Development of a model for predicting the dynamic effect on the stability of rock excavation

M A Karasev, R O Sotnikov, V Yu Sinegubov, N A Egorova, K V Makarov and A I Thorikov

Saint-Petersburg Mining University, 2, 21 line, Vasilievsky island, St. Petersburg, 199106, Russia

E-mail: karasevma@gmail.com, ross61@mail.ru, vs.geotechburo@gmail.com, s175043@stud.spmi.ru, xmarcix@yandex.ru, dron15_117@mail.ru

Abstract. The present work is devoted to the prediction of the excavation stability and analysis of the geo-mechanical processes near the excavation under dynamic impact. The development of a numerical model of the forecast of the development of a stress-strain state with allowance for the dynamic effect taking into account the geometric parameters of the mining development, the speed and nature of the application of the load, and the formation of zones of intense fracturing in its vicinity are performed. The influence of the intensity of the dynamic effect on the nature of the manifestation of geo-mechanical and geodynamic processes in the vicinity, the movement of the contour of the rock excavation, and the probability of ejection of the rock mass are determined.

1. Introduction

The development of ore deposits involves the occurrence of geo-mechanical and geodynamic activity manifested in various forms of excavations stability. The loss of stability in overstressed rock masses composed of rocks predisposed to brittle fracture can be manifested in the form of significant local deformations of the rock contour related to the zones of active rocks fracture [1]. Rock fracture can be accompanied by the release of rock mass from the vicinity zone of the excavation, namely, rock bump takes place. Currently, the fastening system including dynamic (flexible) anchors and support elements that ensure the transfer of load from the rock mass to the anchor from the perimeter of excavations is preferable to be used in order to ensure the stability of excavations located in such conditions. Various variants of the anchor system were developed and tested both in laboratories and in mines, where they proved their worth. At the same time, the problem of choice of the type of dynamic support and its parameters has not been solved yet and is mainly based on empirical dependencies.

The solution of the task requires the study of the following problems: the first – to study the development of geo-mechanical and geodynamic processes in the area of excavations under dynamic impact; the second – to develop the model of dynamic anchor fastening system into account its actual mechanical characteristics; the third – to analyze the results of the application of dynamic anchorage and its parameters on the stability of excavations. The paper focuses on the first problem, that is, the forecast of the development of geodynamic processes in the area of excavations.

As the result of rock bump, the following forms of the loss of excavations stability can be observed: the formation of new cracks in the rock mass in the vicinity; stratification of rocks in the
vicinity, rock crushing; extrusion of rocks in the sides and arch; rock uplift in excavation bases; drop-out of rock mass along the cracks; release of rocks, etc.

The degree of excavations damage as a result of rock bump can be divided into three types [2, 3]. The first type is characterized by minor damage when the rocks in the vicinity excavation can be broken or exfoliated by an amount of not more than 0.25 m. The second type is defined by moderate damage when the rocks in the vicinity zone are considerably broken. The significant displacement of the rock contour is observed. In this connection, the zone of rock exfoliation is in the range from 0.25 to 0.75 m. The third type is characterized by the extensive damage when the size of the zone of rock exfoliation is more than 0.75 m. The support of the excavation can also be considerably damaged. The third type of rock damage in the vicinity excavations caused by local extrusion of rocks from the zone of intensive stratification and cracking involves rapid development of the rock contour displacement which can reach 300 mm or more. The degree of excavation damage determines the type and parameters of the support to ensure the stability.

The process of energy transfer from the seismic event to the rock in the vicinity zone resulting in deformation, damage and fracture of the rock is described by the numerical model of dynamic impact of the remote seismic event on the excavation contour. The numerical modeling was made in a plane deformation (fig. 1). The model included the set of solid elements responsible for the parameters of rock mass in the area of the excavation and the set of damping elements providing the condition of seismic waves moving outside the model without their reflection from the boundaries.

![Figure 1](image_url)

**Figure 1.** Geometric representation of the numerical model of the forecast of stress-strain state in the excavation area under seismic impact: 1 – zone of seismic waves damping; 2 – zone of the main rocks; 3 – sources of seismic impact; 4 – excavation

The task was solved in the conditions of the initial stress state field. The vertical stress was taken to be equal to 15 MPa and horizontal stresses of 30 MPa. In the model, the rock mass was considered to be monolithic undisturbed mass having the average strength of 100 MPa in the conditions of uniaxial compression.

The Johnson-Holmquist Model was used to describe the mechanical behavior of rocks under the dynamic impact. It allows taking into account the influence of the loading rate of the material on the strength and the degree of rock damage.
In general, the equation of the surface of the plastic flow of the Johnson-Holmquist model [4, 5] can be written as:

\[
\sigma^* = \sigma^*_i - D \left( \sigma^*_i - \sigma^*_f \right),
\]

where

\[
\sigma^*_i = A \left( p^* + T^* \right)^N \left( 1 + C \ln \varepsilon^* \right) \leq \sigma^*_{i,\text{max}},
\]

\[
\sigma^*_f = B \left( p^* \right)^M \left( 1 + C \ln \varepsilon^* \right) \leq \sigma^*_{f,\text{max}},
\]

where \( \sigma^* \) - normalized equivalent stresses, \( \sigma^* = \sigma / \sigma_{\text{HEL}}; \sigma_{\text{HEL}} \) – the Hugnoit elastic limit in terms of equivalent stresses; \( D \) – index of the degree of the material damage, \( 0..1; p^* \) - normalized pressure, \( p^* = p / p_{\text{HEL}}; p \) – average stresses; \( p_{\text{HEL}} \) – average stresses at HEL; \( T^* \) - normalized strength at hydrostatic tension, \( T^* = T / T_{\text{HEL}}; T \) - strength at hydrostatic tension; \( \sigma^*_i \) - normalized strength of the not damaged material in terms of equivalent stresses, \( \sigma^*_{i,\text{max}} = \sigma^*_i / \sigma_{\text{HEL}}; \sigma^*_f \) - normalized strength of the damaged material in terms of equivalent stresses, \( \sigma^*_{f,\text{max}} = \sigma^*_f / \sigma_{\text{HEL}}; \sigma^*_{\text{max}} \) – normalized maximum strength of the not damaged material in terms of equivalent stresses, \( \sigma^*_{\text{max}} = \sigma^*_{i,\text{max}} / \sigma_{\text{HEL}}; \sigma^*_{f,\text{max}} \) – normalized maximum strength of the damaged material in terms of equivalent stresses, \( \sigma^*_{\text{max}} = \sigma^*_{f,\text{max}} / \sigma_{\text{HEL}}; A, B, C, M, N \) – parameters of strength condition.

Let us transform the above presented equations using the indicator of strength in uniaxial tension:

\[
q^* = \left( A(1 - D) + B \left( p^* \right)^N \right) \left( 1 + C \ln \varepsilon^* \right);
\]

\[
\dot{q}^* = \frac{q}{\sigma_{\varepsilon,i}}; \quad p^* = \frac{p}{\sigma_{\varepsilon,i}}; \quad T^* = \frac{T}{\sigma_{\varepsilon,i}}; \quad \varepsilon^* = \frac{\varepsilon}{\varepsilon_0}; \quad E = 0.043 \rho^{3/2} \sqrt{\sigma_{\varepsilon,i}}; \quad G = \frac{E}{2(1 + v)}
\]

\[
K_1 = \frac{E}{3(1 - 2v)}; \quad T = 0.62 \sqrt{\sigma_{\varepsilon,i}}; \quad \mu = \frac{\rho}{\rho_0} - 1; \quad P_{\text{crush}} = \frac{\sigma_{\varepsilon,i}}{3}; \quad \mu_{\text{crush}} = \frac{P_{\text{crush}}}{K_1},
\]

When performing numerical calculations, the following parameters of the Johnson-Holmquist model were taken into account to determine the resulting indicators of dynamic impact (table 1).

| Line 1 | \( \rho_0, \text{kg/m}^3 \) | \( G, \text{Pa} \) | \( 30.5\times 10^7 \) | \( 3.3 \times 10^{-4} \) | \( A \) | \( 1.73 \) | \( B \) | \( 0.79 \) | \( N \) | \( 100 \times 6 \) | \( 0.005 \) | \( 1 \) | \( \varepsilon_0 \) |
|--------|----------------|---------|----------------|----------------|-------|-------|-------|-------|-------|----------------|----------------|-------|-------|
| Line 2 | \( T, \text{ Pa} \) | \( \sigma_{\text{max}} \) | \( 7 \times 10^5 \) | \( 7 \times 10^7 \) | \( P_{\text{crush}}, \text{ Pa} \) | \( 50 \times 6 \) | \( 0.002 \) | \( 3.47 \times 10^{-6} \) | \( 0.11 \) |
| Line 3 | \( D_1 \) | \( D_2 \) | \( 9 \times 10^9 \) | \( 1.0 \) | \( \varepsilon^*_{\text{f, max}} \) | \( 999 \) | \( 0.01 \) | FS | |
| Line 4 | \( K_1, \text{ Pa} \) | \( K_2, \text{ Pa} \) | \( 1 \) | \( 0 \) | |

The simulation of the formation of seismic wave by the detonation of explosives in boreholes was carried out using the JWL state equation (the John-Lee-Wilkerson model) [6, 7]. The state equation in the units of internal energy stored in mass unit \( E_m \) can be written as:

\[
p = A \left( 1 - \frac{\rho \varepsilon}{R_1 \rho_0} \right) \exp \left( -R_1 \frac{\rho_0}{\rho} \right) + B \left( 1 - \frac{\rho \varepsilon}{R_2 \rho_0} \right) \exp \left( -R_2 \frac{\rho_0}{\rho} \right) + \omega \rho E_m,
\]
where $A$, $B$, $R_1$, $R_2$, $\omega$ - are the model constants, selected for each type of explosive; $\rho_0$, is the density of the explosive; $\rho$ is the density of the explosion products. The JWL model constants for emulsion explosives are summarized in table 2.

Table 2. Constants of state equation of explosives

| The explosive          | $\rho_0$, kg/m$^3$ | $A$, Pa | $B$, Pa | $R_1$ | $R_2$ | $\omega$ | $c_d$, m/s | $E_0$, J/m$^3$ | $p_{bs}$, Pa | $K_{pd}$, Pa |
|------------------------|-------------------|---------|---------|-------|-------|----------|------------|----------------|--------------|-------------|
| Emulsion explosive     | 1140              | 3.85e11 | 5.045e9 | 5.487 | 1.171 | 0.24     | 5573       | 3.26e6         | 2.1e+010    | 3.3e9       |

When performing the numerical simulation, the area of blasting operations was distanced from the excavation contour at the distance sufficient for the transition of the wave from spherical one to flat, which was equal to 10 m for the conditions under consideration [8]. The intensity of seismic impact was changed due to the change of $E_0$ index. The resulting indicator was the movement speed of $p_{gsv}$ rock particles. The determination of the movement speed of the rock particles $p_{gsv}$, the displacement of the contour of the rock exposure $u$ and the size of the zone of brittle rock fracture $h_b$ were calculated.

The results of the calculation of rock mass response in the area of the excavation are presented in the form of diagrams of displacements development, movement speed of rock particles and the rock mass damage. The displacements of the excavation contour (figure 2a) and the movement speed of the rock particles (figure 2b) are presented as the dependences of the change of these parameters on time from the moment of the occurrence of the seismic event. The results are presented for different intensity of seismic impact.

![Figure 2](image.png)

**Figure 2.** Displacements development of the rock excavation contour (a) and the formation of the damaged zone (b) as the functions depending on the movement speed of the rock particles

The pictures of the formation of longitudinal and shear cracks in the contour zone in the dependence on the intensity of seismic impact are shown in fig. 3.

Considering the development of displacements in time, continuous development of the displacements of the rock contour up to the intensity index from 0.7 to 1.0 ($p_{gsv_d} = 0.7\text{-}1.0$) is noticed. This shows that contouring of the rock mass section with its further release into the excavation space has taken place under the impact of seismic event.

Special attention should be paid to the kinetic energy extruded from the rock mass justifying the choice of dynamic support parameters under such influence. The decrease of the intensity of seismic impact below 0.7 still has a serious impact on the development of geodynamic processes and damage...
of rock mass in the vicinity of the mining excavation. However the release of rock mass is not observed.

Figure 3. The distribution of damages in the area of the excavation: a – movement speed of rock particles 5 m/s; b – movement speed of rock particles, 10 m/s; c – movement speed of rock particles, 15 m/s; d – movement speed of rock particles 20 m/s

It should be noted in the conclusion that the paper presents the selected results of the research of the evaluation of seismic event impact on the stability of rock excavation. Thus, seismic event itself is considered as dot blast occurring in the vicinity of mining excavation. Empirical experiments permitting to ascertain the veracity of the backgrounds introduced in the paper for the simulation of rock damage in the vicinity under seismic impact will be made at the next stage. Further studies will be devoted to the development of the mathematical model of the functionality of dynamic anchors of various structures and to the combination of the forecast model of geodynamic processes in rock mass in vicinity and the developed model of mechanical behavior of dynamic anchors.

References
[1] CAMIRO: Canadian Rockburst Research Program 1990–1995 1995 A comprehensive summary of five years of collaborative research on rockbursting in hard rock mines (CAMIRO Mining Division)
[2] Tannant D D, McDowell G M, Brummer R K and Kaiser P K 1993 Ejection velocities measured during a rockburst simulation experiment In: 3rd Int Symp on Rockbursts and Seismicity in Mines pp 129–33
[3] Yi X and Kaiser P K 1993 Impact testing of rockbolt for design in rockburst conditions. International J. of Rock Mechanics and Mining Sci. Geomech Abstr. 31 671–85
[4] Johnson G R and Holmquist T J 1994 An improved computational constitutive model for brittle materials High-Pressure Sci. and Technol. (American Institute of Physics)
[5] Holmquist T J, Johnson G R, Cook W H 1993 A Computational Constitutive Model For Concrete Subjected To Large Strains, High Strain Rates, and High Pressures. Int. Symp. on Ballistics 14 591–600
[6] Choi S, Wang J, Munfakh G and Dwyre E 2006 3D nonlinear blast model analysis for underground structures GeoCongress 2006 ASCE pp 1–6
[7] Liu H 2009 Dynamic analysis of subway structures under blast loading Geotechnical and Geological Engineer. 27 699–711

[8] Gospodarikov A P, Vykhodtsev Y N and Zatsepin M A 2017 Mathematical Modeling of Seismic Explosion Waves Impact on Rock Mass with a Working Zapiski Gornogo instituta 226 405–11 DOI: 10.25515/PMI.2017.4.405