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MODELING OF THE GEOMECHANICAL STATE OF THE ROCK MASSIFS BEING UNDERMINED REPEATEDLY

Abstract. The geomechanical model is proposed and the technology of numerical simulation is developed. Carried out computer simulation of the geomechanical state of the being undermined repeatedly rock massifs of the 3rd potash level of the Starobin deposit taking into account its structural and strength features, as well as the technological schemes of the primary mining. The regularities of the stress-strain zones formation in the undermined rock mass containing mined out mine workings and inter-panel pillars were determined. It is shown that the stability of the workings located in the undermined areas significantly depends on the time passed since the primary mining and on the location of the workings in the massif relative to the location of the primary mining operations. It is determined that the most dangerous for repeated mining are the areas of generalized shear, since the processes of rock mass movement and failure are most likely to be active in these areas. In the areas of generalized compression, the processes of compaction of caved rock take place. As a consequence, after a considerable period of time, the state of the rock massif in these areas can be treated as approximating to the natural state, without additional structural failures. In such areas, the effective mechanical characteristics of the rock massifs are practically restored. Therefore, the greatest stability of mine workings will be achieved when they are placed in the area of generalized compression stress state in the zone of caved, compacted rocks of the mined out roadways and faces.

Keywords: geomechanical model, stress-strain state, ultimate state criteria, rock massif, working

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МОДЕЛИРОВАНИЕ ГЕОМЕХАНИЧЕСКОГО СОСТОЯНИЯ ПОВТОРНО ПОДРАБАТЫВАЕМЫХ МАССИВОВ ГОРНЫХ ПОРОД

Аннотация. Предложена геомеханическая модель, разработана технология численного моделирования и выполнено компьютерное моделирование геомеханического состояния повторно подрабатываемого массива горных пород Третьего калийного горизонта Старобинского месторождения с учетом его структурных и прочностных особенностей, а также технологических схем первичной отработки. Установлены закономерности формирования зон напряженно-деформированного состояния в подработанном массиве, вмещающем погашенные очистные выработки и межпанельные целики. Показано, что устойчивость выработок, расположенных в областях повторной подработки, существенным образом зависит от времени, прошедшего со времени первичной подработки, и от места расположения выработки в массиве относительно места проведения первичных горных работ. Установлено, что наиболее опасными для повторного размещения выработок являются зоны обобщенного сдвига, так как в них наиболее вероятна активизация процессов сдвижения и разрушения породных масс. В областях обобщенного сжатия происходят процессы уплотнения обрушенных породных масс. Вследствие этого по истечении значительного периода времени состояние массива горных пород в данных зонах можно рассматривать как приближенное к естественному, без дополнительных структурных нарушений. В таких областях эффективные механические характеристики массивов горных пород практически восстанавливаются. Поэтому наибольшая устойчивость выработок будет достигнута при размещении их в области напряженного состояния обобщенного сжатия в зоне обрушенных, уплотненных пород отработанных очистных ходов и лав.

Ключевые слова: геомеханическая модель, напряженно-деформированное состояние, критерии предельного состояния, массив горных пород, выработка

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Introduction. Recently the question of mining the remaining mineral reserves in the areas of the 3rd potash layer, mined out more than 40 years ago with the use of different mining systems – pillar and room and pillar systems – has acquired special relevance to maintain the raw material base of the mines of Starobin potash salt deposit. To assess the technological possibility, safety and economic feasibility of additional ore extraction from specific sections of the rock strata, it is necessary to study the condition of mining systems at such sections of the mine field by performing the geomechanical modelling of the stress-strain state of the rock massif, taking into account its structural and strength characteristics, as well as technological schemes of mining. At the same time, as a rule, there is no detailed information on the geological structure of the undermined rock massif at the start of repeated mining. Analysis of previous researches in the field of rock massif geomechanics showed that after mining operations, geomechanical processes, caused by man-made disturbance of the natural deflection of the rock mass stress-strain state, is a multistage temporal process, in the development of which several characteristic stages can be identified, due to structural changes in the rock mass in the area of mining operations and changes of the stress-strain state in the considered area of the massif with the time [1–4]. Besides, the geomechanical state of the workings being designed for mining in the areas of repeated undermining also depends on the time of executing the mining in relation to the time of finishing the primary mining (primary undermining) and the location of the mine workings in the rock massif in relation to the primary mining [5]. However, until now, many basic principles and theoretical ideas about the geomechanical state and characteristics of the undermined massif when workings are re-located therein remain fragmentary and incomplete. Therefore, the implementation of numerical studies of the geomechanical state of specific areas of the undermined salt massif of the 3rd potash layer was accompanied by significant difficulties associated with the need to develop adequate approaches to the construction of numerical geomechanical models. The development of such approaches and construction technology of the numerical geomechanical model, which are presented, in particular, in papers [6, 7], is the basis for the numerical experiments on the geomechanical modelling of the undermined salt massif in several sections of the mine field (western panels No. 18, 22 and 24) of mine No. 3 planned for repeated mining. In turn, the results of the numerical studies have been summarized to provide general recommendations for the location of the development workings of the new extraction pillars.

It should be noted that the implementation of research related to the construction of mechanical, mathematical and numerical models and calculation schemes for the study of geomechanical processes in rock massifs with a large-scale system of underground workings is an urgent task not only for the Republic of Belarus, but also for all countries with a developed mining industry, see, for example, [8–11].

The purpose of the research presented in the article was to study, using the developed geomechanical numerical model and computer modeling algorithm, the geomechanical state of the re-worked mountain range of the Third potash horizon of the Starobinskoye field, taking into account its structural and strength features, as well as technological schemes during the primary mining of the rock layer. As a result of the studies carried out, it was necessary to establish the regularities of the formation of stress-strain zones in the massif in areas containing extinguished treatment workings and inter-panel pillars, and to issue recommendations for the placement of new workings in re-worked rock massifs.

Basic provisions for carrying out modelling studies. Effective way to estimate type of the stress-strain state, in which these or those parts of undermined rock massif are situated, is using Nadai–Lode parameter, which is determined by principal stresses components and characterizes bulk stressed state [1, 2]: the value in limits [–1; –0.5] corresponds to generalized tension state; the value in limits [–0.5; 0.5] corresponds to generalized shear state; the value in limits [0.5; 1] corresponds to generalized compression state. At the same time, the type of stress state has a significant influence on geomechanical processes in the rock massif and, accordingly, determines the mechanism of its continuity, strength and failure processes [1, 6]. Thus, in generalized compression regions, failure processes due to large acting compressive stresses are most likely to occur. In the generalized strain regions, the processes of rock discontinuity as a consequence of tensile stresses and deformations prevail. In generalized shear regions, there are large mutual displacements of layers and blocks. It is obvious that such "primary" processes subsequently have an important influence on the structure and state of the newly undermined massif. Let us explain this conclusion in terms of geomechanics of processes. In the areas where generalized compression zones were formed after the primary undermining, the processes of rock compression and rock failure prevailed. Therefore, after the shear processes in the undermined massif have ceased, especially after a considerable period of time, the rock massif in these areas can be regarded as "natural" without additional structural disturbances. In the areas of generalized tensile stress after primary undermining, it is most likely that the continuity of the massif is broken by layering and the formation of fractured areas. As a consequence, even after shear processes in the undermined massif have ceased, such areas do not "heal" completely (of course, this depends on the properties of the rocks where such areas have appeared) and may appear during repeated mining. Finally, in the areas of generalized shear after primary undermining, especially in layered rock massifs, areas of significant mutual displacement appear and a new block structure is formed in the massif. It is obvious that even after a long period of time the adhesion coefficient in these areas of the massif differs considerably from the initial one. Consequently, it is not recommended to re-locate workings in such areas, as activation of shear and fracture processes along previously appeared slip lines is most likely in these areas.

Based on the above mentioned, it is clear that the choice of mine workings location in the repeatedly undermined massif has a considerable influence on the geomechanical state and rock mass stability in the vicinity area of the workings contour.

It should be noted that the performance of modeling studies requires the use of techniques to consider changes in the mechanical characteristics of the undermined rock massifs, which occurred due to disturbances in its continuity of different nature and the time passed after the undermining [7]. Additionally, it is important to select adequate criteria for the ultimate state and strength characteristics of repeatedly undermined rock massifs [6].

Geomechanical modelling of the undermined massif. Numerical studies were carried out for several sections of the mine field of the 3rd potash level of the mine No. 3 (Figure 1) and consisted of two stages.

The first stage of the research was to study the geomechanical condition of the undermined rock strata in the panels No. 22 and 24, which were mined out using the pillar mining system. The second stage of the study involved studying the geomechanical condition of the undermined rock strata in the section of the panel No. 18, which was mined out by the room and pillar mining system.

The initial conditions for the first stage of the study are as follows. Panel No. 22 was mined out by the longwall face No. 35 with extraction of the 4th sylvinite layer and leaving the layers 2,2–3,3. Panel No. 24 was mined out by the longwall face No. 7 which mined out the 2nd and the 3rd sylvinite layers and left the 4th sylvinite layer. Figure 2 shows a vertical section of the salt massif in the study area. Another object of study is a service entry (see position 3 in the Figure 2), which was driven in the pillar between the longwall faces No. 7 and 35. It was 4.5 m wide and 3.0 m high. The roof of the mentioned entry was secured with rows of KAMB anchors of length L = 1.2 m.

The modelling studies were carried out taking into account the sequence and time of mining the extraction pillars: first the face No. 7 and then the face No. 35. The service entry (see position 3 in the Figure 2) was driven after a considerable period of time after the completion of the mining the mentioned faces.

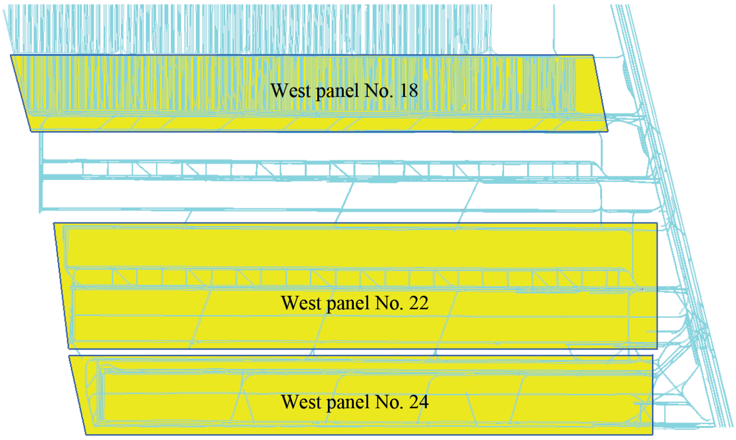

Figure 1. Excerpt from the plan of the 3rd potash level of the mine No. 3, with highlighting the studied areas

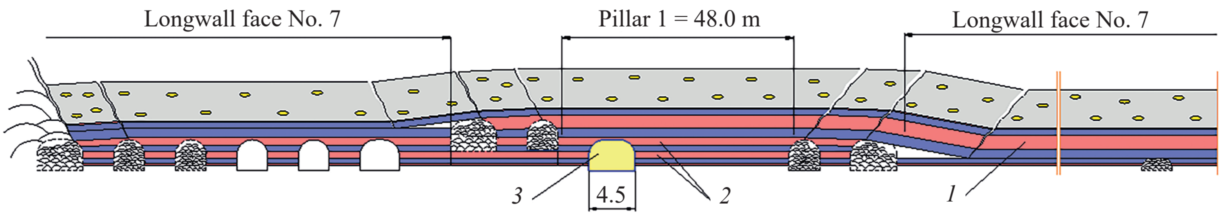

Figure. 2. Cross section of the studied area of the rock massif on the section of the panels No. 22 and 24:
1 – sylvinite layer 4; *2* – sylvinite layers 2 and 3; *3* – service entry

The computer modelling technique took into account changes in the physical and mechanical properties of the rock strata according to the approach described in the paper [7]. At the first stage of the study, the geomechanical state of the rock massif was modelled during the mining out the face No. 7 in the layers 2, 2–3, 3. After mining out this face, physical and mechanical properties of the corresponding section of the rock massif (in the collapse and fracture areas) were changed according to the algorithm proposed in the paper [7]. After that, the geomechanical state of the rock massif was modelled taking into account the mining out the face No. 35 in the layer 4. After this face was mined out, the physical and mechanical properties of the new sections of the rock massif were also changed. After that, according to the described procedure of numerical calculations sequence, modelling aimed at study of geomechanical state of the rock massif undermined by faces the No. 7 and 35 in the vicinity area of the service entry located in the pillar between the faces was executed. In this case, the state of the massif in the vicinity area of the entry contour was studied before and after anchoring of the entry roof.

The geomechanical numerical model was built considering the following generalized layers: the underlying salt layer with a thickness of 400 m, above it a 22 m thick underlying salt layer, followed by a 6 m thick rock salt layer, sylvinite layer 1 (0.33 m), layer 1–2 (0.5 m), sylvinite layer 2 (0.7 m), layer 2–3 (0.6 m), sylvinite layer 3 (0.7 m), layer 3–4 (0.95 m), sylvinite layer 4 (1.2 m), reduced layer including layer 4–5 and sylvinite layer 5 (0.7 m) and the overlying rock salt layer (8.0 m, 22.0 and 679.25 m).

The geometric dimensions of the considered rock massif area were chosen taking into account the absence of influence of the mined out faces on the condition of the distant boundary areas of the massif (650 m from the face positions).

The physical and mechanical properties of rocks and anchor material used as initial data are given in the Table.

The second stage of the research was carried out by modelling the geomechanical state of the newly undermined rock massifs in the vicinity area of the exploratory workings driven in the roadways at the section of the western panel No. 18, which was mined out in 1978–1980 using the room and pillar mining system. The modelling studies were carried out taking into account the mining sequence and the time of the mining operations. This included the fact that the exploratory workings were driven over a considerable period of time (more than 40 years) after the end of the mining operation.

Physical and mechanical properties of materials

Material	Density, kg/m^3	Young's modulus, GPa	Poisson's ratio	Shear modulus, GPa	Compressive strength, MPa	Tensile strength, MPa	Tensile strength, MPa	Adhesion coefficient, MPa
Sediment layer	2043	1.0	0.30	0.38	–	–	–	–
Clay and marl strata	2000	5.0	0.30	1.92	–	–	–	–
Rock salt	2300	1.75	0.28	0.68	30.0	1.0	1.209 625	2.738 612
Sylvinite	2300	1.64	0.29	0.64	26.3	1.0	1.220 858	2.828 427
Underlying salt	2300	2.0	0.35	0.74	35.2	2.0	1.102 798	4.195 235
Caved debris	2300	0.175	0.30	0.068	30.0	1.0	1.209 625	2.738 612
Steel	7852	200.0	0.30	76.90	0	460.0	–	–

When performing numerical experiments for the exploratory working, the positioning of the roof working was considered on the roof of the 2nd sylvinite layer without cutting the 1st sylvinite layer. During the computer modelling, as in the first stage of the research, changes in the physical and mechanical properties of the rock strata were taken into account. First, the geomechanical state of the rock massif was modelled during the mining the concerned area by means of pillar or room and pillar mining systems. After mining, the physical and mechanical properties of the corresponding section of the rock massif (in the collapse and fracture areas) were changed according to the algorithm proposed in the paper [7]. Following this, the route of the exploratory workings was modelled in accordance with the described numerical sequence procedure.

The geomechanical numerical model was built considering the following generalized layers: the upper sediment layer of 108.5 m thick, the clay and marl strata of 303.0 m thick and the underlying rock salt layer with a thickness of 518.5 m. The selection of such effective layers is based on the lithological description of exploration well No. 137. In the exploratory workings at issue, we considered interlaying of sylvinite with rock salt.

The geometric dimensions of the considered rock massif area were chosen taking into account the absence of influence of the mined out faces on the condition of the distant boundary areas of the massif (400 m from the faces and workings' positions).

The general scheme of geomechanical computer model construction for solving problems of rock mechanics and massifs is presented in [12]. The content of stages and algorithms of numerical implementation of all stages of geomechanical computer model construction are described, in particular, in the papers [2, 6, 12].

The model problem was solved in two-dimensional formulation. Calculations were performed as an iterative sequence of solving problems in the quasi-static formulation. The behaviour of the layers was considered in the framework of the theory of linearly deformable quasi-homogeneous and quasi-isotropic media [2].

The boundary conditions at the lower boundary of the underlaying salt layer correspond to the rigid anchorage condition (the influence of mining does not extend to the given depths). The side boundaries are subject to side pressure of $\rho g h$ when the initial stress state is calculated. In subsequent iterations, taking into account the presence of mining works, the boundary condition corresponds to the displacement limitation condition along the X-axis. The model problems were solved by taking into account the gravity forces.

Summary of the results of the numerical experiments. Some of the results of the performed series of numerical experiments are shown in the Figures 3 and 4.

The processing of the results enabled us to formulate important conclusions about the geomechanical state of the repeatedly undermined rock massifs and the stability of the mine workings located in such areas of the rock strata. So, in respect to the situation of mining the rock massif by the faces No. 7 and 35 and location of the working in the pillar between these faces (the first block of the research) it was determined that as a result of the primary mining the face No. 7 and then the face No. 35 generalized shear stress state area is formed in the pillar area between the faces (see Figure 3, *a*).

In generalized shear areas after the primary undermining, particularly in bedded rock massifs, areas of significant interlayer displacement appear. Even after a considerable period of time, the adhesion coefficient in these areas of the massif is significantly different from the original coefficient. Consequently,

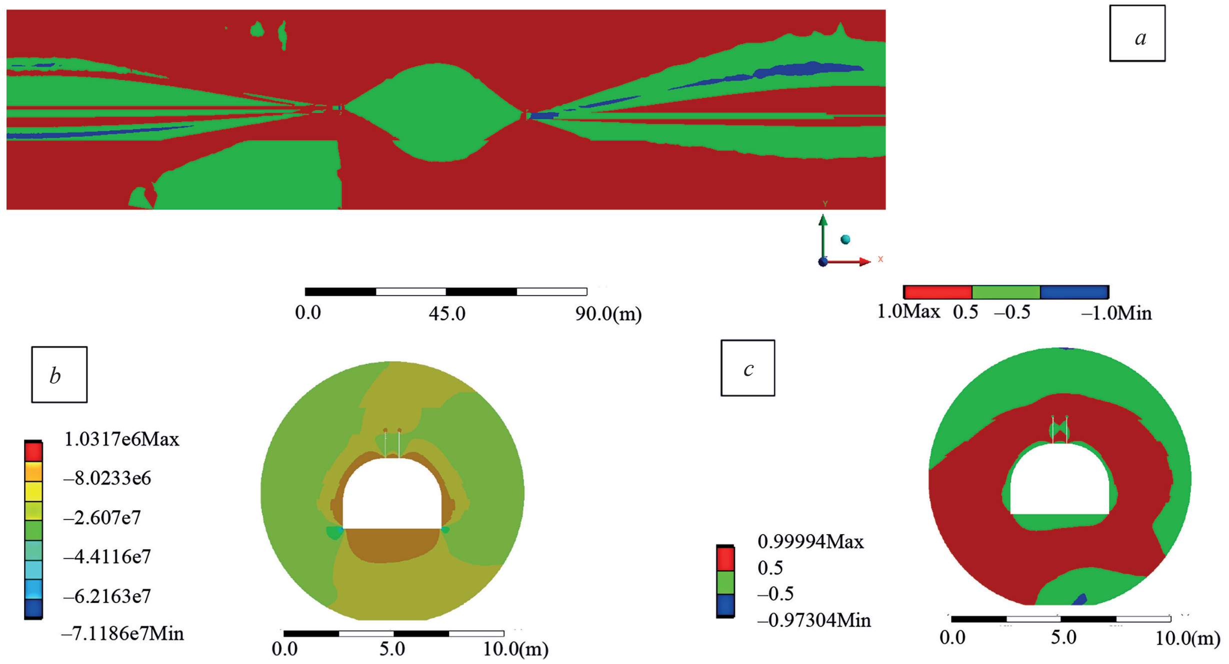

Figure 3. Examples of the formation of stress-strain state zones in the rock massif at the section of the western panels No. 22 and 24: a – distribution of the Nadai–Lode coefficient in the massif in the area between the faces, taking into account the rock collapse after successive driving the faces No. 7 and 35; b – horizontal main stresses in the vicinity area of the service entry; c – distribution of the Nadai–Lode coefficient in the vicinity area of the service entry

it is not advisable to re-locate workings in these areas, as they are most likely to activate shear and failure processes along the slip lines. After driving the service entry, an irregular stress state is formed in the vicinity area of its contour. The main horizontal stresses vary from compressive to tensile stresses (see Figure 3, *b*). In addition, a generalized shear stress state occurs in the vicinity of the working contour (see Figure 3, *c*). In this case, the dimensions of the generalized shear zones in the side boundary area and in the working floor extend deep into the massif at distances of tens of centimetres. All these facts together activate the deformation processes along the latent slip surfaces in the vicinity area of the working contour and initiate significant displacements in the side boundary area of the working.

The picture is different if the working is located in the zone of the mined out faces (see Figure 3, *a*). In this zone, an area of generalized compression is formed after the primary undermining. In such areas the processes of compaction of the caved rock masses take place. Therefore, after a considerable period of time, the state of the rock massifs in these areas can be regarded as "almost natural" without additional structural disturbances. In such areas, the effective mechanical characteristics of the rock massifs are practically restored.

In the case of mining the rock massif in the area of western panel No. 18 (second stage of the research), it was found that, as in the case of room and pillar mining, extensive zones of generalized shear stress are formed in the rock massif as a result of pillar mining (see Figure 4). As in the previous example (the first stage of the research), zones of significant mutual displacement appear in such zones after primary mining. Accordingly, the re-location of workings in such zones is not recommended, as they are most likely to activate the shear and failure processes along the slip lines.

A different picture can be seen in the collapse areas above the mined out face space. In these areas, the caved rocks are compacted over time and the mechanical characteristics of the rock massifs are practically restored. Thus, the location of mine workings in the area of caved compacted rocks is a priority in terms of their stability, which is confirmed by the results of monitoring the deformation pattern of exploratory workings. At the same time, the results of numerical modelling show that there is no ultimate state in terms of reaching critical tensile and compressive stresses along the contour of the workings in question.

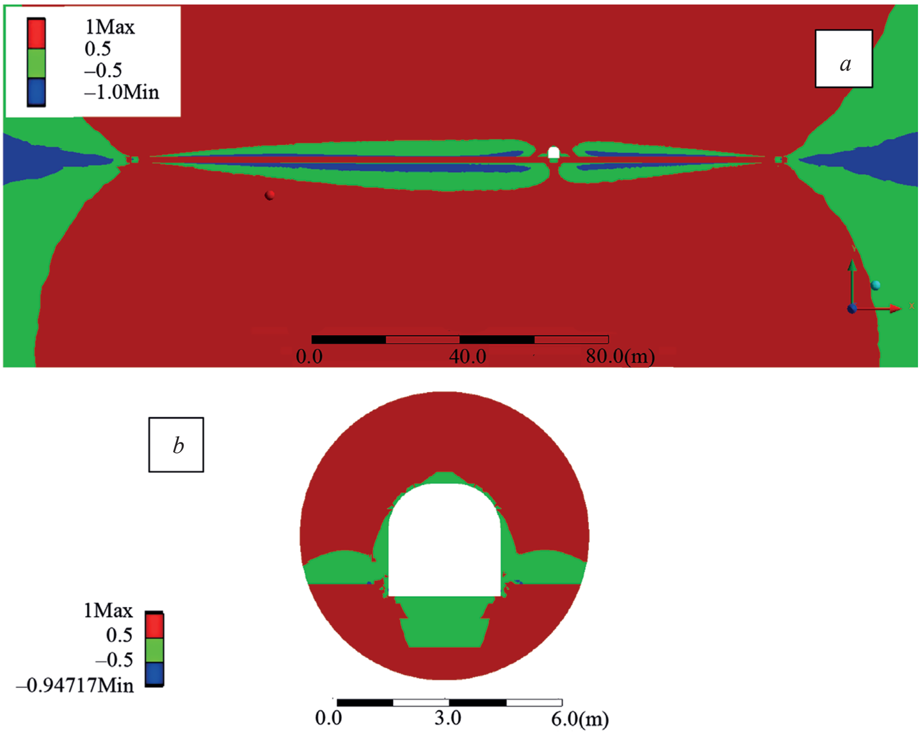

Figure 4. Examples of the formation of stress-strain state zones in the rock massif at the section of the western panel No. 18: *a* – distribution of the Nadai–Lode coefficient in the massif after driving the exploratory working; *b* – distribution of the Nadai–Lode coefficient in the vicinity area of the contour of the exploratory working

Conclusions. Carried out geomechanical modelling of the repeatedly undermined rock massifs of the 3rd potash level of the Starobin deposit taking into account its structural and strength features, as well as the technological schemes of the primary mining. The processing of the results of the series of numerical experiments enabled us to formulate important statements about the geomechanical state of the repeatedly undermined rock massifs and the stability of the mine workings located in such areas of the rock strata.

It is shown that the geomechanical state of the workings located in the repeatedly undermined areas significantly depends on the time passed since the primary mining and on the location of the workings in the massif relative to the location of the primary mining operations. The most dangerous for repeated mining are the areas of generalized shear, since the processes of rock mass movement and failure are most likely to be active in these areas. It is demonstrated that in this case, in the vicinity of the contour of the mined out area, deformation processes are activated by latent slip surfaces and displacements of considerable values are initiated along the mine workings contour. In the areas of generalized compression, the processes of compaction of caved rock take place. That is why after a considerable period of time, the state of the rock massif in these areas can be treated as approximating to the natural state, without additional structural disturbances. In such areas, the effective mechanical characteristics of the rock massifs are practically restored. Accordingly, locating the workings in the area of collapsed, compacted rock is a priority in terms of their stability. The numerical modelling results show that there is no limit state in terms of reaching the critical tensile and compressive stresses along the contour of the considered workings.

The performed researches enable us to develop methodological recommendations for choosing the most optimal location of mine workings in repeatedly undermined rock massifs, previously mined out by pillar or room and pillar mining systems.

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