Study of Stress Concentration on the Contour of Underground Mine Workings

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Abstract

Kryvyi Rih iron ore basin consists of complex structured ore deposits and is developed by the underground method at depths of over 1000 m. The underground method is used to mine reserves of rich iron ores with a useful component content of more than 59% applying bulk ore and rock caving systems. This leads to significant changes in the stress state of the rock massif. During underground operations, mine workings are strained and in some cases destructed. As a result, enterprises are constantly increasing operating costs for maintaining mine workings, which adversely impacts the cost of production. Industrial research results demonstrate that in most cases workings fail in their upper part which is vaulted in shape. Available methods for determining the state of rocks around mine workings do not fully take into account physical and mechanical properties of the rocks in which the working is located. The developed technique allows determining not only the destructive pressure impacting the workings, but also the angle at which the destructive force acts. This technique differs from the available ones in taking into account not only mining and geological characteristics of the deposit, but also most factors of physical and mechanical properties of rocks. This technique helps to choose a rational place for driving mine workings at the stage of design, thus avoiding significant additional cost for their maintenance.

Keywords: *stress, working, vault of stable equilibrium, pressure, stability, ultimate strength, rocks*

1. INTRODUCTION

Underground mining of mineral deposits leads to significant changes in the primary stress state of the rock massif that cause man-made disasters of a geomechanical nature [1–3]. In solving this problem, experimental research methods are used the results of which are the basis for determining the positive and negative nature of the change in the stress state of the rock massif [4–6]. The change in stresses occurs due to changes in the forces of mutual attraction and mutual repulsion between ions in the crystal lattice of rocks resulting in internal forces that counteract external ones [7–9].

According to [10–13], various measures to change the stress state of the rock massif lead to an increase in stability of mine workings through reducing concentration of stresses or cutting the cost of drilling and blasting due to increased concentration of stresses in the rock massif.

It is proved that if an elementary cube is separated from a stressed rock massif, three stress vectors can generally be detected on each of its faces: two tangential (mutually perpendicular) and one normal, Fig. 1, [14–16].

The internal stress state of the rock volume under consideration is a stress tensor and looks as follows

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

where σ_z is the internal stress arising in the rock MPa; τ_{ik} is tangential stresses arising in rocks, MPa; p_{ik} is a set of stresses relative to three mutually perpendicular areas at one point; n_i is a single normal vector to the corresponding plane under consideration; i, k are indices of the axes of coordinates x, y, z.

Stress concentration on the contour of workings can be reduced by changing their cross-sectional shape depending on the ratio of stresses acting in the cross-sectional plane of the workings. At that, the shape of the workings can be elliptical, arched, vaulted, round, tent-shaped, rectangular, rectangular-vaulted, etc. [17–19].

However, to ensure technological processes (drilling of the massif, ore drawing and haulage, ventilation, etc.), it is necessary to create workings of a large cross-sectional area which significantly reduces stability of the workings regardless of their shape.

The required area of underground mine workings depending on application of the relevant type of equipment is given in Table 1 [20, 21].

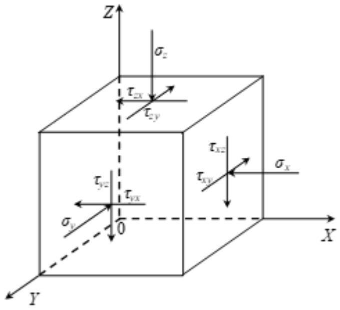

Fig. 1. Distribution of stress vectors in an elementary volume located in the rock massif

Rys. 1. Rozkład wektorów naprężeń w jednostkowej objętości znajdującej się w masywie skalnym

Tab. 1. Area of mine workings in underground mining at mineral deposits of Kryvyi Rih iron ore basin (Ukraine)

Tab. 1. Powierzchnia wyrobisk górniczych w górnictwie podziemnym na złożach kopalin Krzywego Rogu (Ukraina)

Mine workings	Mine workings area, when applying:	
	traditional equipment	self-propelled equipment
Capital workings (crosscut), m^2	12-18	18-24
Preparatory workings (haulage drift, haulage ort), m^2	8-16	16-20
Subsidiary workings, m^2:		
- drilling	8-12	14-18
- undercut	4-8	8-12
- raise	2-4	4-6
- transport	4-7	10-14
- reloading rooms	6-14	22-25
Compensation rooms, m^3	3750-45000	3750-45000

Thus, according to data of mining enterprises of Kryvyi Rih iron ore basin, retimbering of capital, preparatory and subsidiary underground workings averages 3–10%, 5–15% and 10–25% respectively.

2. PURPOSE

The present study aims to determine stress concentration on the contour of underground mine workings to reduce operating costs for their maintainance. For this, it is necessary to solve the following tasks:

1. To study the impact of the field of primary stresses of a multi-module massif on formation of a destructive force arising on the contour of the vaulted mine working.

2. To improve the method for determining the active zone that leads to destruction of the mine working.

3. ANALYSIS OF RESEARCHES AND PUBLICATIONS

The rock massif of Kryvyi Rih iron ore basin is comprised of a complex of rocks with their own mining, geological, physical and mechanical properties. In terms of geomechanics, rocks of the rock massif should be considered in relation to adjacent rocks as an elastic or plastic inclusion. If an external load is applied to such a complex of rocks, a complex field of stresses is formed in it depending on geometrical and physical-mechanical parameters of the rock massif area under study. Therefore, the larger the volume of the massif where the field of stresses is being determined, the greater the number of geological and tectonic factors impacting the final result is.

Ideally, the gravitational forces formed in an undisturbed massif are composed of vertical and horizontal stresses, which can be determined by the expressions [22–24]

$$\sigma_z = \gamma H, \quad \sigma_x = \sigma_y = \frac{\mu \sigma_z}{(1-\mu)}, \tag{2}$$

where σz is vertical stresses, MPa; σ_x, σ_y are horizontal components of the vertical stress, MPa; γ is the volumetric weight of rocks, H/m^3; H is the depth of mining, m; μ is Poisson ratio.

Changes in the stress field on the contour of the working as well as determination of places of maximum stress concentration with respect to the exposure surface are treated in works by a great number of scientists including M.M. Protodyakonov, I.A Turchaninov, Z.M. Galaev, G.N. Kuznetsov, M.I. Stupnik, V.M. Tarasyutin, V.O. Kalinichenko, V.I. Bondarenko, A.M. Zorin etc. The results of many years of studies of the stress state of the rock massif enable arguing that the structure of the primary stress field is impacted by the following factors: gravitational forces, tectonic forces and residual stresses [22–27]. Every particle located at a depth is pressed by the weight of overlying rocks, it transfers this pressure in all directions, and due to the impossibility of displacement, horizontal stresses arise [22–24]. When determining stresses in the rock massif, the scope of studies must be limited to a structural block, then the obtained fields of primary gravitational-tectonic stresses will be characteristic of this structural block [25–27].

Due to the fact that a real rock massif is not an ideal environment, the earth's crust can be divided into geoblocks represented by more than 20 ranks according to its disturbances. According to [23], dimensions of geoblocks are on average: 1 m, 10 m, 100 m, 1 km, 10 km, 100 km, 1000 km and over. Disturbances of each rank have their own strains and their own field of the gravitational-tectonic stress.

According to [22, 24, 27], tectonic stresses in the vertical direction should equal zero, and in the horizontal direction they should have the maximum and the minimum value with the azimuth of their action: σ_{1t}, σ_{2t}, σ_{1g}, and σ_{2g}. Thus, in the ideal case, the total of gravitational-tectonic stresses is determined by the formulas

Tab. 2. Classification of rocks and ores of Kryvyi Rih iron ore basin

Tab. 2. Klasyfikacja skał i rud Krzyworoskiego zagłębia rud żelaza

Compressive strength, MPa	Rocks	Degree of fracturing		
		weak < 5; $K_{s.w.}$ = 0.9-1.0	medium 6-15; $K_{s.w}$ = 0.5-0.8	great > 15; $K_{s.w}$ <0.5
> 140	Jaspilite, hematite quartzites	*I*	*II*	*III*
120-140	Oxidized, magnetite quartzites	*II*	*III*	*IV*
70-120	Quartz-chlorite, aspid schists, colour hornfels	*III*	*IV*	*V*
40-60	Colour and chlorite schists, martite ores	*IV*	*V*	*VI*
< 40	Colour ores	*VI*	*VI*	*VI*

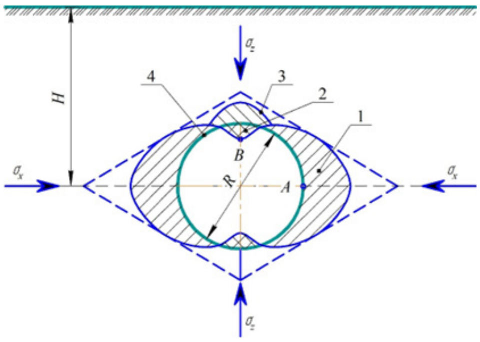

Fig. 2. Formation of stresses on the contour of the round working: 1 – the area of compressive stresses; 2 – the area of tensile stresses; 3 – the beginning of vault formation; 4 – the contour of the mine working

Rys. 2. Powstawanie naprężeń na obrysie wyrobiska okrągłego: 1 – obszar naprężeń ściskających; 2 – obszar naprężeń rozciągających; 3 – początek formowania się sklepień; 4 – zarys wyrobiska kopalnianego

$$\sigma_{1g} = \sigma_{1t} + \frac{\mu_1 \gamma H}{1-\mu_1}, \quad \sigma_{2g} = \sigma_{2t} + \frac{\mu_2 \gamma H}{1-\mu_2}, \tag{3}$$

where σ_{1t}, σ_{2t} are tectonic stresses, MPa, σ_{1g}, σ_{2g} are gravitational stresses, MPa.

Under the impact of external forces, rocks are subjected to linear strains ε which are determined by the expression

$$\varepsilon = \frac{\left(l' - l\right)}{l} = \frac{\Delta l}{l}, \tag{4}$$

where l′ is the length of the edge of the separated elementary cube l after straining, mm; Δl is the change in the length of the edge of the elementary cube after straining, mm.

By separating linear and shear strains into their constituent vectors along the coordinate axes, the strain tensor, which determines the nature of the strain of any point in the body, has the form

$$\varepsilon_{ki} = \begin{vmatrix} \varepsilon_x & \frac{1}{2}\tau_{xy} & \frac{1}{2}\tau_{xz} \\ \frac{1}{2}\tau_{yx} & \varepsilon_y & \frac{1}{2}\tau_{yz} \\ \frac{1}{2}\tau_{zx} & \frac{1}{2}\tau_{zy} & \varepsilon_z \end{vmatrix} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right), \tag{5}$$

where u is the general designation of any strain.

In this tensor (5), two of any tangential stresses τ lying in the same plane and directed oppositely, must be equal, since the body is in equilibrium, and therefore, the total moment of forces relative to the center of the elementary cube equals zero [22, 25].

Given that the opposite shear strains are equal to each other, the strain tensor is symmetrical. The nature and value of the strain depend on the type and value of applied stresses. An increase in load leads to an increase in strains, and when ultimate strength is exceeded, the rock is destructed [28–30].

Depending on the ratio of values of these strains, rocks can be divided into elastic-fragile (the plastic zone is practically not observed until destruction), elastic-plastic (destructive strain is preceded by a zone of plastic strain) and plastic (elastic strain is practically not available) [24, 31–33]. The rock massif of Kryvyi Rih basin is heterogeneous, therefore, at the same depth, different stresses act on the mine working and cause different strains [24–36].

Thus, on the contour of the working with a large radius of curvature, there appear angular points that are foci of high concentration of stresses resulting in partial destruction of the contour of the working with changed stresses on it. The working is being destructed until it acquires stable outlines [37–40]. The contour of the working is under destruction throughout its entire life. To maintain the mine workings throughout this period, various types of timbering are used according to the developed classification given in Table 2.

Rocks of Kryvyi Rih iron ore basin are divided into six classes: I – very stable; II – stable; III – medium stability; IV – low stability; V – very low stability and VI – unstable.

Depending on the compressive strength and the class of rock stability, the following types of timbering are used to maintain mine workings: class I – timberless, sprayed-concrete, anchor; class II – sprayed-concrete, anchor with mesh; class III – anchor with sprayed-concrete concrete, metal; class IV – metal, anchor with reinforced sprayed-concrete; class V – yieldable steel arch, anchor with elongated anchors with reinforced sprayed concrete; class VI – paired steel arch yieldable, round tubbing.

4. METHODS

According to [17–21], tensile and compressive stresses occur around workings, Fig. 2, while at points A and B there are maximum compressive and tensile stresses respectively.

The maximum stress-strain state around the round working in the gravitational-tectonic field of primary stresses is described by the following expressions for the elastic medium [13, 19, 41–43]

a) b)

Fig. 3. Condition of underground mine workings under pressure at the depth of 1350 m (u/m "POKROVSKA", the JSC "KRYVBASZALIZRUDKOM"):
a – without destruction of mine workings; b – destruction of the working in its upper part

Rys. 3. Stan podziemnych wyrobisk górniczych pod ciśnieniem na głębokości 1350 m („POKROVSKA", „KRYVBASZALIZRUDKOM"):
a – bez niszczenia wyrobisk górniczych; b – zniszczenie wyrobiska w jego górnej części

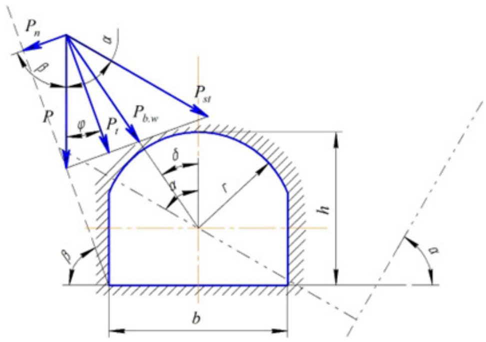

Fig. 4. Computational scheme for determining the destructive load on the contour of the working

Rys. 4. Schemat obliczeniowy wyznaczania obciążenia niszczącego na kontur wyrobiska

$$\begin{cases} \sigma_r = \left(1-\frac{a^2}{r^2}\right)\left(\frac{\sigma_z+\sigma_x}{2}-\left(1-\frac{3a^2}{r^2}\right)\frac{\sigma_z-\sigma_x}{2}\cos 2\theta\right), \\ \sigma_\theta = \left(1+\frac{a^2}{r^2}\right)\left(\frac{\sigma_z+\sigma_x}{2}+\left(1+\frac{3a^2}{r^2}\right)\frac{\sigma_z-\sigma_x}{2}\cos 2\theta\right), \end{cases} \quad (6)$$

where σr, σθ are normal and tangential stresses respectively, MPa; a is the radius of the working, m; r is the distance from the center of the working to the elementary volume, m; θ is the calculated angle at which normal and tangential stresses act on the contour of the mine working, degrees.

If compressive stresses on the contour of the working exceed ultimate compressive strength of the rocks, the working is destrructed 1, at that there is an increase in the span and a decrease in the contour of the vaulted part, which in turn leads to occurence of tensile stresses 2 in the roof with subsequent formation of the caving vault 3.

The main condition for stability of the boundary equilibrium at any site is described by Coulomb law and looks as follows [44–46]

$$\tau_{zx} \geq \tau_0 + \sigma_n tg\rho, \quad (7)$$

where τ_{xy} is shear forces, MPa; τ_o is initial shear resistance, MPa; σп is the normal stress at a given site, MPa; ρ is the angle of internal friction of rocks, degrees.

The normal and tangent stresses included in (7) are determined by the system of equations

$$\begin{cases} \sigma_n = \sigma_z \cos\theta, \\ \tau_{zx} = \sigma_z \sin\theta, \end{cases} \quad (8)$$

If there are no compacting stresses, the initial shear resistance is equal to adhesion of rocks. According to [13, 24, 47], the initial shear resistance is determined depending on the characteristics of the rock massif:

- for a homogeneous massif

$$\tau_0 = \tilde{n}$$

- for a microlayer massif

$$\tau_0 = (0.6\ldots0.7)c;$$

- for individual layers and contacts

$$\tau_0 = (0.2\ldots0.5)c;$$

where c is adhesion of rocks for the main thickness of the massif, H/m².

In layered rocks on the contour of the working, a local fall is observed, manifestation of which occurs due to a decrease in ultimate strength of rocks and the coefficient of adhesion between the layers. The value of the strength characteristics on contacts between the layers is considerably less, so destruction in the massif occurs on contact between the rocks.

Stresses arising on the contour of the working lead to its destruction, which in turn adversely impacts heterogeneous properties of the multi-module massif.

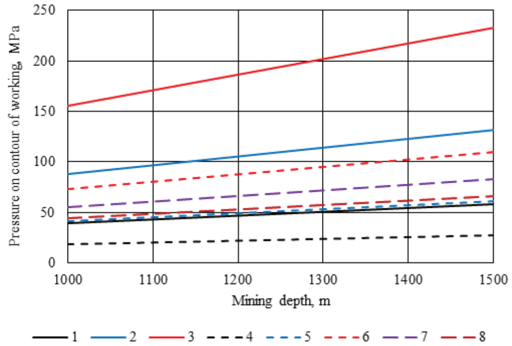

Fig. 5. Dependencies of the value of the active load on the contour of the working beyond the zone of the stoping operations impact on the depth of mining, the radius of the vaulted part of the mine working and rocks: 1–3 – the working is in magnetite ores with the radius of 2, 3 and 4 m respectively; 4–6 – the working is in schistous rocks with the radius of 2, 3 and 4 m respectively; 7, 8 – calculations according to (9) for magnetite ores and schistous rocks respectively

Rys. 5. Zależności wartości obciążenia czynnego od obrysu wyrobiska poza strefą oddziaływania postoju na głębokość urabiania, promień sklepienia wyrobiska i skały: 1–3 – eksploatacja odbywa się w rudach magnetytu o promieniu odpowiednio 2, 3 i 4 m; 4–6 – wyrobisko w skałach łupkowych o promieniu odpowiednio 2, 3 i 4 m; 7, 8 – obliczenia wg (9) odpowiednio dla rud magnetytu i skał łupkowych

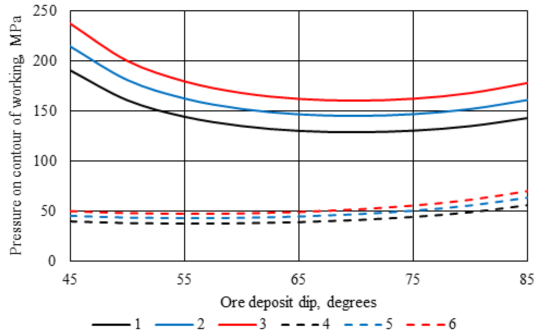

Fig. 6. Dependencies of the value of the actual load on the contour of the workins beyond the zone of stoping operations impact on the angle of the ore deposit dip, the depth of mining and rocks: 1–3 – the working is in magnetite ores at the depth of 1200, 1350 and 1500 m respectively; 4–6 – the working is in schistous rocks at the depth of 1200, 1350 and 1500 m respectively

Rys. 6. Zależności wartości rzeczywistego obciążenia od konturu wyrobisk poza strefą zatrzymania eksploatacji, od kąta upadu złoża, głębokości eksploatacji i skał: 1–3 – wyrobisko w magnetycie rudy na głębokości odpowiednio 1200, 1350 i 1500 m; 4–6 – wyrobisko w skałach łupkowych na głębokości odpowiednio 1200, 1350 i 1500 m

5. RESULTS

In Kryvyi Rih iron ore basin, ore bodies are represented by complex structured deposits [32–34]. Mine workings driven are destructed over time. In most workings, the roof is destroyed with formation of a vault of various configurations and sizes, Fig. 3.

Rock caving is caused by a significant span of exposure or results from the action of destructive compressive or tensile stresses.

As the radius of the vault curvature decreases, compressive stresses increase and tensile stresses decrease, and vice versa, when the radius of the vault curvature increases in the areas of the working contour, compressive stresses decrease, and tensile stresses increase.

For an arbitrary elementary site oriented at the angle β_{zx} in the ore massif adjacent to the open pit contour, normal σn and tangential τ stresses arise, which are determined by the formulas

$$\begin{cases} \sigma_{n_i} = \sigma_{z_i} \cos^2 \beta_{zx} + \sigma_{x_i} \sin^2 \beta_{zx} + \tau_{z_i x_i} \sin 2\beta_{zx}, \\ \tau_{zx} = 0{,}5\left(\sigma_{z_i} - \sigma_{x_i}\right) \sin 2\beta_{zx} - \tau_{z_i x_i} \cos 2\beta_{zx}. \end{cases} \quad (9)$$

Thus, the destructive pressure (weight of rocks) arising and acting on the contour of the working is determined by the expression

$$P_{b.w} = \pm \frac{P_t \sin\left(\alpha + \beta - 90\right)}{l}, \quad (10)$$

where $P_{b.w}$ is the destructive force acting on the contour of the working, MPa; P_t is the weight of the overlying rocks, H/m^3; l is the arc length of the working vault contour, m.

On performing relevant transformations of (9) and after transition from the polar coordinate system to the rectangular one, and substituting the obtained values into (7), the formula of the boundary equilibrium on the contour of the workings is obtained, Fig. 4

$$\frac{P_t \sin 2\left(\alpha + \beta - 90\right)}{r^2} = \tau_0 + \gamma H \cos \beta tg \rho, \quad (11)$$

where β is the angle of displacement of rocks, degrees.

On multiplying the right and left parts of (11) by the square of the radius of the working and performing relevant transformations, the value of the maximum destructive force on the contour of the working is obtained which provides the boundary equilibrium

$$P_t = \frac{r^2 \tau_0 + r^2 \gamma H \cos \beta tg \rho}{\sin 2\left(\alpha + \beta - 90\right)}. \quad (12)$$

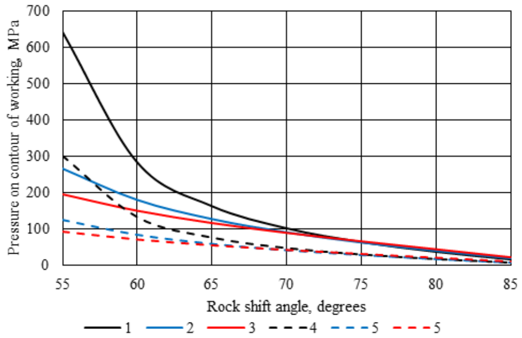

Fig. 7. Dependencies of the active load value on the contour of the working beyond the zone of the stoping operations impact on the angle of rock shift, the angle of the dip of the ore deposit and rocks: 1–3 – the working is in magnetite ores with the deposit dip of 40, 50 and 60 degrees respectively; 4–6 – the working is in schistous rocks with the deposit dip of 40, 50 and 60 degrees respectively

Rys. 7. Zależności wartości obciążenia czynnego od konturu wyrobiska poza strefą zatrzymania eksploatacji na kąt przesunięcia skały, kąt upadu złoża rudy i skał: 1–3 – wyrobisko jest w rudach magnetytu o spadku złoża odpowiednio 40, 50 i 60 stopni; 4–6 – wyrobisko w skałach łupkowych o nachyleniu złoża odpowiednio 40, 50 i 60 stopni

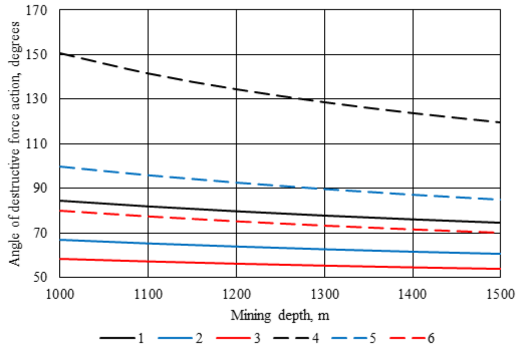

Fig. 8. Dependencies of the change in the angle of active pressure on the contour of the working on the mining depth, the radius of the vaulted part of the working and rocks: 1–3 – the working is in magnetite ores with the radius of the vaulted part 2, 3 and 4 m respectively; 4–6 – the working is in schstous rocks with the radius of the vaulted part 2, 3 and 4 m respectively

Rys. 8. Zależności zmiany kąta parcia czynnego od konturu wyrobiska na głębokości urabiania, promienia sklepionej części wyrobiska i skał: 1–3 – wyrobisko występuje w rudach magnetytu o promieniu części sklepionej odpowiednio 2, 3 i 4 m; 4–6 – wyrobisko w skałach łupkowych o promieniu części sklepionej odpowiednio 2, 3 i 4 m

On performing relevant transformations, the final equation of the destructive force acting on the contour of the working is obtained

$$P_{b.w} = \frac{r^2\tau_0 \sin\alpha + r^2\gamma H \sin\alpha \cos\beta tg\rho}{\sin 2(\alpha+\beta-90)}. \qquad (13)$$

Based on (13), the dependencies of distribution of the destructive pressure on the contour of the working on the depth of mining, the angle of the ore deposit dip and the angle of shift of the hanging wall rocks are built, Fig. 5–7.

Fig. 5 shows that with an increase in the depth of mining operations, the pressure on the contour of the working increases. Thus, with an increase in the depth of mining from 1000 to 1500 m and a change in the radius of the vaulted part from 2 to 4 m, the pressure on the contour of the working increases from 39.8 to 233.3 MPa if the working is driven in magnetite ores. If the mine working is driven in schistous rocks, the pressure on its contour increases from 18.2 to 109.4 MPa. Comparing the obtained values enables the conclusion that if workings are located in schistous rocks, the pressure on their contour is almost 2 times smaller than in magnetite ores.

Thus, for conditions of Kryvyi Rih iron ore basin, it is reasonable to locate mine workings in waste rocks to reduce the cost of their maintenance and re-timbering.

Comparing the results of our study with those in [48] enables the conclusion that the pressure acting on the contour of the working does not depend on the radius of the vaulted part (curves 7 and 8). However, the nature of the pressure change calculated by (9) and proposed (13) is almost the same, which indicates reliability of the results.

It should be noted that the angle of the ore deposit dip significantly impacts the rock pressure around the mine working. Thus, the minimum magnetite ores pressure on the working acts at the angle of the ore deposit dip from 65 to 75 degrees, and if the working is located in schistous rocks – from 50 to 60 degrees.

Thus, depending on physical and mechanical properties of rocks at the same depth and angle of the ore deposit dip, the pressure on the mine working differs significantly for magnetite ores and schistous rocks.

As is seen from Fig. 7, with an increase in the angle of rock shift, the pressure on the contour of the mine working decreases significantly. Analysis of the graphs given reveals that if the shift of rocks exceeds 65–70 degrees, the pressure on the mine working contour stabilizes regardless of the ore deposit dip.

Thus, when designing a mining system or a scheme of opening, it is necessary to have a complete geological char-

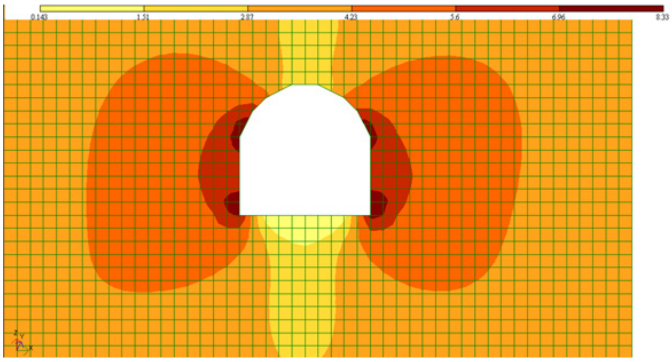

Fig. 9. Epures of equivalent stresses acting around the mine working

Rys. 9. Diagram naprężeń równoważnych działających wokół wyrobiska górniczego

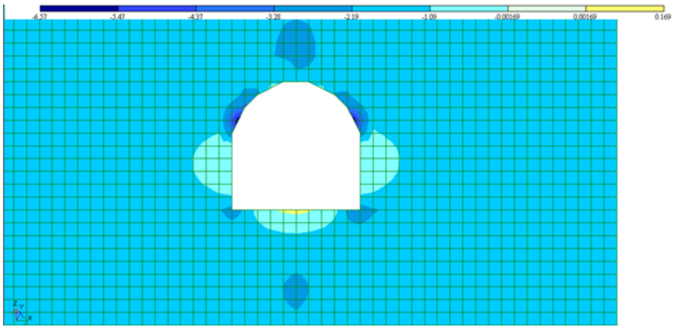

Fig. 10. Epures of vertical stresses according to Mohr theory acting around the mine working

Rys. 10. Diagram naprężeń pionowych według teorii Mohra, działające wokół wyrobiska górniczego

acteristic and physical and mechanical properties of rocks. Therefore, creation of underground mine workings in certain rocks enables reduction of costs for maintaining the workings during their life period.

If the destructive pressure determined by (13) is greater than the rock ultimate compressive strength (Table 2), the working is stable and subject to strains at the angle δ, Fig. 4.

Depending on physical and mechanical properties of rocks, the angle of action of the maximum stresses on the contour of the working is determined by the formula

$$\delta = ar\cos\frac{r^2\tau_0 + r^2\gamma H\cos\beta tg\rho}{2[\sigma_{st}]}, \qquad (14)$$

where $[\sigma_{st}]$ is the rock ultimate compressive strength, MPa.

Based on (14), dependencies of the change in the angle of the destructive force action on the depth of mining, the radius of the working and physicomechanical properties of rocks are built.

Fig. 8 shows that with an increase in the depth of mining from 1000 to 1500 m, the angle of action of the destructive force that occurs on the contour of the working decreases from 150 to 54 degrees. With an increase in the radius of the working from 2 to 4 m for magnetite ores at the depth of 1300 m, the angle of destructive force action decreases from 78 to 55 degrees.

Thus, the angle at which the destructive force acts on the contour of the working depends on physical and mechanical properties of rocks, the radius of the vaulted part and the depth of mining.

The LIRA 9.4 software package is applied to confirm reliability of the proposed methods and determine the field of actual stresses around the vaulted mine working. To determine the stress-strain state of the rock massif, the finite element method is used which allows solving systems of equations with a large number of unknowns.

The above complex is also used to solve the issues of the stress-strain state: in a linear-elastic medium; within the framework of the nonlinear theory of elasticity and in the elastic-plastic formulation by step-by-step and step iteration methods with automatic selection of a load step. The results of calculating equivalent and vertical stresses at a mine working height of 5 m and the radius of the vaulted part of 3 m in the homogeneous rock massif of magnetite ores at the depth of 1350 m are shown in Fig. 9, 10.

The epures of equivalent and vertical stresses in Fig. 8, 9 show that the greatest stresses arise on the contour of the mine working in its vaulted part, and the angle of the destructive pressure action is 60 degrees.

Thus, modeling by the finite element method confirms reliability of the methods for determining the active zone of the destructive force on the working contour when mining iron ore deposits of Kryvyi Rih iron ore basin (see Fig. 8, curve 2).

The results of the present study prove that stability of mine workings depends on the acting stresses that occur in a multi-modular rock massif on the contour of the workings in their vaulted part. The angle of the maximum destructive force action act is determined. When designing, this will allow determining measures to increase stability of mine workings, as well as extend their life without additional operating costs.

CONCLUSIONS

As a result of the study conducted, it is established:

1. The contour of the horizontal working in a homogeneous and heterogeneous massif is impacted by a destructive

field of stresses around which a vault of stable equilibrium is formed. The contour of the working is affected by a destructive pressure at the angle of over 50 degrees.
2. When mining and geological conditions change, stability of mine workings can be provided if they are located in strong rocks, or in rocks with increased angles of their shift. This will reduce the destructive pressure on the contour of the mine working.

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Literatura – References

1. Pysmennyi, S., Fedko, M., Chukharev, S., Rysbekov, K., Kyelgyenbai, K., & Anastasov, D. (2022). Technology for mining of complex-structured bodies of stable and unstable ores. IOP Conference Series: Earth and Environmental Science, 970(1), 012040. https://doi.org/10.1088/1755-1315/970/1/012040.
2. Pysmennyi, S., Chukharev, S., Khavalbolot, K., Bondar, I., & Ijilmaa, J. (2021). Enhancement of the technology of mining steep ore bodies applying the "floating" crown. E3S Web of Conferences, 280, 08013. https://doi.org/10.1051/e3sconf/202128008013.
3. Pysmennyi, S., Chukharev, S., Kyelgyenbai, K., Mutambo, V., & Matsui, A. (2022). Iron ore underground mining under the internal overburden dump at the PJSC "Northern GZK". IOP Conference Series: Earth and Environmental Science, 1049(1), 012008. https://doi.org/10.1088/1755-1315/1049/1/012008.
4. Sobczyk, W., Perny, K.C.I., Sobczyk, E.J. (2021). Assessing the Real Risk of Mining Industry Environmental Impact. Case Study. Inzynieria Mineralnathis, 1 (1), 33–41. https://doi.org/10.29227/IM-2021-01-05.
5. Radwanek-Bąk, B., Sobczyk, W., Sobczyk, E.J. (2020). Support for multiple criteria decisions for mineral deposits valorization and protection. Resources Policy, 68. 101795. https://doi.org/10.1016/j.resourpol.2020.101795.
6. Sobczyk, W. (2015). Sustainable development of Middle East region. Problemy Ekorozwoju – problems of sustainable Development, 10 (2), 51–62.
7. Stupnik, N.I., Kalinichenko, V.A., Fedko, M.B., & Mirchenko, Ye.G. (2013). Influence of rock massif stress-strain state on uranium ore breaking technology. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2, 11–16.
8. Stupnik, N., & Kalinichenko, V. (2012). Parameters of shear zone and methods of their conditions control at underground mining of steep-dipping iron ore deposits in Kryvyi Rig basin. Geomechanical Processes During Underground Mining - Proceedings of the School of Underground Mining, 15–17.
9. Stupnik, N.I., Kalinichenko, V.A., Fedko, M.B., & Mirchenko, Ye.G. 2013. Prospects of application of TNT-free explosives in ore deposites developed by uderground mining. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 1, 44–48.
10. Petlovanyi, M., Lozynskyi, V., Zubko, S., Saik, P., & Sai, K. (2019). The infuence of geology and ore deposit occurrence conditions on dilution indicators of extracted reserves. Rudarsko Geolosko Naftni Zbornik, 34(1), 83-91. https://doi.org/10.17794/rgn.2019.1.8.
11. Bazaluk, O., Petlovanyi, M., Lozynskyi, V., Zubko, S., Sai, K., & Saik, P. (2021). Sustainable Underground Iron Ore Mining in Ukraine with Backfilling Worked-Out Area. Sustainability, 13(2), 834. https://doi.org/10.3390/su13020834.
12. Bazaluk, O., Petlovanyi, M., Zubko, S., Lozynskyi, V., & Sai, K. (2021). Instability Assessment of Hanging Wall Rocks during Underground Mining of Iron Ores. Minerals, 11(8), 858. https://doi.org10.3390/min11080858.
13. Galayev, N.Z. (1990). Upravleniye sostoyaniyem massiva gornykh porod pri podzemnoy razrabotke rudnykh mestorozhdeniy [Management of the state of the rock mass in the underground mining of ore deposits]. (Moscow: Nedra).
14. Stupnik, M.I., Kalinichenko, V.O., Fedko, M.B., & Kalinichenko, O.V. (2018). Investigation into crown stability at underground leaching of uranium ores. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 6, 20–25.
15. Bazaluk, O., Rysbekov, K., Nurpeisova, M., Lozynskyi, V., Kyrgizbayeva, G., & Turumbetov, T. (2022). Integrated monitoring for the rock mass state during large-scale subsoil development. Frontiers in Environmental Science, 10, 852591. https://doi.org/10.3389/fenvs.2022.852591.
16. Stupnik, M., Kalinichenko, V., Fedko, M., Pysmennyi, S., Kalinichenko, O., & Pochtarev, A. (2022). Methodology enhancement for determining parameters of room systems when mining uranium ore in the SE "SkhidGZK" underground mines, Ukraine. Mining of Mineral Deposits, 16(2). 33–41. https://doi.org/10.33271/mining16.02.033.

17. Stupnik, M., & Kalinichenko, V. (2013). Magnetite quartzite mining is the future of Kryvyi Rig iron ore basin. Annual Scientific-Technical Colletion - Mining of Mineral Deposits 2013, 49–52

18. Lozynskyi, V., Medianyk, V., Saik, P., Rysbekov, K., & Demydov, M. (2020). Multivariance solutions for designing new levels of coal mines. Rudarsko Geolosko Naftni Zbornik, 35(2), 23-32. https://doi.org/10.17794/rgn.2020.2.3.

19. Stupnik, N.I., Fedko, M.B., Pismennyi, S.V., & Kolosov, V.A. (2014). Development of recommendations for choosing excavation support types and junctions for uranium mines of state-owned enterprise skhidhzk. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5, 21–25.

20. Lyashenko, V., Andreev, B., & Dudar, T. (2022). Substantiation of mining-technical and environmental safety of underground mining of complex-structure ore deposits. Mining of Mineral Deposits, 16(1), 43-51. https://doi.org/10.33271/mining16.01.043.

21. Issayeva, L., Togizov, K., Duczmal-Czernikiewicz, A., Kurmangazhina, M., & Muratkhanov, D. (2022). Ore-controlling factors as the basis for singling out the prospective areas within the Syrymbet rare-metal deposit, Northern Kazakhstan. Mining of Mineral Deposits, 16(2), 14-21. https://doi.org/10.33271/mining16.02.014.

22. Takhanov, D., Muratuly, B., Rashid, Z., & Kydrashov, A. (2021). Geomechanics substantiation of pillars development parameters in case of combined mining the contiguous steep ore bodies. Mining of Mineral Deposits, 15(1), 50-58. https://doi.org/10.33271/mining15.01.050.

23. Stupnik, M.I., Kalinichenko, O.V., & Kalinichenko, V.O. (2012). Economic evaluation of risks of possible geomechanical violations of original ground in the fields of mines of Kryvyi rih basin. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 6, 126–130.

24. Malakhov, G.M. (1990). Upravleniye gornym davleniyem pri razrabotke rudnykh mestorozhdeniy Krivorozhskogo basseyna [Management of rock pressure in the development of ore deposits of the Krivoy Rog basin]. (Kyiv: Naukova dumka).

25. Pysmenniy, S., Shvager, N., Shepel, O. Kovbyk, K., & Dolgikh O. (2020). Development of resource-saving technology when mining ore bodies by blocks under rock pressure. E3S Web of Conferences, 166, 02006. https://doi.org/10.1051/e3sconf/202016602006.

26. Turchaninov, I.A., Iofis, M.A., & Kaspar'yan, Z.Z. (1989). Osnovy mekhaniki gornykh porod [Fundamentals of rock mechanics]. (Leningrad: Nedra).

27. Zorin, A.N., Kolesnikov, V.G., & Minayev, S.P. (1986). Upravleniye sostoyaniyem gornogo massiva. [Managing the state of the mountain range]. (Kyiv: Naukova dumka).

28. Morkun, V., & Morkun, N. (2018). Estimation of the crushed ore particles density in the pulp flow based on the dynamic effects of high-energy ultrasound. Archives of Acoustics, 43(1), 61–67.

29. Golik, V., Komashchenko, V., Morkun, V., & Zaalishvili, V. (2015). Enhancement of lost ore production efficiency by usage of canopies. Metallurgical and Mining Industry, 7(4), 325–329.

30. Morkun, V., Morkun, N., & Tron, V. (2015). Distributed control of ore beneficiation interrelated processes under parametric uncertainty. Metallurgical and Mining Industry, 8(7), 18–21.

31. Fedko, M.B., Muzyka, I.O., Pysmennyi, S.V. & Kalinichenko, O.V. (2019). Determination of drilling and blasting parameters considering the stress-strain state of rock ores. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 1, 37–41. https://doi.org/10.29202/nvngu/2019-1/20.

32. Stupnik, M., Kalinichenko, V., Fedko, M., Kalinichenko, O., Pukhalskyi, V., & Kryvokhin, B. (2019). Investigation of the dust formation process when hoisting the uranium ores with a bucket. Mining of Mineral Deposits, 13(3), 96–103. https://doi.org/10.33271/mining13.03.096.

33. Golik, V., Komashchenko, V., Morkun, V., & Irina, G. (2015). Improving the effectiveness of explosive breaking on the bade of new methods of borehole charges initiation in quarries. Metallurgical and Mining Industry, 7(7), 383–387.

34. Kyelgyenbai K., Pysmennyi S., Chukharev S., Purev B., & Jambaa I. (2021). Modelling for degreasing the mining equipment downtime by optimizing blasting period at Erdenet surface mine. E3S Web of Conferences, (280), 08001. https://doi.org/10.1051/e3sconf/202128008001.

35. Stupnik, N.I., Fedko, M.B., Kolosov, V.A., & Pismennyy S.V. (2014). Razrabotka rekomendatsiy po vyboru tipa krepleniya gornykh vyrabotok i sopryazheniy v uslovii uranovykh shakht GP "VOSTGOK". Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5, 21–25.

36. Kalinichenko, V., Dolgikh, O., Dolgikh, L., & Pysmennyi, S. (2020). Choosing a camera for mine surveying of mining enterprise facilities using unmanned aerial vehicles. Mining of Mineral Deposits, 14(4), 31-39. https://doi.org/10.33271/mining14.04.031.

37. Pysmennyi, S., Peremetchyk, A., Chukharev, S., Fedorenko, S., Anastasov, D., & Tomiczek, K. (2022). The mining and geometrical methodology for estimating of mineral deposits. IOP Conference Series: Earth and Environmental Science, 1049(1), 012029. https://doi.org/10.1088/1755-1315/1049/1/012029.

38. Kalinichenko, V., Dolgikh, O., & Dolgikh, L. (2019). Digital survey in studying open pit wall deformations. E3S Web of Conferences, 123, 01047.

39. Kalinichenko, O., Fedko, M., Kushnerov, I., & Hryshchenko, M. (2019). Muck drawing by inclined two-dimensional flow. E3S Web of Conferences, 123, 01015.

40. Stupnik, M.I., Kalinichenko, O.V., Kalinichenko, V.O. 2012. Technical and economic study of self-propelled machinery application expediency in mines of krivorozhsky bassin. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5, 39–42.

41. Panchenko, V., Sobko, B., Lotous, V., Vinivitin, D., & Shabatura, V. (2021). Openwork scheduling for steep-grade iron-ore deposits with the help of near-vertical layers. Mining of Mineral Deposits, 15(1), 87-95. https://doi.org/10.33271/mining15.01.087.

42. Zeylik, B., Arshamov, Y., Baratov, R., & Bekbotayeva, A. (2021). New technology for mineral deposits prediction to identify prospective areas in the Zhezkazgan ore region. Mining of Mineral Deposits, 15(2), 134-142. https://doi.org/10.33271/mining15.02.134.

43. Morkun, V., Morkun, N., & Tron, V. (2015). Distributed closed-loop control formation for technological line of iron ore raw materials beneficiation. Metallurgical and Mining Industry, 7(7), 16–19.

44. Stupnik, M., Kalinichenko, O., Kalinichenko, V., Pysmennyi, S. & Morhun, O. (2018). Choice and substantiation of stable crown shapes in deep-level iron ore mining. Mining of Mineral Deposits, 12(4), 56–62. https://doi.org/10.15407/mining12.04.056.

45. Stupnik, N., Kalinichenko, V., Pismennij, S. & Kalinichenko, E. (2015). Features of underlying levels opening at “ArsellorMittal Kryvyic Rih” underground mine. New Developments in Mining Engineering 2015: Theoretical and Practical Solutions of Mineral Resources Mining, 39–44.

46. Rysbekov, K., Bitimbayev, M., Akhmetkanov, D., Yelemessov, K., Barmenshinova, M., Toktarov, A., & Baskanbayeva, D. (2022). Substantiation of mining systems for steeply dipping low-thickness ore bodies with controlled continuous stope extraction. Mining of Mineral Deposits, 16(2), 64-72. https://doi.org/10.33271/mining16.02.064.

47. Stupnik, N.I., Fedko, M.B., Kolosov, V.A., & Pismennyy S.V. (2014). Development of recommendations for choosing excavation support types and junctions for uranium mines of state-owned enterprise skhidhzk. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5, 21–25.

48. Stupnik, M., Kalinichenko, V., Fedko, M., Pysmennyi, S., Kalinichenko, O., & Pochtarev, A. (2022). Methodology enhancement for determining parameters of room systems when mining uranium ore in the SE “SkhidGZK” underground mines, Ukraine. Mining of Mineral Deposits, 16(2). 33–41. https://doi.org/10.33271/mining16.02.033.

Badanie koncentracji naprężeń na konturze wyrobisk kopalni podziemnych

W kopalni Krzywy Róg występują złoża rudy o złożonej strukturze, wydobywane metodą podziemną z głębokości ponad 1000 m. Stosując systemy zawałowe eksploatuje się złoża bogatych rud żelaza o zawartości składników użytecznych powyżej 59%. Prowadzi to do znacznych zmian stanu naprężeń masywu skalnego. Podczas prac podziemnych wyrobiska kopalniane podlegają naprężęniom, a w niektórych przypadkach ulegają zniszczeniu. W efekcie przedsiębiorstwa stale podwyższają koszty eksploatacji wyrobisk górniczych, co niekorzystnie wpływa na koszty produkcji. Wyniki badań przemysłowych wskazują, że w większości przypadków wyrobiska zawodzą w swojej górnej części. Dostępne metody określania stanu skał wokół wyrobisk górniczych nie uwzględniają w pełni właściwości fizycznych i mechanicznych skał, w których znajduje się wyrobisko. Opracowana technika pozwala na określenie nie tylko ciśnienia destrukcyjnego działającego na wyrobiska, ale również kąta działania siły destrukcyjnej. Technika ta różni się od dostępnych tym, że uwzględnia nie tylko cechy górniczo-geologiczne złoża, ale także większość czynników właściwości fizykomechanicznych skał. Technika ta pozwala już na etapie projektowania na dobór racjonalnych miejsc prowadzenia wyrobisk górniczych, unikając w ten sposób znacznych dodatkowych kosztów ich utrzymania.

Słowa kluczowe: *naprężenie, praca, sklepienie równowagi stabilnej, ciśnienie, stabilność, wytrzymałość graniczna, skały*