РАЗРАБОТКА ПОЛЕЗНЫХ ИСКОПАЕМЫХ

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GEODYNAMIC SAFETY WHEN INCREASING THE DEPTH OF UNDERGROUND MINING OF ORE DEPOSITS*

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Abstract
Statement of the problem (relevance of the paper): the paper describes main scientific and practical results of studies on increasing geodynamic safety, while increasing the depth of underground mining of ore deposits, using operational control data and the forecast for the stressed state of the rock mass with various dynamic signs of rock pressure, and prevention of rock bursts. Using the example of ore deposits in Ukraine, we analyzed physical properties of rocks and new hypothesis of rock pressure, taking into account the relation between the excavation of ore and rocks and time and area, determining parameters of structural elements of development strategies. **Purpose of the paper**: the paper aims at increasing geodynamic safety, when increasing the depth of ore deposit underground mining, by controlling and forecasting the stressed state of the rock mass with various dynamic signs of rock pressure, and by preventing rock bursts. **Methods used**: we applied advanced methods of mine, laboratory and experimental studies, theoretical and physical simulation, and analysis and generalization of the results of studies using standard and recommended techniques. **Novelty**: novel elements include the systematization of technological solutions for managing developed areas of the mine, taking into account the technology-related factors affecting the energy state of the mass, and showing ways to minimize its impact on the technology of ore and nonmetallic mineral resources mining. **The result**: the paper proposes to change the impact rate of the technology-related state of the mass formed by subsequent, contiguous mined-out areas, a method for destroying the rock pillars separating their cavities, which reduces the energy tension of the mass by 6 times and the secondary water cut of the ore deposits in the lying side of the mine field. This makes it possible to carry out preparatory excavations without the use of supports and to increase a stope area by 1.5–2 times. The change in the shape of the mined area of the mine by the formation of unloading cracks makes it possible to reduce the energy parameters of the mass by 0.3 times, when developing the three underlying floors over ore deposits.
Keywords: underground mining, geodynamic safety, competence of the outcrop, energy zone.

Introduction

Scientists from Ukraine, Russia, Germany, Austria, Switzerland, France, England, the USA, Canada, South Africa and other developed mining countries of the world actively engaged in the development of technologies for underground extraction of minerals with increasing depth of development in tense rocks [1–5]. Most researchers took into account changes in the array's tension due to the degree of influence on the parameters of the strength of the workings and development systems. Such an approach made it impossible to reveal the physical nature of the phenomenon of zonal disintegration of rocks, which manifests itself around all without exception, underground workings. Therefore, the provision of geodynamic safety with increasing depth of underground mining of ore deposits on the basis of operational control data and prediction of a tense state of the rock mass with various forms of dynamic manifestation of rock pressure, prevention and prevention of mountain attacks is an important scientific, practical and social task [6–9].In order to solve the problems, the authors carried out studies in the field of providing geodynamic safety with increasing depth of underground mining of ore deposits based on the data of operational control and prediction of the tense state of the rock mass with various forms of dynamic manifestation of mountain pressure, prevention and prevention of mountain bumps, with the help of theoretical, laboratory and industrial methods, theoretical analysis and generalization of research results according to standard and new methods [1–9].

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Theory and methods of research

The authors use the systematic approach, which contains an analysis of the results of research and design work on the development of new technologies and technical means for underground mining of ore deposits to ensure geodynamic safety while increasing the depth of underground mining of ore deposits. The physical properties of rocks and the new hypothesis about mountain pressure are analyzed taking into account the estimation of the stability of the outcrops, revealing the patterns of their deformation and destruction, linking the excavation of ores and rocks in time and space, defining the parameters of the design elements of the development systems, the methods of fastening and the corresponding types of crepe. Theoretical experiments were carried out using thermodynamic, improved and developed energy methods by the authors [4].

Summary of research results

The level of concentration of stresses in the massif at large depths necessitates the transition to a technology with a continuous recess and a straightforward front of purification works. Development systems with chamber recess and laying of the developed space with different compositions and strength in a wide range of mining conditions allow not only to ensure the safety of mining operations, to reduce the probability of rock blows, but also to significantly improve the quality and completeness of extraction of reserves from the interior, which is gaining increasing importance in the competitive struggle for markets of sale [5]. The presence in the mine fields of up to 50% of the developed spaces that have access to the surface of the surface allows us to change their typology and, as a consequence, to change the degree and nature of influence on the host array. For example, it is possible from the developed spaces that have access to the surface of the surface to form the «blind». This makes it possible to change the voltage fields in the massif of the discharge zone of the developed spaces and to create favorable conditions for the pressure factor at the site of mining operations. It is proposed to separate the developed space by means of forming an artificial whole in its cavity. The simulation of possible variants of transformation of the developed spaces showed that the formation of artificial helicopters consisting of the host rocks and the bookmark array is effective. The artificial heaps perceive the pressure of the rocks of the hanging side and reduce the tension in the region of the reference pressure. They also violate the aerodynamic and hydrodynamic relationship with the surface of the day and reduce air leakage through the excavated space, as well as the penetration of atmospheric precipitation into the mine preparation and cleaning faces of the mine.

1. Classification of methods for studying the state of rocks

The development of deposits in various conditions of occurrence, different properties of ores and rocks is characterized by cracking, stratification, collapse, collapse, shock hazard and other forms of manifestation of energy of mountain pressure. An analysis of mining and geodynamic conditions for the development of ore deposits in Ukraine has shown that dynamic manifestations of rock pressure indicate a high level of elastic potential energy of rocks of domestic ore deposits. The processes of accumulation of stresses in the massif and destruction of rocks, arising in the process of exploration of deposits, are studied by a variety of methods. The basis of most applied research methods is the principle of the dependence of different properties of rocks with their strained-deformed state under the influence of natural and artificial energy fields in the array. In spite of the variety of methods and means of diagnostics used and the control of the strained-deformed state of the array, they can be grouped into functional classes (physical, laboratory, and analytical). In turn, the classes are subdivided into groups (visual, surveying, mechanical, geophysical, etc.) and further on the species. Using the sign «way of representing the array", the existing classification was improved **(Table 1)**.

2. Separation of extended developed spaces

The development of ore deposits of Kryvbass by traditional systems of development to the depths of 1200–1300 m determined the formation of IPs, which represent on the earth's surface the funnel of displacement, and in the interior - void, partly filled with collapsed rocks. These cavities contribute to the redistribution of the initial stresses of the undisturbed massif and to the formation of areas of reference pressure at the mining sites. Through the developed space, an aerodynamic bond with the surface is established, which increases the air leakage into the mine's ventilation network, and the hydrodynamic bond increases the secondary watering of the production units [6]. Effective is the formation of artificial helicopters consisting of the enclosing rocks and the rock massif. Thus, for example, it is possible from the IPs having access to the earth's surface to form the «blind» VPs. The main element of the proposed technological solution is the formation of artificial helicopters with different ways of forming shut-off elements for different mining conditions in the northern group of mines of the Kryvyi Rih basin **(Fig. 1)**.

Table 1.Classification of the stress-strain state of rocks

Class	Group	View
I. Natural (industrial)	Visual	Observations and Assessments
	Mine Surveying	Mine surveying surveys
	Mechanical	Unloading the array
		Compensation load
		Pressure differences
		Elastic inclusions
		Well deformation
		Depth Ramp
	Geophysical	Acoustic
		Ultrasound
		Radiometric
		Electrometric
		Geomagnetic
II. Physical (laboratory)	Investigation of the properties of rocks	Density
		Mechanical
	Equivalent materials	Modeling on the press
		Centrifugal modeling
	Optical polarization	Modeling on the press
		Centrifugal modeling
		Volume photoelasticity
	Electrodynamic analogies	Electrical grids
		Conductive materials
III. Analytical (theoretical)	Mechanics of rocks	Solid environment
		Elasticity
		Plasticity
		Creep
		Boundary differences
		Boundary elements
		Finishing elements

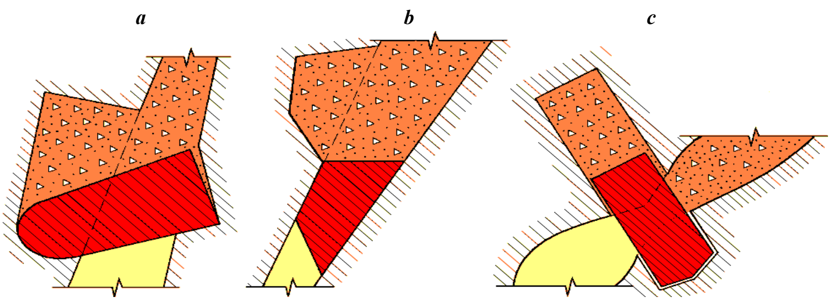

Fig. 1. Principal schemes of the formation of locking elements of the type «shutter» (***a***), «plug» (***b***) and «gate» (***c***) in the formation of artificial helicopters

The space over the artificial whole is filled with a dry or hardening tab. The experience of re-exploration of the deposits of Kryvbas testifies to the fact that the rocks that are destroyed in the developed space, with the condition of absence of movement, are converted into a monolith over time [7]. The experience of the Irtysh mine speaks of the fact that the dry bookmark occupies a significant part of the pressure of the enclosing rocks [8]. When modeling the bookmarking process in laboratory conditions, it was found that with a porosity of 10–12%, the laying material can accept a load of up to 5 MPa with shrinkage not exceeding 13%. Provided that the rock placement is kept in a stationary state and in the presence of a moist medium, its bearing capacity approaches the bearing capacity of the hardening bookmark. Homogenization of the dry rock massif under the influence of static forces of gravity, dynamic forces of explosive waves and the infiltrational influence of atmospheric precipitation helps to create an artificial whole, approaching its properties to the natural.

3. Investigation and substantiation of technological parameters of the developed spaces

The development of ore deposits at Kryvbasa mines is carried out primarily by chamber systems of development (70% of the total volume) and various variants of underground collapse of ores and adjacent rocks (30%) **(Table 2)**.

The treatment of ore deposits by systems without the maintenance of adjacent rocks leads to the formation of developed spaces (IPs), in the zones of influence of which stocks of various mineral raw materials fall. These are rich, poor and oxidized ores, related minerals, building materials, stone of precious stones, etc. [9]. The development of the Kryvbass deposits in complex technogenic conditions is deeply studied by B. M. Andreyev, whose work gives a classification of technogenic factors and methods of their accounting [10]. However, to date, no technical solutions have been proposed for reducing the influence of the main man-made factor in the Kryvbass – VP of mines. To this end, the authors proposed a number of technical solutions for the management of IP at the mines «Kryvbas». The revealed patterns of distribution of voltage fields and the nature of the deformation of the enclosing FP of the array, as well as the presence in the mine fields of a large number of different types of isolated VPs, create favorable conditions for the selection and application of effective methods for controlling the energy status of a rock massif. Reduction of mountain pressure in the areas of conducting preparatory and treatment works is accompanied by resource saving due to the use of less metal-intensive fastening of preparatory workings, increasing the size of the waste chambers, reducing the size of inter-and inter-chamber helicopters. In particular, the VP of «Ternovskaya» mines of PJSC «Kryvorozhsky PJSC» is represented by 1275 m of stale and stratum deposits deposited to the horizon. The collapse of the rocks of the hanging side in the mine field is negligible. Stabilization of the parameters of the displacement zone begins at depths of 500 - 600 m. On the northern flank of the fields of the Ternovskaya mine, there is a canned debris of poor ore «Bulimmerka Magnetite» and a developed deposit of rich ores «8P». The transformation of the VC of the mine to reduce the pressure of the mountain on its lying side is possible due to the destruction of voltage concentrators - natural breeding helicopters separating the separated VPs. This leads to the displacement of the region of energy concentration to the lower end of the newly formed VP, the decrease in the mass of the craters that are destroyed in the IP and the increase of the hydroplastic capacity of the VP **(Fig. 2)** [11–14].

Table 2

Classification of technological solutions for «Kryvbas»

Class deposits	Condition of the next rocks	The essence of the technological solution	Place of Execution mining works
I. Without an exit under sediment («blind»)	Movement rocks is absent	Connection of closeup VPs	Loose gaps between deposits
II .With an exit under sediment		Change forms of PP mine	Lower boundary VP shaft
III. With an exit under sediment	Destruction rocks to the daytime surface	Separation of extended IPs to the detached ones	Middle part VP shaft

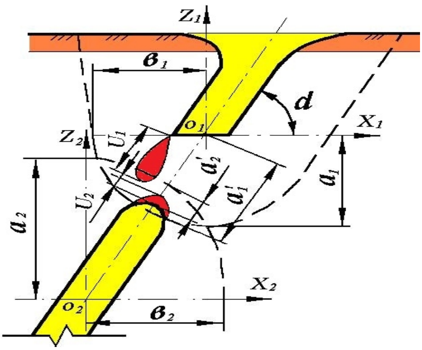

Fig. 2. The calculated scheme of parameters of the destruction of a natural integer

In **fig. 2** the following symbols are given: a1 and b1 are the vertical and horizontal semiaxes in the array of the adjacent energy zone of the IP, which extends to the earth's surface, directed along the axes O1Z1 and O1X1, m; a2 and b2 are the vertical and horizontal half-axes in the array of the contour zone of the VP, which exits to the earth's surface and surrounds the «blind» VP, and directed along the axes O2Z2 and O2X2, m; α – angle of propagation VP, hailstones; a11 and a12 are the depths of the contour energy zones of the «blind» and emerging on the surface of the VP, m; U1 and U2 are the depths of possible fracture in the breeding unit, respectively, from the SP that has an exit to the earth's surface and the «blind» VP, m. The main technological parameters for deep mines on the example of Kryvbas, Ukraine are determined in the following sequence. The size of the adjacent energy zone of the PE along the rocks' stretch was determined according to the method [15–17]. The size of the contour energy zone extending to the earth's surface of the VP, located in the breeding heap, m

$$a_1^1 = \sqrt{\frac{\left(a_1^2 + в_1^2\right)\left(a_1 в_1\right)^2}{\left(a_1 в_1\right)^2 + 1}} . \qquad (1)$$

Depth of the margin energy zone of the «blind» VP, located in the breeding wholeness, m.

$$a_2^2 = \sqrt{\frac{\left(a_2^2 + в_2^2\right)\left(a_2 в_2\right)^2}{\left(a_2 в_2\right)^2 + 1}} - 0{,}5 h_{ВП} \sin a , \qquad (2)$$

where $h_{ВП}$ – vertical span of the «blind» VP, m.

Depth of propagation of the area of possible destruction in the massif of the generic integral for the VP, going out on the earth's surface, m

$$U_1 = H\left(-0{,}0047\,\sigma_{сж} + 0{,}9\right) , \qquad (3)$$

where H – Depth of propagation VP, m; $\sigma_{сж}$ – The strength of the rocks for compression, MPa.

The parameters of drilling and blasting works for deep wells in the field of transient stresses can be efficiently performed by cutting off contouring wells with bursts of column charges according to the method [18]. This reduces the energy costs of blasting and drilling up to 25%. The method of drilling a rock integral is determined based on the location of preparatory and trench excavations on the corresponding horizon. As the results of the calculations for the conditions of the Ternovskaya mine show, the destruction of natural helicopters separating the separated VPs allows to reduce the tension of the massif by 6 times and eliminate the secondary watering of the deposits located in the lying part of the pipeline. This makes it possible to carry out preparatory work without applying the crepe and increasing the height of the waste chambers to 120–150 m [19]. The reserves of rich ore «Kryvbas» at the depth of 1100–1260 m to the north of 227 MO were originally intended to be worked out after the complete working out of magnetite quartzites with the use of traditional technologies for working out of mine fields existing in the Krivoy Rog Basin. In 1996, the relevant recommendations were developed in order to develop technological solutions to reduce the reserves of canned rich ores while maintaining the possibility of further processing of the balance reserves of magnetite quartzites of the GNIGRI GVUZ «KNU» (Kryvyi Rih) in 1996. They reveal the possibility of partial extraction of up to 2.7 million tons of rich ore reserves from the guarded whole, while maintaining the possibility of further processing of magnetite quartzites from the deposit «Northern» due to the abandonment of barrier helicopters in the interior [20].

The collapse of the rocks of the hanging side occurs with the lagging behind the front of the clearing works on 1–2 working floors. The displacement of the rocks of the hanging side stops from a depth of 450–550 m. From these depths, the surface displacement process stabilizes and passes into a partial dome-shaped destruction of the enclosing rocks around the developed space. The angles of displacement and breaking of the rocks by the stretch correspond to 80º, in the hanging and lying sides – 55º. The «Yubileinaya» mines are represented by the «Nest 1–2» and «Home» depleted to a depth of 1100 m **(Fig. 3)**.

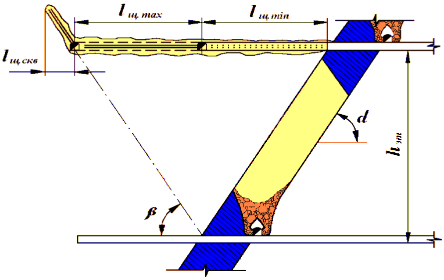

Fig. 3. Schematic diagram of the parameters of the discharge fracture

In **fig. 3** the following conditional symbols are given: lmin.min and m.sub.max – the lengths of fractures where changes in the array intensity occur within the first lower floor and, accordingly, the unloading of the second underlying floor, m; lsh.skv is the length of the section of the crack formed by the exploding of the wells at which the unloading of three or more lower floors occurs, m; heath is the height of the floor under construction, m; α and β – respectively, the angles of incidence and displacement of the rocks of the hanging side of the reservoir, deg.

Investigations have made it possible to establish that the power of the IP, varying from 5 to 90 m, has a small effect (up to 6%) on the overall level of the intensity of the host massif, and the increase of the contour energy zones occurs on the magnitude of the change in the power of the cultivated deposit, leaving the depth of influence unchanged and, accordingly, Voltage values [21, 22]. This fact made it possible to conclude that in the massif around the cracks formed similar energy zones with parameters similar to the developed space. The results of the research allowed to develop a method for reducing the pressure of the mountain for the conditions of working out of preserved reserves at the mine «Yubileinaya» due to the formation of unloading cracks. The essence of the process of unloading the underlying massif lies in the development of the crack of the underlying portion of the deposit. For IPs having an exit to the earth's surface, a crack is formed in the hanging side, above its level. The formation of the fracture contributes to an increase in the horizontal span of the VP and, as a consequence, an increase in the contour energy zone and the redistribution of the initial voltage fields. At the same time, the displacement of the reference pressure region, which envelops the treated chambers, takes place in the direction of the formation of the crack and discharges the shaft cleaning units from the pressure of the rock [23]. The presence of tapping workings in the hanging side of the VP reduces the cost of forming the crack and increases its length. On the basis of the research carried out and the results obtained, the authors determined the following parameters and sizes below the established expressions and dependencies.

Total length of unloading crack, m

$$l_m = l_{m,\min} + l_{m,\max} + l_{m.скв}. \quad (4)$$

The length of the fracture site at which the mass of the intensity changes within the first underlying floor, m

$$l_{m.\min} = h_{эm} tg\left(\frac{\pi}{2} - \alpha\right), \quad (5)$$

where $h_{эm}$ – floor, height of workable m; α – angle of fall of the deposit, deg.

The length of the fracture site at which the second lower floor is unloaded, m

$$l_{m.\max} = h_{эm} tg\left(\frac{\pi}{2} - \beta\right), \text{ м}, \quad (6)$$

where β – angle of rotation of the hanging side, degrees.

The length of the fracture site formed by the exploding of provocative wells, in which the unloading of three or more underlying floors occurs, m

$$l_{m.скв} = l_{скв} tg\left(\frac{\pi}{2} - \beta\right) + 0{,}5W, \quad (7)$$

where $l_{скв}$ – ength of discharge wells, m; W – line of the least resistance of the explosive, m.

The regularity of the number of unloaded floors from the length of the crack

$$l_{m.скв} = l_{скв} tg\left(\frac{\pi}{2} - \beta\right) + 0{,}5W, \text{ sht.} \quad (8)$$

The maximum lengths of each fracture site are taken from the technical capabilities of deep drilling machines [24]. Thus, the measures taken to reduce the negative influence of the developed space allow us to justify the technological parameters of the mining preparatory and treatment underground work of the Krivoy Rog iron ore basin. Expected economic effect only from the reduction of the pressure on the prepared and ready for production reserves is more than 600 thousand. UAH / year, taking into account the management of the state of the massif, reducing to 15–30% of total costs of sewage, transport, ventilation, etc.

Direction of further research

The development of technologies for the extraction of ore raw materials in the conditions of technogenesis should be based on the classification of deposits and development systems on the basis of the «energy state of the array at the time of development", which determines the methods for separating material from the array. It is also necessary to consider the constant change in mining and geological and man-made factors [25–27]. The systematization of technological solutions for the management of the developed space of mines while working out, in particular, Krivbass deposits, takes into account the man-made factors affecting the energy status of the massif and shows ways to minimize its influence on the extraction technology of ore and non-metallic minerals, taking into account the developed mining countries of the world [28].

Conclusions

1. It is established that minimization of the influence of extended developed spaces on the energy status of mineral deposits is realized by separating extended developed spaces and forming artificial cavities in their cavity, which allows to reduce the energy saturation of the massif in the field of mining operations up to 6 times and reduce costs by 15% on drainage, transport and ventilation of the mine.

2. It was shown that for the change in the intensity of the influence of the technogenic state of the massif formed by the successively-developed spaces, a method is proposed for the destruction of the generic helicopters separating their cavities, which allows reducing the energy intensity of the massif to 6 times and secondary watering of ore deposits in the lying side of the mine field. This makes it possible to carry out preparatory work without the use of fasteners and increase the size of cleaning chambers in 1,5–2 times.

3. It is recommended that the change in the shape of the developed space of the mine by creating unloading cracks allows us to reduce the energy saturation of the massif by 0.3 times when working out three underlying floors on ore deposits.

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ИНФОРМАЦИЯ О СТАТЬЕ НА РУССКОМ ЯЗЫКЕ

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ГЕОДИНАМИЧЕСКАЯ БЕЗОПАСНОСТЬ ПРИ УВЕЛИЧЕНИИ ГЛУБИНЫ РАЗРАБОТКИ РУДНЫХ МЕСТОРОЖДЕНИЙ

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Аннотация
Постановка задачи (актуальность работы): описаны основные научные и практические результаты исследований повышения геодинамической безопасности при увеличении глубины подземной разработки рудных месторождений на основе данных оперативного контроля и прогноза напряженного состояния горного массива с различными формами динамического проявления горного давления, профилактики и предотвращения горных ударов. На примере рудных месторождений Украины проанализированы физические свойства горных пород и новые гипотезы о горном давлении с учетом увязки выемки

руды и пород во времени и пространстве, определения параметров конструктивных элементов систем разработки. **Цель работы:** повысить геодинамическую безопасность при увеличении глубины разработки рудных месторождений путем контроля и прогноза напряженного состояния горного массива с различными формами динамического проявления горного давления, профилактики и предотвращения горных ударов. **Используемые методы:** применялись усовершенствованные методы шахтных, лабораторных и математических исследований, теоретического и физического моделирования, а также анализ и обобщение результатов исследований по известным и разработанным методикам. **Новизна:** к ее элементам относится систематизация технологических решений по управлению выработанным пространством шахт, которая учитывает техногенные факторы, влияющие на энергетическое состояние массива, и предопределяет пути минимизации его влияния на технологии добычи рудных и нерудных полезных ископаемых. **Результат:** для изменения интенсивности влияния техногенного состояния массива, сформированного последовательно-сближенными выработанными пространствами, предложен способ разрушения породных целиков, разделяющих их полости, что позволяет снизить энергетическую напряженность массива до 6 раз и вторичную обводненность рудных залежей в лежачем боку шахтного поля. Это дает возможность проведения подготовительных выработок без применения крепей и увеличения размеров очистных камер в 1,5–2 раза. Изменение формы выработанного пространства шахты путем образования разгрузочных трещин позволяет снизить энергетическую насыщенность массива в 0,3 раза при отработке трех нижележащих этажей по рудным залежам.

Ключевые слова: подземная разработка, геодинамическая безопасность, устойчивость обнажений, энергетическая зона.

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