Determination of shapes and sizes of radial cracks formed by blasthole charges and hydraulic fracturing in a layered rock mass

EN Sher
Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: ensher@gmail.com

Abstract. The features are investigated and a design diagram is developed for radial cracks propagation in a layered rock mass during blasting of borehole charges and hydraulic fracturing. To calculate the stress state of an elastic rock mass with cracks, we used the boundary element method in a three-dimensional formulation. As a result of these calculations, the influence of the strength properties of rock mass layers on the shape of radial cracks and their area was determined.

1. Introduction
In mining operations, blasting has become a routine work in recent years. A large number of boreholes are pre-drilled in the target block of rock mass according to the borehole grid pattern. The parameters of drilling and blasting operations (e.g. spacing between wells in a row and distance between the rows; charge distribution along a borehole axis) are determined by dimensions of the failure zones of borehole charges. Dimensions of failure zones of single borehole charges in a homogeneous rock mass are estimated in a number of publications [1–3]. For a more accurate theoretical evaluation of both drilling and blasting parameters, it is important to take into account the structure of the blasted massif. It may have stronger or weaker alternations. A similar situation occurs when hydraulic fracturing is applied to the layered rock mass.

During the blasting of elongated borehole charges in a fragile monolithic rock, a major failure volume occurs in the zone of radial cracks. The length and shape of cracks induced by blasting of elongated charge of a given length, are estimated according to the developed software for calculating the evolution of the system of flat radial cracks with uniform angular distribution [4]. According to the zonal model of blasting [5–7], after the explosive charge is detonated, the elastic compressive wave propagates from the borehole deep into the rock mass, and is followed by a crushing front. The elastic wave stresses decrease as it propagates, thereby slowing down the crushing wave front. At this, radial cracks may form and develop in the case, when the rate of elastic wave propagation decreases to the level of the maximum rate of crack propagation, which is accompanied by the appearance of azimuthal tensile stresses [3]. In this case, the crushing (breakdown) wave front is arrested, while radial displacement of the elastic medium is fixed at the contact with the crushed rock. The elastic medium expansion attained at the first stage of the blasting is subsequently preserved due to the resistance to radial compression of the crushed rock, whose deformation is governed by the law of dry friction. As such, this expansion results in a system of radial cracks developing in the elastic zone of a rock mass.
Since the final dimensions of the radial cracks generated by blasting are much larger than the crushing zone radius, the simulation assumes that their development in the elastic plane begins in parallel with propagation of the radial system $N$ of rectangular cracks located along the axis of the elongated charge and whose dimensions are determined by the blasting charge length and the radial size of the crushing zone $r_d$. It is also assumed that the initial stria edges of these cracks are loaded with a constant pressure $p_d$, thereby ensuring the opening of cracks $d_0$ which is interpreted as displacement of the boundary (attained at the first stage of blasting failure) between the elastic zone and crushing zones.

2. Numerical simulation results

For calculation of the radial cracks geometry in the final (dynamic) stage of their propagation, we consider the quasi-static process of crack evolution, with the cracks opening $d_0$ increasing consecutively. The stress state of the elastic medium near the crack front is determined at each calculation step, in order to detect potential medium failure and the crack growth. The displacement discontinuity method was used to calculate 3D stress state of the medium in an elastic space with a radial system of flat cracks with uniform angular distribution and loaded with internal pressure [8, 9]. This method implies that the crack surface is split into square elements spaced at an interval, within which the opening and displacements of the crack edges are considered constant. Thus, cracks are arranged into a set of displacement elements described by the Burgers vectors, whose components may be previously unknown. These are determined from the requirement to fulfill the boundary conditions for stresses in the centers of the displacement elements as a result of solving the corresponding system of linear equations that yields the coefficients interpreted as the factors of the elements’ mutual influence. The mutual influence coefficients were calculated using the Peach–Keller formulas, which represent the stress tensor components at an arbitrary point in the elastic domain next to the displacement discontinuity through the contour integrals along its boundary. The same formulas were used to calculate stresses near the edges of cracks to determine their propagation projections.

The previously developed software programs [8, 9] were modified for calculating the cracks propagation as a result of blasting and hydraulic fracturing operations in a rock mass containing layers with reduced/enhanced strength parameters. These have been complemented with account of changes in the strength properties of the medium varying depending on the coordinate of the point tested for failure potential. In the case of a layered medium, along with the $z$ value (the $z$ axis is perpendicular to the layers), the point is assigned to a particular layer. The variants for two-layer and interlayer media are implemented. In the first case, the $z_0$ coordinate of the layer boundary was introduced. The tensile strength is assumed to be $\sigma_t$ at $z < z_0$ for a medium and $\sigma_t \beta$ at $z > z_0$, for different medium. The parameters $z_0$ and $\beta$ are set in the program. An calculation example of the geometry cracks initiated by the elongated charge blasting for this variant is presented in the dimensionless form in Figure 1. The calculations are performed for the case of two diametrically opposite cracks and different values of the crack opening $d_0$ on the initial striae determined from the BB charge radius. The calculations also assumed that the gaseous post-detonation products do not penetrate into the cracks, and edges of the newly formed crack are free from loads. It can be seen that in a stronger upper layer at $z > z_0$, the crack propagation extent is less, than in the lower layer.
Figure 1. Configuration of the blasting-induced radial cracks: (a) in a homogeneous rock mass ($\beta = 1$); (b) in a rock mass with enhanced strength in its upper part ($\beta = 1.5$).

Results of the calculations of the configuration of cracks initiated by the elongated charge blasting in the presence of an interlayer within the main layer are shown in Figure 2. Given that it was assumed that the charge center is located in the middle of the interlayer (with respect to its height), the cracks’ configurations are therefore shown only in the first quadrant of the plane ($x, z$). It is evident that the BB charge distribution along the borehole needs to be corrected for more uniform evolution of cracks, thereby reducing or increasing the BB charge linear distribution in the interlayer.

Figure 2. Configurations of radial cracks initiated by the elongated charge blasting in a rock mass containing layers: (a) with reduced strength ($\beta = 0.5$) and (b) with enhanced strength ($\beta = 1.8$) at $z < 20$.

The problem of fracture propagation modeling has thus far been fairly well studied with respect to hydraulic fracturing. In addition to the classic one-dimensional models [10, 11], 2D and 3D models have been developed. Given that the implementation of the latter is quite problematic, pseudo-3D models to construct approximate structures are used for practical purposes [12, 13].

The developed software allows calculating configurations of hydraulic fracturing cracks in a layered medium, in the case when the fracking is produced using a low-viscosity fluid, where the crack edges can be assumed to be loaded with a constant pressure along their surface.

The calculations were performed for the initially circular crack propagation directions in the $x, z$ plane of in the layer $|z| < 10$ adjacent to stronger rock masses. In practice, the initially circular crack is caused by the rock failure around a borehole drilled horizontally in the direction of minimal compression. The calculation results in dimensionless form are shown in Figure 3. The symmetry with
respect to the axis \( z = 0 \) has been taken into account. It is evident that with increasing strength of the external layers of the rock massif, the circular fracture initiated by hydraulic fracturing propagates mainly along the layer with lower strength, passing into the Perkins, Kern, and Nordgren variant of the crack evolution.

![Figure 3](image1.png)

**Figure 3.** Configuration of a circular hydraulic fracturing crack propagation in a layer adjacent to stronger rocks during the strengthening: (a) \( \beta = 1.5 \); (b) \( \beta = 2.5 \).

Results of the study of the interlayer effects on the hydraulic fracturing–induced cracks propagation are shown in Figure 4. A comparison of the crack geometries shows that the presence of a weakened layer favors predominantly propagation of a hydraulic fracturing crack, thereby reducing equilibrium pressure and hence the crack propagation in the surrounding stronger rock mass, whereas the presence of a stronger layer will yield the opposite result.

![Figure 4](image2.png)

**Figure 4.** Hydraulic fracturing crack evolution: (a) in rock massif with an enhanced (\( \beta = 1.8 \)) and (b) reduced (\( \beta = 0.5 \)) strengths at \( |z| < 20 \); (c) with no interlayer.

3. Conclusions

A design scheme for determining the configuration and size of circular cracks formed during the borehole charge blasting in a layered rock mass has been developed. The calculations have shown that for a uniform rock failure pattern along the borehole, it is necessary to adjust the linear distribution of the BB charge taking into account the strength (mechanical) properties of the layered rock mass.

A design scheme for determining the configuration and size of a hydraulic fracturing crack formed in a layered rock mass is proposed. It was found that a decrease in rock strength of the layer leads to an increase in the size of a crack propagating in it. This reduces the equilibrium pressure, causing thereby a reduction in the transverse dimensions of the crack in the stronger surrounding rock mass. However the presence of a stronger layer increases the crack size in the surrounding rock mass.
Acknowledgements
The study was carried out in the framework of the Basic Research Program, Project Registration No. AAAA-A17-11712209002-5.

References
[1] Mosinets VN 1976 Crushing and Seismic Action of Blasting in Rocks Moscow: Nedra (in Russian)
[2] Kutuzov BN and Andrievskiy AP 2002 A New Theory and New Technologies for the Destruction of Rocks by Elongated Explosive Charges Novosibirsk: Nauka (in Russian)
[3] Aleksandrova NI and Sher EN 1999 Effect of dilation on rock breaking by blasting of a cylindrical charge Journal of Mining Science Vol 35 No 4 pp 400–408
[4] Sher EN and ChernikovAG 2015 Calculation of the parameters of the radial system of cracks formed during the blasting of an elongated charge in fragile rocks J.Fundamental and Applied Mining Sciences No 2 pp 299–303 (in Russia)
[5] Grigoryan SS 1967 Some questions of the mathematical theory of deformation and destruction of solid rocks Journal of Applied Mathematics and Mechanics Vol 31 No 4
[6] Rodionov VN, Adushkin VV, Romashev AN et al 1971 Mechanical Effect of Underground Blasting Moscow: Nedra (in Russian)
[7] Chadwick P, Cox AD and Hopkins HG 1964 Mechanics of deep underground explosions Philosophical Transactions for the Royal Society of London. Series A, Mathematical and Physical Sciences Volume 256 Issue 1070 pp 235–300
[8] Crouch SL and Starfield AM 1983 Boundary Element Methods in Solid Mechanics London: George Allen & Unwin
[9] Mikhailov AM 2000 Calculation of the stresses around a crack in a three-dimensional case Journal of Mining Science Vol 36 No 5 pp 445–451
[10] Kristianovich SA and Zheltov YP 1955 Formation of Vertical Fractures by Means of Highly Viscous Fluids 4th World Petroleum Congress Rome, Italy
[11] Perkins TK, Kern LR 1961 Widths of hydraulic fractures Journal of Petroleum Technology Vol 13 No 9 pp 937–949
[12] Geertsma J 1989 Chapter 4. Two-dimensional fracture propagation models, Recent advances in hydraulic fracturing Monograph Series 12 Eds Gigley J, Holditch S, Veatch DNR, Richardson TX: SPE Vol 12 pp 81–94
[13] Adachi JI, Detournay E and Peirce AP 2010 An analysis of the classical pseudo-3d model for hydraulic fracture with equilibrium height growth across stress barriers International Journal of Rock Mechanics and Mining Sciences Vol 47 No 4 pp 625–632