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THE EFFECT OF DIFFERENT LOADING CONDITIONS ON THE EFFECTIVENESS OF EXPLOSIVE FRAGMENTATION OF SOLID MEDIA BY CHARGES WITH VARIABLE CROSS-SECTIONAL SHAPE

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Abstract. The degree of preconditioning of the rock mass, taking into account the properties of the rocks being broken, determines the effectiveness of blasting operations, which comprise a wide range of means and technological processes. One current challenge is the selection and justification of improved borehole charges to develop modern, resource-saving technologies for explosive fragmentation of structurally complex rock masses in open pit mines of ore and non-ore mineral deposits. A shortcoming of many studies that justify rational parameters for drill and blasting operations is an incomplete consideration of rock fabric and its fracturing, which affects the pattern of grain-size distribution and the fragmentation behavior on the bench during explosive fragmentation. For this reason, the present work favors experimental investigations. The purpose of the work is to substantiate an optimal charge design with a variable cross-section by conducting experimental research into the influence of different loading conditions on the efficiency of explosive fragmentation of a solid medium using physical models. It was found that, when sand–cement model specimens are fragmented by charges of different cross-sectional shapes, the mode of fragmentation depends on the dynamic loading conditions and on the interface between the explosive and the solid medium. The efficiency of fragmentation was assessed by processing and segmenting images of the fragments from destroyed model specimens using the U-CARFnet and U-Net methods. It was established that detonation of an explosive charge shaped as a square prism produces a uniform grain-size distribution in the fragmented model that follows a logarithmic trend. Moreover, using a square-prismatic charge is the most economically efficient option. Such a charge promotes the formation of a multi-gradient, multi-directional loading pattern on the surface of the charge cavity in the solid medium, which improves the explosive's useful work coefficient. The experimental results obtained for selecting and justifying the rational design of borehole charges can be used to adjust drill-and-blast parameters for the conditions of Ukraine's granite open pit. The proposed blasting technology has been tried out at the "Uman Granite Open Pit" LLC open pit and has shown its effectiveness.

Keywords: solid medium, charge cavity, explosive material, explosive fragmentation, stress wave.

1. Introduction

Ukraine possesses substantial deposits of both metallic and non-metallic mineral resources, concentrated in a massif of hard rocks of metasomatic and metamorphic origin that make up the Ukrainian Shield. These rocks have a complex structure, and their fragmentation requires additional measures to achieve effective fragmentation measures that involve improving existing and developing new resource-efficient methods for rock fragmentation and mineral processing, mechanizing production processes with high-technology equipment, using modern explosives, and carrying out careful planning. The effectiveness of an explosive charge in rock is determined by its ability to perform useful work in crushing and moving the rock mass. From this it follows that effective control of the blasting process depends on the correct choice of charge design. By "charge design" we mean the combination of geometric and technological parameters such as the shape of the charge and its cavity, the position of the initiation point, the combinations of explosives used, the charge length, and the ratio of the parts of the charge occupied by explosive and by stemming. On the basis of geometry, elongated charges are divided into two main groups: charges with constant

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cross-section and charges with varying cross-section along their height [1–7]. Variable-section charges exhibit pronounced maxima and minima of energy potential along their height. In the detonation of such charges the role of tensile stresses in rock failure increases and the energy required to produce failure under tension is an order of magnitude lower than that required under compression. The quality of the fragmented rock mass (mean fragment diameter) is the most widely used indicator of blasting effectiveness and can have a significant impact on the productivity of material-handling equipment (excavators) during excavation, as well as on the safety of mining operations. Therefore, rapid and accurate assessment of blast quality is crucial for subsequent mine planning, for substantiating drilling and blasting parameters, and for selecting appropriate equipment and execution procedures. Thus, the degree of fragmentation achieved with the available drilling equipment, taking into account the properties of the rocks being broken (their strength and structural features), primarily determines the efficiency of blasting operations. These operations encompass a wide range of means and technological actions: the choice of explosive and initiation systems, the diameter and design of the blasting hole charge, initiation schemes that govern interaction between individual charges and their groups, blasting conditions (the degree of rock saturation, the presence of a supporting wall), and the type of stemming used.

Therefore, the selection and substantiation of improved borehole charge designs are one of the conditions for the establishment of modern resource-saving explosive technologies of rock fragmentation in open pits of ore and non-ore minerals, is an urgent scientific and applied task.

Analysis of modern research and publications. As is well known, a substantial fraction of the explosive energy is expended in the zone immediately adjacent to the charge cavity (typically within two to three charge radii), where intensive comminution of the rock occurs, leading to losses of recoverable material in open pit for construction aggregates. Adjustment of the specific energy of the explosion applied to rock fragmentation is achieved by changing the area of direct contact between the borehole charge and the rock to be broken, or by creating conditions that reduce the dynamic effect of the detonation on the surface of the charge cavity. For effective control of the blast action it must be borne in mind that the tensile and shear strength limits of rocks are roughly an order of magnitude lower than their compressive strength. Since the energy intensity of fracturing a solid medium is proportional to the square of its strength limit for a given mode of loading, the energy required to fracture a rock by tensile stresses is about 100 times lower than that required under compressive stresses. The useful effect of cylindrical charges in rock fragmentation can therefore be increased by regulating the specific explosive energy along the charge length in combination with enhancing the role of tensile stresses in the rock being fractured [8, 9], for example through the use of elongated combined charges: charges interspersed with inert, air or water gaps; charges of variable diameter along the column height; or charges with various cross-sectional shapes.

From the above, it follows that there are several methods for forming borehole charges both along their length and across their cross-section. These methods include:

- forming a continuous column of explosive along the height of the charge cavity in the borehole [2];
- creating enlarged sections in the drilled cylindrical cavities with a diameter greater than that of the primary cavity [3, 4];
- placing inside the charge cavity a continuous column of explosive enclosed in polyethylene sheaths of variable diameter (conical in shape), which taper towards the borehole collar, and with various cross-sectional configurations [5, 6];
- placing hollow shapes made of inert materials inside the charge cavities [7];
- using borehole charges separated by an air gap [10–12].

One of the methods for achieving more efficient use of explosive energy in rock fragmentation is the use of borehole charges separated by an air gap [10–12]. Introducing air gaps into a borehole charge can not only reduce the peak shock pressure because of the presence of the cavities, but also increase the duration of the explosive action on the rock mass and raise the stress intensity in the rock due to the interaction of shock waves propagating through the rock mass from the two separated charge segments when they are initiated simultaneously. A shock wave travelling within a borehole not only imparts dynamism to the whole process but also continuously transmits its energy into the surrounding medium, which determines the increased intensity of rock fragmentation. The effectiveness of borehole charges that are separated by air gaps has been demonstrated by many years of blasting practice in both open pit and underground conditions when excavating rocks of varying strength.

In recent years, practical methods and means for forming air gaps when fragmentation water-saturated rocks [13] have appeared and have been tested in granite open pit. Thus, the beneficial effect of an explosion on rock fragmentation can be enhanced by using borehole charges spaced by either air or inert gaps, for example, an inert annular gap between the explosive and the borehole wall [14]. In such arrangements the mass of explosive in the borehole is reduced, yet the stored energy can still be sufficient to fracture the rock. The gain in blasting efficiency is achieved by increasing the duration of the explosive action on the rock mass and by creating a non-uniform (varying-gradient) load along the length of the charge. This effect is realized, in particular, when using elongated charges of variable diameter [3, 4]. Such charges are produced by placing polyethylene sheaths (sleeves) of variable diameter into drilled boreholes and filling them with explosive. As the charge diameter changes, the energy transmitted to the rock mass changes, producing a stress field with varying gradients in which tensile stresses play an increased role in rock failure. The effectiveness of these charges has been confirmed in blasting operations in iron-ore and flux open pits in Ukraine.

As a result of the rapid development of computer software in modern technologies for processing experimental data, image processing technology has achieved significant progress and is now widely applied not only in the mining industry [15] but also across various fields, employing threshold-based segmentation of images of blasted rock masses [16]. A qualitative assessment of the size distribution of blast fragments and the composition of the fragmented rock mass are among the key indicators used to evaluate the efficiency of blasting operations in open pit mines. In [17], a method was proposed for segmenting rock masses using cumulative particle size distribution curves, which was applied to the positioning and recognition of fragments of fractured rock. The development of software for analyzing the results of blasting operations enables the evaluation of blast efficiency based on key indicators such as the histogram of block size distribution in blasted rock, the cumulative particle-size distribution curve, and analytical approaches to determining the mean fragment diameter, such as the Rosin-Rammler law [18]. This makes it possible to rapidly detect and identify the rock mass fragmented by the blast, thereby providing technical support for optimizing blasting parameters and justifying the design of an efficient borehole charge of explosive material.

One of the shortcomings of studies devoted to the justification of rational parameters of drilling and blasting operations for assessing the quality of crystalline rock mass fragmentation is the insufficient consideration of the rock structure, its fracturing, and the orientation of fractures within the mass. These factors significantly influence the distribution of the granulometric composition and its fragmentation on the bench during rock fragmentation. Therefore, in this work, preference is given to experimental investigations. Addressing the above-mentioned issues requires the implementation of urgent measures aimed at improving existing and developing new technical solutions to enhance the efficiency of blasting hard crystalline rocks of complex structure, taking into account mining and hydrogeological conditions of mineral extraction. In this regard, research related to the selection and substantiation of new borehole charge designs (for example, with a variable cross-sectional shape) forms the basis for rational technological parameters of new resource-saving methods for rock fragmentation, which are based on the consideration of the fracture-tectonic structure of rock masses and remain relevant today.

Previously unsolved part of the problem. At present, there is no universal, comprehensive (theoretical and experimental) approach that encompasses: the selection of charge design and explosive type; the initiation of explosive charges with due regard to the characteristics of the rock mass being fragmented; and the subsequent acquisition of information on rock-mass fragmentation by segmenting images of the blasted material on an open pit bench. Taking these factors into account would help to overcome difficulties in predicting the distribution (fragmentation) of the particle-size composition of rock mass broken by blasting and would support the justification (optimization) of rational blasting parameters.

The purpose of the work is to substantiate an optimal charge design with a variable cross-section by conducting experimental research into the influence of different loading conditions on the efficiency of explosive fragmentation of a solid medium using physical models.

2. Methods

The work presents the results of experiments carried out using physical modelling methods to study explosive fragmentation of a solid medium under field conditions in a granite open pit, using scaled models. The granulometric quality of the fragmented material produced by charges with different cross-sectional shapes was assessed by segmenting images of fragments from the test specimens using U-CARFnet and WipFrag methods, followed by processing with a computer program. The granulometric data are presented as a particle-size distribution curve, histograms and granulometric class data.

Research Objectives. The mechanism of explosive fragmentation produced by charges of variable cross-section was determined under different loading conditions in order to justify rational charge designs that optimize the particle-size distribution of the fragmented models.

3. Experimental Part

To select and justify rational explosive charge designs for subsequent industrial application, the M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, in collaboration with Cherkasy State Technological University of the Ministry of Education and Science of Ukraine, carried out experimental studies of the explosive fragmentation of a solid medium using model charges under open pit conditions in a granite open pit, with evaluation of their destructive capacity (mean fragment diameter) and the newly generated surface.

Because conducting experiments to justify the designs and parameters of borehole charges of explosive material with various cross-sectional shapes under industrial conditions is difficult, the method of physical modelling was chosen to study the processes of fragmentation of a solid medium using scaled models under different dynamic-loading conditions. A cubic model with a side length of 150 mm was selected as the modelling specimen. The specimens were made from a sand-cement mixture with water added in a ratio of 1:1:0.5. Cement of grade M500 was used as the binder, and fine river sand served as the aggregate.

To simulate loading conditions of the solid medium that imitate blockiness and fracturing of the rock mass, the prepared cement paste was poured into a special steel form measuring 150×150×150 mm. An embedded mesh with 10 mm openings was placed in layers along the height of the specimen at intervals of 30–40 mm. A charge cavity (borehole) 16 mm in diameter and 85 mm deep was formed in the center of each model (Fig. 1).

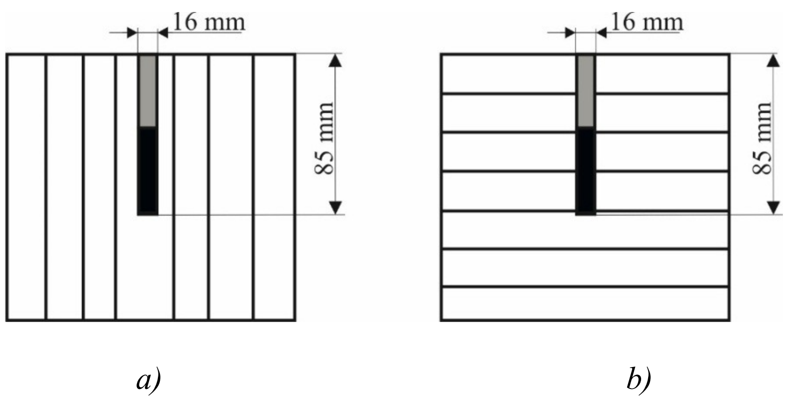
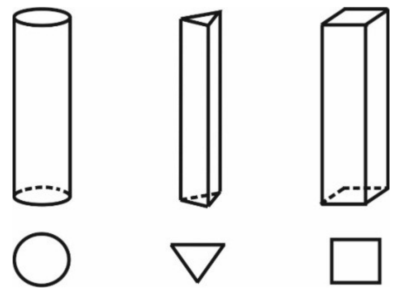


Figure 1 – Scheme of models of an anisotropic rock mass with layering arranged parallel (*a*) and perpendicular (*b*) to the charge axis

When preparing the sand-cement models, it was taken into account that the borehole diameter must be no smaller than the critical detonation diameter of the explosive (the minimum diameter of a cylindrical explosive charge at which detonation can propagate along the charge length). Once the models had attained 30% of their ultimate strength they were extract and air-cured until maximum strength was reached, in accordance with [19–22]. Simultaneously with the manufacture of the principal models, specimens with edge length 40 ± 2 mm were produced to evaluate the physic-mechanical properties of the fractured solid, in accordance with [19–22]. Test results indicated: specimen mass m = 131.2·10^{-3} kg; density ρ = 1910 kg·m^{-3}; longitudinal wave velocity C_p = 3080 m·s^{-1}.

For the three series of experimental investigations, 19 models were prepared (six models for each series plus one trial model) and explosive charges of various shapes were fabricated (Fig. 2).

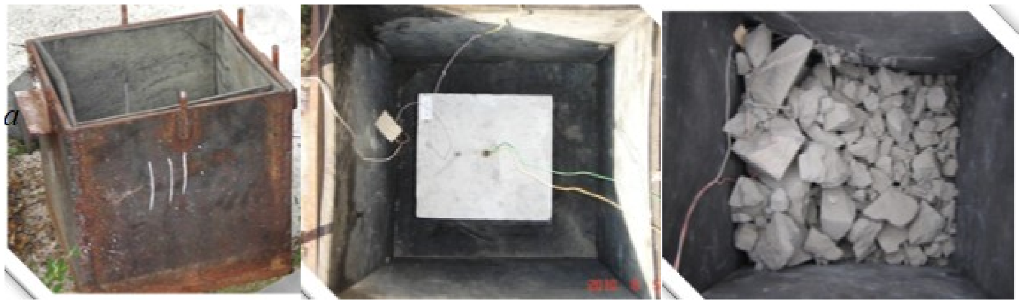


a) *b*) *c*)

Figure 2 – Designs of explosive charges with a constant cross-section (*a*), a triangular cross-section (*b*), and a square cross-section (*c*)

In Fig. 2 the explosive was placed in a casing made of thin paper (tracing paper). A mixture of pentaerythritol tetranitrate (PETN) (80%) and solid rocket propellant (20%) with a total mass of 1.0 g was used as the explosive charge [23].

The prepared charges, fitted with an initiator and connected to the non-electric initiation system “Impulse”, were placed into the model’s charge cavity and into the blast chamber [24] (Fig. 3).



a) *b*) *c*)

Figure 3 – Appearance of the explosion chamber (*a*) with a model before the explosion (*b*) and after the explosion (*c*)

The cavity mouth (Fig. 3) was sealed with stemming material having a particle size of 0.25 mm. The charges were detonated using an explosive device. The data obtained from the fragmentation of the models by the explosive energy of charges with various cross-sectional shapes were evaluated using the sieve analysis method according to the procedures of L.I. Baron, through segmentation of images of the ejected fragments of the solid medium samples using the U-CARFnet and WipFrag methods [25, 26]. Based on the results of the fragmentation, the mean fragment diameter was calculated, cumulative granulometric distribution curves were constructed, and the data were subsequently processed using computer software.

4. Results and discussion

During the analysis of the granulometric composition, the following parameters were determined: the total mass of the fragmented model; the content of fine and coarse fractions; the area of newly generated surfaces; and the diameter of the average particle (Table 1).

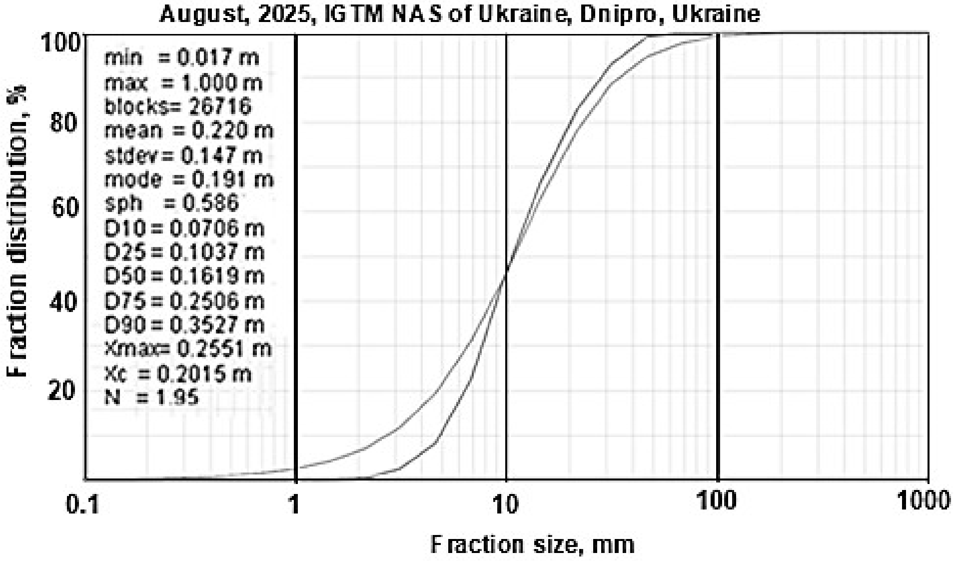
Table 1 – Results of the fragmentation of sand-cement models caused by the explosion of explosive charges of various cross-sectional shapes under different conditions of energy transfer to the fragmentation medium

Explosive charge designs	Loading conditions	Mass of the destroyed model m, kg	Diameter of the middle piece d_{mid}, sm	Composition of fractions (%) in models destroyed by explosion		Newly formed surface S, sm^2
				$d_i < 20$ mm	$d_i > 50$ mm	
Cylindrical charge of solid construction	⊥ stratification	5.687	3.45	27.0	53.0	35527.0
	‖ stratification	5.74	2.82	29,0	56.0	47494.3
Charge in the form of a square prism	⊥ stratification	5.732	3.71	31.0	45.0	35286.6
	‖ stratification	5.60	2.91	36.3	47.0	42030.0
Charge in the form of a triangular prism	⊥ stratification	5.70	3.35	20.0	60.0	29783.6
	‖ stratification	5.662	3.06	26.2	67.8	32545.4

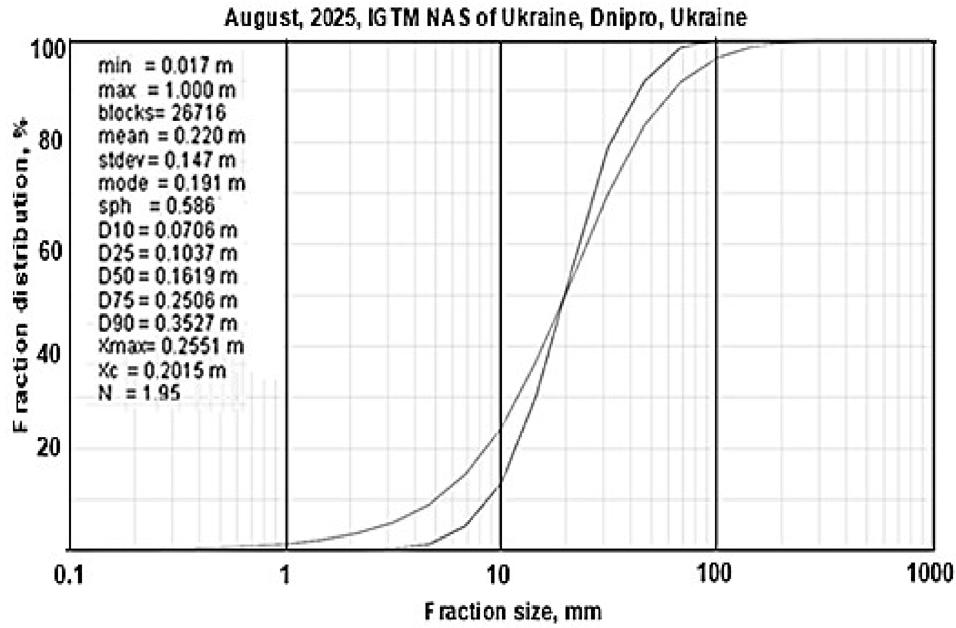
Table 1 contains the following symbols: ‖ – parallel stratification of sand-cement models; ⊥ – perpendicular stratification of sand-cement models.

Based on sieve analysis and the processing of segmented fragments from samples of models destroyed by explosive charges of various cross-sectional shapes, cumulative particle-size distribution curves were generated using the U-CARFnet and WipFrag methods [25, 26] with the aid of a computer program (Fig. 4).

Analysis of the obtained results (Table 1, Fig. 4) shows that the yield of fractions in the range from $d_i < 20$ mm to $d_i > 50$ mm of the fragmented models for all charge types depends both on various dynamic loading conditions and on the contact between the explosive and the solid medium. It was found that, under loading of a solid medium with parallel stratification, the mean fragment diameter for all charge types decreases by up to 20% while the area of newly formed surface increases by up to 30%. The analysis (Fig. 4) indicates that detonation of a charge shaped as a square prism causes the granulometric distribution of the fragmented model to change according to a logarithmic law. This demonstrates that using a charge of this shape promotes the formation, at the surface of the charge cavity, of multi-gradient and multi-directional loading on the solid medium, thereby improving the blast efficiency.



a)



b)

Figure 4 – Cumulative distribution curves of the granulometric composition of fragmented sand-cement models with parallel (*a*) and perpendicular (*b*) layering during the detonation of an explosive charge in the form of a square prism

The experimental results on the selection and justification of a rational borehole charge design can be used to adjust drilling and blasting parameters for the conditions of Ukrainian granite open pits. The proposed blasting technology was tested at Uman Granite Open Pit LLC and demonstrated high effectiveness.

5. Conclusions

The conducted investigations allow the following conclusions to be drawn:

1. It was established experimentally that, when sand-cement model specimens are fragmented by charges of various cross-sectional shapes, the yield of fractions in the range from $d_i < 20$ mm to $d_i > 50$ mm for all charge types depends on differing conditions of dynamic loading at the explosive solid medium interface.

2. To assess the effectiveness of rock fragmentation and to reduce processing time and segment fragment images, the U-CARFnet and U-Net methods were used.

3. It is experimentally demonstrated that, under loading of a solid medium with parallel bedding, for all charge types the mean fragment diameter is reduced by up to 20% while the area of newly formed surface increases by up to 30%. Detonation of a square-prismatic explosive charge produces a relatively uniform particle-size distribution of the fragmented model, which varies according to a logarithmic law.

4. Results from studies on the selection and justification of an economical charge geometry show that a square-prismatic charge is the most effective for rock fragmentation from an economic standpoint. Its use enables the generation on the charge-band surface of loads with varying gradients and directions and improves the overall efficiency of the blast.

5. The experimental results on the selection and justification of an optimal borehole charge geometry can be used to adjust drilling and blasting parameters for the conditions of Ukrainian granite quarries. The proposed blasting technology was tested at the Uman Granite Open Pit LLC and demonstrated high effectiveness.

Conflict of interest

Authors state no conflict of interest.

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ВПЛИВ РІЗНИХ УМОВ НАВАНТАЖЕННЯ НА ЕФЕКТИВНІСТЬ ВИБУХОВОГО РУЙНУВАННЯ ТВЕРДОГО СЕРЕДОВИЩА ЗАРЯДАМИ ЗМІННОЇ ФОРМИ ПЕРЕРІЗУ

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Анотація. Рівень підготовки гірничої маси з урахуванням властивостей гірських порід, що руйнуються, визначає ефективність вибухових робіт, які включають в себе широкий комплекс засобів і технологічних операцій. Однією з актуальних завдань є вибір і обґрунтування удосконалених конструкцій свердловинних зарядів з метою створення сучасних ресурсозберігаючих технологій вибухового руйнування гірських порід складної будови на кар'єрах рудних і нерудних родовищ корисних копалин. Одним із недоліків робіт, присвячених обґрунтуванню раціональних параметрів буропідривних робіт є недостатньо повний облік структури гірських порід та її тріщинуватості, що впливає на характер розподілу гранулометричного складу та фрагментацію порід на уступі при вибуховому руйнуванні. Тому в цій роботі перевага надається експериментальним дослідженням. Метою роботи є обґрунтування раціональної конструкції заряду змінної форми перерізу шляхом проведення експериментальних досліджень впливу різних умов навантаження на ефективність вибухового руйнування твердого середовища на моделях. Встановлено, що при вибуховому руйнуванні піщано-цементних моделей зарядами з різної формою перерізу, характер руйнування залежить від різних умов динамічного навантаження та на контакті «вибухова речовина – тверде середовище». Оцінка ефективності руйнування твердого середовища здійснювалася шляхом обробки та сегментації зображень фрагментів зразків зруйнованих моделей за допомогою методів U-CARFnet і U-Net. Встановлено, що при детонації заряду вибухової речовини у вигляді квадратної призми, спостерігається рівномірний характер розподілу гранулометричного складу зруйнованої моделі, який змінюється за логарифмічною залежністю. Встановлено, що використання заряду вибухової речовини у вигляді квадратної призми є найбільш ефективним з економічної точки зору. Використання такого заряду сприяє формуванню на поверхні зарядної порожнини різноградієнтного та різнонаправленого навантаження твердого середовища, що покращує коефіцієнт корисної дії вибуху. Отримані результати експериментів по вибору і обґрунтуванню раціональної конструкції свердловинного заряду можуть бути використані при коригуванні параметрів буропідривних робіт для умов гранітних кар'єрів України. Запропонована технологія ведення вибухових робіт пройшла випробування на кар'єрі ТОВ «Уманський гранітний кар'єр» і показала свою високу ефективність.

Ключові слова: тверде середовище, зарядна порожнина, вибуховий матеріал, вибухове руйнування, хвиля напруги.