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DEVELOPMENT OF NATURAL UNDERGROUND ORE MINING TECHNOLOGIES IN ENERGY DISTRIBUTED MASSIFS

Об'єктом дослідження є технологія і технічні засоби для підземного видобутку руд в енергонарушених масивах. Одним із найбільш проблемних місць є утворення техногенних порожнеч, які впливають на виникнення і перерозподіл напряженно-деформаційного стану (НДС) масиву гірських порід. Їх існування в земній корі провокує вплив геомеханічних і сейсмічних явищ, аж до рівня землетрусів.

В ході дослідження використовувалися:

– дані літературних джерел і патентної документації в області технологій і технічних засобів для підземного видобутку руд в енергонарушенних масивах, обґрунтування технологічних параметрів експлуатаційних блоків;

– лабораторні та виробничі експерименти;

– фізичне моделювання і підбір складів твердіючих сумішей.

Виконано аналітичні дослідження, порівняльний аналіз теоретичних і практичних результатів за стандартними і новими методиками за участю авторів.

Розглянуто питання сейсмогеодинамічного моніторингу НДС масиву гірських порід при безпечній розробці рудних родовищ скельного типу. Показано взаємодію природних і техногенних систем, що забезпечують геомеханічну збалансованість рудовміщуючих масивів. Досліджено можливості управління геомеханіки масиву із заповненням техногенних порожнеч різноміцними сумішами і хвостами підземного вилуговування металів із некондиційних руд. Дана типізація процесів і сформульовані відмінні ознаки підземного блокового вилуговування металів із скельних руд в аспекті управління геодинамікою масиву. Показана принципова оцінка комбінованих технологій із раціоналізацією використання НДС гірського масиву для регулювання знаку і величини напружень в природних і штучних умовах. Зроблено висновки щодо ефективності керованої взаємодії природних і техногенних систем, що забезпечують геомеханічну збалансованість масивів і земної поверхні в районі освоєння надр протягом довгого періоду часу. Результати досліджень можуть бути використані при підземній розробці рудних родовищ складної структури України, Російської Федерації, Республіки Казахстан та інших розвинених гірничодобувних країн світу.

Ключові слова: *напруженно-деформаційний стан, гірський масив, підземна розробка, природоохоронна технологія, геомеханічна збалансованість.*

1. Introduction

In the case of man-made intervention in the subsoil, the interaction of natural and technical systems that en-sure the geomechanical balance of the masses in the area of subsoil development becomes a general issue in the development of ore deposits. At the same time, it should be possible to monitor the stress-strain state (SSS) of the

rock massifs for a long period of time. Each mountain object has its own field and responds to external influences [1, 2]. Under the influence of mining in the upper layers of the lithosphere, a zone stands out where displacements and deformations exceed permissible values [3, 4].

Therefore, the study of the mechanism of occurrence and redistribution of the SSS factors of the rock massif to ensure the livelihoods of the population living in the zones of influence of mining regions is an important scientific, practical and social task that requires an operational solution [5, 6].

2. The object of research and its technological audit

The object of research is the technology and technical means for underground ore mining in energy-disturbed massifs. One of the most problematic places is the formation of man-made voids that affect the occurrence and redistribution of the stress-strain state (SSS) of the rock massif. Their existence in the earth's crust provokes the influence of geomechanical and seismic phenomena, up to the level of earthquakes.

3. The aim and objectives of research

The aim of research is the development of environmental technology for underground mining of ores in energy-damaged massifs of complex structure based on the study of the mechanism of occurrence and redistribution of stress-strain state factors of a rock massif. This will ensure the livelihoods of the population living in the zone of influence of the mining region. To achieve this aim it is necessary to solve the following objectives:

1. To establish how it is possible to ensure the conservation of the earth's surface from destruction.

2. To determine the dependences for predicting the rate of oscillation of the rock massif from the reduced charge mass per deceleration stage and the blasting conditions for deposits of complex structure.

3. To recommend new environmental and resource-saving technologies and technical means for underground mining of ore deposits of complex structure in energy-disturbed massifs.

4. Research of existing solutions of the problem

Mining enterprises operate in direct contact with industrial zones, residential agglomerations, natural sites, including water, agricultural land, negatively affecting them [7, 8]. Underground mining under guarded facilities with a small depth of development are technologically complex and dangerous [9, 10]. Geodynamic processes increase with time. So, in the bowels of the Sadon deposits (North Caucasus, Republic of North Ossetia-Alania), over the two-century history of development, up to 5 million m^3 of unfilled man-made voids have been accumulated. Such a volume of voids takes part in changes in the geodynamic and seismic conditions in the earth's crust. There is a hypothesis that dynamic processes in their voids are the cause of catastrophic manifestations, for example, the Kolka glacier in the Karmadon gorge of North Ossetia and others [11, 12].

Analysis of man-made voids shows that with an increase in the depth of development of ore deposits and the duration of the existence of chambers, the number of self-collapsing rocks in them increases. So, at the Frunze mine (Kryvbas, Ukraine) at a depth of 0–100 m there was one collapse, and at a depth of 300–400 m there were already twenty-five. At the Comintern mine (Kryvbas, Ukraine) had eight collapses at a depth of 300–400 m, and reached thirty-five at a depth of 600–700 m. Underestimation of these factors leads to the collapse of the surface in large areas, air strikes in underground workings and the social tension of residents living in the zone of influence of mining. This was confirmed during the collapse of the day surface on an area of 16 hectares of the Ordzhonikidze mine in Kryvbas (Ukraine) in 2010 [13, 14]. The nature- and resource-saving technology of repayment of voids with a hardening mixture is characterized by high cost and insufficient quality of binders and aggregates. Involvement in the production of alternative components of the mixture is limited by their insufficient strength, transportability and cost.

Among the main directions of solving this problem identified in scientific resources, the following hypotheses can be distinguished. Thus, it has been proved by the practice of mining deposits localized in rock massifs that the well-known theory described in [1] is more applicable for controlling their state. In accordance with this theory, only a mass of rocks enclosed within the arch, with a height significantly less than the depth of work, affects the development. In the future, this theory is concretized. In particular, the author of [2] established a decisive parameter – the tensile strength of the rocks that form the beam. And the author of the work [3] linked it with the stability of the rock layer in the roof of the mine. The author of the work [4] defined the stable position of the mine as the equality between the strength of jammed rocks that form a hinged arch with an massif within the arch of natural equilibrium. The stability of the massif is ensured under the condition of sufficient mechanical strength of the lower row of jammed structural blocks, loaded with an massif of rocks within the arch of natural equilibrium. Subsequently [5, 15], scientists determined that the conservation of the earth's surface from destruction is ensured by the regulation of the level of stresses in different strength sections, the interdependence of ore excavation in time, space and its degree of preparedness for mining. And on this basis, new environmental and resource-saving technologies and technical equipment have been proposed that have yielded positive results in the underground mining of ore deposits in Ukraine, the Russian Federation, Kazakhstan and other developed mining countries of the world.

Thus, the results of the analysis allow to conclude that the formation of man-made voids, which affect the SSS occurrence and redistribution of the rock massif, is an important issue to solve. Their existence in the earth's crust provokes the influence of geomechanical and seismic phenomena, up to the level of earthquakes.

5. Methods of research

In the course of the study, let's used the methods of complex generalization, analysis and evaluation of practical experience and scientific achievements in the field of:
- technologies and technical means of underground ore mining in the energy distributed massifs of complex structure;
- underground geotechnology;
- theories and practices of explosive destruction of solid media.

Let's also use methods of continuum mechanics, mathematical statistics, and methods of studying wave processes using standard and new methods of leading experts from developed mining countries of the world with the participation of the authors.

6. Research results

6.1. Model of natural and man-made stresses of rock massifs.
Models that would satisfactorily describe the mechanism of geomechanical processes and induced seismicity do not exist. The state of rock massifs in the process of ore mining is adjusted by the phenomenon of relaxation. The transfer of the massif to a guaranteed stable or unstable state and the limitation of convergence of production circuits are ensured by optimizing the bearing capacity of anthropogenic structures by comparing the strength of anthropogenic processes with geological processes in natural conditions and optimizing the reliability coefficient.

Reducing stress levels to a safe value is ensured by engineering measures that contribute to the movement of rocks without destroying their integrity [16]. The strength condition of the natural-man-made system is described by the Vetrov-Golik model [4, 8, 9]:

$$\sigma_1 \pm k\sigma_{2,3} \leq \sigma_{com} =$$
$$= \begin{cases} \sigma_{com}^0 = \int\limits_0^{Z_{0\max}} fx(\mathrm{d}x_1,\mathrm{d}x_2...\mathrm{d}x_n) \rightarrow \begin{cases} \sigma_{fill} = \int\limits_0^{Z_{0\max}} fx(dH_S), \\ \sigma_{fill} = \int\limits_0^{Z_{0\max}} fx(dH_S + dH_C), \end{cases} \\ \sigma_{com}^{res} \quad \text{at } H_C = H \rightarrow \sigma_{fill} = \int\limits_0^B fx(dH), \end{cases} \quad (1)$$

where σ_1, $\sigma_{2,3}$ – respectively, the horizontal and vertical (along the x, y and z axes) principal stresses, MPa; k – coefficient of geological conditions, units; σ_{com} – stresses in the upper layer of the host rocks, MPa; σ^0 – stresses in the vicinity of the mine, MPa; σ_h^{res} – residual rock strength, MPa; Z_0 – flat span of roof rocks, m; $x_1,...x_n$ – rock characteristics, units; σ_{fill} – strength of the filling massif, MPa; B – passage of the caving zone, m; H, h_c – respectively, the height of the caving zone and the influence of the mine, m; h_S – height of the filling massif, m.

The state of massifs is described by Hooke's condition:

$$\Sigma\sigma = T_y \cdot \Sigma\varepsilon \cdot \kappa; \quad \Sigma\varepsilon = T_n \cdot \Sigma\sigma \cdot \kappa, \quad (2)$$

where σ – main stresses, MPa; ε – strain; T_e and T_s – effective tensors, respectively, of elasticity and suppleness; κ – discreteness coefficient.

Fracture zones are formed in the massif, characterized by weakening of the rocks. In the zone of disturbed rocks with a thickness of 0.5 to 10 m, the attenuation coefficient decreases from 0.25 to 1.15. The zone of increased attenuation has a thickness of 0.5–1.5 m. The coefficient of structural attenuation increases to the periphery to 0.15. This means a decrease in strength compared to an unbroken massif from 1.5 to 6.0 times.

6.2. Use of residual strength of disturbed rocks.
Stresses in the disturbed massif are determined by the ability of structural blocks to self-jam due to the residual strength of the rocks and is described by a model of the form:

$$\sigma_{p.m} = f\left(\sigma^{res}, d_1, d_2, R_{com}, H, h_c, ..., x_n\right) = \int\limits_{\min}^{\max} f\left(x_1, ..., x_n\right), \quad (3)$$

where σ^{res} – residual rock strength, MPa; X_n – filling and massif parameters, MPa.

The parameters of the limiting arch of self-jamming of structural blocks of rocks are described by a model of the form:

$$\alpha = d_I\left(\frac{10R'_{com}}{KHV_c} - 1\right) \Rightarrow [\sigma]_{crit} < [\sigma]_{p.n}^{res}, \quad (4)$$

where α – the half-span of the limiting arch of jamming, m; 10 – conversion coefficient, kg/cm^2 in t/m^2; V_c – the mass of rocks, t/m^2; H – the depth of the heel of the arch, m; K – the safety factor.

The safety of the massif is ensured by dividing it into sections where the strength is determined by the stress of the rocks not in the massif to the surface, but only in its lower layer, the height of which depends on the width of the flat span of the undermining of the massif. If this condition is not fully ensured, voids are laid.

Seismically safe technology is subject to restrictions:
– seismic explosive tremors do not exceed permissible displacement velocity limits for objects from 1.0 to 3.0 cm/s;
– shielding of seismic blast waves;
– limitation of the mass of the explosive charge (EC) for one slowdown of 1500 kg;
– limiting the number of simultaneously exploded operational blocks by two;
– application of the delay interval between explosions of at least 50 m·s.

6.3. The model of managing geomechanics of rock massifs by laying hardening mixtures of various strengths.
The geomechanical balance of the massifs in the area of subsurface development is ensured by the replacement of the extracted ores with an artificial massif [17]. The degree of deformation of natural-man-made structures and the earth's surface under the influence of mining was estimated by modeling the methods of repayment of man-made voids using the photo-elasticity method. The deposit of Northern Kazakhstan with dimensions along a strike of 2500 m, an uprising of 500 m and a thickness of 10 m·s with a scale of 1:20,000 was identified by a model of 125×25×5 cm. The bulk weight of the epoxy is 1.2 g/cm^3, the elastic modulus is 2.7 MPa. The massif was accepted as a homogeneous, disturbed geological fault, and a large tectonic crack, which corresponds to the conditions of ore deposits. In the first series of models, voids were left open, in the second – filled with discrete rocks, in the third – with a hardening mixture of low strength (up to 2.5 MPa), and in the fourth – they were filled with a strong (over 2.5 MPa) hardening mixture. Based on the measured main stresses, stress diagrams were constructed around the mine, which was the basis for assessing the weakening of the massif under the influence of mining. It is established that the distribution of the main stresses with all the scatter of values obeys a general regularity and the graph curves are close in shape. In the area of production blocks, wells

were drilled, oriented with respect to rock schistosity and mining directions. In the wells, displacement sensors for the walls of the wells were installed, the readings of which were recorded by tensometric equipment [18].

The magnitude of the main stresses in the massif varies from 1.0 to 9.2 MPa, depending on the state of man-made voids and the place of their measurement (Table 1).

Table 1

The magnitude of the main stresses in the simulation, MPa

The main stresses in the massif	Without filling	Filling		
		Discrete mixture	Low strength mixture	Durable mix
Hanging side				
σ_x	8.9	5.4	5.0	3.8
σ_γ	7.8	5.0	4.4	3.2
Lying side				
σ_x	7.7	4.8	4.8	3.6
σ_γ	6.9	4.7	4.7	3.0

The stability condition is described by a model of the form:

$$\sigma_1 - \sigma_2 \geq \sin\delta(\sigma_1 + \sigma_2) + \sigma_{com} + (1 - \sin\delta), \qquad (5)$$

where σ_1, σ_2 – the horizontal and vertical main stresses, MPa, respectively; δ – the angle of internal friction, degrees; σ_{com} – rock compressive strength, MPa.

The stress in the massif is described by a model of the form:

$$G_n = \gamma \cdot H \cdot \frac{G_m}{\sigma_v}, \qquad (6)$$

where γ – rock density, t/m³; H – depth of the measured point, m; σ_v – the stress in the model, MPa.

With a lateral thrust λ from 0.5 to 1.5, the angle of inclination of the force vector to the vertical axis $\alpha=0$, the filling module 0.1 MPa, the enclosing rock module 1.4 MPa, the stresses in the model will be:

$$\sigma_n = \sigma^{1.0} \cdot n, \qquad (7)$$

where $\sigma^{1.0}=0.1$ kgf/cm² per lane; n – lane number at the model point.

Options for the status of treatment chambers: without filling and with filling. With a lateral thrust coefficient $\lambda=0.5$, the maximum principal stresses in the areas of the vault locks and the chamber walls are 7.6·7.5=57 MPa, and at the top of the ceiling vault 7.6·2.0=15.2 MPa. In the interchamber pillar, the maximum compressive principal stresses amounted to 7.6·6.5=49 MPa. When the coefficient of lateral thrust $\lambda=1.0$ in the areas of the locks of the arch, the ceiling and the walls of the chamber, the main stresses are: 7.6·6.5=49 MPa. On the whole, the maximum principal stresses decrease: 7.6·5.5=42 MPa. With a side expansion coefficient $\lambda=1.5$ in the areas of the locks of the roof and chamber walls, the main stresses are 7.6·6.5=49 MPa, and in the roof arch up to 7.6·8.5=64 MPa versus 15 with a side expansion coefficient of 0.5. When changing the coefficient of lateral thrust from 0.5 to 1.5, the stresses in the ceiling increased from 41 to 140 MPa. The laying of chambers with hardening mixtures reduces the level

of main stresses in the ceiling by about 2 times. With options without fillings in the inter-chamber pillars, the magnitude of the main stresses increases. The simulation results are as follows:
– when laying voids with hardening mixtures without unloading the main stresses, the roof subsidence reaches 105 mm in terms of nature;
– when filling voids with hardening mixtures, lower principal stresses occur during a one-stage mining procedure with unloading of the mass by ore mining;
– the main stresses during unloading through the roof and soil differ by 20–30 %, but unloading through the soil is preferable. The artificial pillar remains stable until the principal stresses at the wave front exceed the tensile strength of the filling material [19].

6.4. Model implementation technologies. The model of interaction between natural and technical systems is based on the replacement of the rock massif with an massif of hardening mixtures, the strength of which is comparable to or slightly lower than the rock mass. The unloading of the massif from dangerous main stresses is carried out by development on the roof of the mine or underworking on the soil. The safety of the massif and the land surface above it is estimated by comparing the dimensions of the zone of the hazardous influence of the workings with the depth of work. The dependence of the quality indicators of field development on the parameters of geomechanical processes is described by a model of the form:

$$\sigma \cdot \kappa_f = \int_{l_{min}}^{l_{max}} fx\left(d_{X_1}, d_{X_2}...d_{X_n}\right) \to \Pi, R = \int_{l_{min}}^{l_{max}} fx\left(dh_f + dh_n\right), (8)$$

where s – the main stresses in the zone of influence of the workings, MPa; κ_f – stress correction factor; l_{max}, l_{min} – respectively, the maximum and minimum spans of rock outcrops, m; $x_1...x_n$ – technological, physical, mechanical and other characteristics of rocks; L, D – respectively, losses and dilution of ores, fractions of units; h_f, h_n – respectively, the height of the zone of influence of the mine workings and the filling mass, m.

Disturbed rocks within the resulting arch can form a solid structure [20]:

$$\alpha = d_1\left(\frac{10R_{com}}{KH\gamma} - 1\right), \qquad (9)$$

where a – the half-span of the arch of jamming of rocks in the roof of the mine, m; d_1 – horizontal size of the structural block of rocks, m; R_{com} – rock resistance to volume compression, kg/cm²; 10 – conversion factor kg/cm² to t/m²; γ – volumetric weight of rocks, kg/m³; H – the depth of the arch heel of jamming of rocks in the roof of the mine, m; K – safety factor, units.

The support of the rocks by the tab provides volumetric compression conditions to increase its strength by 1.2–1.4 times. Protection of the filling massif from the seismic effect of the explosion is performed by shielding. The dependence of the rate of rock oscillations on the weight of the explosive charge, obtained experimentally and by calculation, has good convergence (Fig. 1). The nature of the dependence of the oscillations of rock particles at the front of seismic waves on the distance to the center of the explosion is interpreted in Fig. 2.
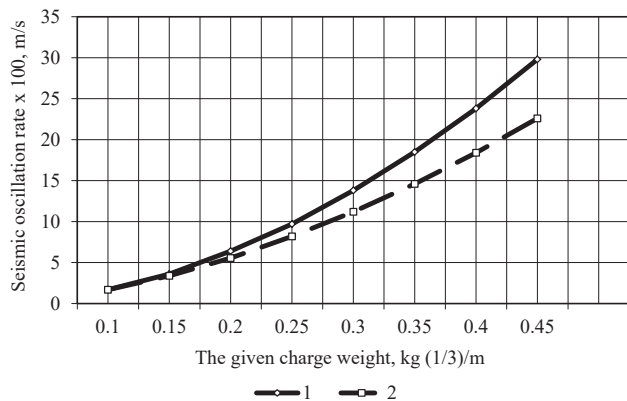
Fig. 1. The dependence of the speed of seismic vibrations of a rock massif on the weight of simultaneously explosive charge of explosives: 1 – based on correlation analysis and experimental data processing; 2 – estimated
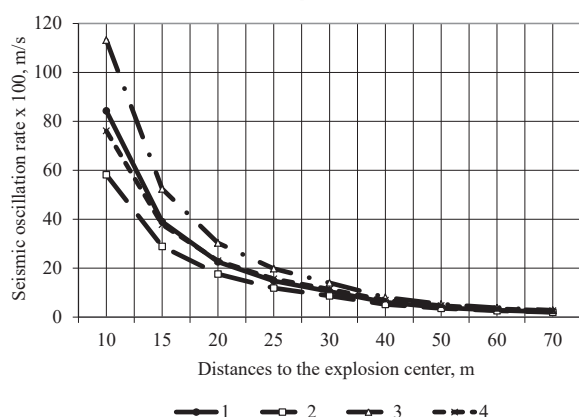
Fig. 2. Dependence of the speed of seismic vibrations of the rock mass on the weight of the simultaneously explosive charge of explosives and the distance to the epicenter of the explosion for the conditions of two mines: 1, 2 – with an explosive weight of 500 kg; 3, 4 – with an explosive weight of 800 kg

6.5. Management of geomechanics of rock massifs during underground metal leaching. The development of underground leaching of metals from ores of rock deposits differs from traditional technology:

– filling the voids separated from the massif by the rock mass involved in maintaining geomechanical stability;
– issuance on the earth's surface of only part of the rock mass (up to 30 %) to ensure compensation space during the breaking and ore packing;
– extraction of metals from ores in special technological installations located in underground workings.

The stability of the ore-bearing massif is determined by the presence of a set of natural equilibrium is described by a model of the form:

$$L_p = 2d_2\sqrt{\frac{10R_{com}}{\kappa_2\gamma d_1}}, \qquad (10)$$

where d_1 and d_2 – respectively, horizontal and vertical sizes of structural blocks, m; γ – bulk weight of rocks, kg/m^3; κ_2 – safety factor. If the roof is composed of rocks whose deformations do not exceed the boundaries of the plastic, the permissible span of the flat shape of the main roof is described by a model of the form:

$$L_0 = 1.71\sqrt[3]{\frac{10R_{com} \cdot d_m^2}{\kappa_2\gamma}}. \qquad (11)$$

If there is a part of the ore-conducting seam in the roof, the ability to self-jam is reduced, and the permissible span of the direct roof of a flat shape is described by a model of the form:

$$L = 1.48dH_2\sqrt[3]{\frac{10R_{com}}{\kappa_2\gamma_B}}. \qquad (12)$$

A flat span can be increased by fastening structural blocks, for example, with anchor support due to an increase in the moment of thrust, is described by a model of the form:

$$L_f = 2.98dH_2\sqrt{\frac{10R_{com}}{\kappa_2\gamma_B}}. \qquad (13)$$

In two-stage mining, the reference pressure is redistributed to the second-stage chambers, and the load on the structure is determined by the mass of rocks within the natural balance of the rocks. Damaged rocks within the arch are deformed, but can form a solid structure and not interfere with the ore mining process [21].

6.6. Implementation results. As a result of a complex of scientific research, the authors establish the modern technical level of the development system used, its elements and basic technological processes are standardized. A set of standards has been drawn up for the enterprise «The development system for sub-floor drifts (orts) with the laying of the worked out space with a hardening mixture. Parameters and sizes». This set of standards regulates (depending on geological conditions) the length, width and height of the chambers of the first, second and third stages of excavation, their maximum permissible values. This takes into account changes in the strength properties of the filling when it hardens and the depth of development, the height of the sub-floor and the bottom of the block, the distance between the outlet loading and delivery workings (draw raise). They depend on the thickness of the ore body and the height of the floor, the shape and size of the cross sections of the main block workings. Technological parameters of the development system: the equipment used, the method and mechanization of ore production, the procedure for mining and breaking chamber reserves, the location and diameter of boreholes are also determined depending on previously standardized parameters and sizes of chambers. This set of standards has been introduced at the ore mines of Ukraine, the Republic of Kazakhstan, and the Russian Federation during the underground mining of ore deposits of complex structure and has been successfully used by specialists from technological and geological surveying services [22].

The modeling of the state of the massif around the mine workings for the conditions of production blocks at the mines of Kryvyi Rih ZIOC OJSC (Kryvyi Rih, Ukraine) was carried out using modern software products. When studying the state of the massif using the finite element method, normal and maximum tangential stresses tending to zero were obtained on the mine circuit (Fig. 3).

Scales of Fig. 3 denotes mechanical normal stresses. An ellipsoidal shape has been proposed for the structural elements of operating blocks at these mines of OJSC, excluding self-collapse of ore, rocks and providing for filling the treatment space with filling material.
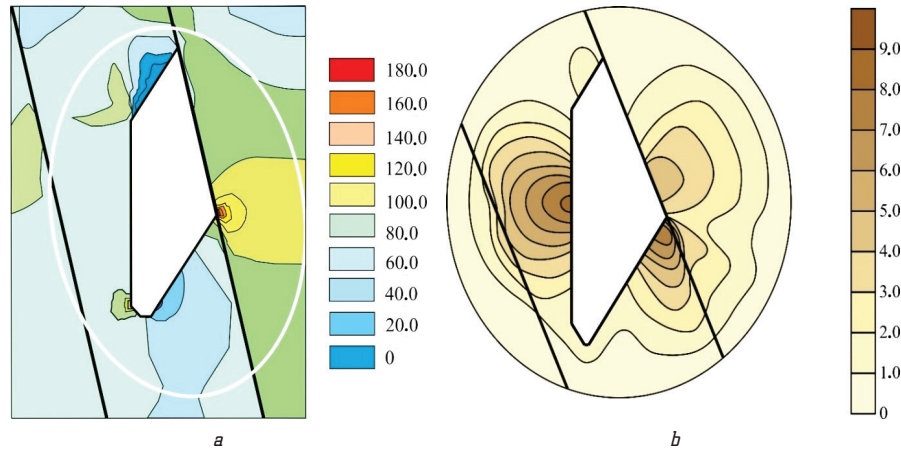
Fig. 3. Development of the stress-strain state and the formation of unloading and stress concentration zones around the treatment chamber at a depth of 1000 m, modeled by: *a* – the finite element method – (kN/m^2); *b* – thermodynamic method (MPa)

As a result of theoretical, laboratory and industrial studies, a methodology was developed for calculating the rational parameters for the preparation of operational blocks at the Prohodcheska mine of the Private Joint-Stock Company Zaporizhzhia Iron Ore Plant (Dniprorudne, Ukraine). The essence of the method consists in the fact that it is rational to carry out the laying of preparatory workings in places with similar or maximally reduced energy saturation of the rocks. The laying along the boundaries of the lines that outline the energy zones makes it possible to conduct them without fastening.

At the same time, the primary chambers affect the laying paths of the hanging side of the workings, and the secondary chambers of the lying side of the workings (Fig. 4) [23].
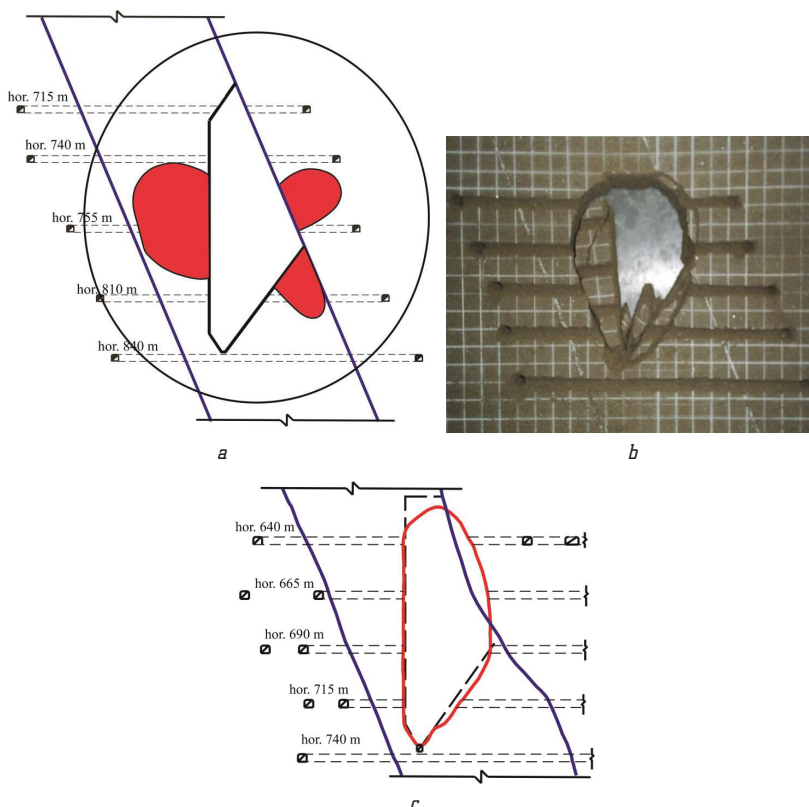
6.7. Research prospects. The obtained results do not exhaust the problem of environmental and resource conservation, environmental protection and human protection. The development of methodological foundations for optimizing mining technology should lead to:
– creation of an appropriate subsystem for the automation of design and planning of mining operations;
– improving technological and environmental safety of the environment;
– rational use and protection of mineral resources;
– human life safety in the zone of influence of mining operations [24, 25].

Thus, the induced geomechanical processes correspond to natural geodynamic processes, which results in an imbalance in the earth's crust. Management of the massif by regulating natural and man-made stresses improves the safety of operations, reduces ore dilution, and improves the concentration of mined ore. The danger of stress amplification is manifested when superimposing seismic blasting operations on the ore-containing discrete massif and the adjacent plot of the earth's surface. The greatest danger is the destruction of the massif during the explosion of a large volume of explosives. The interaction of natural and technical systems that ensure the geomechanical balance of massifs and the earth's surface in the area of subsurface development with the possibility of monitoring the SSS of a rock massif over a long period of time is controlled by regulation of ore mining regimes.

6.8. Further research. After analyzing the methods, technologies and technical means for determining the strength of rocks, the authors expanded the classification of research methods by introducing a synergistic group. This significantly allows to investigate the phenomenon of zonal structuring of the massif around the mine workings. The authors note that it is also very important to study the dependences of the quantity, size and shape of energy zones. On this basis, it is more accurate

Fig. 4. The results of studies of the effectiveness of the method of preparing blocks at the mines of PJSC «Zaporizhzhia IOP»: *a* – theoretical; *b* – laboratory; *c* – industrial

to identify damped stresses and annular regions of deformation and to choose the effective fastening of mining and capital workings, as well as mining operations [26].

7. SWOT analysis of research results

Strengths. Based on the study of the mechanism of occurrence and redistribution of SSS of rock massifs, an environmental protection technology for underground ore mining in energy-disturbed massifs is proposed. It allows to ensure the livelihoods of the population living in the zone of influence of mountain objects (mines, waste dumps and off-balance ones, according to the content of the useful component, ores, industrial sites for filling complexes, preconcentration and heap leaching of metals from substandard ore raw materials, tailings, etc.).

Weaknesses. The main negative impact of mining technology on the environment and humans is the high cost of ensuring the livelihoods of the population living in the zone of influence of mountain objects, the removal of large areas of land from use, etc. Therefore, it is necessary to provide funds for the following activities:

– deep processing of industrial waste (tailings), which have a wide variety of mineral forms compared with conventional ores;

– reclamation of the territory of industrial sites and the territory adjacent to them after the end of operation;

– landscaping of the reclaimed territory with grass and shrubs;

– continuous monitoring of environmental components in the zone of influence of mountain objects.

Opportunities. For the processing of industrial waste (tailings), which have a wide variety of mineral forms compared to conventional ores, it is necessary to create new technologies based on the latest achievements of science and technology. It is necessary to conduct intensive research aimed at solving the problem of disposal of accumulated waste from mining and metallurgical production. Implementation of effective methods for the extraction of metals from such wastes will improve the environmental situation in the areas of their storage and will provide an increase in the mineral resource base of the mining industry. The wide involvement of ore dressing tailings in the production of man-made reserves, as well as the processing of off-balance dumps, in terms of the content of useful components, of ores in modular plants, provide an additional source of meeting the industrial demand for metals. As well as reducing environmental pollution in developed mining countries of the world [27].

Threats. It should be noted separately the need to create protective forest belts along transport routes (automobile, railway, slurry pipelines, etc.). Territories where the maximum permissible concentration (MPC) of pollutants is exceeded should be transferred to the sowing of industrial crops, in the waters – ban fishing, bathing, etc. In order to prevent dust transfer of contaminated material outside mountain objects, sanitary protection zones and strips around it is advisable to plant them with tall tree species that will inhibit wind speed over these objects. These include mines, waste rock dumps and off-balance ones, according to the content of the useful component, ores, filling complexes, sites of preconcentration and heap leaching of metals from substandard ore raw materials, tailings, etc. In this case, dust will settle in these forest stands and will not come to other territories, including settlements. In addition, it is necessary to develop scientific and methodological foundations, technologies and technical means to increase the fertility and efficiency of soil use in industrial zones of mountain objects, as well as to assess their impact on the environment and humans [28].

8. Conclusions

1. It has been established that the conservation of the earth's surface from destruction is ensured by the regulation of the level of stresses in different strength sections, the interdependent extraction of ore in time, space, and its degree of preparedness for mining. So, in the zone of disturbed rocks with a thickness of 0.5 to 10 m, the attenuation coefficient decreases from 0.25 to 1.15. The zone of increased weakening has a thickness of 0.5–1.5 m. The coefficient of structural attenuation increases to the periphery to 0.15, which means a decrease in strength compared to an unbroken massif from 1.5 to 6.0 times.

2. An empirical dependence has been determined for predicting the speed of oscillations of the rock massif from the reduced charge mass per deceleration stage and the blasting conditions for deposits of complex structure of the form $y=ab$ (a and b are coefficients depending on the seismic-acoustic properties of the rock massif and blasting conditions). In particular, the backing of rocks by the tab provides conditions for volumetric compression to increase its strength by 1.2–1.4 times.

3. The new environmental and resource-saving technologies and technical equipment recommended in the work yielded positive results also in underground mining of ore deposits of complex structure:

– Ukraine: SE «Eastern MPP» (Zhovti Vody), Kryvbas (Kryvyi Rih), PJSC «ZIOP» (Dniprorudne);

– the Russian Federation, Priargunsky industrial mining and chemical association PJSC, the enterprise of the ARMG Uranium Holding Co. (Krasnokamensk), Sadon Lead-Zinc Plant (Mizur, North Caucasus, North Ossetia-Alania);

– The Republic of Kazakhstan, JSC «Tselinnoye Mining and Chemical Combine» (Stepnogorsk).

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