Rock Breakage by Explosives

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Abstract

Having indicated the importance of blasting in mining and introducing some of numerous researches that have increased the level of understanding the mechanisms of rock breakage by explosives, a well-known assertion that there are no blasting models based on constitutive relationships describing the rock fracture has been repeated. The blasting model based on constitutive relationships has been introduced. The formations of the radial tension cracks around blast holes have been explained. The separations of the zones with different densities of radial cracks have been proposed, and then it has been shown the usage of the radius of the radial cracks zones for the design of the blasting pattern.

Keywords: *rock blasting, radial cracks, p-wave stress, rock breakage, burden*

1 Introduction

In the days gone by, at present, and in the forthcoming days, it is impossible to conceive the hard rock mining without blasting. This is the main reason why the great number of mining engineers has dealt with this issue, both theoretically and practically. Mathematical descriptions of these mining processes have been completely limited in use, therefore in practice are only used empirically derived formulae for the selection of blasting pattern parameters and formulae to control granulation of blasted rock.

These formulae have been derived due to experiments mainly conducted on synthetic material (such as *Plexiglas, Epoxy and concrete*), and less frequently in the natural rock massif. All these studies have provided significant insight into the mechanisms of rock breakage by explosives, and numerous researchers, (Rustan A. Vutukuri VS., 1983), (Dick RD, Fourney WL, Wang XJ, C. Young, 1993), (Fourney, 1993), and many others have increased with their work the level of understanding of this process.

It is possible to find throughout plenty of different studies the numerous descriptions of the rock breakage around the blast hole after its initiation, though all of them can be comprised by the description (BN Whittaker, RN Singh, G. Sun, 1992): “After the detonation of explosive, the whole blast hole is filled with gaseous detonation products at very high pressure and temperature. This pressure is exerted immediately on the wall of the blast hole, generating radial compressive stress, which is so much higher than the strength of the rock that a thin zone (Figure 1) is formed around, the blast hole in which the rock has yielded and been extensively broken or crushed by granular cracking, microcracking, differential compression of the particles and matrix of the rock and other forms of plastic deformation."

Experts have been presented with a lot of empirical and semi-empirical models for assessment of the perimeter of the crushing zone around the blast hole, (II'yushin, 1971), (Vovk A, A Mikhalyuk, Belinskii I., 1973), (Szuladzinski, 1993), (Djordjevic, 1999), (Kanchibotla SS, Valery W, Morrell S., 1999), (Essen, S., I. Onederraa, H.A. Bilginb., 2003). Blasting models, however, based on constitutive relationships describing the main properties of rock fracture, don't still exist.

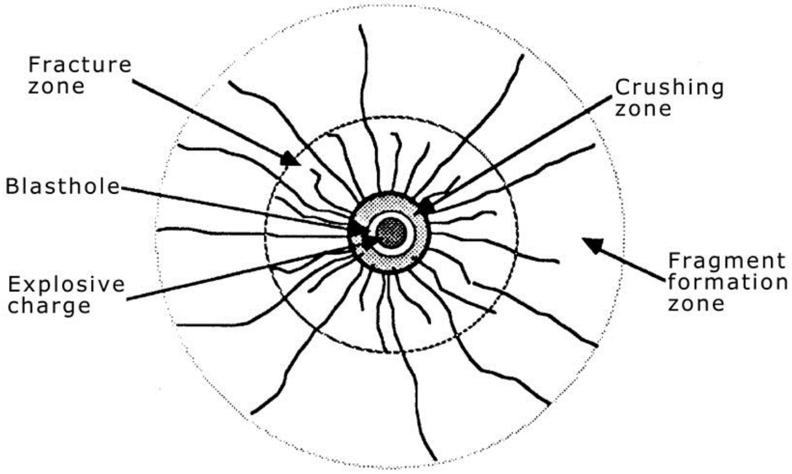

Figure 1 Schematic illustration of processes occurring in the rock around a blast hole, showing formation of crushing zones, fracture zones and fragment formation zone

(BN Whittaker, RN Singh, G. Sun, 1992)

2 Rock Blasting Theory

Detonation of an explosive charge in rock results in dynamic loading of the walls of the borehole and generation of a stress wave that transmits energy through the surrounding medium.

Pressure wave extends from borehole walls circularly around the borehole (Figure 2). At the distance r_{cn} from the borehole compressive stress of the rock in the radial direction is:

$$\sigma_{rc} = P_h \frac{r_h}{r_{cn}} \quad [1]$$

Where:

σ_{rc}- radial compressive stress
P_h- borehole pressure
r_h- borehole radius
r_{cn}- crack zone radius

On the other hand:

$$\sigma_{rc} = Me_r \quad [2]$$

Where:

$$M = E \cdot \frac{(1-\nu)}{(1+\nu)(1-2\nu)} \quad [3]$$

$$k = \frac{(1-\nu)}{(1+\nu)(1-2\nu)} \quad [4]$$

$$\sigma_{rc} = E \cdot k \cdot e_r \quad [5]$$

M- pressure wave modulus (G. Mavko, T. Mukerji, J.Dvorkin, 2009)
e_r- radial strain
E- Young`s modulus of rock
ν- Poisson's ratio

Or:

$$e_r = \frac{\sigma_{rc}}{E \cdot k} \quad [6]$$

Therefore:

$$e_r = \frac{P_h \cdot r_h}{E \cdot k \cdot r_{cn}} \quad [7]$$

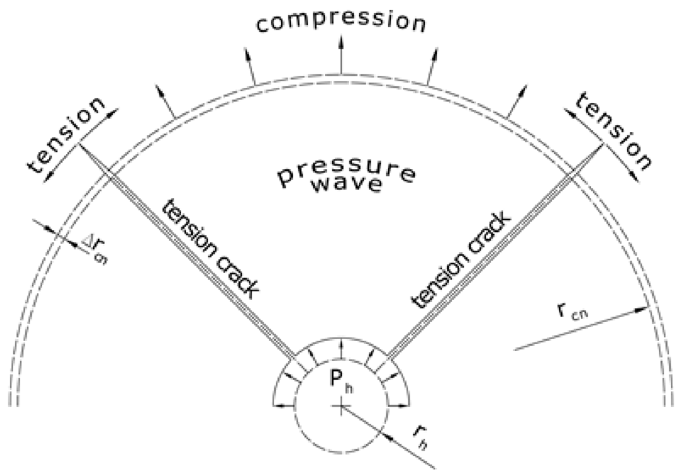

Figure 2 Schematic illustration of rock blasting model

At the distance r_{cn}, before the pressure wave gets to it, the perimeter of the closed circular ring zone of rock mass is:

$$O_r = 2\pi r_{cn} \quad [8]$$

When the pressure wave reaches the closed circular ring zone of rock mass, it is moved to a new position with a radius$(r_{cn} + \Delta r_{cn})$, and with the perimeter:

$$O_{(r_{cn}+\Delta r_{cn})} = 2\pi(r_{cn} + \Delta r_{cn}) \quad [9]$$

Therefore:

$$O_{(r_{cn}+\Delta r_{cn})} = 2\pi(r_{cn} + e_r r_{cn}) \quad [10]$$

Once the closed circular ring zone of rock mass is subjected to tension with a lateral strain:

$$e_l = \frac{O_{(r_{cn}+\Delta r_{cn})} - O_{r_{cn}}}{O_{r_{cn}}} = e_r \qquad [11]$$

For the formation of the radial tension cracks it is required tensile strain:

$$e_t = \frac{\sigma_t}{E} \qquad [12]$$

Where:

e_t- tensile strain
σ_t- tensile strength
E- Young`s modulus of rock

In addition, the number (n) of radial tensile cracks formed at a distance r_{cn} will be:

$$n = \frac{e_l}{e_t} \qquad [13]$$

Therefore, it is:

$$n = \frac{P_h r_h}{k \sigma_t r_{cn}} \qquad [14]$$

Therefore:

$$r_{cn} = \frac{P_h r_h}{k \sigma_t n} \qquad [15]$$

In addition to fracturing model proposed in this paper finite element method model was constituted using software Phase2 (Rocscience, 2008) simulating blasting process and fracture propagation. Circular model with fixed boundary conditions was used, where in the middle of model blast hole is located. Model was processed in several phases where in each phase blast hole pressure is incremented until its final value is reached. By this method of applying pressure it was possible to follow tension crack formation and propagation.

After few processing phases, as it is shown in Figure 3, tension failure occurs in elements followed by shear failure after pressure is raised. Tension failure occurs along linear trajectories forming radial cracks. Also, it is shown that distribution of Major Principal Stress corresponds to pressure wave propagation.

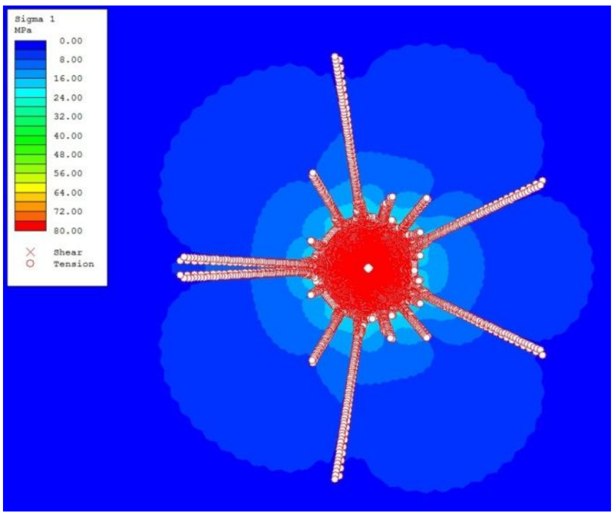

Figure 3 Contours of Major Principal Stress with Yielded Elements

In Figure 4 Minor Principal Stress distribution is shown. It could be seen that in area in front of elements where tension failure has occurred tension stress is raised and if stress is increased further failure will occur. In Figure 5 and Figure 6 principal stress trajectories and deformation vectors are shown.

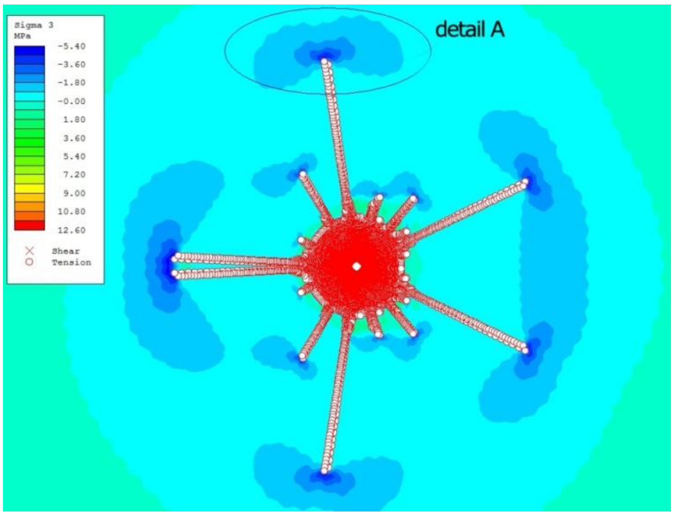

Figure 4 Contours of minor principal stress with yielded elements

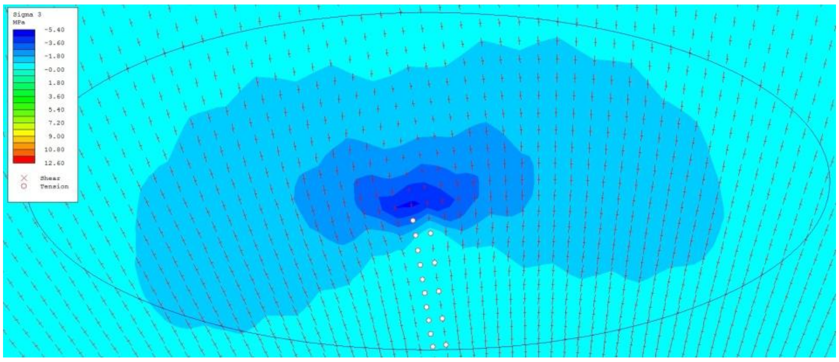

Figure 5 Contours of minor principal stress with principal stress trajectories

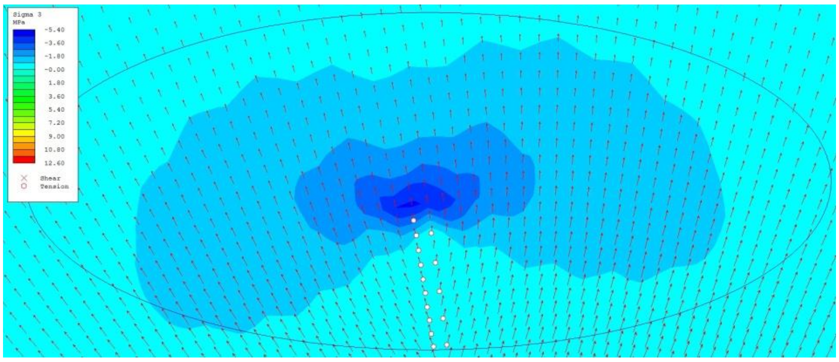

Figure 6 Contours of minor principal stress with deformation vectors

2.1 Calculating crushing zone radiuses

Therefore, for the borehole radius $r_h = 0.051m$ and the borehole pressure $P_h = 2GPa$ in granite with tensile strength $\sigma_t = 14MPa$, Poisson's ratio $\nu = 0.3$ (Figure 7, Table I) will be:
Table I Zone radius with crack density

n	2	4	8	16	32
$r_{cn}(m)$	2.71	1.35	0.68	0.34	0.16

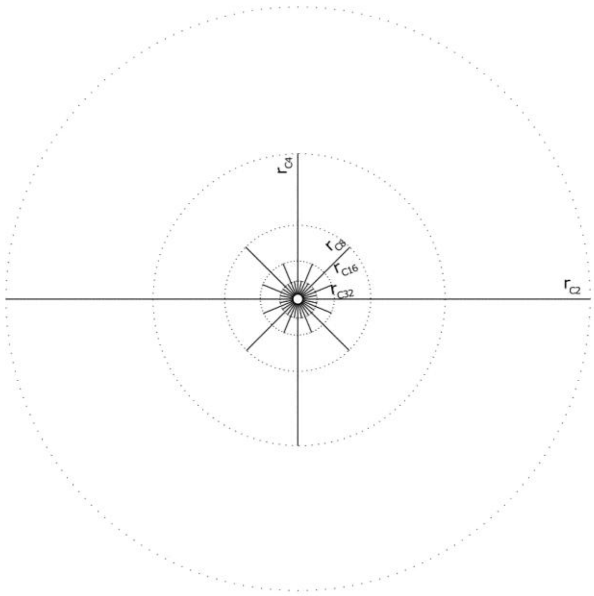

Figure 7 Zone radiuses with crack density

Consequently, the space around the explosive charge is to be divided into zones with different density of radial cracks. The practical importance for the design of the blasting pattern lies in the zones r_{c4}, r_{c8}, r_{c16} and r_{c32}, with the angle between the radial cracks 90°, 45°, 22,5°and 11,25°.

3 Determination of the burden

The key parameter for the design of blasting pattern with cylindrical explosive charge is the burden. Determining the distance between explosive charge and free surface is nothing more than the adjustment of its power with the strength of rock massif that needs to be disintegrated. The distance is calculated in two situations, when free surface is "unlimited" and when the free surface is "limited".
In situations when the free surface is unlimited, (Figure 8), for a normal crater ($\alpha = 90°$), for the distance from explosive charge to free surface, burden can be calculated according to the following formula:

$$B = r_{c4} \cdot cos45^{\circ} \qquad [13]$$

Or

$$B = \frac{0.17 P_h r_h}{k\sigma_t} \qquad [14]$$

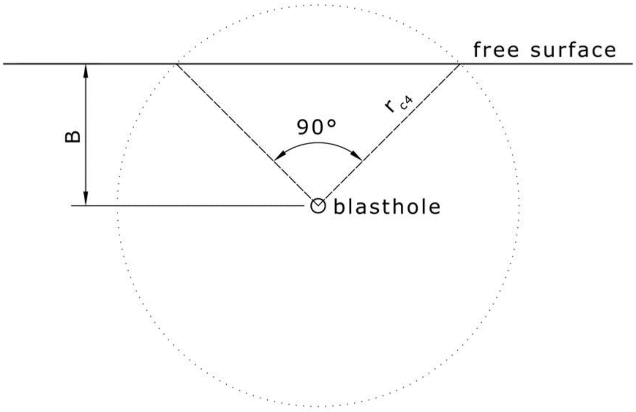

Figure 8 Burden for unlimited free surface

Blasting with one free surface perpendicular to the axis of blast holes is common in underground mining exploitation. The most important operation in the blasting procedure is to create an opening in the face to develop another free surface in the rock. This is the function of the cut-holes.

In the parallel-cut-hole that is most commonly used the key parameter is the distance between central empty blast hole and cut-hole that is activated first. These blast holes are found in the zone r_{c32}; therefore the distance (Figure 9) can be calculated from the equation:

$$32d = 2\pi r_{ch} \quad [15]$$

Or,

$$r_{ch} = 5d < r_{c32} \quad [16]$$

Where

r_{ch} - distance between empty and first activated cut-hole
d - diameter of the empty cut-hole

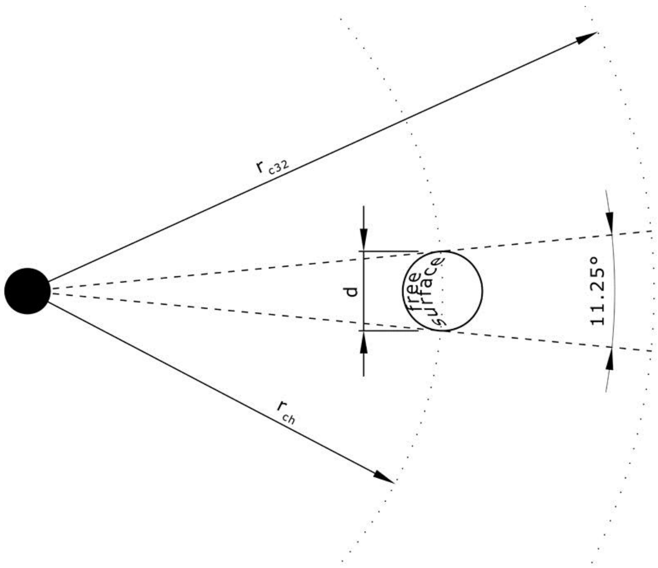

Figure 9 The distance between the empty and charged cut hole

All other blast holes, due to limited free surface, have to be at the distance $B_1 < B$, (Figure 10), and this distance is calculated by the formulae in the Table II.

Table II The distance from blast hole to limited free surface

Zone	α	Burden
32	11.25°	$B_1 = 5S < r_{c32}$
16	22.5°	$B_1 = 2.5S < 0.98r_{c16}$
8	45°	$B_1 = 1.2S < 0.92r_{c8}$
4	90°	$B_1 = 0.5S \leq B$

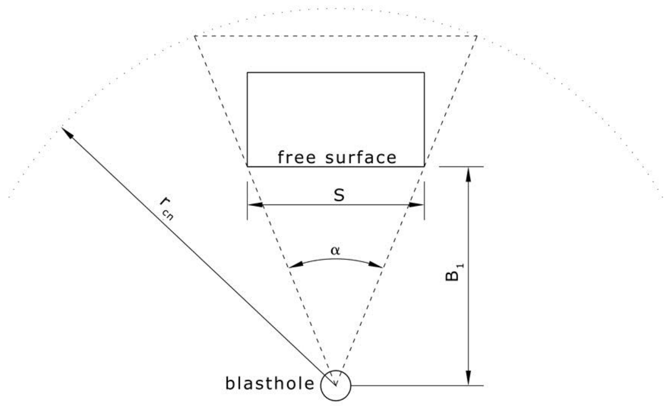

Figure 10 The distance from blast hole to limited free surface

4 Conclusion

In accordance with the importance of blasting in hard rock mine exploiting, there are many empirical and semi-empirical models for assessment of the perimeter of the crushing zone around the blast zone. However, there is still no blasting model based on constitutive relationship that describes the main properties of rock fracture.

The detonation pressure is transferred through the blast hole wall onto the surrounding massif and radially is extended around the blast in a form of pressure wave. By moving away from its source, the pressure wave weakens in proportion to the distance. In accordance to radial pressure, rock particles are moving in the same manner as the pressure wave. Regarding that, the deformation wave is corresponding to the pressure wave. Radial dilatation can be calculated due to pressure and Young's modulus at the certain distance.

Once the pressure wave reaches the closed circular zone of rock mass, the closed circular zone of rock mass moves to a new position and its radius is increased for the radial strain, it is inevitably prone to stretching, and lateral strain is the result of that.

According to the ratio between lateral strain, at the certain distance from the blast hole, and the tensile strain, the number of tension radial cracks could be calculated. Therefore, zones with different crack density may be singled out around the blast hole, this has the great significance for the calculation of the distance between blast hole and free surface and for designing of the blasting pattern.

Therefore, it is obvious that the density of radial cracks around blast hole is proportional to:

- Explosion pressure that generates the pressure wave,
- Blast hole radius that defines the area used for the transfer of the pressure of the gases in the blast hole onto the adjacent rock.

On the other hand, the radial crack density is inversely proportional to:

- Distance from the blast hole,
- Tensile strength of the rock that is mined,
- Coefficient k (Formula [4]) which is in function of Poisson's ratio.

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