DEM simulations of dynamic impact on a rock mass complicated with a cavity and a tectonic disturbance

GN Khan and EP Rusin*

Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia

*E-mail: gmmlab@misd.ru

Abstract. The effect of a blast on a rock mass complicated with a cavity and a tectonic disturbance is considered. The disturbance is an extended broken rock layer located in the vicinity of the cavity. It is shown that the layer reduces the effectiveness of dynamic action on the cavity. The dependence of stability of the cavity exposed to the shock wave on the thickness of the layer and on the strength properties of the rock mass is revealed.

1. Introduction
Correct evaluation of stability of underground workings during blasting operations is an urgent task to ensure the safe conduct of mining operations. However, such an evaluation may be difficult in the case of inhomogeneous composition of the rock mass in the mine working vicinity. We believe that the most efficient numerical tool for studying the indicated problem is the discrete element method (DEM) that allows solving rock mechanics dynamic problems including those with heterogeneous composition of the rock mass. In this study, with the help of DEM, the dynamic impact of a blast on a mine working in the presence of a tectonic disturbance in the form of a broken rock layer located between the working and the explosive charge is simulated.

As it is known, there is a similarity between rocks and granular materials [1–4] and, in particular, in the fact that rocks possess the most important property of a granular medium – dilatancy. This property is one of the determining ones for the formation of the stress-strain state of rock masses before and after their breaking. In DEM [5], a simulated medium is represented by a set of individual particles – discrete elements. Due to this, DEM automatically takes into account dilatancy and is widely used to study mechanical, including dynamic, processes occurring in rock masses [6, 7]. The interaction between particles is described by means of forces arising at their contacts. In the formulation of the problem, the physical and mechanical characteristics of the elements, boundary conditions, the initial distribution of particles in space and the initial distribution of their linear and angular velocities are set. For each particle, equations of rigid body dynamics are compiled. After that, the Cauchy problem is solved for the system of second-order ordinary differential equations.

2. Results and discussion
Further, the effect of a blast wave on the stress-strain state of a rock mass complicated with a cavity and containing a tectonic disturbance is investigated by DEM. In this case, a modification of the proposed in [8] and tested in solving dynamic problems [9] medium mathematical model based on the linear viscoelastic model [10] is used.
Figure 1 shows the computation scheme: a rectangular region \( l \) with dimensions \( a \) and \( b \), filled with discrete elements that simulate a two-dimensional rock mass. The boundary of the computational domain is composed of boundary discrete elements (BDE) for which boundary conditions are set: the linear and angular velocities of the BDEs of the lower and lateral sides are equal to zero, the BDEs of the upper one are ordinary discrete elements and are free of stress from above.

![Figure 1](image.png)

**Figure 1.** Computation scheme: \( a, b \) – dimensions of the rectangular computational domain; \( l \) – a rock mass modeled with discrete elements with radii \( r \) from a given range of values; \( 2 \) – tectonic disturbance in the form of a vertical layer having a width \( l \); \( 3 \) – a cavity with a radius \( r_c \); \( 4 \) – the rock mass sections composed of discrete elements of smaller dimensions than in the rest of the mass; \( Oxy \) – the coordinate system whose origin \( O \) is located in the center of the cavity \( 3 \); \( x_l \) – a distance from point \( O \) to the far boundary of the layer; \( q \) is an explosive charge composed of discrete elements located in a circle with a radius \( r_q \) and with the center at point \((x_q, 0)\); \( A \) – a fragment of the computational domain.

The mass contains a tectonic disturbance \( 2 \) in the form of a rectangular layer of broken rock with zero cohesion, with a width \( l \), and a circular cavity \( 3 \) with a radius \( r_c \), the cavity center located at a depth of \( b/2 \). The origin \( O \) of the selected Cartesian coordinate system \( Oxy \) coincides with the center of the cavity. The gravity force is directed against the \( Oy \) axis. The layer \( 2 \) boundary that is farthest from the cavity is located at a distance \( x_l \) from point \( O \). The explosive charge \( q \) is modeled with discrete elements located within a circle of a radius \( r_q \), the circle centered at point \((x_q, 0)\). The charge detonation is simulated by imparting initial velocities \( v_q \) to the charge discrete elements at the moment \( t_0 = 0 \). The velocities \( v_q \) are directed from point \((x_q, 0)\) to the centers of the charge elements.

Elements with different radii \( r \) have characteristics \( \rho, E \) which are a density and an elasticity modulus, respectively. At the contacts between the elements, the following parameters are set: \( \varphi, C, \varepsilon, k \) – a contact friction angle, a cohesion, a cohesion rupture deformation and a coefficient of restitution, respectively. The layer \( 2 \) is composed of discrete elements with the same characteristics as those of the particles of the mass, except for the cohesion \( C_l = 0 \) and the elastic modulus \( E_l \), i.e. the tectonic disturbance consists of a granular material – a broken rock.

The radius \( r \) of the elements in the zones \( 4 \) and in the charge area with a radius of \( r_q = 0.25 \text{ m} \) is selected from values uniformly distributed in the range of 0.04 to 0.05 m, in the rest of the mass – from 0.20 to 0.25 m. The smaller dimensions of the elements in the zones \( 4 \) make it possible to
simulate the mass deformation process in the vicinity of the cavity and of the charge during the blast in more detail. The physical and mechanical characteristics of the rock mass elements are taken as follows: \( \rho = 2500 \text{ kg/m}^3, \) \( E = 10 \text{ GPa}, \) \( k = 0.3, \) \( \phi = 17^\circ, \) \( \varepsilon = 0.05. \) The computations were carried out for different values of cohesion \( C = 5, 10, 15, 20 \text{ MPa}. \) The elasticity modulus \( E_l \) of the layer 2 elements is taken equal to 50 MPa. The dimensions of the computational domain are taken as \( a = 50 \text{ m}, \) \( b = 3 \text{ m} ; \) the radius of the cavity is \( r_c = 2 \text{ m}, \) the distance from its center to the farthest boundary of the layer and to the center of the charge are respectively \( x_l = 14 \text{ m}, x_q = 18 \text{ m}. \) The width \( l \) of the layer in different versions of computations was chosen from 0 to 8 m with a 2 m interval.

The search for the explosive energy necessary for the destruction of the cavity was carried out by means of a series of computations with different energy values by the bisection method. The destruction of the cavity is understood as the rupture of the cohesion contacts in the mass in the vicinity of the cavity. Figure 2 shows a fragment of the rock mass computational domain at two intermediate stages \( t_1 \) and \( t_2 \) of the development of the front \( \Phi \) of the shock wave arising in the mass without tectonic disturbance (Figure 2a) and with a disturbance of width \( l \) equal to 4 m (Figure 2b) as a result of detonation of charges \( q_0 \) and \( q_4 \) with energies \( W_0 = 0.83 \text{ GJ} \) and \( W_4 = 3.00 \text{ GJ}, \) respectively, necessary for the destruction of the cavity. Subscripts in the designations of charges and their energies correspond to the width \( l \) of layer 2.

![Figure 2](image_url)

*Figure 2.* Intermediate stages \( t_1 \) and \( t_2 \) of the development of the shock wave leading to the loss of stability of the cavity at \( C = 5 \text{ MPa}: \) \( a, b \) – for the width \( l \) equal to 0 and 4 m, respectively; \( \Phi \) is the front of the shock wave; \( q_0 \) is a charge with energy \( W_0 = 0.83 \text{ GJ}; \) \( q_4 \) – a charge with energy \( W_4 = 3.00 \text{ GJ}. \)

It follows from the above illustration that, in the absence of a tectonic disturbance (Figure 2a), the explosive charge detonation results in propagation of a cylindrical shock wave in the mass. In the presence of a broken layer (Figure 2b), the front \( \Phi \) of the shock wave loses velocity in it (Figure 2b, stage \( t_2 \)) and a part of its energy due to a significantly lower elasticity modulus of the layer elements and to the lack of cohesion between them. When a force is applied to the medium, the layer elasticity modulus that is lower than that of the mass leads to a greater deformation of the layer and, respectively, to a greater dissipation of energy in it than in the mass. In addition, energy dissipation occurs in the granular medium of the tectonic disturbance due to friction between the particles of the medium. Therefore, in the layer 2, the shock wave front \( \Phi \) loses its velocity and, accordingly, its energy. Consequently, for the destruction of a cavity in a mass with a tectonic disturbance, a charge of greater power is required than in a mass without it, at the same distance of the charge from the cavity.
The presence of a broken layer located between a cavity and a charge leads to distortion of the shock wave front $\Phi$ and to the effect of shielding the cavity by the layer from the dynamic impact arising from the detonation of the charge.

Figure 3 shows the deformation patterns at the moment of the onset of loss of stability by the cavity during the explosion of charges $q_2$, $q_4$, $q_6$, and $q_8$ with energies $W_2 = 2.13$, $W_4 = 3.00$, $W_6 = 3.67$, $W_8 = 4.03$ GJ in a mass with a broken layer of width $l$ equal to 2, 4, 6 and 8 m, respectively, $C = 5$ MPa. The computation results show that with an increase in the value of $l$, an increase in the charge $q$ is required, which is necessary for the destruction of the cavity. In Figure 3, an important effect is seen accompanying the action of compressive stress on the mass: when the cavity loses stability, the fracture crack in the vicinity of the cavity has the form of a spiral directed from the boundary of the cavity deep into the mass. This corresponds to the nature of the development of cracks in the form of Chernov-Lüders slip bands observed in physical experiments during compression of a rock sample with a circular hole [11].

![Figure 3](image)

**Figure 3.** The stage of loss of stability of a cavity in a rock mass with cohesion $C = 5$ MPa: $a$, $b$, $c$, $d$ – detonation of charges $q_2$, $q_4$, $q_6$, $q_8$, respectively, with energy $W_2 = 2.13$, $W_4 = 3.00$, $W_6 = 3.67$, $W_8 = 4.03$ GJ in a mass with a layer of width $l$ equal to 2, 4, 6, 8 m.

In Figure 4, shown are the computed graphs of the dependence of the detonated charge $q$ energy $W$ required for the loss of stability by the cavity on the width $l$ of the broken layer at a fixed value of $x_q = 18$ m and different values of cohesion $C$ in the mass.

![Figure 4](image)

**Figure 4.** Dependence of the charge energy $W$ required for the destruction of a cavity with a radius of 2 m on the width $l$ of the broken layer at different values of the rock mass cohesion $C$. 
Based on the analysis of the graphs shown in Figure 4, an empirical formula is obtained for calculating the energy for \( l > 0 \)

\[
W = k C^{3/2} l^{1/2},
\]

where \( k = 0.124 \) at the given value of \( x_q = 18 \) m. The maximum discrepancy between the energy values calculated using this empirical formula and by DEM does not exceed 8%.

3. Conclusions

A tectonic disturbance in the form of a broken rock layer located in the mass between a cavity and a blast source weakens the impact of the shock wave on the cavity. When the cavity loses stability, a spiral crack develops from its boundary deep into the mass. This corresponds to the nature of the development of cracks in the form of Chernov-Lüders slip bands observed in physical experiments during compression of a rock sample with a circular hole. An empirical formula is obtained for calculating the charge energy required for the destruction of the cavity depending on the values of cohesion and the width of the broken layer.

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