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NUMERICAL STUDY OF THE INTERACTION OF ROCK BOLTS WITH THE BLOCK-STRUCTURED ROCK MASS

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Abstract. In order to ground parameters of rock bolting for mine workings, it is necessary to study the stressedly-deformed state of the host rock and the elements of rock bolting. Under certain mining and geological conditions, the rock mass is broken by cracks and divided into blocks. Methods designed for modelling solid environments are not sufficient for the study of a block-structured rocks. In this regard, the purpose of this work was to develop a method of studying the state of block-structured rock mass around the mine working with rock bolting and to ground the possibility of preventing the rock blocks from sliding with the help of rock bolting structure.

As a result of the work, a numerical model of a block-structured rock mass with a mine working supported with rock bolts, which were modeled using two-node rod finite elements, was developed. Cracks were simulated using a four-node contact finite element, which has zero thickness, and the initial coordinates of the nodes of its opposite sides coincide. The generation and growth of a crack can occur in the form of its opening or displacement along its surface. A method was developed, which, due to the introduction of special contact elements into the finite-element scheme, allows simulating the stressedly-deformed state of rocks with cracks. The use of the proposed method of studying the block-structured rock mass makes it possible to check the efficiency of the rock bolting elements during the development of the supporting scheme.

Using the developed method, the relative displacement of the block formed in the mine roof was investigated in four cases: when the mine working is not supported, the mine working is supported with the use of simple, reinforced and powerful rock bolting structures. It was shown that in the cracked rocks divided into blocks, the displacement of the rock block reaches a maximum in the unsupported mine roof. The simple rock bolting structure almost does not prevent the rock block from shifting into the mine working space, together with a row of rock bolts installed vertically. The inclination of the rock bolts by 70° to the mine face in the reinforced rock bolting structure significantly improves the condition of the mine roof; its displacement is reduced by 87%. And the use of the powerful rock bolting structure blocks the movement of the rock-bolts block almost completely, by 93%. Therefore, the reinforced and powerful rock bolting structures allows you to keep the cracked rock mass divided into blocks in a stable condition.

Keywords: block-structured rocks, mine working, rock deformation, rock bolting structure, numerical simulation.

1. Introduction

In order to ground such parameters of rock bolting as the length and diameter of rock bolts, the density of their location [1–6], angles of inclination [7–9] and others [10–15], it is necessary to study the stressedly-deformed state of the rock mass and elements of rock bolting. An in-depth study of the impact of steel rock bolts, which are fixed along their entire length with a polymer, on the host rocks allows to choose optimal supporting schemes, which helps to increasing the stability of mine workings and the safety of miners [16, 17].

In some studies, the presence of rock bolts is taken into account by strengthening the properties of the near-contour rock layer, for example, using the equivalent simulation method for the bolted rock mass [18–20]. This simulation method very roughly models the influence of rock bolting on the structure stability and does not provide an opportunity to ground the choice of the rock bolts location scheme for specific geological conditions. The spring-slider model for the passive bolts presented in [21] is often used, in which the action of a rock bolt is modelled by the axial force assignment, which is determined according to displacement curve obtained from pullout tests. The mechanical behaviour of reinforcement elements can be modelled in a 3D discrete element method, using structural elements [22]. They can simulate the resistance to pullout force that results from the combined effect of shear forces developed at the interface between the steel bolt and the rock or the grout and the axial stiffness of the steel itself.

There are models, which are closer to the real mechanism of a rock bolt action in the rock mass. This is a model of a linearly elastic rock bolt with an elastic-plastic grout, where rock bolts are discretized by 1D structural elements which are coupled to the solid finite-element mesh by dedicated spring-slider connectors [10]; as well as a model of an elastic-plastic rock bolt simulated with the help of rod finite elements with appropriate physical and mechanical properties, which is fixed in the hole with a polymer grout simulated with the help of contact finite elements, which are rigidly connected on one side with the finite elements of the rock mass, on the other side with rod finite elements of rock bolts [23, 24].

Under certain mining and geological conditions, the rock mass is broken by cracks or a cracks system, which divide it into blocks. Mine observations show that cracks also occur between rows of rock bolts, the distance between which exceeds the distance of their effective interaction. In weak rocks, rock blocks formed by natural or induced means can be moved into the mine working space. There are many modern scientific works, in which numerical simulation of simple rock bolting structures in fractured rocks [10, 25] with a stochastically generated discrete fracture network is performed. Reinforcement of natural joints in rock masses was studied on the basis of the discontinuous deformation method or block-cutting analysis, which can provide solutions for large displacements and failures of blocky structures [26, 27].

Therefore, to study the stressedly-deformed state of a rock mass separated by cracks or a block-structured rocks, methods designed for modelling solid environments are not enough, and it is necessary to have a good understanding of the behaviour of rock bolts in deformed jointed rock masses [3] to choose such a rock bolting structure, which will effectively prevent the rock blocks from sliding. In this regard, the purpose of this work is to develop a method of studying the state of block-structured rock mass around the mine working with rock bolting and to ground the possibility of preventing the rock blocks from sliding with the help of rock bolting structure.

To achieve this goal, the following tasks were solved:

1) to develop a numerical model of a block-structured rocks with mine working and rock bolting;

2) to develop a method of studying the state of block-structured rocks around the mine working with rock bolting;

3) to investigate the effectiveness of rock bolting structures of different levels when they are used in a block-structured rock mass.

2. Methods

The hypothesis of continuity within each rock block was adopted during the simulation, and it was also assumed that the rock mass is homogeneous within each rock layer. The time-dependent stressedly-deformed state of the rock mass around the mine working is described by a system of equations [28, 29]:

$$c_g \frac{\partial}{\partial t} u_i = \sigma_{ij,j} + X_i(t), \tag{1}$$

where u_i – displacements, m; c_g – the damping coefficient, kg/(m^3·s); $\sigma_{ij,j}$ – derivatives of the stress tensor components along horizontal axis x and vertical axis y, Pa/m; t – time, s; $X_i(t)$ – projections of the external forces acting on the volume unit of a solid body, N/m^3.

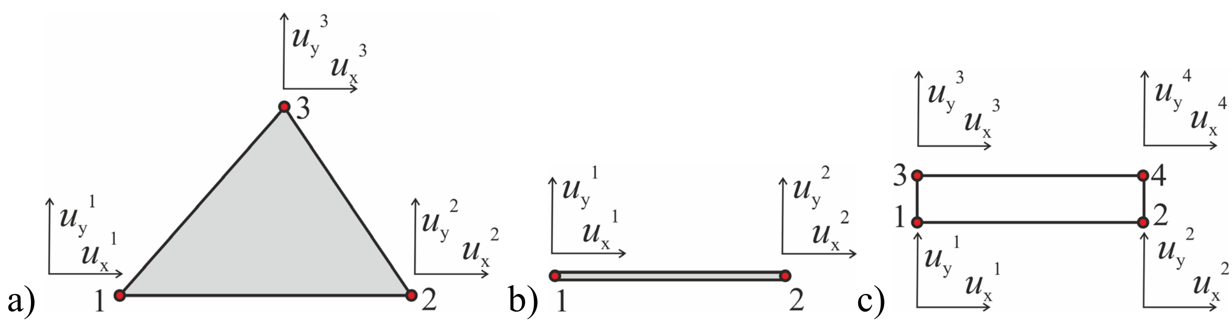
The initial and boundary conditions for this task are:

$$\sigma_{yy}\big|_{t=0} = \gamma H; \quad \sigma_{xx}\big|_{t=0} = \lambda\gamma H; \quad u_x\big|_{t=0} = 0; \quad u_y\big|_{t=0} = 0; \tag{2}$$

$$u_x\big|_{\Omega_1} = 0; \quad u_y\big|_{\Omega_2} = 0, \tag{3}$$

where σ_{xx}, σ_{yy} – components of the stress tensor, Pa; γ – average weigh of the overlying rock seams, N/m^3; H – mining depth, m; λ – the side thrust coefficient; u_x, u_y – components of the displacement vector, m; Ω_1 – the vertical boundaries of the outer contour; Ω_2 – the horizontal boundaries of the outer contour.

The problem was solved in an elastic-plastic setting using the Coulomb-Mohr strength criterion [30, 31]. To solve equation (1) with initial and boundary conditions (2) and (3), the finite element method [32, 33], implemented on the authors' software, was used. The studied area was approximated by triangular finite elements, figure 1a. Rock bolts were modeled using two-node rod finite elements, figure 1b. To model the multi-point interaction of the rock bolt with the host rocks, each anchor was divided into several sequentially located rod finite elements contacting the elements of the host rocks at nodal points.



a) triangular finite element; b) rod finite element; c) four-node contact finite element.

Figure 1 – Schemes of finite elements, which were used in modelling the block-structured rock mass and rock bolts

As it is known, the process of rock disintegration consists of two stages: the crack generation and its growth. Each of them is subject to its own laws; accordingly, there are strength criteria for each stage. The process of crack generation was not considered in this work. The possibility of preventing the displacement of already formed blocks in the mine roof using rock bolts was studied to prevent the mine roof from collapsing. The crack was simulated using four-node finite elements (figure 1c), based on the Goodman contact element [34, 35]. This element has zero thickness, and the initial coordinates of the nodes of opposite sides (crack edges) coincide. This element can be deformed by shifting and rotating one side relative to the other one. The generation and growth of a crack can occur in the form of opening or shifting along its surface.

The coefficients of the stiffness matrices for rock bolts and cracks elements are included in the global stiffness matrix of the entire system by adding their elements according to the global node numbering system.

The verification of the developed numerical model was performed based on the results of comparing the calculated values and the actual measurements of the mine roof displacement. The lowering of the rock-bolts block, formed in the roof of the 351 roadway in the "Ternivska" mine, occurred during the transition from the frame support to the frame-rock bolt one with the location of the rock-bolts in the cross-sectional plane of the roadway, figure 2.

Figure 2 – Photo of the rock-bolts block, which was taken during the re-supporting of the emergency region of the 351 roadway

For the mining and geological conditions of the 351 roadway, the displacements of rock-bolts blocks were calculated using the developed model. Figure 3 presents a graph of changes in the height of the roadway section at the emergency region based on the results of the calculation and measurements of the mine roof displacement. The deviation of the obtained calculation results from the actual mine roof displacements does not exceed 25%.

When performing the calculations, a longitudinal section of a 3-m-high mine working, located at a depth of 800 m, was considered. It was assumed that the distance between the rows of rock bolts is 0.8 m, and the length of the bolt is 2.4 m.

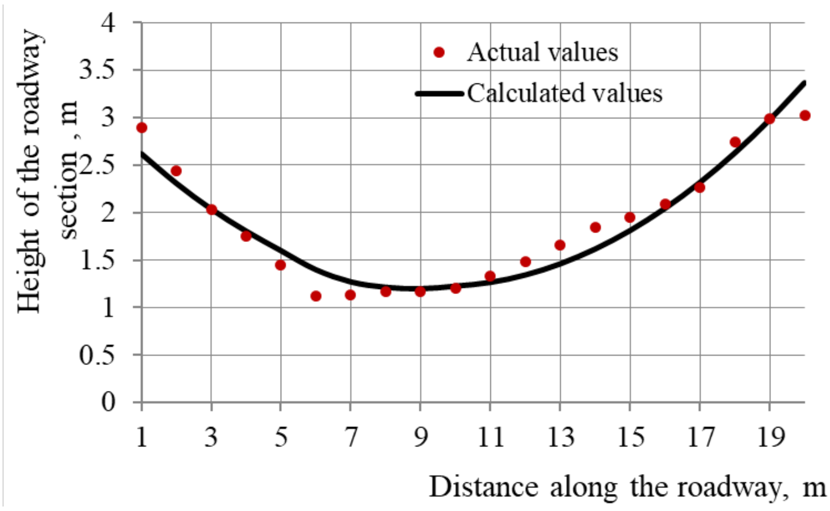


Figure 3 – Changes in the height of the roadway section at the emergency region

The stress field was analysed using the geomechanical parameter Q^*, which characterizes the difference of the principal stress tensor components:

$$Q^* = \frac{\sigma_1 - \sigma_3}{\gamma H},$$

where σ_1, σ_3 – maximum and minimum component values of the principal stress tensor, Pa.

3. Studying the state of block-structured rocks around a mine working with rock bolting

The study of the state of block-structured rock mass around the mine working with rock bolting is possible by adding special contact elements that simulate cracks in the rock to the calculated finite-element scheme. Such a numerical model allows you to study the performance of rock bolting elements in rocks with cracks (or divided into blocks) to justify the technological parameters of the support.

The method consists in sequentially performing the following operations:

1) to create of a finite-element model of a rock mass with a mine working of the required cross-sectional shape;

2) to add rod finite elements, which simulate rock bolts to the model;

3) to add four-node contact finite elements of the required length, with zero thickness and matching initial coordinates of the opposite sides, which must be allocated in the places of the expected location of the cracks;

4) to optimize the finite-element mesh for the calculation model of the block-structured rock mass with mine working and rock bolts;

5) to export the obtained finite-element model to a software environment that implements the finite element method;

6) to set the rigidity of contact interaction of contact finite elements;

7) to set the physical and mechanical properties of rock bolts and each rock layer;

8) to set the initial stresses equal to the rock pressure in the finite elements that model the rock mass, and the initial zero displacements;

9) to set conditions for the model fixation, which block the vertical movements of the grid nodes on the horizontal borders of the model and the horizontal movements of nodes on the vertical borders;

10) to add coefficients of stiffness matrices of rock bolts elements and cracks to the global stiffness matrix of the entire system according to the global node numbering system;

11) to perform a numerical calculation, to determine the values of stresses and deformations in each element of the rock mass model and rock bolts;

12) to determine the values of displacement of rock blocks;

13) to go to the next time step;

14) to perform steps 11–13 in a cycle until the desired time step.

The use of contact finite elements for simulation of cracks between rock blocks allows you to adequately reproduce the relevant mining and geological features of the rock mass and the impact of technological operations on it, namely:

- sliding of the one crack edge relative to the other one;
- interaction of rock blocks separated by cracks during mining operations;
- the influence of the rock bolts layout in the block-structured rocks on the stability of the mine working.

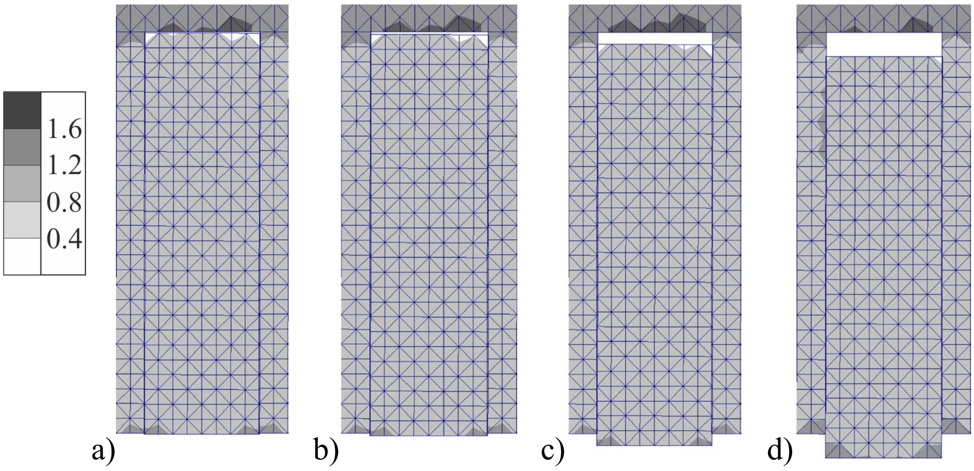
In this way, a numerical model is created for the study of the block-structured rock mass with the mine working, which is supported with rock bolting. The advantage of the proposed method is taking into account the influence of the cracks system in the rock mass around the mine working on the process of rock deformation, as well as the opportunity to investigate the movement of rock blocks formed by cracks and the influence of parameters of the spatial rock bolts layout on stability of the mine working in the block-structured rocks.

The use of the proposed method of studying the block-structured rock mass makes it possible to check the efficiency of the rock bolting elements in the block-structured rock mass during the development of the supporting scheme.

4. Effectiveness of rock bolting structures of different levels when they are used in a block-structured rock mass

As an example, a block formed by cracks in the mine roof was considered, and the stress in the rocks around the mine working was calculated using the method described above. Figure 4 shows the displacements of the block bounded by horizontal and vertical cracks at different steps of the deformation process.

Before starting mining operations, the field of initial stresses is formed in the rock mass. Mining takes rocks out of equilibrium. When the mine face is moved, the host rocks are displaced inside the formed cavity, the stresses are redistributed. At the boundary of the weakening surface, for example at the contact of two rock layers, the condition of strength is violated and a horizontal crack appears, figure 4a. Further, vertical cracks form, figure 4b. Starting from the roof surface, the frictional resistance along the formed cracks decreases, and the rock block, already having reduced adhesion to the rock mass, under the influence of its weight, begins to move downwards, into the mine working, figure 4c, 4d.



a) b) c) d)

a) formation of the horizontal crack; b) development of the vertical cracks; c) and d) displacement into the mine working.

Figure 4 – Steps of displacement of the rock block in the mine roof

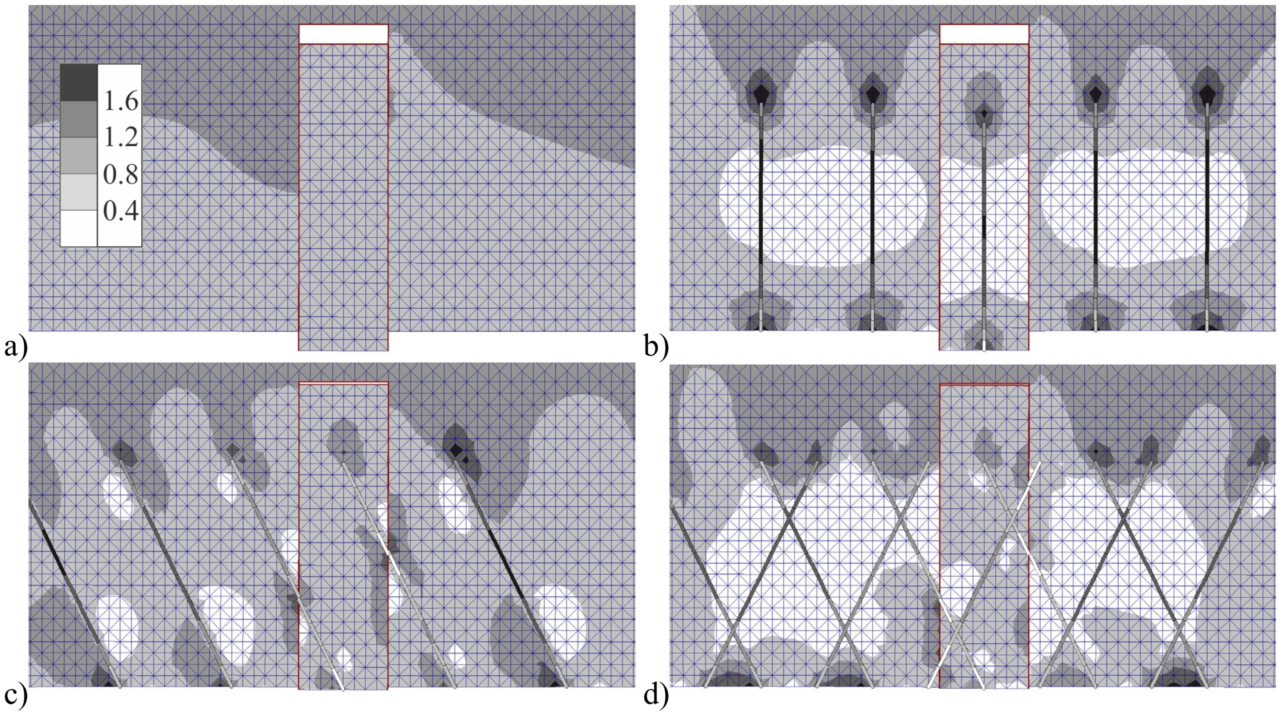
The behaviour of near-contour rocks is determined both by its physical and mechanical properties, and by the presence of cracks and weakening surfaces, which leads to their division into blocks. Displacement of such blocks along structural weakening surfaces is the least energy-intensive process, which is the most probable variant for deformation of the host rock.

Using the developed numerical model of the block-structured rocks, the relative displacements of the block formed in the mine roof were investigated when rock bolting was applied. The angle of inclination of the rock bolts determines the level of the rock bolting structures [9]. Rock bolts are installed:

- in the cross-sectional plane of the mine working for simple rock bolting structures (RBSs);
- with a slope of 70–75° to the mine face for reinforced rock bolting structures (RBSr);
- with a 70–75° inclination of part of the rock bolts to the mine face and with a 70-75° inclination of the other part of the rock bolts to the mouth of the mine working for powerful rock bolting structures (RBSp).

Four cases were considered: the mine working is not supported, the mine working is supported with a simple, reinforced or powerful rock bolting structure. To simplify calculations, it was assumed that the block is formed around one rock-rock bolt support. The block dimensions correspond to the dimensions of this support. The calculation results are shown in figure 5.

Under the action of gravity, the rock block moves inside the mine working, the adhesion of the crack edges at this stage of deformation does not allow the block to fall out completely, figure 5a. Almost the same displacements are observed in figure 5b, in the case when the mine working is supported with RBSs. The simple rock bolting structure does not prevent the displacement of the block if the horizontal separation crack runs at a height greater than the length of the rock bolt. It is clearly visible in figure 5b that the vertical cracks, which limit the rock block with one rock bolt, tear the bolts-reinforced area of the mine roof, where $Q < 0.8$, into the parts. Integrity of the roof rocks is broken.



a) unsupported mine working; b) mine working with RBSs; c) with RBSr; d) with RBSp.

Figure 5 – Distribution of Q parameter values and displacement of the rock block in the mine roof

When using RBSr (figure 5c) the bolts-reinforced area of the mine roof, where $Q < 0.8$, is only partially intersected by zones with increased Q parameter values, in which $0.8 < Q < 1.6$. It can be seen that the displacement of the rock block is much smaller compared to the previous cases. Inclined rock bolts increase adhesion of vertical cracks. Cohesion forces play the main role in ensuring the stability of block-structured rocks. Therefore, in order to prevent the block from sliding along the vertical cracks, it is necessary that the frictional forces should exceed the shear forces caused by the weight of the rocks in the block and directed along the cracks.

In the mine roof, which is supported with RBSp, figure 5d, there are practically no displacements of the rock block. The mine roof reinforced by rock bolts along the entire length remains in a serviceable condition when $Q < 0.8$. The integrity of the near-contour rocks, which is necessary to ensure effective maintenance-free operation of the mine working, is preserved with the help of the powerful rock bolting structure.

Figure 6 shows the graph of changes in displacements of the mine roof depending on the type of support.

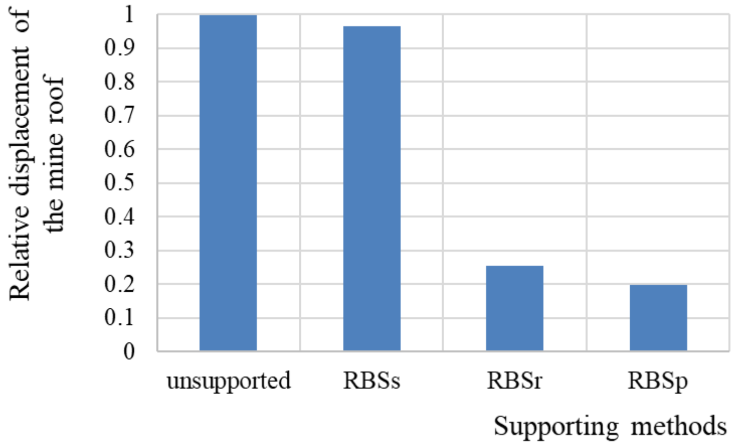


Figure 6 – Relative displacement of the mine roof with different supporting methods

In a cracked rocks divided into blocks, the displacement of the rock block reaches a maximum in the unsupported mine roof, figure 6. The RBSs structure only slightly, by 5%, prevents the rock block from shifting; together with a row of rock bolts installed vertically, it descends into the mine working space. The inclination of the rock bolts by 70° to the mine face in the RBSr structure significantly improves the condition of the mine roof, its displacement is reduced by 87%. And the use of the powerful rock bolting structure blocks the movement of the rock-bolts block almost completely, by 93%, figure 6.

Therefore, the reinforced and powerful rock bolting structures allows you to keep the cracked rock mass divided into blocks in a stable condition.

5. Conclusions

In order to ground such parameters of rock bolting for mine workings as the length of bolts, the density of their location in the rock, and the angles of their inclination, it is necessary to study the stressedly-deformed state of the host rock and the elements of rock bolting. Under certain mining and geological conditions, the rock mass is broken by cracks, which divide it into blocks. Methods designed for modelling solid environments are not sufficient for the study of a block-structured rocks. In this regard, the purpose of this work was to develop a method of studying the state of block-structured rock mass around the mine working with rock bolting and to ground the possibility of preventing the rock blocks from sliding with the help of rock bolting structure.

As a result of the work, a numerical model of a block-structured rock mass with a mine working supported with rock bolts was developed. Rock bolts were modeled using two-node rod finite elements, cracks were simulated using a four-node contact finite element, which has zero thickness, and the initial coordinates of the nodes of its opposite sides coincide. The generation and growth of a crack can occur in the form of its opening or displacement along its surface. Verification of the developed model was carried out based on the results of a comparison of the calculated and actual values of the roof displacement in the 351 roadway in the "Ternivska" mine, where the block formed by the rock bolts in the mine roof was lowered.

A method was developed that, due to the introduction of special contact elements into the finite-element scheme, allows simulating the stressedly-deformed state of rocks with cracks. The use of the proposed method of studying the block-structured rock mass makes it possible to check the efficiency of the rock bolting elements in the block-structured rock mass during the development of the supporting scheme.

Using the developed method, the relative displacement of the block formed in the mine roof was investigated in four cases: when the mine working is not supported, the mine working is supported with the use of simple, reinforced and powerful rock bolting structures. It was shown that in the cracked rocks divided into blocks, the displacement of the rock block reaches a maximum in the unsupported mine roof. The simple rock bolting structure almost does not prevent the rock block from shifting into the mine working space, together with a row of rock bolts installed vertically. The inclination of the rock bolts by 70° to the mine face in the reinforced rock bolting structure significantly improves the condition of the mine roof; its displacement is reduced by 87%. And the use of the powerful rock bolting structure blocks the movement of the rock-bolts block almost completely, by 93%. Therefore, the reinforced and powerful rock bolting structures allows you to keep the cracked rock mass divided into blocks in a stable condition.

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ЧИСЕЛЬНЕ ДОСЛІДЖЕННЯ ВЗАЄМОДІЇ АНКЕРНОГО КРІПЛЕННЯ З БЛОЧНО-СТРУКТУРОВАНИМ ПОРОДНИМ МАСИВОМ

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Анотація. Для обґрунтування параметрів анкерного кріплення гірничих виробок необхідно дослідження напружено-деформованого стану вміщуючих порід і елементів анкерного кріплення. В певних гірничо-геологічних умовах породний масив розбито тріщинами і поділено на блоки. Для дослідження блочно-структурованих порід не достатньо методів, призначених для моделювання суцільних середовищ. У зв'язку з цим метою цієї роботи є розробка способу дослідження стану блочно-структурованого породного масиву навколо гірничої виробки з анкерним кріпленням та обґрунтування можливості запобігання зсувам породних блоків за допомогою анкерного кріплення.

В результаті виконання роботи розроблено чисельну модель блочно-структурованого гірського масиву з гірничою виробкою, закріпленою анкерами, які моделювались дво-вузловими стрижневими скінченими елементами. Тріщини моделювались чотири-вузловими контактними скінченими елементами, які мають нульову товщину, а початкові координати вузлів їх протилежних сторін збігаються. Утворення та зростання тріщини може відбуватися у вигляді її розкриття або зсуву вздовж її поверхні. Розроблено спосіб, який за рахунок введення до скінчено-елементної схеми контактних елементів дозволяє моделювати напружено-деформований стан порід з тріщинами. Використання запропонованого способу дослідження стану блочно-структурованого породного масиву надає змогу перевірити працездатність елементів анкерного кріплення при розробці схеми кріплення гірничої виробки.

З використанням розробленого способу було досліджено відносні зміщення блоку, утвореного в покрівлі виробки, в чотирьох випадках, коли виробка незакріплена, виробка закріплена із застосуванням простої, посиленої і потужної конструкцій анкерного кріплення. Показано, що в тріщинуватому, розділеному на блоки масиві, зміщення окремого блоку сягає максимуму у виробці з незакріпленою покрівлею. Проста конструкція анкерного кріплення майже не перешкоджає зсуву породного блоку разом з рядом анкерів, встановлених вертикально, в простір виробки. Нахил анкерів на 70° на вибій у посиленій конструкції значно покращує стан покрівлі, її зміщення знижується на 87%. А застосування потужної конструкції блокує переміщення породно-анкерного блоку практично повністю, на 93%. Отже, посилена і потужна конструкції анкерного кріплення дозволяють зберігати тріщинуватий, розділений на блоки масив, у стійкому стані.

Ключові слова: блочно-структуровані породи, гірнича виробка, деформування порід, конструкції анкерного кріплення, чисельне моделювання.