THE RESOURSE-SAVING TECHNOLOGY OF MINING COMPLEX STRUCTURED IRON IRE DEPOSITS

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In order to keep their positions in the world markets, mining enterprises of the Kryvyi Rih iron ore field using the deep-mine method need to develop a resource-saving technology for the development of the fields represented by complex-structure ore deposits. Development of the resource-saving technology must be carried out at the initial stage which is directly related to ore extraction and affects content of iron in the extracted ore mass. Growth of iron content in the extracted ore mass can be achieved through the use of selective development of the extraction blocks by means of the chamber development systems.

The existing procedure of determining structural components of the chamber system of development applied at the Kryvbas mines does not take into account thickness of the overlying strata on the side of the hanging wall of the cleaning chamber when calculating the exposure strike. Therefore, it is necessary to improve the procedure for determining the structural components of the chamber system of development when working out complex ore fields, in order to obtain high extraction rates.

For the development of the extraction block, it was suggested to carry out the cleaning works sequentially from the hanging to the lying wall of the complex-structure ore field with the use of the chamber system of development with leaving the non-ore or ore-containing inclusion in the pillar. This sequence of cleaning will reduce concentration of tensile and compressive stresses in the middle part of the non-ore or ore-containing inclusion which will contribute to a 1.5–2.0-time increase in its stability.

It has been established that stability of the cleaning chamber, in addition to its dimensions and physico-mechanical properties of the ore, is influenced by horizontal thickness of the inclusion, safety factor, its life span and the sequence of cleaning in the extraction block. Thus, at the safety factor of rocks of the non-ore inclusion less than 10-12, it is expedient to use the sublevel-chamber version of the development system, otherwise, the horizonal-chamber version.
Keywords: deep mining, iron ore, stress, stability, chamber system of development

1. Introduction

Today, iron ores are extracted by strip and deep mining. Poor ores (magnetite quartzites) are extracted by conventional strip mining and rich ores (ferruginous quartzite) by deep mining. As an exception, magnetite quartzite is extracted recently by deep mining at Ordzhonikidze mine. Gigant-Glyboka and Pershotravneva mines extracted this ore right up to 1997.

In the geological and mining context, the Kryvyi Rih iron ore field is a complex-structure field composed of single, parallel-approaching deposits and separated pockets with useful component content in the massif within 10-37 % to 58-67 % [1, 2]. In some regions of the ore deposits, there are non-ore or ore-containing inclusions (BOI) with the useful component content much smaller than the cut-off grade relative to the ore massif under development. The volume of reserves of non-ore or ore-containing inclusions with a content of useful component less than the cut-off grade makes 5–12 % for rich ores and 10-15 % for poor ores of the total field volume.

Development of the deposits represented by complex-structure ore deposits (CSOD) by deep mining with the use of conventional development systems results in a 3–6 % reduction of iron content in the extracted ore relative to the basic content of the useful component in the ore massif. With an increase in iron content in the extracted ore mass, the loss of ore is increased by 1.5-2.0 times, which leads to a lower mining efficiency, and as a consequence, to the loss of positions in the world markets. Thus, development of the resource-saving technologies that will enable efficient development of complex-structure ore deposits of the Kryvyi Rih field is of very high importance. It should be noted that modernization of the technological processes must begin from the first stage of production (massif destruction, extraction and delivery of ore) which will significantly improve technical and economic indicators of mining and processing.

2. Literature review and problem statement

The issues of working out the technology, criteria, and methods for controlling the process of raw dressing taking into account the indicators of energy efficiency, environmental and economic components were considered in [3,4]. To solve the problem of resource conservation, it is necessary to use an integrated approach to the concept of hierarchical management of ecological and economic systems taking into account features of the functioning elements and using the theory of organizational and technical management.

A series of studies aimed at establishing dependences of the extraction indicators on the action of rock pressure and the extraction sequence and determining the rational values of parameters of the main structural members of the mining systems were dedicated to the development of the complex-structure deposits [5, 6].

It was proved that mining, geological, and technical conditions influence efficiency of extraction of the field reserves. The main factors of successful development of the CSOD include the sequence of cleaning, rock pressure, intensity of works, number and stability of pillars, floor height, relative location of chambers and pillars in deposits of the main strike.

Experience of the mines of the Kryvyi Rih field has proved that efficiency of the development of the complex-structure deposits is influenced by the sequence of cleaning excavation, thickness and strength of the intermediate stratum (non-ore inclusion) and the mining system [7]. When developing the CSOD by the chamber method with leaving pillars, the number of the latter should be minimal, as they are stress initiators and complicate conditions for further development of deposits. When determining the zones of displacement and the zones of relief in mining the parallel bodies, it was proved that the rock pressure in the ore-containing rocks of the hanging wall is much lower than in the underlying rocks of the underwall [8-10].

It was established in [11-13] that the advanced development of the hanging wall layers reduces the rock pressure in the layers of the main strike. Such controversial conclusions on the sequence of cleaning have arisen because of the fact that these studies were conducted under different conditions and at different depths. The authors of study [14] have identified various zones of rock pressure variation determined by the advanced mining of one of the layers as well as a temporary lag of works and their spatial and mutual arrangement. The bearing pressure in rocks is distributed unevenly along the strike but focuses on the flanks of the excavated space. As a result, the zones of stress relief and concentration appear in the rocks between the deposits [15, 16]. Stress concentration can be reduced by means of bulk extraction while controlling the ore quality.

The results of the study on optimization of ore extraction and processing set forth in [17] have led to a conclusion that the indicators of efficiency of managing the processes of ore dressing significantly depend on accuracy of current information on parameters of the technological processes. In most cases, electromagnetic, ultrasonic, and radiometric methods are used in development of non-destructive ore testing methods.

Based on the critical analysis of the studies devoted to the issues of mining and processing of mineral resources, the following conclusions can be drawn:

1. Iron content in the extracted ore can be raised at the first stage by the use of resource-saving selective mining, without application of the dressing process. In this case, development of deposits with horizontal thickness of non-ore or ore-containing inclusions less than 12 m is offered to be carried out by the conventional deep-mine method with involvement of dressing works.

2. The negative effects of weakening of bearing capacity of the intermediate stratum which adversely affect its stability during formation of the next chamber are not taken into account in the advance extraction of deposits with non-ore or ore-containing inclusions.

3. There are no substantiated scientific and practical recommendations concerning development of the complex-structure deposits by the chamber method which enables not only growth of iron content in the extracted ore but also a differential approach to the issue of raising the chamber stability.

Thus, it is necessary to improve the resource-saving technology when developing the CSOD. This will ensure not only higher iron content in the extracted ore mass but also increased chamber stability. Therefore, it is necessary to determine how dimensions of the non-ore or ore-containing inclusion affect structural components of the chamber method.

3. The aim and objectives of the study

The study objective was to substantiate stable parameters of structural elements of the chamber system in the development of complex-structure ore deposits which will improve indicators of ore mass extraction owing to selective extraction. In order to achieve this objective, it was necessary to determine the maximum permissible steady width of the chamber roof exposure depending on the structural elements of the chamber system of development and thickness of non-ore or ore-containing inclusions in selective development of complex-structure ore deposits.

4. Materials and methods used in studying the stability of non-ore or ore-containing inclusions in the application of chamber development systems

Solution of many issues related to development of mineral resources and study of geological and tectonic development of the earth's crust are based on the results of experimental studies of the stressed state of the rock massif. These studies are determined by the massif breakage in the course of deep-mining operations resulting in technogenic disasters of geomechanical nature which have both positive and negative effect.

An elementary cube taken from a stressed body has, in a general case, nine stress vectors in its faces: σ_x, σ_y, σ_z (normal) and τ_{xy}, τ_{xz}, τ_{yx}, τ_{yz}, τ_{zx}, τ_{zy} (tangential) that form the so-called stress tensor characterizing the stressed state in a given point *O* of the solid body and having the form

$$s_{ij} = \begin{vmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{vmatrix} = p_{ik} \times n_i, \quad (1)$$

where σ is the internal force stress occurring in the massif, N/m^2, (t/m^2); τ are tangential stresses occurring in the massif, N/m^2, (t/m^2); p_{ik} is the cumulative stress, three mutually perpendicular areas around one point; n_i is the normal unit vector to the corresponding study area; *i, k* are indices of the coordinate axes *x, y, z*.

The indices indicate the strain direction and relative shifts which characterize the change of the parallelepiped shape and in which the coordinate plane an angle straining takes place that causes destruction of a non-ore or ore-containing inclusion [18].

In many cases of determining pillar stability, it is considered in mining as a fixed beam and in order to ensure its stability, the maximum stresses must meet the condition

$$\left.\begin{aligned} \sigma_{\max} &\le [\sigma], \\ \tau_{\max} &\le [\tau], \end{aligned}\right\} \quad \sigma \square \tau, \tag{2}$$

where [σ] is the material strength limit, N/m^2, (t/m^2); [τ] are permissible tangential stresses, N/m^2, (t/m^2).

The authors of studies [8–10] argue that in calculating the pillar stability, the main criterion is strike but a zone of cracks is formed in rocks under the influence of pressure. Therefore, when determining maximum permissible stresses bringing about reduction in strength limit of the pillar consisting of rocks, it is necessary to take into account the massif structure and the time of its existence.

In most cases of deep mining, pillars have a rectangular shape, so the middle part of the exposure strike is the most dangerous and the maximum stresses are determined from formula

$$\sigma_{\max} = \frac{M_x}{W_x} \le [\sigma], \tag{3}$$

where M_x is the value of the maximum bending moment in the part z of the BOI exposure strike along the x axis, N/m, (t/m); W is the moment of resistance of the pillar.

It should be noted that deflection is the main component of the vector of shift of points in the rock massif, so the value of deflection is small compared with the pillar thickness, i.e. $w \ll h$.

The maximum stresses occurring in the pillar represented as a fixed beam are determined from expression

$$\sigma_{\max} = \frac{6 \times M_x}{l \times h^2}, \tag{4}$$

where l is the exposure strike (the pillar length), m; h is the pillar thickness (normal thickness of the BOI), m.

Studies [5, 11, 15] have proved that not all rectangular bodies can be regarded as a fixed beam in calculations of maximum stresses. In the case when thickness of the pillar is considerably less than its length, the pillar should be regarded as a thin rigid plate and not as a fixed beam.

In accordance with the Kirchhoff's first and second assumptions and Cauchy's formulas, we have obtained expressions for determining components of the tensor of stresses σ_x, σ_y, τ_{xy} in the plate through the function of deflection w in its middle plane

$$\sigma_x = -\frac{E \times z}{1-\mu^2} \times \left(\frac{\partial^2 w}{\partial x^2} + \mu \frac{\partial^2 w}{\partial y^2} \right);$$

$$\sigma_y = -\frac{E \times z}{1-\mu^2} \times \left(\frac{\partial^2 w}{\partial y^2} + \mu \frac{\partial^2 w}{\partial x^2} \right);$$

$$\tau_{xy} = -\frac{E \times z}{1+\mu^2} \times \frac{\partial^2 w}{\partial x \times \partial y}, \quad (5)$$

where E is the Young's modulus; μ is the Poisson coefficient.

After corresponding transformations of expressions (5), conditions of the BOI stability at maximum stresses in its middle part are obtained:

$$\begin{cases} \sigma_x = \dfrac{6 \times M_{x\max}}{m_{BOI}^2} \leq [\sigma], \\ \sigma_y = \dfrac{6 \times M_{y\max}}{m_{BOI}^2} \leq [\sigma], \\ \tau_{xy} = \dfrac{6 \times H}{m_{BOI}^2} \leq [\tau]. \end{cases} \quad (6)$$

Let us consider the technological processes taking place in the development of ore fields by deep mining. Deposits of the Kryvyi Rih iron ore field are conventionally mined from the lying to the hanging wall. According to the performed analysis, it was found that it is expedient to mine from the hanging to the lying wall when developing the complex-structure ore fields by deep mining [5, 6]. However, mining operations must be carried out from the hanging to the lying wall when developing the CSOD. Let us consider how the extraction technology changes in the selective development of the CSOD with extraction from the hanging to the lying wall and the use of the chamber development method.

The proposed technology foresees a certain procedure for conducting mining operations depending on the mining and geological conditions of the CSOD while the development of the cleaning block is carried out in two stages: *Stage I*. Ore is extracted initially in the hanging wall leaving the non-ore inclusion in the cleaning block as a pillar; *Stage II*. The remaining ore in the lying wall is removed from the block depending on the sequence and priority of the mining operations.

In order to obtain high rates of extraction of the ore mass using the chamber development system, it is necessary to ensure stability of pillars, exposures and the BOI for the entire time of development in the cleaning blocks. Consequently, depending on the stage and sequence of mining operations in the extraction block, different loads will be applied to the BOI. Depending on loading of the BOI, a field of tensile or compression forces is formed in the massif [2, 6].

It is known from the theory of material resistance that if a specimem is evenly loaded over time, normal stresses grow in it to the ultimate compression strength of the material. As soon as the compressive stresses become larger than the compressive strength of the BOI or linear strains appear, the interchamber pillar will be destroyed. Thus, in order to maintain integrity of the BOI which is an interchamber pillar, it is necessary to fulfill the following condition during the cleaning works in the block

$$\begin{cases} \sigma \le \sigma_k \cong [\sigma_{st}], \\ \varepsilon = 0, \end{cases} \qquad (7)$$

where σ are normal stresses, MPa; σ_k are critical stresses, MPa; $[\sigma_{st}]$ is the rock compression strength, MPa; ε are the linear strains.

In the event that the compression and tensile stresses are acting in time, normal stresses in the BOI initially grow and then fall. When loading is repeated, linear strains appear in the pillar significantly reducing compression strength of the rock. When the load increases in time, normal stresses grow in the pillar according to expression (7) and when the load falls, normal stresses do not reach the limit strength of the rocks which leads to the pillar destruction under the following boundary conditions

$$\begin{cases} \sigma \square \ \sigma_k \cong \sigma_v \square \ [\sigma_{st}], \\ \varepsilon \ne 0. \end{cases} \qquad (8)$$

In view of the above, it is necessary to determine parameters of the structural elements of the chamber system of development when working in the cleaning block from the hanging to the lying wall with a provision of stability of the non-ore or ore-containing inclusion.

5. The results obtained in the study of stable parameters of the cleaning chamber in stable ores

To obtain high extraction rates in the case when the cleaning block is represented by a complex-structure field, it is expedient to apply selective development of ore reserves [3]. The selective development of the cleaning block differs from the conventional mining in that the ore reserves are extracted in two stages.

The first stage involves ore extraction from the hanging wall of the deposit with dimensions of the structural elements determined by the procedure [19] with formation of a cleaning chamber. It should be noted that according to the method [19], the width (thickness) of the non-ore or ore-containing inclusion does not affect parameters of the cleaning chamber of the first stage.

After removal of the caved-in ore from the first cleaning chamber, the inter-chamber ore pillars and the ceiling are not caved-in at this stage. Therefore, when determining the time of existence of exposure and pillars, it is necessary to take into account the total time to be spent for extraction of the cleaning block (including the second stage). Thus, it is necessary to make changes in the existing procedure of determining time of existence of pillars and exposures for the cleaning chamber of the first stage. The time of existence of the exposure (t_o) and the pillars (t_c) for the cleaning chamber of the first stage when developing the block represented by the complex-structure field is determined by the formula

$$t_o(t_c) = t_v + t_p + t_z + t_{r1}, \qquad (9)$$

where t_v is the time for the development of the caved-in rock mass from the cleaning wall of the chamber, month; t_p the time for preparatory and cutting work in the wall of the second stage of development (according to the practice, it takes 3–7 months), month; t_z is the time for drilling and blasting (caving-in) of a rock mass in the wall of the second stage of development (according to the practice, it takes 2–6 months), month; t_{r1} is the time for preparation and mass caving-in of pillars and ceiling around the cleaning chamber of the first and second stages of development (according to the practice, it takes 1–3 months), month.

In determining the parameters of cleaning chamber of the second stage, it is necessary to take into account the previous calculation values of the first cleaning chamber which include the chamber width along the seam strike and the width of the inter-chamber pillars with the following boundary conditions

$$\begin{cases} a_{II} = a_I; \\ c_{II} = c_I; \\ b_{II} \leq b_I, \end{cases} \quad (10)$$

where a_I, a_{II} is the width of the first and second cleaning chambers along the seam strike, m; c_I, c_{II} is the width of the inter-chamber pillar relative to the first and second cleaning chambers, m; b_I, b_{II} is the sloped strike of the exposure relative to the first and second cleaning chambers, m.

According to paragraph 4, it was established that when the normal thickness of the non-ore or ore-containing inclusion is 5 times less than the exposure strike, then in accordance with the theory of material resistance, the pillar should be considered as a fixed beam and as a thin rigid plate in other cases. Maximum stresses arise in the middle part of the exposure strike when the BOI is represented as a beam and determined by formula (3). Substituting the input values in formula (3) and performing corresponding transformations, we obtain an expression for definition of the maximum permissible stable strike of the BOI exposure

$$l_{\text{BOI}} = \frac{4 \times [\sigma] \times h_{\text{th}}^2}{q} = \frac{4 \times [\sigma] \times m_{\text{BOI}}}{a_{II} \times \gamma_{\text{BOI}}} = \frac{4 \times K_f \times f \times \text{K}_{\text{str.o}} \times m_{\text{BOI}}}{a_{II} \times \gamma_{\text{BOI}} \times \text{K}_z}, \quad (11)$$

where $[\sigma]$ is the limit compression strength of the BOI rocks, t/m^2; h_{th} is the pillar thickness, m; m_{BOI} is the normal thickness of the non-ore or ore-containing inclusion, m; γ_{BOI} is the volume weight of the BOI rocks solids, t/m^3; K_f is the factor of conversion of rocks durability in stress; f is the coefficient of durability of rocks of the non-ore or ore-containing inclusion by the scale of Prof. Protodiakonov; $K_{\text{str.o}}$ is the coefficient of structural weakening of rocks by cracks (taken from 0.65 to 0.95); K_z is the factor of safety of rocks (taken 1.5-2.0).

The criterium of stability of exposures and pillars is satisfaction of inequality (12) in which values of the actual equivalent strike of exposure (11) are compared with geometric dimensions of the inclined exposure in the cleaning chamber of the second stage of development [19], m

$$l_{\text{th}} = \frac{a_{II} \times m_{\text{BOI}}}{\sqrt{a_{II}^2 + m_{\text{BOI}}^2}} \le l_{\text{BOI}}, . \qquad (12)$$

In the case when the normal thickness of BOI is 5 times less than the strike of the exposure or the chamber width along the seam strike, stability of BOI is calculated as for a plate. The stresses occurring in the plate are determined by formula (6).

In accordance with the conditions of static equivalence, the internal moments occurring in the plate and expressed in terms of the strike of exposure of the plate are determined by the following differential equations

$$M_x = -D \times \left(\frac{\partial^2 \omega}{\partial x^2} + \mu \times \frac{\partial^2 \omega}{\partial y^2} \right),$$
$$M_y = -D \times \left(\frac{\partial^2 \omega}{\partial y^2} + \mu \times \frac{\partial^2 \omega}{\partial x^2} \right), \qquad (13$$
$$M_{xy} = -D \times (1-\mu) \times \frac{\partial^2 \omega}{\partial x \partial y},)$$

where M_x,M_y are the bending moments along the x,y axes, respectively; μ is the Poisson coefficient; D is the bending stiffness of the plate and ϵ is the physico-geometric characteristic of the plate in bending determined by

$$D = \frac{E \times m_{\text{BOI}}^3}{12 \times (1 - \mu^2)}, \qquad (14)$$

where E is the Young modulus.

The moment of bending of the plate by the transverse forces is described by the differential equation

$$\frac{\partial^4 \omega}{\partial x^4} + 2\frac{\partial^4 \omega}{\partial x^2 \partial y^2} + \frac{\partial^4 \omega}{\partial y^4} = \frac{q}{D}. \qquad (15)$$

The differential equation (15) is solved by numerical methods with taking into account boundary conditions (16) while it should be borne in mind that BOI represents a fixed plate

$$\begin{cases} \omega\big|_{x=0}^{x=a} = 0, \\ \left.\frac{\partial \omega}{\partial x}\right|_{x=0}^{x=a} = 0, \end{cases} \text{and} \begin{cases} \omega\big|_{y=0}^{y=a} = 0, \\ \left.\frac{\partial \omega}{\partial y}\right|_{y=0}^{y=a} = 0. \end{cases} \qquad (16)$$

In the development of the fields with the use of systems with an open cleaning space, there are three possible options for formation of cleaning chambers which differ in the ratio of the chamber width to the exposure strike. For engineering calculations, we offer an equation for determining maximum bending moments for different ratios of the cleaning chamber length to the exposure strike

$$\begin{cases} M_{\text{x max}} = C_1 \times l_{\text{BOI}} \times m_{\text{BOI}} \times \gamma_{\text{BOI}} \times a_{II}^2 \Big|_{l_{\text{BOI}}^2 \geq a_{II}}, \\ M_{\text{y max}} = C_2 \times l_{\text{BOI}} \times m_{\text{BOI}} \times \gamma_{\text{BOI}} \times a_{II}^2 \Big|_{l_{\text{BOI}}^2 \geq a_{II}}, \\ M_{\text{x max}} = C_3 \times a_{II} \times m_{\text{BOI}} \times \gamma_{\text{BOI}} \times l_{\text{BOI}}^2 \Big|_{l_{\text{BOI}}^2 < a_{II}}, \\ M_{\text{y max}} = C_4 \times a_{II} \times m_{\text{BOI}} \times \gamma_{\text{BOI}} \times l_{\text{BOI}}^2 \Big|_{l_{\text{BOI}}^2 < a_{II}}, \end{cases} \tag{17}$$

where C_1, C_2, C_3, C_4 are correction factors of bending moments. They are taken accordingly.

Substituting the input values (17) in expression (6) and performing corresponding transformations, we obtain the formula for determining the maximum permissible BOI exposure strike depending on the width of the cleaning chamber of the second stage and the exposure strike

$$l_{\text{BOI}} = \frac{[\sigma] \times m_{\text{BOI}}^2}{3 \times C_1 \times a_{II}^2 \times \gamma_{\text{BOI}}} = \frac{\text{K}_f \times f \times \text{K}_{\text{str.o}} \times m_{\text{BOI}}^2}{3 \times C_1 \times a_{II}^2 \times \gamma_{\text{BOI}} \times \text{K}_{\text{z}}}. \tag{18}$$

In the case when the chamber length along the strike is greater than the inclined exposure strike determined for the camera of the first stage (Fig. 5*c*), the stable strike of the exposure is determined from the expression

$$l_{\text{БРВ}} = \sqrt{\frac{[\sigma] \times m_{\text{БРВ}}^2}{3 \times C_1 \times a_{II} \times \gamma_{\text{БРВ}}}} = \sqrt{\frac{\text{K}_f \times f \times \text{K}_{\text{стр.о}} \times m_{\text{БРВ}}^2}{3 \times C_1 \times a_{II} \times \gamma_{\text{БРВ}} \times \text{K}_{\text{з}}}}. \tag{19}$$

Thus, according to the results of theoretical studies, parameters of the structural elements of the chamber system of development for mining complex-structure ore fields in various mining and geological conditions are determined.

Reliability of the results obtained in theoretical studies can be proved with the help of laboratory or mathematical modeling. When creating an object in a laboratory environment, it is necessary to observe a correct reproduction of the rock massif by producing equivalent materials [20]. However, the disadvantage of this modeling method consists in large tensions and long time required for both model creation and development. Mathematical finite element modeling is the most effective method. This method allows one not only to create a model of a corresponding size but also change its characteristics in a short time.

Thus, simulation of the change in the stress field in a rock massif around the cleaning chambers at various stages of development was conducted with the help of the ANSIS software system.

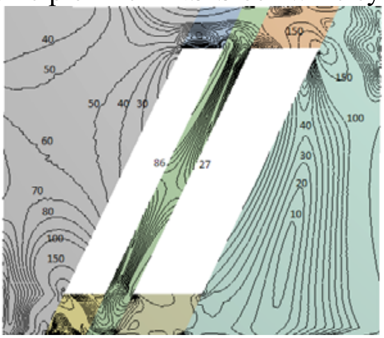

Fig. 1. Results of simulation of the CSOD development from the hanging to the lying wall at compression strength of the non-ore inclusion equal to 160 MPa; the simulation stages: initial, intermediate, and final, respectively

A total of 9 series of studies were conducted. They differed in physical and mechanical properties of the ore massif and the BOI. All other indicators (development depth, horizon level, thickness) remained unchanged.

When conducting studies on the model, the field of equivalent stresses in the massif around the cleaning chambers and in the middle part of the non-ore inclusion was recorded at different development stages. The safety factor of the non-ore or ore-containing inclusion is determined by the expression

$$K_{st} = \frac{K_{str.o}}{K_z}, \qquad (19)$$

where $K_{str.o}$=0,65-0,95 is the factor of structural weakening of rocks by cracks (taken 0.85); K_z=1,5-2,0 is the safety factor of the rocks (taken 1,5).

At a horizon level of 90 m, the inclined strike of the exposure is 104 m, and, taking into account the expression (19), it is 58.9 m. According to the simulation results, it was found that the exposure maintains its stability at the level of 90 m (the inclined exposure strike of 58,9 m), the cleaning chamber width of 25 m at the BOI strength greater than 120 MPa. In the case when strength of the rocks is less than 120 MPa, the exposure strike will be unstable, the BOI and the cleaning chambers will be destroyed.

6. Discussion of the results obtained in the study of stable parameters of the cleaning chamber

According to the study results, the NDGRI procedure for determining structural components of the chamber method used in the development of complex-structure ore fields was improved. It will provide stability to the cleaning chambers for the entire period of the development of ore reserves and enable extraction of clean ore from the cleaning chambers. In order to maintain positions in the world market, the mining enterprises practicing deep-mine extraction must introduce resource-saving technologies at the first stage of extraction. This will raise iron content in the extracted ore mass by 2-4 % without additional capital and operating expenditures.

The sequence of cleaning works and the inclined exposure strike for determination of the structural members of the chamber system of development during the CSOD development were substantiated. Cleaning works in the extraction block should be carried out sequentially from the hanging to the lying wall of the complex-structure ore deposit by means of the chamber system of development with leaving of a non-ore or ore-containing inclusion in the pillar. This will reduce concentration of tensile and compressive stresses in the middle of the non-ore or ore-containing inclusion. This will make it possible to improve stability of the cleaning chambers at the contact with BOI by 1.5–2.0 times. It should be noted that the inclined exposure strike has a significant influence on stability of the cleaning chamber and depends on physical and mechanical properties and the horizontal thickness of ore and the BOI, the time of its existence, the sequence of cleaning works in the extracted pillar and the depth of the extraction development.

Thus, development of the extraction blocks of the presented CSOD by the chamber development systems will significantly improve ore mass extraction rates, and in some cases, exclude dressing of the ore mass from the production complex at the final stage. This will contribute to reduction of ore extraction costs and expansion of the world market.

It should be noted that there is a 2-time increase in the life span of the cleaning chambers and pillars in the development of the CSOD by selective method. In order to ensure stability of the cleaning chambers with taking into account the safety factor, a 1,5-time increase in dimensions of the inter-chamber pillars and the ceiling is necessary when the horizonal-chamber system of development is used.

Development of the extraction pillar by sublevel/ chamber development systems will make it possible to reduce pillar dimensions to increase the volume of cleaning chambers, thus expenses for preparatory and cutting works will increase.

The results of the performed studies can be used in the development of the fields of naturally rich iron ores containing non-ore inclusion. It has been established from analysis of the mining and geological characteristics of the Kryvyi Rih field that application of the selective development method with chamber development systems will reduce from 20 % to 10 % volumes of non-ore rocks dumped on the earth's surface. This will contribute to an increased output of marketable products with iron content in the ore mass of 63–65 % by 0.5 million tons at annual productivity of the enterprise 6.0 million tons.

These studies are innovative for conditions of the Kryvyi Rih iron ore field. For example, the issue of using a combination of development systems within an extraction block, e.g. the chamber system of development and the system with massive ore and rock caving and their sequence in extraction of cleaning panels was not yet solved.

7. Conclusions

Stability of the cleaning chamber exposure strike depends not only on the width and life span of the cleaning chamber of the second development stage but also on physical and mechanical properties of the non-ore or ore-containing inclusion. For example, at a horizon level of 75–90 m, stability of the cleaning chamber is ensured when its width along the strike does not exceed 15 m. In cases when the sublevel height is 25–30 m, stability of the cleaning chamber is affected by thickness and strength of the non-ore or ore-containing inclusion. For example, when the BOI durability is more than 12 and its horizontal thickness is more than 10 m, it is expedient to apply the horizon development version of the chamber system in stable ores. In other cases, in order to ensure high extraction rates, it is advisable to apply the sublevel-chamber versions.

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