Study of Compensation Room Impacts on the Massif Stability and Mined Ore Mass Quality

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Abstract

The paper presents the study and a functional analysis of requirements of the world metallurgical industry to the quality of underground iron ores at underground mines of Ukraine. There are found dependencies of the impact of the shape and parameters of compensation spaces on their stability and broken ore quality indicators. It is proved that a vertical trapezoidal compensation room possesses the highest stability and is stable within the range of all the considered depths, even in ores with hardness of 3–5 points. Less atabiity is demonstrated by a vertical compensation room of a vaulted shape with minor falls in the abutment of the room vault in ores with hardness of 3–5 points at the depth of 2000 m, and a tent-shaped one where falls of varying intensity occur in the lower part of inclined exposures of the tent in ores with hardness of 3–5 points at the depth of 1750 m or more. The horizontal compensation room is of the lowest stability; falls occur in ores with hardness of 3–5 points at the depth of 1400 m, and at the depths of 1750–2000 m it remains stable only in harder ores. It is established that the use of compensation rooms of high stability makes it possible to achieve their maximum volume, increase the amount of pure ore extracted, reduce its dilution, enhance the quality of the mined ore mass and concequently increase its price and competitiveness of marketable products.

Keywords: *underground mining, iron ore, compensation rooms, stress-strain state, stability, quality*

1. INTRODUCTION

Today, Ukraine posesses significant reserves of rich iron ores which are mined by the underground method. The main problem of underground mining is a decrease in the quality of the extracted raw materials due to deepening of mining operations.

In addition, completeness of extraction of broken ore and its deteriorated quality are factors that significantly ipmact economic results of underground mining. Currently, in Ukraine underground mining of iron ore is accompanied with ore losses and dilution at the level of 14–20% and 12–18% respectively. As a result, up to 20% of underground iron ore is lost.

Such rather low extraction degrees are largely due to obsolete mining equipment and technology. This causes losses of part of broken ore underground and dilution of a certain part of the reserve with waste rocks. Mining technologies that allow minimizing or even eliminating broken ore losses and dilutiion are expensive and used only in particularly difficult mining conditions.

Thus, achievement of maximum mining efficiency can be provided by establishing the optimal ratio between values of ore extraction indicators and the amount of allowable costs for ore production.

In our opinion, the mined ore quality can be enhanced by increasing the volume of compensation rooms, which will increase the amount of pure ore extracted from them, reduce ore dilution and enhance the mined ore mass quality. This results in the increased price and competitiveness of marketable products.

2. PURPOSE

The presented paper aims to theoretically and experimentally substantiate and develop efficient technological means of controlling the quality of raw materials through the study and selection of optimal shapes and sizes of compensation rooms.

For this, the following tasks are solved in the paper:

- analysis of relevant researches and publications;
- substantiation of the research methods;
- presentation of the study results and corresponding conclusions.

3. ANALYSIS OF RESEARCHES AND PUBLICATIONS.

Compensation rooms are known to be used when applying mining systems with breaking ore and country rocks to compensate for the increased volume of ore during its bulk caving [1–4,11].

Such systems are used in our underground mines in conditions of insufficient hardness and stability of both ore and country rocks. Iron ore deposits are mined mainly within the depths of 1200–1400 m with further deepening to 1800–2000

Tab. 1. Physical and mechanical properties of ore and caved rocks

Tab. 1. Właściwości fizyczne i mechaniczne rudy i skał zawałowych

Parameters	Units of measurement	Ore			Caved rocks
		1P (*f*=3-5)	2P (*f*=4-6)	3P (*f*=5-7)	
Young modulus	MPa	22000	25000	28000	5000
Specific weight	kg/m^3	3700	3650	3600	2300
Compressive strength	MPa	30	40	50	4
Tensile strength	MPa	3	4	5	0.2
Poisson ratio		0.30	0.28	0.26	0.24

Tab. 2. Pressure of caved rocks on the rock massif (computer-aided modeling)

Tab. 2. Nacisk skał zawałowych na masyw skalny (modelowanie komputerowe)

Parameter	Unit of measurement	P1	P2	P3
Pressure of caved rocks on massif, vertical/lateral	MPa	8.2/29	9.7/3.4	11.5/4

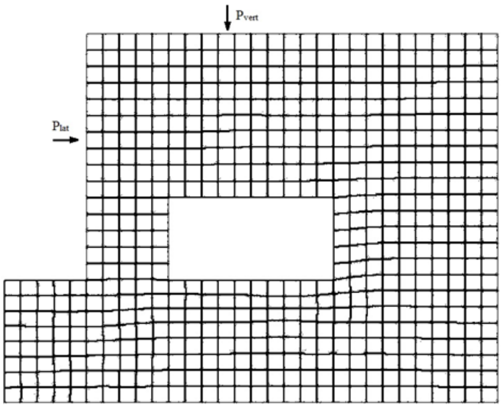

Fig. 1. Finite-element model with the horizontal compensation room

Rys. 1. Model elementów skończonych z pomieszczeniem kompensacji poziomej

m. Considering the above facts as well as negative effects of rock pressure at deep levels, the problem arises of choosing the most rational shape of compensation rooms [5–8,16].

It is established that the shape of the compensation room significantly impacts the stress-strain state (SSS) of the rock massif around it, which in turn impacts its stability [9–12]. Therefore, data on such disturbances is crucial both at the stage of designing and in the process of mining the deposit [11,13–15,17].

So, in practice, there is applied operational assessment of values of actual stresses in the massif, prediction of the nature of their change in creating compensation rooms [18–22]. This information allows assessing the input data on enhancement and development of new shapes of compensation spaces, selecting the optimal parameters of compensation rooms and determining the rational technology of their creation [23–27,29,30].

4. METHODS.

The main idea of the presented paper consists in finding a shape that would make it possible to avoid formation of areas of high compressive stresses which, as a rule, are concentrated around the corner areas of the rooms. It is also necessary to avoid emergence of areas of tensile stresses that are the most dangerous due to the fact that the tensile strength of rocks is an order of magnitude less than the their ultimate compressive strength [28,31–36].

The finite element method (FEM) and the specialized Ansis 2021-P2 software package are used for modeling [11,37–42].

In the course of the study, models of the following shapes of compensation rooms are processed: horizontal, vertical (rectangular, trapezoidal and vaulted), inclined (with different angles of inclination of the roof of these rooms – 20, 35 and 50 degrees), tent, trench, elliptical (parabolic) and spherical. For correct comparison, sizes of compensation rooms of different shapes are the same.

For each shape of the compensation room, finite-element models are developed that simulate mining of the extraction panel. The size of the finite elements is 2 m. Fig. 1 exemplifies the finite-element model with a horizontal compensation room.

To study the impact of ore hardness on the stress-strain state of the massif and stability of rooms, 3 types of ores are put in the model: with hardness of 3–5 (average 4), 4–6 (average 5) and 5–7 (average 6) points (Protodyakonov scale of hardness).

The main physical and mechanical properties of ore are given in Table 1.

The values of the caved rocks pressure on the ore massif P_1, P_2 and P_3 correspond to the mining conditions of Krivbas deposits at the depth of 1400, 1750 and 2000 m respectively and are given in Table 2.

5. RESULTS

The volume of each compensation room directly depends on the coefficient of loosening and the volume of ore to be caved during bulk blasting. Given that the compensation room is located in the ore massif and does not come into con-

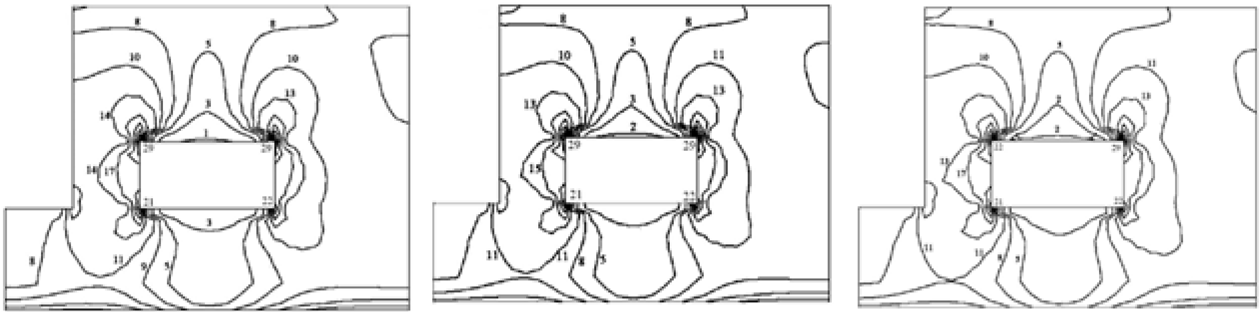

Fig. 2. Isolines of the principal stresses σ1 of the rock massif during creation of a horizontal compensation room in the panel: the pressure of caved rocks P1, ores with hardness a) 3–5, b) 4–6, c) 5–7 points respectively

Rys. 2. Izolinie naprężeń głównych σ1 masywu skalnego podczas tworzenia poziomego pomieszczenia kompensacyjnego w panelu: ciśnienie skał zawałowych P1, rudy o twardości a) 3–5, b) 4–6, c) 5–7 punktów

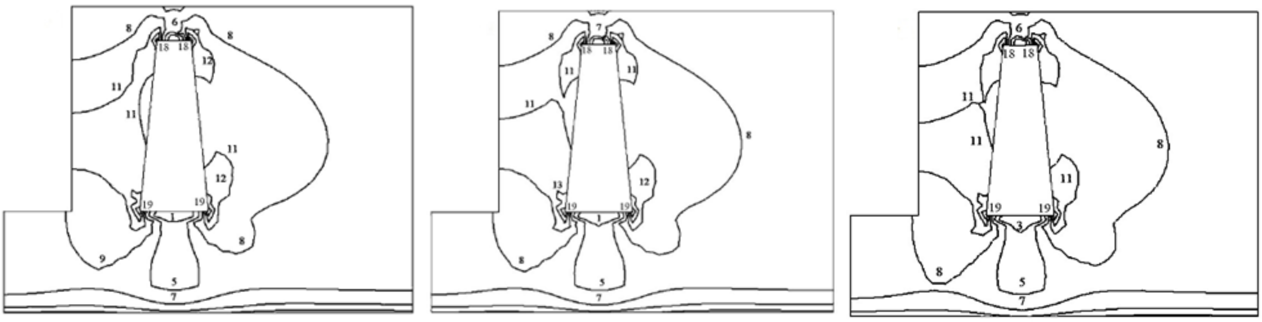

Fig. 3. Isolines of the principal stresses σ1 of the rock massif when creating a vertical trapezoidal compensation room in the panel: pressure of caved rocks P1, ores with hardness a) 3–5, b) 4–6, c) 5–7 points respectively

Rys. 3. Izolinie naprężeń głównych σ1 masywu skalnego przy tworzeniu w panelu pionowego trapezoidalnego pomieszczenia kompensacyjnego: ciśnienie skał zawałowych P1, rudy o twardości a) 3–5, b) 4–6, c) 5–7 pkt.

tact with waste rocks, it is resonable to increase the volume of compensation to increase the amount of pure ore extracted. By increasing the proportion of high-quality pure ore to be extracted from the compensation room during its creation, we enhance the quality of the mined ore mass on the whole.

Nowadays, in underground mines of Kryvyi Rih basin, the most common shapes of compensation rooms are classic ones: horizontal, vertical and inclined. Many scientific and technical developments are devoted to the search for other, more efficient shapes. The latter include trapezoidal, which is a kind of vertical room, tent, trench, parabolic (vaulted) and other shapes. The main idea behind such studies is to find a shape that would make it possible to avoid creation of areas of very high compressive stresses which, as a rule, are concentrated around the corner areas of the rooms. The shape of the rooms should reduce the possibility of emergence of areas of tensile stresses that are the most dangerous as the tensile strength of most iron ores is almost an order of magnitude less than their ultimate compressive strength.

Fig. 2 shows the results of modeling and isolines of the principal stresses σ1 of the rock massif when creating a horizontal compensation room in a panel in ores with hardness 1P, 2P and 3P respectively.

The figures demonstrate that the nature of distribution of the stress field around the compensation room is fully consistent with the classical ideas: areas of increased compressive stresses are concentrated around the corner areas of the room, and in the central part of the horizontal exposure there is an area of reduced compressive stresses. This confirms adequacy of the developed models and the modeling results obtained.

As is seen from the figures, at the same depth, with such a slight difference in ore hardness, absolute values of stresses do not practically differ from each other. Regarding the impact of the depth of operations, a very significant increase in the level of compressive stresses is observed in the corners of the room, which is also a natural phenomenon since this is a consequence of an increase in rock pressure.

Analysis of stability of the horizontal compensation room in different conditions reveals that in ores with hardness of 3–5 points at the depth of 1400 m, the maximum values of compressive stresses in the upper corners of the room practically reach the ultimate strength for these ores, i.e, in general, the room remains stable, but small local ore falls are possible in these areas. In harder ores at this depth, the room is stable.

With an increase in the depth of operations to 1750 m in ores with hardness of 3–5 points, the compensation room of this size loses its stability and fails, and in harder ores it remains stable.

At the depth of 2000 m, stability problems may occur in the form of small local ore falls in these areas. In harder ores at this depth, the room remains stable.

At the depth of 2000 m, stability problems may occur in such rooms when they are created in ores with hardness of 4–6 points, especially at increased fracturing degrees of the ore massif.

The value of the maximum principal stresses in the rock massif during creation of a horizontal compensation room is determined by the formula:

$$\sigma_1 = 24.678e^{0,1608H_p};$$

$$R^2 = 0.9987.$$

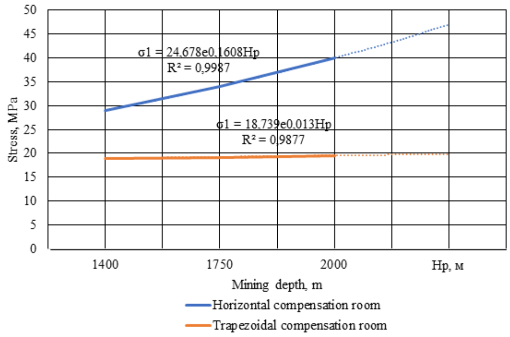

Fig. 4. Dependency of the value of the maximum principal stresses on the shape of compensation rooms and the depth of mining operations

Rys. 4. Zależność wartości maksymalnych naprężeń głównych od kształtu komór kompensacyjnych i głębokości eksploatacji

where σ_1 is the value of the maximum principal stresses
H_p is the depth of mining operations, m;
R^2 is the value of approximation reliability.

The results of modeling and isolines of the principal stresses σ1 of the rock massif during creation of the most common vertical rectangular compensation room in the panel in ores of different hardness (P1, P2 and P3) enable establishing the following.

Distribution of the stress field is characteristic of rooms of this shape: areas of concentration of high compressive stresses occur at the corners of the room, and areas of reduced compressive stresses are located in the central part of the roof and vertical exposures of the room.

At the same depth, at different ore hardness, values of stresses do not practically differ from each other. As in the previous option, there is a significant impact of the depth of operations on the stress-strain state of the massif. But the level of maximum compressive stresses is by15–20% smaller than for similar conditions (equal ore hardness and depth of operations) in the horizontal compensation room. A decrease in compressive stress values is not so significant either, which indicates higher stability of the vertical compensation room. Only at the depth of 1750 m with the ore hardness of 3–5 points in the upper corners of the room there may occur small falls, and at the depth of 2000 m volumes of falls will lead to failure of the crown of the room and its filling with overlying caved rocks. In harder ores, rooms remain stable throughout the range of the depths under consideration.

In addition to other shapes of compensation spaces, the authors propose an option of a vertical trapezoidal compensation room, Fig. 3.

The studies conducted enable asserting that in the proposed option, the nature of the stress field distribution is close to the previous ones. At the same time, compared to the previous option of the vertical rectangular compensation room, the level of maximum compressive stresses is much lower (by 25–30%) than in the most problematic upper corners of vertical rooms. This can be explained by a much smaller span of the roof of the room. As a result, compensation rooms of vertical trapezoidal shape remain stable at all the considered depths, even in ores of minimum (3–5 points) hardness.

The value of the maximum principal stresses in the rock massif during creation of a trapezoidal compensation room is determined by the formula:

$$\sigma_1 = 18.739e^{0.013H_p};$$

$$R^2 = 0.9877.$$

where σ_1 is the value of the maximum principal stresses
H_p is the depth of mining operations, m;
R^2 is the value of approximation reliability.

The graph of the dependency of the maximum principal stresses value on the shape of compensation rooms and the depth of mining operations is presented in Fig. 4.

6. CONCLUSIONS

Based on the modeling of the stress-strain state of the rock massif around compensation rooms of various shapes and its impact on their stability, the following conclusions can be drawn:

1. The level of the stress-strain state of the ore massif around compensation rooms with a small difference in ore hardness mainly depends on the depth of operations, and their stability is impacted by the value of stresses in particular conditions and physical and mechanical properties of ore which directly depend on its hardness.

2. The highest stability, as compared to all the others, is demonstrated by a vertical compensation room of a trapezoidal shape which remains stable within the range of all the considered depths, even in ores with hardness of 3–5 points.

3. Less stabiity is demonstrated by a vertical compensation room of a vaulted shape with minor falls in the abutment of the room vault in ores with hardness of 3–5 points at the depth of 2000 m, and a tent-shaped one, where falls of varying intensity occur in the lower part of inclined exposures of the tent in ores with hardness of 3–5 points at the depth of 1750 m or more but do not significantly impact its stability.

4. The inclined compensation room (roof inclination of 35–50°; minor falls occur primarily in ores of small (3–5 and 4–6 points) hardness but they do not impact significantly its stability at all the depths), the vertical rectangular compensation room (stability problems only occur in ores with hardness of 3–5 points at the depth of 2000 m) and the inclined compensation room (with the roof inclination angle of 20°) are somewhat inferior to the above mentioned ones. Regardless of falls, trench, elliptical and spherical compensation rooms only fail in ores with hardness of 3–5 points at the depth of 2000 m.

5. The horizontal compensation room demonstrates the lowest stability, falls occur in ores with hardness of 3–5 points

at the depth of 1400 m, and at greater depths (1750 and 2000 m) it remains stable only in harder ores.

6. The study conducted and practices of Kryvbas underground mines that extract rich iron ores enable the conclusion that so-called "unconventional" shapes of compensation rooms, in particular vertical trapezoidal ones, should find wider application.

7. Compensation rooms of higher stability enable their volume increase in ores of low stability, which will lead to a possible increase in the amount of pure ore extracted, reduced ore dilution and, accordingly, enhanced quality of the mined ore mass. This will result in the increased price and competitiveness of marketable products of our underground mines.

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Badanie wpływu kompensacji na stabilność górotworu oraz jakość wydobywanej rudy

Artykuł przedstawia studium i analizę funkcjonalną wymagań światowego przemysłu metalurgicznego co do jakości rud żelaza w podziemnych kopalniach Ukrainy. Stwierdzono zależności wpływu kształtu i parametrów przestrzeni kompensacyjnych na ich stateczność i wskaźniki jakości rudy. Udowodniono, że komora wyrównawcza w kształcie trapezu pionowego charakteryzuje się największą stabilnością i jest stabilna w zakresie wszystkich rozważanych głębokości, nawet w rudach o twardości 3–5 punktów. Mniejszą stateczność wykazuje komora kompensacji pionowej o kształcie sklepionym z niewielkimi spadkami w przyczółku sklepienia komory w rudach o twardości 3–5 punktów na głębokości 2000 m. Komora z opadami o różnym natężeniu występuje w dolnej części nachylonych odsłonięć namiotu w rudach o twardości 3–5 punktów na głębokości 1750 m lub większej. Pomieszczenie kompensacji poziomej ma najmniejszą stateczność; spadki występują w rudach o twardości 3–5 punktów na głębokości 1400 m, a na głębokościach 1750–2000 m pozostają stabilne tylko w rudach twardszych. Stwierdzono, że zastosowanie komór kompensacyjnych o dużej stabilności umożliwia osiągnięcie ich maksymalnej objętości, zwiększenie ilości wydobywanej czystej rudy, zmniejszenie jej rozrzedzenia, poprawę jakości wydobywanej masy rudy, a co za tym idzie, wzrost jej ceny i konkurencyjności rynkowej.

Słowa kluczowe: *górnictwo podziemne, ruda żelaza, pomieszczenia kompensacyjne, stan naprężenie-odkształcenie, stateczność, jakość*