

Modelling of fracture initiation near a cave back and its implications for hydraulic fracturing concurrent to cave mining

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Abstract

Rock mass pre-conditioning has been applied in the mining industry since it was first trialled at Northparkes in 1997, to continue its wide application in large cave mines such as Cadia East and El Teniente mines. The most known application is based on hydraulic fracturing techniques transferred from the experience of the oil and gas industry to create additional fractures in the rock mass prior to initiating undercutting. In the mining industry, the aim is to reduce the rock mass quality to obtain an improved cave performance and other benefits such as better seismic response and reduced fragmentation. In addition to pre-conditioning, there are other experiences of hydraulic fracturing concurrent to an existing cave back. In this context, documented experiences from Northparkes, Grasberg and Cadia East mines were carried out by applying hydraulic fracturing to induce caving after a stalled or slowed cave propagation. Applications concurrent to cave mining do not follow the same rules as applied prior to undercutting (pre-conditioning) for fracture initiation and propagation. Furthermore, these have not been clearly explained in terms of the supporting fundamental physics.

The present work proposes an elastic closed form solution to estimate fracture initiation demand when the hydraulic fracturing is interacting concurrent to a cave back. This analytical model was able to explain the reduced demand of breakdown pressure due to the modified stress field near a cave back (near field stress). In addition to this result, there are preliminary implications for cave engineering applications to support cases of cave induction but also new potential applications for directional caving as conceptualised in the present work. This development is part of a current ongoing research that will also consider aspects related to fracture propagation.

Keywords: *hydraulic fracturing, pre-conditioning, post-conditioning, fracture initiation, caving mechanics*

1 Introduction

The use of hydraulic fracturing techniques has been applied in the mining industry to improve cave performance by pre-conditioning the rock mass. The main purpose is to downgrade the geomechanical rock mass prior to starting the cave mining process. The best way to illustrate this concept was explained by Van As & Jeffrey (2000) for cave induction at Northparkes in which hydraulic fracturing may create additional fractures to decrease the Mining Rock Mass Rating (MRMR) to move the rock mass further into the Caving zone of the graph (Figure 1).

Following this first industry experience in Northparkes in 1997, several other cave mines have applied pre-conditioning over time to introduce innovations to the caving process by combining hydraulic fracturing with confined blasting (Catalan et al. 2017) or combining undercut variant and hydraulic fracturing (Pardo & Rojas 2016). These efforts have focused on applying pre-conditioning and positive outcomes in terms of a better seismic response (Morales et al. 2007), cave propagation (Catalan et al. 2017) or fragmentation (Brzovic & Gonzalez 2019). Even though these results have been successful, the fundamental concepts and models were taken from the experience of oil and gas, but further opportunities for improvement under different geotechnical conditions and deeper cave mining need to be investigated, and new applications identified (Rimmelin et al. 2020).

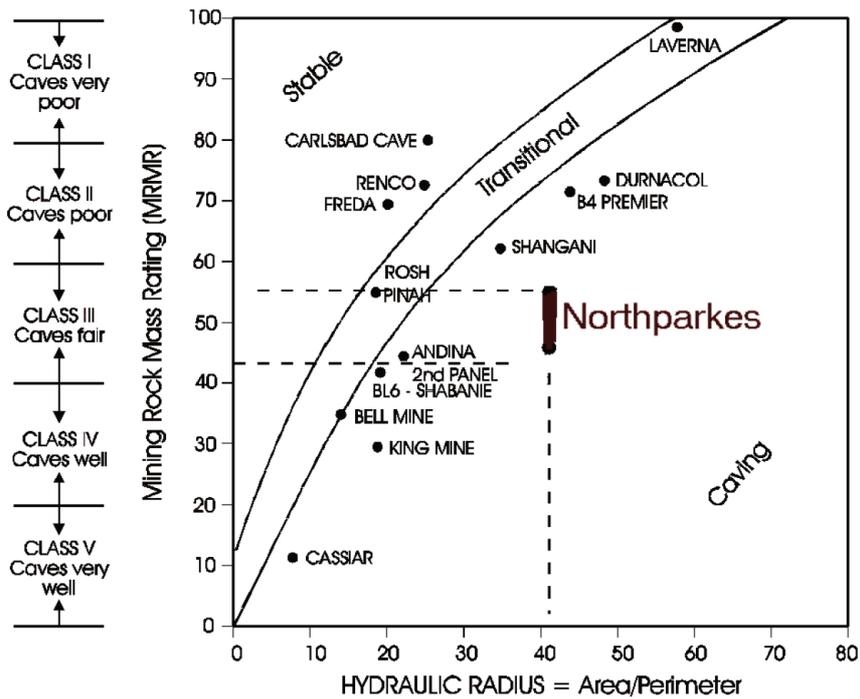


Figure 1 Laubscher’s caveability diagram showing a decrease of the MRMR for the same hydraulic radius (van As & Jeffrey 2000, adapted from Laubscher 1990)

Potential new hydraulic fracturing applications in cave mining were identified by He et al. (2016) who introduced the concept of prescribed hydraulic fractures that induce the creation of additional fractures in different orientations, to optimise the pre-conditioning process. The prescribed orientation of hydraulic fractures could be obtained by the pre-location of propped fractures to create a local modified stress condition, taking advantage of the stress shadow effect (Figure 2). The fracture re-orientation promotes the creation of an additional joint set to follow an orientation useful for caving.

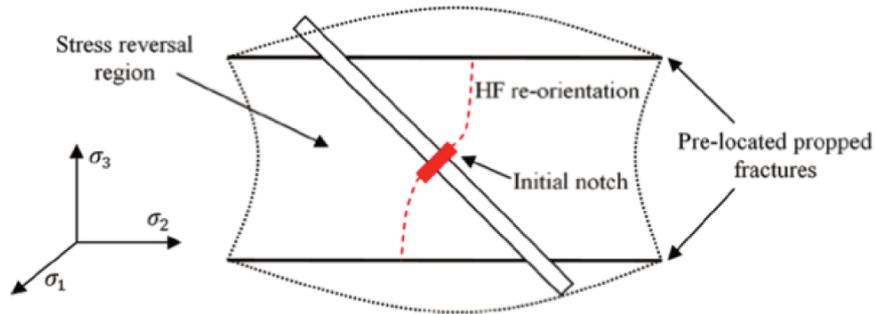


Figure 2 Concept of prescribed hydraulic fractures (He et al. 2016)

These efforts have focused on pre-conditioning but there is a potential for innovation when the undercutting or caving process has already started or what can be understood as ‘post-conditioning’. There are few empirical industry experiences to re-induce caving by applying hydraulic fracturing concurrent to cave mining (Van As & Jeffrey 2000). Post-conditioning offers an opportunity to enable and optimise cave performance (Figure 3). Even though the empirical outcome was a successful result, the concepts and theory behind the process which came from the oil and gas industry have not yet been adapted to the cave mining environment.

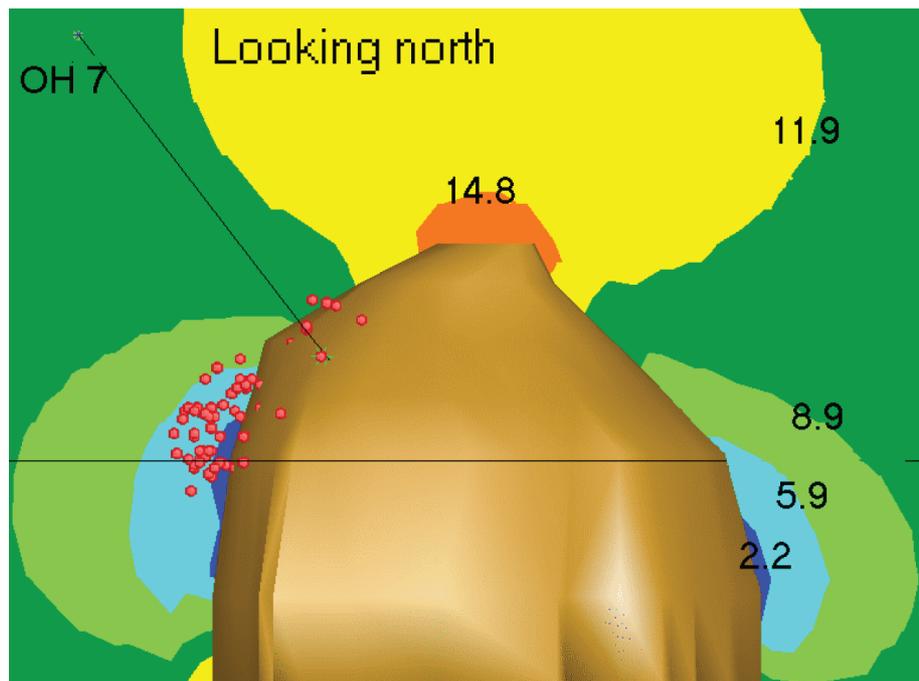


Figure 3 Hydraulic fracturing borehole OH7 applied in November 1997 in Northparkes to induce caving. Figure showing stress contours (in MPa) (Van as & Jeffrey 2000)

2 Model of fracture initiation

Following on from the previous context of rock mass conditioning applications, there remains the problem of providing a theoretical framework and formulations to address a proper design for post-conditioning concurrent to cave mining. The present work proposes a closed form formulation to solve the problem of identifying the demand for fracture initiation near a cave (Figure 4). Under this configuration, any point close enough at a distance 'd' from the cave can be affected by a higher stress anisotropy, the condition of which may remain even beyond the abutment stress zone. An elastic formulation of the breakdown pressure (Belyadi et al. 2019) can show the impact of a higher stress anisotropy:

$$P_b = 3\sigma_3 - \sigma_1 + \sigma_T - P_o \quad (1)$$

where:

- P_b = breakdown pressure.
- σ_1 = major principal stress.
- σ_3 = minor principal stress.
- σ_T = tensile strength.
- P_o = pore pressure.

By re-organising terms to introduce the stress ratio σ_1/σ_3 into Equation 1:

$$P_b = \left(\frac{3}{k} - 1\right)\sigma_1 + \sigma_T - P_o \quad (2)$$

where:

- k = stress anisotropy (σ_1/σ_3).

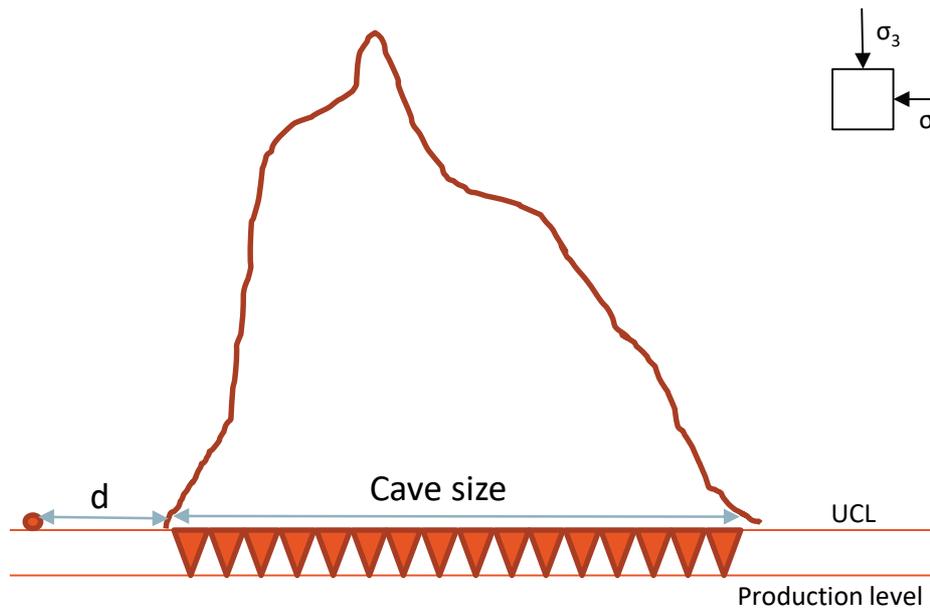


Figure 4 General configuration of a point located at distance ‘d’ of a cave under and a far field σ_1 and σ_3 corresponding to major and minor principal stresses

2.1 Analytical solution of fracture initiation near a cave

A solution composed of two parts is proposed. The first represents the value of breakdown pressure on the surface of the cave, and the second term represents the variation of the breakdown pressure with the distance ‘d’ from the cave:

$$P_b(d) = P_b^0 + \frac{\partial P_b}{\partial d} \cdot d \quad (3)$$

where:

$P_b(d)$ = breakdown pressure as function of ‘d’.

P_b^0 = breakdown pressure required on the cavity.

$\frac{\partial P_b}{\partial d}$ = derivative of breakdown pressure with respect to the distance ‘d’ to the cave.

The first term is obtained using Equation 1 and the tensile strength at rock mass scale, which can be done using the formulation proposed by Hoek et al. (2002). The disturbance factor due to blast damage and stress relaxation is considered zero for simplicity:

$$\sigma_T = \left(\exp\left(\frac{GSI-100}{9}\right) \right) \frac{\sigma_{ci}}{m_i \left(\exp\left(\frac{GSI-100}{28}\right) \right)} \quad (4)$$

where:

σ_T = tensile strength.

σ_{ci} = uniaxial compressive strength of the intact rock material.

m_i = Hoek–Brown parameter of the intact rock material.

GSI = Geological Strength Index.

Even for a good quality rock mass, it is possible to demonstrate that tensile strength will most likely have values close to 1 MPa. For example, for a $\sigma_{ci} = 150$ MPa, $m_i = 16$ and $GSI = 65$, σ_T is estimated that the rock

mass tensile strength is 0.67 MPa. This value is very low compared to the principal stresses in a very high stress condition and is assumed to be zero for the sake of this model.

Assuming a cave with an air gap (i.e. no support from caved material), and no presence of pore pressures (cave fully drained), the breakdown pressure required on the surface of the cave back is estimated using Equation 1, considering tensile strength and pore pressure are equal to zero:

$$P_b^0 = 3\sigma_3 - \sigma_1 \quad (5)$$

The second term of the model requires the development of the equations of the stress field around a circular excavation (Kirsch, 1898) to estimate the derivative of the breakdown pressure with respect to the distance (Figure 5). Firstly, we establish the breakdown pressure as equivalent to the tangential stress close to the surface of the excavation at a distance 'd' plus the tensile strength. Since tensile strength is constant and assuming no pore pressures around the cavity, the derivative of the breakdown pressure is equal to the derivative of the tangential stress for $r = s + d$:

$$\frac{\partial P_b}{\partial d} = \frac{\partial \sigma_{\phi\phi}(r=s+d)}{\partial d} \quad (6)$$

$$\sigma_{\phi\phi}(r = s + d) = \frac{1}{2}(\sigma_{max} + \sigma_{min}) \cdot \left(1 + \frac{s^2}{(s+d)^2}\right) - \frac{1}{2}(\sigma_{max} - \sigma_{min}) \cdot \left(1 + \frac{3s^4}{(s+d)^4}\right) \cdot \cos 2\phi \quad (7)$$

where:

$\sigma_{\phi\phi}(r=s + d)$ = tangential stress at a distance 's + d' from the centre of the excavation.

s = size of the excavation (e.g. front cave size).

d = distance from the excavation (cave).

ϕ = angular coordinate.

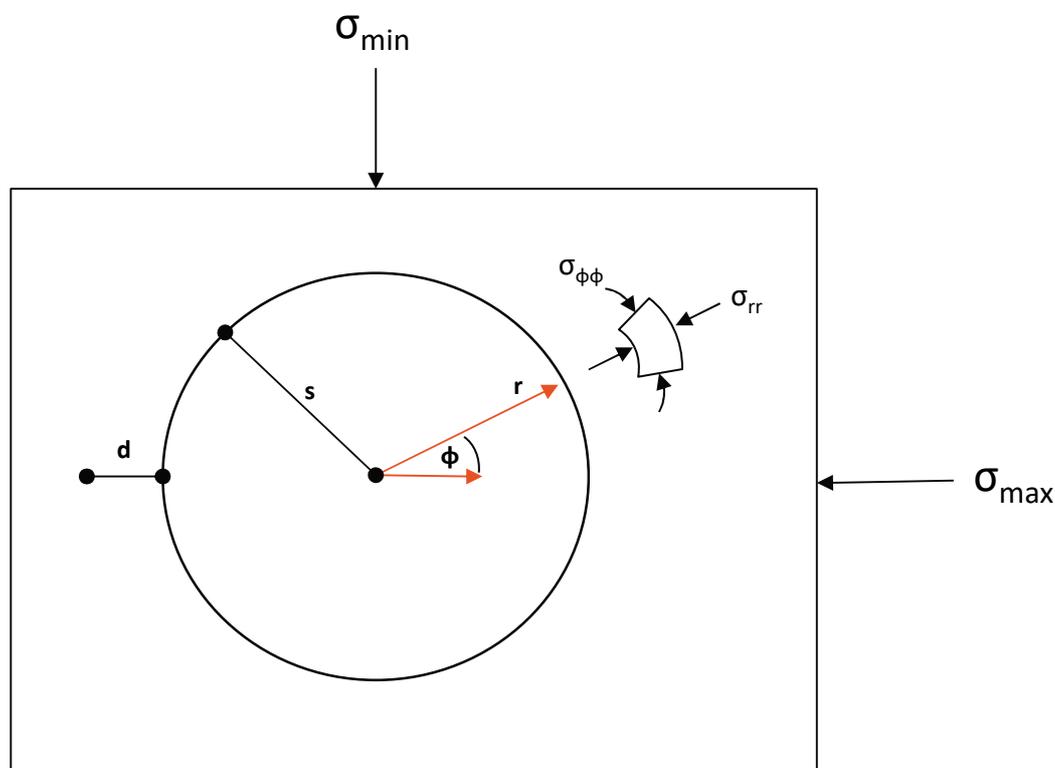


Figure 5 Stress distribution around a circular excavation under far field stress (Kirsch 1898)

Then, by also including that $s \gg d$ for the circular excavation to represent the cave size scale, and 'd' a distance close to the cave and horizontal location ($\phi = 0$), the 2nd and 4th degree functions can be developed:

$$\frac{s}{(s+d)} = 1 - \frac{d}{(s+d)}$$

$$\frac{s^2}{(s+d)^2} = 1 - 2\frac{d}{(s+d)} + \frac{d^2}{(s+d)^2}$$

$$\frac{s^2}{(s+d)^2} \approx 1 - 2\frac{d}{(s+d)} \quad (8)$$

$$\frac{s^4}{(s+d)^4} \approx 1 - 4\frac{d}{(s+d)} \quad (9)$$

By applying these approximations (Equations 8 and 9), into Equations 6 and 7, and using the maximum and minimum stress for major and minor principal stresses, the expression for $\frac{\partial P_b}{\partial d}$ is developed as follows:

$$\frac{\partial P_b(d)}{\partial d} = (5\sigma_1 - 7\sigma_3) \cdot \frac{\partial \left[\frac{d}{(s+d)} \right]}{\partial d}$$

$$\frac{\partial P_b(d)}{\partial d} = (5\sigma_1 - 7\sigma_3) \cdot \left[\frac{1}{(s+d)} + \frac{d}{(s+d)^2} \right]$$

$$\frac{\partial P_b(d)}{\partial d} \approx (5\sigma_1 - 7\sigma_3) \cdot \frac{1}{s} \quad (10)$$

Finally, combining (5) and (10) into (3), enables a closed form model of fracture initiation to express the breakdown pressure as a function of the distance 'd':

$$P_b(d) = (3\sigma_3 - \sigma_1) + \frac{1}{s}(5\sigma_1 - 7\sigma_3) \cdot d \quad (11)$$

In this model, the parameter 's' can be understood as the size of the cave equivalent, assumed circular. For example, the breakdown pressure reaches the minimum value $(3\sigma_3 - \sigma_1)$ at $d = 0$ and the breakdown pressure gradually increases in the horizontal direction until reaching a maximum value at a distance of pre-mining conditions. A more general form also considers the vertical direction:

$$P_b(d) = \begin{cases} \left[(3\sigma_3 - \sigma_1) + \frac{1}{s}(5\sigma_1 - 7\sigma_3) \cdot d \right], & \text{in the horizontal direction} \\ \left[(3\sigma_1 - \sigma_3) - \frac{1}{s}(7\sigma_1 - 5\sigma_3) \cdot d \right], & \text{in the vertical direction} \end{cases} \quad (12)$$

In the vertical direction, opposite to horizontal, and assumed σ_1 horizontal as the case of most caves (Rimmelin et al. 2020), breakdown pressure has a maximum value for $d = 0$ which gradually decreases until reaching pre-mining conditions. In the vertical direction, it is interesting to understand the zone of unconfinement (loosening) that can be estimated by developing the radial stress vertically with respect to the distance 'd', using the Kirsch (1898) formulation:

$$\sigma_{rr} = \frac{1}{2}(\sigma_1 + \sigma_3) \cdot \left(1 - \frac{s^2}{(s+d)^2} \right) + \frac{1}{2}(\sigma_1 - \sigma_3) \cdot \left(1 - \frac{4s^2}{(s+d)^2} + \frac{3s^4}{(s+d)^4} \right) \cdot \cos 2\phi \quad (13)$$

By applying the approximations (8) and (9), the following expression is obtained:

$$\sigma_{rr} = \frac{1}{s}(3\sigma_1 - \sigma_3) \cdot d \quad (14)$$

Then, the vertical loosening zone 'd*' is obtained by making $\sigma_{rr}(d^*) = \sigma_3$

$$d^* = \frac{s}{(3k-1)} \quad (15)$$

This result shows that the unconfined zone (loosening) above the cave back is related to the stress ratio and cave size only, based on the assumptions presented in this paper.

2.2 Implications for cave engineering

Equation 11 is consistent with the expectation of a low breakdown pressure related to a higher stress ratio, which in this case reaches a critical value of $\sigma_1:\sigma_3 = 3:1$ to make the first term of the model zero. There is also another critical stress ratio related to the second term of the model, which is $\sigma_1:\sigma_3 = 7:5 = 1.4$ that can be understood as a lower limit. In this regard, the model predicts a change in the behaviour of the cave propagation, making it more difficult to apply hydraulic fracturing to re-induce caving from vertical holes above the cave that has stalled.

At a low stress ratio, the model shows little or no opportunities for post-conditioning because the breakdown pressure does not vary with the distance to the cave. This can also be understood as good natural conditions for caving. From an opposite viewpoint, as long as the stress ratio decreases, the model predicts zones of high breakdown demand which makes pre-conditioning less efficient and highly demanding.

The problem of low stress ratios could be expected at very great depth, but the proposed model also offers an opportunity for a potential solution by taking advantage of applying hydraulic fracturing concurrent to cave mining conditions. Figure 6 shows the results for Equation 11 for different stress ratios until the boundary limit with pre-mining conditions, for horizontal distance from the cave which varies in the range of 50–80 m for this example of cave size and stress field. The process can be enabled by applying post-conditioning soon after cave initiation (undercutting) by allocating hydraulic fractures ahead in the range of expected lower breakdown pressure demand (Figures 6 and 7).

This post-conditioning application can be used as a second stage following pre-conditioning for anticipated very deep high stress environments to enhance cave performance.

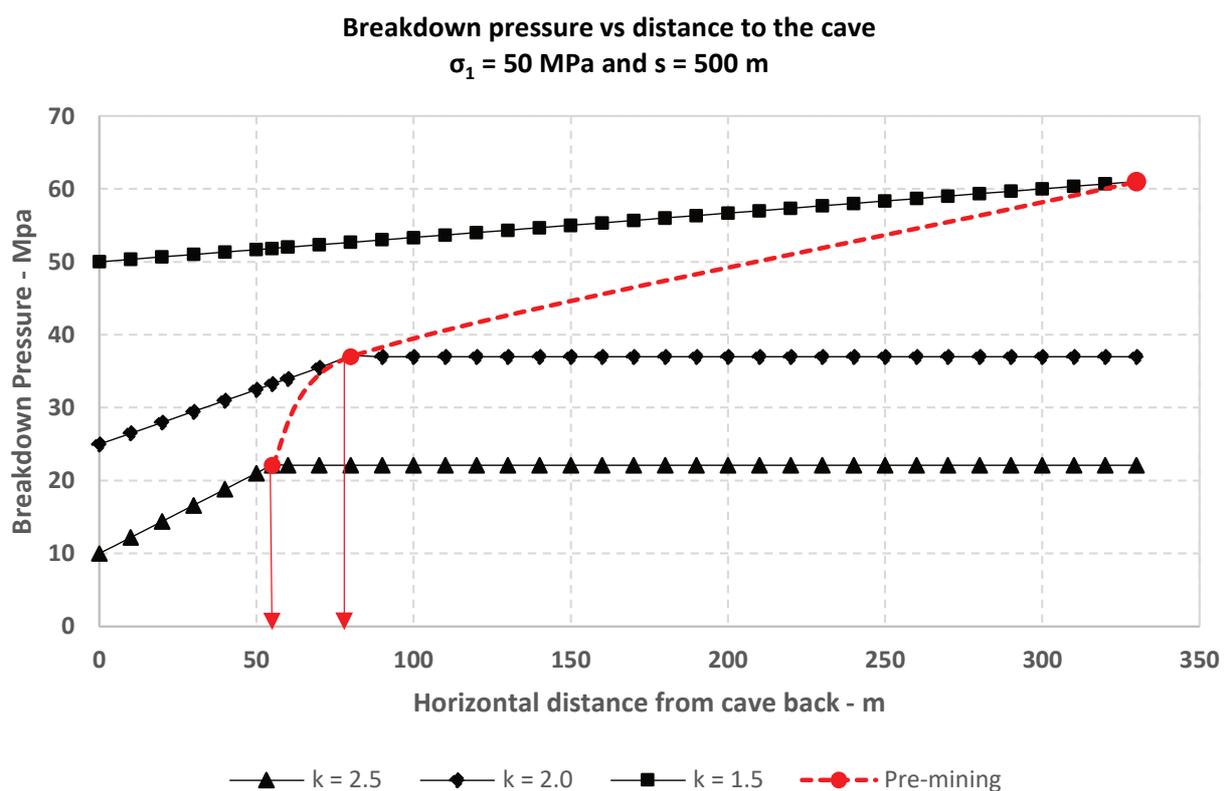


Figure 6 Modelling of breakdown pressure versus distance to cave in the horizontal direction. Results are based on a major principal stress of 50 MPa and cave size of 500 m

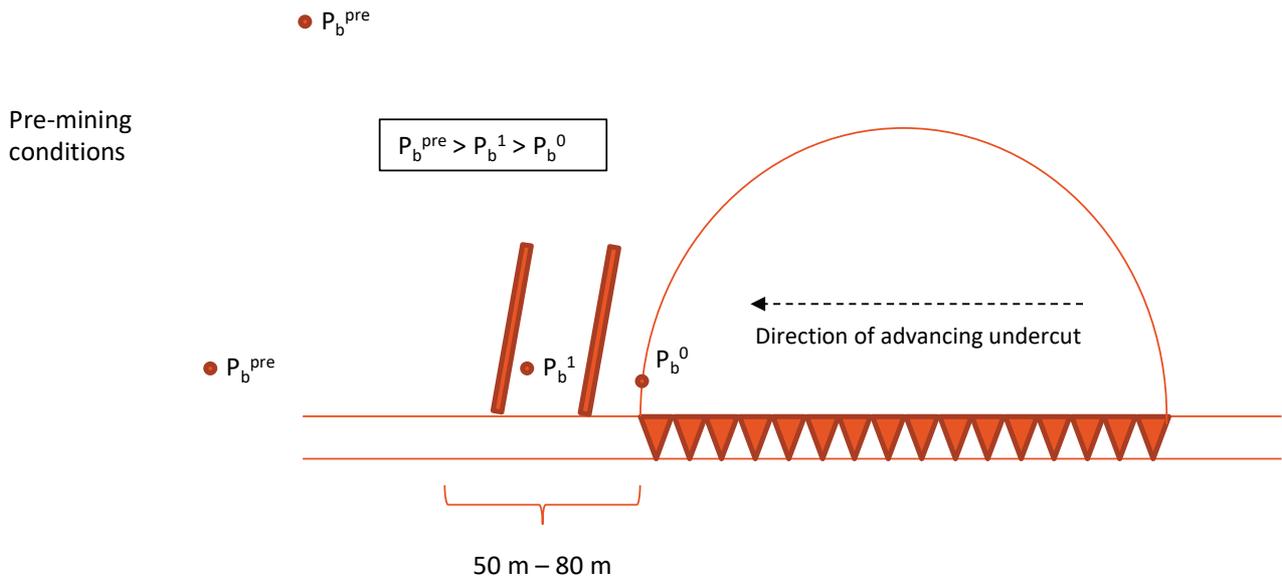


Figure 7 Application of hydraulic fracturing concurrent to cave mining conditions (post-conditioning). Zone of 50–80 m based on the assumptions in Figure 3

Equation 11 also predicts a higher breakdown pressure demand in the vertical direction which means vertical fracturing is not the preferred path of cave propagation, due to expected higher horizontal compressive stress (Figure 8). In spite of these conditions, Equations 14 and 15 anticipate a zone of low confinement associated with vertical stresses lower than σ_3 (Figure 9), which also represents an area of higher stress anisotropy (Figure 10). These results combined explain why the application of hydraulic fracturing actually works to re-induce caving from the upper levels such as at the historic cases of Northparkes or Grasberg.

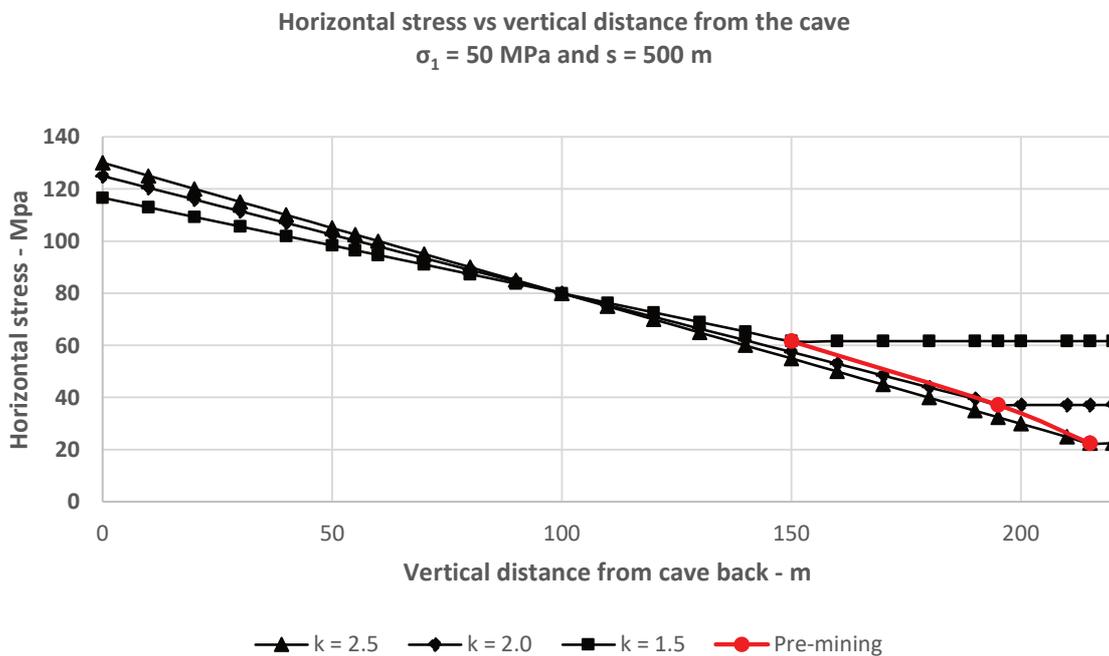


Figure 8 Higher horizontal stress (tangential stress in the vertical direction) versus distance from above the cave at different stress ratios

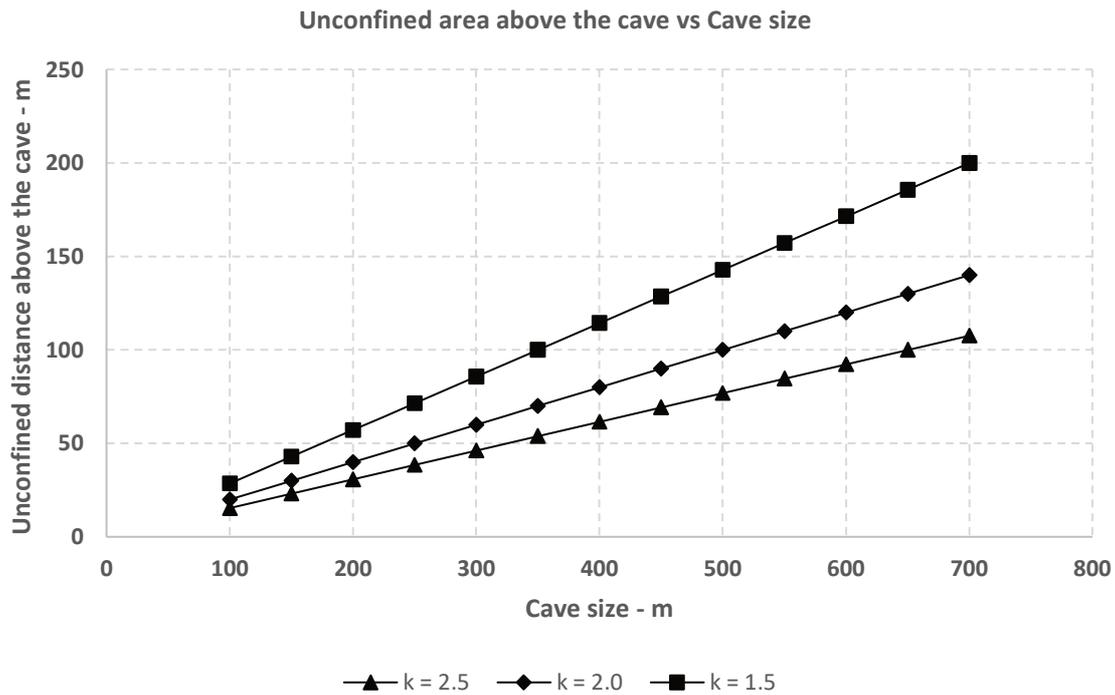


Figure 9 Unconfined area above the cave at different stress ratios. The area is represented by the vertical distance from above the cave

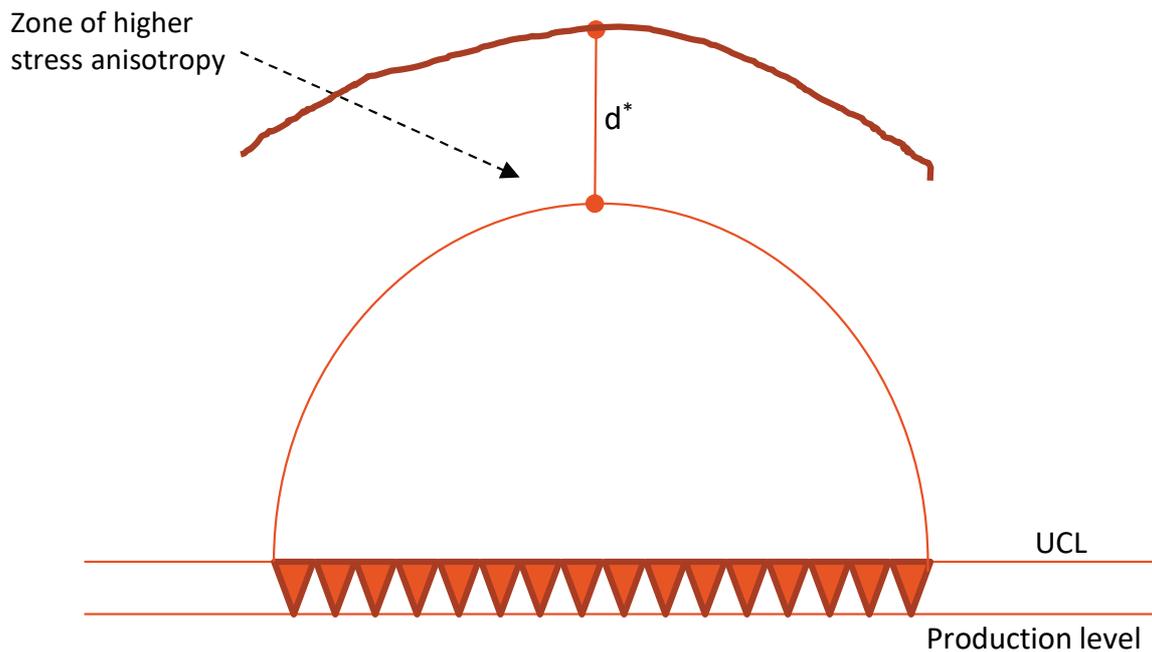


Figure 10 Zone of higher stress anisotropy associated with a combination of high vertical stress and low tangential/horizontal stress

The extension of this model to different sub-vertical angles expands the application of cave re-induction to a new application of cave engineering. The application of hydraulic fracturing from sub-vertical angles may result in additional fracturing parallel to the cave to force a propagation in a specific direction or what can be named 'directional caving'. This concept of directional caving can be designed by applying hydraulic fracturing in several stages, as long as new zones of higher stress anisotropy are created (Figure 11).

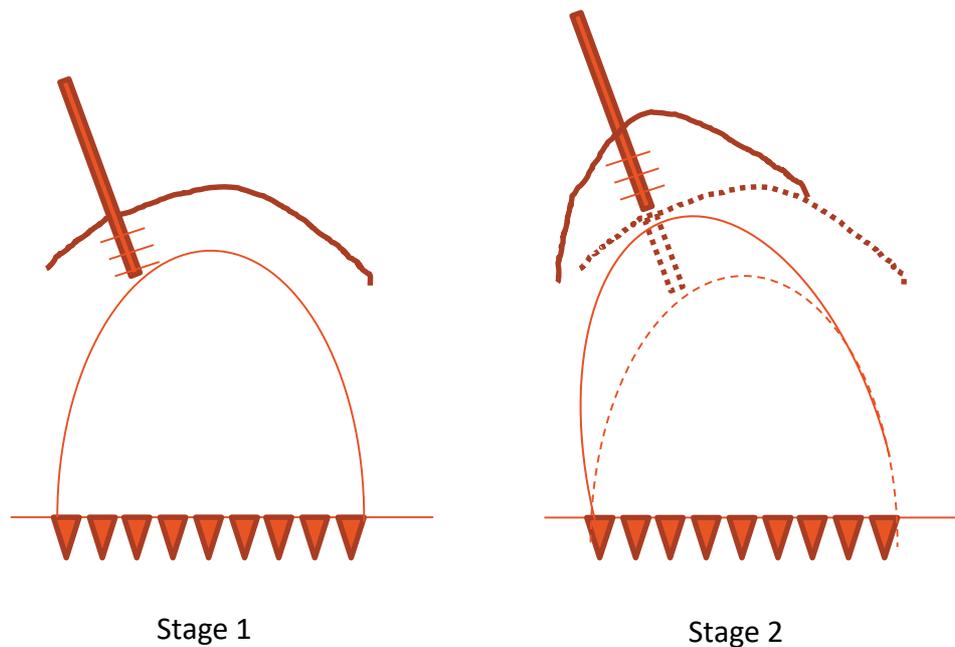


Figure 11 Conceptualisation of directional caving implemented in stages

3 Conclusion

The present work has provided an analytical model to explain rock mass conditioning concurrent to cave mining conditions. The model has been developed to estimate not only the aspects related to fracture initiation, in order to explain the feasibility of re-inducing caving utilising hydraulic fracturing, but also to introduce opportunities for new applications in cave engineering. The first new application presented in this paper is based on the implementation of hydraulic fracturing ahead of the cave front in the direction of advancing undercut, within the area of higher stress anisotropy, as a potential second stage of post-conditioning following a first stage of rock mass pre-conditioning. Secondly, it is proposed that a novel application named ‘directional caving’ can utilise hydraulic fracturing to potentially change the orientation of cave propagation. This second application, if confirmed in the field, has the potential to unlock resources underneath sensitive areas on surface and reduce cave propagation through uneconomic or unfavourable zones.

This development is part of an ongoing research on hydraulic conditioning concurrent to cave mining conditions, or rock mass post-conditioning, which is validating this model using field data from existing cave mines. This research also aims to explain aspects of fracture propagation in cases of rock mass post-conditioning to expand and deepen the present work.

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