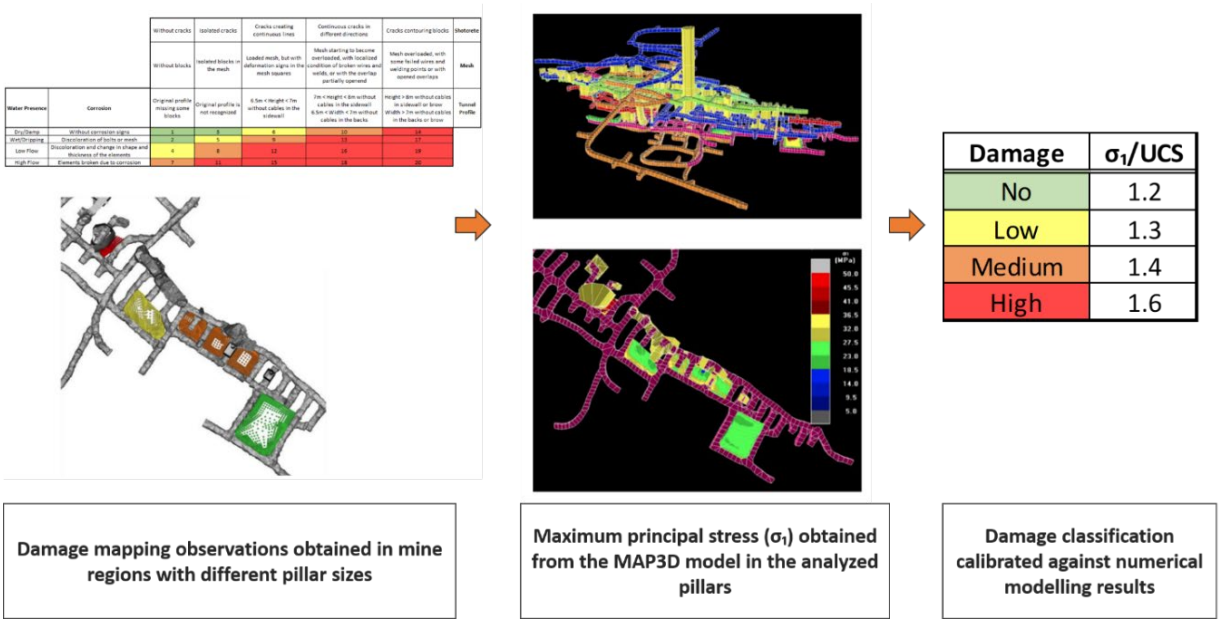
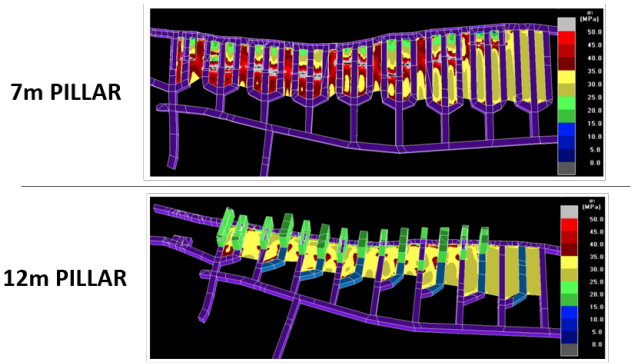



**Figure 16 Calibration workflow used to correlate observed damage levels using the damage mapping matrix presented in Table 2 with Map3D numerical modelling results to define a damage classification criterion based on the $\sigma_1$/UCS ratio**




| Pillar Size | s1/UCS | Exp. Damage |
|---|---|---|
| 7m | 1.8 | High |
| 12m | 1.5 | Medium |

**Figure 17 Evaluation of alternative mine layout scenarios with 7 and 12 m based on damage mapping calibration results**

# 6 Monitoring and risk management

After the implementation of a compatible support system and an optimised development profile, a monitoring strategy should be established to verify its effectiveness as well as to anticipate any major safety concerns in the mine tunnels. The monitoring applied in squeezing and weak ground can be categorised into displacement/convergence measurement, support performance assessment and visual damage mapping.

Displacement and convergence monitoring can be measured at the tunnel surface or within the subsurface. At the surface, scanning is one of the most widely used methods. Figure 18 presents an example of a tunnel experiencing between 30 and 40% of deformation in 14 months. In addition to that, subsurface monitoring can be conducted using extensometers, inclinometers and borehole cameras, which can estimate, for example, the extent of the yielded zone (Figures 9 and 10).

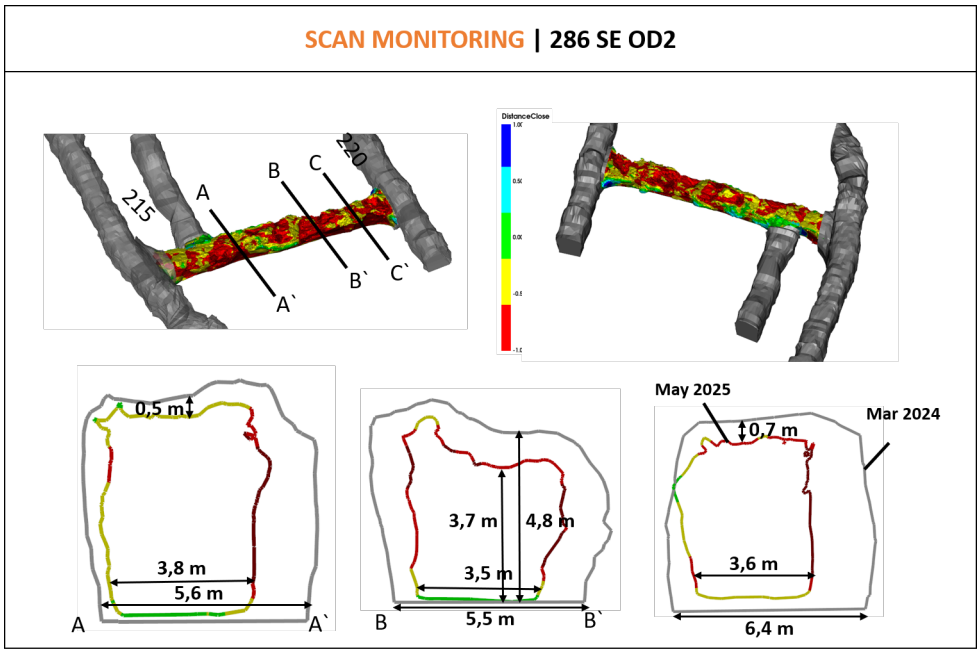



**Figure 18 Scan monitoring carried out in a waste drift parallel to the foliation showing deformations between 30 and 40%**

To validate and calibrate the design of the rock support, instrumented bolts or cable bolts can also be installed, providing data on the progressive load of these elements as the excavation advances. The results obtained are a valuable input to estimate the support demand for future support designs.

Although it requires minimal additional investment and is one of the simplest monitoring tools, damage mapping carried out through visual underground inspections remains one of the main tools for managing the geotechnical risk in squeezing ground. Since failure develops gradually in this environment – as opposed to a sudden failure in a rockburst event – the degree of damage in the support system can be classified, enabling prioritisation of actions.

Table 2 provides an example of a damage mapping matrix built by the authors of this paper specifically for squeezing ground at an underground mine with extreme squeezing conditions, which can be used as a preliminary approach to quantify the risk, and plan correction actions accordingly. This methodology considers the condition of the surface support, tunnel profile as well as the corrosion and water content, and has proven to be a practical and well-standardised means of evaluating the tunnel safety risk. Although these observations are relevant for assessing the tunnel risk, they are limited to conditions visible at the excavation surface and may not fully represent the condition of the rock mass or embedded support elements. An additional factor considered to prioritise the actions using this tool is the quantity of escape routes, because only one escape route in the analysed area could generate the risk of entrapment.

# 7 Performance

Figure 19 presents an example of an operation with extreme squeezing tunnels where significant improvement in drive conditions was obtained after implementation of design adjustments, ductile ground support and horseshoe shaped development profile. These measures eliminated the extensive rehabilitation previously required, which in some cases had resulted in drives remaining non-operational because of the significant reduction in their effective width. Overall, the results indicate that the implemented measures contributed to improved ground stability and maintained drive serviceability.

**Table 2 Damage mapping matrix developed specifically for squeezing ground used as a preliminary risk assessment tool to support rehabilitation prioritisation and decision-making**

| | | Without cracks | Isolated cracks | Cracks creating continuous lines | Continuous cracks in different directions | Cracks contouring blocks | Shotcrete |
|---|---|---|---|---|---|---|---|
| | | Without blocks | Isolated blocks in mesh | Loaded mesh, but with deformation signs in mesh squares | Mesh starting to become overloaded, with localised broken wires and welds, or with overlap partially opened | Mesh overloaded, with some failed wires and welding points or with opened overlaps | Mesh |
| **Water presence** | **Corrosion** | **Original profile missing some blocks** | **Original profile is not recognised** | **6.5 m < height < 7 m without cables in the sidewall** | **7 m < Height < 8 m without cables in the sidewall 6.5 m < Width < 7 m without cables in the backs** | **Height > 8 m without cables in sidewall or brow Width > 7 m without cables in the backs or brow** | **Tunnel profile** |
| Dry/damp | Without corrosion signs | 1 | 3 | 6 | 10 | 14 | |
| Wet/dripping | Discoloration of bolts or mesh | 2 | 5 | 9 | 13 | 17 | |
| Low flow | Discoloration and change in shape and thickness of the elements | 4 | 8 | 12 | 16 | 19 | |
| High flow | Elements broken due to corrosion | 7 | 11 | 15 | 18 | 20 | |

| | With 2 escape routes | With 1 escape route |
|---|---|---|
| Green: no actions | No action plan required | No action plan required |
| Yellow: low risk action | Action to be executed within the quarter | Area needs to be barricaded and action executed immediately |
| Orange: medium risk action | Action to be executed within 1 month | Area needs to be barricaded and action executed immediately |
| Red: high risk action | Action to be executed within 7 days | Area needs to be barricaded and action executed immediately |

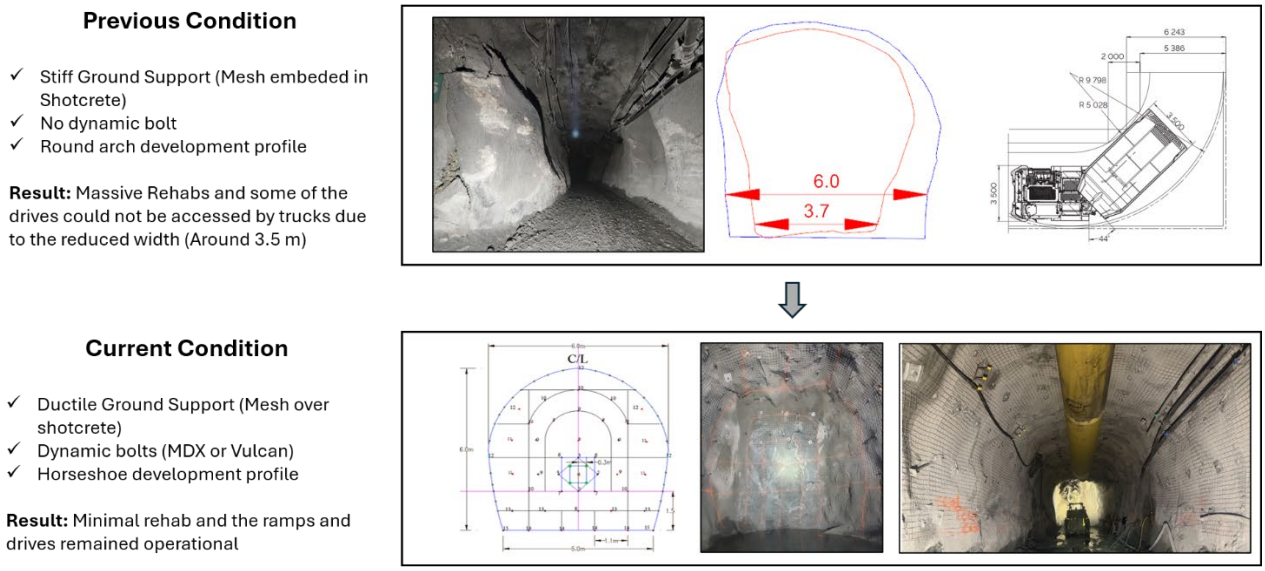



**Figure 19 Tunnel conditions before and after the implementation of the ductile ground support and horseshoe development profile**

# 8 Conclusion

Weak rock masses subjected to squeezing conditions represent one of the most significant geotechnical challenges in underground mining. Conventional approaches based primarily on increasing support capacity often prove insufficient, resulting in recurrent rehabilitation, elevated support costs, and reduced excavation serviceability.

This paper illustrates that squeezing ground can be effectively managed through an integrated approach that combines squeezing level estimation, ground support selection, development profile optimisation, monitoring and mine layout adjustments.

A practical damage mapping matrix developed specifically for squeezing ground was presented as a preliminary risk management tool to support rehabilitation prioritisation and decision-making. Surface and subsurface monitoring techniques, including scanning, extensometers, borehole cameras, and instrumented support elements, were also discussed as key tools for understanding ground behaviour and validating support performance.

The paper further highlights that geomechanical considerations should extend beyond support design. Development profile optimisation can reduce buckling potential in anisotropic rock masses, while mine layout optimisation can reduce damage potential by minimising stress concentrations and adverse excavation interactions.

The successful management of squeezing ground requires an integrated strategy that addresses the root causes of deformation rather than relying solely on stronger support systems. Such an approach can improve safety, reduce rehabilitation requirements, increase excavation service life, and contribute to a more sustainable and productive mining operation.

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