Lyashenko V.,
Khomenko O.,
Chekushina T.,
Topolnij F.

JUSTIFICATION OF SAFE UNDERGROUND DEVELOPMENT OF MOUNTAIN DEPOSITS OF COMPLEX STRUCTURE BY GEOPHYSICAL METHODS

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

The study used:

– data from literary sources and patent documents in the field of technologies and technical means for underground mining of ores in energy disturbed massifs of complex structure, substantiation of safe technological parameters of operating units;

– laboratory and production experiments;

– physical modeling and selection of compositions of hardening mixtures.

Analytical studies, comparative analysis of theoretical and practical results using standard and new methods were carried out with the participation of the authors.

The issues of geodynamic monitoring of the stress-strain state of the rock mass for the safe development of rock-type ore deposits are considered. The interaction of natural and man-made factors is shown to ensure the geomechanical balance of ore-bearing massifs and the earth's surface in the area of subsoil development over a long period of time. The safe geometrical and technological parameters of the chamber system for the development of ore deposits of complex structure with backfilling of the worked-out space with hardening mixtures, including environmental safety, as well as the social factor, are substantiated, which are implemented in the instructions, standards and practice of ore mines in Ukraine. The research results can be used in underground mining of ore deposits of complex structure in Ukraine, the Russian Federation, the Republic of Kazakhstan and other developed mining countries of the world.

Keywords: *ore deposits, underground mining, geomechanics of rock massifs, drilling and blasting operations, technological and environmental safety.*

1. Introduction

Safe development of deposits of complex structure by chamber systems with solidifying backfill is ensured by stable parameters of the chambers, determined on the basis of regulatory documents providing for continuous mining of ore deposits [1, 2]. The ore deposits of the state enterprise «Vostochny Mining and Processing Plant» (SE «VostMPP», Ukraine) have a number of common features of the genesis associated with faults, complex morphology of ore deposits and technological schemes of mining. This allows to formulate recommendations for forecasting and preventing the manifestation of rock pressure of various forms during their development [3, 4].

The mines of SE «VostMPP» with the existing topology of mine workings, the presence of voids, form a complex geotechnical system. It leads to dangerous dynamic phenomena (intense stabbing during excavation, reduction of the section of the workings up to their elimination, significant collapse, peeling and shooting of rocks). An increase in the depth of mining, the volume of the voids of the worked out chambers on the overlying horizons (exceeds 1.5 million m^3) significantly changes the geodynamic regime of the geological environment [5, 6].

The experience of mining enterprises shows that the problem of combating various forms of dynamic manifestation of rock pressure can be successfully solved provided that mining operations are streamlined. As well as compliance with the rules for the operation of deposits and the implementation of recommendations for forecasting, prevention and prevention of rock bursts at the stages of design, construction and preparation for their development [7, 8].

Therefore, the substantiation of the technological and environmental safety of underground mining of ore deposits of complex structure, taking into account the geomechanical and seismic substantiation of the optimal parameters and

mining schemes is an important scientific, practical and social task that requires an effective solution [9, 10]. This provides a rational way to control rock pressure by using chamber mining systems with backfilling of the goaf with hardening mixtures of various composition and strength [11, 12].

2. The object of research and its technological audit

The object of research is the technology and technical means for underground mining of ores in energy disturbed massifs of complex structure, in which one of the most problematic places is the formation of man-made voids. They, in turn, affect the emergence and redistribution of the stress-strain state (SSS) of the rock mass. In the development of near-surface reserves of ore deposits, SSS redistribution provokes these phenomena, up to the level of earthquakes.

3. The aim and objectives of research

The aim of research is to substantiate the safety of underground mining of ore deposits of complex structure by geophysical methods, taking into account the geomechanical and seismic substantiation of rational parameters and mining schemes. Thanks to this, the stability of the outcrops of mountain ranges and the safety of the earth's surface, water bodies and residential buildings in the zone of mining influence are achieved. To achieve this aim, it is necessary to solve the following objectives:

1. To identify possible technical measures to ensure the stability of the rock mass and the preservation of the earth's surface from destruction.

2. To propose mathematical models to substantiate the safe parameters of the chambers, as well as the hardening filling mixture and the stability of outcrops for the conditions of the development of ore deposits.

3. To recommend mathematical models to substantiate the safe parameters of the chambers, which ensure an increase in the technological and ecological safety of the environment in the zone of influence of mining operations.

4. Research of existing solutions of the problem

The study of the safety of underground mining of ore deposits of complex structure by geophysical methods, taking into account the geomechanical and seismic substantiation of the rational parameters of the production blocks, was carried out by many leading specialists of the developed mining countries of the world [13, 14], in particular, in:
– Kryvbas, Ukraine;
– JSC «Poltava MPP», Ukraine;
– PJSC Zaporizhzhia Iron Ore Plant (PJSC ZIOP), Ukraine;
– State Enterprise «Ukrainian Research and Design Institute of Industrial Technology» (SE «UkrNIPIIprom-technologii») and SE «VostMPP», Zhovti Vody, Ukraine;
– State Enterprise «Kirovgeology», Kyiv, Ukraine;
– National Technical University «Dnipro Polytechnic» and the N. Polyakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGM NAS of Ukraine), Dnipro, Ukraine;
– State Higher Educational Institution «Kryvyi Rih National University», Kryvyi Rih, Ukraine;

– Joint Stock Companies «VNIPIpromtechnologii», Moscow and «VNIMI», St. Petersburg, Russian Federation [15, 16].

The management of the stress-strain state of the rock mass and the seismic action of the explosion was addressed by:
– Federal State Budgetary Institution of Science «Institute of Physics of the Earth named after O. Schmidt» of the Russian Academy of Sciences (IPE RAS), Moscow, Russian Federation;
– «Eastern Research Mining and Metallurgical Institute of Non-Ferrous Metals» (JSC «VNIITSVET»), Ust-Kamenogorsk, Republic of Kazakhstan;
– JSC Research Institute for the Problems of Kursk Magnetic Anomaly named after L. D. Shevyakov (JSC RIKMA), Gubkin, Russian Federation, etc.

Abroad, these studies were carried out in the USA, Germany, France, Chile, Australia and other developed mining countries of the world [17, 18].

Stability assessment of the roof of the working of the correct shape is carried out according to the value of the equivalent span of constant width and unlimited length of this roof. This assessment is called the method of equivalent spans and, as practice shows, gives reliable results. The equivalent span value is determined by the following well-known methods:
– Protodyakonov method (1933) [1];
– Slesarev method (1948) [2];
– Vetrov method (1975) [3];
– Borysov method (1980) [4];
– Fisenko method (1980) [5];
– Khomiakov method (1984) [6];
– Mosinets and Sleptsov method (1986) [7] and others.

At the same time, with an increase in development depth, the stable equivalent span decreases, which is explained by an increase in rock pressure, and with a decrease in development depth, it increases.

The preservation of surface buildings and structures in the zone of influence of mining largely depends on the intensity and nature of the passage of wave processes during explosions in elastic rock massifs, which form patterns corresponding to their geomechanical and geotechnical conditions [19, 20]. The fulfillment of these tasks is possible with constant studies of the regularities of the propagation of seismic waves and the use of technological methods that reduce the volume of explosive by one deceleration (intra-fan deceleration, decrease in the sublevel height, counter blasting with separation of the seismic wave front, shielding, etc.) [21].

Thus, the results of the analysis allow to conclude that the formation of man-made voids is an important issue for solving the problem. This affects the emergence and redistribution of the stress-strain state of the rock mass, as well as an increase in the technological and ecological safety of the environment in the zone of influence of mining operations.

5. Methods of research

The authors give an analysis of previously performed research and control observations, as well as instrumental measurements of the geomechanical state of the rock mass, the seismic action of the explosion with instruments and equipment. Mathematical analysis, statistical processing of results, determination of dependencies, calculation and justification of indicators by standard and new methods were also performed.

During the study, the following terms were used:

The principles of safe mining are the basic geomechanical rules governing the procedure for the extraction of ore bodies in a stressed massif, the observance of which excludes the possibility of creating artificial stress concentrators in it on the scale of an ore body, a mining block. Full satisfaction of these principles allows the creation of safe flow diagrams and development systems.

Stress-strain state of the rock mass (SSS) is the subject of mining geomechanics.

Mining geomechanics – rock mechanics – the science of strength, stability and deformability of rock mass and mining facilities under rock pressure (natural and caused by mining).

Mechanical properties of rocks characterize changes in the shape, size and continuity of rocks under the influence of mechanical loads, which are created as a result of the action of natural (rock pressure, tectonic movements) or artificial factors (blasting). Mechanical loading causes stresses and deformations in rocks. By the type of deformations and the connection with the stresses that caused them, the mechanical properties are divided into the following properties:

– elastic (Young's modulus, bulk modulus, etc.);

– plastic (Poisson's ratio, total deformation modulus, plasticity ratio, etc.);

– strength (ultimate strength of rocks in compression and tension, etc.);

– rheological (relaxation period, long-term strength, etc.).

5.1. Geophysical research methods. When developing complex-structured ore deposits, they are used at mining enterprises for diagnostics associated with the determination of zones of increased concentration or heterogeneity of the mountain massif. For elastic-plastic properties of rocks, control of the stress-strain state of a rock mass in the process of conducting and developing mining operations (geomechanical and, as an integral part, seismic monitoring). To ensure the stability of mine workings and prevent the dynamic manifestation of rock pressure, forecasting various sections of the rock mass and ores according to the degree of rock burst hazard and prevention of the dynamic manifestation of rock pressure [22, 23]. Geomechanical monitoring of the rock mass and pillars of various purposes is carried out by means of sound and mine surveying instruments, string strain gauges, depth and ground benchmarks. As well as optical instruments, electrical circuits, visual and indirect methods for changing the mineralization of mine waters and other methodological and instrumental geomechanical support. To expand the use of geophysical methods at mining enterprises, it is necessary to create small-sized noise-resistant means for recording measurement parameters, methodology, interpretation of the results of field observations, verification and standardization of equipment.

The following geophysical methods are most mastered in underground conditions at mining enterprises:

– acoustic (acoustic emission method), based on the registration of acoustic signals in a rock mass at various loads in the frequency range 10–100 kHz;

– seismoacoustic, registering seismoacoustic processes in the frequency range 100–1000 Hz;

– seismic, registering seismic waves generated in the rock mass, in the range of 30–5000 Hz;

– electrometric, based on the dependence of the electrical resistance of rocks on their stress state.

The use of geophysical methods in this frequency range makes it possible to quickly obtain sufficiently complete information about the state of the rock mass both at small bases in mine workings and in large areas within mine fields. The complex use of geophysical methods makes it possible to assess the stress state of rocks and changes in their elastic and strength properties.

The implementation of geophysical methods significantly increases the efficiency and manufacturability of forecasting rock bumps, especially forecasting the degree of rock burst hazard in individual areas of ore deposits. Further development and improvement of seismic methods for forecasting rock bursts in the direction of creating express methods for geoinformation support of mining operations is underway. In each specific case, one or a set of methods is used, depending on the goals and objectives of the research, the availability of equipment and trained specialists. Of the listed seismic methods for determining the stress state of a rock mass, the method of acoustic emission is widely used [24, 25].

5.2. Sound measuring devices. For operational control, forecasting the state of the rock mass, sound-metric portable and stationary devices are used as the most accurate and simple means and methods of observation (Table 1). The method of piezoelectric effect is used as the basis of devices that capture sound impulses of destruction (mountain noises), arising at the moment of violation of the integrity of the internal connections of the rock and ore massifs. Portable sound-measuring devices (sensors and indicators of sounds of destruction and sound-measuring stations) are intended for carrying out preventive and regular observations in places where there are no observation stations [26, 27].

When assessing the degree of stability of an underworked rock mass, the most important characteristic is the dependence of its sound activity on the magnitude of stresses and deformations, obtained at various stages of loading of rock and ore samples in laboratory or in natural conditions. Numerous experiments and experiments show that at stresses of 60–80 % of the destructive values, the sound activity of the rock mass increases sharply.

Table 1

Sound measuring devices and systems

Name of devices and systems	Model	Frequency response, Hz	Developer
Sonic destruction indicator	ZIR-3	$0–5\cdot10^3$	SE «NIGRI», Krivyi Rih, Ukraine
Sound measuring device	ZP-5, ZP-6	$20–2\cdot10^4$	JSC «VNIPIprom Technologies», Moscow, Russia
Dual channel recorder	REM-1	$50–4\cdot10^4$	SE «UkrNIPII promtechnology», Zhovti Vody, Ukraine
Dual channel digital meter	AER-2SH	$4–40\cdot10^3$	IF and IHP AS, Bishkek, Republic of Kyrgyzstan
Stationary seismic acoustic equipment	Groza-16	$20–4\cdot10^4$	SPA «Sibtsvet avtomatika», Krasnoiarsk, Russia

Organization of monitoring in order to ensure safe ore mining technology should be subordinated to the solution of the following main tasks:

– determination of the conditions for ensuring the necessary stability of the elements of the rock massif, preparatory and treatment workings, underground and surface structures and other objects;

– efficient organization of mining operations, forecasting and timely application of measures to prevent dynamic manifestations of rock pressure;

– establishment of patterns and parameters of the rational interaction of the elements of the rock mass with each other, as well as with the laying of man-made space and elements of engineering structures during mining.

6. Research results

6.1. Brief description of ore deposits of complex structure.
The near-surface reserves of the Michurin deposit of the SE «VostMPP» (Ukraine), a significant part of which lies under the Ingul River, industrial and civil buildings and structures, are represented by steeply dipping ore bodies of various capacities.

The length of the ore bodies is from 600 to 700 m along the strike (mainly 100–250 m), along the dip from 150 to 400 m.

The ores and the rocks enclosing them are strong: the strength coefficient on the scale of prof. M. Protodyakono $f=14-18$, massive and have a non-layered structure. Towards the surface, there is a significant deterioration in the quantitative and qualitative characteristics of fracturing, both for individual deposits and for the field as a whole.

On the upper horizons, the rocks are weathered: the coefficient of decreases to 6. The deposit is developed by a chamber development system with backfilling of the goaf with a hardening mixture (Fig. 1).
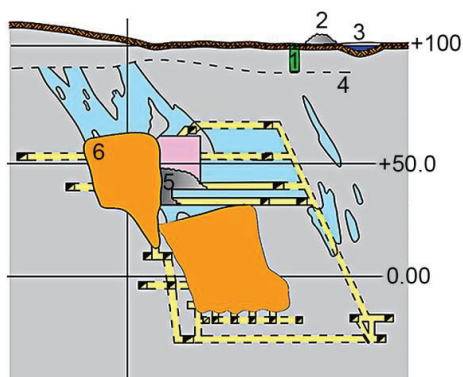

Fig. 1. Chamber mining system with end discharge of ore:
1 – anti-filtration curtain; 2 – dam; 3 – Ingul river;
4 – lower boundary of the weathering crust; 5 – broken ore;
6 – chambers worked out and extinguished
by hardening backfill

Mining operations are developing at a depth of 40–50 m to 350 m. The chambers are mined in sublevels 10–15 m high. Ore breaking is performed with borehole charges 57 and 65 mm in diameter drilled with NT-2 and PK-75 machines (Ukraine). Parallel down-wells with a diameter of 85 and 105 mm are drilled with NKR-100 M machines (Ukraine) to form cutting slots.

6.2. Assessment of the geomechanical state of the rock mass.
Mining operations at the ore deposits of the SE «VostMPP» have been carried out since 1968 at the Ingul mine, which mines two deposits:

1) Michurin – at floors 210–150 m, 280–210 m, mining has begun at floors 280–350 m;

2) Central (Eastern zone) – in floors 230–160 m, 300–230 m.

The Smolinsk mine has been operating the Vatutino deposit since 1972, where by now the main part of the reserves has been worked out, mining operations are being carried out at the levels of 550–640 m, the working excavation at the floors of 460–550 m.

In the development projects of the Michurin, Central, Vatutino and Novokostiantynivka fields, the main issues of opening, the method and procedure for developing the fields have been resolved. Residual reserves, represented by individual ore bodies, are subject to development after the extraction of the main reserves. Opening of deposits on the horizons is carried out by cross-ways and field drifts in hanging and recumbent sides, knocked together by orts arrivals. The sublevels are opened with a field drift in the hanging side and drill workings for ore.

The main development systems are sublevel drifts and orts with the extinguishing of the voids of the spent chambers by a hardening backfill. For this, each deposit is divided into treatment blocks, which are worked out by a series of primary and secondary chambers. In the blocks of the first stage, the extraction of reserves is carried out, as a rule, from the middle, in the secondary blocks – from the flanks.

The deposits of the Ingul, Smolinsk and Novokostiantynivka mines are characterized by the presence of numerous inclusions of waste rocks and substandard ores, interlayers inside the deposits. The deposits are often interrupted, wedged out and reappeared, disintegrating into separate bodies with a complex morphology. The development of such deposits is associated with the need to have a developed network of mine workings, which significantly affects the geomechanical state of the rock mass. By the end of the mining of the horizon, the rock mass, where the cleaning and filling works were carried out, has a complex geomechanical structure.

For operational control, forecasting the stress-strain rate of the rock mass, sound measuring devices were used, in particular, portable ones as the simplest means and methods of observation (developed by SPC «A and M», manufactured in conjunction with the repair and mechanical plant (RMP) SE «VostMPP», Ukraine) and others (Fig. 2). The method of piezoelectric effect is used as the basis of devices that catch sound impulses of destruction (mountain noises) arising at the moment of violation of the integrity of the internal connections of the rock and ore massifs. The amplification factor of such devices does not exceed 10^5, and the total mass of the set is no more than 10 kg. For sound-measuring devices, the main element in the set of equipment is a piezoelectric geophone (sensor-receiver of sounds of destruction). It is an insulated sleeve made of a stainless tube with a diameter of 38–42 mm and a length of 150–220 mm, inside which a piezoelectric element with dimensions of $65\times20\times3.5$ mm or $65\times20\times2.5$ mm is fixed in a special holder in a special holder. The sounds of destruction passing through the rock mass cause mechanical vibrations of the piezoelectric element, as a result of which an electrical potential difference arises on opposite sides, which is recorded.
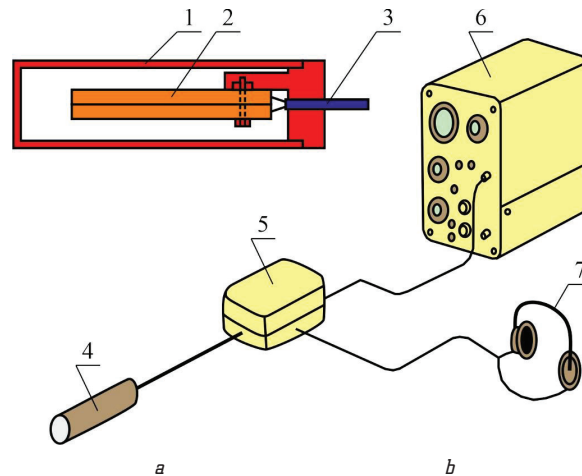
Fig. 2. Scheme of the sound measuring method of sounding a rock mass:
a – sensor design; *b* – working diagram: 1 – sensor body; 2 – crystal of Rochelle salt; 3 – cable; 4 – sensor;
5 – amplifier; 6 – oscilloscope; 7 – headphones

Sounds of destruction passing through the rock mass cause mechanical vibrations of the piezoelectric element. As a result of this, an electrical potential difference arises on opposite faces, which is recorded. Based on the results of field tests of the elements of the rock mass carried out at the Michurin field of the SE «VostMPP» (Ukraine) during the development of near-surface reserves, the dependences of the frequency of the sounds of destruction on the value of stresses σ (Fig. 3), according to the formula [28, 29]:

$$\sigma = a \cdot N_P^b, \qquad (1)$$

where N_i – the number of pulses per minute; a and b – respectively, the coefficients characterizing the structural and strength properties of the rock mass.

Remote systems for sound measuring control over chambers and the array as a whole showed that the redistribution of stresses in the array occurs within 15 minutes after a massive explosion and then does not exceed 0–10 pulses/min. Sound measuring observations in 14 out of 23 chambers of the blocks confirmed the stable state of the array (pulse intensity 0–17 pulses/min). It has been established that with stable outcrops of chambers for 2–2.5 years, their further state remains stable. It is possible to exclude these chambers from the list subject to sound-measuring control. Instrumental measurements with sound-measuring instruments also established the state of stability of mountain ranges at a pulse

intensity of 0–3 pulses/min. This is confirmed by a visual inspection of the outcrops of chambers of 10 operational blocks in floors 280–520 m of the Smolinsk mine of the SE «VostMPP» (Ukraine). The surveyed chambers and the mountain range as a whole are in a stable state, there is no danger of rocks collapse [30, 31].

The forecast classification of rock massifs by fracturing and their main mining technology indicators of stability and fragility are presented in Table 2.
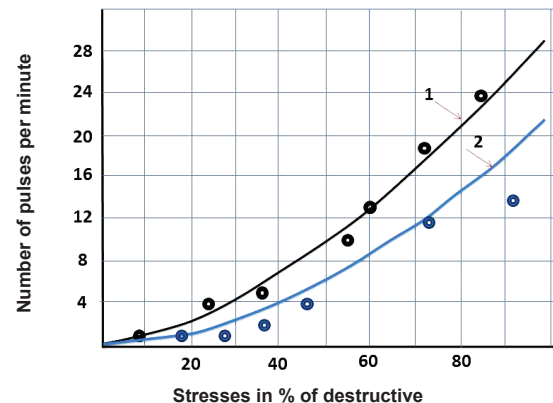

Fig. 3. Dependence of the frequency of sounds of destruction on the magnitude of stress for various types of rocks: 1, 2 – respectively, medium and strongly fractured massif

Table 2

Forecast classification of rock massifs

Characterization of fracturing of rock massifs	Core recovery, %	Structural attenuation factors	Indicators of fracturing and blockiness			Transition factors	
			specific fracturing, number of cracks/m²	distance between cracks (edge of the reduced cube), cm	proportion of pieces with a diagonal of more than 700 mm, %	sustainability	fragility
Weakly fractured	>80	0.4–0.5	0–8	>35	70	1.5–1.7	1.1–1.4
Medium fractured	45–80	0.2–0.4	8–15	15–35	20–70	1.0	1.0
Heavily fractured	30–45	0.1–0.2	15–30	5–15	1–20	0.5–0.6	0.6–0.9
Shattered	<30	<0.1	>30	<5	0	<0.5	0.4–0.5

6.3. Initial data on the hardening backfill. The stability of horizontal and vertical outcrops of the filling is in direct proportion to the quality of the filling mixture, the time of hardening and solidity (Fig. 4).
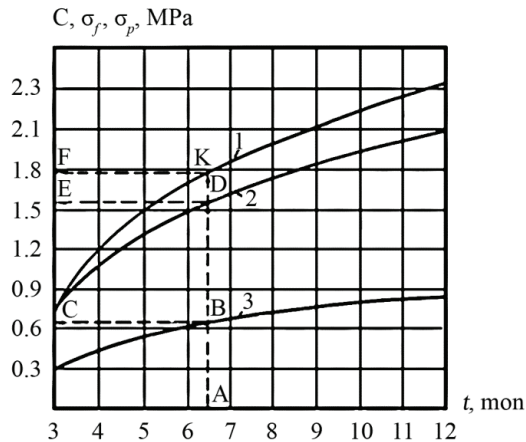

Fig. 4. Strength characteristics of the backfill depending on the hardening period (t): 1, 2, 3 – respectively, the adhesion coefficient (C), the ultimate strength in bending (σ_f) and tensile (σ_p), MPa; key: A–B–C; A–D–E; A–K–F

6.4. Determination of basic parameters of chambers. The geometrical parameters of the chambers should ensure the stability of the massif outcrops without significant collapse (no more than 300 m^3) that impedes the development of reserves of the production block. The authors divide the methods for determining the geometric parameters of chambers into two groups: analytical and empirical. Analytical methods are based on the provisions of the theory of elasticity and plasticity, but ignorance of the initial stress state, insufficient accuracy of the constants of physical and mechanical properties of the rock mass reduce the effectiveness of these methods [25, 26]. The empirical method is based on the use of graphical data analysis using patterns and functional dependencies. Examples are the method of functional characteristics, for the development of instructions for determining the geometric parameters of storey-chamber development systems in Kryvbas (Ukraine). The method of JSC «VNIMI» (Russian Federation) – for establishing the dimensions of chambers and pillars in chamber systems for the development of ferrous and non-ferrous metal ores [27, 28]. Based on the results of many years of research on a complex of scientific research works in the underground development of deposits of complex structure in energy disturbed massifs, the authors propose mathematical models to substantiate the safe parameters of the chambers (Table 3).

The calculations of the parameters were carried out on the basis of the following conditions: stable ore and host rocks of medium fracturing, strength according to the scale of prof. Protodyakonov 12–18, the angle of incidence of deposits is more than 50°. When the thickness of the ore bodies is 3–15 m, a system of development by sublevel drifts is used and more than 15 m – by sublevel orts. Floor heights 60 and 70 m, sublevels 15–18 m; the order of development of sublevels is soil-ledge, drilling with ascending fans of wells with a diameter of 57 and 65 mm; voids are filled with a hardening backfill with strength from 1.5 to 6.0 MPa. The technological parameters of the development system are given in Table 4 [32, 33].

Thus, the forms of dynamic manifestation of rock pressure are due to a number of factors, the most significant of which are: natural, developed network of tectonic faults near the Main fault. Also, mining, depending on the methods of mining, the ruggedness of the massif by mine workings, conducting work at the same time by several faces, excavating stressed pillars, conducting mining operations under pillars. Man-made, associated with the consequences of mining and the seismic effect of explosions, the creation of almost instantaneous large outcrops during the long wall mining of ore bodies [34, 35]. Based on the analysis of the geomechanical situation in the development of deposits, conditions are presented that promote or reduce the dynamic manifestations of rock pressure during the development of ore deposits (Table 5).

Table 3

Safe parameters of chambers for deposits of complex structure

Parameters	Calculation formulas
Equivalent spans at outcrops, m (L_{eq}):	–
correct shape	$L_{eq} = \dfrac{a \cdot b}{\sqrt{a^2 + b^2}}$
irregular shape	$L_{eq} = \dfrac{2.5 \cdot S}{P_o}$
Outcrop stability criterion, m (L_{eq}):	$L_{eq} = L_{ed} = \dfrac{L_{eo}}{1.1}$
Stable spans, m:	–
Horizontal ($L_{h.eq}$)	$L_{h.eq} = \dfrac{a \cdot b}{\sqrt{a^2 + b^2}}$
Vertical ($L_{h.eq}$)	$L_{v.eq} = \dfrac{a \cdot H}{\sqrt{a^2 + H^2}}$
Equivalent span (L_{eo}, m) taking into account the lifetime of outcrops (t, month)	$L_{eo}^2 \cdot t = \text{const} = A$
Equivalent spans for backfill, m:	–
horizontal	$L_{h.eq} = \sqrt{\dfrac{2\sigma_{iz} \cdot h_{cl}}{\gamma_z \cdot K_z}}$
vertical	$L_{v.eq} = \dfrac{2C_m}{\gamma_z \cdot K_z}\,\text{ctg}\left(45° + \dfrac{\rho}{2}\right)$
Outcrop stability, m:	–
length (a)	$a = \dfrac{L_{h.eq} \cdot b}{\sqrt{b^2 + L_{h.eq}^2}}$
width (b)	$b = \dfrac{L_{h.eq}^2 \cdot a}{\sqrt{a^2 + L_{h.eq}^2}}$
height (H)	$H = \dfrac{L_{v.eq} \cdot a}{\sqrt{a^2 + L_{v.eq}^2}}$

Table 4

Development system technological parameters

Parameters	The value of indicators at the thickness of ore bodies, m		
	from 3 to 6	from 6 to 15	from 15 to 90
Chamber sizes, m: height length width	60–70 40–70 3–6	60–70 30–60 6–15	60–70 15–90 12–15
height, m: sub-floor bottoms	10–13 8–13	16–20 11	16–20 11
Distance between outlet workings, m	8	8–10	8–10
Mining scope: within the boundaries of the block 1000 t of balance reserves, m³; per 1 m of deposit thickness, m³	140–70 23.0	70–28 4.7	80–42 4.8
Order of mining block reserves	Through the chamber		After two chambers – stocks of the first stages of excavation, the second – after three
Direction of stock removal of chambers	Center to flank or flank to flank		From the hanging side to the recumbent, or vice versa
The order of extraction of reserves on the sublevel	Soil step		Soil step
Cutting gap formation	Down up		Down up
Drill hole location	Fanny		Fanny
Borehole diameter, mm when clearing stocks of chambers when forming a cutting gap	65 85	65 85	65 85
Method of ore release	Delivery horizon	Gravity	
Oversized output, %	4–5	5–7	
Strength of hardening filling mixtures, MPa: for bottoms (ceilings) and chambers of the first stage of development for chambers of other stages of development	2.5 1.2	3.0 1.5	6.0 2.0

Table 5

Characteristics of the conditions of dynamic manifestation of rock pressure

Characteristics of conditions	
Contributing	Reducing
– residual tectonic stresses; – presence of discontinuous structures: faults, dikes, numerous pinches and apophyses; – intermittency of ores and rocks, lithological varieties, within rock inclusions in ore bodies; – increased water content, confined to zones of crushed and highly fractured rocks; – possibility of the formation of foci of overstressed rock mass as a result	– continuous mining system with backfilling of the worked-out area; – presence of vertical unloading layers (cutting slots) with chamber mining systems
– action of geodynamic factors and seismic and explosive shaking; – increasing the depth of mining; – mining of ore deposits from flank to flank	– insignificant presence of zones (1–2 %) of crushed (unstable) rocks; – insignificant watering of ore deposits
– the ledge form of the bottom during the cleaning work; – formation of large areas of outcrops in the final stage of breaking out benches from sublevel drifts (orts); – presence of a significant volume of unbound voids	– sand-slag (cementless) compositions of filling mixtures

The results do not exhaust the problem of nature and resource conservation, environmental and human protection. The development of methodological foundations for optimization of mining technology should lead to:

– creation of an appropriate subsystem for automation of design and planning of mining operations;
– improving the technological and ecological safety of the environment;

– rational use and protection of subsoil;
– safety of human life in the zone of influence of mining operations [36, 37].

6.5. Implementation results. As a result of a complex of scientific research works, the authors established a modern technical level of the applied development system, and also compiled an Instruction on justification of the

safe conduct of mining operations and the procedure for mining ore deposits at the mines of SE «VostMPP». It sets out the main provisions, geomechanical characteristics of ore deposits and defines the criteria for assessing the stress-strain state of a rock mass. The conditions for the safe conduct of mining operations, the procedure for determining the size of hazardous zones and brittle destruction of rocks, prone to dynamic manifestation of rock pressure of various forms, are described. The substantiation of a safe procedure for the development of ore deposits within the mine field is given. The safety of mining operations in adjacent ore bodies and ore deposits, as well as the safety of mining rock massifs under the dynamic action of an explosion are shown. Measures are given to safely conduct mining operations and reduce the dynamic manifestation of rock pressure of various forms, including seismic safe masses of explosive charges. Shown is their impact on the safe conduct of mining operations in the depth interval of 300–1000 m during the development of ore deposits by chamber mining systems with backfilling of the worked-out space at the mines of the SE «VostMPP». This Instruction is approved and is successfully used by specialists of technological and geological and mine surveying services.

6.6. Research prospects. In a market economy, when mining enterprises, in pursuit of profit, resort to unregulated selective development of a deposit, which is accompanied by negative economic consequences (damage) [38, 39], it becomes important to introduce innovative technologies of the mining and metallurgical complex based on mathematical modeling of technological processes and geoinformation systems. (GIS). GIS is an information system that provides collection, storage, processing, display, analysis, modeling and dissemination of spatially coordinated data [40, 41].

Despite the variety of methods and tools used for diagnostics and control of the stress-strain state of a rock mass, they can be combined into three classes according to their functional purpose: analytical methods, methods of field observations, and modeling methods. Field observations include visual, mine surveying, mechanical, geophysical, chemical-physical and combined methods. This makes it possible to predict the stability of the massif, structural elements of development systems and safe conditions for conducting work under water bodies and in difficult mining-geological and mining-technical conditions of mineral deposits.

The successful solution of the set tasks is associated not only with the research, but also with the revision of the system of organization and planning of mining operations in underground mines. Since there is a need to create geotechnical control systems and services for forecasting and preventing dynamic manifestations of rock pressure, which affect the safety of mine workings and the stability of chamber outcrops.

7. SWOT analysis of research results

Strengths. Based on the analysis of the geomechanical situation in the development of ore deposits of complex structure, conditions are proposed that promote or reduce the dynamic manifestations of rock pressure during the development of ore deposits. And also the «Instruction on the substantiation of safe mining and the procedure

for the development of ore deposits at the mines of the SE «VostMPP» was drawn up and approved.

Weaknesses. The main negative impact of mining technology on the environment and humans is the high cost of preserving the day's surface and ensuring the vital activity of the population living in the zone of influence of mountain objects, withdrawing large areas of land from use, etc. Therefore, it is necessary to provide funds for the following measures:
– deep processing of man-made waste (tailings), which have a wide variety of mineral forms in comparison 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 shrub vegetation;
– constant monitoring of environmental components in the zone of influence of mountain objects.

Opportunities. The obtained results of the study do not exhaust the problem of nature and resource conservation, environmental protection and human protection. The development of methodological foundations for the optimization of mining technology should lead to:
– creation of an appropriate subsystem for automation of design and planning of mining operations;
– improving the technological and ecological safety of the environment;
– rational use and protection of subsoil;
– safety of human life in the zone of influence of mining.

The research results can be used in underground mining of ore deposits of complex structure in Ukraine, the Russian Federation, the Republic of Kazakhstan and other developed mining countries of the world.

Threats. In order to prevent the dust transfer of contaminated material outside the mountain objects, it is advisable to plant the sanitary protection zones and strips around them with tall tree species that will restrain the wind speed over the specified objects. These include mines, waste rock dumps and off-balance ones, in terms of the content of the useful component, ores, stowing complexes, pre-concentration and heap leaching sites of metals from substandard ore raw materials, tailings, etc. In this case, dust will settle in these forest plantations and will not enter 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 facilities, as well as assess their impact on the environment and humans.

8. Conclusions

1. It is substantiated that the geometric parameters of the chambers, the stability of vertical and horizontal outcrops depend on the intensity of mining and laying the chambers. The faster the chamber is worked out and laid, the more exposure is allowed.

2. A functional relationship between the magnitude of stresses in a rock mass and the number of impulses (sounds of destruction) per minute, characterizing its structural (a) and strength (b) properties, is proposed, described by a curvilinear relationship of the form $y = axb$. This relationship makes it possible to quickly establish stable parameters of outcrops with a probability of 0.8.

3. Mathematical models are recommended to substantiate the safe parameters of the chambers, which ensure an increase in the technological and ecological safety of the environment, the rational use and protection of the subsoil, as well as the safety of human life in the zone of influence of mining operations.

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Lyashenko Vasil, *PhD, Senior Researcher, Head of Research Department, State Enterprise «Ukrainian Research and Design Institute of Industrial Technology», Zhovti Vody, Dnipropetrovsk region, Ukraine, e-mail: vilyashenko2017@gmail.com, ORCID: http://orcid.org/0000-0001-8361-4179*

Khomenko Oleh, *Doctor of Technical Sciences, Professor, Department of Mining Engineering and Education, Dnipro University of Technology, Ukraine, e-mail: rudana.in.ua@gmail.com, ORCID: http://orcid.org/0000-0001-7498-8494*

Chekushina Tatiana, *PhD, Leading Researcher, N. V. Melnikov Institute of Comprehensive Exploitation of Mineral Resources of Russian Academy of Sciences, Moscow, Russia, e-mail: tanija_ch@mail.ru, ORCID: http://orcid.org/0000-0001-9261-1105*

Topolnij Fedor, *Doctor of Biological Sciences, Professor, Department of General Agriculture, State Higher Educational Institution «Central Ukrainian National Technical University», Kropyvnytskyi, Ukraine, e-mail: topolniy@gmail.com, ORCID: http://orcid.org/0000-0002-3363-4646*