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Predicting the Stress-Strain State of a Massif at The Stage of Creating A Protective Cover in the Conditions of Developing Iron Ore Deposits Under Water-Bearing Strata

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Abstract*: *The methods of developing iron ore mines under water-bearing strata without draining the covering stratum are analyzed. To exclude water breakouts into the mine openings during development, a protective cover is made. The stress-strain state of the ore massif at the stages of creating the protective cover and development of the first tier has been studied. The stress-strain state for two variants of creating and excavating the first tier has been studied. In the first variant, a protective cover is first created, and then the first tier is developed. In the second variant, the cover is created, and the tier is developed simultaneously. The regularities have been found in the distribution of vertical stress coefficients in the ore massif and of the limit state zones around the excavations in the first tier.

Index Terms*: *an iron ore deposit, stress-strain state, stability, interaction of workings.

I. INTRODUCTION

Currently, in Russia and other countries, large water-free ore deposits have been almost worked out. Further development of the mineral resource base in many regions is related to the necessity of developing deep and watered deposits characterized by very complicated hydrogeological conditions.

One of the efficient ways of developing deposits under the water-bearing horizons without draining the covering strata is leaving a protection cover that prevents water breakthrough into the mine [1, 2]. In developing deposits with a high degree of water content, systems of development with flushing of the worked-out space are used in most cases. The use of consolidating filling during the ore extraction provides an opportunity to reduce losses and dilution of the ore mass, to reduce the negative effect of mining operations on the water-resistant tier, and to prevent the collapse of the earth's surface in ensuring the safety of mining operations.

Let us analyze the ore deposits developed under a flooded tier in complex geological conditions.

The mine n.a. Gubkin is developing the Korobkovskoe deposit at the Kursk Magnetic Anomaly. Banded iron formations are covered by a thick tier of the moist sandy-clayey rocks that tend to transition to quicksand condition. Mining the ore using the staged room and pillar ore excavation system is performed within a single excavation level 60 m high under a protection cover 70 – 100 m thick that rests on a system of interchamber pillars. The loss of ore in them reaches 57 – 60 %, which, along with the significant reserve of strength in the "cover – chambers – pillars" structure, also determines a significant loss of ore reserves in the subsoil. The water inflow to the mine workings reaches 300 m3/h [3].

The Zaporozhye mine is developing the Yuzhno-Belozerskoye deposit of rich iron ores with the content of iron (Fe) up to 62 %. The reservoir thickness varies from 80 m in the North branch to 230 m in the South branch. The dip is steep, its angle is 65÷70° to the East. The complicating factors in the development of the deposit are the depth of the mining operations up to 600 m, the presence of seven water-bearing horizons in the covering massif of sand-clay sediments characterized by high head of up to 200 m. The complexity of the hydrogeological conditions has determined the use of the staged room and pillar ore excavation system of development with sublevel ore stopping, followed by filling of the worked-out space with consolidating mixtures. Ore is extracted under the protection of an ore cover 60 m thick. The height of the tier is 100 m, the width of the chamber is 30 m. The Yakovlevskoe iron ore deposit is unique in terms of the stock and the high content of iron in the ore (over 65 %), as well as the complexity of geological and hydrogeological conditions. The Yakovlevskoe deposit is characterized by a high degree of flooding. The groundwater in the deposit is significant in the formations of the sedimentary cover, within which there are seven water-bearing horizons. The total thickness of the flooded area exceeds 700 m. All water-bearing horizons have high heads. Directly above the ore body, the high-pressure Lower Carboniferous water-bearing horizon is placed with the heads of 420 – 440 m, which is confined to limestones, in the lower part of the cross-section of which irregular clay tiers are observed.The Lower Carboniferous water-bearing horizon that lies above the ore body is associated with fractured and karst limestones, and less frequently — with sands and sandstones. The depth of the bottom of the water-bearing horizon is 500 – 550 m, its thickness is 20 – 80 m, the operating head in 2010 exceeded 350 m.

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The filtering coefficients vary from 0.01 m/day to 12 m/day, depending on the fracturing rate and the cavernous porosity of the rocks. In the bottom part of the coal deposit cross-section, one can trace a band of limestones 6.0 – 22.5 m thick, which rests on rich iron ores (RIO) and forms a two-tier impermeable column.

The ore-crystal water-bearing horizon is confined to the rocks of the fractured zone of the weathering crust of the Precambrian crystalline formations and sediments in the zones of tectonic disturbances, and is represented by iron ores, banded iron formations, and schists. The depth of the water-bearing horizon is 450 – 690 m. The water-bearing horizon is subartesian, its head above the cover in the undisturbed state is 450 – 560 m. Within the limits of the minefield, the water-bearing horizon is drained. The conditions of groundwater filtering in this complex and heterogeneous mass are determined by the porosity and by the degree of rocks fracturing. Rich iron ores are characterized by the coefficient of infiltration from 0.04 m/day to 0.28 m/day. The coefficient of slates' and quartzites' infiltration does not exceed 0.01 m/day.

The vertical thickness of the ore deposit varies in a wide range from 20 to 50 m near the bed-side, in the middle part — up to 100 – 200 m; close to the hanging wall, it increases to 350 – 400 m. The width of the deposit ranges from 200 to 600 m [4, 5]. The ores in place are represented by a thick tier of intercalating various ores with tiers of micaceous iron martite thin-wall micaceous quartzites and gangue quartz with the thickness from a fraction of a meter to several meters. The ore-bearing strata are sloping, almost steep, the length of the ore body along the openings is 240 – 280 m, or more [6]. In the deposit, the ledge ores are mainly represented by friable thin porous varieties of iron-glist and iron-glist-martite composition, which amount to 59.5 % of total reserves. The ores have a characteristic bluish tinge, and are called "the blue"; they are physically friable, powdery, and porous, with mildly expressed structural correlation.

The martite-hydro-hematite ores - the "Blue Paints" – are quite common at the deposit, and make up to 25.2 % of the total reserves. Their coloring is layerwise-spotted from dark red to gray-brown. The ores are mostly not strong, loosely compacted, with thin-plate joining.

The content of iron depends on the mineral composition of the ores. At the site of immediate mine development, the average iron content is 62 %, which is observed in iron-glist and martite-iron-glist ores, while in the martite-hydro-hematite ores and goethite ores, the iron content is always lower.

Breakthroughs of groundwater from the Lower Carboniferous water-bearing horizon are the most dangerous factors that can result in irreversible consequences and accidents during mine construction and operation.

Analysis of the physicomechanical properties of the rocks and ores shows that properties of the ores with various mineralogical compositions are significantly different. Dense martite and hydro-hematite-martite ores have the strength limits under uniaxial compression on average from 16.7 to 20.1 MPa, specific cohesion from 4.3 to 5.8 MPa, and internal friction angles — from 35 to 38· . The ultimate strength under uniaxial compression of loose ores varies from 1.02 to 2.1 MPa, specific adhesion — from 0.4 to 0.6 MPa, the internal friction angles — from 27· to 34· · the ores are characterized by high porosity that reaches 42 % in friable ores [7, 8, 9].

The Yakovlevskoye deposit of rich iron ores is developed under the protection of a cover 65 m thick, and an artificial cover represented by a system of parallel horizontal workings filled with a concrete-based hardening compound [10, 11].

The system of development with descending order of tier mining, ore crushing with a combined machine and cast consolidating filling is one of the most versatile in the harsh conditions of mining. The composition and properties of the consolidating filling will be determined by the results of studies [12, 13]. The low strength characteristics of the ore have determined the choice of mechanical method of ore separation from the rocks with combined machines using a beam actuating device. The protective cover is formed, and the underlying tiers are developed in passes 4.9 m wide, the height of tiers is assumed to be 4 m, and is chosen based on the parameters of the combined machine [14].

II. THE METHODS OF STUDYING AND THE CALCULATION OF THE STRESS-STRAIN STATE OF THE ORE AND BACKFILL MASSIFS DURING MINING OPERATIONS IN THE TIERS BASED ON THE CONDITION OF THE PROTECTIVE COVER

A. Determination of the modeling task

Studying the stress-strain state of the massif around the mine workings when building the protective cover and developing the underlying tiers is a challenging geomechanical problem, the solution of which should consider the initial stress-strain state of the ore massif, the physical-mechanical properties of ore and the backfill rocks, the nature of their contact interaction, and the mining procedure [15, 16]. For solving this task, numerical modeling was used with the finite element method (FEM) implemented in the Simulia Abaqus software package [17, 18, 19]. Despite some idealization of the field conditions, the use of FEM allows approximating the calculated scheme to the real facility, and also provides an opportunity to examine the facility in a wide range of conditions by changing the properties of the environment and the geometrical parameters of the model. Unit 5 was chosen to be the object of study. In unit 5, a number of mine workings should be made followed by flushing for completing the construction of the protective cover in this unit.

At this site, mines are developed in friable ores and are characterized by intense manifestations of the rock pressure in the form of cavings and ore collapsings from the walls and the roof along the entire length of the workings, which threatens the safety of mining operations.

Modeling is intended for studying the stress-strain state of the ore massif at various stages of development, and for arranging excavations during the construction of the protective cover and development of the first tier.

Numerical modeling of the excavations' arrangement and development was performed for the plane-strain deformation. The real massif was considered to be a dense medium, and was replaced by a considerable bounded domain 1,300 m wide and 200 m high (Figure 1) [7]. The dimensions of the model were chosen to exclude the effect of the boundary conditions on the distribution of stresses and deformations around the mine workings. The soil of the protective cover excavations was located at the depth of 65 m from the top edge of the model, which corresponded to the thickness of the ore column above the upper tier (the residual ore pillar).

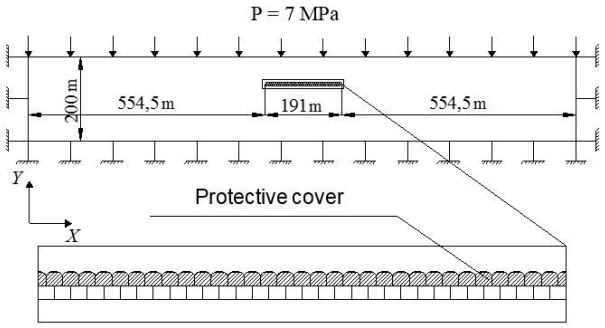

Fig. 1. Layout diagram inherent in the bounded elemental model

The method of specifying the boundary conditions had been chosen, which prohibited in the model the displacement along the side borders of the domain in the direction of axis *X*, along the lower border - in the direction of axis *Y*, the top border of the model remained freely deformable.

The natural stress-strain state of the massif was determined by vertical strain of 7 MPa applied to the top border of the finite element model. The value of the vertical stresses is adopted in conformity with the earlier calculations of the stress-strain state of an inhomogeneous ore massif as a result of draining the immediate working area on the border between the carbon limestone and the ore body.

Discretization of the calculated domain of the model was implemented so that the minimum geometric dimension of the finite element was 0.3 meter on the workings' outline, and the maximum one with increasing the distance was 5 m. This was used for thickening the finite element mesh in the vicinity of the ongoing excavations. Flat four-node finite first-order elements were chosen as the used type of finite elements. The total number of elements was 72,324.

The ores of the Yakovlevskoye deposit have limited plasticity. The processes of elastic-plastic rocks' deformation with the formation of limit state zones are formed around the workings. The model of the massif used for the characterizing the rock strength based on the Coulomb's strength condition is the following:

$$\tau_s = C + \sigma_p tg\rho,$$

where τ_s is the maximum shearing stress at the shift site; C is the rocks' adhesion; ρ is the angle of internal friction; and σ_p is the normal strain at the shift site.

To consider the effect of fractures on rocks' and ores' strength and adhesion, numerical methods of determining the coefficient of structural weakening were used [20, 21].

The containing ore massif is represented by the elastic-plastic isotropic medium with the physicomechanical characteristics of iron-glist-martite ore. Physicomechanical characteristics of the ore massif and the flushing material were adopted according to the results of the laboratory and field mining studies performed by the VIOGEM and the Mining University (Table 1).

Table 1. Physicomechanical properties of the ore and flushing rocks

Material name	The module of deformation E, MPa	The coefficient of Poisson μ	Specific gravity ρ MN/m^3	Adhesion C, MPa	The angle of internal friction φ, deg
Loose iron-glist-martite ore	1,300	0.26	0.034	0.4	28
Dense iron-glist-martite ore	2,230	0.24	0.036	4.3	38
Flushing material	6,000	0.26	0.019	2.84	28

The problem is solved in three stages:

- the first stage is obtaining the natural field of the stress-strain state of the massif;
- the second stage is excavation and flushing the workings in the protective cover; and
- the third stage is excavation and flushing the workings in the first tier under the protective cover.

In the numerical solution of the problem, two variants of forming the protective cover are considered. In the first variant, with the aim of preserving the protective mass above the water-bearing complex, the procedure of mining operations was adopted with leaving a separating pillar between the excavations of the first stage of the separating pillar that has the width of two excavation passes.

Numerical modeling of the arrangement of the protective cover excavations was performed with the underfilling of 0.4 m. The value of underfilling may be reduced by grouting [22, 23, 24].

In the developed numerical model, the authors considered the following sequence of mining operations with the formation of the protective cover:

- performing the excavations of the first stage at the distance of two excavation spans; flushing the excavations of the first stage; performing the excavations of the second stage adjacent to the flushed excavations of the first stage; flushing of the excavations of the second stage; performing the excavations of the third phase next to the flushed excavations; and flushing of the excavations of the third

stage.

Performing and flushing of the excavations of the first stage under the protective cover in the numerical model were performed in the same way.
Figure 2 shows a fragment of the finite element mesh and the order of the excavations.

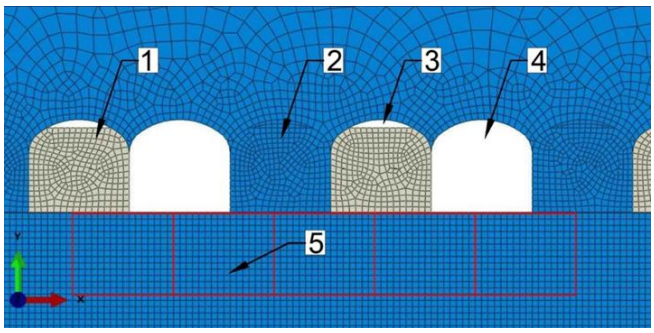

Fig. 2. A fragment of the mesh of the finite element model (step 3 of the calculation)

1 – the excavation of the first stage filled with concrete; 2 – the excavation of the third stage;
3 – underfilling of 0.4 m; 4 – the excavation of the second stage, passed next to the first one; 5 – the excavation under the protective cover

In the second variant, the sequence of excavation and flushing considered the actual state of mining works in the formation of the protective cover at the Yakovlevskoye ore deposit (Figure 3) - the ore pillars in a protective cover were developed after completing the mining operations in the first tier (Figure 3).

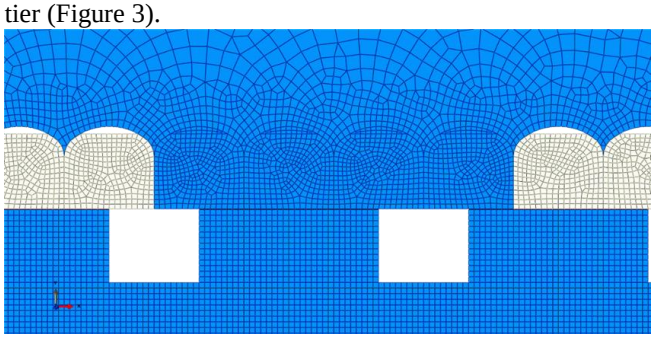

Fig. 3. A fragment of the mesh of the finite element model: 1 – the flushed excavation of the protective cover; 2 – ore pillar (4 excavation spans);
3 – the excavation of the first tier

III. THE RESULTS AND ANALYSIS OF THE RESULTS OF NUMERICAL MODELING OF THE STRESS-STRAIN STATE OF THE MASSIF IN FORMING THE PROTECTIVE COVER AND FLUSHING OF THE FIRST TIER

The regularities of forming the areas of the limit state around the excavation for the first variant of creating a protective cover and flushing of the first tier are shown in Figures 4 and 5 - curves of limit state areas' distribution after excavation of the workings of the first stage of the first tier under the formed protective cover (all excavations of the protective cover have been completed and flushed).
The limit state areas around the excavations were determined using the methods of solving elastic-plastic problems [25, 26]. The limit state areas around workings had been calculated, the analysis of which showed their rapid growth in the walls of the excavations. When the first stage workings appear in the tier, they have the shape of a sliding wedge. Subsequent completion of adjacent workings and reduction of the width of the dividing ore pillar result in closure of the limit state zones, from which one can draw a conclusion about the loss of the bearing capacity of the ore pillar. For assessing the stability of mine workings, the results of research [27] were used.
Figure 4 shows the regularities of distribution of the coefficient of vertical stress concentration in an ore massif at various stages of protective cover and first tier excavation (at the distance of 2.5 m from the roof of the workings in the protective cover, in the first variant of excavation), the analysis of which shows that the highest concentrations are observed at the junctions between the workings of the first (I) and second (II) stages. The authors have studied the regularities in the changes of the stress-strain state in the second variant of creating the protective cover, when part of the workings of the protective cover are not excavated, and the mining operations in the first tier of ore are performed under the entire pillar with width of four working spans. Analysis of the calculation of the size of limit state areas in a loose ore massif after the excavations shows that their sides show clearly pronounced areas of the limit state in the form of sliding wedges. In the ore massif protruding into the project cross-section of the protective cover working, plastic deformations are confined to the contact areas of the ore-bearing massif. The existence of these zones and their large size indicate high probability of rock pressure manifestations in the form of fall-outs and ore slides inside mine workings. The highest concentration was observed in the ore massif adjacent to the sides of the excavations in the protective cover. The intensity of collapse depends on the span of the ore pillar between the flushed workings. With pillar width equal to one width of the working, the area of plastic deformation includes almost the entire designed cross-section of the working. With increasing the width of the ore pillar, the size of plastic deformation areas reduces.
For qualitative assessment of the considered variants, let us present vertical displacements in the relative form (Figure 5). For basic displacement values are the displacements obtained in the first variant; in Figure 5, they are individual. The displacements obtained in the second variant are shown in red. As one can see, in building workings according to the second variant, the values of displacements in individual sites are significantly lower, the difference reaches 15 – 20 %. The displacements do not increase significantly, only about 5 – 7 %. Figures 6 and 7 show the curves of changing the coefficient of vertical strain concentration in various variants of the excavations in the protective cover. The concentration factor was determined as the ratio of the natural vertical strains before mining to the

strains caused by excavation.

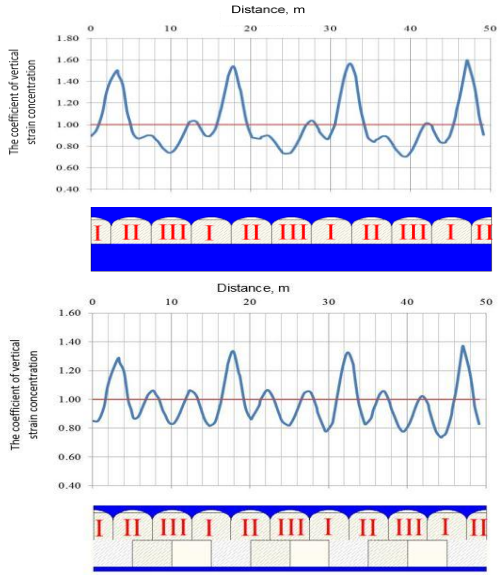

Fig. 4. Patterns of vertical strain concentration factor distribution in the ore massif at various stages of the excavations in the protective cover and the first tier (at the distance of 2.5 m from the roof of the workings in the protective cover, in the first variant of mining)

Analysis of the vertical strain concentration distribution (Figures 6, 7) shows that their distribution is determined by the layout and the order of the workings flushed with concrete. Hence follows the possibility of control with the use of the technology of strain concentration in the cover and the first tier.

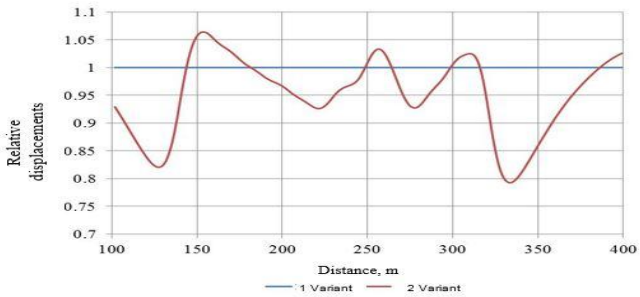

Fig. 5. Relative vertical displacements of the ore cover (at the distance of 9 m from the workings in the protective cover)

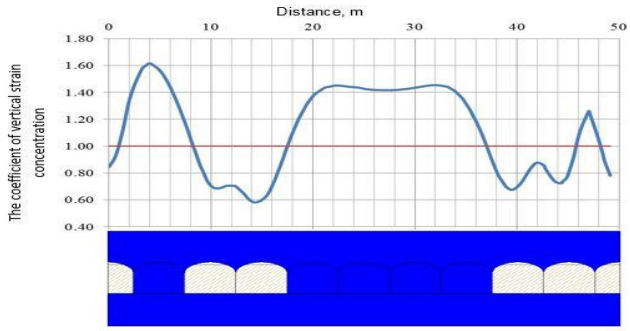

Fig. 6. Regularities of changing the coefficient of vertical strain concentration in the ore massif (at the distance of 2.5 m from the workings in the protective cover, variant 2)

IV. DISCUSSION

For the first variant of creating a protective cover and for its interaction with the workings in the first tier during the excavation of the ore body, it has been determined that

- during the first stage, limit state areas are formed in the walls in the first tier in the form of sliding wedges. During the subsequent excavation in the second stage, closure of the limit state areas is observed, which results in a further loss of the pillar bearing capacity;
- the coefficient of vertical strain concentration in the backfill massif features a periodic nature of changes, reaching the values of 1.5 – 1.6 in the cover at the junction of the worked-out excavations in the first and second stages.

For the second variant of creating a protective cover in the conditions of the excavations in the first tier under the ore pillar, it has been determined that

- in the walls of the workings under the pillar, wall slipping is also observed, which reaches the highest value in the areas of contact between the ore and the flushing material;
- the regularities of changing the coefficients of strain concentration in the ore-filling massif are determined by the size and layout of the worked-out and flushed excavations, and have the wave nature of changes, reaching the highest value of 1.8.

In general, in the second variant of creating a protective cover, the geomechanical processes of interaction between the workings are more diverse, increased absolute values of the greatest values of coefficients of vertical strain concentration and vertical displacements of the ore cover are observed (approximately by 5 – 7 %).

Along with the more complex formation of the stress-strain state in the second variant, one should note the complexity of mining works' organization and flushing chambers.

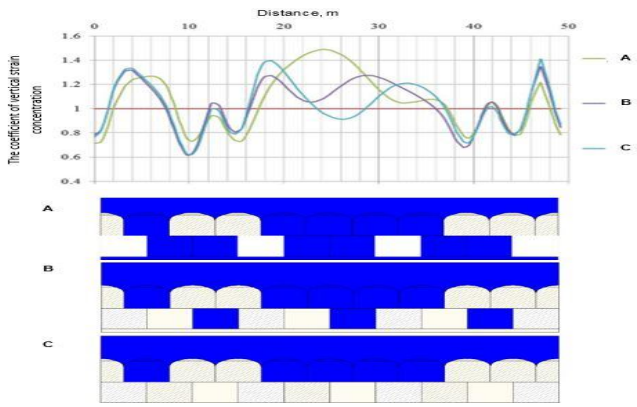

Fig. 7. Regularities of the coefficient of vertical strain concentration distribution in the ore massif at various stages of the excavations in the first tier (at the distance of 2.5 m from the workings in the protective cover, variant 2); A, B, C are horizontal cross-sections of the massif

V. CONCLUSION

The results of calculating the stress-strain state of the massif and analysis of the two variants of forming the protective cover and excavation of the first tier during the development of iron ore deposits in harsh geological and hydrogeological conditions show that, from the geomechanical point of view, the most appropriate is the first variant with first forming

the protective cover, followed by the excavations in the first tier of the ore body.However, from an economic point of view, the cost of forming the protective cover during the development of the first tier may be reduced by selling the ore extracted.

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