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# An overview of numerical modelling in forecasting infrastructure stability and ground support behaviour applied to cave mining

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## Abstract

*As deeper orebodies are targeted for exploitation using caving methods, the mining footprints are set at greater depths. Extraction levels set at depths greater than 1,000 m are becoming a norm in existing operations and future projects. These depths require better understanding of rock mass conditions as well as the complex caving-induced stresses impacting the developments through the life of mine (LoM) but, in reality, caving mine footprints are designed and constructed when there is limited orebody knowledge. Numerical models provide the means to combine recent developments in the generation of geotechnical block models that provide an understanding of rock mass strength heterogeneity across the footprint with the predicted cave-induced stresses as a function of draw strategy to forecast infrastructure stability and ground support performance during the LoM. The level of numerical assessment for excavation stability and forecasting support behaviour depends on the stage of study, the information available at that stage and how vital the underground infrastructure is for the operation. This paper describes the natural progression of numerical modelling workflow from concept study to pre-feasibility, feasibility study and, lastly, the construction stage. The outputs that can be expected from the numerical models at each of those stages pertinent to ground support design are discussed, with consideration given to the rock mass behaviour hosting the infrastructure.*

**Keywords:** *cave mining, numerical modelling, infrastructure stability, ground support*

## 1 Introduction

Cave mine footprints are designed and constructed when there is limited orebody knowledge. This limited understanding of rock mass behaviour presents a challenge given that infrastructure will be constructed within a rock mass that can be highly heterogeneous, as in the case of porphyry-type deposits where tunnels within a cave footprint can be excavated under weak and strong rock varying within a short distance. Also, as mines get deeper, e.g. depths greater than 1,000 m, there is an increasing demand to not only understand the behaviour of jointed rock masses prone to squeezing but also rock masses that are more massive, sparsely jointed and often heavily veined, in which the rock mass is expected to spall and bulk. This means that the deformation of tunnels is highly localised as well as the solicitation of the ground support. Another consequence of mining at depth is the high level of in situ stresses that are encountered. This has consequences in terms of the expected ground deformations and the higher potential for rockbursting and fault-slip seismicity. The typical cave establishment process presents a challenge in understanding the magnitude and orientation of induced stress as well as the stress path these excavations are exposed to during the life of mine (LoM).

Recent developments in the generation of mine-wide point load test Is50 and rock mass strength block models through systematic point load testing of cores from select boreholes, the application of machine learning to provide continuous estimates of Is50 along all boreholes with available geological and

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geotechnical data, and the application of synthetic rock mass (SRM) testing to estimate tunnel-scale or cave-scale rock mass strength from the local statistical distribution of core-scale strengths (Is50), have enabled mines to have a relatively good picture of the spatial variability of intact and rock mass strength across the footprint at early stages of mine planning (Pierce et al. 2022a).

These advances, in combination with the ability of numerical models to forecast complex mining and excavation-induced stresses surrounding developments, allow forecasting of the likely excavation response and ground support behaviour when subjected to loading/unloading scenarios. The reliability of these models can improve from one stage of mine planning to another as more information becomes available and the opportunity for back-analysis is presented by placing early developments underground.

# 2 Infrastructure and ground support: key design questions

A good understanding of rock mass conditions and stresses is critical for infrastructure and ground support design, as discussed in this section.

## 2.1 Rock mass conditions

The rock mass characteristics relevant to mine design are:

- Rock mass jointing and behaviour – how jointed the rock mass is, and if behaviour is dominated by shearing (near excavations) or brittle spalling. From the numerical modelling standpoint this will be a deciding factor for the type of analysis required, and is discussed further in Section 4.3.
- Rock mass strength and spatial variability of strength – as mentioned in Section 1, the recent developments in the generation of rock mass strength block models provide a means to inform numerical models with the heterogeneity of rock mass strength across the footprint for stability assessment rather than assuming a homogenised strength across each geotechnical domain. Figure 1 shows an example of a spatial variability of Is50 across the footprint of a block cave with three macroblocks that were represented in a numerical model for footprint stability assessment.
- Scale-dependency of rock mass strength – rock strength decays as size increases. The rate at which the strength decays with size is a function of inherent veining and structure in the rock mass. Fuenzalida et al. (2022) shows that cave-scale, crusher-scale and tunnel- or pillar-scale strength is different for the Cadia East mine. The scale at which the rock mass strength is estimated should be consistent with the type of infrastructure considered for stability assessment.

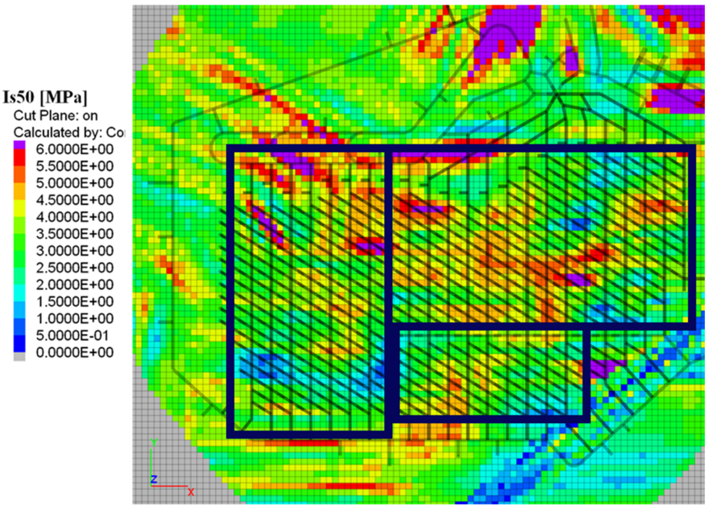



**Figure 1 A spatial variability of Is50 (typically a conversion factor of 20 to 25 is used for Is50 to intact unconfined compressive strength) across the footprint of a block cave. Black boxes show different macroblocks**

## 2.2 Excavation and mining-induced stresses

Cave mining is unique in the sense that tunnels (in particular, those in the footprint) are exposed to a loading cycle whereby there is an initial increase in induced stresses beyond the far-field stresses followed by a relaxation stage as the cave passes over the tunnel. The stresses surrounding the tunnel can increase again locally, depending on draw conditions. This loading/unloading cycle is accompanied by the rotation of principal stresses surrounding the tunnel. The loading stages can be summarised as follows:

1. Pre-mining stress
2. Abutment loading
3. Relaxation due to cave passing over
4. Cave loading.

The stress path and associated damage at the end of each loading stage surrounding a tunnel at the extraction level of a cave mine is shown in Figure 2. It is interesting to note that the unloading stage due to the cave passing over can be associated with increasing damage in the tunnel walls. This is due to the accelerated reduction in minor principal stress compared to the major principal stress in the tunnel periphery during unloading, which results in a localised stress path intersecting with the rock mass peak strength envelope (therefore, fracturing the rock). In general, considering the rock mass condition in terms of the damage it has incurred at previous stages of loading cycles is relevant when assessing the stability and ground support requirements. The above discussion highlights the two minimum requirements of numerical tools when used for infrastructure stability assessment within the context of cave mining: (1) the ability to capture the correct loading path for the caving footprint; and (2) the ability to account for rock mass strength degradation as a function of loading and deformation. This is typically accounted for using strain-softening numerical models in continuum analysis or SRM models in discontinuum assessment.

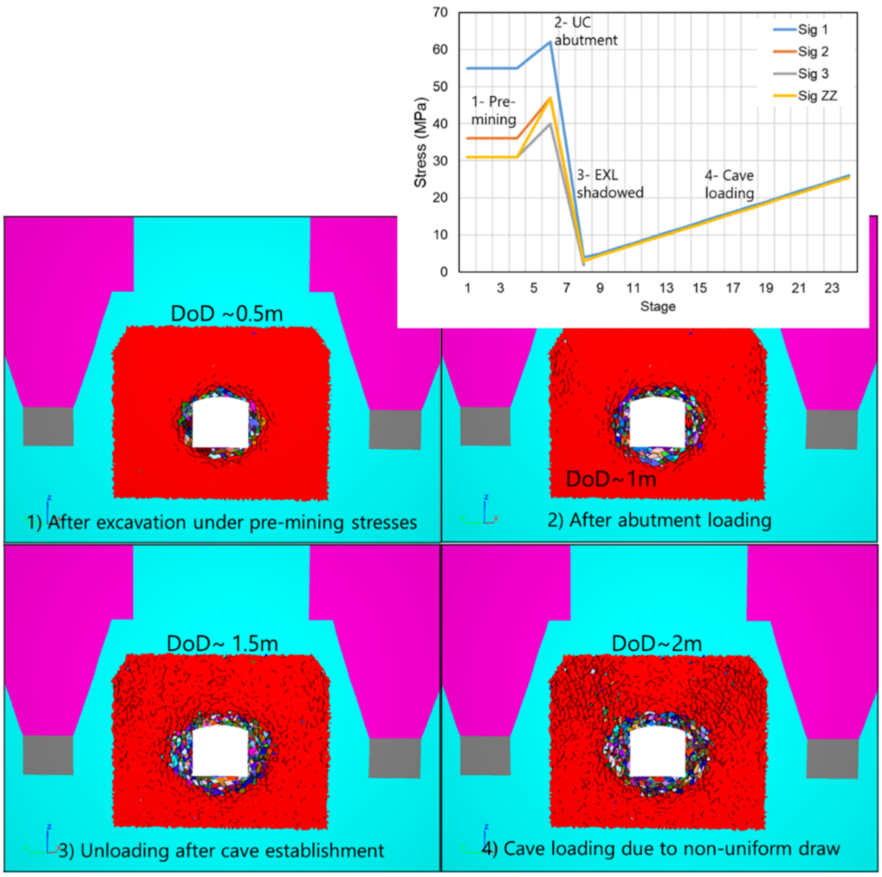



**Figure 2 The stress path and associated damage at the end of each loading stage surrounding a tunnel at the extraction level of a cave mine (DoD is depth of damage)**

# 3 Numerical modelling workflow

The level of numerical assessment for excavation stability and forecasting support performance depends on the stage of study and how vital the underground infrastructure is for the operation. Typically the process starts with simpler models and evolves towards more complex (and more demanding, in terms of computational overhead and numerical run time) representations of the excavation, rock mass and ground support.

The typical level of numerical model complexity needed to assess infrastructure stability at different stages of a cave mining project is shown in Figure 3. Implicit or explicit infrastructure stability assessment refers to:

- Implicit assessment – the excavations are not represented in the model. Zone-based parameters such as cave-induced stresses, damage parameters, etc. are painted on the wireframe of the planned developments.
- Explicit assessment – the infrastructure is explicitly represented and excavated in the model. Therefore a combined effect of excavation-induced and caving-induced stresses can be captured in the vicinity of the openings.

At the concept study stage, typically elastic numerical modelling is sufficient for estimation of cave back stresses and the cave propagation factor (Pierce et al. 2022b) to assess caveability. The same model can be used to outline the level of stresses that are anticipated on the footprint during the LoM.

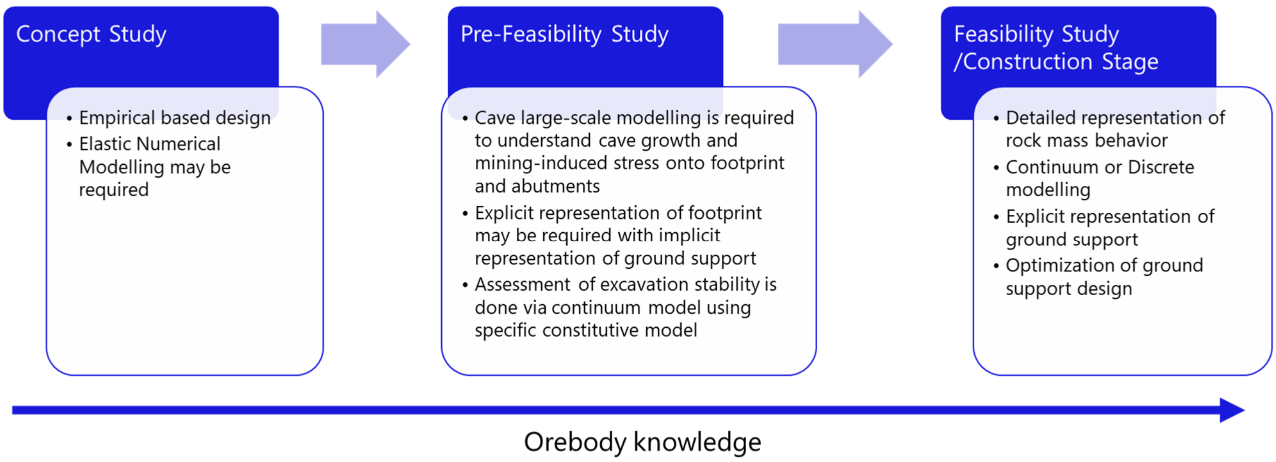



**Figure 3 Numerical modelling workflow for excavation stability and ground support design assessment**

At the pre-feasibility study (PFS) stage a thorough analysis of caving is required. This typically involves a coupled stress-cave flow analysis such as the FLAC3D-MassFlow modelling methodology described in Fuenzalida et al. (2018). In this approach the caving process is simulated by explicitly modelling each isolated movement zone (IMZ) derived from MassFlow (ITASCA 2023a) in FLAC3D (ITASCA 2023b) to determine the yielded zone, cave back and airgap associated with mass drawn. After one cycle of extraction MassFlow reports the location of the movement zones and the presence of air (if any) to the continuum FLAC3D model (Figure 4). FLAC3D solves stresses associated with the presence of these zones and estimates the yielded zone surrounding the cave. FLAC3D then informs MassFlow which zones (initially inactive) could now be mobilised. The procedure is repeated until the draw schedule used as an input in MassFlow is completed. One of the advantages of the coupled approach is its inherent ability to simulate drawbells connecting the undercut and extraction levels. This allows the study of the effect of the abutment and cave stresses on the extraction level by modelling draw zones as individual entities (IMZ) that can interact and overlap within each other in the near field. Figure 5 shows an example of point loading the extraction level ahead of the cave due to isolated draw condition captured using the coupled caving approach.

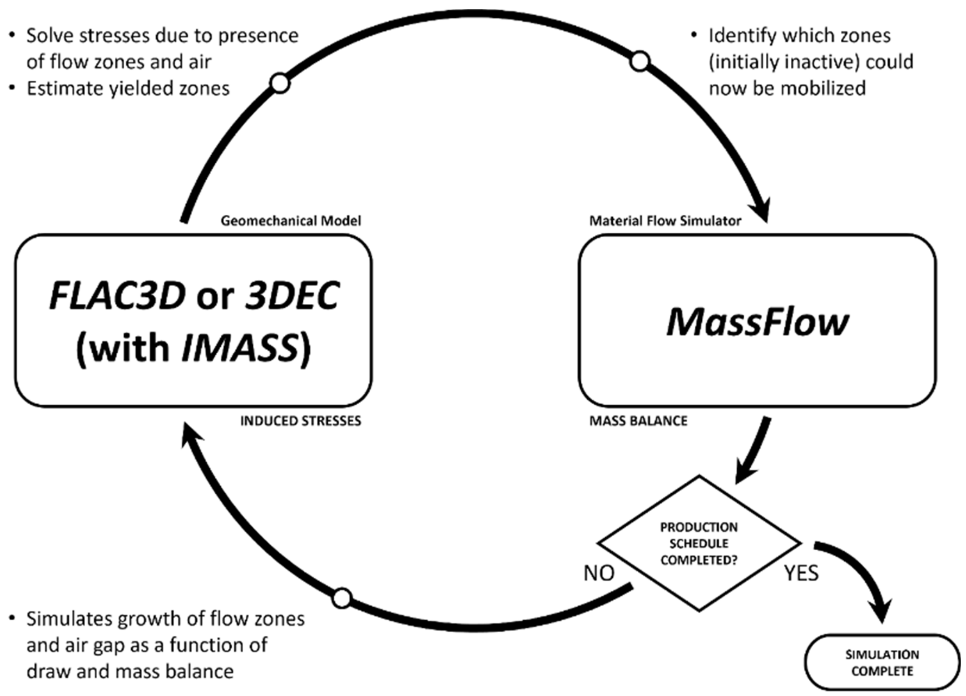
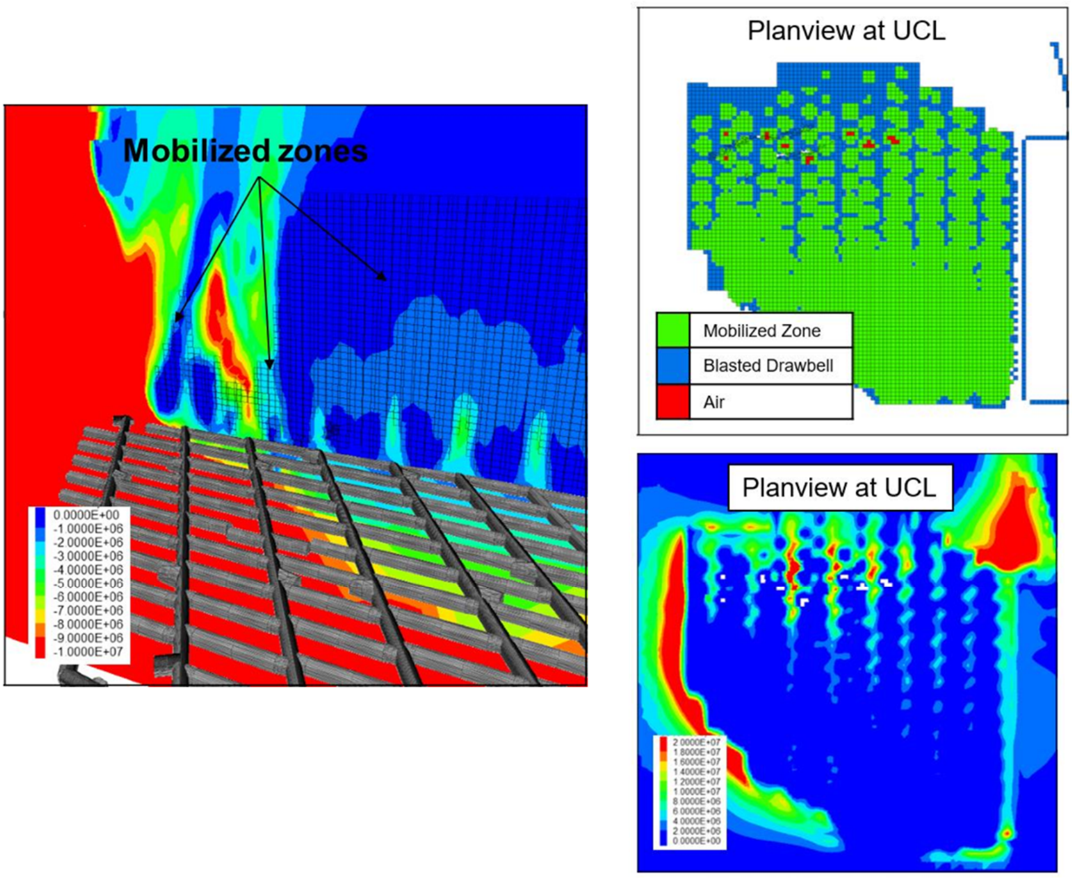



**Figure 4 Conceptual scheme of the coupled FLAC3D-MassFlow approach**




(a) (b)

**Figure 5 (a) Induced vertical stresses (Pa) on the footprint; (b) Deviatoric stresses (Pa) indicating isolated draw conditions (Fuenzalida et al. 2018)**

The coupled caving models can be used to paint stresses, damage parameters and/or other calculated parameters such as forecasted closure strain on the wireframe of developments in the abutments of a growing cave to assess the stability of the underground infrastructure network during the LoM (implicit assessment). The implicit assessment will be discussed in more detail in Section 4.1.

The next level of complexity is to represent the drifts explicitly in the footprint at a sector or panel scale following the planned development schedule (see Section 4.2). The first pass implicit assessment provides a good idea of critical sections of the footprint prone to a higher level of squeezing or damage in order to narrow the explicit simulations. These models that are typically constructed at the PFS or feasibility study (FS) stages allow for direct assessment of the depth of damage using evolving parameters in strain-softening constitutive models, such as loss of cohesion or tensile strength. The damage parameter (sloss) in IMASS is another indicator that can be used to delineate damage in continuum models. A description of the IMASS constitutive model can be found in Ghazvinian et al. (2020a). In IMASS, damage, disturbance and the associated loss of strength (i.e. softening and weakening) is captured in two phases. During phase 1, damage is the result of the fracturing of intact rock due to stress changes. This causes a small (negligible) increase in porosity and permeability as most of the damage is associated with the accumulation of plastic shear strain. Once the rock mass reaches the critical plastic shear strain, phase 1 ends and its strength is equal to the post-peak strength. During phase 2, additional straining and disturbance are the result of the rearrangement of rock blocks causing a significant increase in porosity and permeability. The loss of strength is dependent on the accumulation of bulking. Once the rock mass reaches the maximum bulking limit, phase 2 ends and the rock mass reaches the ultimate residual strength. The sloss damage parameter ranges between 1 at peak strength to –1 at its ultimate residual strength. At zero (post-peak strength) it indicates cohesion in the rock mass is lost and the friction angle is at its highest (mobilised friction angle) at near zero confinement. This provides a good indicator for the assessment of damage around developments (when explicitly excavated in the models).

Due to the size of panel-scale explicit models the ground support is typically not explicitly represented in those models. For a detailed assessment of excavation performance and ground support behaviour, local explicit models are simulated during the FS or construction stages. These models are usually constructed at scales representing a crusher chamber or an intersection on the extraction level, etc. whereby the ground support data can be included in detail. The local explicit models are discussed in Section 4.3.

# 4 Excavation stability and ground support design assessment

## 4.1 Implicit assessment

In implicit assessment the performance of underground infrastructure from the nearby zones is analysed by painting relevant stress, damage and calculated strain quantities on their wireframes. Below is a list of the parameters that are typically used:

- Principal stresses and deviatoric stress – incremental and maximum cave-induced stresses that will be experienced by the infrastructure can be evaluated.
- Stress to strength ratio – this parameter can be calculated in different ways depending on what is assumed for stress (major principal stress, tangential stress, etc.) and strength (intact strength, rock mass strength or global rock mass strength). The stress level index (SLI) is a form of stress to strength ratio used for brittle ground. SLI is calculated as $(3\sigma_1 - \sigma_3)/\sigma_{ci}$ , where $\sigma_1$ and $\sigma_3$ are in-plane major and minor principal stresses perpendicular to the tunnel axis and $\sigma_{ci}$ is intact unconfined compressive strength (Kaiser 2019). SLI can be used as an indicator for the potential depth of strainbursting for dynamic ground support design (Lowther et al. 2022). It can also be used to calculate closure strain.

- Cave-induced closure strain – closure strain for rock masses with behaviour primarily dominated by shearing (squeezing grounds) can be calculated using the convergence relationship for unsupported tunnels suggested by Hoek & Marinos (2000), $\varepsilon = 0.2(\sigma_{cm}/p_0)^{-2}$ where $\sigma_{cm}$ is global rock mass strength and $p_0$ is in situ stress (can be approximated as the major principal stress). Closure strain for brittle rock masses can be estimated from the extreme depth of damage ($\frac{d_f^e}{a} = 1.25\,SLI - 0.51$, where a is tunnel radius) or mean depth of failure ($d_f^m = d_f^e/4.0$) suggested by Kaiser (2019) using excavation span and an assumption for rock mass bulking surrounding the excavation. The closure strain can be categorised into support classes as shown in Table 1, based on the benchmarking study by Board et al. (2006) which collated experience with production level closure from 10 different caving operations worldwide to provide a forecast on performance and the potential risk of damage and squeezing of the caving footprint. An example of maximum SLI and the associated support class experienced by the undercut level of a cave mine through the LoM is shown in Figure 6.
- Sloss-based damage categories – image categories can be defined based on sloss parameter thresholds in IMASS from the cave-scale models to provide an operational forecast of how long the infrastructure surrounding a cave will remain serviceable and when rehabilitation work will be needed to keep the infrastructure serviceable. This approach is discussed in Ghazvinian et al. (2020b).

**Table 1 Empirical relationship between strength-to-stress ratio, closure strains and support class in cave mines (Board et al. 2006), typically global rock mass strength is used for strength-to-stress ratio**

| Support class | Strength/stress ratio | Closure strain | Issues/behaviour | Typical support: extraction level |
|---|---|---|---|---|
| I | >30% | <2% | Few major stability issues<br>Minor shotcrete cracking | Bolt and mesh: 2 m long, 1–1.25 m spacing<br>Mesh on backs, walls<br>Shotcrete: 75–100 mm |
| II | 15–30% | 2–5% | Minor squeezing<br>Shotcrete cracking; serviceable with repair | Bolt and mesh: 2–3 m long, 1 m spacing<br>Mesh on backs, walls<br>Shotcrete: 100 mm |
| III | <15% | >5% | Moderate to severe squeezing | Bolt and mesh: 2–3 m+ long, 0.8–1 m spacing<br>Mesh on backs and walls<br>Cable bolting intersections<br>Shotcrete: 100–150 mm fibre-reinforced shotcrete<br>Flexible support elements<br>Layered shotcrete, wire mesh |

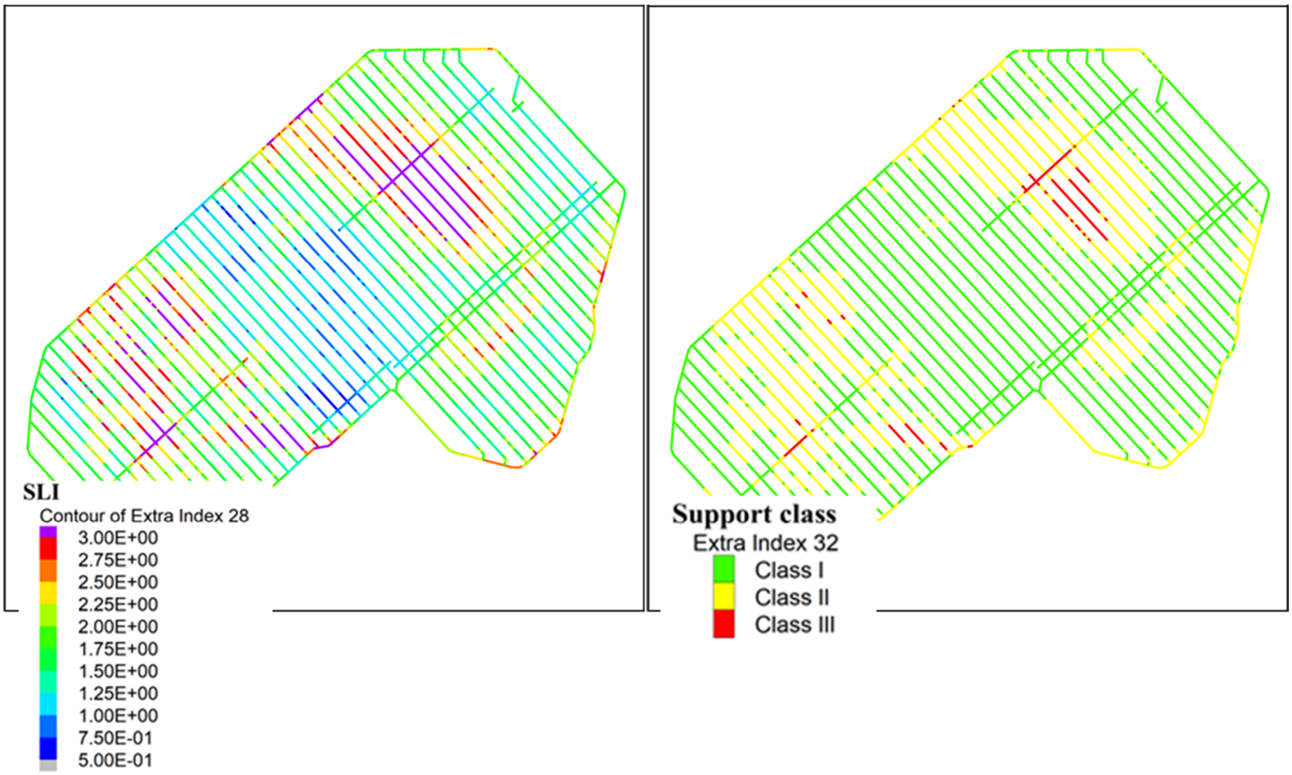



**Figure 6 The stress level index and associated support class experienced by the undercut level of a cave mine through the life of mine**

## 4.2 Explicit assessment

Explicit representation of developments at panel or sector scale are occasionally performed at the PFS level but more frequently at the FS stage of caving projects. It can offer a few benefits over implicit assessment at the cost of being more computationally intensive. Below is a summary of some advantages that explicit models can offer:

- The impact of excavation size and geometry on forecasted damage is captured.
- The combined effect of excavation-induced and caving-induced damage is captured.
- The effect of undercutting methodology can be assessed.
- The effect of extraction ratio is inherently included.
- For rock masses with different cave-scale and tunnel-scale (or crusher-scale) strengths, strength at the proper scale can be initialised in the model surrounding the developments independent of cave growth.

The zone size in the explicit models needs to be refined sufficiently to properly capture the development of damage or deformation in the excavation walls. Excavation of developments and blasting of undercut rings and bells follow the development sequence while cave shapes (from the coupled caving analysis) are imposed on the model at given increments (monthly, quarterly, bi-annual, etc.). Ground support can be represented implicitly by adding support pressure to excavation surfaces. Figure 7 shows an example of a cave extraction level at two stages during the LoM, with the deviatoric stresses impacting drifts in the abutments and below the cave.

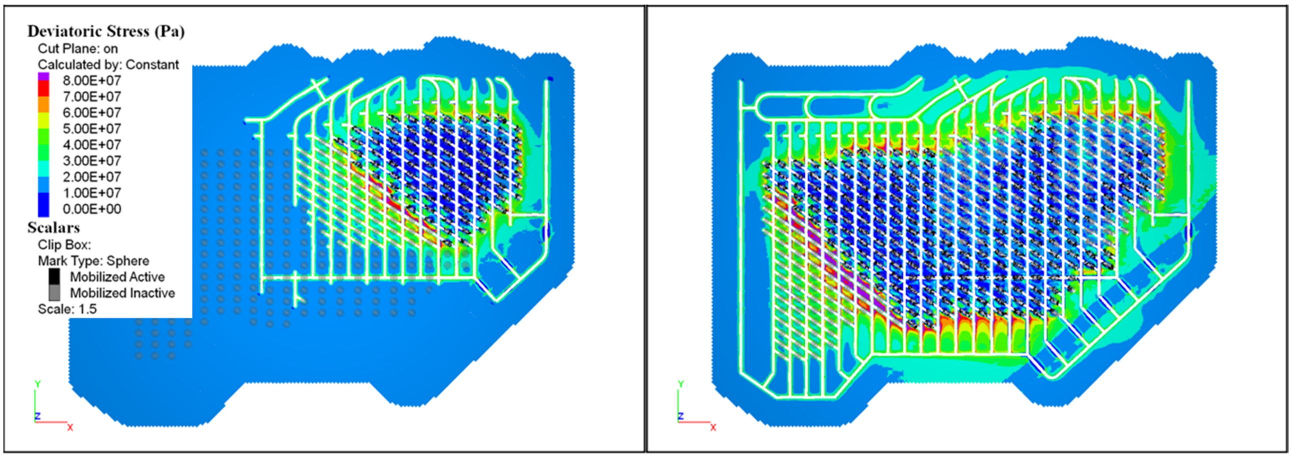



**Figure 7 Contour of deviatoric stress on the extraction level at different stages of cave development**

It is difficult to capture the correct depth of damage and convergence surrounding the developments in one model without a properly calibrated dilation model. Therefore, typically, one of those parameters is extracted from the explicit models. Figure 8 shows contours of sloss painted across the extraction level of the cave at the end of LoM. This can be used to delineate the anticipated depth of damage surrounding drifts and plan for appropriate support design according to different levels of damage anticipated for different macroblocks. Spatial variation of rock mass strength across the footprint was captured in this model, informed by the Is50 block model shown in Figure 1.

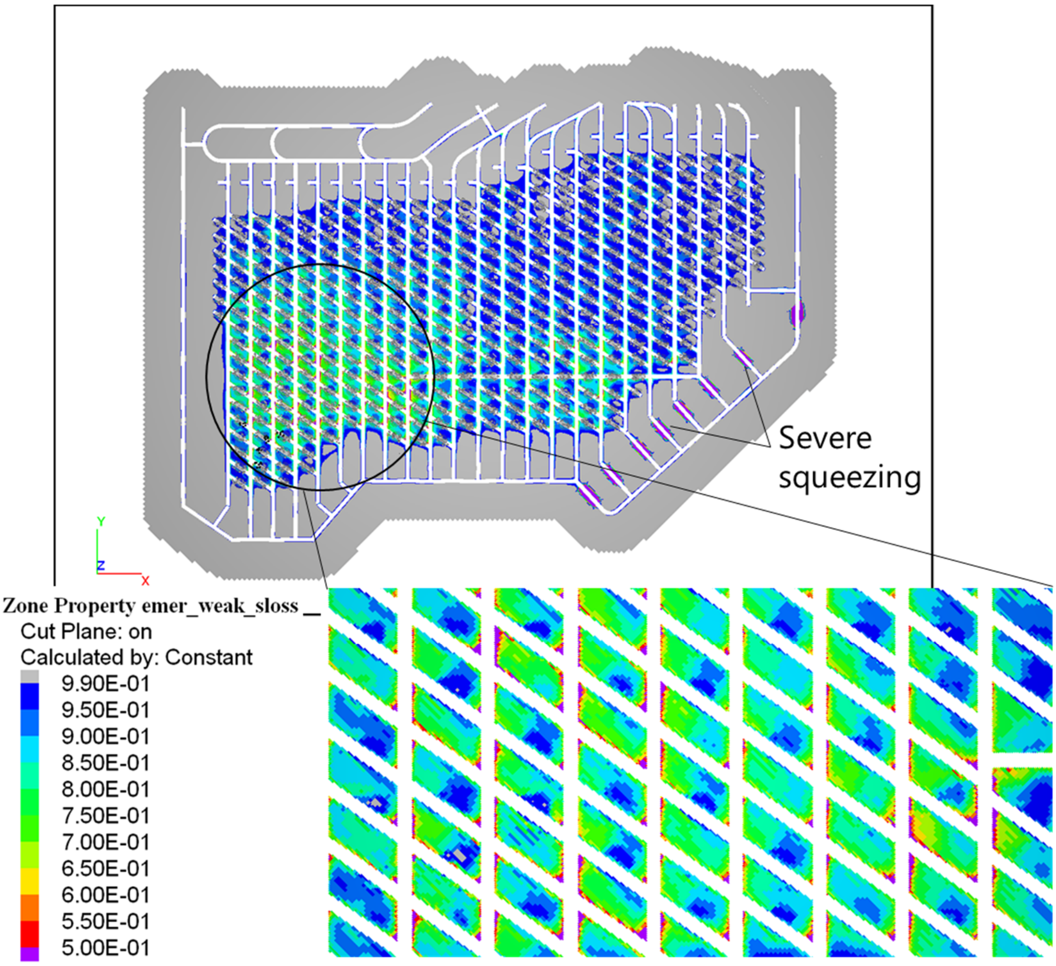



**Figure 8 Contours of sloss and damage experienced by the pillars on the extraction level of a cave mine at the end of life of mine**

## 4.3 Local explicit models

Local explicit models are constructed for infrastructure that is vital to operations, such as crushers or critical excavations where damage and convergence are anticipated. These models are typically focused on a small area of the footprint with the goal of representing the rock mass behaviour as accurately as possible, and often include detailed representations of ground support to forecast the excavation performance, identify the yielding mechanisms involved in defining the ultimate mining-induced load capacity of the infrastructure, and to assess and optimise ground support design.

The rock mass behaviour must be considered when deciding on the type of local explicit model, whether continuum or discontinuum. Another important consideration is the purpose of the analysis. Is it estimating the damage surrounding an excavation? Is it assessing the ground support design?

For rock masses where the anticipated near-field rock mass yielding mechanism will be governed by plastic shearing without significant dilatancy, using continuum models is appropriate. In the absence of structures (e.g. jointing, small faults etc.) that may localise shearing on ground support, those models could also be used for assessment of ground support design. Figure 9 shows an example of a continuum assessment of a ground support design comprising a sprayed concrete liner with liner stress controllers and cable bolts for extraction level intersections in very weak ground.

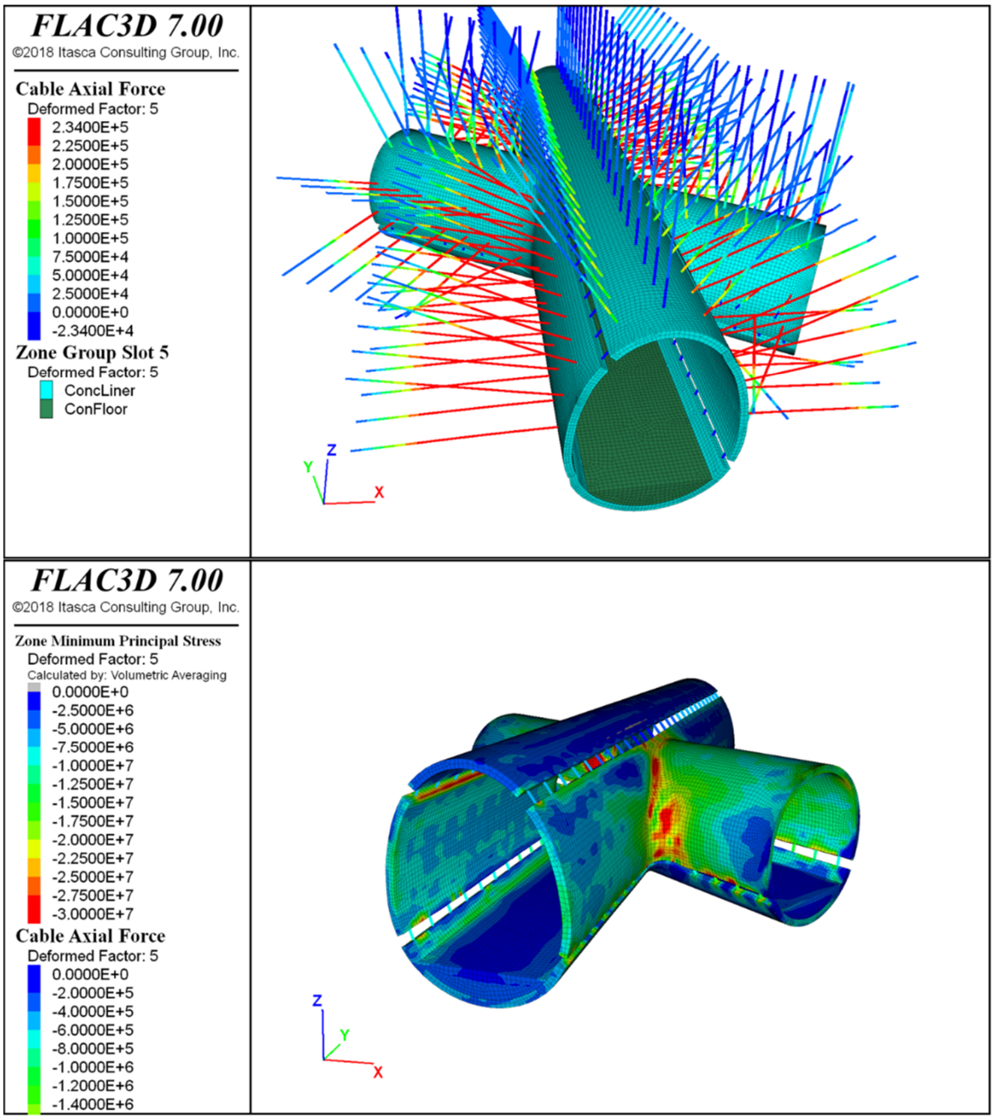



**Figure 9 Continuum assessment of a ground support design for extraction level intersections in very weak ground. Top: cable axial forces (N); Bottom: concrete liner stresses (Pa)**

Continuum models are also adequate for assessment of the depth of stress-induced damage in the walls of excavations in brittle ground, as shown in Figure 10. However, if the true mechanical representation of rock mass yielding mechanisms surrounding an excavation in massive and heavily veined rock masses (such as porphyry-type deposits) is needed (see example in Figure 2) – for instance, for assessment of ground support design or forecasting bulking in the walls – the continuum models will fall short. In these scenarios discontinuum representation of the rock mass is required.

The behaviour of brittle rock masses close to and far from an excavation differ significantly as the failure mechanism changes from predominantly tensile fracturing (spalling) to confined shear. Bonded block models (BBM) are a subset of SRMs that can provide the means to accurately capture this behaviour (Garza-Cruz et al. 2014). A major benefit of the BBM approach is the emergent sensitivity of the dilation angle to confinement, so a reliable measure of convergence and depth of damage can be attained. The solicitation of the ground support in brittle ground is highly localised due to shearing and the opening of existing joints and new fractures (i.e. spalling and bulking). Most of the deformation happens in the fractures, and BBM is well suited for this because it can capture unidirectional bulking. Figure 11 shows an example of BBM analysis in *3DEC* (ITASCA 2023c) for support design assessment. The stress fracturing, slip on horizontal joints and relaxation in the immediate back of the stope, and the associated ground support response that is captured using this discontinuum approach, can be observed in this example.

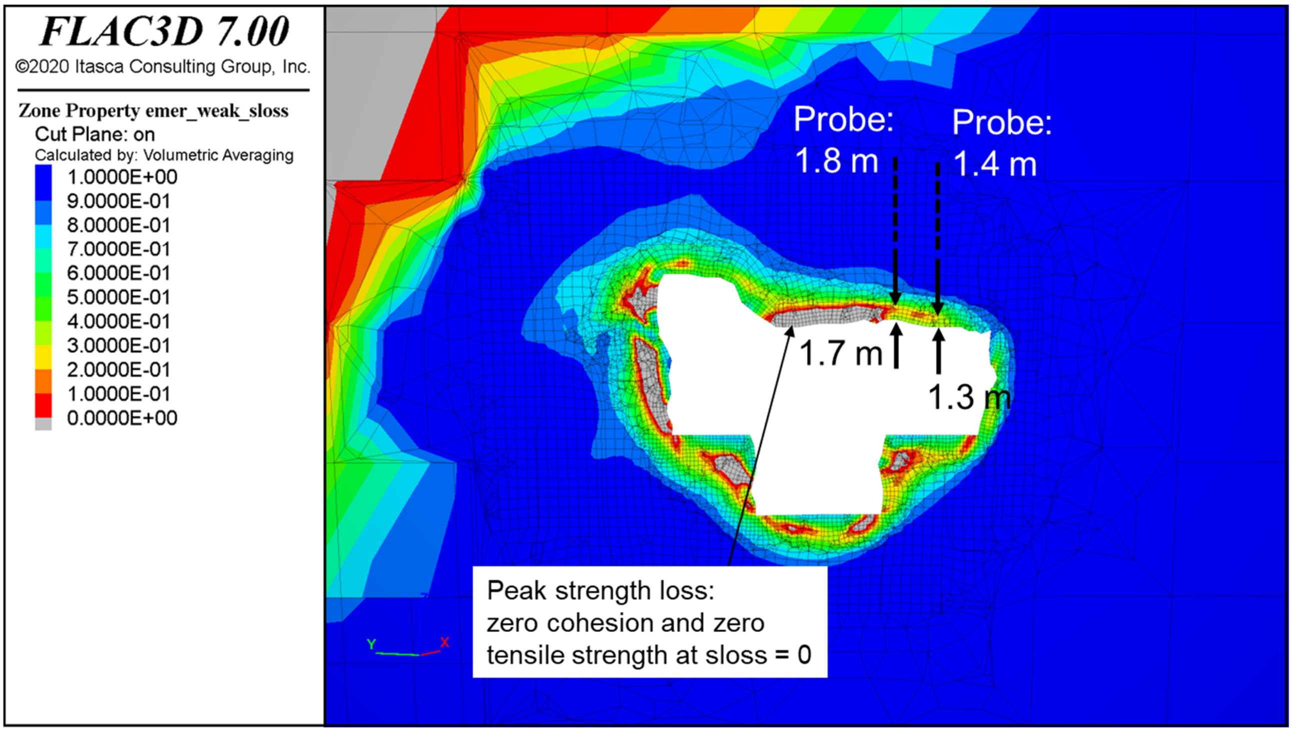



**Figure 10 Back-analysis of damage observed in the back of a crusher chamber using the continuum model**

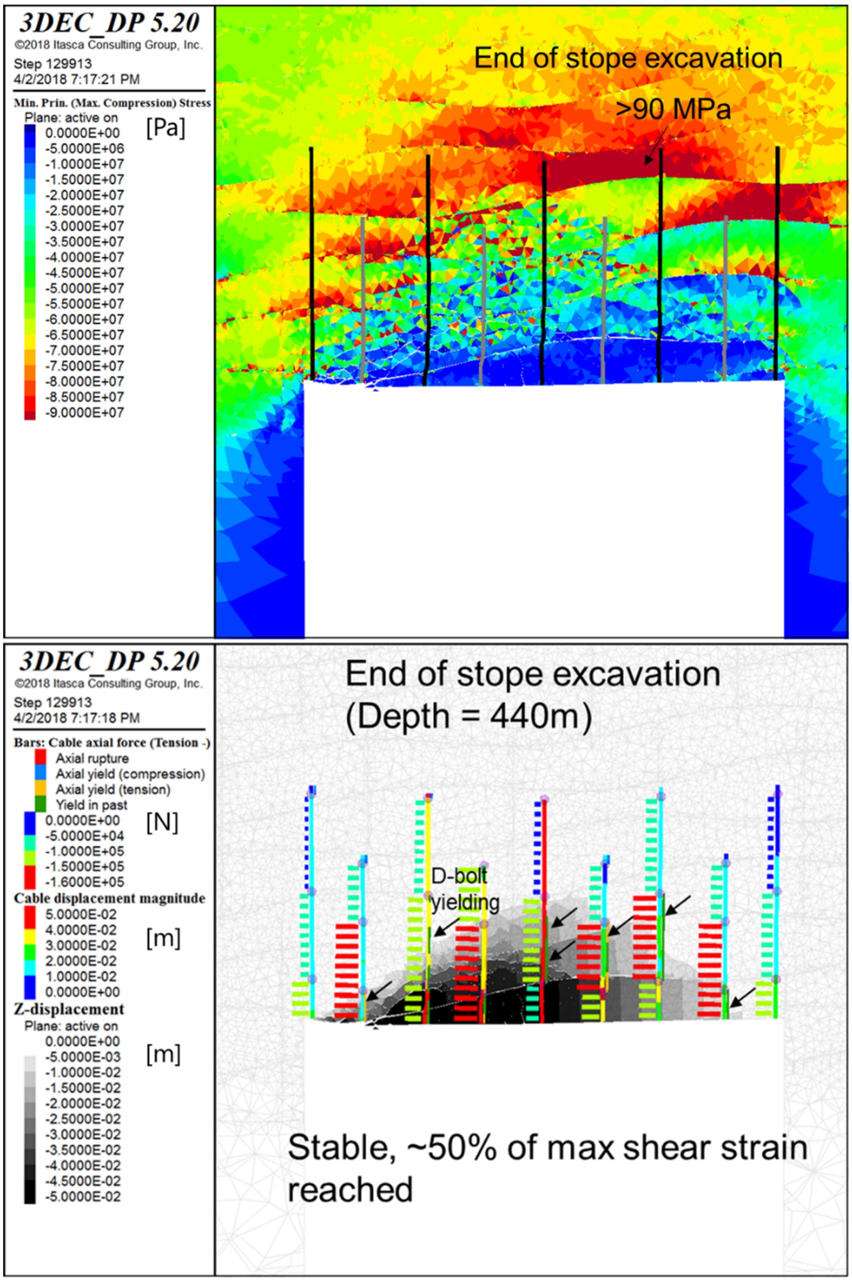



**Figure 11** **Top: stress fracturing, slip on horizontal joints and relaxation in the immediate back of the stope; Bottom: the associated support response (after Garza-Cruz et al. 2019)**

# 5 Summary

An overview of the numerical modelling workflow for assessment of infrastructure stability and ground support design for cave mines was provided in this paper. Discussion concluded that the level of numerical assessment for excavation stability and forecasting ground support performance depends on the stage of study and how vital the underground infrastructure is for the operation. Typical continuum models are the most effective tool for understanding the stress distribution on a mine-scale and sector-scale, and for verifying the reliability of the large-scale design. When detailed excavation stability knowledge and the assessment of ground support performance are the main goals of analysis, the choice of continuum/discontinuum modelling will depend on the rock mass behaviour. Commonly, continuum models are adequate for squeezing rock masses with no dilatancy, and discontinuum models are required to capture the mechanisms involved in the yielding of massive and heavily veined rock masses.

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