Effect of blast damage on pillars of caving mines

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ABSTRACT: This paper presents an assessment in terms of the influence that blast damage can have over rock pillars and the behavior of rock mass using 3D numerical modelling. The utilization of this approach enables the calibration of model parameters and highlights the framework concerning limit loads and deformations that can occur in production drifts, as well as their association with pillar stability. Its relevance becomes substantial during the construction of underground mines and when utilized for decision-making in project design, where the impact of blasting plays a crucial role in achieving high-quality engineering work.

Keywords: Pillars, Blast Damage, Caving, Numerical Modelling.

1 INTRODUCTION

During the extraction level construction of an underground mine by Block Caving or Sublevel Caving that will include drifts and galleries arrangements or openings, the blasting effect on the strength and deformability of the pillar is quite significant. The excavations proximity develops some relaxation or induced damage that if not considered, will have relevant implications on the behavior of the rock mass in the short and long term. Although some examples have been found where the impact of this type of damage is exposed (Jessu *et al*, 2018), these do not take into consideration the inherent shape of the tunnels, their arrangement, or the intersections between them generated, as is the case of the pillars formed in large-scale underground mining.

While other assessments, such as the one conducted by Renani & Martin (2018), take into account the intersection of drifts, they do not consider the induced effects of blasting damage on the strength and deformability of the pillar. The present paper examines the level of impact that considering such damage has when utilizing Hoek & Brown's (2002) approach, along with the recommendations that were issued prior to the 2018 update. The assessment specifically applies to pillars frequently employed in large-scale underground mining methods like Panel Caving and Sublevel Caving. It is important to note that this paper solely addresses geotechnical stability concerns and does not delve into issues related to mining method geometries or support systems.

2 BLASTING DAMAGE TO PILLARS BETWEEN DRIFTS

The fundamental objective of an excavation process is the fragmentation and removal of material resulting in an opening such as a drift or tunnel. In the case of the rock mass and given its hardness, explosives are widely used, whose selection to achieve good fragmentation and optimal use of energy involves an important variety of considerations, which can lead to the excavation's contours being left with some damage level.

Furthermore, Hoek (2018) describes that when rock excavations are developed the removal of material implies a relief of stresses that allows the surrounding rock to relax and expand. Hence, the objective of a good design is to control dilation and the consequent displacements in order to mitigate the failure of the surrounding rock mass. Optimum results can be achieved by a careful selection of opening shape, the method of excavation, smooth blasting and, if necessary, considering supports and reinforcements. In the case of tunnels, blasting control is particularly necessary, due to the impacts that may generate the occurrence of unexpected geotechnical. Figure 1 shows an example of a tunnel with poor blast control in its final state, compared to one developed with carefully evaluated controls.

Figure 1. Example of tunnels with damage control system, to the left Drill & Blast of poor quality *(http://www.bradshawcc.com/projects/441/view/)*, to the right Drill & Blast of good quality *(Kuzyl & Martino, 2008)*.

To consider the effect of this damage on geotechnical analyses, a common approach is to penalize the rock mass strength at the periphery of the excavation, by reducing the strength parameters (Hoek *et. al.* 2012; Sharifzadeh & Pah, 2014) or by increasing the fracturing induced by blasting (Shen & Barton, 1997). It is evident that considering different depths of damage will have obvious implications on the analytical or numerical response of the excavations.

Figure 2 shows an example where the effect of this damage is present in a pseudo-continuous model indicating that adding this effect to the analysis could help detect instabilities in the excavation.

In the case of pillars built between tunnels, these will present damage that will not only affect the behavior surrounding the excavation, but will influence the stability of the pillar itself, since they diminish the intact core that constitutes the pillar; thus, the depth where the damage occurs becomes an element of importance to be consider in any assessment.

According to Hoek (2012), the most critical scenario arises from a poorly designed and carelessly executed blasting condition. In such cases, the damage can extend up to two to three meters around the tunnel, along with a significant damage factor value (D=0.8). In this context, questions arise regarding the rock stability impact of deeper induced damage if the rock mass is more vulnerable or if the recommended damage factor value is not as severe as recommended.

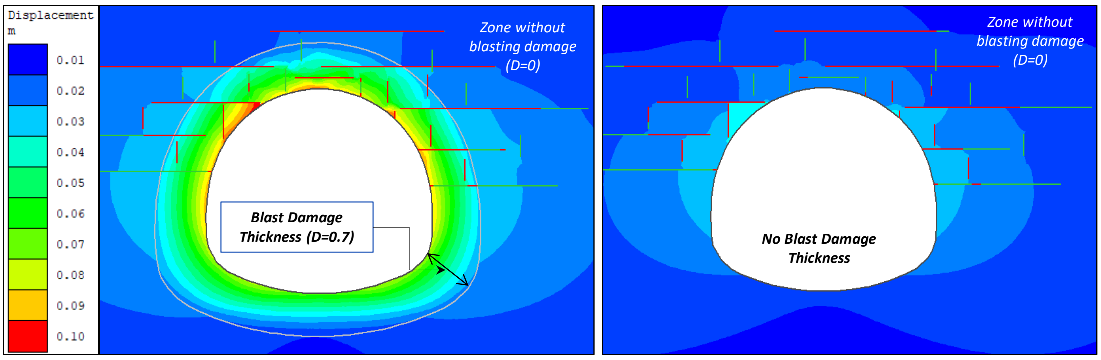

Figure 2. Impact of blasting damage on a pseudo-continuous model, to the right, the result of blasting damage applied to the thickness surrounding the opening, the left shows the model free of damage.

3 INFLUENCE OF BLASTING DAMAGE ON PILLARS

An evaluation of various blast-induced damage conditions was conducted using a localized 3D model of a pillar. Figure 3 illustrates the geometry of the local model of a pillar (Bustamante E. & Montiel E., 2022; Russo *et. al* 2022), generated in FLAC^{3D} (Itasca, 2009) where the relationship of the affected area by blasting damage can be observed, in regard to an arrangement where four tunnels with dimensions of five meters intersect creating a pillar that is fifteen meters wide between them.

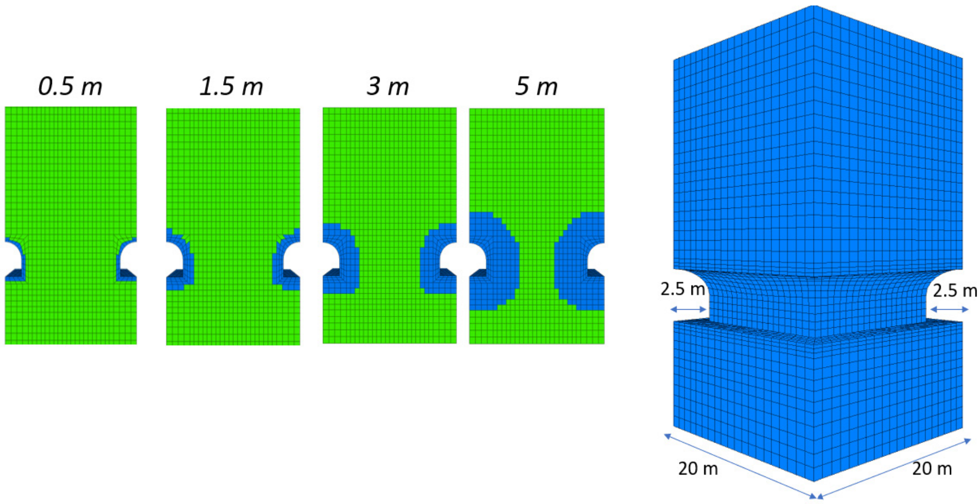

Figure 3. Example of visualization of area affected by blasting damage in a tunnel array.

These models consisted of three stages, an initial stage where the stress state was established, a second stage that involved tunnel excavation with damage blasting addition and a third stage corresponding to the pillar's factor of safety calculation (FoS), for this purpose the strength reduction criterion (Duncan ,1996) was used. To visualize the damage effect, the properties were calibrated so that the pillar in Figure 3 had a limit stability condition (FoS=1) if the damage condition represented a poor blasting *(*damage factor $D = 0.7$*)* and with a thickness of five meters, going deeper than that indicated in Hoek's (2012) recommendations.

The values obtained for this exercise indicated a rock mass quality ranging from regular to poor, with GSI (Geological Strength Index) of 30, mi (Hoek-Brown constant) of 12, and σ_{ci} (uniaxial compressive strength) of 45 MPa. It is important to emphasize that the only prevailing state of stress is the gravitational field. Nevertheless, it should be noted that the tensor field represents a hydrostatic condition, which can undergo significant alterations, particularly at greater depths where these pillars are located. For a more comprehensive understanding of how these pillars respond to variations in characterization, it is advisable to consult the study by Bustamante E. & Montiel E., 2022. The assessment results are presented in Figure 4, where the evaluated cases are categorized based on whether damage was considered and the influence of the depth of damage on the factor of safety as levels of damage intensity increase.

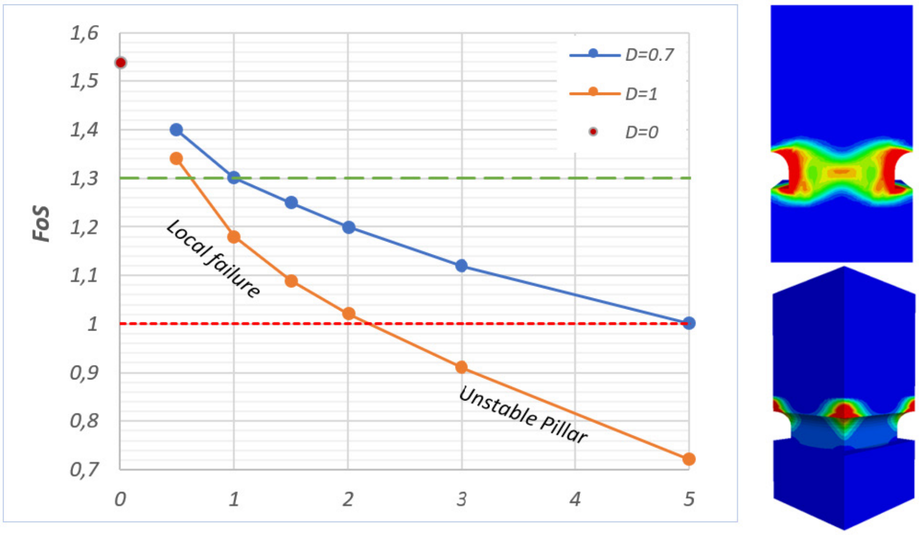

Figure 4. shows the obtained results, the graph on the left displays the results; core failure mechanism are shown to the right and above; local failure mechanism are shown to the right below, associated with very high blast damage conditions.

The graph in Figure 4 adds the result of considering the pillar without blast damage. The FoS decreases with increasing depth of damage and intensity. At a thickness of five meters and a damage factor of 1.0, the pillar is in equilibrium. The failure mechanism generally occurs in the pillar's core.

For damage D = 1, the failure mechanisms are characterized by being located from 0.5 to 2 m thick, failing locally in the tunnel vault and at the intersection between the tunnels. When the depth of damage exceeds two meters the pillar collapses due to its own weight, returning to the core failure mechanism, which is also evident in the FoS falling below one.

It is important to point out that the effect of considering the damage due to recklessness in the use of explosives *(D = 0.7)* implies a reduction of the FoS from *1.5* to *1.1*; that is, *27%* and if this factor is at its highest limit *(D = 1.0),* the pillar becomes unstable. It is evident that in this unfavorable scenario, attaining an acceptable factor of safety following blasting would necessitate reinforcing the pillar. However, this approach is conceptually impractical due to the significant costs involved and the potential risks it poses throughout the mining project life of mine (LOM).

4 THE EFFECT OF BLASTING DAMAGE ON THE PRODUCTION LEVELS OF SUBLEVEL AND PANEL CAVING MINES

The pillars designed for the Panel and Sublevel Caving methods should take into account the impact of blasting by considering at least two different anticipated depths of damage. Additionally, it is essential to incorporate the expected maximum stress levels that the pillars could experience in order to anticipate any potential instability. In this assessment a maximum abutment stress of 55 MPa was expected. Although the Sublevel Caving pillars offer higher resistance *per se,* in this evaluation the convergence measurement was considered to study the behavior of the tunnels under incremental load, resulting in a necessary deformational comparison.

To achieve this solution, the pillars were instrumented with a series of points to measure the strain as a function of closure (Hoek & Marinos, 2000), having as limits of behavior the values of *2.5%* and *5%* for conditions "controllable with light support" and " heavy reinforcement situations" respectively. The geometrical arrangement of the pillars; as well as the monitoring points required to measure the strain are shown in Figure 5. To evaluate the abutment stress, the pillars were loaded at the top until they reached failure, monitoring the strain at each increment.

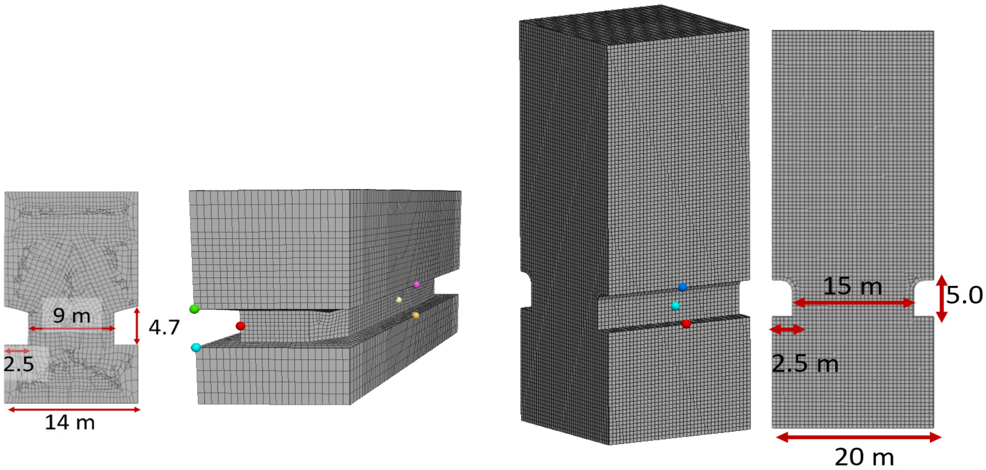

Figure 5. Geometric arrangement of the pillars to be compared and convergence measurement points.

The geotechnical properties of the rock mass correspond to a $GSI = 50$, $m_i = 14$ and $\sigma_{ci} = 48\ MPa$ with an initial vertical stress of *22 MPa* and a stress ratio of $k = 1.5$. Two depths of damage were evaluated, specifically at 0.5m and 1.5m (thickness), with a damage factor (D) of 0.7. Figure 6 illustrates the graph of "Normalized Stress vs. Strain" for each case, as it represents the direction where the highest deformation was observed.

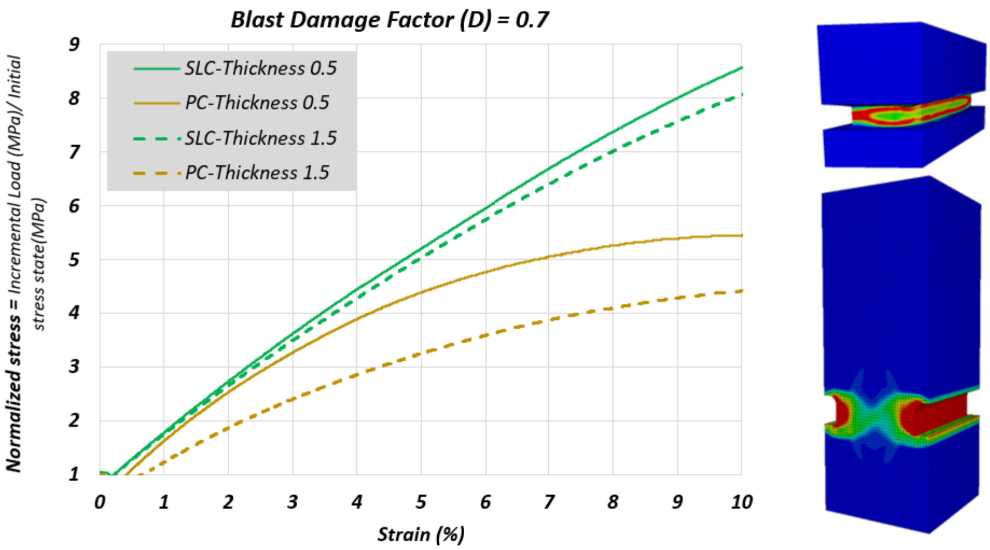

Figure 6. Pillars response plot and failure mechanisms of each local model, note that the corners of the Panel Caving pillar are more damaged than along the tunnels.

The obtained solution at a strain of 2.5% indicates that the different pillars, in their respective damage conditions, can support an approximate stress of 66 MPa (approximately three times the initial vertical stress), except for the Panel Caving case with a thickness of 1.5 m, which can withstand approximately 45 MPa. When considering a "Heavy Support" condition, the Sublevel Caving pillars show minimal changes due to blast damage, as they can withstand approximately five times the initial vertical stress. However, in the case of Panel Caving, the difference becomes apparent, as the one-meter difference in thickness corresponds to a decrease in strength from 4.5 times the initial vertical stress (in the case of 0.5 m thickness) to 3.2 times the initial vertical stress (in the case of 1.5 m thickness). In this regard, it can be stated that exercising caution during blasting operations ensures that either of the two cases meets the expected Maximum Abutment requirements by incorporating moderately robust reinforcements to achieve a sufficient margin of safety. However, it becomes critically important to handle explosive usage with utmost care, especially in the case of Panel

Caving. It is worth emphasizing that this criterion is significantly different from the ultimate strength of each pillar, which is attained with a strain of 12% in the case of Panel Caving. For a thickness of 0.5m, the ultimate strength values are approximately 4.5 times the initial vertical stress, while for a thickness of 1.5m, it is approximately 3.5 times the initial vertical stress. On the other hand, for Sublevel Caving, the maximum load is only reached with a strain exceeding 20%, resulting in significantly higher strength values of over 8 times the initial vertical stress for both thicknesses. However, operating the pillars at their maximum load would lead to an uncontrollable strain condition.

5 CONCLUSIONS

This paper has presented a comparison of the effects of incorporating blast damage through the utilization of local 3D models. It emphasizes the evaluation of the deformational response at the tunnel level, which ensures the limitation of loads to safe values, yet without directly assessing the failure of the pillars themselves.

This form of assessment demonstrates great versatility, as it can greatly contribute to decision-making in project design. Furthermore, it can be applied to scenarios involving parameter calibration and even support response, owing to the comprehensive capacity, flexibility and level of detail it offers. It is evident that further exploration of the utilization of these models is necessary to form sound engineering judgments regarding the anticipated response of intricate geometries and complex excavation processes.

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