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Prediction of the Geomechanically Safe Parameters of the Stopes during the Rich Iron Ores Development under the Complex Mining and Geological Conditions

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Abstract
The geomechanical validation of the stopes parameters for the Yakovlevsky rich iron ore deposit conditions was performed. It has been established that in the rich friable ores the stopes walls pass to the limit state. For the mine production capacity improvement and cost reduction of the mined iron ore, it is suggested to change the stopes cross-sectional shape to polygonal profile with the increased geometric parameters. The stress-strain behavior of the rock mass with polygonal profile chambers was studied. The regularities of the limit state zones formation were revealed for the compact, the medium-density and the friable ores in case of the chambers height of 12 and 16 meters. The recommendations for their stability assurance during the mining operations were given.

Keywords: iron ore deposit, workings shape, stress-strain behavior, stability.

INTRODUCTION

The Yakovlevsky iron ore deposit of the Kursk Magnetic Anomaly is characterized by rather complex hydrogeological and engineering-geological conditions. According to the classification of the solid mineral deposits reserves, it is referred to the second complexity group [1].

According to the data obtained during the geological exploration at the Yakovlevsky deposit area, the basement rocks with which the rich iron ores are associated occur under the sedimentation mass sheet at the depth of 470-550 m. The Lower Carboniferous limestone is the direct roof of the ores with thickness varying from 10 m to 50 m. The average trend of the basic deposit structure is north-western – 320°. Generally, the rocks north-eastern dip angle within the slope mine varies from 60° to 70° [2].

The vertical thickness of the ore deposit lies within the wide range and varies from 20 m to 50 m near the footwall, from 100 m to 200 m in the middle section and goes up to 350-400 m near the side wall. The deposits width varies from 200 m to 600 m [3-4].

At the Yakovlevsky deposit, the two genetic types of the rich iron ores can be distinguished: the parent or eluvial (residual) ores, that is, the laterization products of the banded iron formations of different types, and the redeposited (aqueous) ores, that is, the products of the parent ores washing-out and redeposition.

Generally, the parent ores are presented at the deposit by the friable fine-pored varieties of the iron-micaceous and iron-micaceous-martite structure; the present ores content is approximately 59.5% of the total stock. The ores are of the faint bluish tinge; therefore, they were named the “blue ores”. By the physical properties, the ores are friable powdery pored with poor structural bond.

The hydrohematite-martite ores, that is, the “blue ores”, are rather widely spread at the deposit; their content is 25.2% of the total stock. The ores have the layer-by-layer maculose color from dark red to brownish. The ores are usually weak, poorly consolidated with thin-slabby parting.

The iron content depends on the ores mineral composition. The average iron content on the primary mining area is 62%. The iron occurs in the iron-micaceous and martite-iron-micaceous ores, while the iron content in the martite-hydrohematite and goethite ores is always lower.

The moisture content in the natural ores varies from 5.3% in the solid ores to 17.2% in the friable ores; the average moisture content is 9.8%.

The presence of seven confined aquifers was established during the hydrogeological research conduction. The Lower Carboniferous and the crystalline-ore horizons are the basic aquifers which have an impact on the water inflows in the underground workings during the Yakovlevsky mine development. Both horizons have the hydraulic connection [5].

The ground waters breakthrough from the Lower Carboniferous aquifer is the most dangerous factor, which can result in the irreversible effects and failures during the mine development and operation [6-7].

The analysis of the stress-strain properties of the rocks and the ores shows that the properties of the ores of different mineral composition differ markedly. The values of the uniaxial compressive strength of the compact martite and hyprohematite-martite ores vary from 16.7 to 20.1 MPa, the specific coupling values vary from 4.3 to 5.8 MPa, the angles of internal friction vary from 35 to 38°. The uniaxial compressive strength of the friable ores varies within the range of 1.02-2.1 MPa, the specific coupling – 0.4-0.6 MPa, the angles of internal friction – 27°-34°, the ores are characterized by high porosity, which reaches the value of 42% for friable ores.

One of the most effective methods of the deposits development under the aquifers without the overburden draining is in reservation of the safety floor pillar which prevents the waters inflow in the rock workings [8-9]. During the deposits development with the high degree of invasion, the development systems with stowing are used in the majority of cases. The use of the consolidating stowing during the processing procedures of the ore production permits to decrease the losses and dilution of the rock ore, minimize the negative impact of the mining operations on the water-resistant strata, work out the ores stock in protective pillars and protect the earth surface against caving by means of the mining operations safety ensuring [10].

The development system with the layers mining in descending order, continuous ore breaking and solid consolidating stowing was used. Due to the ore low strength, the mechanical ore separation from the rock mass by the boom miners was used. The safety floor pillar formation and the underlying layers work out are performed by the stopes with the width of 4.9 m. The layers height chosen on the base of the boom miner parameters is 4 m [11].

During conduction of the field studies over the stability conditions of the mine workings under the Yakovlevsky mine safety overlap, the large ore cleavages from the walls were found along the whole length of the workings; the cleavages depth in the roof reaches 0.8-1.3 m. The actual contour of the unsupported working is of the trapezoid form with the long base in the roof; its actual dimensions are inconsistent with the design dimensions. The working is unsupported, the stable condition of the ore croppings is not provided. Usually, the workings are driven the next but three with dividing pillars of different width. The workings are stowed by the consolidating mixture; then the second, the third and the fourth stage workings are driven adjacent to the concrete filling.

On the basis of the field studies results, it was established that during the mine workings driving in the friable ores under the safety overlap the rock fragmentation is characterized by the shear surfaces formation in the working walls, the parameters of which depend heavily on the stress-strain properties of the ore. The workings lose stability, the safety operation conditions are not ensured.

METHODOLOGY: Investigation and Calculation of the Stress-Strain Behavior.

The initial stress state of the rock mass, the stress-strain properties of the ore and filling mass, the nature of their contact interaction, the mining operations sequence, etc. should be considered during investigation of the rock mass stress-strain behavior (SSB) in case of the slicing system transition to the polygonal profile chambers. For the present problem solving, the numerical simulation based on the finite elements method (FEM) was used. Numerical simulation was implemented in the Simulia Abaqus software package. Despite the idealization of the actual conditions, the use of FEM permits to bring the calculation model near to the real object and also provides an opportunity to study the object within the wide range of conditions by means of the change of the medium properties and geometrical parameters of the model. The method is based on numerical calculation of the partial differential equations system.

The stope, where the pillar mining was performed in the second and subsequent layers and where the first layer filling served as the artificial roof, was taken as the object of study. The workings driving at the present section is performed in the friable ores and is followed by the intense rock pressure manifestation in the form of the rock inrush formations and the ore caving from the walls along the whole workings length, which creates a threat to the mining operations safety.

The numerical simulation of the workings driving and flushing is performed in the plane deformation statement. The real rock mass was considered as the solid medium and it was changed by the significant finite domain with the width of 1300 m and the height of 200 m. The model dimensions were selected in such a way as to eliminate the boundary conditions influence on the stresses and strains distributions around the workings.

The boundary conditions are as follows: the displacements along the domain lateral edges were prohibited in X-direction, along the bottom edge – in Y-direction, the top edge of the domain remained freely deformable. The lying wall of the safety overlap is located at the depth of 65 m from the model top edge, which corresponds to the rock ore dimensions above the top layer (safety ore pillar).

The natural strain-stress behavior of the rock mass was prescribed by vertical intensities σ_y = 7 MPa, exerted on the top edge of the finite-element model, and the horizontal intensities σ_x = 4 MPa. The vertical and horizontal intensities values were taken in accordance with the previous calculations of the inhomogeneous rock mass stress-strain behavior caused by draining of the primary work out area at the boundary "Carboniferous limestone-ore body" [12].

The Yakovlevsky deposit ores have contained plasticity. The processes of elasto-plastic deformation of the rocks occur around the workings with nonlinear deformations zones formation [12-14].

Discretization of the model calculation domain was implemented in such a manner that the minimum dimension of the finite element was 0.25 meters on the workings contour, and the maximum dimension with distance from the workings line was 30 meters (the model boundaries). Thereby the finite elements mesh refinement was performed in the neighborhood of the workings. The flat six-node finite elements were used as the finite elements type.

The Mohr-Coulomb elasto-plastic model of the rocks deformation was taken as a model for the stress-strain behavior investigation. The quantitative and qualitative assessment of the enclosing rock ore SSB obtained by the present model is in good agreement with the field conditions [3-4].

The elasto-plastic model used for the rocks strength determination is based on the Mohr-Coulomb strength condition (the limit state condition):

$$\tau_s = C + \sigma_N tg\rho, \qquad (1)$$

where τ_s is the maximum shear stress at the shear area; C is the rocks coupling; ρ is the angle of internal friction; σ_N are the normal stresses at the shear area.

The enclosing rock ore is presented by the nonlinearly-deformable isotropic medium with stress-strain properties of the iron-micaceous-martite and hydrohematite-martite ores. The stress-strain properties of the rock mass and the filling material were accepted on the basis of results of the laboratory and the field underground investigations performed by "VIOGEM" OJSC and the Mining University (Table 1) [5].

Table 1. Stress-strain properties of the rock ore and the filling mass.

Material title	Strain modulus E, MPa	Poisson ratio μ	Specific weight ρ, MN/m^3	Coupling C, MPa	Angle of internal friction φ, degrees
Iron-micaceous-martite ore					
weak, friable	1300	0.26	0.034	0.4	28
chloritized, middle-density	1920	0.26	0.035	1.4	36
carbonatized, compact	2230	0.24	0.036	4.3	38
Hydrohematite-martite ore					
chloritized, middle-density	1920	0.25	0.033	1.8	35
carbonatized, compact	2420	0.24	0.035	5.8	38
Filling material					
solid filling	6000	0.26	0.019	2.84	28

The first stage is calculated by means of the geostatic solver, which permits to exclude the so called "historical" displacements. The rock ore with no weaknesses in the form of chambers was considered. It was necessary for creation of the natural stress state field in the rock ore. In this case, due to the mathematical statement peculiarities of the program solver applied at the present stage, any rock ore displacements under the load were prohibited. As a consequence, the stress field was formed in the rock ore which prevented the displacements under the gravitational forces; in other words, the static equilibrium state occurred. The obtained stress field can be considered as the natural stress state field of the rock ore.

RESULTS

Calculation of the stress-strain behavior of the rock ore and the filling mass in case of the slicing system transition to the polygonal profile chambers

With the purpose of the mining operations efficiency improvement during the Yakovlevsky rich iron ores deposit development, it is required to justify the stopes parameters in case of the slicing system transition to the polygonal profile chambers. For the present problem solving, the diagrams of transition to the chambers with the increased geometric parameters were developed and the stress-strain behavior of the rock ore and the filling mass was calculated.

The discovered effect of the workings stability improvement in case of the workings trapezoidal profile as compared to the rectangular profile was used for the pillar-and-breast system of the friable rich ores. The paper authors have suggested the steep deposits development technique with consideration of the peculiarities of the ores stress-strain and structural properties [15].

The slicing system diagram of the friable rich ores with the polygonal chambers and the sequence of their mining are presented in Figure 1.

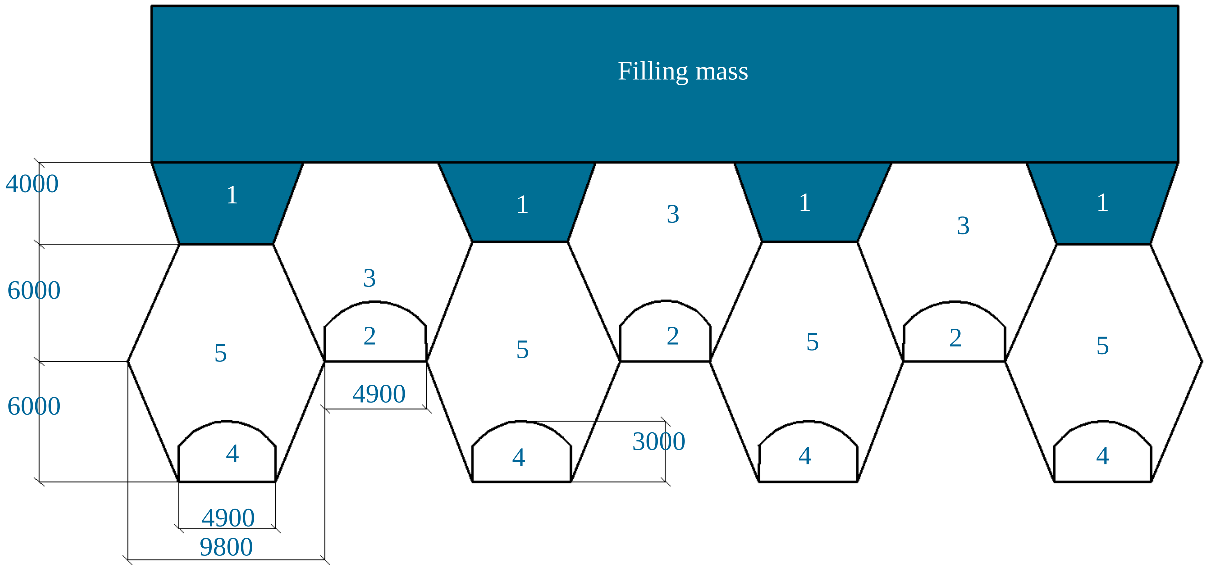


Figure 1. Diagram of the slicing system with stowing and polygonal chambers formation with the layers mining in descending order and the staggered ordering of the adjacent chambers, the chambers height is 12 m and 16 m. 1-5 mining operation stages are presented.

The chambers dimensions selection is based on the chambers stability assurance condition. The chambers stability calculation is presented below. At first, the chambers 1 are mined and filled. Then the cross drifting 2 is performed, and on the basis of the cross drifting the chambers 3 mining and filling is performed. After the strength development in the chambers 3, the cross drifting is performed on the basis of which the chambers 5 mining and filling is performed. The ore breaking out in the chambers 3 and 5 will be performed with the use of wells drilled from the crosscuts 2 and 4 and with the use of explosive treatment. The chambers dimensions are selected with consideration of the mined ores strength.

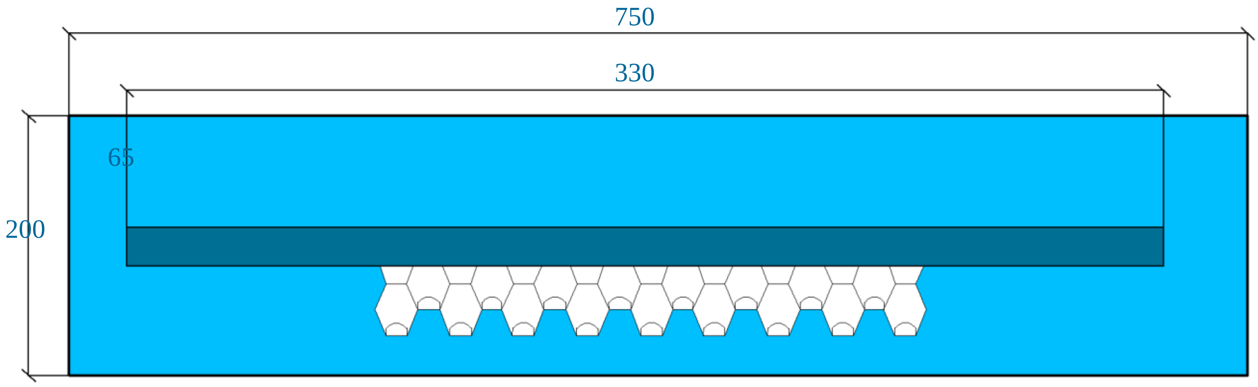


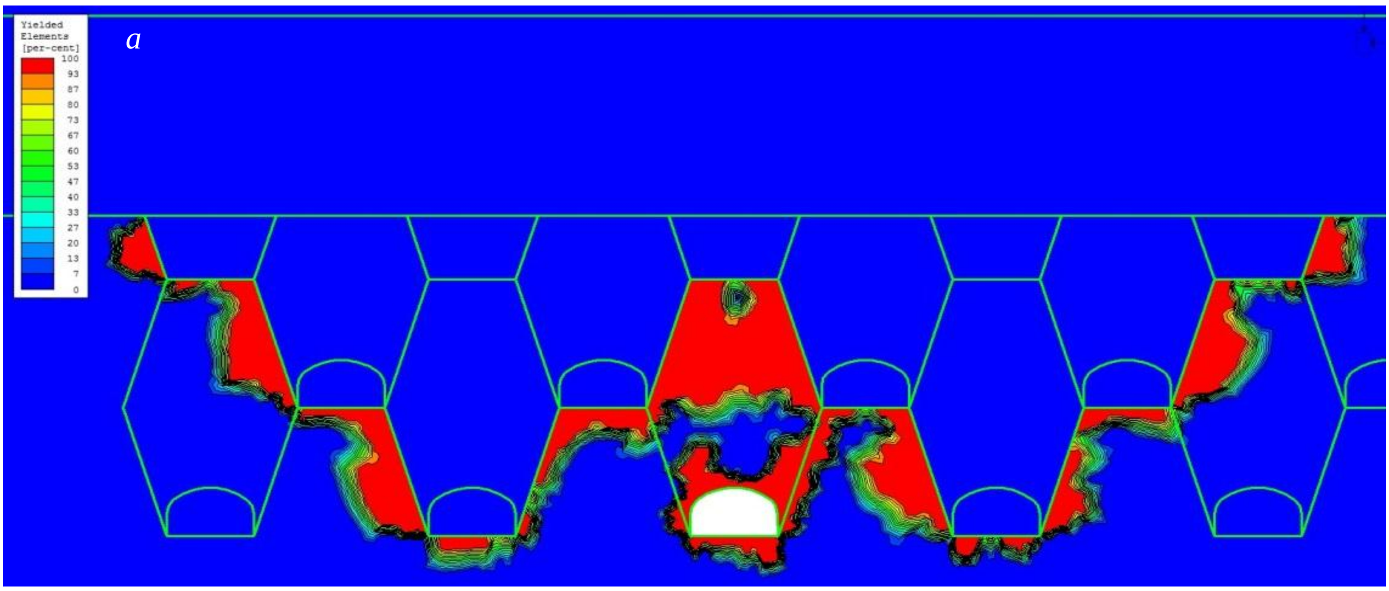
Figure 2. Principle diagram used in the finite-element model.

The principal diagram of the SSB calculation of the rock ore enclosing the workings is presented in Figure 2. The simulated section of the rock ore is fixed against the displacements along the model edges in the directions perpendicular to the fixed edges. Before the workings and chambers driving and flushing, there is a quasistatic equivalent stresses field inside the rock ore.

The numerical simulation results of the rock ore stress-strain behavior

The numerical simulations results of the rock ore stress-strain behavior were obtained for different ore types (Table 1) in case of the chambers height of 12 m and 16 m. The configurations of the rock ore limit state zones around the chambers at different mining operations stages are presented in Figures 3-6.

The installation of the glass-reinforced plastic roof bolting with the length of 2.2 m, the elastic modulus of the anchors material of 40 GPa and the Poisson ratio of 0.26 was calculated with the purpose of stability improvement of the development workings in the friable iron-micaceous-martite ores. The calculations results are presented in Figure 7.



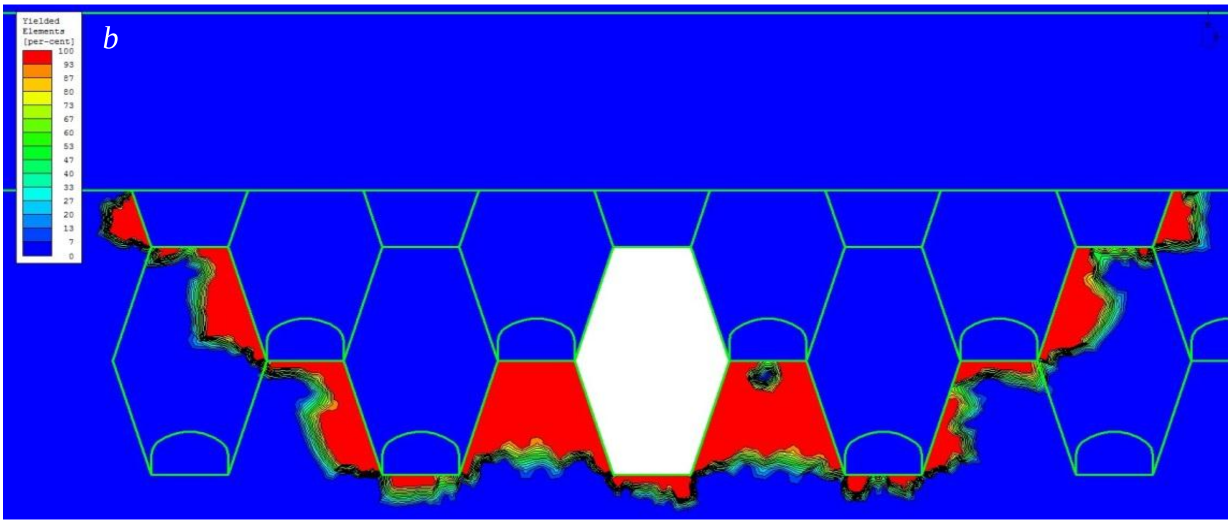


Figure 3. The distribution diagram of the limit state zones formation. The rock ore is presented by the iron-micaceous-martite friable ore. The chambers height is 16 m (*a*-filled chambers; *b*-filled workings).

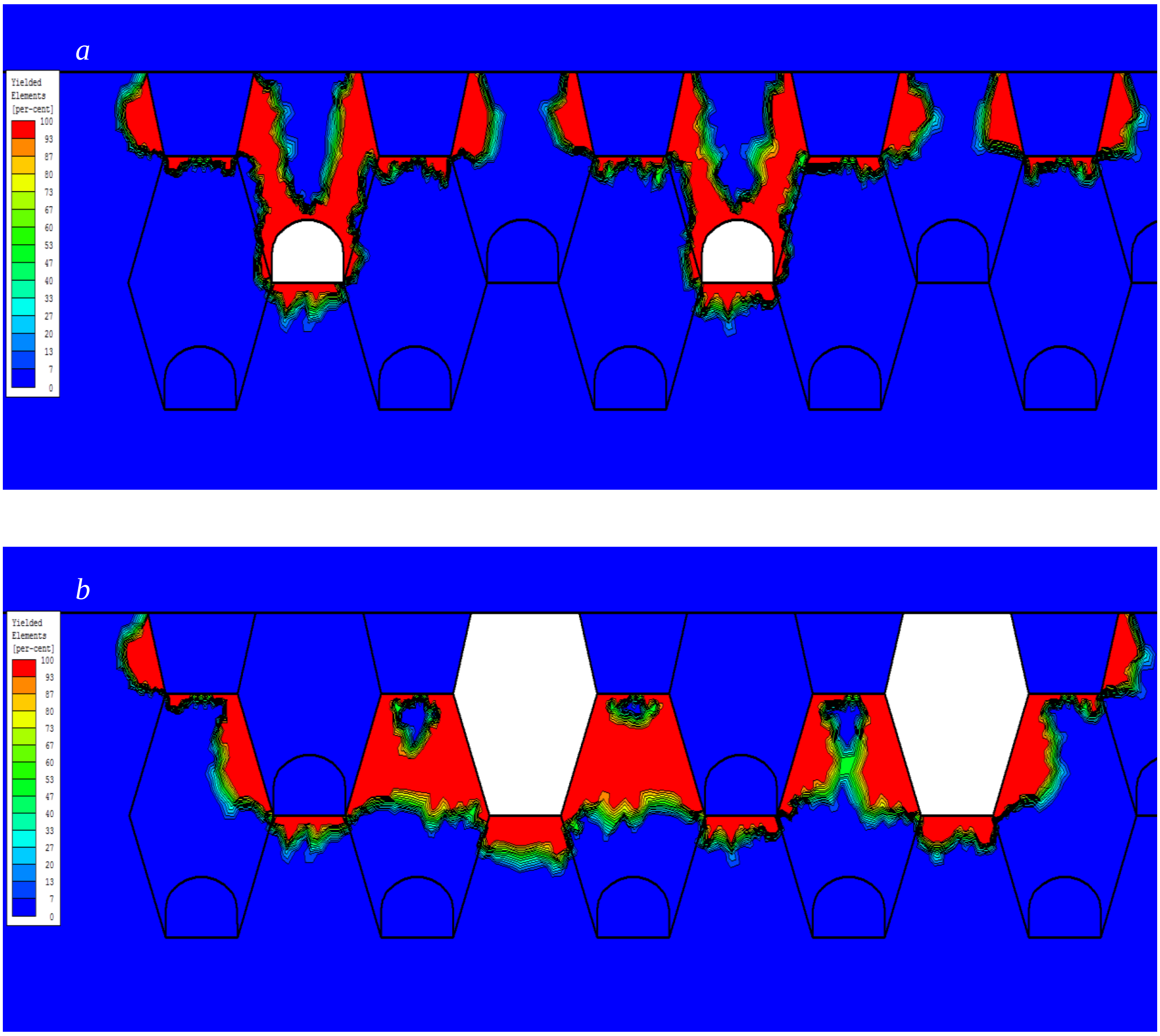


Figure 4. The limit state zones formation. The rock ore is presented by the **iron-micaceous-martite friable ore**. The chambers height is 12 m (*a*-filled chambers; *b*-filled workings).

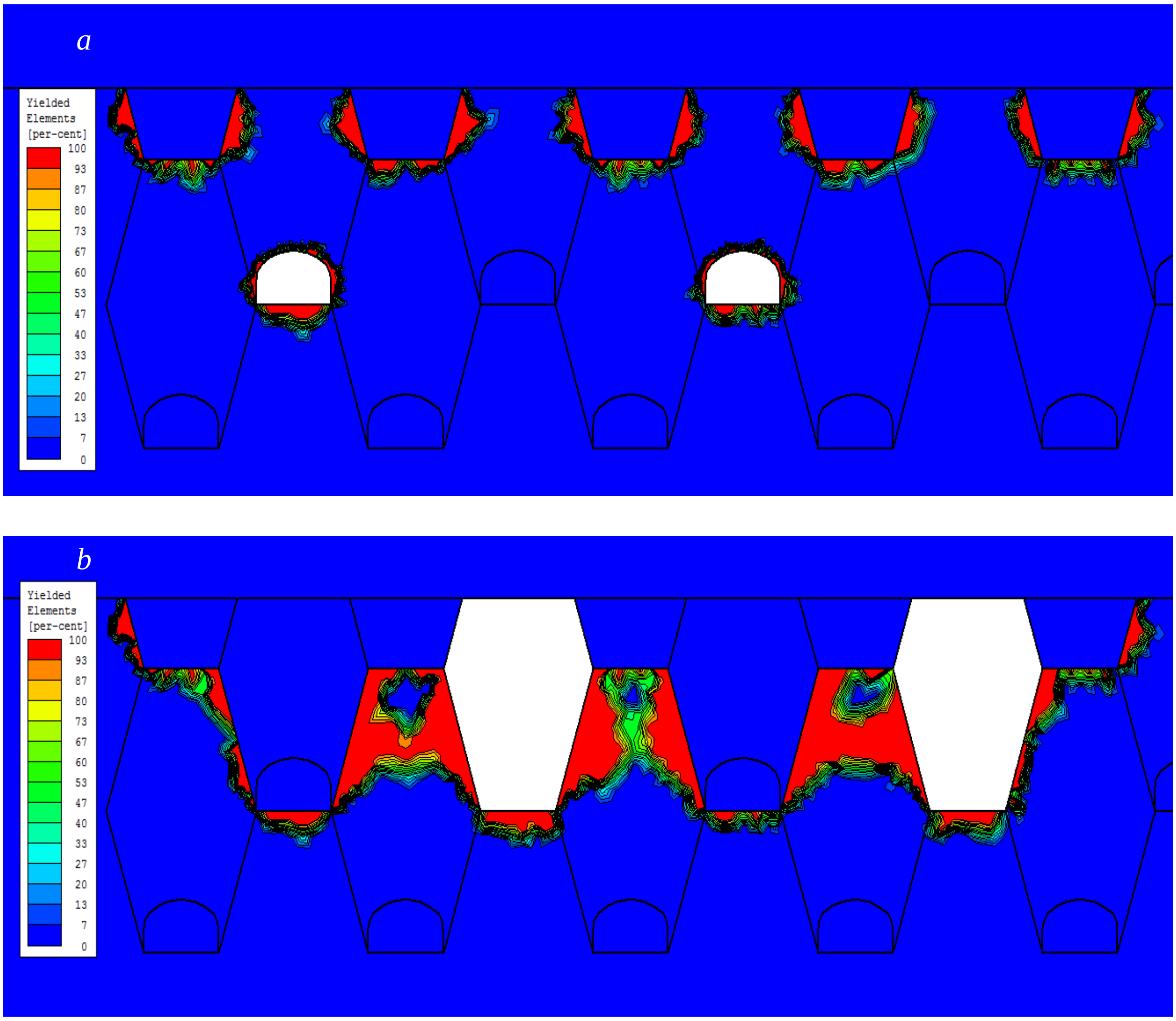
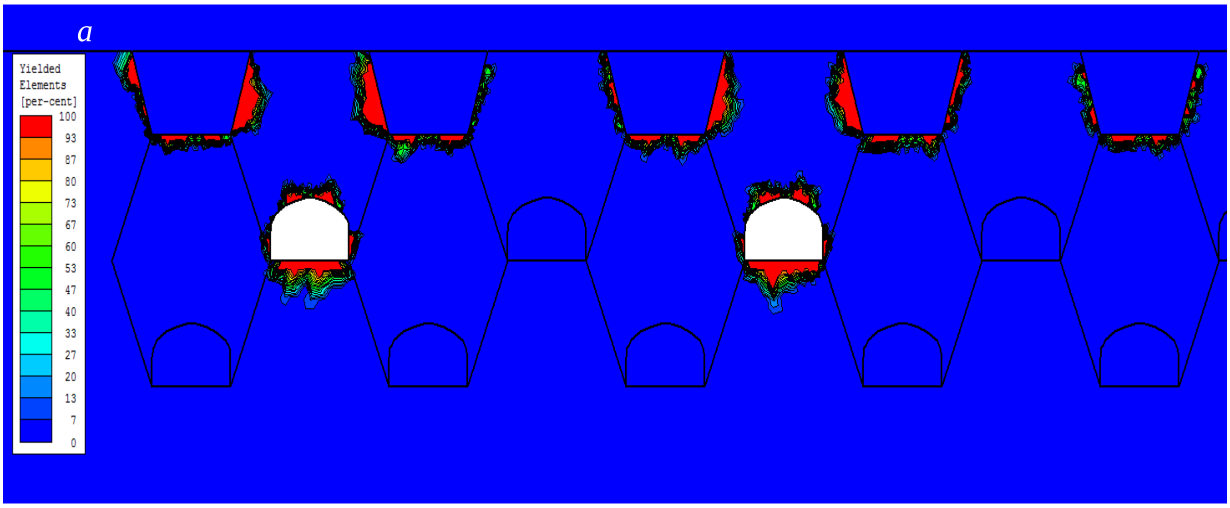


Figure 5. The limit state zones formation. The rock ore is presented by the **middle-density hydrohematite-martite ore**. The chambers height is 16 m (*a*-filled chambers; *b*-filled workings).



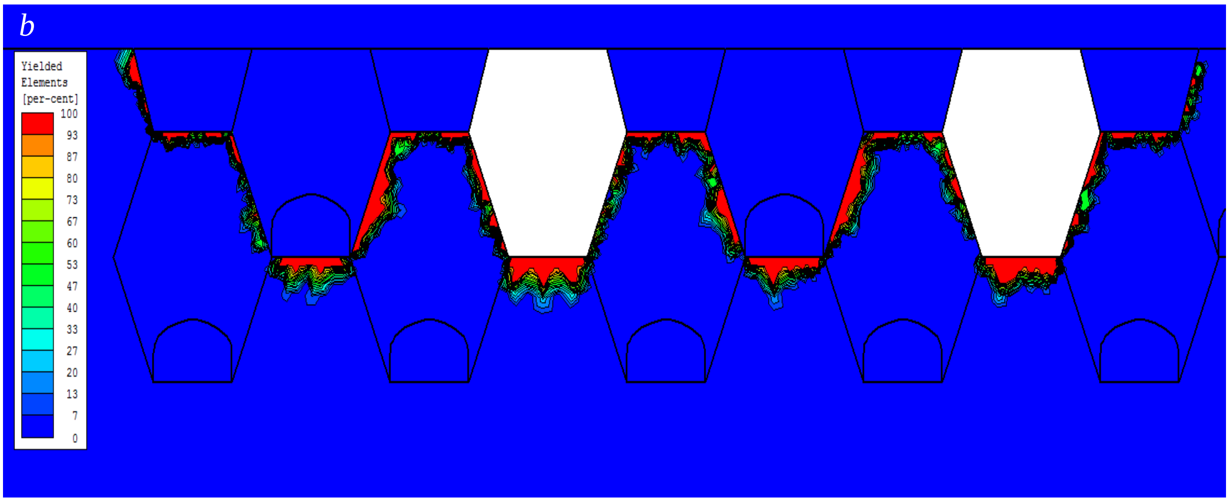
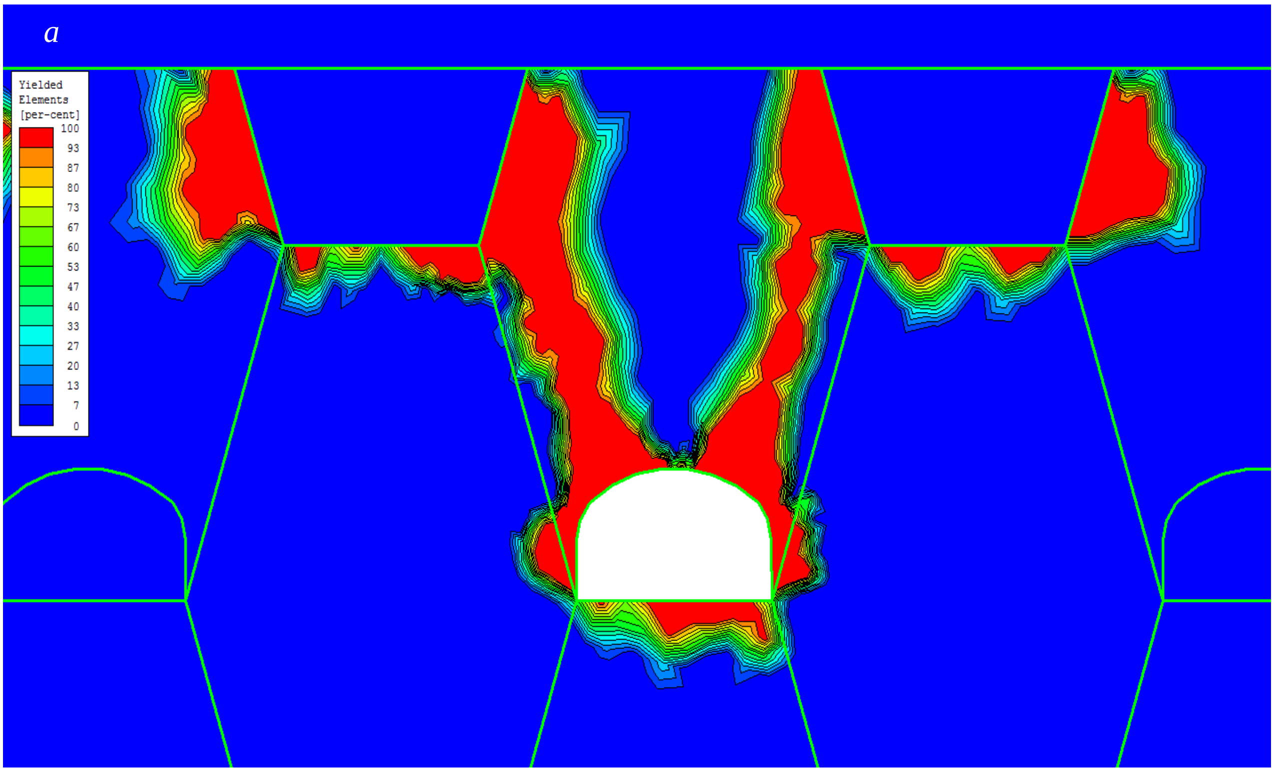


Figure 6. The limit state zones formation. The rock ore is presented by the **middle-density hydrohematite-martite ore**. The chambers height is 12 m (*a*-filled chambers; *b*-filled workings).



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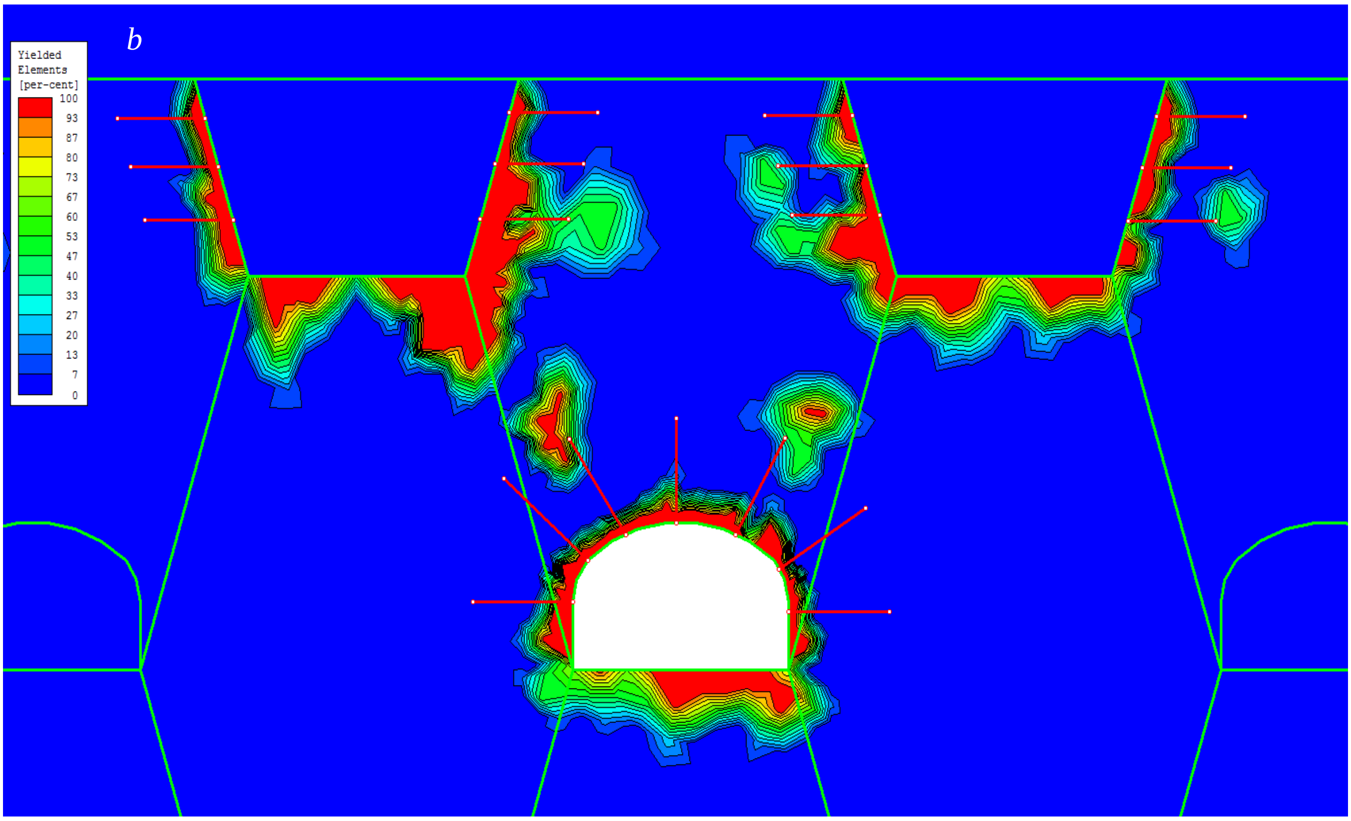

Figure 7. The limit state zones formation in the working walls (*a*-unsupported; *b*-supported by the glass-reinforced plastic roof bolting)

DISCUSSION

During the first stage trapezoidal profile workings driving under the filling mass, the most intensive process of the limit state zones formation is observed in the friable iron-micaceous ores. The present zones dimensions and configuration depend on the workings driving sequence and the ore type. The most intensive process of the limit state zones formation occurs in the friable iron-micaceous-martite ores.

During the stopes mining with the height of 16 m and 12 m, the following features were identified:

- the intensive growth and the subsequent closing of the limit state zones as well as the loss in the working stability in the form of the rock inrush from the roof to the height of the mining stope are observed;
- the local limit state zones with the maximum linear dimensions of 1.5 m and 0.2-0.3 m respectively occur in the middle-density iron-micaceous-martite ores in the workings roof;
- the local limit state zones with the maximum linear dimensions of 0.35 m and 0.2 m respectively occur in the compact iron-micaceous-martite ores in the workings roof;
- the local limit state zones with the maximum linear dimensions of 0.7-0.5 m and 0.3-0.2 m respectively occur in the middle-density hydrohematite-martite ores in the workings roof;
- the local limit state zones with the maximum linear dimensions of 0.35 m and 0.2 m respectively occur in the compact hydrohematite-martite ores in the workings roof.

The development workings in the compact iron-micaceous-martite and hydrohematite-martite ores maintain their stability, but during the workings driving in the friable and the middle-density ores it is required to work out the measures to the development workings and the dividing pillars stability assurance.

With the purpose of stability assurance, it was suggested to install the strengthening glass-reinforced plastic roof bolting which improves the bearing capacity of the near-contour rock mass.

CONCLUSION

The calculation results of the rock ore stress-strain behavior during the polygonal workings driving and stowing are presented. At the next stage, it is suggested to consider the system design and organization of the technological processes during the mining operations, which will permit to improve the technical and economic performance of the stope with the mining operations safety preservation by means of the stopes dimensions increase.

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