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ROCK FAILURE

Blasting Methods of Stress State Determination in Rock Mass

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Abstract—The methods for the determination of stress state in rock mass using the energy of explosion are substantiated. The industrial tests are performed with a view to sizing zones of squeezing and radial fracturing in mines of Priargunsky Mining and Chemical Works. It is found that the fracturing zone radius decreases and the squeezing zone diameter increases with the grater depth of mining operations. The theoretical formulas for calculating stresses depending on sizes of squeezing and fracturing zones, physical and mechanical properties of rocks and detonation characteristics of explosives are obtained. The validity of the formulas is proved in comparison with the method of stress measurement in parallel drill holes at the Antei deposit of Priargunsky MCW. The method of stress determination by blasting is suitable for operational application during heading in mines.

Keywords: Rock mass, stress state, explosion energy, squeezing zone, radial fracturing zone, physicotechnical properties, stress formulas, validity.

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INTRODUCTION

The choice of methods and parameters in underground mining is governed by many factors: physicotechnical properties of rocks, structural and fracturing characteristics of rock mass, as well as its stress–strain state. Stress state of rock mass is determined by theoretical and experimental methods. The theoretical methods began developing in the early 20th century [1–9] and are being continuously improved.

The experimental approaches to determination of stress–strain states in rock mass were extensively developed in the second half of the 20th century. They enjoy wide application and are described in detail in [10–12]. Such methods include: unloading from stresses based on using elastic expansion of an element when separated from rock mass, e.g. in coring; load compensation grounded on recovery of elastic strain in partly unloaded rock mass during its re-loading; pressure difference—when hydraulic cells placed in borehole record variations of pressure with time. In the method of elastic inclusions, measurements are taken by photoelastic sensors in boreholes. Drilling method consists in measurement of transverse and longitudinal deformation of borehole walls. In the method of parallel holes, sensors are installed in a drill hole and carry out measurements while the parallel hole is drilled. Then stress values are calculated. The method of core disking allows estimating rockburst hazard.

The values of stress in rock mass are determined using acoustic emission, ultrasonic, and electrometrical methods based on obtaining calibration relations in laboratory tests and measuring the respective indexes in rock mass. All methods lists need proper expensive equipment and consume much time.

In [13] the method is proposed to estimate stress in rock mass in dynamic destruction of mine roofs and sidewalls from the relation:

$$P = 0.7\sigma_c\,, \tag{1}$$

where σ_c is the uniaxial compression strength, MPa.

The maximum normal stress is calculated by deformation of borehole walls from the formula:

$$P = 0.85\sigma_c\left(3.85\frac{d_2}{d_1} - 0.5\right), \qquad (2)$$

where d_1 and d_2 are the initial and later measured diameters of borehole, respectively, mm.

These methods are as a rule applicable to rockburst-hazardous rock mass, and it is impossible to determine stresses if the stress state is minor (no failure or deformation of exposures in mines and boreholes).

This study puts forward an operation method of rock pressure determination using blast energy.

1. GENERAL PROVISIONS

In order to substantiate the blasting method application to stress determination in rock mass, a series of industrial tests and theoretical studies has been carried out [14]. The idea of the method is that the pressure that arises within a very short time span upon detonation of explosive charge in a blast hole depends mainly on the detonation velocity and loading density. The blasthole pressure creates a zone of squeezing in rock mass at the contact with explosive charge, and rock is crushed into fine fragments in this zone. Then follows the radial fracturing zone where radial cracks propagate from the charge center [15] (Fig. 1). The most stable blast pressure is created at the hole bottom.

The blasting effect was studied experimentally in heading operations in mines of Priargunsky Mining and Chemical Works (PMCW). In the mines Tsentralny, Vostochny, Glubokii, nos. 2, 4, and 8, working faces of exploration, heading and stoping cuts were used at depths of 180–600 m. In trachydacite, felsite, conglomerate, and basaltic andesite rocks after breakage cycle, the sizes of zones produced by blast effect were measured: diameter of squeezing zone (a “barrel”), radius of radial fracturing zone, and number of radial fractures. Additionally, the particle size distribution was analyzed in the “barrel”. The latter was 0.1 to 0.3 m long. The blasting parameters were: ammonite 6ZhV explosive charge 32 mm in diameter; blast hole diameter 40 mm and length 1.8 m. Altogether more than 200 measurements were taken in the cut blastholes (table).

The tests on determining diameters of the “barrels”, D_c, and radii of the fracturing zones, R_t, were carried out in trachydacite rock mass at the actual mining depth. Trachydacite possesses minimum variable physicotechnical properties and consistent natural fracturing. The depth of mining was 180, 340, 420, and 600 m, the number of blastholes was 100. The test results are presented in Fig. 2 as experimental curves of the squeezing zone diameter and fracturing zone radius versus the mining depth.

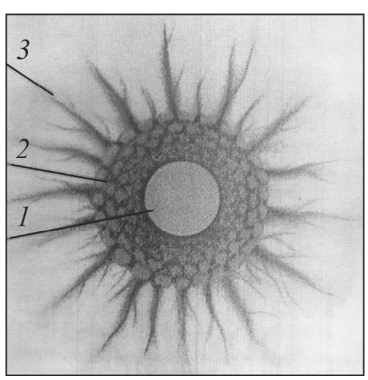

Fig. 1. Explosive rupture of rock mass: *1*—explosion cavity; *2*—squeezed zone; *3*—radial fracturing zone.

Experimental parameters of squeezing D_c, and fracturing R_t, zones, as well as number of radial fractures, N, in blasting

Rock/depth below surface	Fracture length, m	Average physical properties				D_c, m	R_t, m	N	N_{bh}
		ν	σ_c, MPa	σ_s, MPa	c, 10^3 m/s				
Granite (mines Vostochny, 8, 6)/ H = 450–600 m	0.15–1.00	0.23	144.0	8.6	5.54	0.05–0.20 (1.2–5.0)	0.1–0.3 (2.5–7.5)	20–50	30
Trachydacite (mines Vostochny, Tsentralny, 8)/ H = 180–600 m	0.05–1.00	0.29	97.2	13.9	4.35	0.05–0.15 (1.2–3.0)	0.15–0.45 (3.8–11.3)	8–16	115
Outsize conglomerate (mines 2, 8)/ H = 180–240 m	0.40–1.50	0.36	54.0	5.7	3.46	0.05–0.07 (1.2–1.7)	0.1–0.3 (2.5–7.5)	5–8	32
Basaltic andesite (mine 4)/ H = 120–180 m	0.15–0.40	0.24	102.7	11.7	4.41	0.06–0.08 (1.8–2.0)	0.1–0.6 (2.5–15.0)	16–24	9
Columnar felsite (mine 4)/ H = 120–180 m	0.15–0.40	0.30	69.5	12.4	3.65	0.05–0.07 (1.2–1.7)	0.2–0.4 (5.0–10.0)	10–15	27

Blasthole diameters are given in bracket; ν—Poisson's ratio; σ_c—uniaxial compression strength; σ_s—uniaxial tension strength; c—P-wave velocity in rock samples, borrowed from [14]; N_{bh}—number of measurement blastholes.

The analysis of the relationships shows that the fracturing zone radius decreases while the squeezing zone diameter increases as the depth of mining grows. The experimental data in the table demonstrate the dependence between the the number of fractures and Poisson's ratio in the form of $N = \nu^{-2}$. In the meanwhile no clear relation between the length and number of radial fractures is found. The reason is that different-type rocks (granite, trachydacite, conglomerate, felsite, and basaltic andesite) possess dissimilar physicotechnical properties and that the measurements were taken at various depths below the ground surface.

2. DETERMINATION OF STRESSES IN ROCK MASS BY THE LENGTH OF RADIAL FRACTURES

The experimental results show that the radius of the squeezed zone nearby the explosion cavity increases with elevating stress state of rock mass (depth), i.e., natural stress state is added with the blasting-produced stress. At the same time, the radial fracturing zone radius decreases with rising pressure as the latter prevents growth of radial fractures.

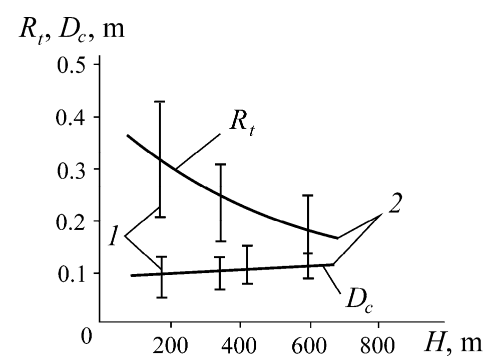

Fig. 2. Relationship of the fracturing zone radius R_t, squeezing zone—"barrel"—diameter D_c under blasting in trachydacite rock mass and the depth H: *1*—experiment; *2*—calculation.

The theoretical studies in [14] provide a formula to determine the radius of the radial fracturing zone under blasting of cylindrical explosive charge:

$$R_t = \frac{\sqrt{\pi}}{8} \frac{D\rho_1 d_0 c\nu}{(\sigma_s + P)\Phi(1-\nu)}, \tag{3}$$

where D, ρ_1, d_0 are, respectively, the detonation velocity, loading density, and the diameter of the explosive charge; c, ν, σ_s are, respectively, the *P*-wave velocity, Poisson's ratio, and the uniaxial tensile strength of rocks; Φ is the fracturing index of rock mass; P is the rock pressure.

The rock pressure *P* derived from (3) is:

$$P = \frac{\sqrt{\pi}}{8} \frac{D\rho_1 d_0 c\nu}{R_t\Phi(1-\nu)} - \sigma_s . \tag{4}$$

The calculation of rock pressure from (4) in granitoides at $\pi = 3.14$; $D = 4.2 \cdot 10^3$ m/s; $\rho_1 = 0.8 \cdot 10^3$ kg/m^3; $d_0 = 0.04$ m; $c = 4.54 \cdot 10^3$ m/s; $\nu = 0.23$; $R_t = 0.1 - 0.3$ m; $\sigma_s = 8.6 \cdot 10^6$ Pa; $\Phi = 6$ [14] (table) yield: $P = 58.5 \cdot 10^6$, $25.0 \cdot 10^6$, $13.8 \cdot 10^6$ Pa at $R_t = 0.1$, 0.2, and 0.3 m, respectively.

The estimation procedure of the radial fracturing zone radius consists in determination of length of each fracture growing from the blasthole, i.e., the distance from the earlier existent generatrix of the blasthole to fracture tip. Then the arithmetic mean fracture length is found, which is the radius of the radial fracturing zone.

3. DETERMINATION OF STRESSES IN ROCK MASS BY THE SIZES OF SQUEEZING AND RADIAL FRACTURING ZONES

From analysis of Fig. 2, with growing rock pressure, the radial fracturing zone radius decreases while the "barrel" diameter increases. Knowing relations for determination of these sizes, it is possible to derive formula independent of detonation parameters of explosives.

According to [14], the squeezing zone radius is given by:

$$R_c = \frac{\sqrt{\pi}}{8} \frac{D\rho_1 d_0 c}{(\sigma_c - P)\Phi} \sqrt{\frac{d_1}{d_2}}, \tag{5}$$

where d_1 is the maximum size of rock fragment in the "barrel"; d_2 is the size of natural joint in rock mass; σ_c is the ultimate compressive strength.

The comparison of (5) and (4) yields the formula for stresses in rock mass at the cut hole blasting moment:

$$P = \frac{\sigma_c R_c \left(\dfrac{d_2}{d_1}\right)^{0.5} - \sigma_s R_t(\nu^{-1} - 1)}{R_t(\nu^{-1} - 1) + R_c \left(\dfrac{d_2}{d_1}\right)^{0.5}} . \tag{6}$$

The calculations using (6) for granite at $\sigma_c = 144 \cdot 10^6$ Pa; $R_c = 0.5D_c - 0.02 = 0.0425$ m; $d_1 = 0.02$ m; $d_2 = 1$ m; $\sigma_s = 8.6 \cdot 10^6$ Pa; $R_t = 0.2$ m; and $\nu = 0.23$ give $P = 38.7 \cdot 10^6$ Pa.

The validity of relations (4) and (6) is proved using the data obtained by the Institute of Mining, SB RAS, in the tests implemented in the Antei deposit operated by PMCW. Stresses in granite rock mass were determined using the method of drilling parallel holes. The test results allowed obtaining empirical relations for depth-dependent stresses [14]:

$$P_z = 4.24 + 0.0233H, \quad P_x = 6.21 + 0.0484H, \quad P_y = 12.8 + 0.0686H, \tag{7}$$

where P_z, P_x, P_y are the vertical, W–E, and N–S components of rock pressure, respectively, MPa; H is the depth below the ground surface, m.

Empirical relations (7) are applicable within a depth range of 452–672 m. The calculations by these relations at $H = 600$ m lead to $P_z = 18.2$ MPa, $P_x = 35.3$ MPa, $P_y = 54.0$ MPa. The average pressure by 97) is 35.8 MPa.

The comparison of the values $P = (13.8 - 58.5) \cdot 10^6$ Pa obtained by (7), (4) and $P = 38.7 \cdot 10^6$ Pa by (6) proves the validity of the formulas for determination of stresses in rocks mass by blasting method at borehole bottom.

The blasting method of tock mass stress determination is mostly advantageous for its promptness. In this method, after blasting, at the new hole bottom surface, the radius of radial fractures, diameter of the "barrels", and the average spacing of natural fractures are measured. Knowing physical and mechanical properties of rocks and detonation characteristics of explosives, as well as using formulas (4) and (6),the values of stresses in rock mass at the moment of blasting are obtained at s distance of ~1.5–2.0 m away from the blast hole bottom (as function of its length).

CONCLUSIONS

It has been found that with greater depth of mining, the radius of the radial fracturing zone decreases and the diameter of the squeezing zone ("barrel") increases. The formulas have been obtained for calculation of rock mass stresses as function of the radial fracturing zone radius, physical and mechanical properties of rocks, natural fracturing, and detonation characteristics of explosives. The stress values calculated from these formulas are comparable with the data obtained by the Institute of Mining, SB RAS, is stress measurement using the method of drilling parallel holes in the Antei deposit of PMCW.

The proposed blasting methods are near real-time and can serve for stress estimation in rock mass.

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