ISSN 2500-0632 (ON-LINE)
MINING SCIENCE AND TECHNOLOGY (RUSSIA)
GORNYE NAUKI I TEHNOLOGII
2020;5(2):104-118
MISIS National University of Science and Technology

ORIGINAL PAPERS / ОРИГИНАЛЬНЫЕ СТАТЬИ

DOI: 10.17073/2500-0632-2020-2-104-118

Development of Environment-Friendly and Resource-Saving Methods of Underground Ore Mining in Disturbed Rock Masses

V. I. Lyashenko[1], **O. E. Khomenko**[2], **V. I. Golik**[3]

[1]State Enterprise Ukrainian Scientific Research and Design Institute of Industrial Technologies (SE "UkrNIPIIpromtekhnologii"), Zheltye Vody, Ukraine;
[2]National Technical University "Dneprovskaya Polytechnica", Dnipro, Ukraine;
[3]North Caucasian Mining and Metallurgical Institute (SKGTU), Vladikavkaz, Russia

Abstract: One of the most problematic aspects in underground ore extraction in mining-disturbed rock masses is backfilling of man-made voids, which affect origination and redistribution of stress-strain state of the rock mass. Their existence in the earth's crust provokes subsidence/collapse of the day surface and also contributes to arising geomechanical and seismic phenomena. The purpose of the study is to substantiate environmental-friendly and resource-saving methods for backfilling of voids in underground ore mining based on revealing the features of rock integrity of the day surface and life-sustaining activity of the population living in the mining-affected area. The main negative consequences of the impact of mining on the environment and humans are high costs for conserving day surface and ensuring life-sustaining activity of the population living in the mining-affected area, as well as removing large areas of land from human activity, etc. Based on the study of a rock mass stress-strain state using geophysical and surveying methods, an environment-friendly method for backfilling of man-made voids in disturbed rock masses is proposed. It enables ensuring the integrity of the day surface and life-sustaining activity of the population living in the mining-affected area (in the vicinity of mines, dumps, sites of backfilling complexes, preconcentration and heap leaching of metals from substandard ores, tailings storage facilities, etc.). Combined geotechnologies are proposed for backfilling of voids during the development of ore deposits by underground block leaching, and scientific and methodological and technical support was provided for drilling and blasting preparation of hard ores and underground leaching of pilot blocks at the Michurinsky deposit of GP VostGOK, Ukraine. The research findings can be used in underground mining of ore deposits of complicated structure.

Keywords: disturbed rock mass, underground ore mining, environmental and resource-saving method, backfilling of man-made voids.

Acknowledgements: Specialists of the following organizations contributed to the creation, improvement and implementation of these research and development:

– State Enterprise "Ukrainian Research and Design Institute of Industrial Technology" (SE "UkrNIPIIpromtekhnologii"), the city of Zheltye Vody, Ukraine;

– State Enterprise "Vostochny Mining and Processing Complex" (SE "VostGOK"), the city of Zheltye Vody, Ukraine;

– National Technical University "Dneprovskaya Polytechnica", Dnepr city, Ukraine

– Institute of Geotechnical Mechanics named after N.S. Polyakov of the National Academy of Sciences of Ukraine (IGTM, NAS of Ukraine), Dnepr city, Ukraine;

– State Higher Educational Institution "Kryvyi Rih National University", Kryvyi Rih, Ukraine;

– Joint-Stock Company VNIPIpromtekhnologii, St. Petersburg, Russia;

– Joint-stock company "VNIMI", St. Petersburg, Russia;

– Tselinny Mining and Chemical Complex, Stepnogorsk, the Republic of Kazakhstan.

For citation: Lyashenko V. I., Khomenko O. E., Golik V. I. Development of environment-friendly and resource-saving methods of underground ore mining in disturbed rock masses. *Gornye nauki i tekhnologii = Mining Science and Technology (Russia)*. 2020;5(2):104-118. (In Russ.). DOI: 10.17073/2500-0632-2020-2-104-118.

Развитие природоохранных и ресурсосберегающих технологий подземной добычи руд в энергонарушенных массивах

Ляшенко В. И.[1], **Хоменко О. Е.**[2], **Голик В. И.**[3]

[1]Государственное предприятие Украинский научно-исследовательский и проектно-изыскательский институт промышленной технологии (ГП «УкрНИПИИпромтехнологии»), г. Желтые Воды, Украина;
[2]Национальный технический университет «Днепровская политехника», г. Днепр, Украина;
[3]Северо-Кавказский горно-металлургический институт (СКГТУ), г. Владикавказ, Россия

Аннотация: Одним из самых проблемных мест при подземной добыче руд в энергонарушенных массивах является погашение техногенных пустот, которые влияют на возникновение и перераспределение напряженно-деформационного состояния (НДС) массива горных пород. Их существование в земной коре провоцирует нарушение дневной поверхности, а также способствует возникновению геомеханических и сейсмических явлений. Цель исследования обоснование природоохранных и ресурсосберегающих технологий погашения пустот при подземной добыче руд на основе установления закономерностей проявления горного давления массива горных пород, что позволит обеспечить сохранность дневной поверхности и жизнедеятельность населения, проживающего в зоне влияния горнодобывающего региона. Основными отрицательными последствиями воздействия горной технологии на окружающую природную среду и человека являются большие затраты на сохранность дневной поверхности и обеспечение жизнедеятельности населения, проживающего в зоне влияния горных объектов, вывод больших площадей земель из экономического оборота и др. На основе исследования механизма НДС массива пород с использованием геофизических и маркшейдерских методов предложена природоохранная технология погашения техногенных пустот в энергонарушенных массивах. Она позволяет обеспечить сохранность дневной поверхности и жизнедеятельность населения, проживающего в зоне влияния горных объектов (шахты, отвалы, промышленные площадки для закладочных комплексов, предконцентрации и кучного выщелачивания металлов из некондиционного рудного сырья, хвостохранилищ и др.). Предложены комбинированные геотехнологии погашение пустот при разработке рудных месторождений подземным блочным выщелачиванием и осуществлено научно–методическое сопровождение и техническое обеспечение буровзрывной подготовки скальных руд и отработки ПБВ опытно–экспериментальных блоков на Мичуринском месторождении ГП «ВостГОК», Украина. Результаты исследований могут быть использованы при подземной разработке рудных месторождений сложной структуры.

Ключевые слова: энергонарушенный горный массив, подземная добыча руд, природоохранная и ресурсосберегающая технология, погашение техногенных пустот.

Благодарность: В создании, совершенствовании и внедрении научных разработок принимали участие и оказывали содействие специалисты следующих организаций:

– Государственное предприятие «Украинский научно-исследовательский и проектно-изыскательский институт промышленной технологии» (ГП «УкрНИПИИпромтехнологии»), г. Желтые Воды, Украина;

– Государственное предприятие «Восточный горно-обогатительный комбинат» (ГП «ВостГОК»), г. Желтые Воды, Украина;

– Национальный технический университет «Днепровская политехника», г. Днепр, Украина;

– Институт геотехнической механики им. Н.С. Полякова Национальной академии наук Украины (ИГТМ НАН Украины), г. Днепр, Украина;

– Государственное высшее учебное заведение «Криворожский национальный университет», г. Кривой Рог, Украина;

– Акционерное общество «ВНИПИпромтехнологии», г. Санкт-Петербург, Россия;

– Акционерное общество «ВНИМИ», г. Санкт-Петербург, Россия;

– «Целинный горно-химический комбинат», г. Степногорск, Республика Казахстан.

Для цитирования: Ляшенко В. И., Хоменко О. Е., Голик В. И. Развитие природоохранных и ресурсосберегающих технологий подземной добычи руд в энергонарушенных массивах. *Горные науки и технологии*. 2020;5(2):104-118. DOI: 10.17073/2500-0632-2020-2-104-118.

Introduction

The main indicators of effective underground ore mining in the course of development of deposits of complex structure are the rock mass characteristics and technogenic mining conditions [1, 2]. The key factor for ensuring day surface stability during ore mining is the factor of void filling [3, 4]. The problem is especially acute in conditions of complicated deposits, in heterogeneous rock masses with high rock strength and complicated structure [5, 6].

Therefore, substantiation of environmentally sound and resource-saving methods for backfilling of man-made voids in the course of underground ore mining on the basis of establishing patterns of manifestation of rock mass pressure to ensure vital activity of the population living in the mining-affected districts is an urgent scientific, practical and social issue requiring development of effective solutions [7]. This study is a continuation of the studies with the authors participation, the main scientific and practical results of which are most fully described in [8, 9].

Objective and tasks

The purpose of the study –is substantiation of environmentally sound and resource-saving methods for backfilling of man-made voids in the course of underground ore mining on the basis of establishing patterns of manifestation of rock mass pressure to ensure stability of the day surface and vital activity of the population living in the mining-affected districts.

In the furtherance of this goal, it is necessary to complete the following tasks.

1. To analyze the factors of rock pressure manifestation in hard rock masses of complicated structure with high intensity of faults/fractures.

2. Identify the conditions for the formation of residual bearing capacity in disturbed rocks under triaxial compression.

3. Determine the conditions of stump blasting, reducing the fragmentation index while blasting a rock mass layer in a closed volume and increasing seismic effect of explosive vibrations.

4. Determine the parameters of seismic vibrations, the ore mass crushing quality and index of fragmentation of the “fragmented” material.

5. Develop environmentally sound and resource-saving backfilling methods for underground ore mining in disturbed rock masses of complicated structure.

Basic Provisions

Review of existing solutions to the problem. Review of man-made voids shows that with increasing the depth of ore mining and the duration of stope (void) existence, the frequency of collapsing rocks in them increases. The review suggests importance of the formation of man-made voids, which affect the occurrence and redistribution of strain-stress state (SSS) of a rock mass. Their existence in the earth's crust provokes collapse (cave-in) of the day surface, as well as effect of geomechanical and seismic phenomena [10, 11].

Research Methods. In the course of the study, we used the methods of complex analysis and synthesis, practical experience and scientific achievements in the fields of:

– geotechnology;

– methods and facilities for backfilling of voids during underground mining of ores in disturbed rock masses;

– theories and practices of explosive rupture of solid media.

Using simulation methods based on equivalent and optically active materials, we studied:

– the effect of disturbance (broken condition) of a rock mass on the stability of mining workings, changing the factors of manifestation of rock pressure with increasing depth of mining;

– dependence of the strain-stress state of the disturbed rocks on the overall dimensions of the mine workings.

Methods of continuum mechanics, mathematical statistics, and methods of studying wave processes were also used [12, 13].

Study of stress and strain development mechanism in the zone affected by underground voids. In the practice of using the techniques and facilities for backfilling of voids during underground mining of ores in disturbed rock masses, the following approaches are the most widespread (Fig. 1).

Isolating voids by bulkheads without backfilling is used when extracting ore bodies of small and medium thickness, flank and blind ore bodies that do not affect underground facilities and the earth's surface [14, 15].

Filling voids by collapse of the enclosing rocks is the most common way that is connected with simplicity of the work organization, high degree of possible mechanization, and low cost. Its disadvantages include difficulties in controlling the void filling completeness and controlling the collapse process while decreasing thickness of ore bodies at depths of more than 500–600 m.

When developing deposits at great depths, the need to change to other methods of void filling arises. The method of void filling by collapse of the enclosing rocks is characterized by significant losses, and dilution and rupture of the rock mass up to the surface [16–18].

Backfilling by solidifying stowing (backfilling) mix provides better performance of subsoil use. Most of the voids is backfilled with mixes while simultaneously extracting, by open-cut and underground methods, thick steeply dipping ore bodies of deposits located in intensely disturbed rocks of medium stability. This approach advantages include minimal costs, relatively small losses and dilution, controllability, integrity of the enclosing rock mass and the earth's surface. The method features include increased requirement for detailed knowledge about a rock mass and permanent geotechnical and seismic monitoring [19, 20]. Recently, in a backfill mix, cement is often replaced with crushed binders mixed with sand and gravel materials. Backfill strength varies widely depending on the purpose of the artificial rock masses. In a number of deposits, a solidifying backfilling mix is used because of the need to preserve the day surface due to environmental conditions and for improving health and safety in mining regions [21, 22].

Combined backfilling of voids when developing ore deposits by underground block leaching method (UBL, a kind of ISL – In-Situ Leaching) is used in developed mining countries (Fig. 2).

During two-stage ore mining, the abutment pressure is redistributed to the stopes of the second stage, and the load on the structures is determined by the mass of rocks inside the arising natural self-supporting rock arch. Disturbed rocks within the arch are being deformed, but can form rugged structure and not interfere with the leaching process [23, 24]. Promising geotechnologies enable winding rich ores to the day surface, whereas the rest of ores is processed in situ (Table 1).

UBL (ISL) development of ore deposits involves the creation of areas of different strength rocks in disturbed rock masses:

– the blocks are filled with ore material, which is mobile and prone to compaction;

– the blocks are characterized by water saturation and decreasing the rock strength;

– during leaching, mineral particles move.

ISSN 2500-0632 (ON-LINE)
MINING SCIENCE AND TECHNOLOGY (RUSSIA)
GORNYE NAUKI I TEHNOLOGII
2020;5(2):104-118
MISIS National University of Science and Technology

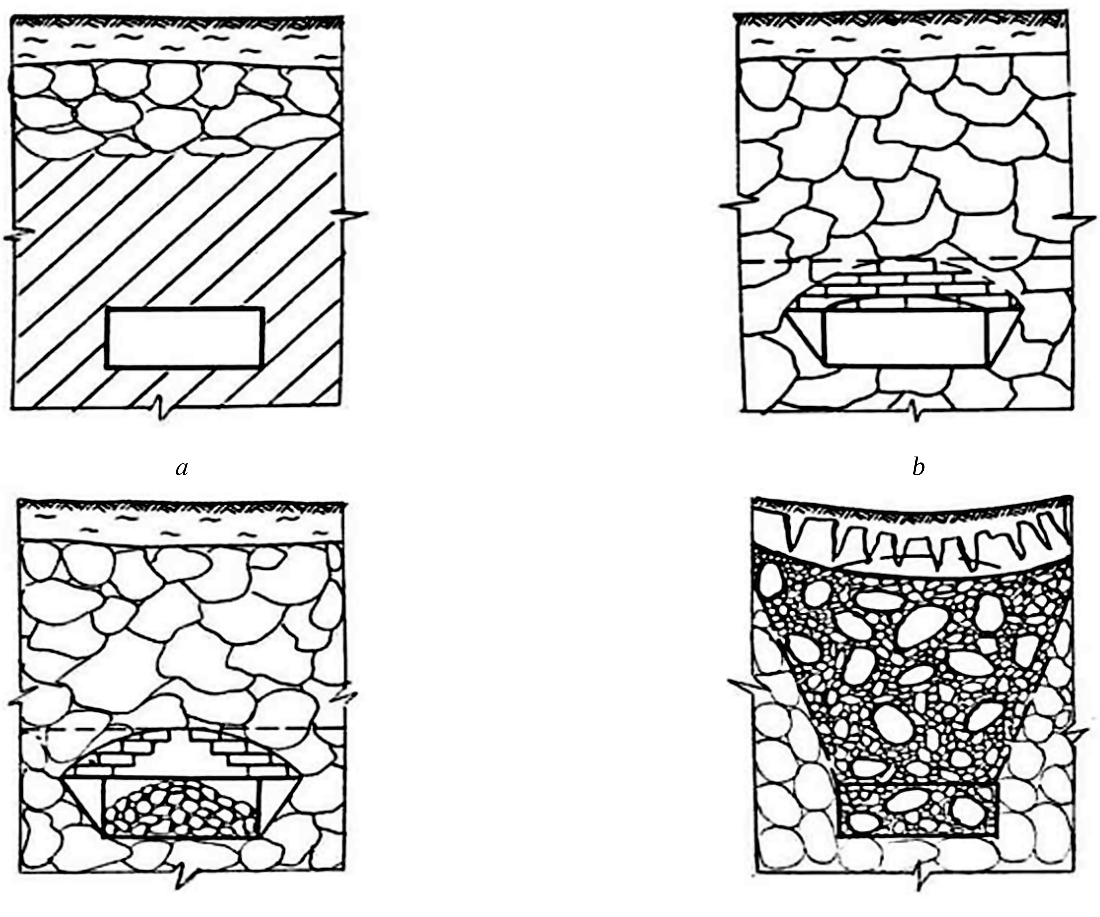

Fig. 1. The impact of voids on the earth's surface (schematics):
a – overlaying hard rock; *b* – flat roof at rock self-strengthening; *c* – rock collapse, not reaching the earth's surface; *g* – rock collapse involving the earth's surface

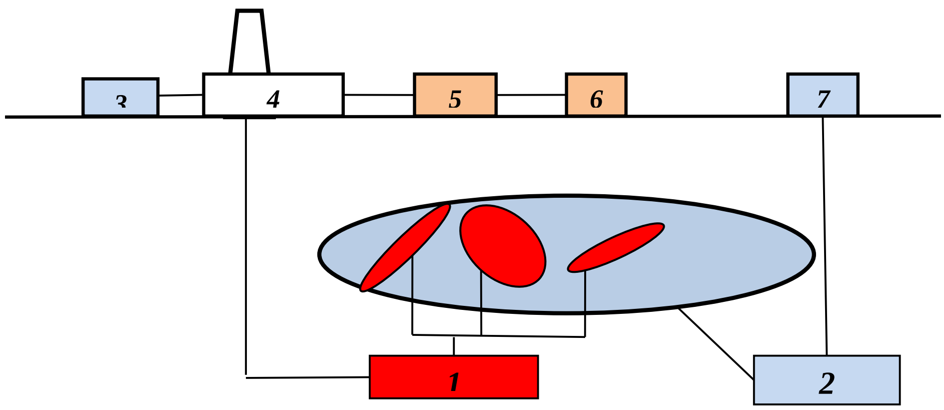

Fig. 2. Combined development of an ore deposit:
1, 2 – rich and poor ores, respectively; 3 – complex for heap leaching of poor and off-balance ores ((heterogeneities); 4, 5 – ore control and concentration plant (CCP) and processing plant (PP), respectively; 6 – stowing complex; 7 – shop for preparation of leaching solutions

Table 1

Typification of underground block leaching processes

Process	Process parameters	Process Conditions
Ore crushing	Providing grain size ranging +20 mm to -50 mm	Uniform ore density. The possibility of creating a compensation space for a blast
Ore spraying	Boreholes in an intact rock mass. Spraying from the ore surface. Applying casing for boreholes within broken ores. Applying fine-grained materials. Hydraulic fracturing	The lack of impervious zones and channels in the broken ore (muck)
Collection of pregnant solutions	Impervious curtains. Waterproofing of leaching areas. Electrovacuum drainage of solutions. Applying synthetic polymeric materials	Prevention of leaching product access to the environment
Process intensification	Physical methods: injection of compressed air, ore blasting, particle size reduction proportional to the concentration gradient, slabbing at variable line of least resistance of charges, control of the release ellipsoid, analysis of ultrasonic vibrations, electromagnetic treatment of solutions. Chemical methods: washing with water with activating additives, injection of chemical compounds. Biological methods: applying bacterial strains	Producing specified loosening. Increasing the content of useful component in pregnant solution to an acceptable value
Leaching completeness control	Downhole methods: rock drilling for introducing monitoring devices, drilling through broken ore with sampling. Roadheading with sampling	Representativeness of the samples and measurements for the whole block

Creation of such areas provokes increasing tensile stresses and loads on the elements of the natural-technogenic system [25, 26]. The balanced state of the ore-hosting rock mass is ensured if the UBL blocks are unloaded (to eliminate critical stresses) by artificial and natural rock masses.

The practice of preparing ore reserves for underground block leaching

Assessment of a blast seismic effect on underground and surface facilities. Recently, mining conditions have become more complicated due to increasing mining depth, extracting ore bodies under built-up areas, and the presence of protecting pillars in the immediate vicinity of the earth's surface. An indispensable requirement for mining operations under these conditions is, on the one hand, providing complete integrity of facilities and the earth's surface and, on the other hand, ensuring the required performance. Mining safety largely depends on the nature and intensity of wave propagation effects during blasting, the state of the rock mass transmitting blasting shocks, and the behavior of different facilities when interacting with waves during blasting.

The main condition for maintaining a rock mass stability at periodic dynamic stresses is preservation of the medium volume, i.e. the magnitudes of stresses arising from blasting should not cause permanent deformations in the rock mass. Then, based on the conditions of keeping a rock mass integrity/stability, the values of relative deformations caused by a blasting, E_e, should not exceed the permissible levels, E_p, i.e.

$$E_e > E_p. \qquad (1)$$

Relative deformations caused by blasting, taking into account the twofold factor of safety

(FoS) of a rock mass, are determined from the expression:

$$E_p = \frac{U_e}{2C_p}, \qquad (2)$$

where U_e is the displacement velocity during blasting, cm/s; C_p is the P-wave (compressional) velocity in a rock mass, cm/s.

Therefore, to ensure the stability and integrity of a rock mass and the environment, the displacement velocity during blasting should not exceed the permissible level U_p, i.e. the following condition must be met:

$$U_p > U_e. \qquad (3)$$

Permissible soil vibration velocities in the base of structures of different classes in different rocks are given in Table 2.

Table 2

Permissible vibration velocities for structures

Rock characterization	Protodyakonov rock hardness index, *f*	P-wave (compressional) velocity, km/s	Permissible soil vibration velocity, cm/s, for buildings of class			
			I	II	III	IV
Regolith, debris	0.5–1.0	1–2	4.1	8.2	12.2	20.4
Highly fractured rocks of high porosity with clay	1–3	2–3	6.8	13.6	20.3	34.0
Hard rock of significant natural fracturing	3–5	3–4	9.5	19.0	28.4	47.5
Relatively monolithic rocks with some fractures and voids	5–9	4–5	12.2	24.4	36.7	60.0
Monolithic rocks, low-fractured	9–14	5–6	14.9	29.8	44.6	74.5
Very hard rocks, monolithic, practically without fractures	14–20	6–7	17.8	35.6	53.3	89.0

As seen from the data of Table 2, subject to observance of the specified parameters, the surface integrity during underground blasting is ensured, and the buildings and structures built on the surface will not be ruptured, since the permissible displacement velocity (1–3 cm/s) for residential buildings is much lower than the permissible velocities for different rocks.

Assessment of the influence of geological conditions on the blasting seismic effect. Review of the historical site survey and geological data showed that topsoil (Q_4), loess-like loams (l_3 $Q_{2\text{–}3}$), sandy loams and loams (N_2–Q_1), and Buchak fine-grained sands (f_2 в) participate in the site sequence (from top to bottom). Total thickness of sedimentary rocks is 12–14 m. The sedimentary deposits everywhere overlay the eluvium of the weathering crust (P_z–M_z) on the crystalline Proterozoic rocks (RR_1). The weathering crust is represented by argillous-clastic material: primary kaolin, silty/sandy medium gravel, sand-clay, depending on the crystalline rock composition.

According to data from monitoring boreholes drilled along the strike of the ore body, the lower boundary of the weathering crust between the axes 61–69 is at a depth of 20–24 m from the earth's surface. The basement crystalline rock in the studied areas until the depth of 60 m are represented by massive texture albitite of medium strength, highly cataclastic and fractured. The production blocks are located almost in the center of the depression funnel, extending longitudinally along the whole deposit. As a result of mining, the groundwater level here drops by 20–30 m below the level of 210 m. The rocks are practically not flooded. The crystalline rocks of production blocks 5–84–86 and 5–88–90 are represented by gray medium-grained (with porphyry aggregates of feldspar crystals) biotite migmatite. There are remnants of silicified biotite gneiss. The rock is slightly fractured, compact, hard. Rare fractures are in layers with carbonate having hardness *f* = 14–15.

In terms of mining and geological conditions, the blocks are located between two tectonic faults. One of the fault is located to the south of the blocks at a distance of 25–30 m, and the second fault is located to the north of the blocks at a distance of 40 m. The width of the tectonic faults ranges from 5 to 10 m. The indicated tectonic faults can serve both as a zone of seismic vibration absorption during passing waves across the fault strike and as waveguides when seismic waves pass along the faults.

In terms of mining and technical conditions, both towards the protected facilities (houses of the village of Kizelgur, Ukraine) and towards the Ingul river, above blocks 5–84–86 and 5–88–90, mined-out and backfilled blocks are located, which, when blasting in the pilot block, will serve as a zone of absorption and reflection of the seismic waves. Each geological structure is characterized by common and local factors affecting seismic wave propagation. The common geological factors that can affect the intensity of blasting-induced seismic waves include loose sediments, tectonic faults (the latter can be considered as possible waveguides), and the rock dip angles. The seismic wave propagation velocity is determined by the degree of the rock mass fracturing.

When a seismic wave passes into the fracturing zones, its intensity may increase or decrease. Loose alluvial rocks are a kind of filter of vibrations in a seismic wave, when the latter is refracted in them.

The vibration intensity depends entirely on the sediment thickness: the higher the thickness, the lower the seismic effect. In a rock mass that is not affected by mining and does not have faults, the seismic effect is enhanced. The seismic effect decreases by 1.5–2.0 times when seismic waves pass through the obstacle in the form of stope mined-out space, mined-out and backfilled blocks. The greatest effect on changing intensity of seismic vibrations is exerted by technological factors of a deposit development:

– in the back side of a blast, the rock mass disturbance velocity is 1.5 times higher than in the flank side, and 2 times higher than towards the front;

– blasting in a block at the underlying level after extracting the overlying blocks and their backfilling leads to 2-fold decrease in the displacement velocity within the seismic wave, and, at blasting of borehole rows when forming blasted slot, to the 1.5-fold decrease;

– passing the blast wave through the mined-out space decreases the vibration velocity by 2 times.

In the case at hand, when preparing production blocks 5–84–86 and 5–88–90 for underground leaching, blast waves will pass through the faults and the mined-out space, which reduce seismic vibrations by 2 times and decrease the seismic effect by 1.5–2.0 times, and through alluvial soils, which also reduce seismic vibrations in about 2 times. Assessing the conditions for extracting production blocks 5–84–86 and 5–88–90, it should be noted that physico-mechanical and hydrogeological properties of the rock mass, the presence of mined-out and backfilled blocks, faults and alluvial soils contribute to keeping the integrity of the day surface and residential buildings in the village of Kizelgur, and are favorable for blasting in the blocks.

Estimation of the permissible weight of explosive charges per a delay. The concentration of blast wave energy in a layer rock mass with fan pattern of borehole charges is unevenly distributed, and the minimum load falls on the ends of the boreholes, whereas the maximum load, to central part of the rock mass (closer to the collars), that affects the crushing quality. Therefore, the wave rupturing processes caused by blasting produce complicated picture, especially in the near zone, not exceeding five radii of the being blasted layer from its center.

Outside of this zone, it is possible to determine dependences of changing the displacement velocities characterizing the disruptive effect of the fan-pattern charges in the being blasted ore layer (per a delay) on the charge spatial position in relation to the protected facility and the distance to it. Since the fan-pattern charges are areal with uneven distribution of energy concentration, its spatial position in relation to the protected facility, along with the distance to the protected facility, is rather important.

The stability of protected underground and surface facilities can be provided by the correct establishing and observation of regulatory restrictions, i.e. establishing permissible displacement velocities for each protected facility. A protected facility is protected from disruptive seismic effects of vibrations of the rock mass and soil of the day surface, provided that the actual displacement velocity caused by underground blasting remains below the permissible level, i.e. the following condition is met:

$$U_{\text{ф}} \le U_{\text{доп}}. \qquad (4)$$

Since the displacement velocity in the protected facility (within the rock mass in underground conditions or on the day surface) is determined by the distance between the charge center and the protected facility, the explosive weight per a delay and the medium through which seismic vibrations from underground commercial blasting pass, then, to substantiate parameters of safe charges in the conditions of Michurinsky deposit of SE VostGOK (Ukraine), pilot-plant studies were conducted. Ensuring the stability of protected facilities located in rock masses (various underground mine workings, stopes, shafts) and on the day surface is achieved by using the well-known formula of M.A. Sadovsky [21], improved by the authors, for estimating the rock mass displacement velocities:

$$U = K\frac{\sqrt[3]{Q^{2,08}}}{R^{2,08}}, \text{ см/с}, \qquad (5)$$

where U is the displacement velocity, cm/s; K is the proportionality coefficient characterizing the properties of the medium transmitting seismic vibrations and equal to 575 for the parallel arrangement of fan-pattern borehole charges in relation to the protected facility, and 145 for the end arrangement; Q is the weight of charge per a delay, kg; R is the distance from the center of the being blasted (by the fan-pattern borehole charges) layer to the protected facility, m.

Thus, depending on the position of the being blasted layer relative to the facility, the dependence is written as:

– at the parallel arrangement $U = 575\frac{\sqrt[3]{Q^{2,08}}}{R^{2,08}}$, cm/s;

– at the end arrangement $U = 145\frac{\sqrt[3]{Q^{2,08}}}{R^{2,08}}$, cm/s.

It can be seen from these dependences that at the end arrangement, the energy decreases by 4 times that is used in estimating the permissible charges per a delay. When estimating the permissible charges per a delay when blasting balance reserves of Michurinsky deposit production blocks, it is recommended to take into account the spatial position of the being blasted ore layer in relation to the protected facility using the following formulas:

– at the parallel arrangement $Q = R^3 \frac{\sqrt[3]{U^3}}{K_1^3}$, kg,

where K_1=545;

– at the end arrangement $Q = R^3 \frac{\sqrt[3]{U^3}}{K_2^3}$, kg,

where K_2=145.

The maximum permissible charges (explosive amount) per a delay for blasting the reserves of production blocks 5–84–86 and 5–88–90 are given in Table 3.

Table 3

The maximum amount of explosives per blast by block

Number of blast/block	Level, m	Borehole fan number	Delay series, ms	Maximum amount of explosives per a delay, kg
1st blast	240-260	3	75	1771
2nd blast	225-240	1	25	2249
3rd blast	210-225	5+5a	150	2832
4th blast	210-263	1+1+1	50	5594
Block 5-84-86	225-210	8-8A	150	2777
Block 5-88-90	263-240	2	50	1969

The amounts of explosives per a delay during counter-blasting with fan-pattern borehole charges when estimating the displacement velocities of rock masses (underground facilities) and the displacement velocities of soils at the base of surface facilities are not summed up, since the direction of the seismic vibration fronts after the simultaneous blasting several layers in a rock mass is mutually opposite. The maximum amount of explosives per a delay in block 5–84–86 is lower than the estimated permissible amount of explosives for all protected facilities in the far zone, except for nearby underground facilities: Shaft 59, exploration drift in axes 59–71 (workings, stopes, substations) located at distances of 22 to 35 m from the blast position (should be restored if required). In block 5–88–90, the maximum amount of explosives per a delay is higher than the estimated permissible level for the following facilities: Ingul river bed, residential buildings, east drift at level 210 m, underground electrical substation at level 210 m, Shaft 71 (92) at level 280 m.

Blasting of reserves of production block 5–84–86 based on the substantiated parameters of drilling and blasting operations provides improvement in the quality of crushing. The effect of fragmented medium due to stump blasting with the optimal ore mass fragmentation indices in the block is 1.30 on the average, and, for block 5–88–90, 1.25. The increased (expected) compression in the lower part of the mentioned block between levels 260 and 240 m after blasting all the reserves of the stope will produce favorable effect on the process of ore leaching and obtaining pregnant solution.

Thus, the combined control of geomechanical state of disturbed rock masses is used in mining of different-grade ores, for example, after extraction of rich ores, when lean ores are leached in UBL blocks [28, 29]. Geomechanical stability of a rock mass is ensured by dividing it into the areas limited in terms of the condition the formation of rock natural self-supporting arch maintaining stable flat roof. Inside the isolated areas, different underground ore mining methods can be applied. Protection of the conjugate areas of the deposit from the blasting seismic effects is ensured, for example, by shielding. The stress level in a geomechanical system is regulated by engineering activities [26, 27]:

– inclination of the artificial rock mass on the ore mass reduces ore dilution by backfilling;

– protecting backfill rock mass at the border of an ore body represents a protective wall that enables extracting the bulk of reserves in favorable mining conditions;- strengthening unstable rocks with roof bolts and steel ropes provides better ore recovery performance.

Thus, the rock mass management is carried out by combined filling, including solidifying backfill mixes and isolation, as well as technical and technological supporting the filling processes using environmentally sound and resource-saving methods [28, 29].

Analysis of research results and general recommendations

Based on the study of arising and redistribution of a rock mass stress-strain state using geophysical and surveying methods, an environmentally sound method for backfilling of man-made voids in mining-disturbed rock masses is proposed [30, 31]. It enables ensuring the stability of the day surface and life-sustaining activity of the population living in the mining-affected area (in the vicinity of mines, waste rock and off-balance low-grade ore dumps, sites of backfilling complexes, facilities for preconcentration and heap leaching of metals from substandard ores, tailings storage facilities, etc.). The main negative consequences of the impact of mining on the environment and humans are high costs for conserving day surface and ensuring life-sustaining activity of the population living in the mining-affected area, as well as removing large areas of land from human activity, etc. Therefore, funds must be provided for the following activities [32, 33]:

– advanced processing of technogenic wastes (tailings), which demonstrate wide variety of mineral forms in comparison with ordinary ores;

– reclamation of industrial sites and adjacent territories after the mine closure;

– landscaping of the reclaimed territory with grass and shrub;

– permanent monitoring of the environment components in the zone affected by mining facilities activity.

For processing of the technogenic waste (tailings) it is necessary to develop new processes to be based on the latest achievements of mining science. The research aimed at reclaiming accumulated waste of mining and metallurgical production should be performed. Implementing effective methods for extraction of metals from the waste will improve environmental situation in the areas of their storage and provide additional volumes of extracted valuable components. Large-scale involvement of tailings in reclaiming, as well as processing of off-balance ore dumps at modular plants will contribute to obtaining an additional source of valuable components and decreasing environmental impact in countries with developed mining industry [32, 33].

It is also necessary to create protective forest belts along transport routes (automobile, railway, slurry pipelines, etc.). The territories where the maximum permissible concentration (MPC) of pollutants is exceeded, should be transferred for sowing industrial crops; in polluted water bodies, swimming, fishing, etc. should be banned [34, 35]. To prevent transfer of dusty contaminated material outside mining facilities, sanitary protection zones and belts around them should be planted with tall tree species that will inhibit wind above these facilities. Such facilities include mines, waste rock and off-balance low-grade ore dumps, sites of backfilling complexes, facilities for preconcentration and heap leaching of metals from substandard ores, tailings storage facilities, etc.). In this case, the dust will captured in these forest stands and will not enter other territories, including settlements [36, 37].

Conclusions

1. It is demonstrated that blasting stope reserves with a preset crushing quality to provide efficient leaching a useful component requires increasing the ore mass compression using stump blasting, where the fragmentation index should be in the range of 1.17–1.20. To achieve the desired quality of crushing, the blasted slot must be located in a block center for using counter blasting when breaking the nearest (to the slot) layers by blasting fan-pattern borehole charges.

2. It is demonstrated that to improve the quality of crushing by increasing the explosive specific consumption for ore mass blasting up to 2.9–3.3 kg/m^3, it is advisable to use blast-hole rings (at blasthole diameter of 85 mm), that allows reducing the blasthole length and their deviation from the preset direction between the levels. To achieve effective crushing quality in a block, stump blasting should be used when blasting of up to eight layers is performed from two sides towards each other, and, in this case, the fragmentation index should be in the range of 1.25–1.30.

3. It is proved that the use of counter blasting of the ore mass to a blasted slot allows increasing the amount of explosives per a delay by a factor of 2 due to decreasing the seismic effect of vibrations after simultaneously blasted two blasthole fans separated by loosened rock mass in the volume of the compensation space. In this case, two fronts of seismic vibrations with mutually opposite direction of movement are formed.

4. The method of blasting the balance reserves of block 5–88–90 based on the estimation of maximum explosive amount per a delay is recommended (using the data of measuring the velocities of soil displacement on the day surface at the base of the protected facilities during blasting operations in block 5–84–86, at the permissible rock mass displacement velocity up to 0.8 cm/s).

References

1. Borisov A. A. *Pressure on horizontal working support*. Moscow, Leningrad: Ugletekhizdat Publ.;1948. 104 p. (In Russ.).

2. Vetrov S. V. *Permissible sizes of rock exposures during underground ore mining*. Moscow: Nauka Publ.; 1975. 223 p. (In Russ.).

3. Borisov A. A. *Rock Mechanics*. Moscow: Nedra Publ.; 1980, 359 p. (In Russ.).

4. Fisenko G. L. *Limit state of rocks around mine workings*. Moscow: Nedra Publ.; 1980, 359 p. (In Russ.).

5. Sleptsov M.N., Azimov R. Sh., Mosinets V. N. *Underground mining of non-ferrous and rare metals*. Moscow: Nedra Publ.; 1986. 206 p. (In Russ.).

6. Avdeev O.K., Pukhalsky V.N., Razumov A.N. Ore reserves mining in the zone of protective pillars under a water body. *Gornyi zhurnal*. 1989;(9):28–30. (In Russ.).

7. *Instructions for safe conduct of mining operations at ore and non-metallic deposits prone to rockburst*. Leningrad: VNIMI Publ.; 1989. 58 p. (In Russ.).

8. Lyashenko V. I., Khomenko O. E., Kisly P. A. Improving seismic safety of underground mining based on applying new explosive charges. *Ferrous metallurgy. Bulletin of Scientific, Technical and Economical Information*. 2019;75(8):912–922. (In Russ.). DOI: 10.32339/0135-5910-2019-8-912–922.

9. Shtele V. I. *The testing bench for modeling geomechanical processes in rock mass*. Inventor's certificate No. 1682559 A1 (USSR); 1991. (In Russ.).

10. Nguyen Ngoc Minh, Pham Duc Thang. Tendencies of mining technology development in relation to deep mines. *Mining Science and Technology*. 2019;4(1):16-22. DOI: 10.17073/2500-0632-2019-1-16-22.

11. *Mining and processing of uranium ores*. Chernov A. P. (gen. ed.) Kyiv: Adef-Ukraine Publ.; 2001. 238 p. (In Russ.).

12. Vysotskaya N. A., Piskun E. V. The main factors of adverse environmental impact of potash production and methods of environmental protection. *Mining Science and Technology*. 2019;4(3):172-180. DOI: 10.17073/2500-0632-2019-3-172-180. (In Russ.).

13. Komashchenko V.I., Vasiliev P.V., Maslennikov S.A. Preparation of reliable resource base for underground development of KMA deposits. *Izvestija Tulskogo gosudarstvennogo universiteta. Nauki o zemle*. 2016;(2):101–114. (In Russ.).

14. Dmitrak Yu.V., Kamnev E.N. JSC "Leading Design-and-Survey and Scientific Research Institute of Industrial Technology" – 65 years of development. *Gornyi zhurnal*. 2016;(3):6–12. (In Russ.).

15. Ping Y. J., Zhong C. W., Sen Y. D., Qiang Y. J. Numerical determination of strength and deformability of fractured rock mass by FEM modeling. *Computers and Geotechnics*. 2015;64:20–31.

16. Dold B., Weibel L. Biogeometallurgical pre-mining characterization of ore deposits: An approach to increase sustainability in the mining process. *Environmental Science and Pollution Research*. 2013;20(11):7777–7786.

17. Eremenko V.A., Lushnikov V.N. Methodology for selecting "dynamic" support for workings at deposits prone to rockburst. *Mining Informational and Analytical Bulletin*. 2018;(12):5–12. (In Russ.).

18. Reiter K., Heidbach O. 3-D geomechanical-numerical model of the contemporary crustal stress state in the Alberta Basin (Canada). *Solid Earth*. 2014;(5):1123–1149.

19. Goodarzi A., Oraee-Mirzamani N. Assessment of the Dynamic Loads Effect on Underground Mines Supports. In: *30th International Conference on Ground Control in Mining*; 2011. P. 74–79.

20. Sokolov I. V., Antipin Yu. G., Baranovsky K. V. Study of design and parameters of the combined system for developing an inclined quartz deposit. *Bulletin of the Tomsk Polytechnic University. Geo assets engineering*. 2017;328(10):85–94. (In Russ.).

21. Sadovsky M. A. *Geophysics and Explosion Physics*. Moscow: Nedra Publ.; 1997. 334 p. (In Russ.).

22. Smirnov S. M., Tatarnikov B. B., Aleksandrov A. N. Selecting method of stoping with backfilling of mine goaf depending on geodynamic conditions of ore mining area. *Mining Informational and Analytical Bulletin*. 2014;(11):45–51. (In Russ.).

23. Khani A., Baghbanan A., Norouzi S., Hashemolhosseini H. *Effects of fracture geometry and Wittke W. Rock Mechanics Based on an Anisotropic Jointed Rock Model (AJRM)*. Verlag: Wilhelm Ernst & Sohn; 2014. 875 p.

24. Shabanimashcool M., Li C. C. Analytical approaches for studying the stability of laminated roof strata. *International Journal of Rock Mechanics and Mining Sciences*. 2015;79:99–108.

25. Wang D. S., Chang J. P., Yin Z. M., Lu Y. G. Deformation and failure characteristics of high and steep slope and the impact of underground mining. In: *Transit Development in Rock Mechanics-Recognition, Thinking and Innovation: Proceedings of the 3rd ISRM Young Scholars Symposium on Rock Mechanics*. USA; 2014. P. 451–457.

26. Iofis M.A., Fedorov E.V., Esina E.N., Miletenko N.A. Development of geomechanics for solving the problems of subsoil conservation. *Gornyi zhurnal*. 2017;(11):98–104. (In Russ.).

27. Khasheva Z. M., Golik V. I. The ways of recovery in economy of the depressed mining enterprises of the Russian Caucasus. *International Business Management*. 2015;9(6):1210–1216.

28. Golik V., Komashchenko V., Morkun V., Burdzieva O. Metal deposits combined development experience. *Metallurgical and Mining Industry*. 2015;7(6):591–594.

29. Karaman K., Cihangir F., Kesimal A. A. comparative assessment of rock mass deformation modulus. *International Journal of Mining Science and Technology*. 2015;25(5):735–740.

30. Golik V.I., Komashchenko V.I., Razorenov Yu. I. Activation of hardening mixture components at underground ore mining. *Izvestiâ Tul'skogo gosudarstvennogo universiteta. Nauki o Zemle*. 2017;(3):113–123. (In Russ.).

31. Kaplunov D. R., Radchenko D. N. Design principles and selection of subsoil use technologies ensuring sustainable development of underground mines. Gornyi zhurnal. 2017;(11):121–125. (In Russ.).

32. Rudmin M. A., Mazurov A. K., Reva I. V., Stebletsov M. D. Prospects for integrated development of the Bakcharsky iron ore deposit (Western Siberia, Russia). *Bulletin of the Tomsk Polytechnic University. Geo assets engineering*. 2018;329(10):87–99. (In Russ.).

33. Mukhametshin V. V., Andreev V. E. Improving evaluation of technologies aimed at optimizing use of resource base of deposits with hard-to-recover reserves. *Bulletin of the Tomsk Polytechnic University. Geo assets engineering*. 2018;329(8):30–26. (In Russ.).

34. Lyashenko V. I., Khomenko O. E. Enhancement of confined blasting of ore. *Mining Informational and Analytical Bulletin*. 2019;11:59–72.

35. Lyashenko V., Topolnij F., Dyatchin V. Development of technologies and technical means for storage of waste processing of ore raw materials in the tailings dams. *Technology audit and production reserves*. 2019;49(3):33–40.

36. Lyashenko V., Khomenko O., Topolny F., Golik V. Development of natural underground ore mining technologies in energy distributed massages. *Technology audit and production reserve*s. 2020;51(1):10–17.

37. Lyashenko V. I., Golik V. I., Dyatchin V. Z. Stockpiling of tailings in underground mined-out space and a tailing dump in the form of solidifying masses. *Obogashchenie Rud*. 2020;(1):41–47. (In Russ.). DOI: 10.17580/or.2020.01.08.

Библиографический список

1. Борисов А. А. *Давление на крепь горизонтальных выработок*. М., Л.: Углетехиздат; 1948. 104 с.

2. Ветров С. В. *Допустимые размеры обнажений горных пород при подземной разработке руд*. М.: Наука; 1975. 223 с.

3. Борисов А. А. *Механика горных пород*. М.: Недра; 1980. 359 с.

4. Фисенко Г. Л. *Предельное состояние горных пород вокруг выработок*. М.: Недра; 1980. 359 с.

5. Слепцов М. Н., Азимов Р. Ш., Мосинец В. Н. *Подземная разработка месторождений цветных и редких металлов*. М.: Недра; 1986. 206 с.

6. Авдеев О. К., Пухальский В. Н., Разумов А. Н. Отработка запасов руды в зоне предохранительного целика под водоемом. *Горный журнал*. 1989;(9):28–30.

7. *Инструкция по безопасному ведению горных работ на рудных и нерудных месторождениях (объектах строительства подземных сооружений), склонных к горным ударам*. Л.: ВНИМИ; 1989. 58 с.

8. Ляшенко В. И., Хоменко О. Е., Кислый П. А. Повышение сейсмической безопасности подземной разработки скальных месторождений на основе применения новых зарядов взрывчатых веществ. *Черная металлургия. Бюллетень научно-технической и экономической информации*. 2019;75(8):912–922. DOI: 10.32339/0135-5910-2019-8-912–922.

9. Штеле В. И. *Стенд для моделирования геомеханических процессов в толще горных пород*. Авторское свидетельство 1682559 А1 (СССР); 1991.

10. Nguyen Ngoc Minh, Pham Duc Thang. Tendencies of mining technology development in relation to deep mines. *Mining Science and Technology*. 2019;4(1):16-22. DOI: 10.17073/2500-0632-2019-1-16-22.

11. *Добыча и переработка урановых руд*. Под общ. ред. А. П. Чернова. Киев: Адеф-Украина; 2001. 238 с.

12. Высоцкая Н. А., Пискун Е. В. Основные факторы неблагоприятного воздействия на окружающую среду деятельности калийного производства и способы ее защиты. Горные науки и технологии. 2019;4(3):172-180. DOI: 10.17073/2500-0632-2019-3-172-180.

13. Комащенко В. И., Васильев П. В., Масленников С. А. Технологиям подземной разработки месторождений КМА – надежную сырьевую основу. *Известия Тульского государственного университета. Науки о Земле*. 2016;(2):101–114.

14. Дмитрак Ю. В., Камнев Е. Н. АО «Ведущий проектно-изыскательский и научно-исследовательский институт промышленной технологии» – Путь длиной в 65 лет. *Горный журнал*. 2016;(3):6–12.

15. Ping Y. J., Zhong C. W., Sen Y. D., Qiang Y. J. Numerical determination of strength and deformability of fractured rock mass by FEM modeling. Computers and Geotechnics. 2015;64:20–31.

16. Dold B., Weibel L. Biogeometallurgical pre-mining characterization of ore deposits: An approach to increase sustainability in the mining process. *Environmental Science and Pollution Research*. 2013;20(11):7777–7786.

17. Еременко В. А., Лушников В. Н. Методика выбора «динамической» крепи выработок для месторождений склонных и опасных по горным ударам. *Горный информационно-аналитический бюллетень*. 2018;(12):5–12.

18. Reiter K., Heidbach O. 3-D geomechanical-numerical model of the contemporary crustal stress state in the Alberta Basin (Canada). *Solid Earth*. 2014;(5):1123–1149.

19. Goodarzi A., Oraee-Mirzamani N. Assessment of the Dynamic Loads Effect on Underground Mines Supports. In: *30th International Conference on Ground Control in Mining*; 2011. P. 74–79.

20. Соколов И. В., Антипин Ю. Г., Барановский К. В. Исследование конструкции и параметров комбинированной системы разработки наклонного месторождения кварца. *Известия Томского политехнического университета. Инжиниринг георесурсов*. 2017;328(10):85–94.

21. Садовский М. А. *Геофизика и физика взрыва*. М.: Недра; 1997. 334 с.

22. Смирнов С. М., Татарников Б. Б., Александров А. Н. Влияние геодинамических условий отработки рудного участка на технологию очистных работ с закладкой выработанного пространства. *Горный информационно-аналитический бюллетень*. 2014;(11):45–51.

23. Khani A., Baghbanan A., Norouzi S., Hashemolhosseini H. *Effects of fracture geometry and Wittke W. Rock Mechanics Based on an Anisotropic Jointed Rock Model (AJRM)*. Verlag: Wilhelm Ernst & Sohn; 2014. 875 p.

24. Shabanimashcool M., Li C. C. Analytical approaches for studying the stability of laminated roof strata. *International Journal of Rock Mechanics and Mining Sciences*. 2015;79:99–108.

25. Wang D. S., Chang J. P., Yin Z. M., Lu Y. G. Deformation and failure characteristics of high and steep slope and the impact of underground mining. In: *Transit Development in Rock Mechanics-Recognition, Thinking and Innovation: Proceedings of the 3rd ISRM Young Scholars Symposium on Rock Mechanics*. USA; 2014. P. 451–457.

26. Иофис М. А., Федоров Е. В., Есина Е. Н., Милетенко Н. А. Развитие геомеханики для решения проблем сохранения земных недр. *Горный журнал*. 2017;(11):98–104.

27. Khasheva Z. M., Golik V. I. The ways of recovery in economy of the depressed mining enterprises of the Russian Caucasus. *International Business Management*. 2015;9(6):1210–1216.

28. Golik V., Komashchenko V., Morkun V., Burdzieva O. Metal deposits combined development experience. *Metallurgical and Mining Industry*. 2015;7(6):591–594.

29. Karaman K., Cihangir F., Kesimal A. A. comparative assessment of rock mass deformation modulus. *International Journal of Mining Science and Technology*. 2015;25(5):735–740.

30. Голик В. И., Комащенко В. И., Разоренов Ю. И. Активация компонентов твердеющих смесей при подземной добыче руд. *Известия Тульского государственного университета. Науки о Земле*. 2017;(3):113–123.

31. Каплунов Д. Р., Радченко Д. Н. Принципы проектирования и выбор технологий освоения недр, обеспечивающих устойчивое развитие подземных рудников. *Горный журнал*. 2017;(11):121–125.

32. Рудмин М. А., Мазуров А. К., Рева И. В., Стеблецов М. Д. Перспективы комплексного освоения Бакчарского железорудного месторождения (Западная Сибирь, Россия). *Известия Томского политехнического университета. Инжиниринг георесурсов*. 2018;329(10):87–99.

33. Мухаметшин В. В., Андреев В. Е. Повышение эффективности оценки результативности технологий, направленных на расширение использования ресурсной базы месторождений с трудноизвлекаемыми запасами. *Известия Томского политехнического университета. Инжиниринг георесурсов*. 2018;329(8):30–26.

34. Lyashenko V. I., Khomenko O. E. Enhancement of confined blasting of ore. *Mining Informational and Analytical Bulletin*. 2019;11:59–72.

35. Lyashenko V., Topolnij F., Dyatchin V. Development of technologies and technical means for storage of waste processing of ore raw materials in the tailings dams. *Technology audit and production reserves*. 2019;49(3):33–40.

36. Lyashenko V., Khomenko O., Topolny F., Golik V. Development of natural underground ore mining technologies in energy distributed massages. Technology audit and production reserves. 2020;51(1):10–17.

37. Ляшенко В. И., Голик В. И., Дятчин В. З. Складирования хвостов в подземное выработанное пространство и хвостохранилище в виде твердеющих масс. *Обогащение руд*. 2020;(1):41–47. DOI: 10.17580/or.2020.01.08.