UDC 622.235.5 DOI: https://doi.org/10.15407/geotm2026.176.048

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ON THE WAVE AND QUASI-STATIC ACTION OF AN ELONGATED EXPLOSIVE CHARGE

Abstract. The article substantiates that, during the explosion of an elongated charge, the rock mass is destroyed within a dynamic stress field, making the quasi-static approach inappropriate. The results were obtained using theoretical methods. An analysis of the processes occurred in rocks, when an elongated explosive charge is blasted, is presented. The aim of the work is to justify the inexpediency of the quasi-static approach for studying rock destruction by elongate explosive charges. With a quasi-static approach, the maximum pressure in the explosion cavity is approximately half the pressure at the Chapman-Jouguet point, which is unjustified. The resulting stress field is smooth, while the mechanisms of the processes occurred in the crushing and grinding zone are not taken into account under this approach, as well as destruction of rock in shock waves and strong compression waves. The rock destruction occurs only in an axisymmetric stationary stress field. In addition, the processes occurred in the presence of packing and the mechanisms of energy loss of detonation products, as well as the key detonation parameters of the explosive are not taken into account. It is obvious that with a quasi-static approach it is very difficult to analyze destruction of the rock with taking into account free surfaces. This is especially true for the upper part of the bench or in the near-face zone of underground mine workings. The quasi-static approach does not consider the role of detonation products in the rock destruction, the interaction of rock fragments during their collision and the fragmentation of the rock mass. Thus, to study the nature of rock destruction by elongated explosive charges, it is absolutely necessary to consider the wave processes occurred both in the explosion cavity and in the rocks. The wave-based approach makes it possible to establish the mechanisms of rock destruction and weakening in a shock wave and in compression and unloading waves. It also enables determination of parameters of all processes that occur in charges of any configuration. The quasi-static approach does not allow the study of some other processes of rock destruction and their influence on the nature of explosive destruction. Nevertheless, a portion of the rock (its small elements) is always destroyed in a quasi-static field, which forms a part of the dynamic stress field. Therefore, when studying rock destruction by elongated explosive charges, it is necessary to consider the dynamic processes occurred in the explosion cavity and the rocks.

Keywords: elongated charges; quasi-static stress field; detonation and shock waves; compression and unloading waves; crushing.

1. Introduction

When studying the rock destruction by elongated explosive charges, most specialists believe that the main destruction processes occur in a quasi-static field generated by detonation products [1-3]. Based on the results obtained from models and explosions of concentrated explosive charges, it is argued that the destruction at the front of the explosion wave occupies approximately 10-15% of the destruction zone radius. At the same time, it is not taken into consideration that, during the explosion of an elongated charge, the initial pressure in the explosion cavity can reach 6-10 GPa (during the collision of detonation waves), which is significantly higher than in case of instantaneous detonation, and that stresses in the rock decrease with distance not according to a power law alone, but according to both to an exponential and power law dependence. During large-scale industrial blasting operations using elongated charges, results were obtained that differ by 2-4 times from the corresponding quasi-static calculations regarding the destructive effect of the explosion [4]. It is commonly assumed that when an explosive explodes in sufficiently strong media with a bulk compression modulus comparable to the initial pressure of the detonation products in the

Received: 14.09.2025 Accepted: 11.02.2026 Available online: 31.03.2026

explosion cavity, no destruction occurs at the explosion-wave front at all, but the bulk compression modulus of, for example, granite is approximately 65-80 GPa [5]. This is significantly greater than the rock strength limit.Some specialists consider rock destruction in waves generated by waves in the explosion cavity. Only a limited number of studies address this issue. Determining in which cases the above approaches should be applied and how reliable the results they provide are is a highly relevant task.

Analysis of current research and publications. In study [6], the efficiency and productivity of continuous media destruction under directed explosion of a charge with variable cross-sectional shapes were assessed. The parameters of the explosion wave and the stress wave were experimentally determined. The destruction of both stressed and unstressed continuous media by an explosion wave was considered in work [7]. In work [8], the mechanisms of crack propagation and the influence of existing fracturing on the behavior of the quasi-static gas phase during an explosion were examined. Work [9] is dedicated to modeling the explosion-induced destruction of rocks under dynamic and static explosive loads. A series of model experiments on explosion under plane deformation conditions were conducted. In work [10], a numerical model of single charges is presented with an analysis of the role of borehole pressure (including the analysis of the quasi-static component). While work [11] is devoted to numerical modeling of the dynamics of crack formation under quasi-static loads. In [12], a review is provided of experimental studies on the crack formation and propagation in rocks due to the quasi-static effect of gaseous detonation products. The authors of [13] conducted experimental studies of the effect of the wave decelerations and interferences on the fragmentation of granite samples. In [14], the dynamics of fracture were investigated with emphasis on the role of quasi-static loading from the cavity or borehole after the passage of the shock wave. The work [15] presents a model for accounting for the quasi-static charge component with consideration of rock impedance. The work [16] demonstrates an analytical modeling of the parameters of the formation of rock mass fragmentation zones around the charge cavity under explosive loading. In [17], the action of detonation gas is simulated as a quasi-static pressure acting on cracks associated with the blast borehole. The results show that the shock wave plays a dominant role in the fragmentation of the rock near the borehole wall and in generating several primary radial cracks further from the borehole. Study [18] proposes a new dynamic analysis of the destruction process, which is able to model the dynamic destruction process taking into account the complexity of the interaction between the stress wave and propagation waves. In [19], a model is shown for predicting zones of destruction induced by spherical charges. Study [20] investigates the dynamic interaction over time of groups of borehole charges and its effect on explosive rock destruction. Study [21] summarizes the distinguishing features of dynamic versus static rock destruction, noting that the physico-mechanical properties of rocks, including stress-wave propagation, strength, fracture toughness, energy distribution, and crack-formation mechanisms, depend on loading rate. Modeling of these features and their application in blasting operations using modern numerical methods is discussed. The drawbacks of most studies devoted to modeling the rock destruction processes is that the destruction mechanisms for elongated charges and for their model equivalents differ substantially [5]. Some works use the acoustic approach. All processes of rock destruction by elongated explosive charges are purely dynamic in nature. The quasi-static approach can be used only when studying the quasi-static destruction of rock elements within a dynamic field.

The aim of the study is to substantiate the inexpediency of using the quasi-static approach for investigating rock destruction by elongated explosive charges.

2. Methods

This work presents the results of theoretical research conducted with using methods of gas dynamics, thermodynamics, continuum mechanics and explosion physics.

3. Theoretical part

Optimal parameters of the stress field for rock destruction. The rock is destroyed under shear or tensile stresses. The work required for destruction and weakening (formation of a new surface) only under tensile or shear stresses is significantly lower than under triaxial compression. In the case of triaxial compression, the required work decreases as the differences between the components of the rock deformation tensor increase. The greater is the stress gradient modulus, the greater are the tensile and shear stresses in the rock and the less work is needed for destruction. Indeed, the particle size d of the rock fragments produced in the crushing zone can be estimated using the formulas:

$$d = \frac{\sigma_s}{\frac{dp}{dr}} \text{ or } d = \frac{\sigma_s}{\frac{dp}{dt}\frac{1}{D}}, \quad (1)$$

where σ_s is the rock shear strength, Pa; p is pressure at the shock-wave front, Pa; r is the distance to the charge, m; t is time, s; D is shock-wave velocity, m/s.

In the zone affected by a strong compression wave, rock particle or fragment size into which it broken can be estimated using the formulas:

$$d = \frac{\sigma_s}{\frac{d\sigma}{dr}} \text{ or } d = \frac{\sigma_s}{\frac{d\sigma}{dt}\frac{1}{C_p}} \quad (2)$$

where σ_s is the compressive stress in the strong compression wave, Pa; C_p is velocity of a strong compression wave, m/s.

In this case, an increase in the rate of pressure or stress change leads to the intensive growth of short cracks resulting in rock weakening. The growth of cracks is accompanied by partial unloading of the surrounding rocks. The rapid increase in stresses within the rock can compensate for this unloading. As the rate of stress increase grows, conditions arise for the progressive growth of short cracks. In the crushing and grinding zone, the rate of pressure and stress change is within the range from 10^8 Pa/m to 10^{12} Pa/m. With a quasi-static approach, this rate decreases not according to a hyperbolic and exponential law, but approximately according to a cubic dependence. Under the quasi-static approach, the maximum pressure of detonation products is twice lower (with an adiabatic index $n = 3$) than with a wave approach. In a compression wave, the cracks, which are perpendicular and parallel to the wave front, grow mainly. In this case, the distance between them is inversely proportional to the amplitude and the gradient modulus [5]. For effective destruction and weakening of the rock (i.e., crack growth in all planes), the waves must propagate in different directions. It should be noted that the strength limit, for example, in shear, varies depending on the load within the wide limits. In the case of a quasi-static field, the rock destroyed only under non-uniform triaxial compression. Thus, the coefficient of explosion energy use is maximal when the explosive charge generates a stress field in the rock, at which the stresses, the rate of their change and their gradient moduli fall within certain ranges. This implies that the energetic parameters of the explosive are not determining. Useful work is performed only within defined ranges of pressure, gradient and the rate of their change in time and space. When the stress field parameters fall outside these defined ranges, energy expenditure on producing dust, intense crushing, and rock heating increases. Moreover, the scattering of rock mass fragments, seismic activity and the percentage of oversized fractions increase.

The chemical reaction zone generates in the rock the field with stress gradient far exceeding those required to destroy the medium. Therefore, the width of the chemical reaction zone is an important characteristic of an explosive.

Summarizing the above, it should be noted that only the wave-based approach can provide a correct solution to the problem of rock destruction by explosion, in contrast to the quasi-static approach, under which it is impossible to take into account the mechanisms of the processes of destruction and weakening of a continuous medium.

Crushing and grinding zone. When a detonation wave propagates, the chemical reaction zone can create a stress field in the rock with a gradient modulus of 10^{12} Pa/m and a stress change rate of 10^{15} Pa/s. Due to this, the rock is destroyed into particles, the minimum size of which can reach 10 nm. In addition, this zone determines the width of the shock wave front in the rock. Therefore, the width of the chemical reaction zone is an important characteristic of an explosive. The coefficient of the explosion energy use significantly depends on it.

An important parameter is the adiabatic index n of the detonation products. The pressure of the detonation products in the explosion cavity decreases with the relative radius of the cavity with an exponent of $2n$. This exponent determines the parameters of the waves in the explosion cavity, and, therefore, the parameters of the stress waves in the rock. It is known that n depends on the volume of the detonation products, but this dependence is usually considered only when analyzing explosions in gases. In this case, the adiabatic index is decomposed into two adiabats with different indices, while in case of explosion of brisant explosives, where the initial stage of the explosion is decisive, the adiabatic index remains unchanged. It is important to take into account the analytical dependence of the adiabatic index *n* on the volume [22]

$$n = \gamma \, ln\left(\frac{\frac{V}{V_d} - b}{1-b}\right)\left(ln\frac{V}{V_d}\right)^{-1}, \tag{3}$$

where V_d is the volume of explosion products at the pressure at the Chapman-Jouguet point; *b* is the volume inaccessible to the molecules of explosion products (covolume); γ is the adiabatic index for explosion products at atmospheric pressure.

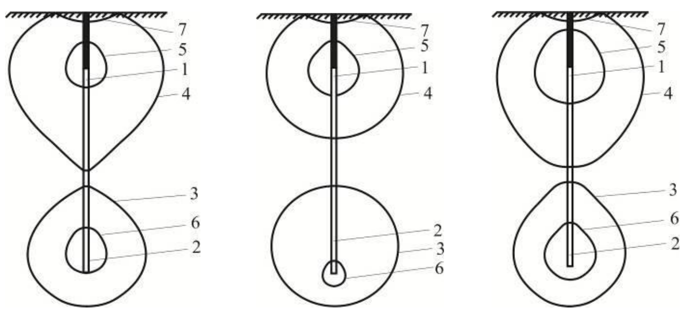
Since formula (3) is not convenient to use, the adiabatic equation for the explosion product (EP) can be written in the form [22]

$$p_d\left(V_d - V_d b\right)^{\gamma} = p\left(V - V_d b\right)^{\gamma}, \tag{4}$$

where *d* is an index denoting the pressure and volume of explosion products at the Chapman-Jouguet point.

It is generally accepted that a detonation wave generates a shock wave in the rock. A defining feature of the shock wave is not its supersonic speed, but the presence of a shock jump (shock discontinuity). Waves that arise in rocks are non-stationary and cannot be described by the commonly known equations for the shock wave. During an explosion in a rock, a non-stationary shock wave in the crushing and grinding zone degenerates into a strong compression wave characterized by supersonic speed and causing rock flow behind the front, but a shock jump is not formed. A strong compression wave is usually referred to as a shock wave. Its propagation, unlike that of a stress wave, is accompanied by the resistance of the medium proportional to its density, the square of the mass velocity and dynamic viscosity. The initial parameters of the shock wave and strong compression wave coincide. In polycrystalline rock, the wave velocities and mass velocities of substance in grains differ, and the rock is destroyed mainly by cutting. The destruction of the rock leads to its heating. The rock strength decreases exponentially with temperature. In crushing zone and partially in grinding zone, the rock flows and the radius of the explosion cavity increases. Calculations of wave processes show [5] that the initial mass velocity of the rock, at the boundary of the “detonation products-rock”, during the passage of the detonation wave, ranges from 100 m/s to 400 m/s depending on the power of the explosive substance and the resistance force of the rock. The increase of the explosion cavity radius is not significant, but the pressure of the detonation products in it decreases at polytropic index $n = 3$ inversely proportional to the sixth power of the radius. The energy expenditure for rock destruction in the zones is at least inversely proportional to the particle size into which the rock is fragmented; therefore, studying the processes in these zones is necessary. With high accuracy, it can be assumed that in the crushing and grinding zones, the energy of the detonation products is absorbed continuously, and the stresses decrease not only according to the power law (quasi-static approach), but at the same time according to the exponential and power laws. In the crushing zone, the rock acquires the properties of a compressible fluid. Therefore, the dimensions of the crushing and grinding zones also largely determine the coefficient of the explosion energy use. The parameters of the processes occurred in the crushing and grinding zones can be obtained only when using the wave-based approach.

The stress field in the rock. Behind the detonation wave front propagating in an elongated continuous explosive charge, a centered rarefaction wave is generated, which passes into the zone of stationary gas. The stress field of an elongated charge depends on the ratio between the detonation velocity and stress wave velocity. When the detonation velocity D is greater than the stress wave velocity C_p, a conical wave is formed in the rock with a variable angle at the apex and stitched to a spherical wave. If the velocity D is less than C_p, the conical wave is stitched to two spheres. Fig. 1 shows the positions of the wave fronts in the rock at the initial stage of the explosion at different ratios of D and C_p. Analysis of the wave processes shows that at all stages of the explosion and at different points of the explosion cavity, the pressure of the detonation products will differ by several times.



a) *b)* *c)*

1, 2 are the upper and lower detonators, respectively; 3, 4 are the fronts of a strong compression wave; 5 is shock-wave front from the packing; 6 is front of a strong compression from reflected wave from the bottom (face) of the borehole; 7 is front of the unloading wave reflected from the surface

Figure 1 – Wave fronts during the explosion of an explosive charge with $D > C_p$ (*a*), $D = C_p$ (*b*) and $D < C_p$ (*c*)

In the case when $D < C_p$, a strong compression wave can lead to compression of the explosive in the charge ahead of the detonation wave front. Emulsion explosives are sensitive to compression. In this case, detonation may begin in the mode of an under-compressed detonation wave, or detonation may cease entirely. When $D=C_p$, the wave front is a sphere passing through the detonation wave front. This leads to an increase in size of the compression zone. As the detonation wave propagates, the pressure behind its front decreases by approximately three times in the centered rarefaction wave. Behind the centered wave is a zone of stationary gas. With a polytropic index n = 3, the length of the rarefaction waves is approximately the same. This implies that the length of the stress-wave impulse generated by the centered rarefaction wave in the detonation products increases constantly (from several charge diameters to several meters).The propagation of the stress wave impulse through the crushing and grinding zone is accompanied by a decrease in its steepness and amplitude. Since, during the propagation of the detonation wave, its length increases significantly, and the steepness decreases, the radii of the zones will decrease, and the local radii of the explosion cavity will increase. This leads to the fact that, during the propagation of the detonation wave, the sizes of rock particles in the crushing and grinding zones will increase. When the detonation waves from the lower and upper detonators collide, the pressure in the reflected waves increases by approximately a factor of 2.4 times. When the shock wave is reflected in the detonation products from the bottom of the blast-hole or borehole, the pressure in the reflected wave increases by a factor of 2.35 times at n = 3. When the shock wave falls on the packing or inert gap, reflected shock waves or unloading waves generated. If the rock resistance is not taken into account, the initial parameters of the shock wave in the packing, composed of granite particles with relative volume α under bottom initiation, are determined by the formula:

$$\begin{cases} u_s = \dfrac{D}{4}\left[1-\sqrt{2n}\,\dfrac{(p_s/p_d)-1}{\sqrt{(n+1)\left((p_s/p_d)+n-1\right)}}\right] = \sqrt{\dfrac{p_s}{\rho}\left[1-(1-\alpha)\left(1+\dfrac{p_s}{A}\right)^{-\frac{1}{m}}\right]}; \\ p_s = D_s u_s \rho, \end{cases} \quad (5)$$

where ρ is the density of the substance of the packing particles; n is the adiabatic index A; m are the coefficients in the Theta equation for the substance of the packing particles; P_s is the pressure in the shock wave; u_s is the mass velocity of the substance; D is the detonation velocity of the explosive; D_s is the shock wave velocity; p_d is the pressure at the detonation-wave front.

The numerical solution of the equations gives the following results: at α=0.25; D = 5000 m/s; A = 22.69 GPa; ρ = 2500 kg/m^3; m = 4, n = 3 P_s = 6.608 GPa, u_s =885.2 m/s, D_s = 2985.99 m/s. With bottom initiation and dry packing: pressure in the shock wave is p = 6.26 GPa, initial mass velocity of the substance is u = 963 m/s, shock wave velocity is D = 3271 m/s;

With bottom initiation (water-saturated packing): p = 7.52 GPa, mass velocity of the substance is u = 692 m/s, shock wave velocity is D = 4858 m/s;

With top initiation (dry packing): p = 0.942 GPa, mass velocity of the substance is u = 344 m/s, unloading wave front velocity is C = 1376 m/s;

With top initiation (water-saturated packing): p = 1.21 GPa; mass velocity of the substance is u = 181 m/s, unloading wave front velocity is C = 2988 m/s.

The waves in the explosion cavity, in turn, excite waves in the rock, the amplitude of which is often many times greater than its dynamic strength limit. Thus, the quasi-static approach does not take into account the pressure change generated by the chemical reaction zone, centered, stationary waves, and also waves reflected from the packing and the bottomhole. The quasi-static approach assumes that the wave velocity is infinitely high.

When considering charges of different configurations, the quasi-static approach becomes suitable. For example, when the charge contains an inert gap, it is necessary to take into account its motion and partial disintegration in the explosion cavity. With the quasi-static approach, it is impossible. As an illustrative example of using the approaches, one may consider a borehole charge of an explosive with an air gap. Quasi-static approach: the pressure at the detonation-wave front is greater than optimal. In the presence of an air gap, the pressure in the explosion cavity instantly decreases (is averaged), leading to a reduction of the crushing zone. Wave-based approach: when a shock wave falls on an air gap, a strong shock wave is generated in the air with a pressure of tens of MPa, and a rarefaction wave appears in the detonation products (with wave-front pressure of approximately 70 MPa). Over a time of approximately 0.2 ms (with an air gap length of 1 m), this wave traverses the gap. During the period of pressure equalization in the gap, the average pressure in it will be at least two orders of magnitude lower than in the absence of gap. Around the air gap, a highly inhomogeneous stress field is generated in the rock, in which the rock is destroyed by cutting and shear. It is known that the presence of an air gap on the floor line significantly improves floor breakage (the rock is cut along the floor line). This supports the validity of the wave-based approach in this case.

The studies of wave processes in the explosion cavity of an elongated charge show that throughout its entire duration, the pressure in different parts of the cavity differs significantly from the corresponding averaged value. Rocks are fractured, and, therefore, their destruction depends on the nature and function of the crack distribution within the massif. The rate of growth of the crack length is several times lower than the velocity of stress waves (rock destruction is extended over time), so the stress field in the rock is constantly changing. This cannot be taken into account with a quasi-static approach. The study of the processes occurred during the rock destruction, considering it as a continuous medium, requires justification. The quasi-static approach does not allow for the study of the action of the absolute majority of explosive charge configurations.

Action of the explosive charge in the middle zone of destruction. As it is known, with a quasi-static approach, a zone of tangential and mainly radial cracks begins to form behind the crushing zone. When the cracks open, the stress field loses continuity, which practically makes it impossible to use quasi-static approach. In a homogeneous rock, the quasi-static field of an elongated continuous charge is axisymmetric. In such a field, only radial and tangential cracks develop (without taking into account the edge effect). It has been experimentally established that majority of microcracks in the rock occur during the passage of the stress wave. When a dry block massif is destroyed, the presence of a crack with a width of 1 mm or more can lead to the destruction of the blocks when they collide. In addition, when the blocks collide, they can be in a stressed state. Therefore, the rock is re-destructed. In the case of a dry or water-saturated block massif, it is impossible to study the stress field during its destruction. If a crack filled with water is compressed, the energy expenditure required for its growth will be minimal. By estimating the parameters of the stress waves reflected from free surfaces and given a known function of crack distribution in the rock, it is possible to consider the process of crack lengths growing and estimate the energy expended on rock destruction and weakening, as well as to predict possible granulometric composition of the rock mass. The known parameters of the stress waves make it possible to consider the motion and collision of rock blocks and to predict the parameters of the rock mass destruction. When using quasi-statics, it is practically impossible to consider the destruction of the rock around the free surfaces of the bench. Besides, this approach does not allow for the investigation of gas-dynamic processes in the packing and cracks. It is known that detonation products penetrate deeply into the rock during the explosion, and the packing ejection is preceded by a cloud of detonation products above the borehole.

Quasi-static rock destruction. To apply the quasi-static approach, it is necessary that: the environment is continuous or piecewise-continuous; the pressure in the explosion cavity instantly increases to an averaged value. The explosion cavity is assumed to be circular cylinder (usually unlimited). Supporters of this approach believe that dynamic processes do not significantly affect the explosion result. Let us consider the simplified process of establishing a field using the example of a continuous borehole brisant explosive charge 10 m in length. Over approximately 1-2 ms the charge undergoes detonation. The passage of the detonation wave is accompanied by the formation of compression and crushing zones, in which tens of percent of the detonation-product energy are absorbed. The rock acquires an initial velocity of approximately 100-300 m/s. Two explosive impulses (from two initiators) are generated in the rock, the amplitude of which is approximately 3-5 GPa. It is obvious that at such a pressure, rock destruction necessarily occurs. During the detonation time, the explosion wave propagates over a distance of about 10 m. Under top initiation, within a time less than 1 ms, a shock wave forms in the packing, and the length of the explosion cavity begins to increase. It is also necessary to take into account that during the formation of the compression and crushing zone, the diameter of the cavity increases, and its radius will not be the same. With the propagation of the detonation wave, the mass velocity of the rock in a given cross-section of the explosion cavity decreases, and whereas in the zone where the detonation waves collide, it reaches maximum values. With the wave-based approach, in a given cross-section of the explosion cavity, over times equal to tens of mks, the pressure will decreases due to rarefaction waves.

Thus, it can be argued that at the stage of intensive rock destruction, wave processes cannot be neglected. The use of the model of rock as a continuous medium when considering the zone of radial cracks requires justification. The rate at which the stress state is established in the rock determines the destruction processes. If the stress field grows quasi-statically, then the longest and most favorably oriented cracks begin to grow in the rock, and their opening results in the loss of stress field continuity.

There is no doubt that during an explosion, a certain part of the rock is destroyed in a quasi-static field. Indeed, when the stress changing in a rock element during its destruction is significantly smaller than the corresponding strength limit, the element is destroyed precisely under quasi-static conditions. Destruction occurs under triaxial loading. For sufficiently large rock element, due to the heterogeneity of the rock local strength and the presence of internal stresses, the destruction begins from the weakest point, and then the process accelerates.

In the quasi-static approach, the rock is assumed to be a continuous medium (or media), which is not, strictly speaking, correct. In the absolute majority of cases, the formation of cracks, i.e., rock destruction and weakening, is not considered. With this approach, it is impossible to fully evaluate the mechanisms of the processes occurred during an explosion.

It is evident that field blasting engineers require simple empirical formulas in practical mining operations; however, considering the variety of rock breaking conditions, the blasting engineer needs extensive experience to apply them. The point is that empirical coefficients are not universal. As a rule, such formulas contain an energy parameter, although it is not the decisive factor. The distance to the charge is included, but the charge size is not.

Ejection and breakage of blasted rock. Ejection and rock movement during a mass explosion begin when stress waves reflected from free surfaces reach the explosion cavity. In this case, a superposition of incident and reflected waves is observed. Spalling phenomena can occur, which is characterized by an almost instantaneous rock fracture along the surface. In the reflected unloading waves propagating along incident waves, cracks predominantly oriented roughly parallel to the wave front tend to grow. The fragmentation of the rock formed during the ejection process is determined by the properties of the packing and the blasting parameters (the charge initiation scheme and deceleration of the charge blasts). It also significantly depends on the configuration of the charges. During the ejection process, collision of rock fragments leads to their destruction. The preparation of the bench floor is governed by the processes occurred during rock destruction and ejection. Its quality depends on the micro- and macrostructure of the rock being blasted and the wave processes in it. Investigating these processes in bench floor preparation and rock ejection using only a quasi-static approach is strictly speaking, impossible.

Real rock masses are characterized by a rather complex fracture-tectonic structure, i.e. the presence of several systems of cracks of different lengths, regularly oriented in space. Due to the action of the explosion, secondary additional cracks, i.e. seismic cracks, are formed in the rock mass, significantly affecting the nature of the stress field.

Seismic effect during an explosion. Only the wave-based approach allows for consideration of the seismic effect of an explosion. In particular, this approach makes it possible to develop effective borehole charge configuration that practically do not generate transverse waves during the detonation of explosives – the waves that are obstacles during geological exploration using the seismic effect of an explosion.

4. Conclusions

The theoretical investigations make possible to formulate the following conclusions:

1. The quasi-static approach assumes that the maximum pressure is half of the detonation pressure, does not account for mechanisms of the processes occurred in the crushing and grinding zone, neglect strong compression waves, considers rock destruction only in an axisymmetric stationary stress field. The processes occurred in the packing are not taken into account. The determining detonation parameters of the explosive such as the detonation velocity, the adiabatic index and the width of the chemical reaction zone are not taken into account. Under this approach, it is very difficult to analyze rock destruction with taking into account free surfaces. This is especially true for the upper part of the bench or the rock near the excavation face in underground mining. The quasi-static approach does not allow evaluation of the role of detonation products in rock destruction, the interaction of rock fragments upon their collision and the formation of the fragmented rock mass.

2. To study the nature of rock destruction by elongated explosive charges, it is necessary to consider wave processes occurred in the explosion cavity and in rock. They allow clarifying the mechanisms of rock destruction and weakening in the shock wave and in compression and unloading waves. It also become possible to determine parameters of all processes occurred in charges of any configuration.

3. The quasi-static approach is usually much simpler, but it does not allow us to study the mechanisms of rock destruction processes and their influence on the nature of destruction during an explosion. Therefore, when studying rock destruction by elongated explosive charges, it is necessary to take into account dynamic (wave-based) approaches.

Conflict of interest

Authors state no conflict of interest.

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ДО ХВИЛЬОВОЇ І КВАЗІСТАТИЧНОЇ ДІЇ ПОДОВЖЕНОГО ЗАРЯДУ ВИБУХОВОЇ РЕЧОВИНИ

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Анотація. Стаття присвячена обґрунтуванню використання хвильового підходу при дослідженні процесів руйнування гірських порід подовженими зарядами вибухових речовин. Доведено, що квазістатичний підхід лише його окремий елемент. Результати отримані теоретичними методами.

Проведений аналіз процесів, що протікають в гірської породі при вибуху подовженого заряду вибухової речовини і проаналізована можливість використання такого підходу. Метою роботи є обґрунтування недоцільності використання квазістатичного підходу при дослідженні руйнування гірських порід подовженими зарядами вибухової речовини. Встановлено (Зельдович,1942), що при квазістатичному підходу максимальний тиск у порожнині вибуху приблизно вдвічі менший, ніж тиск в точці Чепмена-Жуге, що невиправдано. Поле напружень гладке. При цьому не враховуються механізми важливих процесів, що протікають в зоні зминання і подрібнення, не розглядається руйнування гірської породи в ударних хвилях і сильних хвилях стиснення. Руйнування гірської породи відбувається лише в осесиметричному стаціонарному полі напружень. Крім того, не враховуються процеси, які протікають при наявності набивки: механізми втрат енергії продуктів детонації, а також визначальні детонаційні параметри вибухової речовини. Очевидно, що при квазістатичному підході дуже складно розглянути руйнування гірської породи з урахуванням вільних поверхонь. Особливо це стосується верхньої частини уступу або призабійної зони для підземної відбійки. Квазістатичний підхід не дозволяє розглянути роль продуктів детонації у руйнуванні гірської породи, взаємодію кусків породи при зіткненні і формування розвалу гірничої маси. Таким чином, для дослідження характеру руйнування породи подовженими зарядами вибухових речовин потрібно розглядати хвильові процеси, що протікають в порожнині вибуху і породі. Це дозволяє з'ясувати механізми руйнування і знеміцнення породи в ударній хвилі, хвилях стиснення і розвантаження. Також виникає можливість отримати параметри всіх процесів, що протікають у зарядів будь-яких конструкцій. Квазістатичний підхід не дозволяє дослідити ряд механізмів процесів руйнування порід і їх вплив на характер вибухового руйнування. Однак завжди частина гірської породи руйнується у квазістатичному полі, яке є певною частиною динамічного поля напружень. Отже, при дослідженні руйнування породи подовженими зарядами вибухової речовини необхідно обов'язково враховувати динамічні і квазістатичні підходи.

Ключові слова: подовжені заряди; квазістатичне поле напружень; детонаційні і ударні хвилі; хвилі стискання і розрідження; подрібнення.