Гірничо-видобувні підприємства Криворізького залізорудного басейну з підземним способом для збереження світового ринку збуту успішно впроваджують ресурсозберігаючі технології при розробці родовищ представлених складноструктурними рудними покладами. Впровадження ресурсозберігаючої технології необхідно здійснювати на першому етапі, який безпосередньо пов'язаний з видобутком руди та впливає на вміст заліза в видобутій рудній масі. Підвищити вміст заліза в видобутій рудній масі можливо за рахунок застосування селективної розробки виймальних блоків камерними системами розробки.

Існуюча методика, яка застосовується на шахтах Кривбасу для визначення конструктивних елементів камерної системи розробки, при розрахунку прольоту оголення не враховує потужність налягаючої товщі порід зі сторони висячого боку очисної камери. Тому, необхідно розробити методику з визначення конструктивних елементів камерних систем розробки при відпрацюванні складноструктурних рудних покладів, для забезпечення стійкості оголень очисним камерам.

При відпрацюванні виймального блоку запропоновано очисні роботи здійснювати послідовно від висячого до лежачого боку складноструктурного рудного покладу камерної системою розробки, з залишенням в блоці безрудного або рудного включення. Даний порядок очисних робіт дозволить зменшити концентрацію розтягуючих та стискаючих напружень в середній частині безрудного або рудного включення, що сприяє підвищенню його стійкості в 1,5–2,0 рази.

Встановлено, що на стійкість очисної камери, окрім її розмірів та фізико-механічних властивостей руди, впливають горизонтальна потужність включення, коефіцієнт тривкості, час його існування та порядок очисних робіт у виймальному блоці. Тому при коефіцієнті тривкості порід безрудного включення меншим за 10–12 доцільно застосовувати підповерхово-камерний варіант системи в іншому випадку поверхово-камерний варіант системи розробки

Ключові слова: підземна розробка, залізна руда, напруження, стійкість, камерна система розробки

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DEVELOPMENT OF COMPLEX-STRUCTURE ORE DEPOSITS BY MEANS OF CHAMBER SYSTEMS UNDER CONDITIONS OF THE KRYVYI RIH IRON ORE FIELD

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1. Introduction

The explored reserves of iron ore in Ukraine amount to about 76 billion tons which is 18 % of the world reserves. Almost one third of them are concentrated in the Kryvyi Rih iron ore field. 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. Volumes of ferruginous quartzites within the fields of the Saksaganska formation of the Kryvyi Rih field extracted by mining enterprises by means of deep mining are given in Table 1.

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 (Table 1).

Table 1

Mining enterprises extracting ferruginous quartzite of the Kryvyi Rih field by deep mining as of 2015

Mining enterprise	Mine name	Mining depth, m	Reserves within the field, mln. t	
			rich ores	poor ores
Arcelor Mittal Kryvyi Rih JSC	Artem	1.135	120	400
Kryvbaszalizrud-kom JSC	Rodina	1.390	160	1.150
	Oktiabrska	1.265	570	2.860
	Ternivska	1.350	80	60
	Gvardiyska	1.270	100	400
Sukha Balka JSC	Yuvileina	1.260	160	–
	Frunze	1.135	40	–
Total:			1.130	4.470

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.

The presence of 5–9 mineralogic and technological varieties of ore in the massif [3–5] also negatively affects subsequent technological processes of grinding, classification, magnetic separation, flotation. The essence of this influence lies in the fact that the development system does not ensure extraction of the same type of ore for a sufficiently long time. As a consequence, there is a need for frequent changes in setting the flotation equipment. Transition processes in this equipment cause a decrease in overall efficiency of the flotation processes.

Efficiency of the flotation processes can be improved, mining costs reduced and presence in the world market expanded through development of resource-saving technologies and their introduction into deep mining of the complex-structure ore deposits [6–10].

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 [11–14]. 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 [6, 8, 10, 15, 16].

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.

One of the world leaders of deep mining of ore fields is the Kiruna mine, Sweden. When solving the problem of efficient development by the deep-mine method, it was proposed to grade the iron ore according to the content of iron at the first stage of work in underground conditions. For this purpose, a required number of main accessways were arranged. In subsequent development, the enterprise has faced the issue of ensuring stability of the rock massif. Methods for controlling the state of rock massif were developed and implemented [17, 18]. Later, advanced methods were developed for controlling the state of the rock massif violated by underground mining operations [19–21]. However, because of the technological features of deep mining of the deposits of Kryvyi Rih iron ore field, their implementation will lead to a significant increase in the mining costs.

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, 8, 22]. 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 [23–25].

It was established in [26–29] 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 [20] 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 [21, 30–32]. 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 [33–35] 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.

In order to simplify control of the dressing process, authors of studies [36–38] have found that it is expedient to apply the chamber method of development of deposits of the main strike and a system with a massive caving for a parallel strike. The developed technological schemes and passports foresee the development of CSOD with horizontal thickness of the non-ore inclusion of 35 m and larger (the ore and rock must be strong and stable) [39–41]. In this case, parameters of the chamber system of development are determined according to the methodology developed in 1987 by the Research Mining Institute (NDGRI), Kryvyi Rih, Ukraine [40].

In order to solve the problem of raising iron content and reducing ore losses in the development of deposits in the complex-structure fields, it is advisable to apply the approach proposed in [42, 43]. The authors propose modernization of conventional dressing processes through involvement of operations of hydrometallurgical and chemical processing which improve efficiency of dressing by the use of other energy types. This line of ore-dressing update is based on the processes of power influence on the substance in the process of disintegration in an activator and does not take into account the processes associated with extraction of minerals by deep mining.

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. Most authors propose to solve the problem of raising the iron content in the extracted ore by means of an underground or ground-based ore mining and processing complexes which will inevitably lead to a rise in the cost of mining operations and loss of position in the world market.

2. 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.

3. 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.

4. 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:

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

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 [44, 45].

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:

$$\begin{cases} \sigma_{\max} \le [\sigma], \\ \tau_{\max} \le [\tau], \end{cases} \quad \sigma \gg \tau, \tag{2}$$

where $[\sigma]$ is the material strength limit, N/m^2, (t/m^2); $[\tau]$ are permissible tangential stresses, N/m^2, (t/m^2).

The authors of studies [23–25, 44] 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:

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

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:

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

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

Studies [15, 26, 30–32, 44] 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:

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

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 [15, 16]. 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, Fig. 1:

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, 16, 38].

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, Fig. 2, *a*. 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 (item 2 in Fig. 1). 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:

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

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 (Fig. 2, *b*).

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:

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

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.

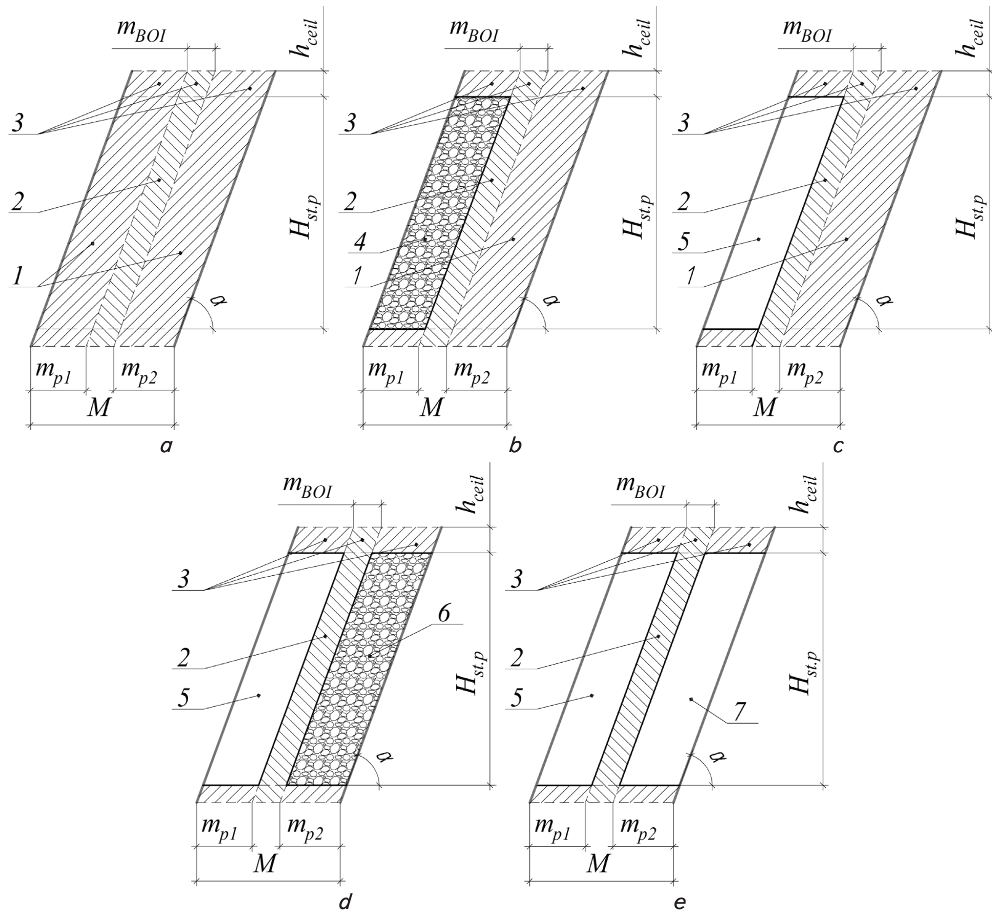


Fig. 1. Schematic diagram of developing the complex-structure ore fields in stable ore deposits by the chamber method: division of an extraction block in cleaning panels of the first and second orders (*a*); removal of crushed ore from the first panel (*b*); the final stage of the development of the first panel (*c*); removal of crushed ore from the second panel (*d*); the final stage of mining ore of the extraction block (*e*); ore massif (1); non-ore or ore-containing inclusion (2); ceiling (3); the caved ore massif (4, 6); a cleaning chamber correspondingly in the hanging and lying walls (5, 7)

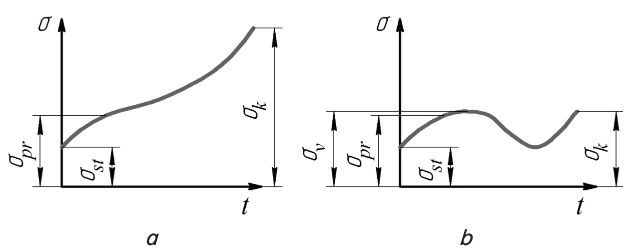


Fig. 2. The nature of distribution of stresses and strains in the material at different stages of loading: when compressive forces are acting in time (*a*); when compressive and tensile forces are acting in time (*b*)

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 [7, 11]. The selective development of the cleaning block differs from the conventional mining in that the ore reserves are extracted in two stages, Fig. 1.

The first stage involves ore extraction from the hanging wall of the deposit with dimensions of the structural elements determined by the procedure [40] with formation of a cleaning chamber 1. It should be noted that according to the method [40], 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:

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

where t_v is the time for the development of the caved-in rock mass from the cleaning wall of the chamber 2, 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.

The structural components of the cleaning chamber 2 cannot be determined by the method [40] because during calculation of the equivalent exposure strike, thickness of the non-ore or ore-containing inclusion of the CSOD is not taken into account. Mining and geological characteristics of the BOI will significantly affect stability of the exposure and the stresses that occur in it over time. Also, this procedure does not take into account the overall stress variations during the time of existence of exposures when determining the equivalent exposure strike of the second stage chamber which significantly affect stability of the non-ore or ore-containing inclusion, Fig. 1.

In determining the parameters of cleaning chamber 2 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:

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

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. Dependence of the minimum width of the cleaning chamber of the second stage on the normal thickness of the BOI is shown in Fig. 3.

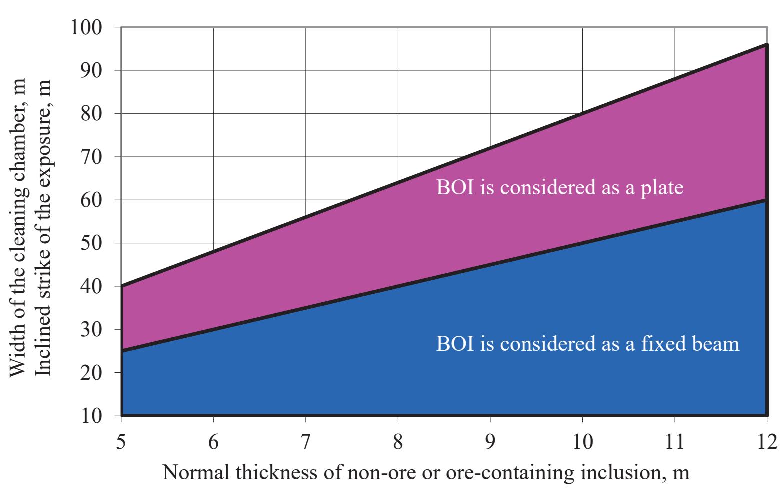


Fig. 3. Dependence of the minimum permissible width of the second stage cleaning chamber on the normal BOI thickness in calculating the exposure strike represented as a fixed beam and the maximum permissible width in calculation of the exposure strike represented as a plate

Fig. 3 shows that a linear function can be used for determining the minimum permissible width of the cleaning chamber of the second stage of developing the wall at which the strike of the exposure will be calculated as a fixed beam or a rigid plate. For example, in development of the CSOD, the width of the cleaning chamber of the first stage was determined by the NDGRI procedure and was 40 m while the normal thickness of the non-ore inclusion in the wall was 9 m, so according to the graph, the BOI should be considered as a fixed beam. In the case when thickness of the non-ore or ore-containing inclusion is be 6 m, then it should be considered as a rigid plate when determining parameters of the BOI development system.

There are many methods for determining parameters of chambers and pillars. They allow one to determine strength, stiffness, stability, cut, shear and other parameters of the pillars. However, most of them are based on the determination of maximum stresses in the middle part of the pillar.

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:

$$l_{BOI} = \frac{4\times[\sigma]\times h_{th}^2}{q} = \frac{4\times[\sigma]\times m_{BOI}}{a_{II}\times\gamma_{BOI}} = = \frac{4\times K_f\times f\times K_{str.o}\times m_{BOI}}{a_{II}\times\gamma_{BOI}\times K_z}, \qquad (11)$$

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; $K_{str.o}$ 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 [40]:

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

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:

$$M_x = -D \times \left(\frac{\partial^2 \omega}{\partial x^2} + \mu \times \frac{\partial^2 \omega}{\partial y^2} \right),$$

$$M_y = -D \times \left(\frac{\partial^2 \omega}{\partial y^2} + \mu \times \frac{\partial^2 \omega}{\partial x^2} \right),$$

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

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

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

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 (Fig. 4).

When the horizon-chamber system of development is used, the length of the cleaning chamber is always less than its horizon (the exposure strike) and in the sublevel-chamber development system, there are two cases: when the chamber length is less than the exposure strike (Fig. 4, *b*) and, conversely, the chamber length is larger than the exposure strike (Fig. 4, *c*).

One or the other version of the chamber development systems is used depending on the mining and geological conditions and parameters of stable exposures of the chambers of the first stage in the development of the complex-structure ore fields determined by the procedure [2, 15].

It should be noted that the diagrams *a* and *b* shown in Fig. 4 are similar to each other by the ratio of the length of the cleaning chamber to its sloping exposure strike ($a < l_{str}$) and on the contrary, the chamber length is less than the exposure strike ($a > l_{str}$) as in the diagram *b*. The ratio of the camera length to the exposure strike is the boundary condition for determining the bending moment.

For engineering calculations, we offer an equation for determining maximum bending moments for different ratios of the cleaning chamber length to the exposure strike:

$$\begin{cases} M_{x\max} = C_1 \times l_{BOI} \times m_{BOI} \times \gamma_{BOI} \times a_{II}^2 \big|_{l_{BOI}^2 \ge a_{II}}, \\ M_{y\max} = C_2 \times l_{BOI} \times m_{BOI} \times \gamma_{BOI} \times a_{II}^2 \big|_{l_{BOI}^2 \ge a_{II}}, \\ M_{x\max} = C_3 \times a_{II} \times m_{BOI} \times \gamma_{BOI} \times l_{BOI}^2 \big|_{l_{BOI}^2 < a_{II}}, \\ M_{y\max} = C_4 \times a_{II} \times m_{BOI} \times \gamma_{BOI} \times l_{BOI}^2 \big|_{l_{BOI}^2 < a_{II}}, \end{cases} \qquad (17)$$

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

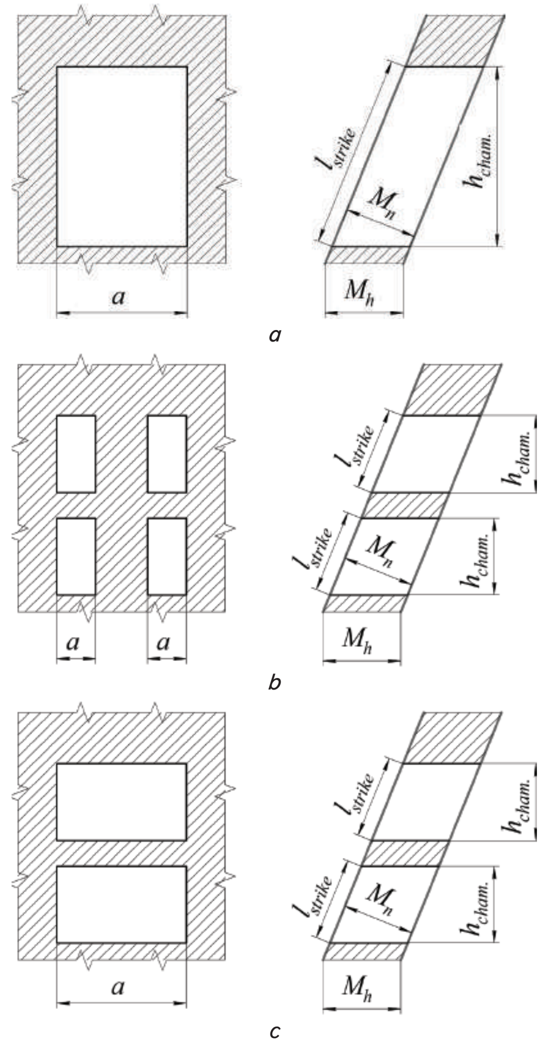


Fig. 4. Diagrams of location of the cleaning chamber in the block along the seam strike depending on the development system: horizon-chamber system with the chamber length less than the exposure strike (*a*); sublevel-chamber system according to the ratio of the cleaning chamber width to the exposure strike (*b, c*)

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:

$$l_{BOI} = \frac{[\sigma] \times m_{BOI}^2}{3 \times C_1 \times a_{II}^2 \times \gamma_{BOI}} = \frac{K_f \times f \times K_{str.o} \times m_{BOI}^2}{3 \times C_1 \times a_{II}^2 \times \gamma_{BOI} \times K_z}. \qquad (18)$$

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. 4, *c*), the stable strike of the exposure is determined from the expression:

$$l_{BOI}=\sqrt{\frac{[\sigma]\times m_{BOI}^2}{3\times C_1\times a_{II}\times\gamma_{BOI}}}=\sqrt{\frac{K_f\times f\times K_{str.o}\times m_{BOI}^2}{3\times C_1\times a_{II}\times\gamma_{BOI}\times K_z}}. \quad (19)$$

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.

Having performed the calculations according to the formula (11), dependences of the minimum exposure strike of the cleaning chamber of the second stage on the normal thickness of non-ore or ore-containing inclusions (Fig. 5) and the length of the cleaning chamber were plotted (Fig. 6).

It is evident from the graphs shown in Fig. 5 that with an increase in the normal thickness of non-ore or ore-containing inclusions from 5 to 12 m, the inclined exposure strike increases from 25 to 60 m at the width of the cleaning chamber of the second stage equal to 25 m and the coefficient of durability of the rocks of non-ore or ore-containing deposit 12 according to Prof. Protodiakonov scale. It should be noted that when the coefficient of durability of rocks is less than 12 and the BOI thickness is 5–6 m, the calculated inclined strike is less than the geometric exposure strike according to the Rivkin procedure [28, 38]. This proves that development of the BOI with thickness less than 5–6 m with the use of development systems with an open cleaning space is impossible for the given geological conditions.

In the case when the coefficient of durability of the BOI rocks is 8–16, the exposure strike increases from 40 to 80 m. Therefore, depending on the coefficient of rock durability and normal thickness of BOI at the width of the cleaning chamber of the second stage of 25 m, two versions of the development system with an open cleaning space can be used: with a sublevel and a horizon cleaning.

By analyzing the graphs presented in Fig. 6, we can conclude that with an increase in the width of the cleaning chamber of the second stage, the exposure strike decreases with a decrease in the coefficient of durability of the rocks from which the non-ore or ore-containing inclusion is formed.

With an increase in the coefficient of durability of rocks from 8 to 16, the width of the cleaning chamber varies from 25 to 45 m at a normal BOI thickness of 10 m.

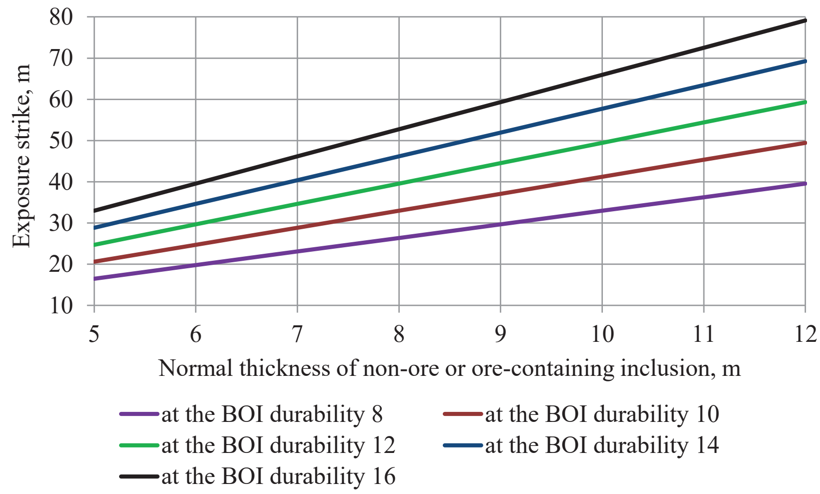


Fig. 6. Dependences of the minimum exposure strike depending on the width of the cleaning chamber of the second stage of the block development and the coefficient of durability of the BOI rocks with normal thickness of non-ore or ore-containing inclusion of 10 m at the factor of structural massif weakening of 0.85 and the safety factor of 1.5

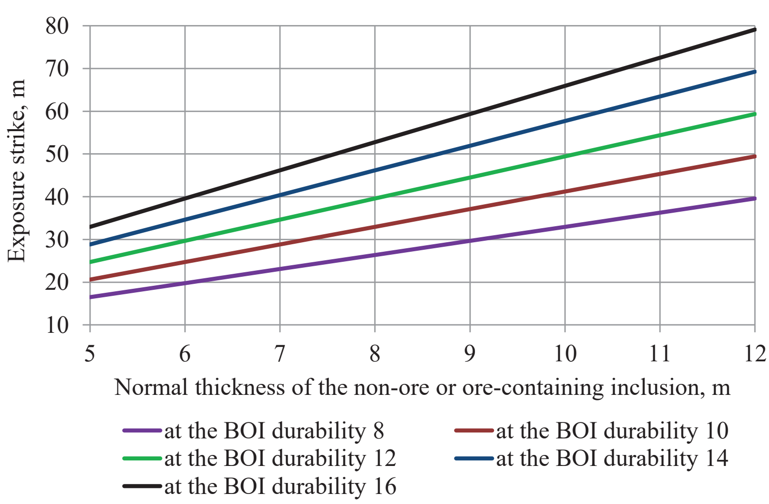


Fig. 5. Dependences of the minimum exposure strike on the normal thickness of the non-ore or ore-containing inclusion with the content of the useful component below the cut-off grade and the coefficient of durability of the BOI rocks at the width of the cleaning chamber of the second stage of 25 m, the factor of structural weakening of the massif equal to 0.85 and the safety factor of 1.5

Analysis of the chamber development systems used in the mines of the Kryvyi Rih iron ore field has established that the width of the cleaning chambers is 20–35 m. Thus, the obtained values will not significantly change the extraction technology in the development of the CSOD by chamber development systems.

According to formula (18), calculations of the exposure strike were performed for ($a<l_{str}$). The study results are shown in Fig. 7 for the normal BOI thickness and in Fig. 8 for the width of the cleaning chamber.

It is evident from the graph shown in Fig. 8 that with increase in the normal BOI, thickness from 7 to 12 m, the exposure strike increases from 26 to 76 m at the coefficient of durability of the BOI rocks equal to 16.

With a decrease in the BOI rock thickness from 16 to 8 and normal thickness of inclusion of 10 m, the strike of exposure in the cleaning chamber of the second stage of development decreases from 54 to 27 m.

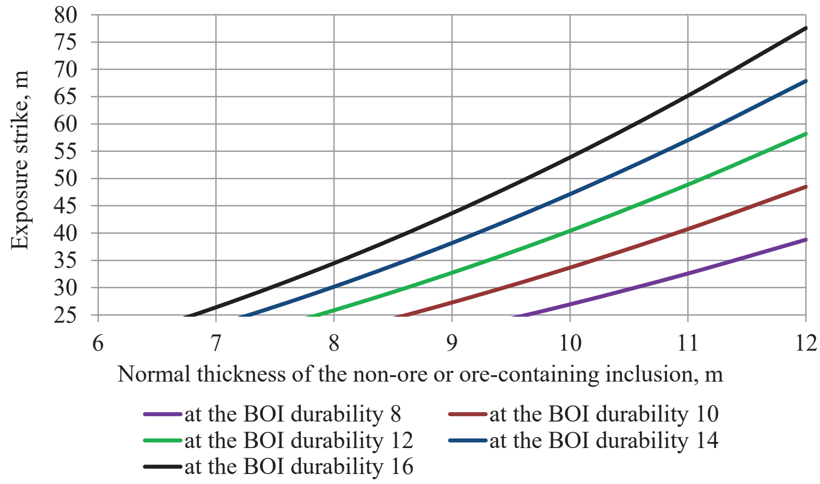


Fig. 7. Dependences of the minimum exposure strike on the normal BOI thickness provided that ($a < l_{str}$) and the coefficient of durability of the BOI rocks at the width of the cleaning chamber of the second stage of 40 m, the factor structural massif weakening of 0.85 and the safety factor of 1.5

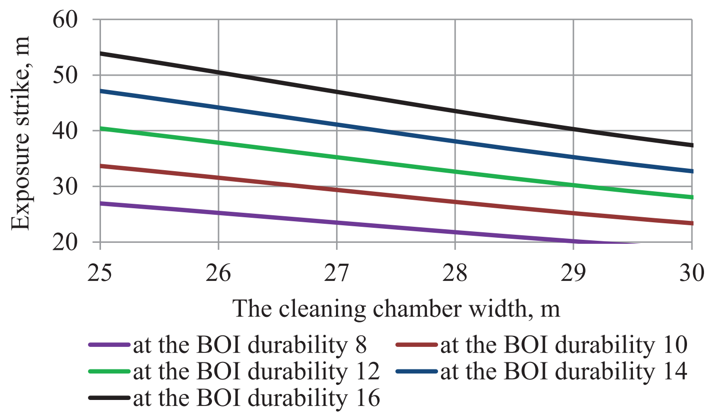


Fig. 8. Dependences of the minimum exposure strike depending on the width of the cleaning chamber of the second stage in the development of the pillar provided that ($a < l_{str}$) and the coefficient of durability of the BOI rocks at the normal BOI thickness of 10 m, the factor of structural weakening of the massif equal to 0.85 and the safety factor of 1.5

With an increase in the cleaning chamber from 25 to 30 m, strike of the inclined camera exposure decreases from 54 to 38 m at the coefficient of durability of the BOI rocks equal to 16 according to Prof. Protodiakonov's scale.

Analysis of the graphs shown in Fig. 7, 8 has established that at a normal BOI thickness less than 10 m and durability less than 10–12, it is expedient to apply version of the sublevel-chamber system of development (Fig. 4, *b*). With an increase in thickness or coefficient of rock durability, it is expedient to apply the sublevel-chamber version for the length of the cleaning chamber along the strike more than the inclined strike of exposure (Fig. 4, *c*).

Analysis of the graphs shown in Fig. 9 shows that the BOI exposure strike increases in a direct proportion to the normal thickness. For example, with an increase in the normal BOI thickness from 5 to 12 m and durability of rocks from 8 to 16, the exposure strike increases from 10 to 35 m. It should be noted that at a normal BOI thickness of 12 m and the cleaning chamber width of 40 m, the exposure strike increases from 25 to 35 m with an increase in the coefficient of durability from 8 to 16.

With an increase in the cleaning chamber up to 60 m at a normal BOI thickness of 10 m and a decrease in its durability factor from 16 to 8, the exposure strike is reduced from 28 to 20 m, respectively. With reduction of the cleaning chamber width from 60 to 40 m at the coefficient of rocks durability equal to 16, the exposure strike increases from 28 to 35 m, Fig. 10.

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 [46]. However, the disadvantage of this modeling method consists in large tensions and long time required for both model creation and development.

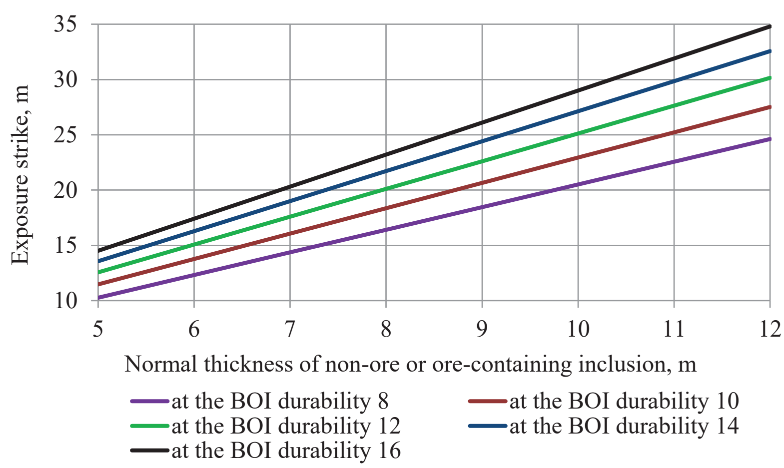


Fig. 9. Dependences of the minimum exposure strike depending on the normal BOI thickness provided that ($a > l_{str}$) and the coefficient of durability of the BOI rocks at the width of the cleaning chamber of the second stage of 40 m, the factor of structural massif weakening equal to 0.85 of the safety factor equal to 1.5

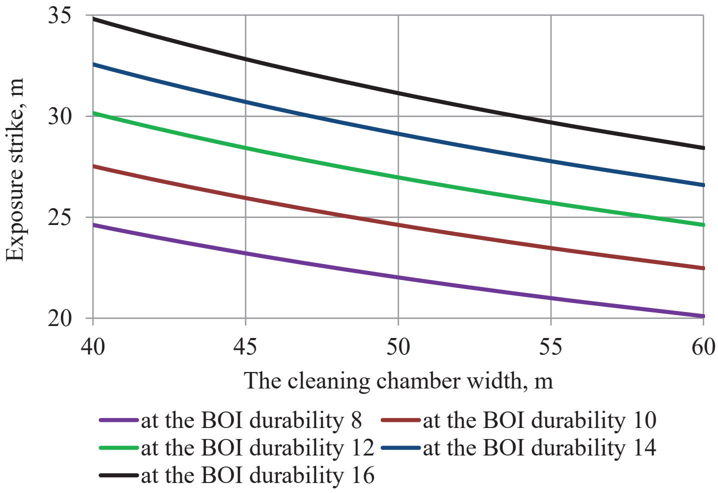


Fig. 10. Dependences of the minimum exposure strike on the width of the cleaning chamber of the second stage in the block development provided that ($a > l_{str}$) and the coefficient of durability of the BOI rocks at the normal BOI thickness is 10 m, the factor of structural massif weakening is equal to 0.85 and the safety factor is equal to 1.5

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:

– initial stage: without development, Fig. 11, *a*;

– intermediate stage: formation of a cleaning chamber in the hanging wall, Fig. 11, *b*;

– final stage: the formation of a cleaning chamber in the lying wall, Fig. 11, *c*.

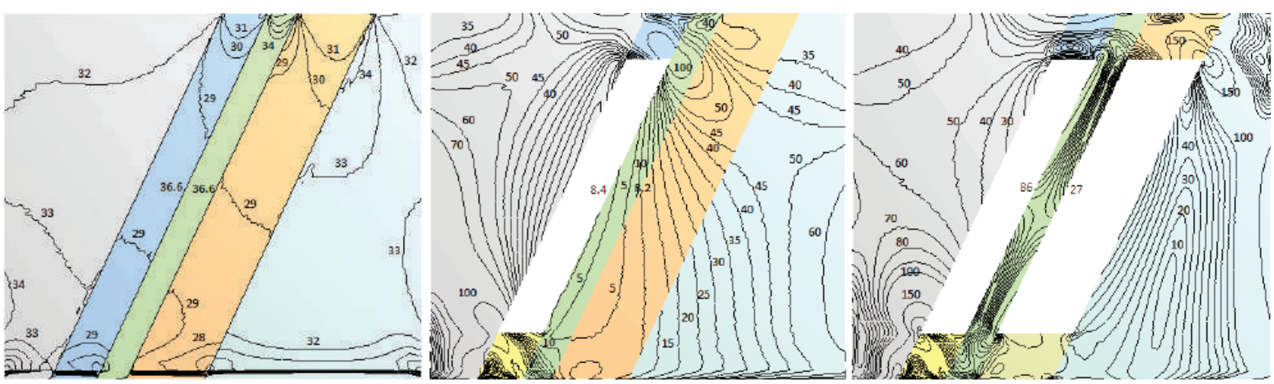
A total of 9 series of studies were conducted. They differed in physical and mechanical properties of the ore massif and the BOI. All other indicators (development depth, horizon level, thickness) remained unchanged.

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, see Fig. 11.

According to the results of the performed studies, dependences of the change of equivalent stresses in the middle part of the non-ore inclusion were plotted, Fig. 12.

It can be seen from the graphs in Fig. 12 that nature of the change of equivalent stresses in the BOI in its middle part is only affected by the sequence of development operations in the extraction block.

At the same time, an increase in the limit of proportionality occurs according to the Hook's law which is caused by the subsequent loading of the material beyond the yield strength [2, 16, 38].



a *b* *c*

Fig. 11. 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, b, c*)

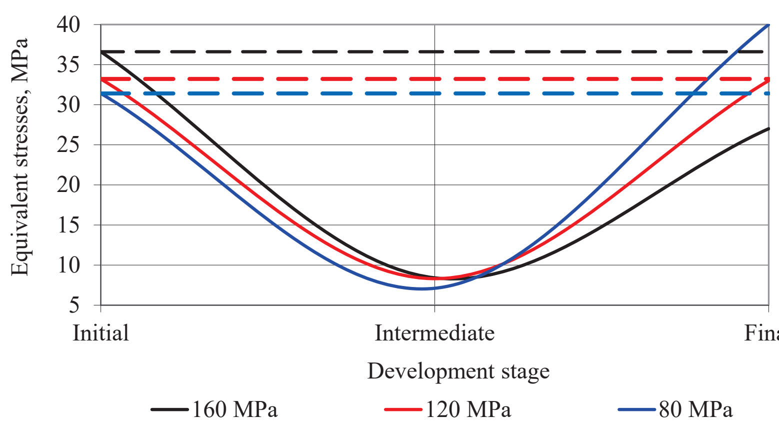


Fig. 12. Dependences of the change of equivalent stresses in the middle part of the non-ore inclusion on the stage of development operations, compression strength of the BOI rocks at the ore strength of 90 MPa at the horizon level of 90 m

Thus, in the case when compressive strength of the non-ore inclusion rocks is more than 120 MPa (rock durability of 12 according to the Prof. Protodiakonov scale), the cleaning chambers of the first and the second stages will be stable. It should be noted that it is practically impossible to reproduce the rock massif by mathematical modeling, so the exposure strike of the cleaning chamber must be reduced by the safety factor.

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.

Comparison of the results of analytical study, Fig. 5, with the simulation results has shown that a cleaning chamber having width of 25 m with an inclined exposure strike of 57 m and strength of 120 MPa will be stable and the difference between the values of the inclined exposure strike does not exceed 3.2 %.

In the case when the BOI strength is 80 MPa, the cleaning chambers will be destroyed at the exposure strike of 58.9 m. According to analytical calculations for the given conditions, the exposure strike should not exceed 39 m, Fig. 5.

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

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.

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.

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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