

Mining of rich iron ore deposits of complex structure under the conditions of rock pressure development

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Abstract. The purpose of research is to increase the ore mass extraction ratio when mining rich iron ores by changing the shape of the stope chamber, as well as to substantiate its stable parameters under the conditions of the rock pressure manifestation. Used in mines existing methodologies for determining the structural elements of mining system are based on calculated equivalent spans of outcropping the stope chambers, which have a rectangular or tent shape. For the first time using the ANSYS software package, it has been determined that the formation of a compensation chamber of quasi-parabolic shape can significantly reduce the stresses concentration around the stope block. Thus, the formation of a stope chamber of a quasi-parabolic shape makes it possible to reduce vertical stresses as compared to horizontal ones without increasing horizontal pressure. When mining the extraction block, it is proposed to form the stope chamber of a quasi-parabolic shape with geometric parameters that directly depend on the parameters of the deposit, the depth of mining, and the direction of main stresses action. Dependences have been determined of the stresses value on the depth of mining and the physical properties of rocks, as well as on the length along the strike of the ore deposit. Thus, depending on the mining depth and length along the strike, rock pressure on the stope chamber of a quasi-parabolic shape decreases under non-uniform loading. The formation of a stope chamber of a quasi-parabolic shape will increase by 1.2 – 1.5 times the volume of pure ore that is recovered from the block.

1 Introduction

Iron ores of the Kryvyi Rih Iron-ore Basin are mined by underground method at a depth below 1350 m with a useful component content of 58 – 67% in the massif [1 – 3]. When using traditional systems of mining, the iron content in the mined ore mass does not exceed 59 – 61%. A decrease in the iron content in the mined ore mass leads to losses in the global

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market, and this is caused by the fact that the market needs products with a higher iron content than 62% in marketable products [4 – 6].

In order to be in demand in the global market, mining enterprises increase the efficiency of mining the deposits by improving certain technological processes, namely: application of various methods for minerals beneficiation in underground or above-ground conditions [7 – 11], the improvement of mining systems used in mines [12 – 18], and introduce the latest technological elements of the mining system at the first stage of underground mining of the stope block, which ensure the extraction of not diluted ore at the level of 88 – 92% [19 – 22]. It should be noted that the proposed technological processes can significantly increase the iron content in the mined ore mass, however, production costs may increase by 1.2 – 1.4 times.

In the Kryvyi Rih Iron-ore Basin, when using traditional mining systems at an increased depth of mining, high and low pressure zones simultaneously arise around the mined-out space. This leads to formation of rock falls [23 – 25], and, as a consequence, to additional ore dilution before mining the stope block (at the stage of the compensation space formation).

The authors in the works [26 – 31] propose to improve the process of the mined ore mass beneficiation by automating the process and taking into account the physical-chemical properties of minerals. This significantly increases the useful component content in the mined ore mass, however, the cost price of marketable products increases, production volumes decrease, and the ecological situation in the region worsens, which requires certain costs for its remediation [32, 33]. Therefore, it is expedient to reduce the ore dilution directly in the block.

In the works [34 – 42], the authors improve the ore mining technology by optimizing certain technological processes. This significantly reduces the production costs and improves working conditions during underground mining operations. The performed laboratory studies confirm the effectiveness of the certain processes modernization [43 – 48]. Thus, with the improvement of a certain technological process, the useful component content in the mined ore mass increases by 1.0 – 1.5%.

It should be noted that the ore deposits of the Kryvyi Rih Iron-ore Basin are heterogeneous and have a complex structure. The development of such deposits by traditional systems of mining leads to worsening the extraction ratio due to waste rock inclusions in the ore massif. The authors of the works [49 – 54] propose various mining systems, which are based on the selective mining of iron ore. This technology includes the stage-by-stage mining of the stope block and the separation of ore from waste rock directly in underground conditions.

This principle of mining is widely used at the Kiruna mine (Sweden), where an iron ore deposit is developed. In order to improve the useful component quality of the mined ore mass in the final product, it is sorted at the stage of transportation in underground conditions [55 – 57]. This enables output of the final product with a useful component of appropriate quality without beneficiation process, in addition, the extraction ratio of pure ore is 90 – 92%. The application in the conditions of Kryvyi Rih Iron-ore Basin of mining technology which is used at the Kiruna mine will lead to an increase in operating expenses by 2 – 5 times.

The operational experience of mines in the Kryvyi Rih Iron-ore Basin has proved that the efficiency of deposits mining is influenced by the order of stope extraction and the system of mining [58 – 60]. Thus, when applying a system of mining with end drawing of ore, the authors of the works [61 – 64] make a conclusion that when the seams from the side of the hanging wall are mined in advance, this reduces the rock pressure in the ore body along the main strike. In order to increase the useful component content in the mined ore mass, the selective mining of rich ores by systems with mass collapse and with an open stope space is proposed. The proposed technological solutions can significantly increase the useful component content in the mined ore mass by 2 – 5% without increasing the production costs and additional beneficiation processes. However, when using these mining systems in unstable rocks, waste rocks penetrate into the compensation space at the stage of preparing

the stope block for extraction, which significantly worsens the extraction ratio [1 – 3].

As a result of research [1, 20], it has been revealed that the shape of the compensation space greatly influences on the rock mass stability in the conditions of the rock pressure manifestation. Thus, it has been proved that when mining the deposit of the main strike using a sloping compensation chamber, the normal stresses in the upper part of outcropping span decrease by 4 times. And the most unstable shape of the chamber is horizontal, due to an increase in normal stresses at significant depths by 2 times compared with vertical or sloping compensation chambers.

According to the practice data and theoretical studies, mine workings of a round, tent and arched shapes are the most stable forms of the mined space. When mining steeply dipping stratified ore deposits, it is practically impossible to mine an extraction block using round or tent-shaped stope chambers. This is explained by the geological conditions of the Kryvyi Rih Iron-ore Basin. If to construct an arch-shaped stope chamber with a height of 45 – 90 m under the conditions of the Kryvyi Rih Iron-ore Basin, it leads to ore losses up to 20 – 25% during mining the pillars between chambers. When decreasing the ore losses to the normative 16%, the pure ore extraction ratio does not exceed 70%.

2 Methods

To solve the problem of increasing the iron content and reducing ore losses during mining of ore deposits with a complex structure, it is advisable to apply the approach proposed in the works [1 – 3]. The authors propose to modernize the traditional beneficiation processes by involving the techniques of hydrometallurgical and chemical processing, which increase the beneficiation efficiency through the use of other energy types. This direction of beneficiation modernization is based on the processes of force action on a substance during disintegration in the activator and is not related to the processes of underground mining of minerals.

Based on the performed critical analysis of the works devoted to mining and processing of minerals, the following conclusions can be drawn:

1. With the purpose of increasing the iron content in the mined ore mass, the authors propose underground or above-ground beneficiation of the mined ore mass, which will lead to an increase in the production costs of marketable products.
2. Increasing the iron content in the mined ore mass by changing the order of mining the blocks and the mining system (chamber systems of mining with a temporary pillar, which is remained between them). However, under the conditions of the rock pressure development, further mining of pillars between the chambers will lead to worsening the extraction ratio of their mining or to the impossibility of their mining.

Thus, there is a need to improve the technology of rich iron ore mining, which could increase the iron content in the mined ore mass under conditions of the rock pressure manifestation at great depths.

3 Results and discussion

The efficiency of mining system is determined by the extraction ratio and the ore mass production costs. To increase the mining system efficiency, it is expedient to increase the volume of the stope chamber while providing it with stable parameters. An increase in the volume of a rectangular-shaped stope chamber by 1.1 – 1.5 times leads to a decrease in its stability and an increase in the pillars width, the time of mining the block (panel), operating expenses, and the expenditures for mining the pillars between chambers.

According to the studies [1 – 3], a shape of the stope chamber should be close to the figure of drawing, which is an ellipse. It should be noted at the same time that the conditions of the chamber stability are not determined. In the work [60], the author states that when

constructing parabolic-shaped stope chambers, the chamber stability and its volume increases (Fig. 1).

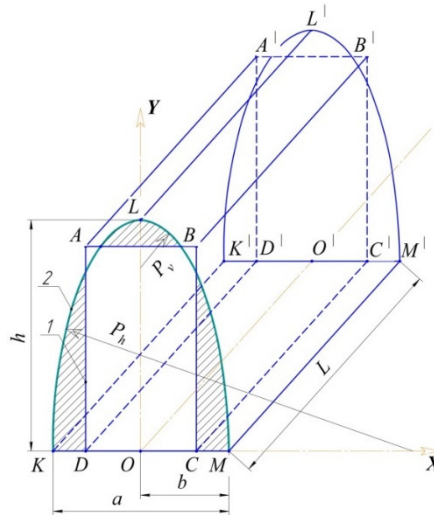


Fig. 1. Computational scheme for determining the volume of a parabolic-shaped chamber: 1 – contour of a rectangular-shaped chamber; 2 – contour of a parabolic-shaped chamber.

The points coordinates of the *KLM* curve, which describes a parabolic-shaped chamber (Fig. 1), are determined by the expression:

$$y = -c \cdot \frac{\int (x^{2k-1} dx)}{\sqrt{(b^2 - x^2)^r}} \text{ at } k > 0,5; 0 < r < 2,$$

where c , k are real numbers; r is smaller odd real number; x , y are current coordinates.

When changing the values of x from 0 to b , the function curve decreases, and the curve *ML* is convex for all values of the derivative $-b < x < b$. The stope chamber stability is ensured in the case when the current maximum stresses in the mine rock massif are less than the ultimate strength of the ore or the rocks surrounding it. The condition of stable equilibrium is described by the expressions [61], t/m^2 :

$$\sigma_{\max} \leq [\sigma], \quad \tau_{\max} \leq [\tau], \quad \sigma \gg \tau,$$

where σ_{\max} is maximum stresses of internal forces in the massif, t/m^2 ; τ is maximum shearing stresses occurring in the massif, t/m^2 ; $[\sigma]$ is ultimate strength of the material, t/m^2 .

It is known that when calculating the pillars stability, the main criterion is bending [66, 67]. However, in the rocks of massif when exceeding the maximum stresses, the zones of fractures are formed, which lead to a decrease in the ultimate strength of the pillar composed by rocks, and eventually to its destruction.

In the work [65], it is proved that the specific weight and depth of mining influence on the main vertical stresses. In the virgin rock massif, the main vertical stresses are maximum, and during underground mining operations they remain unchanged or decrease. Thus, the value of the critical pressure must satisfy the boundary conditions [65, 68], t/m^2 :

$$\begin{cases} [\sigma] \geq \sigma_3; \\ \sigma_3 = \gamma \cdot H, \end{cases}$$

where σ_3 is main vertical stresses, t/m^2 ; γ is specific weight of mine rocks, t/m^3 ; H is depth of mining operations, m.

According to the studies [68, 69], it has been proved that the critical pressure arising on the contour of the chamber depends on the radius of the curvilinear outcropping of the mine working, the angle of the applied load, and the physical-chemical properties of mine rocks. The volume of the parabolic-shaped chamber is determined from the expression, m^3 :

$$V = \pm 2 \cdot L \cdot a \cdot \int_0^b \left(2 \cdot \sqrt[3]{\frac{\sigma_3^2}{[\sigma_{st}]}} \right) \cdot \sqrt[4]{1 - \frac{x^2 dx}{4 \cdot \sigma_3 \cdot \sqrt[3]{\frac{\sigma_3^2 \cdot \cos \beta \cdot \operatorname{tg} \rho}{[\sigma_{st}]^2}}}} \Bigg)^3, \quad (1)$$

where L is length of the stope chamber along the strike, m; a is width of a parabolic-shaped stope chamber, m; β is shear angle of mine rocks, deg.; ρ is angle of internal friction of mine rocks, deg.; $[\sigma_{st}]$ is ultimate compressive strength of rocks, t/m^2 .

It should be noted that the total pressure σ_3 , included into formula (1), is determined as a uniformly distributed load. When determining the load on the stope chamber (extraction block), the weight of the overlying rocks should be taken into account, depending on the order and sequence of mining the block on the level.

The *first* – the load from the rocks is accepted as uniformly distributed when the height of the dynamic arch is greater than the height of the rocks collapsed to the earth's surface. In this case, the chamber is under impact of the total weight of the overlying rocks, which is determined by the formula, t/m^2 :

$$\sigma_3 = \gamma_b \cdot H \cdot K_l, \quad (2)$$

where γ_b is specific weight of collapsed rocks, t/m^3 ; K_l is coefficient of loosening the overlying rocks in the zone of collapse.

The *second* – the load is determined by the weight of the rocks enclosed in the arch of unstable equilibrium, when the height of the unstable equilibrium arch is less than the depth of mining, and the condition is satisfied, m

$$h_v \ll H,$$

where h_v is height of dynamic arch, m.

According to the arch hypothesis [65], the pressure on the block is determined by the weight of the overlying rocks enclosed in the arch of unstable equilibrium or in the dynamically unloaded dome (arch), from which particles move only under their own weight. With a high passing ability of particles and a small angle of internal friction, the displacement occurs very smoothly, and under the impact of vertical forces, the arch collapses, and therefore pulsating shocks are observed.

Velocity of falling out of particles or their replacement in a dynamic arch is determined by the ellipsoid height of the unstable equilibrium, the surface area of the dynamic arch, internal friction between the particles surfaces. The curve of the dynamic arch is described by the equation:

$$y^2 = 2 \cdot p \cdot x,$$

where p is height of the arch figure (dynamic arch), m; x is current coordinate along the axis x-x.

The specific load on the chamber from the host rocks, enclosed in an unstable equilibrium arch, is determined by the formula [68], t/m^2 :

$$\sigma_3 = \frac{\pi \cdot L \cdot \gamma_b}{8 \cdot f_r}, \quad (3)$$

where f_r is coefficient of internal friction.

Vertical pressure is always less than horizontal one, but in some mines, pressure can change reversely. Horizontal pressure is determined by the formula [65], t/m^2 :

$$\sigma_{1,2} = \frac{\mu}{1 - \mu} \cdot \sigma_3, \quad (4)$$

where μ is Poisson's ratio.

Having performed the calculations according to formulas (2), (3) and (4), the dependences of the stresses value on the depth of mining and the rocks physical properties have been constructed (Fig. 2).

It can be seen from the graphs in Fig. 2 that with a uniformly distributed load, with an increase in the depth of mining from 800 to 1600 m, the pressure increases from 1760 to 3520 t/m^2 , while the horizontal pressure decreases from 828 to 1656 t/m^2 . In the case when the pressure does not depend on the weight of the unstable equilibrium arch and on the mining depth, and remains constant, with a length 1000 m along the strike of the mine field, the pressure is 1727 t/m^2 .

Fig. 3 presents the dependences of the pressure change in the arch on the length of the ore deposit along the strike.

It can be seen from Fig. 3 that with an increase in the length of mining the ore deposits from 600 to 1400 m, the pressure in the arch increases from 1036 to 2418 t/m^2 . Thus, it is possible to reduce the pressure in the block by reducing the length of mining the ore deposits, leaving supporting pillars or distributing the deposit into separate extraction blocks.

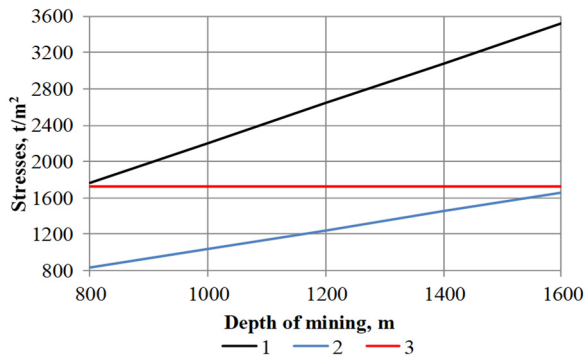


Fig. 2. Dependences of the stresses value on the depth of mining and the rocks physical properties: 1 – uniformly distributed vertical load; 2 – horizontal load; 3 – load in the arch.

In order to confirm theoretical studies, laboratory experiments have been performed by numerical method using finite elements. To do this, using the ANSYS software package, the research has been conducted on the distribution of equivalent stresses around the stope chambers of rectangular and quasi-parabolic shapes (Fig. 4).

It should be taken into account that this software package is able to calculate the equivalent stresses in the massif. Using the ANSYS software package, the stable parameters of the stope chamber structural elements, such as width, length, equivalent stretch of outcropping, have been determined according to the mining-and-geological conditions of the Ternivska mine of PJSC “Kryvbaszalizrudkom”.

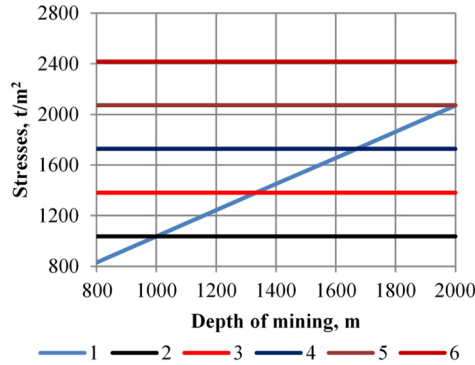


Fig. 3. Dependences of the stresses value on the depth of mining and length along the strike of the ore deposit: 1 – horizontal load; 2, 3, 4, 5 – the load in the arch with a deposit length of 600, 800, 1000, 1200 and 1400 m, respectively.

The following data were initial for the calculations: specific weight of the rocks is 2800 kg/m^3 ; ultimate compressive strength is 60 MPa ; ultimate tensile strength is 9 MPa ; Young's modulus is 50000 MPa ; Poisson's ratio is 0.23 ; cross-sectional area of a chamber is 1970 m^2 ; depth of mining is 1200 m . The parameters for the rectangular-shaped stope chamber are as follows: width – 33 m , height – 60 m . For a parabolic-shaped chamber: the radius of the vertical outcropping – 77.5 m , the radius of horizontal outcropping – 5 m , the width of the stope chamber – 50 m and the height – 60 m .

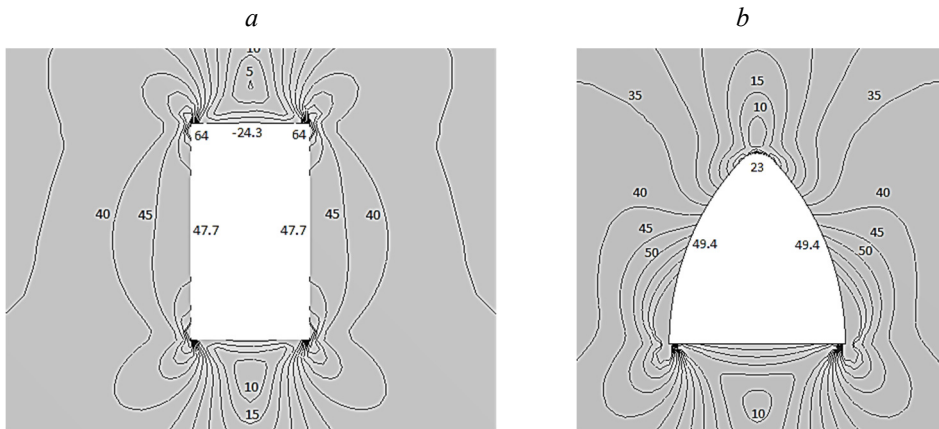


Fig. 4. Distribution of equivalent stresses around the stope chamber: a – rectangular-shaped; b – parabolic-shaped.

By analyzing the calculated data (Fig. 4), it has been determined that on the contour of the stope chamber in the middle part compressive stresses act, which differ by no more than 3.45% . It should be noted that the volume of the parabolic-shaped stope chamber is increased by 1.2 times compared to a rectangular-shaped chamber, while the equivalent stresses from the sides of the chamber have the same values.

Thus, it can be argued that a change in the shape of the stope chamber provides it with additional stability by changing the tensile stresses to compressive ones in the upper part of the chamber.

4 Conclusions

It has been determined that in unstable rocks at a depth of 1350 m and a deposit length along the strike of 600 m, vertical stresses are less than horizontal ones by 370 t/m². In this case, the stope chamber width increases depending on the ratio of vertical and horizontal outcroppings from 1.08 to 1.55 times, ensuring its stability. With an increase in the length of the deposit along the strike from 600 to 1400 m with a radius of vertical outcropping of 90 m, the chamber width should be reduced from 1.55 to 1.23 times.

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