UDC 622.235.5/.62

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PROCESSES OF INITIAL STAGE OF EXPANSIONS OF EXPLOSIVE CAVITY IN BLASTHOLE CHARGE

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ПРОЦЕСИ ПОЧАТКОВОЇ СТАДІЇ РОЗШИРЕННЯ ПОРОЖНИНИ ВИБУХУ СВЕРДЛОВИННОГО ЗАРЯДУ

Purpose. Research into processes that occur in the blasthole and rock during the first 300 μs after a detonation wave passing the given blasthole cross-section and determine the effectiveness of rock fracture.

Methodology. The analytical method of research based on fundamental positions of solid medium mechanics was applied.

Findings. The mechanisms of rock fracture in fine-dispersed crushing zone were considered. The valuation of dependences versus time of the blasthole radius increase, the displacement velocity of blasthole walls and of the detonation products pressure changing during the first 300 μs after the explosion, was fulfilled. It is shown that the pressure in fine-dispersed crushed zone decreases exponentially and is inversely proportional to the square root of the distance to the blasthole axis.

Originality. It was found that the main mechanism in the fine-dispersed destruction zone is instantaneous rock destruction by shear stress. The particles size, into which the rock breaks down, is directly proportional to the width of chemical reaction zone in the explosive. Dependencies of explosion cavity radius, rock fracture velocity at the contact with detonation products and detonation products pressure on time are estimated using the adiabatic equation for detonation products with a constant index, taking into account that a strong compression wave is formed in the rock. It is shown that pressure decreases exponentially from the distance to the borehole axis in the fine-dispersed destruction zone.

Practical value. The result of this work makes it possible to develop explosives with small fine-dispersed destruction zone and substantiate charges parameters with inert and water interval, thus reducing the size of a fine-dispersed destruction zone.

Keywords: *explosion, fine-dispersed crushed zone, shock waves, pressure and rarefaction waves*

Introduction. More than 90 % of explosive energy is spent on the blasting destruction of rocks in the explosion near zone. Pressure jumps after explosion, at the rock-explosive contact, overcoming the rock mass resistance to uniform compression, crush and grind rocks, increasing the size of the charging cavity. After initial increase in charge cavity volume, the pressure of detonation products (DP) decreases, but still remains high enough and acts on the enlarged cavity walls and cracks, made after explosion.

By reducing energy consumption for grinding in the near zone of an explosion, this energy can be redistributed over the entire volume of destruction and thus enhance explosive destruction efficiency. Therefore, it is important to consider processes that take place in a charge chamber and in the rock during the first 300 μs after a detonation wave passes a borehole of a given section. There are many complex wave processes that pass through a borehole, which largely determine the effectiveness of rock destruction and are difficult to describe. Currently, the equation of detonation products state does not consider the interaction of their constituent molecules; correlation between adiabatic value and DP volume is not considered. Moreover, processes of formation and propagation of shock waves (SW) and compression waves (CS) in the rocks, and processes of wave energy absorption as they propagate are poorly investigated.

Therefore, consideration of the processes which occur in the near zone of explosion at its initial stage and their parameters estimation appears relevant.

Analysis of the recent research and publications. A number of studies [1] review explosive mining operation processes and assume that a shock wave is formed in the rock. In our opinion, this is not entirely

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true. Moreover, in this case the authors do not take into account the relation between the volume and adiabatic value of detonation products; nor they regard the fact that formulas for shock waves are obtained for isentropic processes, i.e. the dissipation of mechanical energy in isentropic processes is not considered. In many publications stress field is reviewed as being stationary or quasi-stationary [2]. They assume that the initial pressure is equivalent to the detonation pressure. As shown by the authors, the initial pressure (or σ_{rr}) is about 20 % less. Furthermore, in the zone of fine-dispersed destruction, the rock behaves as a quasi-liquid ratio and charge cavity surface tension relation $|\sigma_{rr}/\sigma_{\theta\theta}|$ is not 3.5, as in [2], but approximately 1. Therefore, the objective of this article is to remedy these shortcomings and to research processes at the initial stage of the deep-hole charge explosion cavity expansion.

Presentation of the main research. As indicated earlier by the authors of this article, pressure p_s is needed to form the shock wave in the rock, and can be calculated by the formula

$$p_s = \frac{2\rho_0 c_l^2}{m+1}, \tag{1}$$

where ρ_0 and c_l are, respectively, the density and the velocity of longitudinal stress waves in the rock; m is coefficient of rock shock compressibility in the Tait equation.

A range of pressures, required for shock wave formation, $p_s = 25–90$ GPa is calculated from (1). This is confirmed by experiments in granite ($\rho_0 = 2610$ kg/m^3; $c_l = 5870$ m/s; $m = 4$) at pressures $p_s \leq 33$ GPa. Only acoustic wave at velocity c_l was recorded. Equation (1) gives the value of $p_s = 35.97$ GPa. Pressure values difference p_s is easy to explain. The shock wave only occurs when the compression wave velocity increases along with pressure increase. The compression wave velocity is determined by the formula $c_r = \sqrt{dp/d\rho}$. Given that the rock pressure and density are related by Tait equation

$$p = A\left(\left(\frac{\rho}{\rho_0}\right)^m - 1\right),$$

where ρ is the density of the rock at the pressure p, then

$$c_r = \sqrt{\frac{Am}{\rho_0}}\left(\frac{\rho}{\rho_0}\right)^{\frac{m-1}{2}} = c_{r0}\left(1 + \frac{p}{A}\right)^{\frac{m-1}{2m}}, \tag{2}$$

where c_{r0} and c_r are, respectively, wave velocity in the rock at atmospheric pressure and at the pressure p.

This implies that p_s must be greater than 33 GPa. Compression waves propagating with velocity $c_r > c_{r0}$, are called strong (SCW).

Unlike the shock wave, the strong compression wave has shock pressure surge. During this surge pressure increases to the shock wave pressure at the interval of about 1 nanometer. In addition, the substance behind the wavefront of a plane shock wave moves with the same mass flow rate and particles displacement rate in medium in the SCW decreases from maximum to zero in the wavefront. It can be argued, that if rock breaks into particles larger than 0.1 mm after the wavefront, then it is not a shock wave. Increased particle size is specified because the pressure in the damped shock wave is lower than the pressure p_s. In this case, rock begins to break down due to its kinetic energy and the wavefront width increases. When the pressure in the wave reaches the rock dynamic yield strength, the shock wave transforms in the compression wave.

Let us review the rock destruction processes near the borehole walls. With the detonation wave (DW) propagation in a borehole, the pressure in the area of chemical reactions increases over time τ to pressure p_d. A strong compression wave is formed in rock after that, with the frontal stress gradient average module in the front which equals (Pa/m)

$$\langle \partial\sigma/\partial r \rangle = \frac{p_d}{c \cdot \tau} \approx (3 \div 5) \times 10^{11},$$

where c is the SCW velocity. Rock shearing

Stress gradient leads to deformations, which are parallel to the wavefront, and causes rock shear. Since the critical stress levels arise simultaneously on the surface of the shear, the destruction occurs instantly. Minimal particle size d can be estimated by the formula (mm)

$$d \sim \sigma_s/(p_d/c \cdot \tau) \leq 0,$$

where σ_s is the dynamic tensile strength of rock shear.

Considering the friction force, the size of subsequent particles will increase.

With SCW propagation, the rock moves in the radial directions, which leads to the radial cracks increase, with the minimal distance order of magnitude between them akin to the minimal particle size d.

Because there are many complex wave processes (dilution and compression waves) in the plane which is perpendicular to the borehole plane, propagation of the SCW in rock is faster than propagation of the detonation wave in the borehole. The components of the tensor compression wave, propagating in the rock, depend highly on the time. The greater the amplitude of the stress in the compression wave, inhomogeneity and rate of change of the stress field are, the smaller the particle sizes into which the rock breaks are. In the near zone of explosion, the rock breaks not only in a compression wave, but also in the quasi-static stress field, created by the expanding detonation products. The rock breaks in the quasi-static field, if the field change during the time of destruction of rock element is substantially smaller than the limit of rock strength. The rock breaks into particles with a size less than 1 mm in the examined zone. The time of destruction in this case, is several microseconds, and during this several microseconds the pressure in the rock changes by an amount less than 10 MPa. It can be said that rock, in any sufficiently strong dynamic stress field, collapses in a quasi-static field starting from a certain element. At a pressure of 4–7 GPa the rock density increases by 4–7 %. If the rock is polycrystal, non-uniform according to its compressibility and durability, then stress concentrators arise in rock, which contribute to the destruction level.

It is necessary to know dependence of near borehole wall rock movement speed on time to evaluate the destructive effectiveness of explosion. Since there are no sufficiently accurate state equations for detonation products and rocks, only movement speed of near borehole walls rocks, can be estimated, assuming that the expansion of the detonation products is adiabatic

$$p_1 V_1^n = p_2 V_2^n, \tag{3}$$

where V_1 and V_2 are initial and final volumes of detonation products; p_1 and p_2 are corresponding pressures; n is an adiabatic index.

During expansion of detonation products the adiabatic index decreases from $n = 3$ to $n = 1.33$. Since it is not possible to take into account the dependence of the adiabatic index on the DP volume, it is generally believed that n is constant.

With the actual loading densities of 500–1000 kg/m^3, a major role is played by the volume of detonation products molecules (covolume). Work [3] substantiates that equation (3) can be re-written as

$$p_1\left(\frac{V_1}{V_0}-b\right)^{\gamma} = p_2\left(\frac{V_2}{V_0}-b\right)^{\gamma}, \tag{4}$$

where γ is the adiabatic index which does not depend on the DP volume; $\frac{V_1}{V_0}$ and $\frac{V_2}{V_0}$ are dimensionless quantities if $V_0 = 1$ m^3; b is inaccessible to molecules part of the volume in 1 m^3 of DP at a chemical spike pressure.

The adiabatic index can be expressed through the average number of freedom degrees of $\bar{i}$ molecules, constituting the detonation products

$$\gamma = \frac{\bar{i}+2}{\bar{i}}.$$

The average number of freedom degrees, contained in the detonation products of gases, is

$$\bar{i} = \frac{\sum \nu_k i_k}{\nu},$$

where ν_k is the number of moles of k gas in DP; i_k is the freedom degree of k gas molecules; ν stands for DP moles.

Covolume value can be calculated by the formula

$$b = 1 - \frac{\gamma}{n}.$$

If the detonation products contain solid particles, then their volume is added to b.

When $V_1 = 1$ m^3 and p_1 corresponds to the detonation wave front p_d, equation (4) can be re-written as

$$p_d(1-b)^{\gamma} = p(V-b)^{\gamma}. \tag{5}$$

If DP volume is expressed through the borehole radius (r_0), then equation (5) takes the form

$$p_d(1-b)^{\gamma} = p\left(\left(\frac{r}{r_0}\right)^2 - b\right)^{\gamma}, \tag{6}$$

where r is the borehole radius at pressure p.

The pressure in the detonation products was calculated according to the formulas (6) and (3). The pressure, calculated by the formula (6), is about four times as large as the pressure, calculated by the formula (3).

The strong compression wave is formed in the rock with detonation wave propagation in the given section of the borehole. The initial rock velocity u_1 at the borehole wall can be calculated by the formula

$$u_1 = \frac{2c_{r0}}{m-1}\left(\frac{c_r}{c_{r0}} - 1\right), \tag{7}$$

where c_{r0} and c_r are the compression wave velocities at the atmospheric pressure p_0 and at pressure p accordingly.

Velocities ratio $\frac{c_r}{c_{r0}}$ can be determined from the equation (2)

$$\frac{c_r}{c_{r0}} = \left(1+\frac{p}{A}\right)^{\frac{m-1}{2m}}.$$

Detonation products velocity on the DP-rock boundary, if dilution wave is formed in the DP, is

$$u_2 = \frac{2c_d}{\gamma-1}\left(1 - \frac{c}{c_d}\right),$$

where c_d and c are the dilution wave velocities at pressures p_d and p accordingly.

Velocities ratio $\frac{c}{c_d}$ can be determined from the equation

$$\frac{c}{c_d} = \left(\frac{p}{p_d}\right)^{\frac{\gamma-1}{2\gamma}}.$$

Considering that $u_1 = u_2$ at the borehole wall

$$u_1 = u_2 = \frac{2c_d}{\gamma-1}\left(1-\left(\frac{p}{p_d}\right)^{\frac{\gamma-1}{2\gamma}}\right) = \frac{2c_{r0}}{m-1}\left(\left(1+\frac{p}{A}\right)^{\frac{m-1}{2m}} - 1\right). \tag{8}$$

Acquired equation (8) allows evaluation of the initial pressure and the rock speed at the borehole wall.

Formula (7) is obtained on the assumption that at the pressures rock behaves as a liquid, i.e. from hydrodynamic equations. SW equations do not take into account that the medium resists the wave and that SW is formed at a pressure more than p_s. From these equations, it follows that SW can occur at any pressure. Given that SW and SCW equations are obtained from the laws of conservation of mass and momentum, the initial values of the substance velocity and pressure in the SWC and SW will match with a sufficiently accurate precision. Assuming that the shock wave is formed at the borehole wall after explosion, it is possible to determine the initial rock displacement speed and the pressure on the borehole wall using the formula for the mass velocity in the shock wave. Then $u_1 = u_2$ equation is

$$u_1 = u_2 = \frac{2c_d}{\gamma-1}\left(1-\frac{p}{p_d}\right)^{\frac{\gamma-1}{2\gamma}} = \sqrt{\frac{p}{\rho_0}\left(1-\frac{p}{A}\right)^{-\frac{1}{m}}}, \quad (9)$$

where ρ_0 is rock density.

The following values were acquired for granite using formulas (8) and (9): $\rho_0 = 2610$ kg/m^3; $c_d = = 3750$ m/s; $\gamma = 1.4$; $A = 23$ GPa; $m = 4$. With explosive minimum value $p_d = 4$ GPa, the pressure on the borehole walls and borehole wall displacement speed, calculated by the formula (8) are: $p = 3.653$ GPa and $u = = 222.4$ m/s, and by the formula (9) are: $p = 3.65$ GPa and $u = = 224.6$ m/s. Reasonably good match of pressure and velocity values confirms the validity of the formula (7).

Wave processes, which are propagating along and perpendicular to the borehole axis, must be considered when determining dependence of DP pressure and rock velocity on time, as well as superposition of compression and dilation waves in rock, coming at the relevant cross-section from the adjacent charge sites. Instantaneous detonation must be considered to estimate $p(t)$ and $u(t)$. It is generally believed, that the initial pressure in the borehole at the instantaneous detonation is $\overline{p} = p_d/2$. Given that only the initial stage of the explosion (t =300 μs) is reviewed, p and u real values will be slightly greater. Let the borehole radius increase abruptly, so that during this leap changes of the rock pressure and velocity can be neglected. Rock velocity at the borehole wall and DP pressure in the borehole at $(j + 1)$ extension leap can be expressed through pressure and velocity values at leap j

$$u_{j+1} = \frac{2c}{\gamma-1}\left(\frac{p_j}{p}\right)^{\frac{\gamma-1}{2\gamma}}\left(1-\left(\frac{p_{j+1}}{p_j}\right)^{\frac{\gamma-1}{2\gamma}}\right) = \frac{2c_{r0}}{m-1}\left(\left(1+\frac{p_{j+1}}{A}\right)^{\frac{m-1}{2m}}-1\right),$$

where j is leap index number; p_j and u_j are pressure and mass velocity of rock after extension leap j; c is dilution wave velocity in DP at the pressure p; p_{j+1} and u_{j+1} are pressure and mass velocity of rock after extension leap $j + 1$.

The radius of the explosion chamber (borehole radius) after leap $j + 1$ can be found from equation (6)

$$r_{j+1} = r_0\sqrt{\left(\frac{p_j}{p_{j+1}}\right)^{\frac{1}{\gamma}}\left(\left(\frac{r_j}{r_0}\right)^2-b\right)+b}.$$

J-th leap time is $\Delta t_j = (r_{j+1} - r_j)u_j$.

The results of calculations are presented in Fig. 1–3. They were obtained with explosive minimum value $p_d = 4$ GPa, dilution wave velocity in DP at pressure p is $c_d = 3750$ m/s; DP adiabatic value $\gamma = 1.4$.

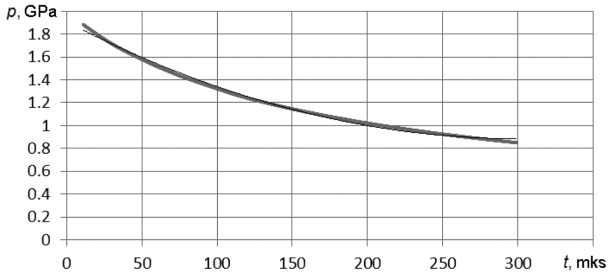

Fig. 1. Dependence of detonation (p) product pressure in the borehole on time (t):

$p = 10^{-5}t^2 - 0.0068t + 1.9076$; $R^2 = 0.9956$ – *correlation relation*

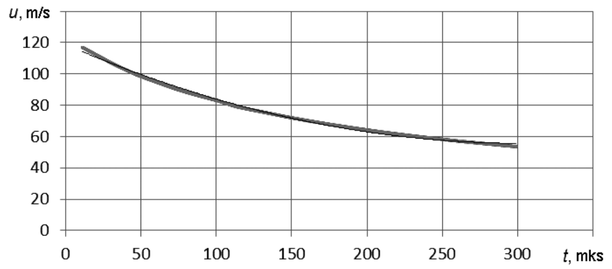

Fig. 2. Dependence of displacement (u) velocity of the rock at the borehole wall on time (t):

$u = 0.0007t^2 - 0.4162t + 118.71$; $R^2 = 0.9957$ – *correlation relation*

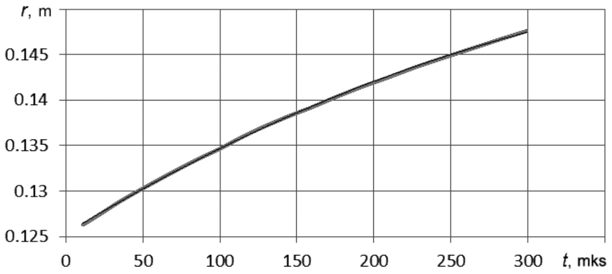

Fig. 3. Dependence of the borehole radius (r) on time (t):

$r = -10^{-7}t^2 + 0.0001t + 0.125$; $R^2 = 0.9998$ – *correlation relation*

Granite was taken as a rock sample with density $\rho_0 = = 2610$ kg/m^3, longitudinal wave velocity $c_{r0} = 5789$ m/s; Teit equation coefficients $A = 23$ GPa, $m = 4$. By the formula $u_x = up_{dx}/p_d$, where p_{dx} is another value of detonation pressure, the borehole walls velocity u_x in the same rock can be estimated with an error of less than 10 % for other values of p_d.

The compression wave damps in the zone of fine destruction according to the power and exponential functions. Indeed, if wave energy absorption coefficient depends only on wave amplitude, then the following equation is true for the plane wave

$$dJ = -\mu(r)Jdr,$$

where dJ is wave intensity change on the rock layer; $\mu(r)$ is linear coefficient of absorption; J is wave intensity at the $[r, r + dr]$ interval.

An expression for the compression wave intensity at the distance r from the borehole axis can be written after integration and consideration of axial symmetry

$$J(r) = J_0 e^{-\mu r} \cdot \frac{r_0}{r},$$

where J_0 is the initial intensity of the wave; μ is the average value of the absorption linear coefficient; r_0 is the borehole radius.

Since the wave intensity is proportional to the square of the pressure, the pressure decrease in the rock with a distance is determined by the formula

$$p(r) = p_0 \sqrt{\frac{r_0}{r}} e^{-\frac{\mu r}{2}}.$$

At a distance $r \le r_0$ size d of particles, into which the rock breaks down, is less than 1 mm, so the coefficient μ is large enough, and DP pressure will be comparable to the dynamic tensile strength at uniform compression after 300–500 μs.

Conclusions. The main mechanism in the fine-dispersed destruction zone – instantaneous rock destruction by shear stress – was found. The size of the particles, into which the rock breaks down, is inversely proportional to the chemical reactions zone width in the explosive. Dependencies of explosion cavity radius, rock velocity at the contact with detonation products and detonation products pressure on time are estimated using the adiabatic equation for detonation products with a constant index, taking into account that the strong compression wave is formed in the rock. It is shown that pressure decreases exponentially from the distance to the borehole axis in the fine-dispersed destruction zone.

The result of this work makes it possible to develop explosives with small fine-dispersed destruction zone and substantiate parameters of charges with inert and water interval, thus reduce the fine-dispersed destruction zone size.

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Мета. Дослідження процесів, що протікають у свердловині та породі в перші 300 мкс після проходження детонаційною хвилею заданого перетину свердловини та визначаючих ефективність руйнування породи.

Методика. Використано аналітичний метод досліджень, заснований на фундаментальних положеннях механіки суцільних середовищ.

Результати. Розглянуто механізми процесів руйнування породи в зоні дрібнодисперсного руйнування. Виконано оцінку залежностей від часу збільшення радіусу свердловини, швидкості зміщення її стінок і зміни тиску продуктів детонації за перші 300 мкс. Показано, що в зоні дрібнодисперсного руйнування тиск убуває по експоненті та обернено пропорційний до кореня квадратного з відстані до осі свердловини.

Наукова новизна. Встановлено, що основним механізмом у зоні дрібнодисперсного руйнування є миттєве руйнування породи від зсувних напружень. Розмір частинок, на які руйнується порода, прямо пропорційний ширині зони хімічних реакцій у вибуховій речовині. Використовуючи рівняння адіабати для продуктів детонації з постійним показником, при врахуванні збудження в породі сильної хвилі стиснення, оцінені залежності зміни від часу радіуса порожнини вибуху, швидкості руйнування породи на контакті із продуктами детонації та тиск продуктів детонації. Показано, що в зоні дрібнодисперсного руйнування тиск убуває по експоненціальній залежності від відстані до осі свердловини.

Практична значимість. Результати роботи дозволяють розробити вибухові речовини з малою зоною дрібнодисперсного руйнування, обґрунтувати параметри зарядів з інертними й водними проміжками, що дає можливість знизити величину зони дрібнодисперсного руйнування.

Ключові слова: *вибух, зона дрібнодисперсного руйнування, хвилі розрідження та стиснення, ударні хвилі*

Цель. Исследование процессов, протекающих в скважине и породе в первые 300 мкс после прохождения детонационной волной заданного сечения скважины и определяющих эффективность разрушения породы.

Методика. Использован аналитический метод исследований, основанный на фундаментальных положениях механики сплошных сред.

Результаты. Рассмотрены механизмы процессов разрушения породы в зоне мелкодисперсного разрушения. Выполнена оценка зависимостей от времени увеличения радиуса скважины, скорости смещения ее стенок и изменения давления продуктов детонации за первые 300 мкс. Показано, что в зоне мелкодисперсного разрушения давление убывает по экспоненте и обратно пропорционально корню квадратному из расстояния до оси скважины.

Научная новизна. Установлено, что основным механизмом в зоне мелкодисперсного разрушения является мгновенное разрушение породы от сдвиговых напряжений. Размер частиц, на которые разрушается порода, прямо пропорционален ширине зоны химических реакций во взрывчатом веществе. Используя уравнение адиабаты для продуктов детонации с постоянным показателем, при учете возбуждения в породе сильной волны сжатия, оценены зависимости изменения от времени радиуса полости взрыва, скорости разрушения породы на контакте с продуктами детонации и давление продуктов детонации. Показано, что в зоне мелкодисперсного разрушения давление убывает по экспоненциальной зависимости от расстояния до оси скважины.

Практическая значимость. Результаты работы позволяют разработать взрывчатые вещества с малой зоной мелкодисперсного разрушения, обосновать параметры зарядов с инертными и водными промежутками, что дает возможность снизить величину зоны мелкодисперсного разрушения.

Ключевые слова: *взрыв*, *зона мелкодисперсного разрушения, волны разрежения и сжатия, ударные волны*

Рекомендовано до публікації докт. техн. наук В. Д. Петренком. Дата надходження рукопису 15.12.15.

UDC 622.02:539.4.011.25

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COMPARATIVE ANALYSIS OF TWO FAILURE CRITERIA FOR ROCKS AND MASSIFS

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ПОРІВНЯЛЬНИЙ АНАЛІЗ ДВОХ КРИТЕРІЇВ РУЙНУВАННЯ ГІРСЬКИХ ПОРІД І МАСИВІВ

Purpose. The analysis of two failure criteria for rocks being in the stress-strain state.

Methodology. The study is based on an integrated approach with the use of analysis and synthesis of the literature sources on the topic related to failure of the rocks with heterogeneous structure, and use of analytical and empirical failure criteria to assess the strength of rocks.

Findings. The analysis of the two failure criteria for compliance with the results of laboratory testing of rocks in the volumetric stressed state is carried out. It is established that the expressions of both analytical criteria reflect the process of rock failure by introducing factors that take into account the mining and geological conditions and mining technology: in the Hoek-Brown criterion – m_b, s, a, D, GSI; in the O. M. Shashenko criterion – ψ, η_0, l_t. Both criteria meet the results of laboratory tests provided m_i coefficient from the Hoek-Brown analytical expression, which takes into consideration rock structure and genesis, should not exceed 4 (mi ≤ 4).

Originality. Analytical comparison of two criteria has shown that, taking into consideration scattering experimental points obtained as a result of laboratory testing of rocks in the volumetric stressed state when $0 \le m_i \le 4.0$, they reflect the fact of the destruction of structurally inhomogeneous rock quite well. However, the Hoek-Brown criterion does not fully take into account the components of the spherical stress tensor ($I = \sigma_1 + \sigma_3$) and if the $m_i > 4$ its application requires additional study.

Practical value. Comparison of the analytical criterion with the results of laboratory testing of structurally heterogeneous materials in the volumetric stressed state allows predicting the rock failure in the massif with the precision of 94 %.

Keywords: *rock failure criterion, Hoek-Brown criterion, A. N. Shashenko criterion, strength in uniaxial compression, geological strength index, coefficient of structural attenuation, coefficient of brittleness*
