Blasting in sublevel caving

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Abstract In sublevel caving, blasting operates under confined conditions, with the fragmented rock bordering the blasted stope and therefore setting unique blasting environment. The deformation resistance of this broken rock plays a crucial role, affecting blasted rock fragmentation and subsequent processes. This article explains the impact of the broken rock (confinement) on the formation of blast-induced fractures due to its inherent deformation. Additionally, strategies to circumvent the negative crater effect at the sublevel drift are discussed. Conversely, when appropriately utilized at the stope's upper side, this effect can lead to reductions in drilling and explosive consumption.

Keywords: sublevel caving; blasting; crater effect; rock fragmentation; explosives;

1 INTRODUCTION

The sublevel caving blasting is characterized by two dominant features: boreholes are drilled in a fan / ring pattern, resulting in non-parallel boreholes within the plane parallel to the *primary* free surface. In sublevel caving, there are two additional free surfaces: one at the top of the stope, which is perpendicular to the primary free surface, and another at the top of the sublevel drift, which is the starting point from which boreholes are drilled. The last one is the only genuine free surface, as it borders solely with air, which offers no resistance to deformation. The other surfaces are bordered by fragmented rock material, which has significant deformation resistance. Hence, these surfaces can be considered conditionally free. This is typically described as blasting under confined conditions.

2 ROCK FRACTURING IN SUBLEVEL CAVING

The fracturing of a rock segment by a single explosive charge occurs in two stages. In the first stage, radial tension fractures form around the explosive charge. This acts as a preconditioning of the rock segment, as the formation of fragments is incomplete and there is no dislocation of the fragments. The second stage occurs only if a free surface is located within a distance of B (burden) or less. During this stage, blast-induced tension fractures form subparallel to the free surface, starting from the free surface and extending towards the explosive charge. This new set of fractures is perpendicular to the preceding set, leading to the formation of fragments that begin moving towards the free surface.

As previously noted in references [1, 2, 3], upon the initiation of the explosive charge within the borehole, a detonation pressure is rapidly generated. This pressure can be determined using known equations:

for explosive with density above 1 g/cm^3:

$$P_b = \frac{\rho_e D^2}{8}$$

for explosives with density below 1 g/cm^3 :

$$P_b = \frac{\rho_e D^2}{4.5}$$

Where:

ρ_e – *explosive density (g/cm^3)*
D *-velocity of detonation (km/s)*

This shock load generates a pressure wave within the surrounding rock, with an intensity experienced by rock particles at the borehole wall as follows:

$$P_s = \frac{\rho_s V_p^2}{8}$$

for explosive with density above 1 g/cm^3, and

$$P_s = \frac{\rho_s V_p^2}{4.5}$$

for explosive with density below 1 g/cm^3.

Where:

P_s – pressure wave intensity in the rock at the borehole wall (GPa),
ρ_s – rock density (g/cm^3),
V_p – p-wave velocity of rock (km/s).

Depending on the properties of the explosive and the rock, the intensity of the pressure wave within the rock can be lesser, greater, or equivalent to the detonation pressure inside the borehole. If the intensity of the pressure wave in the rock exceeds the detonation pressure, as is the case in hard rock blasting using ANFO, then rock particles do not return to their original positions after the passage of the pressure wave. This is due to the pressure inside the borehole, which persists for several milliseconds. Rock particles will revert to a position where the pressure load exerted on them matches the pressure inside the borehole.

When the pressure wave reaches the free surface, rock particles at that surface have no medium to transmit strain energy to and will consequently begin moving in the same direction. The adjacent row of particles will subsequently begin moving in the same direction, and this pattern continues successively. The distance between two rock particles is reduced proportionally to the pressure load. If the rock material behaved as an ideal elastic material, the rock particles would shift to an equilibrium state and proceed to move by an amount equivalent to the compressional strain. In such a scenario, tension would develop between the two particles instead of compression. The strain would have the same magnitude but with an opposite sign. Since real rock exhibit not only elastic but also plastic behavior, only a portion of the energy spent on compression will be recoverable and available for tension following sudden relief.

The tensile strain in the radial direction at a distance B will be given by:

$$e_{rt} = \frac{P_h \, r_h I_{sr}}{kEB}$$

Where:

I_{sr} – strain energy recoverability index:

$$I_{sr} = \frac{E_r}{E_t}$$

E_r – recoverable strain energy
E_t- total strain energy (recoverable + absorbed)

This equation applies to scenarios where only air is present at the free surface. However, in sublevel caving, the free surface is connected to fragmented rock, which possesses significant deformation resistance. Consequently, the tensile strain (e_{rt}) will be reduced by the compression strain of the fragmented rock:

$$e_m = \frac{\sigma_B}{E_m}$$

Where:

$$\sigma_B = P_h \frac{r_h}{B}$$

Where:

σ_B –The pressure load in the radial direction at the interface between solid and broken rock (*MPa*),
P_h – borehole pressure (MPa),
r_h –borehole radius (m),
E_m – deformation modulus of broken rock (MPa).

The tensile strain in the radial direction at a distance B can be expressed as:

$$e_{rt} = \frac{P_h\, r_h I_{sr}}{kEB} - \frac{\sigma_B}{E_m}$$

For a single tension fracture to form, it is required:

$$e_t = \frac{\sigma_t}{E}$$

The number of tension fractures formed at a distance B is given by:

$$n = \frac{e_{rt}}{e_t}$$

The first tension fracture, which is subparallel to the free surface, will form at a distance "b" from the free surface, as described by:

$$b = \frac{B}{n}$$

The subsequent tension fracture forms at a distance "b_1", which is less than "b" due to the increased tensile strain. Similarly, the distance "b_2" is smaller than "b_1", and this pattern continues, as depicted in Figure 1.

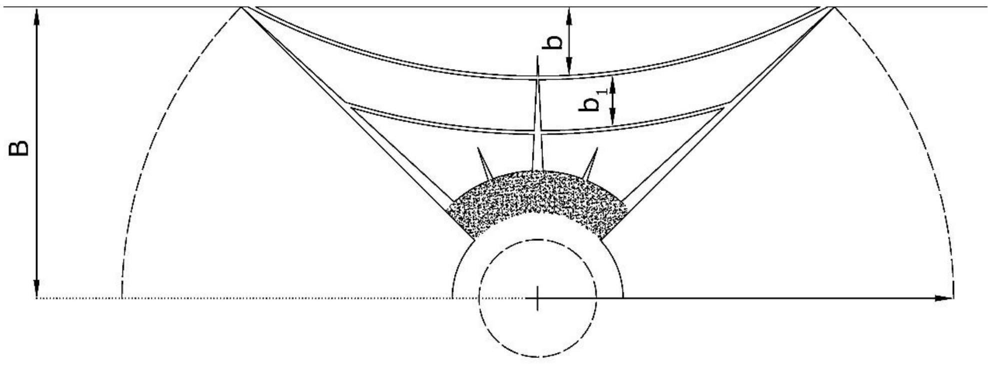

Figure 1 The formation of tension fractures subparallel to the free surface

3 CRATER EFFECT IN SUBLEVEL CAVING

In sublevel caving, the crater effect can manifest either positively or negatively. In the typical scenario where the velocity of detonation and the p-wave velocity of the rock differ, the uncharged portion of the borehole may exhibit a negative crater effect, resulting in a smaller crater [3], Figure 2. If the crater effect occurs, it alters the shape of the sublevel drift at the drawpoint, affects gravity flow, reducing recovery, and poses challenges for subsequent blasts. To prevent the negative crater effect, boreholes that create the roof of the sublevel drift should be entirely filled with explosives. For other boreholes that are only partially filled with explosives, they should be charged in a way that ensures the empty portion of the borehole exceeds the burden B in length.

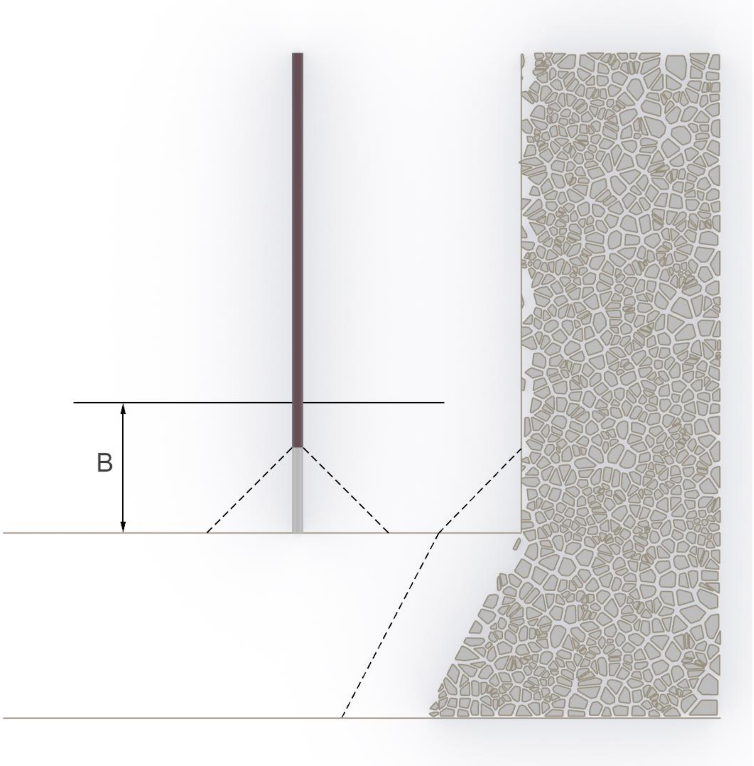

Figure 2 Negative crater effect in the sublevel drift

A more significant crater effect, which could have positive implications, is not commonly utilized in sublevel caving operations. Referring to the typical blasting pattern shown in Figure 3, it is common for boreholes to be drilled completely. However, in instances of poor drilling management, holes might be drilled until the cave is reached, especially when the stope shape is not well recorded. By leveraging the positive crater effect, both drilling length and explosive consumption can be significantly reduced, leading to cost decrease, as illustrated in Figure 4. Also, if the Velocity of Detonation (VOD) aligns with the p-wave velocity of the rock, the results will be more favorable. We will consider case with unaligned velocities.

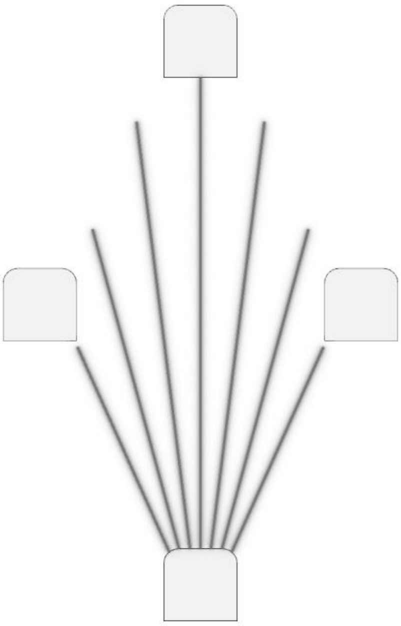

Figure 3 Typical blasting pattern in sublevel caving, after [4]

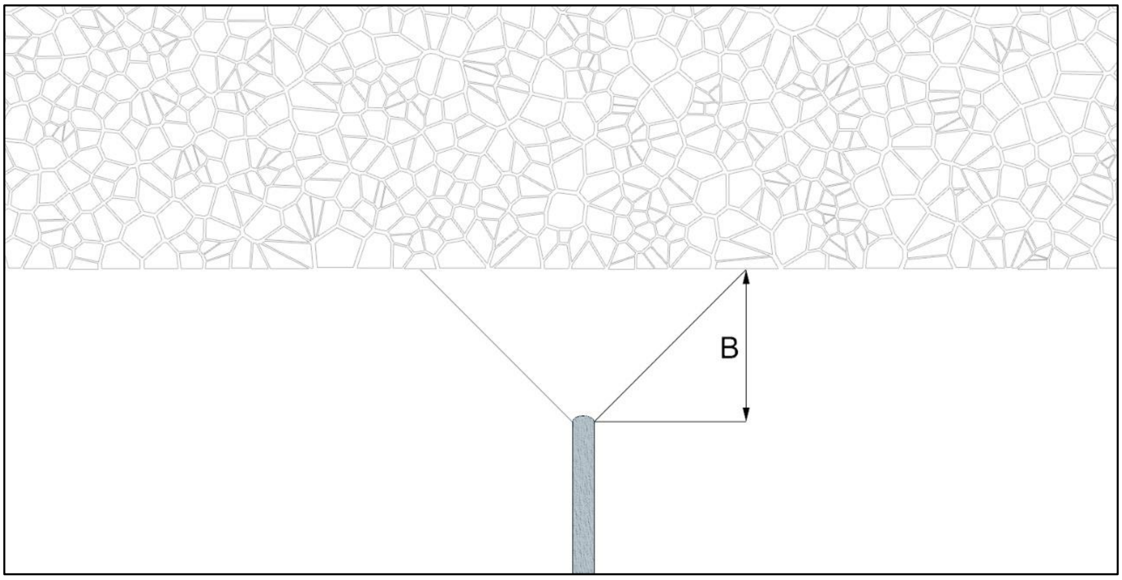

Figure 4 Crater at the end of the explosive charge

Sudden rise of detonation pressure inside of the borehole induces pressure wave in the rock particles. Shape of the pressure wave front depends on the shape of the rock surface that consists of the rock particles that are simultaneously activated by the detonation pressure. The bottom of the borehole is typically flat, though it may exhibit a slight curve when certain button drilling bits are used. For radial tension fractures to form in the space between the bottom of the borehole and the free surface, the shape of the pressure wave front needs to be spherical. To achieve this, the bottom of the borehole, or the geometrical location of the rock particles where the pressure wave is initiated simultaneously, must be spherical, as shown in Figure 5.

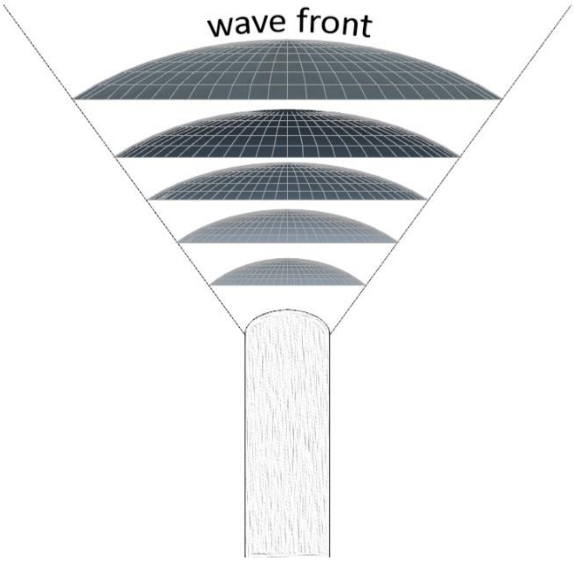

Figure 5 Bottom of the borehole and corresponding shape of the pressure wave front

4 CONCLUSION

In sublevel caving, the blasting environment is distinct in various ways, from the use of non-parallel boreholes in the blasting pattern to the confined blasting conditions. The confinement provided by the fragmented rock preceding the stope significantly influences the formation of blast-induced fractures, primarily by affecting the magnitude of the tensile strain imposed on the blasted rock. This article delves into the confinement influence, introducing expressions that describe the formation of both radial and tension fractures that form subparallel to the free surface. The crater effect, which can be negative in the sublevel drift, can be avoided by fully filling boreholes with explosives and ensuring that the unfilled portion of partially filled boreholes exceeds burden B in length. Conversely, the crater effect can be used to decrease the drilling and explosive requirements. This is closely tied to the shape of the borehole's base and the requirement for the spherical pressure wave formation at the stope's upper regions. Implementing these insights can significantly trim operational costs in drilling and blasting within sublevel caving and can also be adapted to other blasting scenarios.

5 REFERENCES

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