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AUTOMATED FORECASTING OF THE PARTICLE SIZE COMPOSITION OF BLASTED ROCKS DURING BLASTHOLE DRILLING IN HORIZONTAL UNDERGROUND WORKINGS

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Abstract. The article describes an analytical method for determining the particle size composition of the rock mass exploded by blasthole breaking of rocks in horizontal underground workings (tunnels). It is based on taking into account the size of the zones of intensive crushing of rocks around the blasthole charge and the presence of natural jointings in the rock mass. The radii of the zones of intensive crushing are calculated using the preset physico-mechanical properties of the blasted rocks and the physico-chemical characteristics of the applied explosive materials (EMs). The particle size composition of natural jointings is calculated using the average size of the jointing in the rock mass. Based on the combined consideration of these components, an analytical method has been developed for the first time in mining that allows to determine each rock class by size in terms of the blasted rock in the course of driving of horizontal underground workings (tunnels). A software program has been developed for the automated determination of the particle size composition of the blasted rock mass, which interconnects the influence of the physico-technical properties of the blasted rocks, the physico-chemical characteristics of the EM used, and the parameters of layout of charges in the rock mass. With this program, calculations were carried out in relation to the anticipated particle size composition of rocks under various parameters of drilling and blasting operations at the Zhezkazgan mines of Kazakhmys Corporation LLP. The comparison of the theoretical and experimental data types has demonstrated a high degree of their identity. These findings confirm that the proposed theoretical approach to determining the particle size composition of the blasted rocks takes into consideration the actual mechanism of destruction of the real rock mass by explosion in the course of driving of horizontal underground workings (tunnels).

Keywords: ultimate explosion cavity radius, radii of crushing zones, presence of natural jointings, volumes of intensive crushing, automated determination of particle size composition of blasted rocks

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КӨЛДЕНЕҢ ЖЕРАСТЫ ҚАЗБАЛАРЫНДА ЖАРЫЛЫС ҰҢҒЫМАЛАРЫН БҰРҒЫЛАУ КЕЗІНДЕ ЖАРЫЛҒАН ЖЫНЫСТАРДЫҢ ГРАНУЛОМЕТРИЯЛЫҚ ҚҰРАМЫН АВТОМАТТАНДЫРЫЛҒАН БОЛЖАУ.

Аннотация. Мақалада көлденең жер асты жұмысында (туннельдерде) тау жыныстарын жару кезінде жарылған тау-кен массасының гранулометриялық құрамын анықтаудың аналитикалық әдісі сипатталған. Ол жарылыс зарядының айналасындағы тау жыныстарының қарқынды ұсақталу аймақтарының көлемін және тау массасындағы табиғи сынықтарды есепке алуға негізделген. Қарқынды ұсақтау аймақтарының радиустары жарылған тау жыныстарының берілген физикалық-механикалық қасиеттеріне және қолданылатын жарылғыш заттардың физика-химиялық сипаттамаларына сәйкес есептеледі. Натурал бірліктердің гранулометриялық құрамы массивтегі бірліктің орташа өлшемінен есептеледі. Осы құрамдас бөліктердің бірлескен есебінің негізінде тау-кен өндірісінде алғаш рет көлденең жерасты қазбаларын (туннельдерді) жүргізу кезінде жарылған тау жынысындағы өлшемдері бойынша жыныстардың әрбір класын анықтаудың аналитикалық әдісі әзірленді. Жарылған тау жыныстарының физикалық-техникалық қасиеттерінің, қолданылатын жарылғыш заттың физика-химиялық сипаттамаларының және орналасу параметрлерінің әсерін өзара байланыстыратын, жарылған тау-кен массасының бөлшек өлшемдерінің таралуын автоматтандырылған түрде анықтауға арналған компьютерлік бағдарлама әзірленді. жыныс массасындағы зарядтардың. Осы бағдарламаның көмегімен «Қазақмыс Корпорациясы» ЖШС Жезқазған кеніштерінде бұрғылау-жару жұмыстарының әртүрлі параметрлері бойынша тау жыныстарының болжамды гранулометриялық құрамының есептеулері жүргізілді. Теориялық және

эксперименттік мәліметтерді салыстыру олардың сәйкестігінің жоғары дәрежесін көрсетті. Бұл нәтиже жарылған тау жыныстарының бөлшектердің өлшемдік таралуын анықтаудың ұсынылып отырған теориялық тәсілі көлденең жерасты қазбаларын (туннельдерді) айдау кезінде нақты тау-кен массасының жарылыспен жойылуының нақты механизмін ескеретінін растайды.

Түйін сөздер: жарылыс қуысының шекті радиусы, ұсақтау аймақтарының радиусы, табиғи фрагменттердің құрамы, қарқынды ұсақтау көлемдері, жарылған тау жыныстарының гранулометриялық құрамын автоматты түрде анықтау

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АВТОМАТИЗИРОВАННОЕ ПРОГНОЗИРОВАНИЕ ГРАНУЛОМЕТРИЧЕСКОГО СОСТАВА ВЗОРВАННЫХ ПОРОД ПРИ ШПУРОВОЙ ОТБОЙКЕ В ГОРИЗОНТАЛЬНЫХ ПОДЗЕМНЫХ ВЫРАБОТКАХ

Аннотация. В статье описан аналитический метод определения гранулометрического состава взорванной горной массы при шпуровой отбойке пород в горизонтальной подземной выработке (в туннелях). Он базируется на учете размеров зон интенсивного дробления пород вокруг шпурового заряда и содержания естественных отдельностей в массиве пород. Радиусы зон интенсивного дробления рассчитываются по заданным физико-механическим свойствам взрываемых пород и физико-химическим характеристикам применяемых взрывчатых веществ (ВВ). Гранулометрический состав естественных отдельностей рассчитывается по среднему размеру отдельности в массиве. На базе совместного учета этих составляющих впервые в горном деле разработан аналитический метод определения каждого класса пород по крупности во взорванной породе при проходке горизонтальных подземных выработок (туннелей). Разработана компьютерная программа автоматизированного определения грансостава взорванной горной массы, взаимоувязывающего влияния физико-технических свойств взрываемых пород, физико-химических характеристик применяемого ВВ и параметров расположения зарядов в массиве пород. С помощью этой программы проведены расчеты прогнозируемого гранулометрического состава пород при различных параметрах буровзрывных работ на шахтах Жезказгана ТОО «Корпорация Казахмыс». Сопоставление теоретических и экспериментальных данных показали высокую степень их идентичности. Такой результат подтверждает, что предлагаемый теоретический подход определения гранулометрического состава взорванных пород учитывает действительный механизм разрушения реального массива пород взрывом при проходке горизонтальных подземных выработок (туннелей).

Ключевые слова: предельный радиус взрывной полости, радиусы зон дробления, содержание естественных отдельностей, объемы интенсивного дробления, автоматическое определение гранулометрического состава взорванных пород

Introduction

In works (Hekmat, 2018; Faramarzi et al., 2013: 82–94; Shalamanov et al., 2017; Campbell, 2017) focus on the assessment of the quality of the blasted rock mass typically apply the widely known Kuz-Ram model of distribution of the particle size composition of rock cuts named after its authors Kuznetsova and Rosin-Rammler. They are designed to assess the the particle size composition of rocks after the explosion and do not provide a forecast of the quality of crushing before the explosion. Other authors attempt to predict the particle size composition of the blasted rock mass by using neural networks (Huang et al., 2020; Bahrami et al., 2012; Dhekne et al., 2014; Ebrahimi et al., 2016; Enayatollahi et al., 2014; Oraee et al., 2006; Gao et al., 2018; Hasanipanah et al., 2018; Monjezi et al., 2009; Monjezi et al., 2010; Salimi et al., 2012; Sayadi et al., 2013; Shams et al., 2015; Shi et al., 2012; Singh et al., 2016). However, such attempts are not brought to engineering analyses. They do not take into consideration the actual mechanism of destruction of rocks by blasting. The paper presents an alternative rock mass destruction model differing from those aforementioned, which allows for an analytical interconnection of physico-mechanical properties of rocks, fracturing (blockiness) of the rock mass, physico-chemical characteristics of the applied explosive material (EM), and different conditions of exploding the breaking-up rock sheet. This creates conditions for the preliminary calculation of the particle size composition of the blasted block of the rock mass, i.e. his prediction.

The proposed model of destruction of the rock mass by a cylindrical explosive charge is based on the hypothesis of G.I. Pokrovsky (Покровский, 1957: 276), which was further developed in the works of B.R. Rakishev (Ракишев, 1983: 240; Ракишев, 2016: 340). According to the accepted model of rock mass destruction by explosion of a cylindrical charge, the first stage of the explosion encompasses a powerful compression wave formed by the explosion that destroys the rock during the contact “charge—medium” (crushing or transforming it into a plastic state), expands the explosion cavity, while the zone of radial fractures extends from the border of the zone of crushing (fine crushing) (Fig. 1).

The process is initially little different from the phenomena accompanying the explosion in an infinite medium, but the interaction of the compression wave with the free surface leads to a more intensive crushing of the material in its vicinity and in the rock body. During this time, the main destruction of the breaking-up rock takes place, while the explosion cavity of a cylindrical shape achieves its extreme (maximum) position (see Fig. 2 a, b).

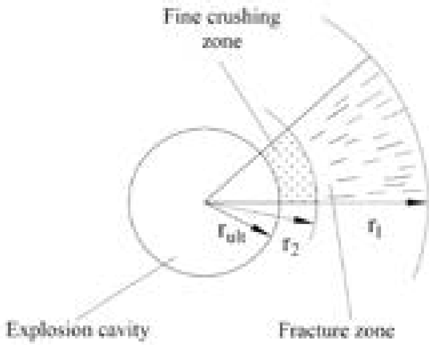

Fig. 1. Structure of the zones of destruction around the explosion cavity: rult is the ultimate radius of explosion cavity, r2 is the radius of the fine crushing zone, r1 is the radius of the fracture zone

The second stage of the explosion encompasses the disruption of the axisymmetric development of the explosion cavity as a result of the influence of the free surface, while gaseous explosion products (GEPs) additionally destroy the breaking-up rock sheet and impart thereto an accelerated motion in the direction of the free surface (Fig. 2 c,d). The main defining factor during this stage is the impact of the GEPs remaining in the cavity.

The third stage involves the distribution of fragments of the broken-up rock under the influence of the GEPs and gravity, and the development of rock disintegration (see Fig. 2 d, e).

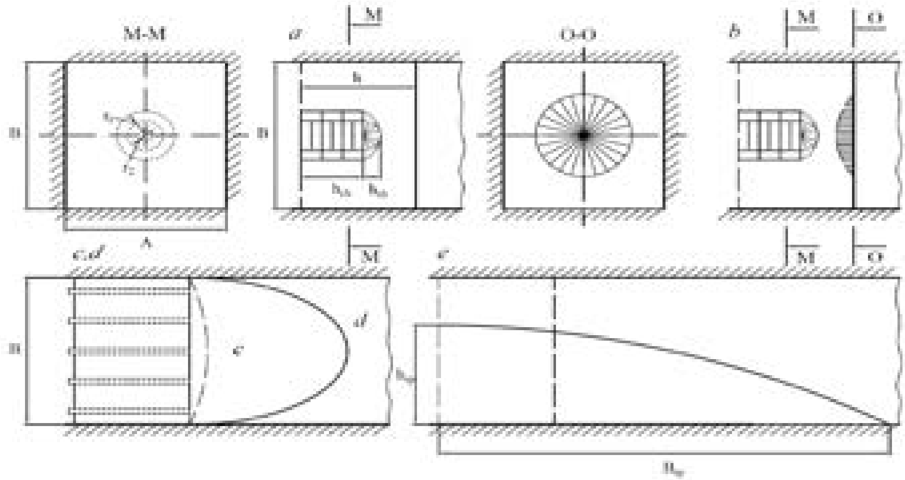

Fig. 2. Outlines of the stages of development of an explosion in horizontal underground workings (tunnels) with a single (a,b) and group (c,d) EM charge: beginning (a) and completion (b) of the first stage, beginning (c) and completion (d) of the second stage; beginning (d) and completion (e) of the third stage; A is the width of the blasted block, B is the height of the blasted block, h is the thickness of the blasted sheet, h_{ch} is the height of a cylindrical charge in the blasthole without overdrilling, h_{sh} is the height of an intensively crushed rock sheet above the column of the charge, $h_{sh} = r_2$, r_2 is the radius of the fine crushing zone, r_1 is the radius of the fracture zone, h_{sp} is the height of rock shotpile at break line of blasting rock mass, B_{sp} – is the width of rock shotpile

Key results of the explosion of EM charges in the breaking-up rock sheet. The key results of the explosion in a solid medium are the ultimate radius of the explosion cavity, the radius of the fine crushing zone, and the radius of the zone of radial fractures (see Fig. 1). Works (Ракишев, 2016: 340; Никифоровский, 272) based on the general theorems of theoretical mechanics and the laws and principles of the theory of elasticity (Станюковича, 1975; Ханукаев,1974: 223; Адушкин, 1961: 94–102; Родионов et al., 1971: 200; Rakishev et al., 2011: 65–69; Rakishev, 2020). Derive the following equation for the relative extreme (maximum, ultimate) radius of the explosion cavity or the main criterion of the explosion effect in a solid medium:

$$\bar{r}_{ult} = (P_i / P_c)^{1/4}, \tag{1}$$

where P_i is the initial pressure of gaseous explosion products (GEPs) in the charging chamber (MPa); P_c is the strength characteristics of the rocks under the conditions of the comprehensive explosion stress (MPa).

The initial pressure of GEPs is calculated using the famous formula (Ханукаев,1974: 223).

$$P_i = \frac{1}{8}\rho_{EM} D^2. \tag{2}$$

Here ρ_{EM} is the density of the EM charge in the blasthole (borehole) (kg/m^3); and D is the velocity of detonation of the EM charge in the blasthole (m/s).

Some sources (Ракишев, 2016: 340; Никифоровский, 272); derive the following equation for the strength characteristics of the rocks under the conditions of the comprehensive explosion stress:

$$P_c = \sigma_{cpr}\left(\frac{\rho_0 c^2}{\sigma_{cpr}}\right)^{1/4}, \tag{3}$$

where σ_{cpr} is the breaking-down point of the rock in terms of compression (MPa); ρ_0 is the rock density (kg/m^3); c is the velocity of the sound in the rock (m/s).

For the radius of the fine crushing zone (see Fig. 1) the following equation is derived:

$$r_2 = r_{ult}\left(\frac{\rho_0 c^2}{5\sigma_{cpr}}\right)^{1/2}. \tag{4}$$

Here r_{ult} is the extreme (maximum, ultimate) radius of the explosion cavity (m): $r_{ult} = \bar{r}_{ult} \cdot r_0$; r_0 is the radius of the blasthole (m).

For the radius of the zone of radial fractures (see Fig. 1) the following dependence is obtained:

$$r_1 = r_2 \frac{\nu}{1+\nu} \cdot \frac{\sigma_{cpr}}{\sigma_t}, \quad (5)$$

where ν is Poisson's ratio, and σ_t is the breaking-down point of the rock in terms of tension (MPa).

The principle of rational layout of EM charges in the blasted rock mass has been formulated, which provides for the largest-scale envelopment of the breaking-up rock sheet by joints formed by the explosion effect. In terms of borehole bench breaking, it is expressed by the following equations (see Fig. 3):

$$(1+k)^{1/2} \frac{\pi r_1}{2W} \approx 1, \frac{2r_1}{a} \approx 1, (1+k)^{1/2} \frac{h_{ch} + h_{sh}}{h} \approx 1, \quad (6)$$

where k is the coefficient taking into account the fractions of destruction of the rock mass both from the effect of the reflected tension waves and the GEPs, $k = 1$; W is the bench toe line of resistance (BTLR) (m); *a* is the distance between boreholes in a row (m); h_{ch} is the height of the cylindrical charge in the borehole without overdrilling (m); h is the height of the blasted block (m); h_{sh} is the height of the intensively crushed rock sheet above the column of the charge, it is equal to the radius of the fine crushing zone.

Inasmuch as the first two explosion stages in terms of both benching-based and non-benching-based breaking proceed in the same manner, the expressions in (6) are also true for cylindrical charges located in underground horizontal workings (tunnels) of different purpose (see Fig. 5). Therefore, the line of least resistance (LLR), which is the shortest distance from the axis of the charge placed in the blasthole to the nearest free surface or W′, is defined from the first correlation of expressions in (6), taking into account the fact that *k*=1, *W′=W□sinα*. Inasmuch as the bench face angle on average is *α* = 63°, then *W′*=0.9□*W*.

Thus, the LLR is equal to:

$$W' \approx 2 \cdot r_1. \quad (7)$$

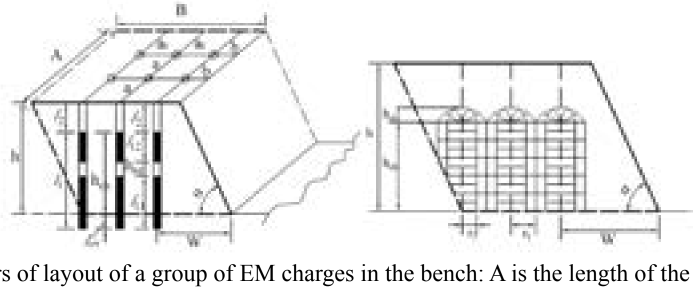

Fig.3. Parameters of layout of a group of EM charges in the bench: A is the length of the blasted block, B is the width of the blasted block, h is the bench height, α is the bench face angle, W is the bench toe line of resistance, b is the distance from the axis of the borehole of the first row to the upper edge of the bench, a is the distance between boreholes in a row, a_r is the distance between the borehole rows, , l_l, l_{11}, l_{12} is the charge length, l_2 is the length of the uncharged part of the borehole, l_{ov} is the length of the overdrill, h_{ch} is the height of a cylindrical charge in the borehole without overdrilling, h_{ag} is the height of the air gap, h_{sh} is the height of the intensively crushed rock sheet above the column of the charge, $h_{sh} = r_2$, r_2 is the radius of the fine crushing zone, r_1 is the radius of the fracture zone

In accordance with the second correlation from (6), the reasonable distance between the blastholes must amount to:

$$a \approx 2 \cdot r_1 . \qquad (8)$$

According to the third correlation from (6), the length of the charge in the blasthole is equal to:

$$h_{ch} \approx 0,7h - h_{sh} . \qquad (9)$$

The length of the undercharging (the uncharged part of the blasthole) may be accepted as equal to (see Fig. 5a):

$$l_2 \geq 2 \cdot r_1 . \qquad (10)$$

The total length of the charge in the blasthole amounts to:

$$l_1 = h_{ch} + l_{ov} . \qquad (11)$$

The length of the overdrill or the depth of the blasthole exceeding the height (thickness) of the blasted block may be accepted as equal to:

$$l_{ov} \approx r_2 . \qquad (12)$$

The length (depth) of the blasthole:

$$l_{bl} = h + l_{ov} . \qquad (13)$$

Analytical determination of the particle size composition of the rock mass exploded by blasthole breaking. The productive capacity of the mining and conveyor equipment in tunnel driving is predetermined by the quality of the blasted rock mass. It is characterized by lumpiness of the rock and the distribution of cuts by size in the disintegration, i.e. particle size composition of the blasted rocks.

The particle size composition of the blasted rocks depends heavily on the physico-mechanical properties of the rock mass, the fracturing (blockiness) of the rock mass, the physico-chemical characteristics of the EM used, and the parameters of layout of charges in the blasted sheet of the rock mass. The fracturing of the rock mass is the sum total of visible and invisible fractures breaking the rock mass into natural

Table 1. Particle size composition of natural jointings in the rock mass

Classes of rock masses by blockiness	Rock masses by blockiness (average diameter of the jointing, m)	Presence in the rock mass (%) of jointings with the size of (m)						
		<0,15	0,16–0,30	0,31–0,45	0,46–0,60	0,61–0,75	0,76–0,90	>0,91
I	Small-block (d_e=0,1m)	63,97 | 63,97	17,43 | 18,39	4,75 | 4,12	1,30 | 1,08	0,35 | 0,27	0,10 | 0,07	0,03 | 0,015
II	Medium-block (d_e=0,3m)	36,03 | 36,03	23,39 | 28,05	15,18 | 14,78	9,85 | 9,03	6,39 | 5,41	4,15 | 3,04	2,69 | 1,35

III	Coarse-block (d_e=0,5m)	16,09 | 16,09	15,64 | 23,36	15,19 | 17,85	14,76 | 15,52	14,34 | 13,27	13,94 | 10,65	13,54 | 6,77
IV	Very coarse-block (d_e=0,7m)	6,71 | 6,71	8,50 | 17,71	10,78 | 16,4	13,66 | 16,98	17,31 | 17,59	21,94 | 17,41	27,81 | 13,90

Note: in numerator – actual, in denominator – virtual value of the presence of natural jointings in the rock mass

jointings, which is characterized by blockiness, i.e. the sizes of natural jointings in the rock mass. The particle size composition of natural jointings of the rock mass is determined by direct measurements or calculated using the average size of jointings based on the author's approach (Никифоровский, 272); The particle size composition of jointings in the rock mass of the Zhezkazgan mines of Kazakhstan, determined by means of calculations and resembling closely the actual one, is presented in table 1.

Let us consider the algorithms of formation of rock cuts by size in different sheets of the blasted rocks, starting from the intensive crushing zone. The structure of this zone consisting of the sum total of the zones of fine crushing and radial fractures is presented in a cross-sectional view of a cylindrical charge in Fig. 1.

In order to accomplish the task, the volume of the intensively crushed rock per unit of length of a cylindrical charge (Fig. 1, 4) should be divided into distinct parts by size of cuts contained therein. The basis thereof is represented by the experimental data obtained in the course of explosion of a meter-long bench composed of mottled clays. As a result of the analysis of these data, the linear size of the cuts located near the outline of the fine crushing zone was found to predominantly represent $2r_0$ (Ракишев, 2016: 340) (Fig. 4a). In this respect, the distance between joints on the inner border of the zone of radial fractures, i.e. the linear size of the rock cut may be accepted to the first approximation as equal to:

$$b_2 = 2 \cdot r_0, \tag{14}$$

where r_0 is the radius of the borehole (blasthole) (m).

Therefore, according to the pattern in (5), the distance between joints on the inner border (see Fig. 4a) of the zone considered, i.e. the linear size of the rock cut will be equal to:

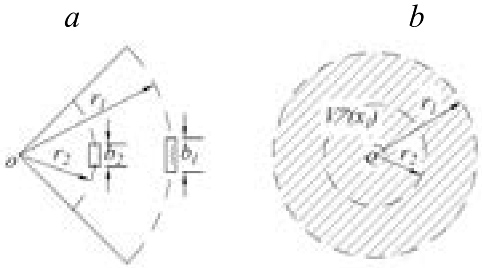

Fig. 4. Distribution of intensively crushed rock cuts around the exploded EM charge: *a* – sizes of rock cuts (b_2, b_1) on the borders of the zones of fine crushing (r_2) and radial fractures (r_1); *b* – distribution of classes of rocks by size $V''(x_1)$ in the zone of intensive crushing.

$$b_1 = b_2 \frac{\nu}{1+\nu} \frac{\sigma_{cpr}}{\sigma_t} \quad (15)$$

Calculations show that in terms of applying blastholes with the radius of r_0=0.025 m, the total volume of the fine crushing zone consists of cuts with the size up to 0.05 m, while the zone of radial fractures contains cuts with the size of 0.051÷0.150 m.

In blasthole breaking, the blasted rock mass is usually divided by the size of cuts into 7 classes in increments of 0.15 m. The first class includes cuts with the size up to 0.15 m, the second class includes cuts sized between 0.16–0.30 m, the third class includes cuts sized between 0.31–0.45 m, the fourth class includes cuts sized between 0.46–0.60 m, and the seventh class includes cuts with the size exceeding 0.91 m.
As the represented data demonstrate, the first size class (0–0.15 m) should include the total volume of rocks of the zones of crushing and radial fractures, while the second class (0.16–0.30 m) and the other size classes should contain the remaining volume of rocks beyond the zone of intensive destruction.

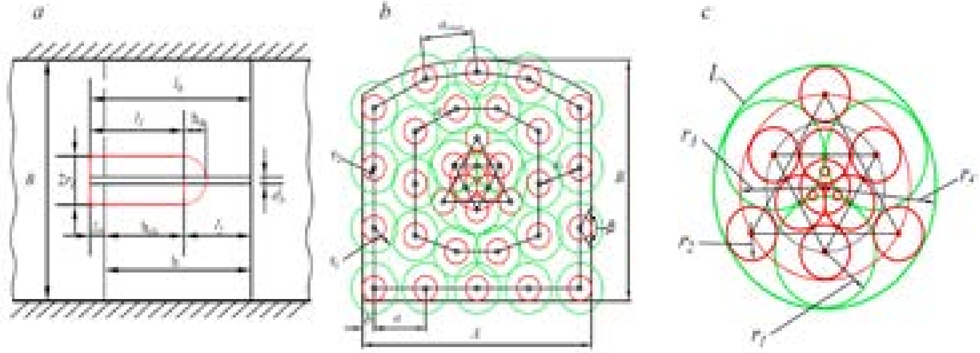

Fig. 5. Parameters of layout of a single charge (a), a group of EM charges (b) and breaking-in cavity (c) in horizontal underground workings (tunnels): A is the width of the tunnel, B is the height of the tunnel, h is the height (thickness) of the blasted sheet, d_b is the diameter of the blasthole, l_b is the length of the blasthole, l_1 is the length of the charge, l_2 is the length of the uncharged part of the blasthole, l_{ov} is the length of the overdrill, h_{ch} is the height of a cylindrical charge in the blasthole without overdrilling, h_{sh} is the height of the intensively crushed rock sheet above the column of the charge, $h_{sh} = r_2$, *a* is the distance between blastholes, b is the distance from the line hole to the contour of the tunnel, a_r is the distance between the rows of blastholes, a_{cont} is the distance between contouring holes, r_2 is the radius of the zone of fine crushing, r_1 is the radius of the fracture zone, r_3 is the radius of the fine crushing zone in the breaking-in (c), r_4 is the radius of the mixed crushing zone in the breaking-in (c), L is the trace of the virtual free surface of a cylindrical breaking-in with the radius r_4.

In terms of the rational layout of blasthole charges of different purpose (see Fig. 5b), the volume of the intensively crushed rock of the breaking-up sheet of the rock mass will be equal to the sum of the volumes of the intensively crushed rock around the breaking-in, outer, and line holes.

For breaking-in charges, i.e. the breaking-in cavity, the radius of the intensive crushing zone will be equal to the radius of a cylindrical breaking-in, i.e. (see Fig. 5c):

$$r_4 = r_3 + r_2\,, \tag{16}$$

where r_2 is the radius of the fine crushing zone around the blasthole charge, and r_3 is the radius of the fine crushing zone in the cut, m.

For the double-row cut (in terms of a smaller section of the working):

$$r_3 = \frac{4}{\sqrt{3}} r_2 \approx 2,3 r_2\,. \tag{17}$$

For the triple-row cut (in terms of a larger section of the working):

$$r_3 = \frac{4}{\sqrt{3}} r_2 + r_2 \approx 3,3 r_2\,. \tag{18}$$

The volume of the intensively crushed rock in the cut:

$$V''_{cut}(x_1) = \pi r_4^2 (h_{ch} + h_{sh})\,, \tag{19}$$

where $V_{cut}''(x_1)$ is the volume of the rocks of the first (x_1) size class in the zone of intensive crushing of the cut, h_{ch} is the charge height (see Fig. 5a), h_{sh} is the height of the intensively crushed rock sheet below the column of the charge, equal to the radius of the fine crushing zone.

The volume of the intensively crushed rock around stoping holes (see Fig. 5b):

$$V''_{stop}(x_1) = \pi r_1^2 (h_{ch} + h_{sh}) N_{stop}\,, \tag{20}$$

where N_{stop} is the number of stoping holes, it.

The volume of the intensively crushed rock around contouring holes (see Fig. 5b):

$$V''_{cont}(x_1) = \pi r_1^2 (h_{ch} + h_{sh}) N_{cont} - \frac{r_1^2}{2}(\beta - \sin\beta)(h_{ch} + h_{sh})(N_{cont} - N_{cor}) - \\ - r_1^2 (\beta - \sin\beta)(h_{ch} + h_{sh}) N_{cor}\,, \tag{21}$$

where N_{cont} is the number of contouring holes, it., N_{cor} is the number of line holes at the corners of the section of the working, $N_{cor} = 4$ шт., β is the segment angle of the zone of radial fractures of the contouring hole falling beyond the contour of the section of the working, $\beta = 2\arccos(r_2 \cdot r_1)$, (rad).

Therefore, the total volume of the intensively crushed rock (of the first class) in horizontal mine workings (tunnels) in terms of the rational layout of blasthole charges will be equal to:

$$V''(x_1) = V''_{cut}(x_1) + V''_{cont}(x_1) + V''_{stop}(x_1)\,. \tag{22}$$

In calculating the volume of rocks of the considered size class in the entire blasted sheet, the correspondent natural jointings contained in the other part of the blasted sheet should be attached thereto, as the rock mass consists of coherent natural jointings of different shapes and sizes that are separated by visible and invisible joints (Rakishev, 2020: 36–46). This volume is proportional to their presence in the rock mass (see Table 1). Thus, the volume of the first size class in the entire blasted rock is determined from the following formula:

$$V'(x_1) = V''(x_1) + p(x_1)\left[V - V''(x_1)\right], \tag{23}$$

where V is the volume of the rock of the blasted rock mass sheet; $V'(x_1)$ is the total volume of the rock of the *1*-st class after the explosion; $p(x_1)$ is the presence of jointings of the *1*-st class in the rock mass, in unit fractions.

The subsequent classes of the rocks by size (above 0.15 m) are formed as a result of fracturing of the rocks of the blasted block into natural jointings during the second stage of the explosion and their crushing as a result of collision of rock cuts in the course of movement during the second and third stages of the explosion

In order to determine such a volume of the crushed rocks, the following experimentally confirmed assumptions were accepted. Rock cuts with the size exceeding 0.91 m as a result of collision will be reduced in the total volume by one half (1/2) of their initial value (see Formula (24)). The crushed part of these cuts is distributed among the lower classes (0.16-0.9 m) evenly, and a 1/10 part of the content of coarse cuts $p(x_7)$ is added to each class. The percentage content of cuts in the sixth class (0.76–0.9 m) will be reduced by 1/3 of its initial value. This crushed part is added to the lower classes (0.16–0.75 m), also evenly. In other words, the fraction of these classes will increase additionally by 1/12 of the class content $p(x_6)$. The fraction of cuts in the fifth class (0.61–0.75) will be reduced by one-fourth (1/4) of its initial value. This fraction will be added to the second, third, and fourth size classes (0.16–0.6) evenly by a 1/12 part of the content of cuts $p(x_5)$. The fraction of cuts of the fourth class (0.46–0.60) will be reduced by one-fifth (1/5) and added to the second and third classes by 1/10 parts. One sixth (1/6) part of the fraction of cuts of the third class (0.31–0.45) will be transferred to the second class. The structure of rock cuts with the size up to 0.15 m does not undergo any alterations. Taken as a whole, the described over-allocation of rock cuts during the second and third stages of the explosion can be presented as follows:

$$\begin{gathered}
q(x_1) = p(x_1),\ q(x_2) = p(x_2) + \frac{1}{6}p(x_3) + \frac{1}{10}p(x_4) + \frac{1}{12}p(x_5) + \frac{1}{12}p(x_6) + \frac{1}{10}p(x_7) \\
q(x_3) = \frac{5}{6}p(x_3) + \frac{1}{10}p(x_4) + \frac{1}{12}p(x_5) + \frac{1}{12}p(x_6) + \frac{1}{10}p(x_7), \\
q(x_4) = \frac{4}{5}p(x_4) + \frac{1}{12}p(x_5) + \frac{1}{12}p(x_6) + \frac{1}{10}p(x_7), \\
q(x_5) = \frac{3}{4}p(x_5) + \frac{1}{12}p(x_6) + \frac{1}{10}p(x_7),\ q(x_6) = \frac{2}{3}p(x_6) + \frac{1}{10}p(x_7),\ q(x_7) = \frac{1}{2}p(x_7).
\end{gathered} \tag{24}$$

Here $p(x_1), p(x_2), \ldots, p(x_7)$ is the actual presence of the cuts of the 1,2,…,7-

th classes in the rock mass, in percent; $q(x_1), q(x_2), \ldots, q(x_7)$ is the over-allocated presence of jointings of the 1,2,…,7-th classes in the rock mass, in percent;

The dependences in (24) represent the virtual presence of natural jointings in the rock mass. The numerical values of the presence of actual and virtual jointings are presented in Table 1.

The volumes of the crushed rock of all classes are directly proportional to the product of their virtual presence in the rock mass by the difference of the volumes of the breaking-up sheet and the intensively crushed rock. In other words, the following is obtained in relation to the volumes of the classes (i ≥ 2) to be determined:

$$V'(x_i) = q(x_i)\left[V - V''(x_1)\right] \tag{25}$$

where V''(xi) is the volume of the intensively crushed rock of the i-th class (i ≥ 2); V'(xi) is the total volume of the rock of the i-th class after blasting; q(xi) is the virtual presence of jointings of the i-th class in the rock mass, in unit fractions;

In order to calculate the particle size composition of the blasted rock, it is sufficient to divide the obtained volumes (23) and (25) by the volume of the breaking-up sheet. Therefore, the presence of separate fractions in the volume of the blasted sheet is defined by the following correlation:

$$p'(x_j) = \frac{V''(x_j)}{V} \tag{26}$$

where p'(xj) is the content of the j-th fraction in the blasted rock mass, in percent.

The system of values p'(xj), as known, represents the particle size composition of the blasted rock mass. Thus, according to the expression in (26), with the preset physico-mechanical, structural properties of the rocks, detonation, energy characteristics of the EM, and parameters and means of explosion, the particle size composition of the blasted ore and rock is calculated timely.

The developed theoretical approach to the determination of the particle size composition of the blasted rocks is based on the actual mechanism of destruction of the real rock mass by the explosion of a cylindrical charge and is thereby fundamentally different from other approaches present in the literature

Automated determination of the particle size composition of the rock mass exploded by blasthole breaking. On the basis of the analytical method of determination of the particle size composition of the rock mass exploded by blasthole breaking, a software program entitled "Particle size composition of the rock mass exploded by blasthole breaking" has been developed in the Microsoft Visual Studio 2019 environment [The program facilitates convenient and flexible calculations in terms of the results of D&B operations, more precisely, the determination of the particle size composition of blasted rocks in horizontal underground workings depending on the source data related to the explosion. The flow graph of the program is presented in Fig. 6.

According to the proposed program for the automated prediction of the particle size composition of the blasted rock mass, the passport of D&B operations was compiled in the course of driving of tunnels (horizontal mine workings) at the East, South, and West Zhezkazgan mines of Kazakhmys Corporation LLP in two cases. The geometrical dimensions of the tunnel: in the first case the height is 5.2 m, the width is 4.65 m, the sectional area S = 22.85 m2, the thickness of the blasted sheet is 3.0 m, in the second case the height is 4.4 m, the width is 4.3 m, the sectional area

S = 18.14 m2, the thickness of the blasted sheet is 3.0 m. In both cases the physico-mechanical properties of the rocks are as follows: rock – gray sandstone, rock density ρ = 2670 kg/m3, velocity of the sound in the rock c = 4300 m/s, σcpr = 166 MPa, σt = 15 MPa, ν = 0.23; the characteristics of the applied granular EM (Rioxam ST): density of the EM ρEM = 1000 kg/m3, detonation velocity D = 3500 m/s. The diameter of the blastholes is 0.052 m. The diameter of the compensation boreholes is 0.089 m. The reasonable parameters of D&B operations calculated using the above data are presented in Table 2, while the particle size composition of the blasted rock mass is presented in Table 3.

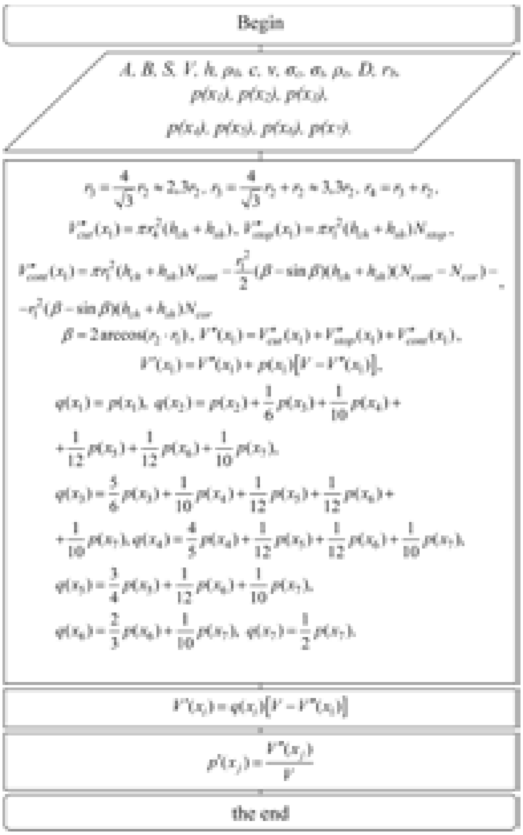

Fig. 6. Flow graph of the program “Particle size composition of the blasted rock mass exploded by blasthole breaking”

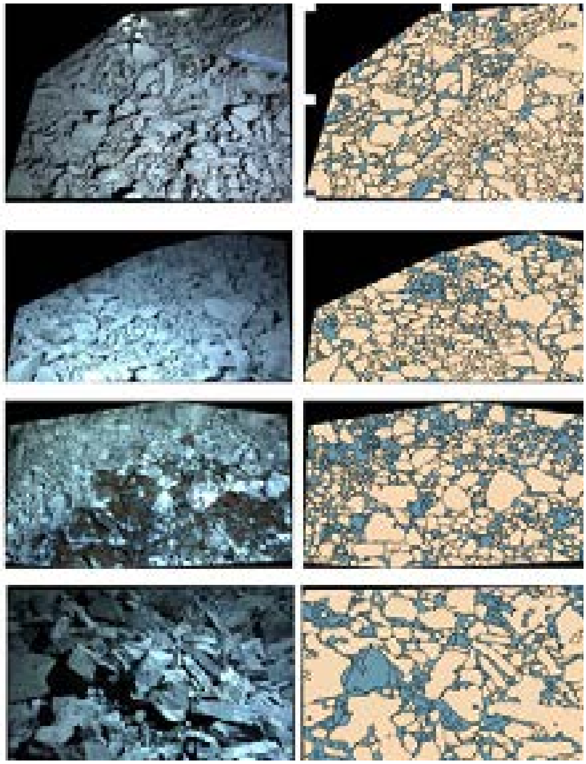

Figure 7. Images of the blasted gray sandstone of the Zhezkazgan mines: (a) – South mine, medium-block; (b) – West mine, medium-block; (c) – East mine, middle-block; (d) – West mine, coarse-block. The image of the disintegration of the blasted rock mass is on the left, the analysis of the image with the use of the device is on the right.

Table 2. Calculated rational parameters of D&B in the tunnel for S = 22,85 м^2 (1), S = 18,14 м^2 (2)

D&B parameters	1	2	D&B parameters	1	2
Ultimate radius of the cavity, r_{ult}, m	0,03	0,03	Length of the undercharge of blastholes, m	1,0	1,0
Radius of the fine crushing zone, r_2, m	0,25	0,25	Number of stoping holes, m	10	8
Radius of the zone of radial fractures, r_1, m	0,50	0,50	Distance between stoping holes, m	1,0	1,0
Number of all blastholes, N, it.	34	29	Number of contouring holes, m	14	14
Number of boreholes (89 mm), it.	3	3	Distance between contouring holes, m	0,9	0,9
Number of breaking-in holes, it.	10	7	Angle of contouring holes, deg.	5	5
Distance between the central cut hole and compensation boreholes, m	0,15	0,15	Capacity of one linear meter of the blasthole, kg	2,1	2,1
Distance between the central cut hole and the first row of cut holes, m	0,3	0,3	Total EM, kg	165,5	141,16

Distance between the central cut hole and the second row of cut holes, m	0,55	0,55	Granular EM (Rioxam ST), kg	158,7	135,36
Distance between the central cut hole and the third row of cut holes, m	0,8	0,8	Cartriged EM, kg	6,8	5,8
Length of the overdrill of blastholes, m	0,25	0,25	Number of cartriges per face, it.	34	29
Depth of blastholes, m	3,25	3,25	Delay time, ms	100	100
Depth of compensation boreholes, m	3,25	3,25	Specific charge of EM, kg/m^3	2,44	2,62
Length of the charge of blastholes, m	2,25	2,25			

a *b*

c

Fig. 8. Cumulative plots of the calculated (●) and actual (■) particle size composition of the blasted rock mass of small-block (a), medium-block (b) and coarse-block (c) rock masses of the Zhezkazgan mines at the section of working S = 22,85 м^2

Table 3. Calculated and actual particle size composition of the blasted rock mass at Zhezkazgan mines

Rock masses by blockiness	Case	Presence in blasted rock mass (%) of cuts with the size of (m)						
		<0,15	0,16–0,30	0,31–0,45	0,46–0,60	0,61–0,75	0,76–0,90	>0,91
Small-block	**1**	**88,5** / 82,2	**7,53** / 11,6	**2,46** / 5,9	**1,38** / 0,3	**0,1** / 0	**0,02** / 0	**0,01** / 0
Medium-block	**1**	**77,28** / 75,9	**9,96** / 14	**5,25** / 7,1	**3,21** / 2,67	**1,92** / 0,33	**1,08** / 0	**0,48** / 0
Coarse-block	**1**	**70,19** / 67,75	**8,3** / 11,55	**6,34** / 7,45	**5,51** / 5,3	**4,71** / 3,8	**3,78** / 2,7	**2,4** / 1,45
Small-block	**2**	**88,74** / 83,55	**6,75** / 9,05	**2,29** / 4,35	**1,54** / 2,15	**0,58** / 0,75	**0,02** / 0,15	**0,01** / 0
Medium-block	**2**	**80,01** / 75,5	**8,76** / 10,4	**4,62** / 6,0	**2,82** / 3,6	**1,69** / 2,7	**0,95** / 1,3	**0,42** / 0,5

Note: in numerator – **calculated,** in denominator – actual value of the presence of fractions of blasted rock cuts

The measurements of the particle size composition of the rocks were conducted using the Porta Metrics™ specialized equipment of the Canadian company Motion Metrics. This universal portable device facilitates the measurement of the particle size composition of the blasted rock mass without using control objects (reference pegs) for the determination of the scale. The user may simply select a face area that they are interested in, capture an image and instantly receive the results through the user-friendly graphical interface. These data include graphs of distribution of rock cut sizes, the range of their sizes, and so forth. Fragments of such images in the settings of the mines of Kazakhmys Corporation LLP are presented in Fig. 7. In terms of the 15 main blasts, more than 150 measurements of the particle size composition of the rocks in different parts of the blasted block have been conducted. The averaged values of separate fractions of the blasted rocks are presented in Table 3. The cumulative plots of the calculated and actual particle size composition of *a* *b*

Figure 9. Cumulative plots of the calculated (●) and actual (■) particle size composition of the blasted rock mass of small-block (a) and medium-block (b) rock masses of the Zhezkazgan mines at the section of working S = 18,14 $м^2$

the blasted rocks are presented in Fig. 8, 9.

The analysis of the data presented in Table 3 and Fig. 8 demonstrates that the largest absolute deviation of the actual value from the calculated one (6.3 %) occurs in small-block rocks for the fraction of cuts with the size up to 0.15 m. These deviations in the other fractions (0.16–0.91 m) lie within 0.01–4 %. In medium-block rock masses, the largest deviation was found (4.04 %) for the fraction of 0.16–0.3. For other fractions the deviation amounts to 0.48-1.85%. In coarse-block rock masses, the largest deviation (3.25 %) occurs for the fraction of 0.16–0.30 m. For other fractions, it fluctuates between 0.21 and 2.44 %.

In the second case (see Fig. 9) the largest absolute deviation (5.19 %) of the actual value from the calculated one occurs in small-block rocks for the fraction of cuts with the size up to 0.15 m. These deviations in the other fractions (0.16–0.91 m) lie within 0.01–2.30 %. In medium-block rock masses, the largest deviation was found (4.51%) for the fraction of cuts with the size up to 0.15 m. For other fractions, it fluctuates between 0.08 and 1.64 %.

The calculated and actual cumulative plots in all rock masses and cases are virtually the same. These findings point at the identical nature of the calculated and actual particle size composition of the blasted rock mass in tunnel driving, which corroborates the validity and authenticity of the new approach to the determination of the particle size composition of the rocks exploded by blasthole charges in horizontal underground workings.

Thus, the developed method for the automated determination of parameters of layout of blasthole charges in the blasted rock sheet and the forecasting of the particle size composition of the blasted rocks, analytically interconnecting the above with physico-mechanical properties of the rock mass, fracturing (blockiness) of the rock mass, physico-chemical characteristics of the applied EMs, and parameters of layout of charges in the blasted rock sheet, is indeed a reliable and effective means of achieving the best results in tunnel driving.

Conclusion

The accepted stage-by-stage model of destruction of the real rock mass under the influence of the explosion of a cylindrical charge has been described. The key results of the explosion in a solid medium derived from that model are presented as follows: strength characteristics of the rocks under the conditions of the comprehensive explosion stress, relative ultimate radius of the explosion cavity, radii of the zones of fine crushing and radial fractures, and the principle of rational layout of charges in the blasted block.

For the first time in the mining science, an analytical approach has been developed that allows to determine the particle size composition of the rock mass exploded by blasthole breaking in horizontal underground workings.

On the basis of the analytical approach developed, a software program has been created to facilitate the automated forecasting of the particle size composition of the rock mass exploded by blasthole charges in horizontal underground workings.

Measurements of the particle size composition of the blasted rock mass have been performed at the Zhezkazgan mines of Kazakhmys Corporation LLP through the use of the PortaMetrics™ specialized equipment. These data confirm the calculated particle size composition of the blasted rock mass in horizontal underground workings.

The fundamental difference of the new approach from its widely known counterparts lies in the fact that the ultimate radius of the explosion cavity formed by the EM explosion in the rock is accepted as the defining indicator of the results of the EM explosion in a solid medium. It represents the integral effect of the explosion in a solid medium, successfully interconnecting the explosion results with the physico-mechanical properties of the rocks, the physico-chemical characteristics of the applied EM, and the explosion conditions.

The results obtained in relation to the explosions with the use of the program of automated forecasting of the particle size composition of the blasted rock mass correlate well with data provided by other authors.

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