Caving 2018 – Y Potvin and J Jakubec (eds)

doi:10.36487/ACG_rep/1815_20_Pierce

REBOP–FLAC3D hybrid approach to cave modelling

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Abstract

The hybrid REBOP–FLAC3D approach allows prediction of the limits of the geomechanical zones defining the cave as a function of production. The results of the model can be used to derive estimates of: (i) caveability and caving rate, (ii) abutment stresses and cave loads, (iii) recovery and dilution entry, (iv) fragmentation, and (v) breakthrough timing and subsidence.

The approach simulates the caving process by explicitly modelling each isolated movement zone derived from REBOP into FLAC3D to determine the yielded zone and cave back associated with mass drawn. After one cycle of extraction, REBOP informs the location of the movement zones and the presence of air, if it exists, to the continuum FLAC3D model. FLAC3D solves stresses associated with the presence of these zones and estimates the yielded zone surrounding the cave. FLAC3D informs REBOP which zones (initially inactive) could now be mobilised. The procedure is repeated until the draw schedule used as an input in REBOP is finished.

Two of the main advantages of the hybrid approach include the capability of studying the potential impacts of isolated draw on cave growth and point loading on the extraction level, as well as the effect of including, explicitly, the airgap and mechanisms of fines migration and rilling on cave growth and subsidence. Two case studies are presented showing the capabilities of the hybrid approach.

Keywords: *cave modelling, cave growth, subsidence, draw control, sinkhole, squeezing*

1 Introduction

Cave mining is the predominant mass underground mining method because of its high productivity rates and low mining costs per tonne with low environmental impact in terms of footprint. At the same time, cave mining is a complex process involving many variables that interact simultaneously with each other.

A key decision in the design of a cave mine is the undercut sequence and draw strategy based on the given in situ stress and rock mass strength. The undercut sequence and draw strategy affects cave propagation and fragmentation. The fragmentation and draw impacts flow zone geometry and hang-up frequency. The flow zone geometry affects recovery, infrastructure stability and, ultimately, drawpoint availability. Because of this complex cycle, there is a growing need to identify the risks associated with each of the variables involved in the caving process. A tool to assess these risks is numerical modelling. Ideally, the caving process would be modelled using a discontinuum (e.g. 3DEC or PFC3D) approach in which pre-existing fractures are explicitly represented in the model because of large deformations, shear along pre-existing joints, fracturing of intact rock blocks and fragmentation of the rock mass. However, the computational size and time requirements to solve mine-scale problems currently make it impossible to solve a problem completely with the discontinuum approach. Therefore, a continuum-based approach is usually used to model the caving process.

The following work describes a new approach to cave modelling using REBOP (Rapid Emulator Based On PFC) and FLAC3D (Itasca Consulting Group 2017), based on a continuum approach, to determine the main factors that affect a caving mine: (i) caveability and caving rate, (ii) abutment stresses and cave loads, (iii) recovery and dilution entry, (iv) fragmentation, and (v) breakthrough timing and subsidence.

2 Conceptual model of the caving process

The caving process involves undercutting of the orebody by driving a series of parallel tunnels across the orebody, and drilling and blasting the pillars between them on retreat. The swell is pulled from drawpoints on the production level below in the case of a post-undercut, or drilling and blasting upholes and rings and pulling the swell from the undercut drift itself in the case of an advanced undercut. When the hydraulic radius of the undercut has reached a critical dimension, a self-sustained cave will develop if the broken and bulked ore is extracted (Brown 2003).

Five key geomechanical zones are associated with caving (Figure 1), based on the conceptual model developed by Duplancic and Brady (1999). The characteristics of each zone are defined as:

- *Elastic zone:* Induced stresses may be high here, but are insufficient to induce measurable microseismicity.
- *Seismogenic zone:* This is where microseismicity occurs within the jointed rock via joint slip and fracture extension.
- *Yielded zone:* This is where the rock mass has disintegrated and lost all of its cohesive and/or tensile strength, but has not moved a significant distance yet. The outer limit of this zone generally coincides with the fracture limit, where visible fractures are evident in intersected openings or on the ground surface, significant offset occurs in open boreholes and time-domain reflectometers break.
- *Airgap:* An airgap can exist if the overlying rock mass retains some level of cohesive and/or tensile strength. As an airgap expands in size, the overlying rock mass may weaken further, causing the advance of the yielded zone and a collapse into the airgap.
- *Mobilised zone:* This is where the disintegrated rock mass has moved a significant distance and is starting to dilate and bulk as a result. The limit between the mobilised zone and the yielded zone is referred to as cave back.

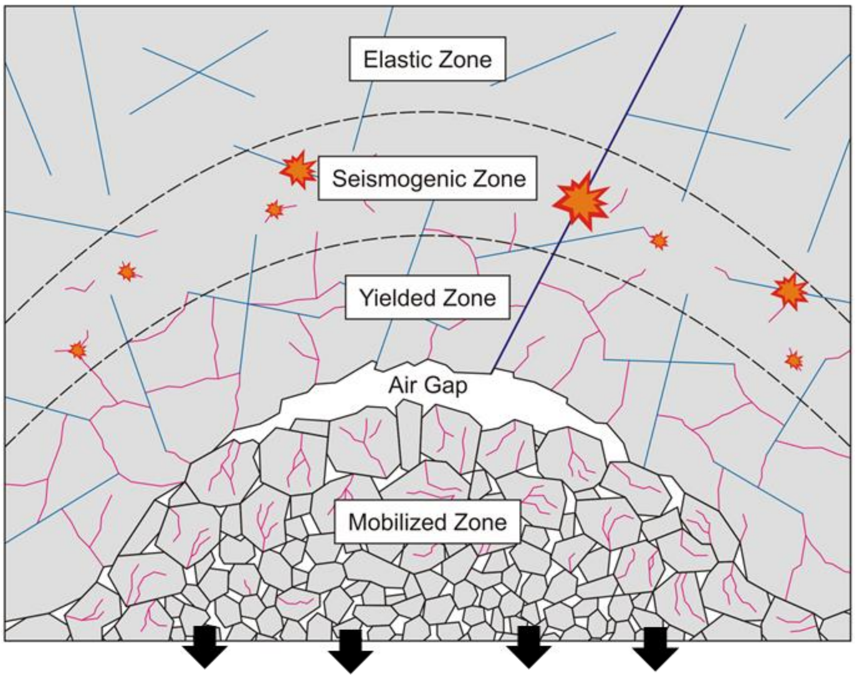

Figure 1 Conceptual model of the caving process modified after Duplancic and Brady (1999)

3 Previous approach to cave modelling

A numerical approach to cave assessment has been developed by Itasca (Board & Pierce 2009; Sainsbury 2012) over the past 15 years during the industry-funded International Caving Study (ICS I & II) and Mass Mining Technology (MMT) projects. The approach considers the changes that the rock mass experiences when caving occurs (cohesion and tension weakening, post-peak brittleness, modulus softening and dilation) and correctly representing production as it marches forwards in time.

To simulate draw, a layer of zones encompassing all active drawpoints for the current year are deleted within the model. Forces are applied to gridpoints on the floor of the deleted volume to represent the resistance provided by the extraction level, while the gridpoints on the roof of the deleted volume have a small downward velocity applied to them that is proportional to the relative draw rate for the nearest drawpoint. The largest pull velocity (i.e. for the drawpoints with the highest production rate) is set low enough to ensure pseudo-static equilibrium throughout the model (i.e. to allow natural gravitational flow of the material and to avoid dynamic 'pulling' of the overlying material). The model is run in small-strain mode (i.e. gridpoint coordinates are not updated), and thus the density of the zones within the cave must be updated constantly (based on the emergent volumetric strain) to maintain mass balance (Figure 2).

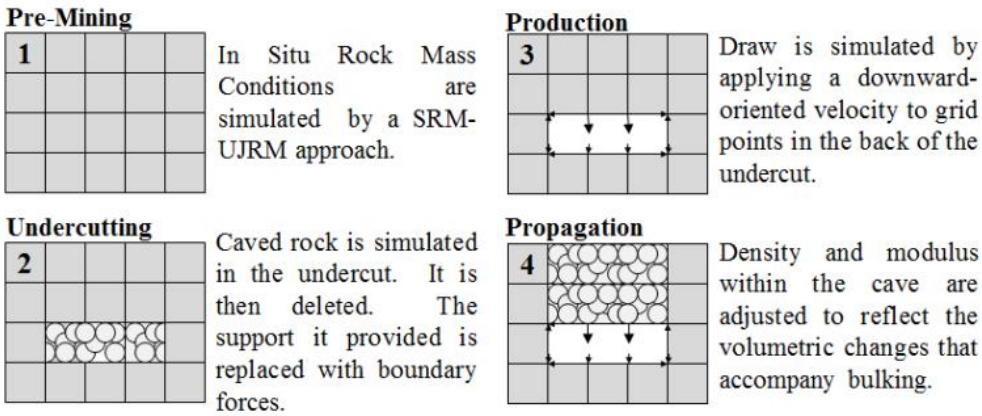

Figure 2 Simulation of production draw from FLAC3D model based on velocities (Sainsbury et al. 2011)

By summing the masses drawn by all the nodes (gridpoints), the total production from the cave within the model may be calculated at any point in time. The model is cycled until the mass produced from the numerical cave is consistent with what is to be produced from the actual cave for the current time increment (as defined by the draw schedule). As the mass is drawn from the model, displacement and yielding can occur in the overlying zones (dictated by the stress state and yield strength of the rock mass) and the cave may progress upward. The process is repeated for the remaining years in the schedule. As old drawpoints cease production, the surrounding zones are converted to a cohesionless caved rock material with a modulus consistent with a bulking factor of 25%, based on Pappas and Mark's work (Pappas & Mark 1993). This allows stresses to redistribute back into exhausted areas of the cave.

The numerical approach to caving simulation has two main limitations:

1. *Low height of interaction zone:* The height of interaction zone (HIZ), i.e. the height above which flow zones overlap or interact sufficiently to permit uniform drawdown, is very low in the draw column. This means that the potential impacts of isolated draw on cave development are not considered.
2. *Small-strain nature of the caving simulation:* Airgap and surface crater development and associated drawdown of material within the crater limits requires critical assumptions such as repose angles and degree of bulking. Also, mechanisms of fines migration and rilling are not being considered.

In order to overcome these limitations, a coupled approach has been developed in order to more accurately capture the impact of caved rock gravity flow on cave growth and vice versa. This approach is similar to other coupled approaches that have been developed to handle the complex coupling between draw and caving (e.g. Beck et al. 2011).

4 REBOP–FLAC3D hybrid approach

The approach simulates the caving process by explicitly modelling each isolated movement zone derived from REBOP into FLAC3D to determine the yielded zone and cave back associated with mass drawn.

4.1 Explicit modelling of drawbells and undercut

The first step is to develop drawbells and/or undercut rings (depending on the undercut method) in FLAC3D. For this, the numerical model is constructed with enough resolution to explicitly represent the undercut development sequence. Figure 3 illustrates an example of drawbell and undercut volumes represented in a non-conformed mesh of hexahedral zones.

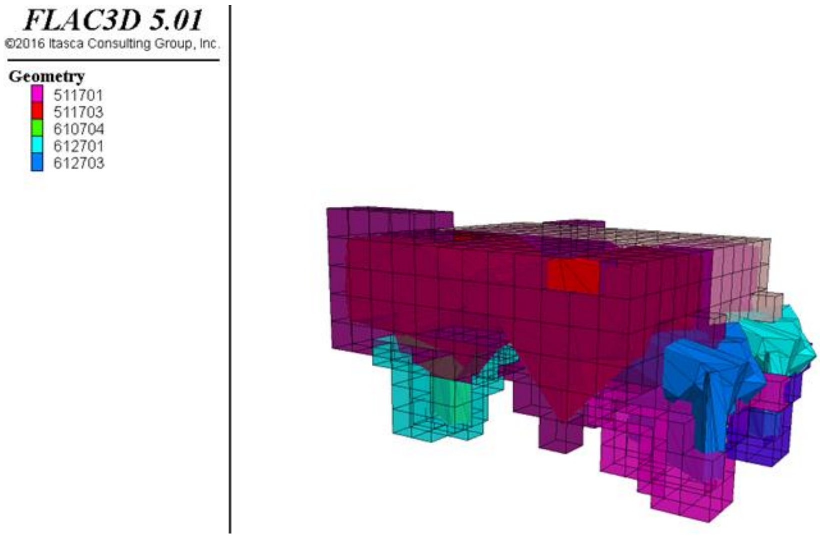

Figure 3 Drawbell and undercut volumes represented in a non-conformed mesh of hexahedral zones in FLAC3D

By explicitly modelling the drawbells and undercut rings, the method allows to study the effect of the undercut method. In the case of conventional or post-undercutting strategy, i.e. undercut drilling and blasting, this takes place after the development of the underlying extraction level has been completed. Drawbells are prepared ahead and are ready to receive the ore blasted from the undercut level. In the case of an advanced undercut, drawbells are only developed behind the undercut front, normally at a 45° angle.

4.2 Rock mass properties for mobilised and yielded zones

The hybrid approach uses the Cave–Hoek constitutive model (Pierce 2013) as in the previous approach to allow the model to account for the changes in the rock mass as the caving process progresses with production. In the numerical model of caving, the rock mass fails at a given peak strength followed by a reduction in strength to a residual, or post-peak level as the rock fractures under further straining.

Peak strength of a jointed rock mass can be estimated using the Hoek–Brown (HB) failure criterion (Hoek et al. 2002). The criterion begins with the properties of intact rock and then introduces factors (block size and joint friction characteristics) to reduce these properties.

On the other end of the spectrum, Barton and Kjærnsli (1981) developed a means to estimate the shear strength of rockfill primarily based on particle roughness and particle strength. Barton's failure criterion is:

$$\tau = \sigma_n \tan\left(R.\log\left(\frac{S}{\sigma_n}\right) + \varphi_b\right) \quad (1)$$

where:

σ_n = normal stress.

R = equivalent particle roughness coefficient.

S = particle intact strength.

φ_b = basic friction angle (generally around 30°).

Figure 4 shows the nomogram that Barton developed to relate rockfill porosity and R as a function of the origin, roundedness, and smoothness of the particles. The upper bound R value is approximately 15, which is appropriate for very sharp, angular, and rough particles, found by extrapolating the nomogram to a porosity of about 10%.

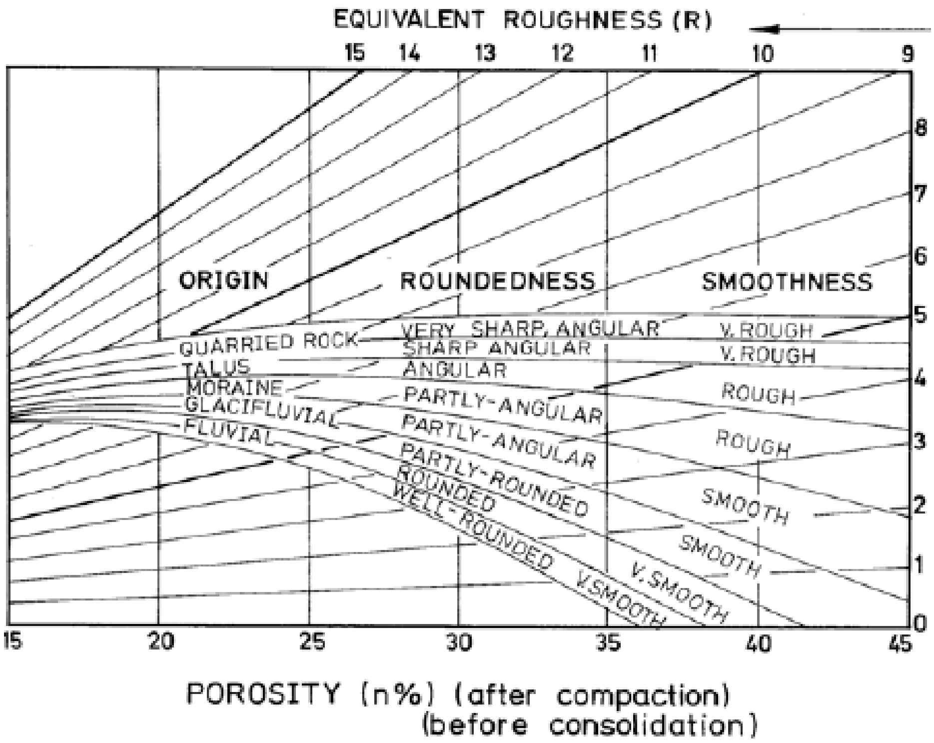

Figure 4 Nomogram of Barton and Kjærnsli (1981) used to estimate equivalent roughness of an assembly of rock fragments based on porosity and fragment roundedness/smoothness

Barton's criterion can be used as a guide for estimating residual rock mass strength. The residual strength is assumed as a rock mass that has bulked to the extent that all rock bridges have been eliminated, but rock blocks are still in a state of interlock. HB parameters then need to be fitted to the Barton rockfill shear strength failure curve that meets this definition, i.e. low-porosity rockfill with very angular particles that interlock.

Extrapolation of Barton's nomogram to 10% porosity is reasonable and results in a roughness coefficient of about 15 for very angular and rough particles. Basic friction is assumed to be 30°. The parameter S is equivalent to the rock block strength.

This suggests having two residual strength envelopes: first when the rock mass has yielded but it has not bulked sufficiently (expected within the yielded zone), and secondly, a failure envelope describing a fully bulked caved rock (expected within the mobilised zone) as shown in Figure 5.

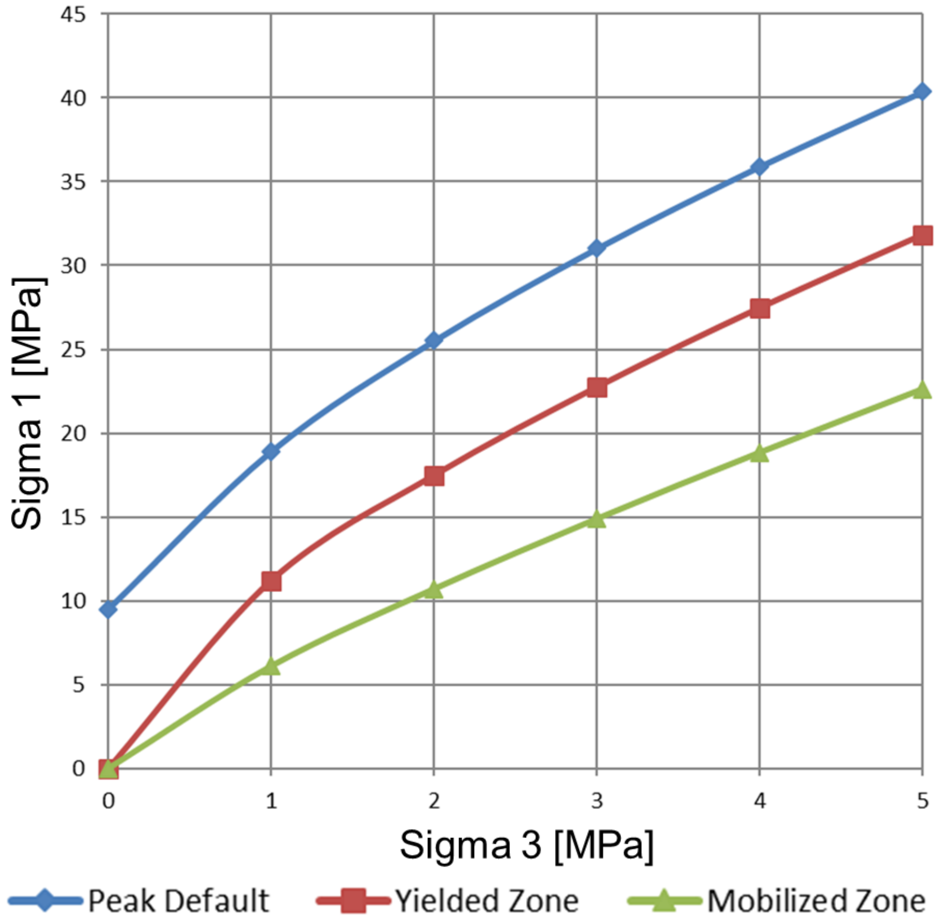

Figure 5 Comparison of HB curves; peak (blue); HB residual fit to Barton rockfill at 0% porosity (red); and HB residual fit to Barton rockfill at 30% porosity (green)

4.3 Production modelling with REBOP

REBOP was developed by Itasca for the industry-funded International Caving Study (ICSI and ICSII) and MMT projects as a tool for rapid simulation of material flow within block, panel, and sublevel caves. REBOP models (Pierce 2010) flow by tracking the growth of the isolated movement zones (IMZ) and the internal material movement associated with draw. Figure 6 illustrates the IMZ growth and material movement with incremental draw.

An IMZ is characterised by a number of discrete disk-shaped layers stacked above each drawpoint. The volume of an IMZ is tracked by balancing the incremental mass drawn from the drawpoint considering material bulking at the periphery of the IMZ. The amount of bulking is controlled at the local level by the average initial and maximum porosities of the material at the periphery as specified in the block model. The relative rate of upward and lateral growth is controlled by the fragmentation and friction angle at the IMZ periphery as specified in the block model. Small-scale physical and numerical experiments reveal that an IMZ tends to develop an approximately ellipsoidal or cylindrical shape with an evolving width that is most strongly controlled by the mean fragment size. As a result, IMZ tends to be narrow in finely fragmented rock and wide in coarsely fragmented rock.

Material movements within an IMZ are tracked via a field of markers, the positions of which are updated daily according to the local velocity profile for each layer within an IMZ. Markers are assigned a tensile strength and fragment size randomly from the input distributions of their parent lithology when they are first created. As markers move down and mix, their diameters are averaged at the perimeter of each disk-shaped layer to control the local IMZ expansion rate, and within each disk-shaped layer to control the internal velocity profile. The velocity profile within an IMZ consists of a shear annulus surrounding a central plug flow zone; the velocity is constant and at a maximum in the plug flow zone, and decays linearly towards zero in the outer shear annulus. REBOP will achieve uniform draw when two or more IMZs overlap through superposition of each isolated velocity profile.

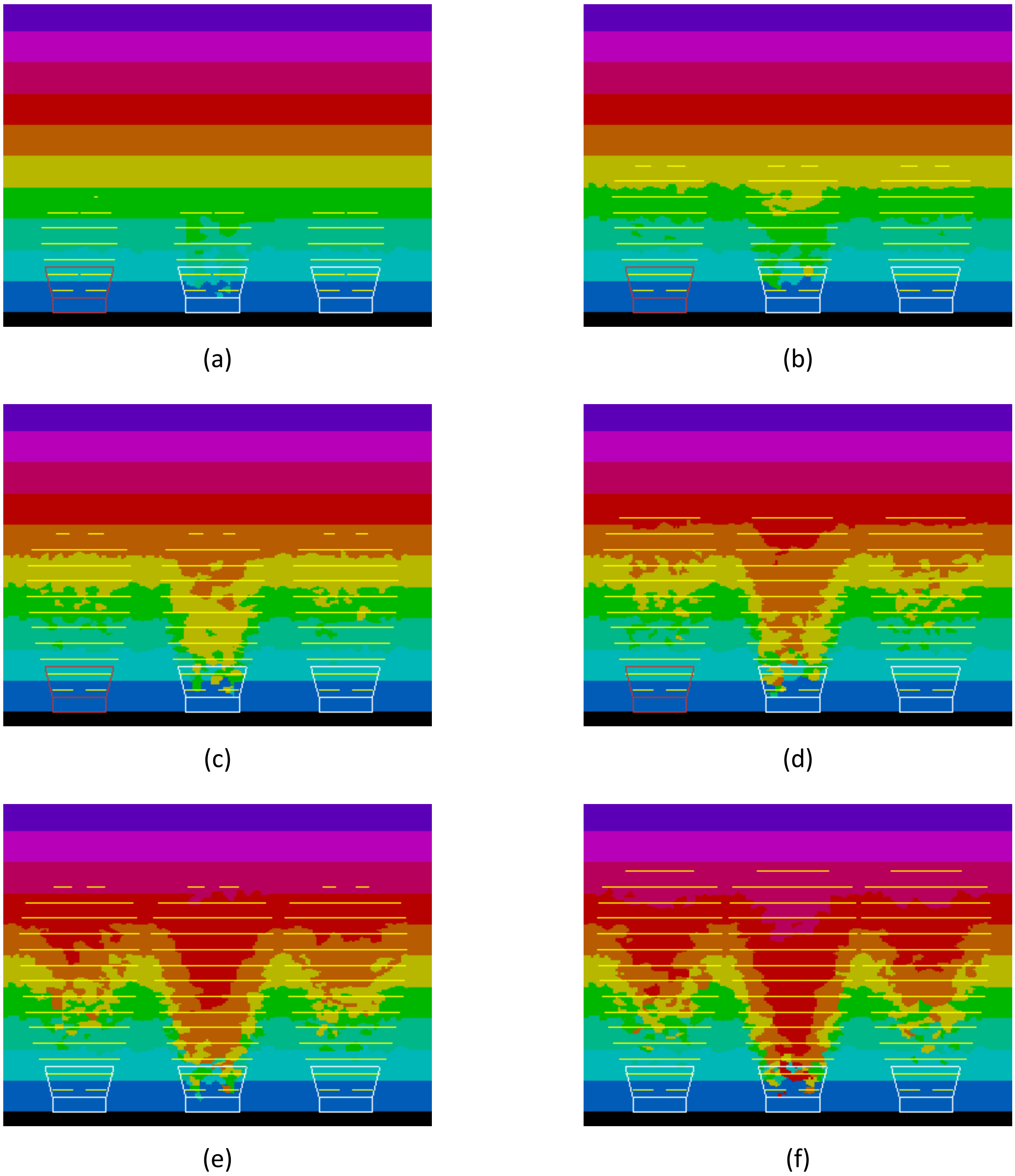

Figure 6 IMZ growth sequence and material movement with incremental draw (steps a–f)

4.4 Hybrid approach

One of the inputs in REBOP is the draw schedule. The first period contains the swell tonnage to pull from drawbells and undercut rings. After this first cycle of extraction, REBOP informs the location of zones that have been mobilised to the continuum FLAC3D model. Stresses are initialised to zero within the active movement zones in FLAC3D and the induced stresses associated with the presence of these zones and the yielded zone surrounding the cave are determined.

A zone is available to flow once it reaches the residual strength, i.e. the rock mass behaves like rockfill angular fragments that have not bulked, with zero cohesion and zero tensile strength and high friction angle.

FLAC3D informs REBOP which zones (initially inactive) could now be mobilised. The procedure is repeated until the draw schedule used as an input in REBOP is finished (Figure 7).

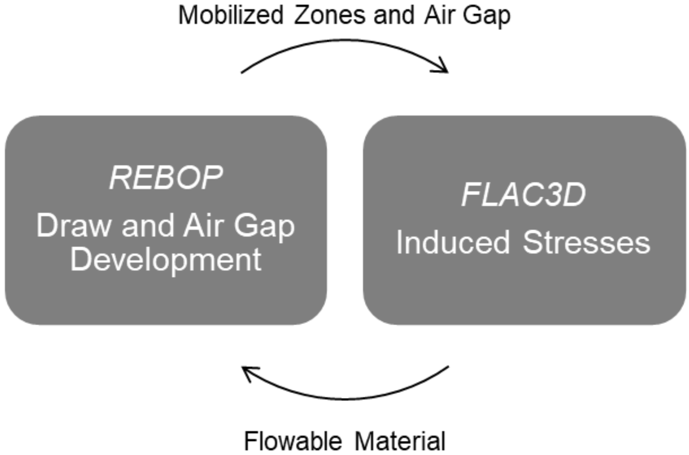

Figure 7 Schematic of the hybrid FLAC3D–REBOP approach

Figure 8 shows an example of a panel caving mine showing contours of mobilised zone (blue), part of yielded zone representing material that has reached the residual strength envelope (yellow), and air (red). Figure 9 shows a section of the same example showing maximum principal stresses (Pa). The geomechanical zones defined in the conceptual model are indicated based on the level of stresses surrounding the cave.

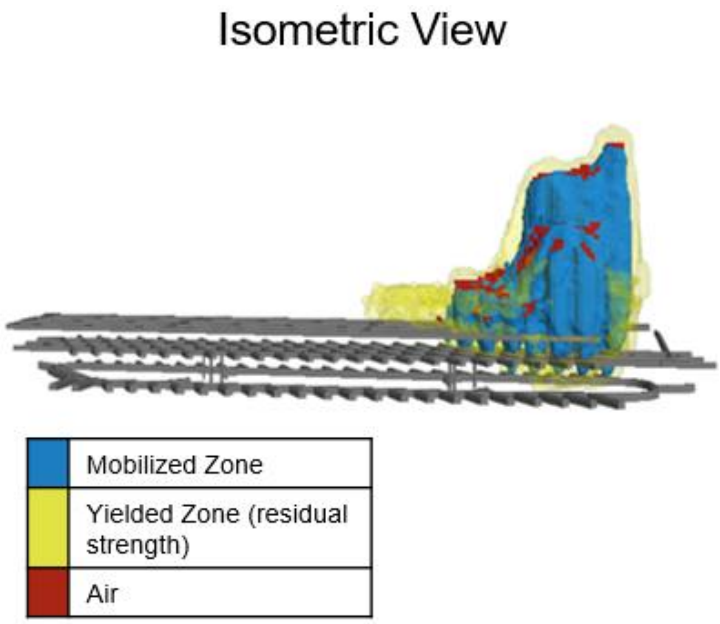

Figure 8 Example of a panel caving mine showing contours of mobilised zone (blue); part of yielded zone representing material that has reached the residual strength envelope (yellow); and air (red)

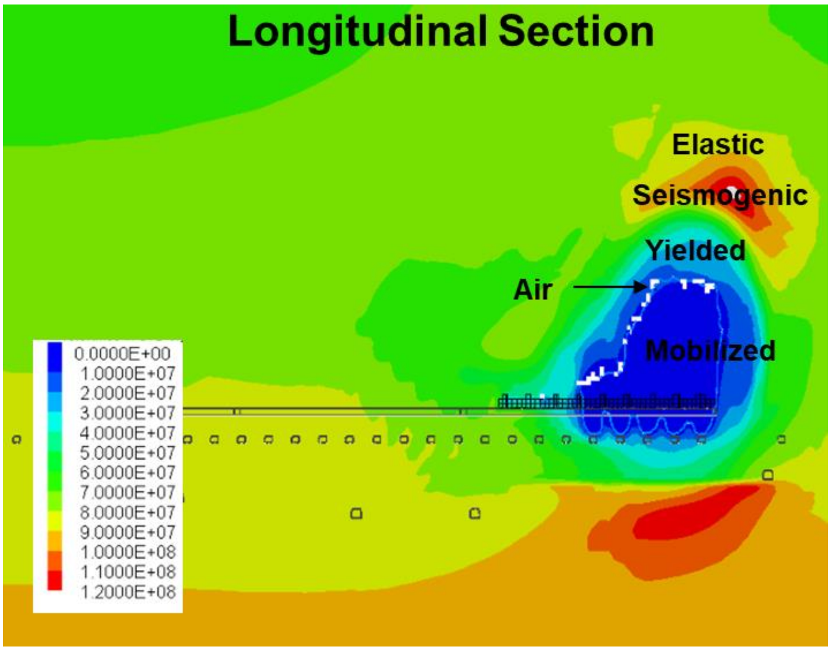

Figure 9 Maximum principal stresses (Pa) in a panel caving mine. The geomechanical zones defined in the conceptual model are indicated based on the level of stresses surrounding the cave

5 Case studies

5.1 Panel caving mine

The mine is adjacent to and below previously caved inactive ground, which can significantly impact pre-caving stresses. In the numerical model, this is accounted for by changing the properties of the previously caved ground to cohesionless, a friction angle of 43°, and a bulking factor of 20%, and by initialising with zero stresses. After settling the material under gravity and reaching equilibrium, the resulting pre-caving stresses in the model are shown in Figure 10.

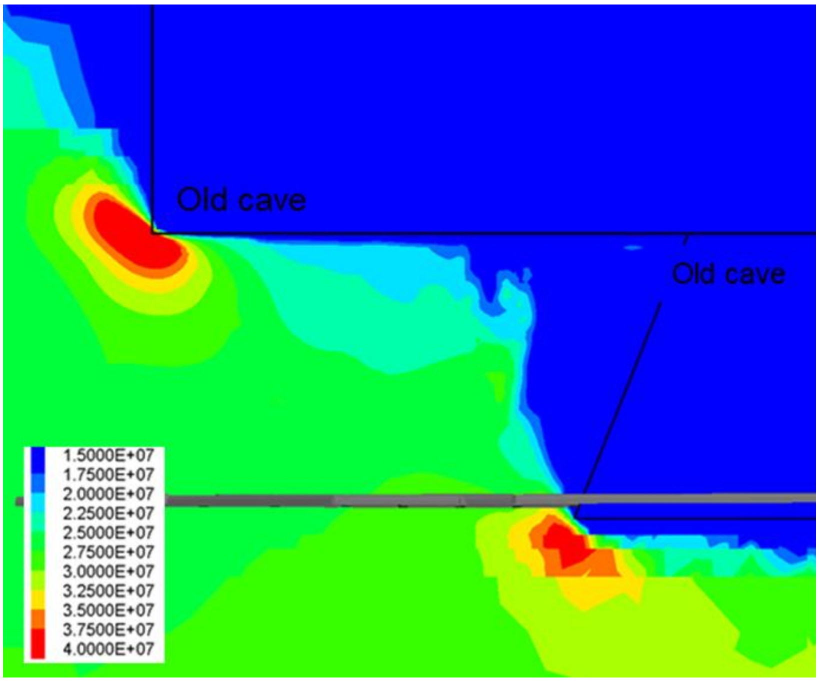

Figure 10 Section showing pre-caving stresses affected by presence of old caves as major principal stress (Pa) from 15 MPa (blue) to 40 MPa (red)

The mine experienced two major events associated with cave propagation and infrastructure instability. The first event was related to cave hang-up and subsequent collapse with a pressure event. Contributing factors to cave hang-up include the inclined cave shape of the adjacent old cave, high rock mass strength variability due to various zones of different alteration, and the effect of early isolated draw above the extraction level.

Figure 11 illustrates the evolution of the airgap, yielding, and mobilised zones. One of the advantages of the hybrid approach is that the undercut and drawbells are explicitly modelled, i.e. development of drawbells and undercut are coupled with the extraction of swell and production tonnage. This allows the observation of air concentration on top of drawbells before the cave propagates. Once the critical hydraulic radius is reached, the model shows first signs of cave activity in the right corner close to the adjacent old cave. The cave arches away from the adjacent previous cave, agreeing well with site observations. Before breach, the model shows extensive local accumulation of air between the cave back and the mobilised material indicating non-continuous sporadic propagation and frequent hang-ups during caving (Figure 12). Also, during this period, it is observed that the panel cave coalesces with the adjacent cave. The model shows cave breakthrough to the old cave located above, thus tapping into pre-existing caved rock. The results of the model agree well with site observations at the mine (Figure 13).

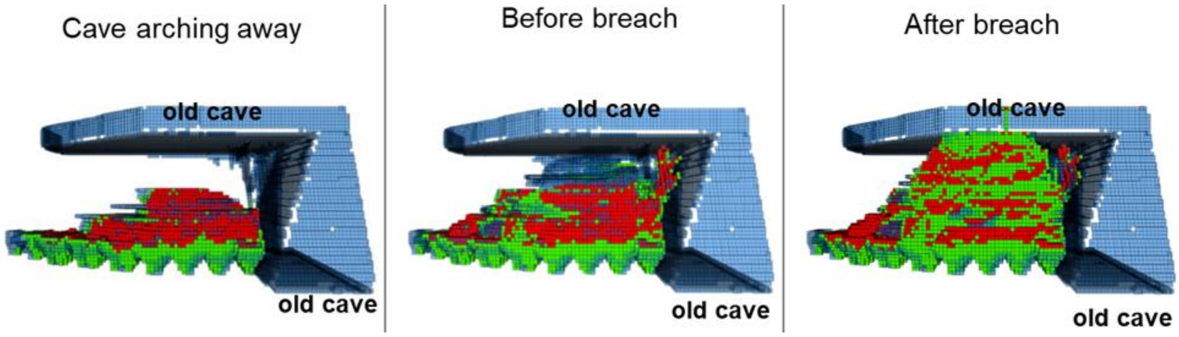

Figure 11 Cave growth showing similar behaviour (hang-up and arching away from previous cave) as site observations. Green is mobilised material, blue represents material has reached the residual strength and air is represented in red

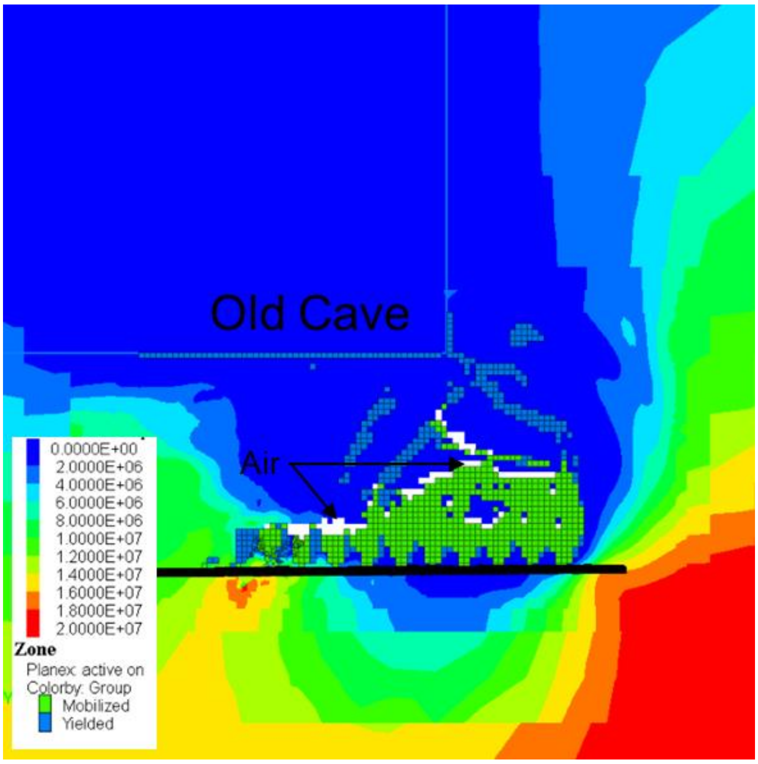

Figure 12 Longitudinal section showing sigma 1 (Pa) and location of the yielded and mobilised zones

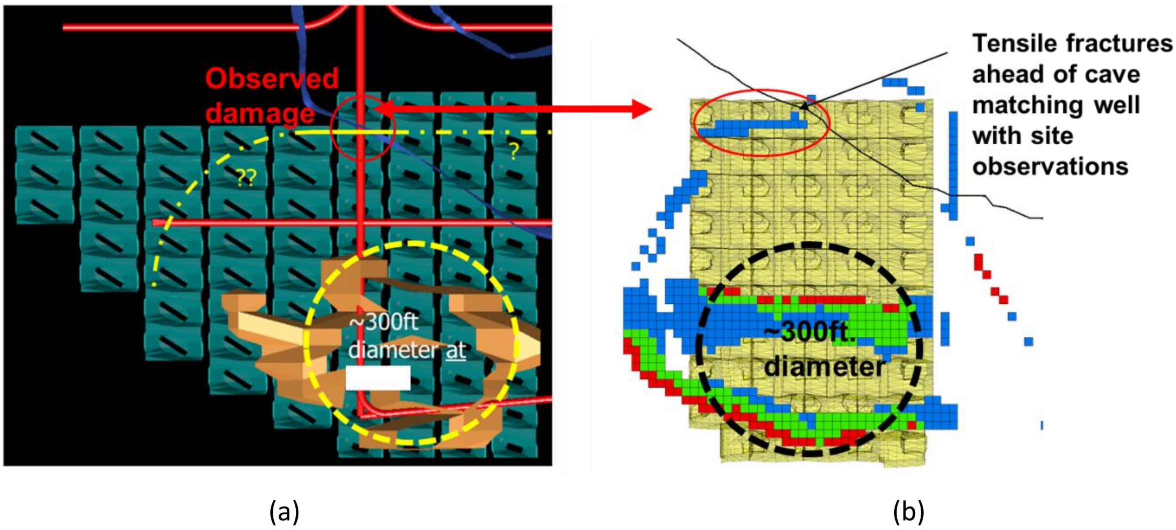

Figure 13 Breakthrough comparison between (a) Site observations; and, (b) Numerical model

The second event was related to a localised collapse on the extraction drift. Contributing factors to the drift closure include rapid undercutting of the panel combined with lower draw tonnages in this drift (increasing the likelihood of stress connection between the cave back and major apex in this location), high local extraction ratio due to the presence of an orepass, and geologic factors such as sub-vertical faults and hard rock local in the major apex (which could act as a stress attractor).

The hybrid FLAC3D–REBOP approach is constructed to have enough resolution to explicitly simulate drawbells connecting the undercut and extraction levels. Explicit modelling of extraction drifts is not accounted for due to computational constraints. Therefore, relationships between stress-to-strength ratios and closure strains, based on empirical data, are used to estimate drift stability conditions (Board et al. 2006). By doing so, this method allows the study of not only cave growth at a large scale, but also 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. This is relevant because, in isolated draw conditions (below the height of interaction zone), relatively large stresses can be distributed onto the extraction level. Figure 14 shows induced vertical stresses (Pa) between mobilised zones (stagnant zones) point loading a drift in the extraction level.

The numerical model is able to capture the mechanism leading to the collapse. A large area of active drawbells with low draw rates (showing isolated draw conditions) inducing high deviatoric stresses is observed in the plan view of the undercut in Figure 15. If poor ground conditions exist within this area of high deviatoric stress, a severe squeezing or even collapse of tunnels at the extraction level could be expected. The risk of severe squeezing or collapse is affected by time. A continuous progression from abutment to cave stresses is what is expected to occur in a panel caving mining method. Convergence issues are more likely to occur when regions of high stress-to-strength persist for a relatively long period of time behind the advancing cave front. The risk of severe squeezing increases where large extraction ratios (orepass locations or cutouts) exist.

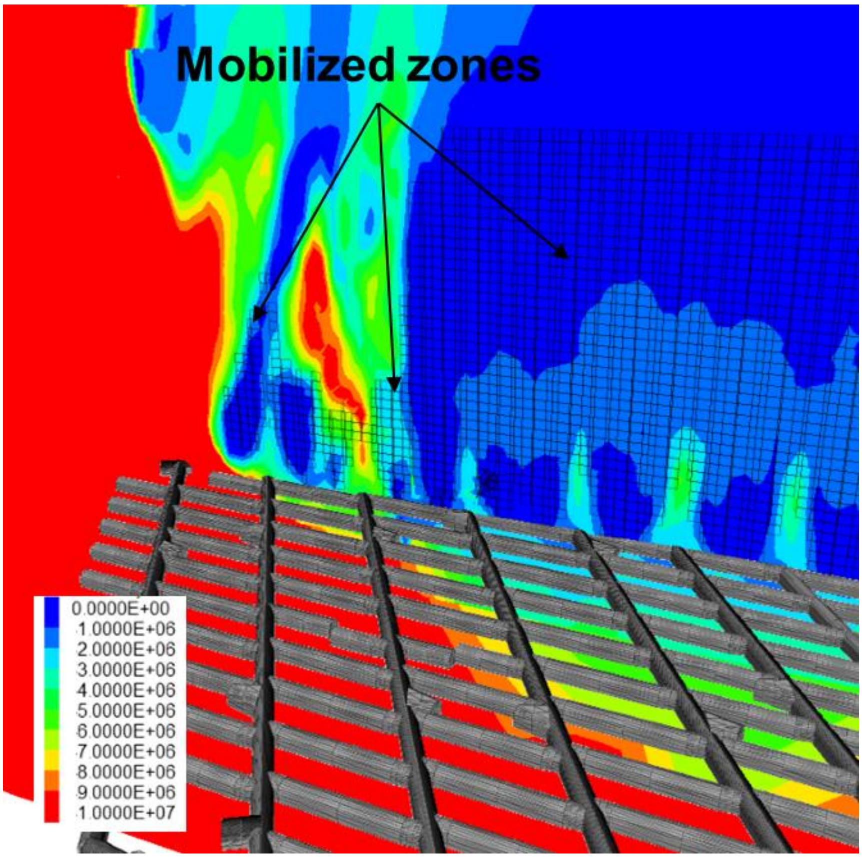

Figure 14 Induced vertical stresses (Pa) between mobilised zones (stagnant zones) point loading a drift in the extraction level

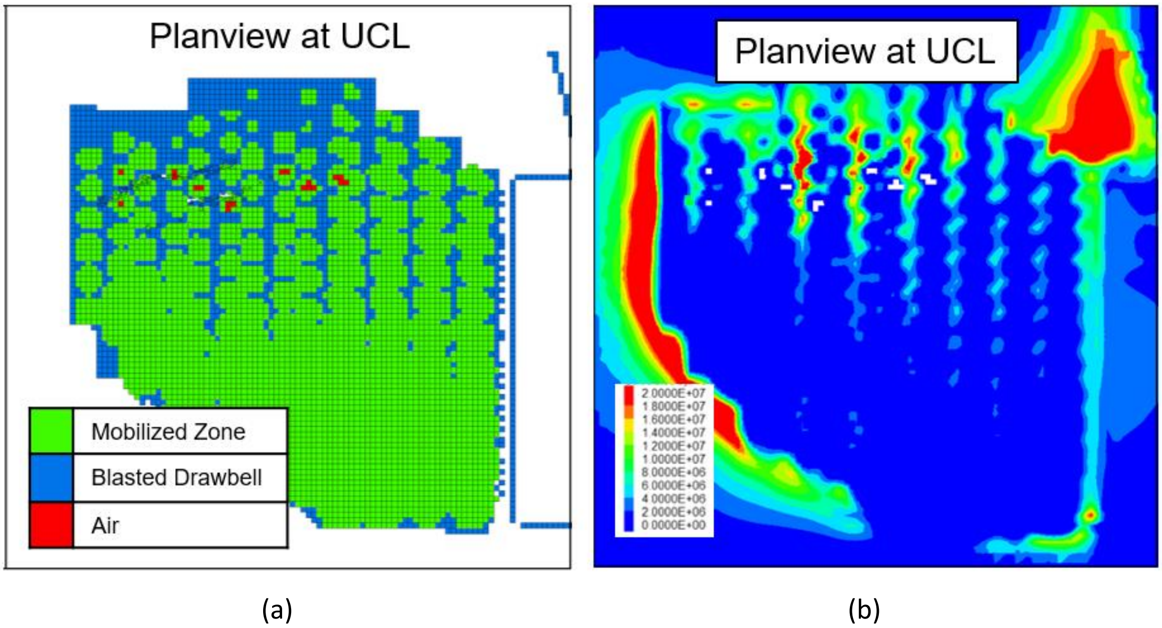

Figure 15 Plan view at the undercut level showing; (a) The zone state; and, (b) Deviatoric stress indicating isolated draw conditions above major apex and stress concentrations in the area of the collapse

5.2 Sublevel caving mine

The mining method in this case study is a level sublevel cave retreat. Unlike traditional sublevel caving mine operations, only one level is mined at a time (Level 1). The mine is located under 80 m of sand cover with an intermediate level (Level 0) that was used for trial mining. Level 0 is located approximately 130 m below the surface while Level 1 is located at 150 m below the surface.

A successful implementation of the method requires a close control of draw to prevent excessive dilution of the ore stream. Two main design factors are critical in order to achieve uniform drawdown and minimise dilution. First, drawpoint spacing should be designed so flow zones overlap and isolated draw is avoided, and secondly, a proper draw strategy should be implemented to protect the crown pillar between the ore and the sand cover. A typical strategy for a sublevel cave mine is to extract only 40–60% of blasted tonnes per ring on the first level and then increase incrementally by 20% for each subsequent sublevel.

The extraction strategy implemented at the mine was aggressive, exceeding 75% extraction of ring tonnes on the first sublevel. Because of this, the operation experienced two airblasts followed by development of a sinkhole through the overburden, connecting the surface to the underground workings on Level 1. Figure 16(a) shows an aerial view of the sinkhole of approximately 55 m in diameter and Figure 16(b) shows sand rilling down into the drawpoint after the second airblast.

(a) (b)

Figure 16 (a) Sudden breakthrough forming a sinkhole at a sublevel caving mine; and, (b) Sand rilling down into the drawpoint

The hybrid approach was used to back-analyse and confirm the hypothesis of the failure mechanism that caused the sinkhole formation.

The inputs in FLAC3D are the in situ stress regime and the rock mass properties for the different rock types present at the mine. The inputs for REBOP are the drawpoint location, sublevel ring dimensions and draw schedule, as well as the initial and maximum porosity and fragment size for the blasted material and the different geological units present at the mine.

The model is able to capture the mechanisms of cave stalling and airgap development that results in sand breaching and sinkhole formation as a function of total mass drawn over time (Figure 17). Surface breakthrough was reproduced with significant accuracy in terms of timing compared to reality. Although the sinkhole shape was not able to be fully captured in the model, the simulated sinkhole diameter matches well with site measurements.

The strength of material located in the crown pillar had to be reduced by 30% of the intact unconfined compressive strength. This allowed the cave to propagate rapidly towards the sand boundary. The fragment size distribution for blasted material assumed a normal distribution (mean of 0.3 m and a standard deviation of 0.15 m). Final porosity of the mobilised material was assumed to be 17%. Reducing the maximum degree of bulking resulted in a larger airgap volume, which is conducive to the sinkhole formation. A small change in the bulking properties of the sand was assumed (initial and final porosity is 13 and 17%, respectively.) Material collapse was enhanced by assuming that the sand initially has some degree of bulking.

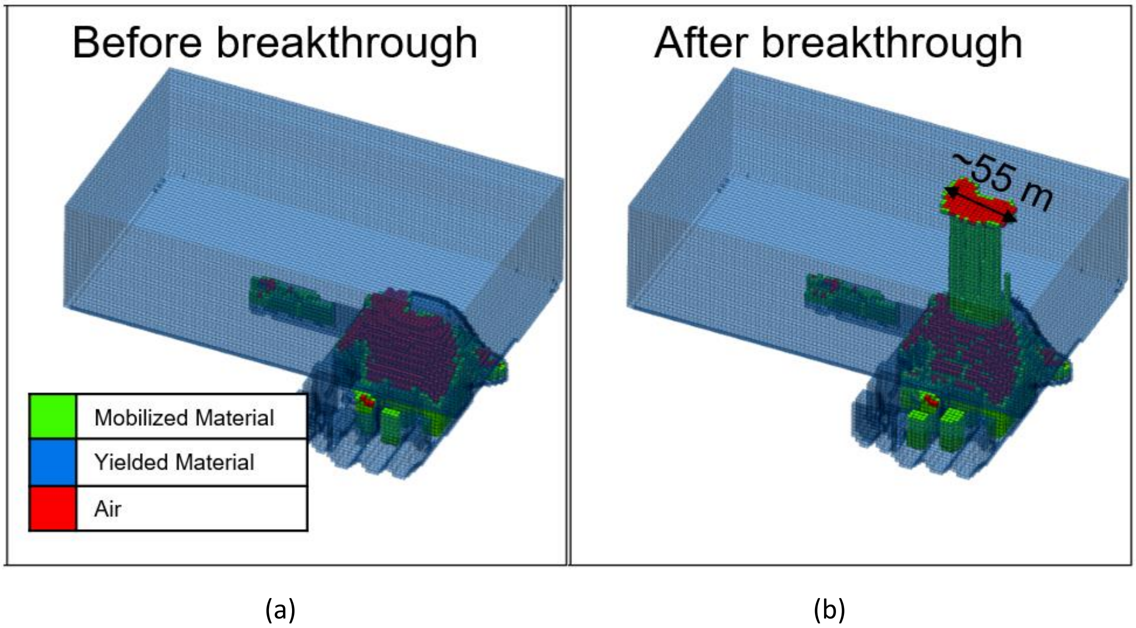

Figure 17 (a) Before breakthrough; and, (b) After breakthrough. Blue represents material that is able to flow, green is mobilised material, and red is air

6 Conclusion and future work

A new hybrid approach has been developed to model the main geomechanical parameters that must be understood in caving: cave growth, fragmentation, infrastructure stability, recovery and dilution, and subsidence.

Two of the main advantages of the hybrid approach include the capability of studying the potential impacts of isolated draw on cave growth, and point loading on the extraction level, as well as the effect of including explicitly the airgap and mechanisms of fines migration and rilling on cave growth and crater development.

Two case studies describe the capabilities and validate the hybrid approach. The first, a panel caving mine, shows the effects of isolated draw on the cave propagation and cave stresses being induced in areas behind the cave front leading to severe squeezing. The second, a sublevel caving mine, shows the effect of aggressive draw strategy close to a sand boundary and development of a sinkhole.

Future work on the approach is the inclusion of time-dependent effects on the stress distribution inside the cave. In particular, adding a time-dependent compaction rule to allow an increase in modulus based on induced deviatoric stress whether material is being actively drawn or not. Additionally, future validations using physical testing would improve the predictive capabilities of this approach.

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