Models and Information Technology Implementation of Contact Interaction of the Edge of a Rock Cutting Tool With Granular Rocks Modeling

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Abstract

In the article a mathematical model of the destruction of strong rocks cracked normal separation for the developed technology of directional splitting of the geological environment with a rock cutting tool a cyclic load is presented. Indicated that quality model indicators are the values of the physicomechanical structure geomaterial, a criterion for the steady growth of a normal separation crack, stress intensity factor of the first kind, the length of the initial crack deepening, angle and type of sharpening the edge of the rock cutting tool. The solution to the problem is based on a numerical model of a plane boundary value problem theory of elasticity. The condition for the opening of microcracks in the contact area is established. cutting part of rock cutting tool with granular rock structures, as well as an indicator of the initial crack output to the surface for model example.

Keywords [1]

Anti-filter screen, rock cutting tool, mathematical model, crack, area of weakened connections, discontinuous displacement method, dummy force method.

1. Introduction

The last decades have been marked by a huge increase of energy and mineral resources consumption. This fact creates a huge amount of industrial waste, which significantly affects the environmental status of the territories. Modern landfills for solid wastes are engineering specialized structures, where organized controlled storage of solid household wastes in compliance with technical and sanitary norms, reducing the negative impact of waste on the atmospheric air, soil, water pool to the normative level.

One of the effective ways to prevent the negative effects of industrial and domestic waste accumulation on the environment is the construction of various types of protective anti-filtering structures. In particular, this problem can be solved by creating in the underlying array rocks antifiltration collector screen, which has the necessary strength characteristics and allows directional collection of filtrates. The arrangement of the screen involves the creation in the array of technological cavity rocks and filling it with hardening barrier material. In the case of reinforcing the cutting edge of the rock-cutting tool, its immersion in the array occurs from the initial moment of impact - the arrival of the initial wave of stress. Under the edge, in the zone of greatest stresses, the core of the seal of the damaged rock begins to grow, due to which a smoother redistribution and transfer of the impact pulse to the array occur. In articles [1,2] theoretical and applied bases of technology of infiltration leaching of uranium from technogenic deposits of complex form underground have been developed and substantiated. A

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key element of the leaching process scheme is the anti-filtration manifold screen, which allows direct filtrate collection. In papers [1, 2, 3] a method of creating an anti-filtration manifold screen in the underlying bedrock, which ensures the filtrate is collected and brought to the surface is proposed. The method involves arranging the screen by creating an inclined process cavity in the underlying rocks and then filling it with a curing barrier material. Also, the method and a destructive device for mining a mountain range and forming a technological cavity is proposed [2, 3].

A review of the problems of the stress-strain state of the region under the action of special loads, rock masses in the vicinity of technological workings and mathematical methods for solving them is given quite fully in the works [1, 4-12]. At the same time, the well-known mathematical methods and research methods of such problems give only a general approach to solving a particular problem, and therefore, for each specific case, in order to obtain reliable results, detailed elaboration is necessary taking into account the specifics of the technology.

Thus, the main goal and objective of the study is to create a mathematical model of the destruction of strong rocks by normal separation cracks for directional cracking of the geological environment by the proposed rock cutting tool in the process of shock-rotational cyclic loading. Schematically, the process of destruction can be described as follows.

2. Main part

The problem of implementing new technologies for mining rock mass when creating technological workings by an underground method is a complex task of computer technologies in the geomechanical theory of stability, the integral components of which are: establishing patterns of formation of stable and unstable cracks; creation of a numerical model of the destruction of granular material; development of algorithms for the implementation of numerical calculations, allowing to establish the patterns of formation and development of cracks in discrete media loaded with various rock cutting tools.

The formation of structural damage occurs due to the violation of bonds between the elements of the microstructure of the material, which always has some heterogeneity. So, metals are characterized by grains and intercrystalline matter, rocks by microheterogeneity of their tectonic formation, concretes and other composite materials by the composition of the matrix and filler, their ratio, filler orientation. With the opening of microcracks in such materials, local microstresses increase, caused by the action of the applied tensile stress, which contributes to the rate of accumulation of local stresses. Consequently, in addition to the existing internal tensile stress, microstress forces begin to act, depending on the morphological features of the environment.

Currently, there are enough models and experimental data that allow us to study the process of formation and development of microcracks in materials. However, not all existing models take into account the structural features of the studied material samples. So, in the process of numerical simulation of fracture when the fracture criterion is fulfilled in a certain computational cell, all the material in this cell is destroyed and is considered a set of small particles. Further, for this cell, the mechanical properties of the material change: the ability to resist stretching is lost, its elastic moduli decrease, and the stress deviator is reset. In this case, not all cracks in the fracture patterns intersect or close, forming contoured particles, which is caused by both certain computational difficulties and physical reasons. The former are associated with large distortions of the computational grid when describing fracture, which is why the calculation cannot be carried out far enough in terms of deformations. On the other hand, the deformation conditions simulated in the calculations inhibit the growth of cracks. Such circumstances complicate the automatic processing of such fracture patterns; therefore, special methods were needed to refine the images obtained in the calculations.

For our case, modeling the destruction of a rock mass by a rock-breaking tool, according to the technological scheme [1,2], has the following distinctive and characteristic features. When the lateral boundaries are far removed from the impact site, plastic deformation develops deep into the massif. The emergence of deformation localization areas on the free surface with close lateral boundaries leads to gouging out of large pieces of geomaterial. In a brittle material, from the sides of the affected area, where tensile stresses arise, the formation of a destroyed area is observed. Repeated exposure, which is characteristic of periods of failure, can lead to the propagation of cracks into the interior of the specimen. A zone of the most loaded and deformed material is formed near the tip of the cutting edge of the rock cutting tool. It is in it that the main part of the destroyed particles is formed. The stress state field has a complex structure and most closely corresponds to a combination of compression and shear. To determine the fractional composition of the spall, it is necessary to calculate the behavior of the mesovolume of the rock under the given impact conditions. For the numerical implementation of the fracture process, further in the main part of the article, a technique is proposed using the node separation algorithm and an explicit description of crack opening, which takes into account the complexity of the interaction of destroyed particles during multiple cracking under conditions of simultaneous compression and shear.

When simulating deformation and fracture processes, which is determined by the process conditions, a dynamic approach is used that includes equations describing the motion of a continuous medium, defining relations that concretize the behavior of a particular material within the framework of the selected medium model. The main system of equations expresses the laws of conservation of mass, momentum and energy, as well as geometric relationships connecting, for example, the components of the strain rate tensor with the components of the displacement velocity vector. For example, nonlinear parabolic equations as a general system of equations for the dynamics of elastoplastic media as kinetic equations, when it corresponds to the physics of the process (similar equations determine the nucleation and propagation of damage and inelastic deformation fronts in a loaded nonlinear medium, which propagate at velocities significantly lower than the propagation velocity elastic disturbances).

A distinctive feature of the choice of a mathematical model for the propagation of an impact crack with repeated exposure to a rock cutting tool [1, 2] is the formation of new cracks and areas of destruction with each new repeated exposure. For this, it is proposed to calculate the stress-strain state near a single crack, describe its behavior, and perform using a stepwise calculation procedure or the stationary grid method. The problem is realized by solving the partial differential equations:

$$\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_x}{\partial y^2}+\frac{1}{1-2\cdot\nu}\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_y}{\partial y\partial x}\right)=0,$$

$$\frac{\partial^2 u_y}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}+\frac{1}{1-2\cdot\nu}\left(\frac{\partial^2 u_x}{\partial x\partial y}+\frac{\partial^2 u_y}{\partial y^2}\right)=0,$$

where u_x – axial OX offset; u_y – axial OY offset; ν – Poisson's ratio.

In an array, the volume of compression increases with the constant gradient of compression to the core of the compression. The growth of stress occurs as a result of the immersion of the cutting edge and the growth of the core of the seal, and as a result of the internal reflection of the wave energy emitted by the edge of the deep into the array. When the stresses reach the boundary value for a given breed, values in the zone bordering the core of the seal begin to give rise to microcracks, which release part of the elastic energy and cause the splitting off of the volume of compression of a particular layer. Part of this layer passes into the core of the seal (adhering to the cutting edge), and the other part forms the region of weakened ligaments around the nucleus. In the future, this process is repeated. In the next, adjacent nucleus, the layer of stress reaches the limit value, the origin of microcracks, their growth and the increase of the area of weakened bonds occurs. At the next time there is an increase of the nucleus again, and so long as the resistance of the breed to the immersion of the edge does not equal the force of the impulse or until the blow ends. This complex spatial problem can be reduced to a plane problem of the theory of elasticity, if we divide it into n elementary problems, as follows. The cutting edge of the rock-cutting tool interacts with the array along the circle arc. It is natural to assume that if a crack occurs and reaches the surface of the face in the furthest point of the arc, the same processes will occur in all other points of the interaction arc. Thus, we arrive at the problem of the propagation of a crack in a half-infinite plate with a damped velocity (Fig. 1).

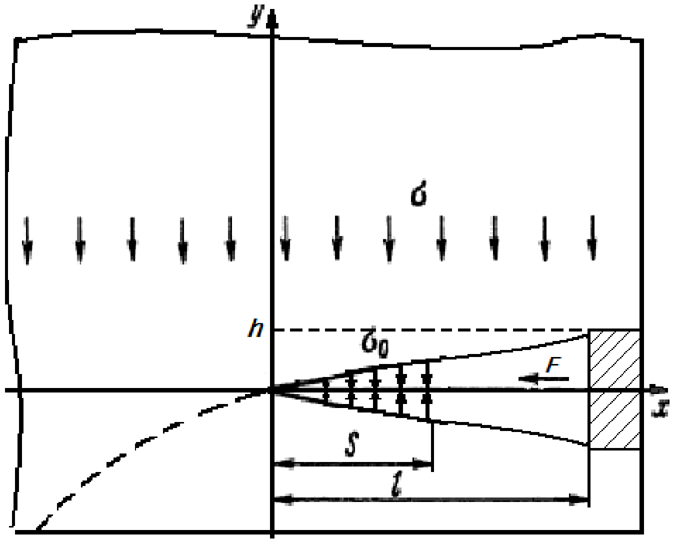

Figure 1: Scheme of propagation of the crevice.

The peculiarity of the problem is the proximity of the crack to the edge. Because of this proximity, the crack will not develop straightforwardly, but will tend to a surface free from stress (surface of the face). This hypothesis is in good agreement with the main provisions of the theory of Bussinesca.

Also, it should be noted that the process of growth of a spall crack also depends on the physicomechanical structure of the geomaterial, the criterion for the stable growth of a normal detachment crack, the stress intensity factor of the first kind, as well as the length of the initial deepening crack, the angle and type of edge sharpening of the rock cutting tool.

In the proposed model, the geological environment (rock), according to [11, 12], has a granular structure, consists of a set of grains that are bonded to each other with cement having microcracks of different order of length. Microcracks differ in aggregate composition, width and shear resistance. It is assumed that adhesion along the length of the crack is absent or an order of magnitude smaller than along cracks of shorter length and width. The angle of friction for smaller cracks is several degrees larger than for long ones. Upon destruction, the rocks exhibit the property of a discrete medium consisting of a set of individual particles that, due to the load, are displaced relative to one another.

Thus, a granular geomedium is modeled by a grid of hexogonal, much smaller compared to body size, homogeneous and isotropic grains with a constant averaged grain diameter of the order of 10^{-1} mm and a mathematical section between grains as microcracks. Between the grain space (microcracks) are filled with a linearly elastic material with properties different from those of the grain (Young's modulus $E=10^n$ n=2,3,4 MPa, Poisson's ratio ν=0,3, intergranular width 0,01-0,-01 mm, shear modulus $G = \frac{E}{2*(1+\nu)}$).

The boundary conditions at the contact boundary of the rock cutting tool were modeled by the case of the action of the wedge-shaped edge of the tool on the rock of the above structure. The brittle properties of a material, regardless of its strength and the method of load application, determine the mechanism of interaction with the working tool. A design scheme for the interaction of a wedge-shaped edge of a rock cutting tool with an array of brittle geological material under impact is presented on the Figure 2. A force P is applied to the tool, under the action of which, overcoming resistance to penetration, the tool is immersed in the array. Let us assume that the width of the tool blade and the width of the interaction area are equal:

$$a = d, \tag{1}$$

where a – interaction area width, m; d – tool blade width, m.

The material has isotropic properties. Also, during the simulation, the following assumptions were made:

- The width of the tool blade is equal to the width of the impact area;
- Material properties are isotropic.

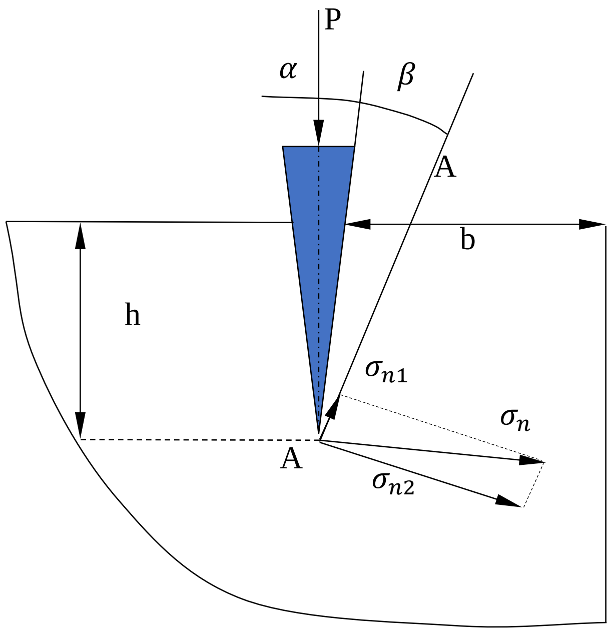

Figure 2: Scheme of the interaction of the wedge-shaped edge of the rock cutting tool with an array of brittle geological material.

t the first stage, a linear contact of the working tool with a step occurs, stresses arise in the material that exceed its contact strength, local destruction of the material is observed and the tool moves deep into the massif. The process is symmetrical, so one half of it is considered. As the tool advances, the contact area of its lateral surface with the material appears, on which a normal force occurs:

$$\sigma_n = \frac{P}{2 \cdot \sin\alpha}, \tag{2}$$

where α – half the angle of the rock cutting tool.

At the same time, the reaction acts from the side of the mass of material:

$$\sigma_n = \sigma_{compr} \cdot S, \tag{3}$$

where σ_{compr} – material compressive strength, Pa;

contact area of the lateral surface of the tool with the material can be calculated with the next formula use:

$$S = \frac{d \cdot h}{\cos\alpha}, \qquad (4)$$

where h – immersion depth of the tool, m.

Equating expressions for σ_n and substituting the value of S, we find the depth of immersion of the edge of the rock cutting tool in the form:

$$h = \frac{P \cdot \cos\alpha}{2 \cdot \sin\alpha \cdot \sigma_{сжат} \cdot d}. \qquad (5)$$

The normal force σ_n can be decomposed into two components σ_{n1} and σ_{n2}, which are directed towards the open surface and the depth of the massif, respectively. Of interest is σ_{n1}, under the action of which shear stresses in the plane A-A, emerging on the free surface:

$$\tau_{\text{A}-\text{A}} = \frac{\sigma_{n1}}{S_{A-A}}, \qquad (6)$$

where $S_{\text{A-A}}$ – cross-sectional area of the material in the plane A-A, m^2.

The component σ_{n1} is equal:

$$\sigma_{n1} = \sigma \cdot \sin\beta, \qquad (7)$$

where β – angle between the lateral surface of the tool and the plane A-A.

Cross-sectional area of the material in the plane A-A is equal to:

$$S_{A-A} = \frac{d \cdot h}{\cos(\alpha+\beta)}. \qquad (8)$$

Normal force σ_n can also be decomposed into components σ_{n3} and σ_{n4}, as shown on the figureg 2. The component σ_{n4} acts at an angle γ and creates shear stresses in the plane A-B, which emerges on the side surface of the step. Using the previous reasoning, the dependencies describing the process of spallation of an array of material can be represented as follows:

$$\tau_{A-B} = \frac{\sigma_{n4}}{S_{A-B}}, \qquad (9)$$

$$\sigma_{n4} = \sigma_n \cdot \cos(\alpha - \gamma), \qquad (10)$$

$$S_{A-B} = \frac{d \cdot b}{\cos\gamma}. \qquad (11)$$

The presented dependences make it possible to determine the angles β and γ, at which the material is "punctured" and "chipped". The above dependences are valid for a limited volume of rock - oversized. According to the design scheme shown in Fig. 2, with the impact interaction of the wedge-shaped edge of the rock cutting tool with the rock area, the normal components of the impact force σ_n create tensile stresses in the A-A plane, in which a split can occur. In addition, shear stresses appear, acting in the planes A-B and A-C, along which, most likely, chipping or gouging occurs, respectively. Depending on the ratio of the energy of a single impact, the strength of the material, the size of the interaction area, as well as the point of impact, the destruction of the rock will occur in one of the indicated planes. Taking into account the previous studies, the model characterizing the boundary conditions for the problem of impact interaction of the wedge-shaped edge of a rock-cutting tool with an array of brittle geological material can be described by the formulas:

$$h = \frac{m \cdot v^2}{2 \cdot F}, \qquad (12)$$

$$v = \sqrt{2 \cdot g \cdot H}, \qquad (13)$$

$$F = 2 \cdot \sigma \cdot \sin\alpha, \qquad (14)$$

$$\sigma_n = \sigma_{compr} \cdot S\ , \qquad (15)$$

$$S = \frac{2 \cdot a \cdot h}{\cos \alpha}, \quad (16)$$

$$T = \frac{m \cdot v^2}{2}, \quad (17)$$

$$S_1 = a \cdot (c - h), \quad (18)$$

$$\sigma_{n1} = \frac{\sigma_n}{S_1} \cdot \cos \alpha, \quad (19)$$

$$\gamma = \frac{\alpha}{2}\ , \quad (20)$$

$$\sigma_{n2} = \sigma_n \cdot \cos(\alpha - \gamma), \quad (21)$$

$$S_2 = \frac{a \cdot b}{\cos \gamma}, \quad (22)$$

$$\tau_2 = \frac{\sigma_{n2}}{S_2}, \quad (23)$$

$$\sigma_{n3} = \sigma_n \sin \beta, \quad (24)$$

$$S_3 = \frac{a \cdot h}{\cos(\alpha + \beta)}, \quad (25)$$

$$\tau_3 = \frac{\sigma_{n3}}{S_3}, \quad (26)$$

where: h – immersion depth of the tool, m; m – impact mass, kg; v – impact velocity, *m/s*; P – impact force, H; g – acceleration of gravity, m/s^2; h – lifting height of the striking part, m; σ_n – normal component of impact force, H; α – half the angle of the tool tip, rad; σ_{compr} – material compressive strength, MPa; S – the area of contact of the lateral faces of the tool with the rock, m^2; a – interaction area width, m; T – the kinetic energy of the instrument at the moment of impact, J; S_1 – split surface area, m^2; c – oversized height, m; σ_{n1} – normal stresses in the split plane, MPa; δ – the angle of inclination of the cleavage surface to the horizon, rad; σ_{n2} – component of the impact force in the cleavage plane, H; S_2 – cleavage surface area, m^2; τ_2 – shear stresses in the cleavage plane, MPa; β – the angle between the split surface and the side edge of the tool, rad; σ_{n3} – impact force component in the split plane, H; S_3 – gouge surface area, m^2; τ_3 – shear stresses in the puncture plane, MPa.

The developed mechanism of the initial stage of impact fracture makes it possible to establish the influence of the energy of a single impact, the strength of the material and the shape of the tool, as well as the point of impact on the main parameters of the fracture process. To increase the stresses in the interaction area, the energy of a single impact should be increased and the angle of sharpening of the working tool should be reduced. The developed mechanism for the destruction of oversized objects makes it possible to establish the dependence of the energy of a single blow, necessary for destruction, on the size, physical and mechanical properties of the rock and the angle of the tool tip.

When modeling the process of destruction of a granular geostructure, which occurs sequentially in two stages [13]: delocalized accumulation of microcracks and their combination into large cracks up to the moment of the formation of main cracks, leading to macrofracture and separation of the body into parts, according to [6], the criterion of critical disclosure of microcracks along the grain boundaries of the material:

$$\delta_{\text{кр}} = \frac{4 \cdot \text{К}_1^2}{\pi \cdot \text{E} \cdot \sigma_{\text{крт}}}, \quad (27)$$

where К_1 – stress intensity factor of the 1st kind, $\sigma_{\text{кр}}$ – material strength limit.

An important component in modeling the process of formation and further propagation of an impact crack is the problem of calculating the stress-strain state in the area of fracture and the formation of new cracks. This requires an algorithm that implements the physical essence of the occurrence of discontinuities. In this case, the calculation of the stress-strain state near a single crack, the description of its behavior, it is advisable to carry out using the well-known methods of fracture mechanics, concerning the description of the crack surfaces, using the stepwise calculation procedure or the stationary mesh method. The implementation of the highest quality calculation of the stress-strain state of an arbitrary fracture region guarantees a more accurate identification of the fracture surfaces, although, according to the principle of the adequacy of the construction of mathematical models, sufficient information content of arbitrary fracture is achieved without a precise description of their surfaces [14, 15].

Thus, it is proposed to explicitly model the occurrence of cracks in the process of mining a rock mass with a rock-cutting tool of percussion action with the creation of new free surfaces. The application of the Lagrange approach to the description of the motion of a medium allows one to interpret the behavior of points and their boundaries as elements of the material structure. We accept that the processes of destruction of geomaterial are localized along the boundaries of the cells. In this case, damage to such non-integral regions leads to the formation of fracture crack surfaces, for which the same number of nodes remained on each of the fracture edges. This procedure is carried out through the division of the nodes of the computational grid, when new boundaries are formed along the boundaries of the computational cells. Such an algorithm of fracture along the boundaries of cells guarantees a better picture of the direction and shape of cracks together with the field of the stress-strain state in the region of the apex. In addition, the inconsistency of the boundaries of the computational cells guarantees the fulfillment of the law of conservation of their mass and nodes, as well as the correspondence of the boundaries of the computational cells during discretization, in the case of interfaces in heterogeneous rock massifs. In the standard method, each of the nodes simultaneously belongs to its four neighboring cells, which determine its mass as the average value of four surrounding cells. For the case of inconsistency of the boundaries of the computational cells, it is observed that it is combined into one node out of four before the destruction of the rock mass begins. At the onset of fracture, which is regulated by the appropriate criterion for the critical opening of microcracks along the grain boundaries of the geomaterial, the group of combined cells disintegrates with the formation of not one, but two three, four nodes in accordance with the shape and direction of the cracks and the area of destruction. The scheme for calculating the parameters of the stress-strain state does not change in this case, since the calculations are performed in the grid cells. After the separation of the group, its constituent nodes belong to the newly formed surfaces of the crack edges. In the further calculation of the crack growth, the corresponding conditions are specified at all newly formed boundaries, which, when opened, are equivalent to the formation of a free surface. As mentioned, when the fracture criterion is met, the crack opens along the boundaries of the corresponding design cells. Since the calculation uses a rectangular mesh, each newly formed crack can be directed in two orthogonal directions, which determines both the fracture area and the shape together with the direction of the cracks. The choice of the partitioning scheme for each node is made by checking the state of each of the cell boundaries, since this determines the configuration of the destroyed area.

The solution of the problem of opening and developing a crack under the influence of the edge of a rock-cutting tool is made on the basis of a numerical model of a flat boundary value problem of the theory of elasticity by methods of discontinuous displacements and fictitious loads. The methods are based on the analytical solution of the problem of the infinite XOY plane, the displacements in which suffer a constant in magnitude discontinuity within the finite segment. The solution is considered as a special module of the boundary-element program of numerical solution. The physical discontinuity displacement is modeled as a linear crack, the sides of which are displaced relative to each other. In this case, the surfaces are shifted by a constant along the entire crack. In the general case, an arbitrary distribution of the relative displacement is considered. The discontinuous displacement method is based on the notion that displacement discontinuities continuously distributed along a crack are replaced by a discrete approximation by breaking the crack into N boundary elements and, within each element, displacement discontinuities are assumed to be constant. Knowing the analytical solution for one constant discontinuity displacement and summing up the effects of all N elements, we find a numerical solution to the problem. For the case when the distribution of displacement discontinuities along the crack is unknown, for the correct formulation of the problem, one needs to know the distribution of the forces applied on the crack contour. In this case, the values of the elementary discontinuity displacements for each of the elements that are necessary to cause such efforts are determined. This is achieved by solving the system of corresponding algebraic equations. The boundary integral equations of this method are equivalent to the following system of linear equations of the form [5, 16, 17]:

$$\begin{cases} \sigma_s^i = \sum_{j=1}^{N} \left(A_{s_s}^{ij} X_s^j + A_{s_n}^{ij} X_n^j \right) \\ \sigma_n^i = \sum_{j=1}^{N} \left(A_{n_s}^{ij} X_s^j + A_{n_n}^{ij} X_n^j \right) \end{cases}, \tag{28}$$
$$i = \overline{1, N},$$

where

$$\begin{cases} X_s^j = P_s^i \\ X_n^j = P_n^i \end{cases},$$
$$1 \le j \le M,$$
$$\begin{cases} X_s^j = D_s^i \\ X_n^j = D_n^i \end{cases},$$
$$M + 1 \le j \le N,$$

$A_{s\,s}^{i\,j}$, — boundary stress influence factors for the problem under consideration. Coefficient $A_{s\,n}^{i\,j}$ gives the actual tangential stress σ_s^i in the center of the *i* segment caused by a constant unit normal load $P_n^i = 1$ attached to *j* segment.

The sum of the initial and additional stresses expresses the total stresses in the *i* element is equal:

$$\begin{cases} \left(\sigma_s^i\right)_n = \left(\sigma_s^i\right)_0 + \sigma_s^i \\ \left(\sigma_n^i\right)_n = \left(\sigma_n^i\right)_0 + \sigma_n^i \end{cases}, \tag{29}$$

Equations (29) were used to construct an algebraic system for finding unknown quantities X_s^j and X_n^j (i = 1, ..., N). Boundary elements ($1 \le j \le M$) are characterized by zero-equal full stresses $\left(\sigma_s^i\right)_n$, $\left(\sigma_n^i\right)_n$ as a result 2*M* equations of the system (28) has next form:

$$\begin{cases} -(\sigma_s^i)_0 = \sum_{j=1}^{N} \left(A_{s_s}^{ij} X_s^j + A_{s_n}^{ij} X_n^j \right) \\ -(\sigma_n^i)_0 = \sum_{j=1}^{N} \left(A_{n_s}^{ij} X_s^j + A_{n_n}^{ij} X_n^j \right) \end{cases}, \tag{30}$$
$$1 \le j \le M.$$

Another 2(*N*-*M*) equations obtained by combining system (28) and the condition $\sigma_n^i = -K_n \cdot D_n$, $\sigma_s^i = -K_s \cdot D_s$, where K_n and K_s - normal and tangential stiffness characterizing the elastic contact element:

$$\begin{cases} 0 = K_s^i X_s^j + \sum_{j=1}^{N} \left(A_{s_s}^{ij} X_s^j + A_{s_n}^{ij} X_n^j \right) \\ 0 = K_n^i X_n^j + \sum_{j=1}^{N} \left(A_{n_s}^{ij} X_s^j + A_{n_n}^{ij} X_n^j \right) \end{cases}, \tag{31}$$
$$M + 1 \le i \le N.$$

Systems (30) and (31) were solved by the standard numerical method.

On Figures 3 and 4 for a fixed shock pulse, the dependence of the crack length on the radius of the rock-cutting tool r (at fixed σ_0) and the tensile strength σ_0 (at fixed r) is shown.

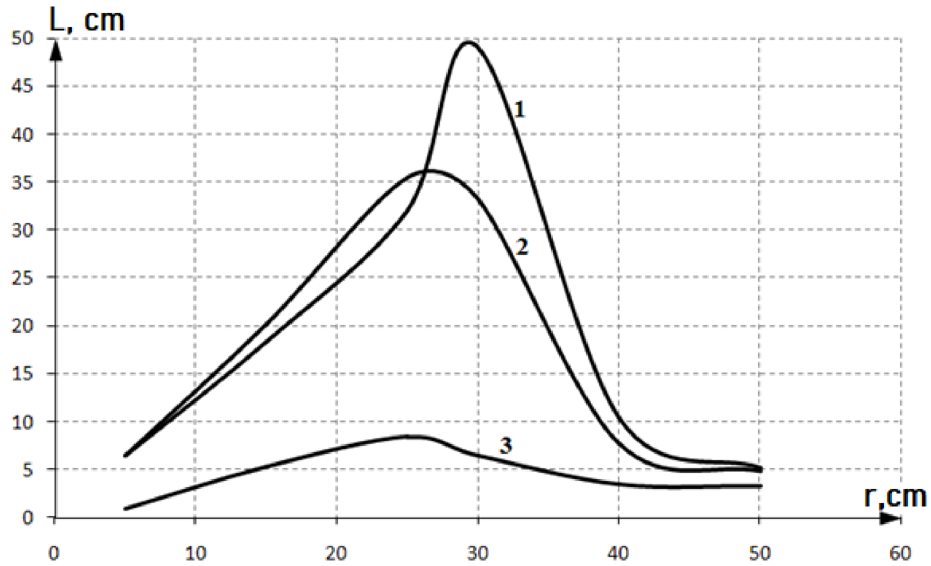

Figure 3: Dependence of the crack length on the radius of the tool:1 - argillites, 2 – sandstones, 3 - granite.

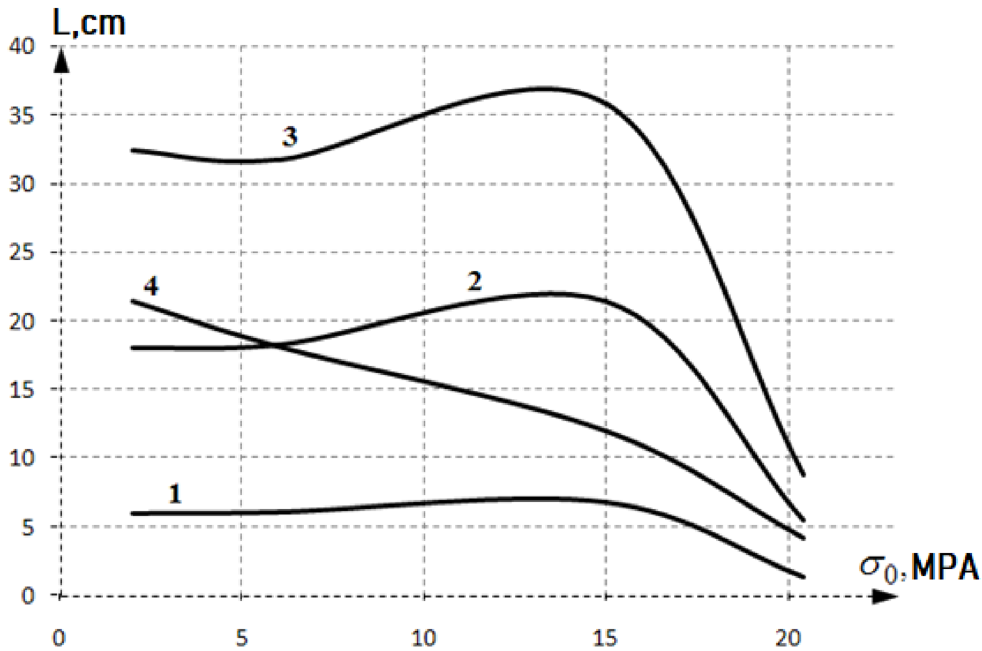

Figure 4: Dependence of the length of the crack on the strength of the rock on the gap: 1.r = 5, 2.r = 15, 3. r = 25, 4. r = 35.

3. Conclusions

1. The formation of microcracks in granular geomaterial occurs along the grain boundaries of the rock in the direction of action of the cutting edge of the rock cutting tool.

2. During the calculations using the boundary element method, it is found that if the initial crack length is much smaller than the distance to the free surface, then the tear gap develops without bending until the crack's length l and its distance D to the surface the values are

approximately in proportion $\frac{2l}{D} \leq 0{,}4$. If this correlation with the growth of the crack ceases to be fulfilled, then its trajectory gradually curves up until the crack reaches the surface.

3. The opening of microcracks in the contact area of the cutting part of the rock cutting tool with rock of a granular structure occurs under the condition of a higher value of tangential stresses of the value of normal stresses for cutting edge sharpening angles $\varphi \leq 37^0$. In the case $\sigma_n = 0$ and $\sigma_\tau = 0$ full cracking occurs along the boundaries of the structural grains of the geomaterial.

4. References

[1] Y. B. Petrivskyi, Scientific basis of geotechnological extraction of uranium from technogenic deposits, Volynski Oberegy, Rivne, 2008, 399pp.

[2] Y. B. Petrivskyi, Creation of anti-filtration collector complex in the rock massif, Bulletin of the Academy of Engineering of Ukraine, 2012, pp. 72-76.

[3] Y.B. Petrivskyi, V.Y. Petrivskyi, M.V. Tymchuk, Method and device for directional destruction of a mountainous area determined by the peculiarities of mining operations. Patent No. 10105525. 25.02.2013.

[4] Q. Zhu, J. Shao, Micromechanics of rock damage: Advances in the quasi-brittle field, Journal of Rock Mechanics and Geotechnical Engineering, Issue 1, Vol. 9, 2017, pp. 29-40. https://doi.org/10.1016/j.jrmge.2016.11.003.

[5] B.K. Atkinson, Fracture Mechanics of Rock, Elsevier Science, 2015, 548pp.

[6] Supriyono, M.H. Ali Adabi, Dual boundary element method for elastoplastic fracture mechanics of shear deformable plate, Engineering Analysis with Boundary Elements, Vol. 117, 2020, pp. 132-142. https://doi.org/10.1016/j.enganabound.2020.04.009.

[7] M. Kumar, U. Deep, P.M. Dixt, Simulation and Analysis of Ballistic Impact Using Continuum Damage Mechanics (CDM) Model, Procedia Engineering, Vol. 173, 2017, pp. 190-197. https://doi.org/10.1016/j.proeng.2016.12.057.

[8] P. Shen, T. Huiming, Y. Nign, D. Xia, A damage mechanics based on the constitutive model for strain-softening rocks, Engineering Fracture Mechanics, Vol. 216, 2019. https://doi.org/10.1016/j.engfracmech.2019.106521.

[9] L.-Y. Zhao, J.-F. Shao, Q.-Z. Zhu, J. A. Nairn, Analysis of localized cracking in quasi-brittle materials with a micro-mechanics based friction-damage approach, Journal of the Mechanics and Physics of Solids, Vol. 119, 2018, pp. 163-187. https://doi.org/10.1016/j.jmps.2018.06.017.

[10] S. Wang, H. Masoumi, J. Oh, S. Zhang, Scale-Size and Structural Effects of Rock Materials, Woodhead Publishing, 648pp. https://doi.org/10.1016/C2019-0-01182-X.

[11] O. Aydan, Rock Mechanics and Rock Engineering, CRC Press, 2019, pp. 394.

[12] H. Fu, W. Chen, J. Fu, Rock Mechanics and Engineering, Woodhead Publishing Series in Civil and Structural Engineering, 2020, 407pp. https://doi.org/10.1016/C2019-0-04623-7.

[13] L. Zhang, Engineering Properties of Rocks, Butterworth-Heinemann, 2016, 378pp. https://doi.org/10.1016/C2014-0-02645-7.

[14] L.L. Da Silva, R. Pitangueira, S. S. Penna, F. B. Barros, A numerical model for simulation of cracking process in quasi-brittle medium, Science and Engineering Journal, 2016, pp. 66-76.

[15] B. Giovanardi, S. Serebrinsky, R. Radovitzky, A fully-coupled computational framework for large-scale simulation of fluid-driven fracture propagation on parallel computers, Computer Methods in Applied Mechanics and Engineering, Vol. 372, 2020. https://doi.org/10.1016/j.cma.2020.113365.

[16] M. Poluenkov, L. Figiel, A cut finite-element method for fracture and contact problems in large-deformation solid mechanics, Computer Methods in Applied Mechanics and Engineering, Vol. 388, 2021. https://doi.org/10.1016/j.cma.2021.114234

[17] J.T. Katsikadelis, The Boundary Element Method for Engineers and Scientists, Academic Press, 2016, 433pp.