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FORECASTING ROCK BURST HAZARD OF TECTONICALLY DISTURBED ORE MASSIF AT THE DEEP HORIZONS OF NIKOLAEVSKOE POLYMETALLIC DEPOSIT

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The subject of the research is the stress-strain and rock burst hazardous state of the ore massif of the Nikolaevskoe polymetallic deposit, formed under the influence of complex mining-geological and mining-technical factors. The purpose of the research is to establish the peculiarities of the formation of technogenic stress fields at the deposit, which is characterized by a block structure, a complex tectonic system and the presence of a large volume of developed spaces. Volumetric geodynamic modeling of the stress-strain state of the massif at different stages of the development of the deep horizons of the deposit was carried out by collecting information on the structure, properties and geodynamic state of the rock mass. The assessment of stress changes taking into account the effect of hypsometry, the configuration of the selvages, the physical-mechanical properties of the ore deposit and host rocks, the presence of tectonic disturbances was made using the developed numerical algorithms, the automation equipment of the initial data and the PRESS 3D URAL software. The simulation made it possible to establish that tectonic faults in the massif lead to a qualitative change in the stress-strain state in certain parts of the ore massif and in the pillars, namely, the reduction of stresses along the tectonic faults and their growth in nearby pillars. The identified features of the distribution of stresses in the tectonically disturbed rock massif of the Nikolaevskoe deposit will allow to identify in advance potentially hazardous areas both at the planning stage of mining operations and during development, as well as to work out effective rock burst measures to increase the safety of mining. The results of research can be used in enterprises with similar mining-geological and mining-technical conditions.

Key words: tectonics; geomechanical condition; stress-strain state; rock pressure; rock burst hazard; pillar; geodynamic modeling; rocks

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Introduction. Deposits of the Far Eastern region are almost universally characterized by a complex geological structure, tectonic disturbance, a variety of conditions of occurrence of ore bodies and physical-mechanical properties of rocks, and the presence of high gravitational-tectonic stresses in rock mass. Additional problems are caused by selective mining due to extremely uneven distribution of reserves in the deposit. The activation of geodynamic processes usually occurs with a transition to deep horizons and an increase in the volume of developed spaces, which significantly affects the stability of undermined spaces and the Earth's surface, the stressed state of pillars and outcrops of stopes also creates additional prerequisites for rock bursts. The most dangerous ones are bursts accompanied by a strong mass shattering infrequently leading to the destruction of a significant number of workings, stopes and pillars, reducing the safety of mining operations. One of the main causes of rock bursts is rock mass [4, 13, 14,].

The great depth of mining operations, the complex block structure of the subsoil with active faults, the high rock bump hazard and the large areas of mined spaces with pillars create conditions for the formation of energy-active zones in the local areas of the rock mass. The geodynamic nature of accidents promotes a more detailed study of the SSS of the ore massif in the mining horizons of different depth.

At present, considerable experience has been gained in managing the rock bump hazardous state of the rock mass, predicting the destruction of mine workings and elements of mining structures (various types of pillars) and preventing rock bursts. Methods for predicting and preventing rock bursts depend on the scale of the problem and have a local or regional level.

A review of the current regulatory documents ensuring safe conditions for the development of rock burst hazardous deposits shows that the determination of the hazard degree of workings or elements of mining structures is carried out mainly by local methods of rock burst hazard prediction. Mine specialists use geomechanical or geophysical methods or (in some cases) a set of forecasting methods to predict the hazard. The geomechanical forecasting methods currently used in the mines of Russia are mainly based on the results of estimating core disruption parameters based on data from drilling exploratory wells and (or) placing indenters in the borehole walls (MHD); geophysical methods are based on the results of the registration of seismic signals. Practical experience shows that local methods for predicting the rock burst hazard are effective mainly in identifying areas of elevated rock pressure in selvages to a depth of 5 m.

To predict the hazard to a greater depth, the data of regional seismological geophysical observations are used, allowing to estimate the zone of destruction in the rock mass as a result of mining operations. To make technical decisions on mining planning in rock burst hazardous conditions, mines build maps of seismic activity of stopes in isolines and combine the latter with mining plans. Continuous seismological geophysical observations of seismic activity in the stopes are carried out by the department of automated seismic monitoring of rock pressure (ASMRP) of the mine. The seismic control data also allows us to estimate the stress state in the vicinity of the source of destruction and to establish the presence, nature and parameters of the movements in the block rock mass. The advantage of the regional method of rock burst hazard prediction is the continuity of experimental observations of the occurrence of rock pressure in real time and the ability to follow the evolution of deformation processes in the rock mass over time. At the same time, the method of regional prediction of has its drawbacks: it is impossible to correctly predict rock burst using instrumental data due to the low efficiency of forecasting seismic phenomena of high energy level.

To prevent rock bursts in mines in accordance with the requirements of regulatory documents they use a complex of measures for reducing the stress by eliminating dangerous sources of stress concentrations in rock mass.

Formulation of the problem. The problem of predicting hazardous geodynamic phenomena is highly relevant at the Nikolaevskoe polymetallic field, the deepest one among currently developed in the Far Eastern region, it is characterized by a complex tectonic structure, a significant amount of developed space (more than 4 million m^3) and depth of mining (more than 800 m) [1]. During the operation of the field, numerous cases of dynamic rock pressure manifestations were noted, as a result of which the field was classified as dangerous for rock bursts from a depth below the horizon – 120 m (vertical depth about 600 m).

The lithological complex of ores and host rocks of the Nikolaevskoe deposit is the following: sheet-like deposit and lenses of infiltration skarns, associated with the contact of limestone with overlapping volcanic rocks; complex bodies confined to limestone blocks isolated from the main horizon; extended veins and vein-impregnated zones localized in the covers of volcanic rocks of the upper floor have high strength and deformation characteristics and the ability to accumulate the potential energy of elastic compression to brittle fracture in a dynamic form [5]. The entire area of the field is divided into three main structural blocks (northern, central and western) with a high-angle east-west trending fault (85-90 degrees to the south-east) and a north-western tectonic zone (almost vertical), referred to the first-order structures. The deposit has a well-defined block structure and is also determined by the lengthy steeply dipping discontinuous tectonic disturbances of the sub meridional strike (TN-1, TN-2, TN-3 with angles of 70-85 degrees), complex north-western dyke-like bodies and flat faults. Individual structural blocks under the influence of natural and technogenic stress fields can shift in the undermined massif towards the undermined spaces, creating high dynamic loads in the massif, and leading to dynamic rock bump manifestations [2, 7, 12].

From 2016-2017 mining operations at the Nikolaevskoe deposit are conducted in the area of the following stopes of the «Vostok-1» ore deposit: the «North-8» block on the floor –375 and –420 m; block 45 in the floor –380 and –420 m; block Nizhny at the horizon 420 m, and also in the area of the Kharkovskoe ore deposit: block 7 in the floor –323 and –348 m, the Krayny block below the horizon 327 m. Over the past year, more than 35 % the ore production volume was provided by mining of the Kharkovskoe ore deposit. According to the results of the analysis of the geomechanical and mining-technical situation, it was found that certain areas of this ore deposit represent a potential rock burst hazard. In addition, the ASMRP system «Prognoz-ADS» shows a rather high level of acoustic activity in this mining area [3]. Despite the regional rock burst hazard forecast, which makes it possible in general to monitor the development trends of a hazardous situation when mining stopes in a block rock massif, there are no quantitative criteria for assessing the danger of rock bursts using this method. In this connection, it is necessary to forecast the stress and rock burst state of the ore massif when mining the Kharkovskoe ore deposit on the floor –323 m in the zone of tectonic disturbances (TD) using the PRESS 3D URAL software package, which allows determining in advance the stresses in the ore massif during advancement of mining operations and develop safe technical solutions to ensure the geodynamic safety of mining operations in hazardous conditions.

Methodology. Methodological support for the prediction and prevention of rock bursts should match the scale of the problem being solved.

The main method for predicting the rock burst hazard of the block rock mass is the geodynamic zoning of the subsoil, which makes it possible to specify the geological structure and isolate tectonically stressed zones (TSZ) and geodynamically hazardous zones (GHZ) or risk zones that are potentially dangerous for mining production. In this case, the GHZ is spatially associated with the TSZ. The increase in the gradient of the rock pressure growth in the selvages and pillars leads to the intensification of movements on the planes of tectonic disturbance displacement in the TSZ and, therefore, to an increase in geodynamic hazard at the relocation of mining operations to the GHZ.

Studies of geodynamic safety of mining operations are carried out considering the principle «from the general to specific» based on the data of a volumetric geodynamic model including information on the structure, properties and geodynamic state of the rock mass. The mining and geodynamic model allows analyzing the past and present geodynamic processes at the fields, and the additional mining and geological and mining and technical information – to specify the position and structure of the GHZ considering the parameters of mining. The goal of geodynamic zoning is achieved as a result of the consistent development of a block (geological and structural), geodynamic, and mining and geodynamic model of a deposit (a field or its section).

The problem of effective use of existing software is associated with the complexity of creating the initial informational geological and structural model of the ore deposit. Basically, this requires a complex accounting of the following geo-informational data in the geologic-structural model: the occurrence elements and the form of the ore deposit elements, as well as a wide range of properties of the calculated elements, including geometric parameters (width, length, height), physical and mechanical properties of ores (rocks), parameters of tectonic disturbances and preventive measures. In this regard, to perform a predictive assessment of the stress-deformed and rock burst hazardous state of the ore massif and pillars, taking into account the complex geological structure of the Kharkovskoe deposit, the configuration of the selvages of the developed spaces and pillars, the physical and mechanical properties of the ore and rock, and the presence of tectonic disturbances it is advisable to use the software «PRESS 3D URAL» [9].

To predict the impact of the selvages (pillars) a reliable energy indicator of rock burst hazard, developed by VNIMI, was adopted:

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$$\eta_{sp} = \left| K_{\text{int, p}} / K_{\text{int}, ad} \right|,$$

where $K_{\text{int, p}} = \sqrt{2\pi r}(\sigma_{z,\text{p}}(x_\text{p}, y_\text{p}) - 1)\gamma H$ – stress intensity factor characterizing the influence of the load on the selvage of the ore deposit, $\text{MPa}\sqrt{\text{m}}$; r – the radius of the calculated ore element located on the border with the goaf, m; $\sigma_{z,\text{p}}(x_\text{p}, y_\text{p})$ – additional stress in the calculated element of the ore deposit, determined using the software «PRESS 3D URAL»; γ – average volume weight of rocks, t/m^3; H – mining depth, m; $K_{\text{int},ad} = 1{,}4\sigma_{\text{com}} f \times \times (M/E_n)\sqrt{m/2}$ – stress intensity factor characterizing the resistance of the selvage of the ore deposit to the current loads, $\text{MPa}\sqrt{\text{m}}$; σ_{com}– compression strength of ore, MPa; m – ore deposit thickness, m; $f(M/E_n)$ – known tabulated function; $M = 0.5E_\text{p}$ – ore (rock) fall modulus in the extreme part of the deformation diagram, MPa; E_o – ore elasticity modulus, MPa; E_p – modulus of elasticity of rock, MPa.

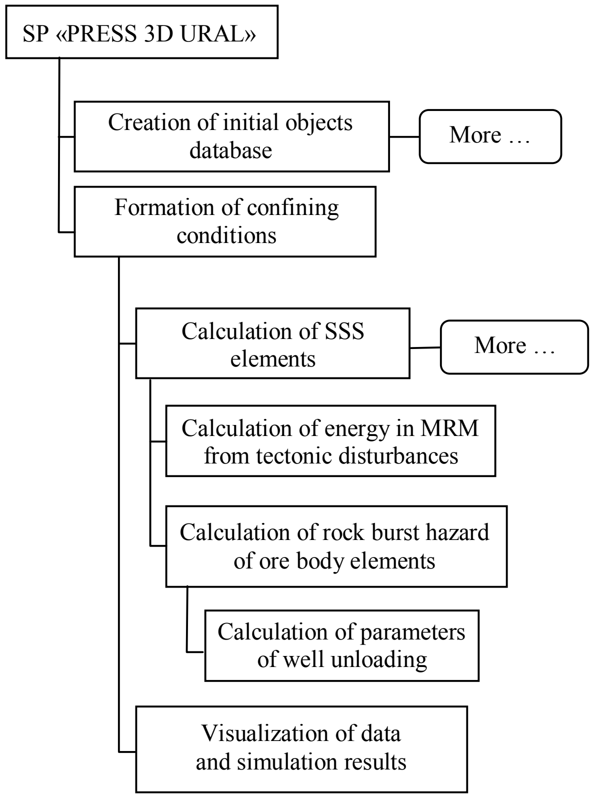

Fig.1. Algorithm for assessing the rock burst hazard of a block ore massif using PRESS 3D URAL software

The «PRESS 3D URAL» software package includes the implementation of three main blocks (Fig. 1):

1) processing of the initial geological and technical documentation with the creation of a database of initial data on objects: geometrical dimensions (width, length and height of developing entry, chambers and pillars); location of stopes (workings for various purposes) in 3D space and ore-bearing elements (ore deposit, different pillars); physical-mechanical properties of roof rocks in stopes and workings for various purposes, as well as ore-bearing elements, parameters of tectonic disturbances and confinement conditions (Fig. 2);

2) numerical-analytical calculation;

3) processing of results for visualization and analysis.

The actual basis for creating a volumetric model of the ore-forming system was the geological material in the form of a uniform system of interconnected sections. As a result, the volumetric model covers the interval of the field vertically 300 m, between absolute marks –220 and –520 m. Contact-infiltration ores deposited in this area are of two types: complex reservoir and sheet-like bodies of considerable size occurring in the endo- and exocontact of a large plate of limestone and contoured conventionally with «lower metasomatites»; ore bodies of complex morphology, confined to scattered smaller blocks of limestone, forming a «tail» among the rocks of the base of the volcanic section of the upper structural floor, contoured by the cover of the «upper metasomatites».

When constructing a geological-structural volumetric model, the fact was considered that the formation of the architecture of the ore-metasomatic system of the Nikolaevskoe field was played by a lithological factor – different-sized limestone fragments surrounded by a silicate medium, and their configuration and position in space. At the same time, the main physical-mechanical heterogeneity of the geological environment of the ore field here is a large plate of limestone (olistolite), the morphological features of which determined the general structure of the field and the direction of its activation in the modern period.

In the quantitative description of the TD-fields (form, type, occurrence elements, angle of internal friction and adhesion of the fault seam), the VNIMI classification is used, considering the nature of the stress distribution at the displacement plane of the tectonic disturbance. At the same

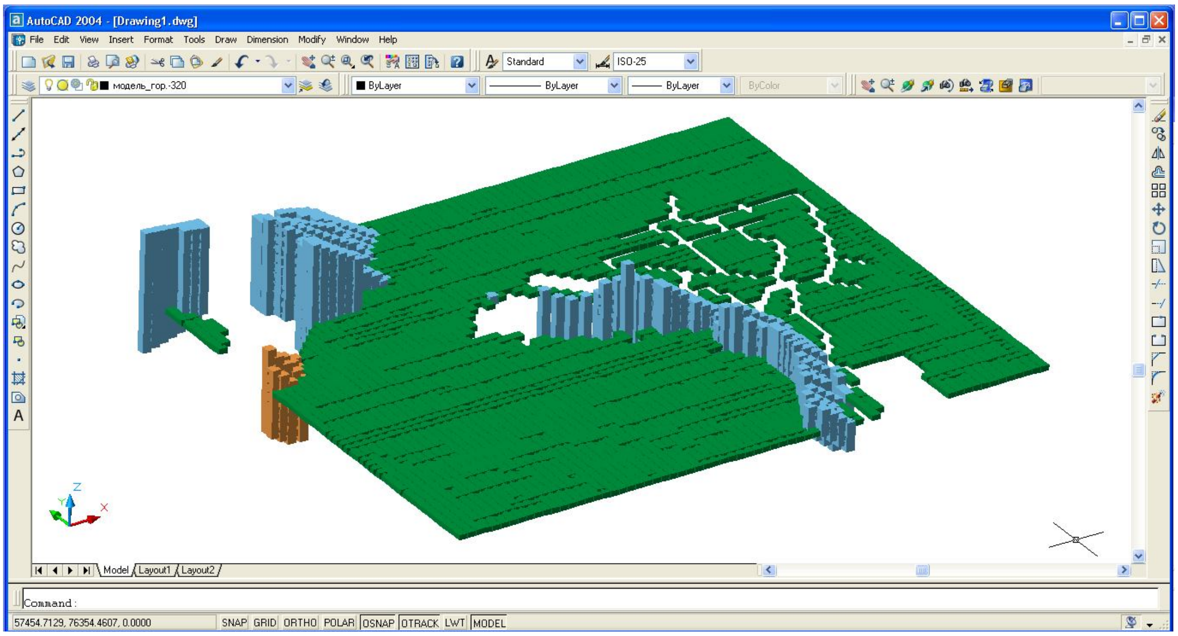

Fig.2. Formation of elements belonging to the ore-rock massif and mine workings

time, the classification, along with the stress state, takes into account the geological structure of the massif in the zone of influence of faults, by which the type of disturbance and stress state are visually determined.

According to the Guidelines for the Safe Mining at Nikolayevskoe and Yuzhnoe fields (OJSC «GMK Dalpolimetall») dangerous for 2008 due to rock burst hazard [10, 11], tectonic disturbances, as a rule, have a steep fall (70-90°). They are characterized by zones of increased fracturing and voids («holes») with a thickness of up to 10-20 m and represent bands of brecciated and intensively recrystallized limestone, in which «holes» are also developed. These tectonic structures, in accordance with the classification of the All-Russian Research Institute of Scientific and Technical Information, are of type II and distinguished by the presence of a discharge zone directly at the disjunctive. Behind the discharge zone in both wings there are transition zones, within which the level of stresses gradually increases. This is followed by zones of high stress concentrations. The geological signs of disturbance of this type in the discharge zone are a developed fractured zone with a width of 2 m or more. The fractured zone is represented by disintegrated loose rock fragments, or fragments, held together by a soft plastic aggregate (clay, shale, etc.). It is also possible the presence of weathered rocks with intensive cracking. The thickness of the seam is 10 cm or more. In this case, there are cases when the fault seam is revealed. Often there is a water cut near the seam, lacing of rocks along the plane of the disjunctive. In the ore deposit, the discharge zone is also characterized by the appearance of a weak plastic variety of ore. In the transition zones, there may be increased fracture. In areas of high stress rocks are denser and stronger. In numerical calculations, the rigidity of ore-bearing elements located directly in the vicinity of the type II tectonic fault displacement is given by lower elastic moduli $E_{t.n} = (1/20)\cdot 51500$ MPa = 2575 MPa.

The values of loads on the soil of the stopes (confinement conditions) directly depend on the interaction of the roof and the soil of the ore deposit. To account for the influence of this interaction, a displacement parameter is introduced. The confinement conditions for stresses removed from the working floor in the elements of the goaf outside the zone of complete displacement are taken equal to one.

When $\eta_{sp} \geq 1.0$ instability is observed in the selvage of the ore deposit, which characterizes its rock burst hazardous state. For an early prediction of the transition of potentially dangerous areas (yellow color) to dangerous (red color), the following color gradation is adopted: green for $\eta_{sp} < 0.7$; yellow for $0.7 \leq \eta_{sp} < 1.0$ and red for $\eta_{sp} \geq 1.0$ [8] (Fig.3, 4).

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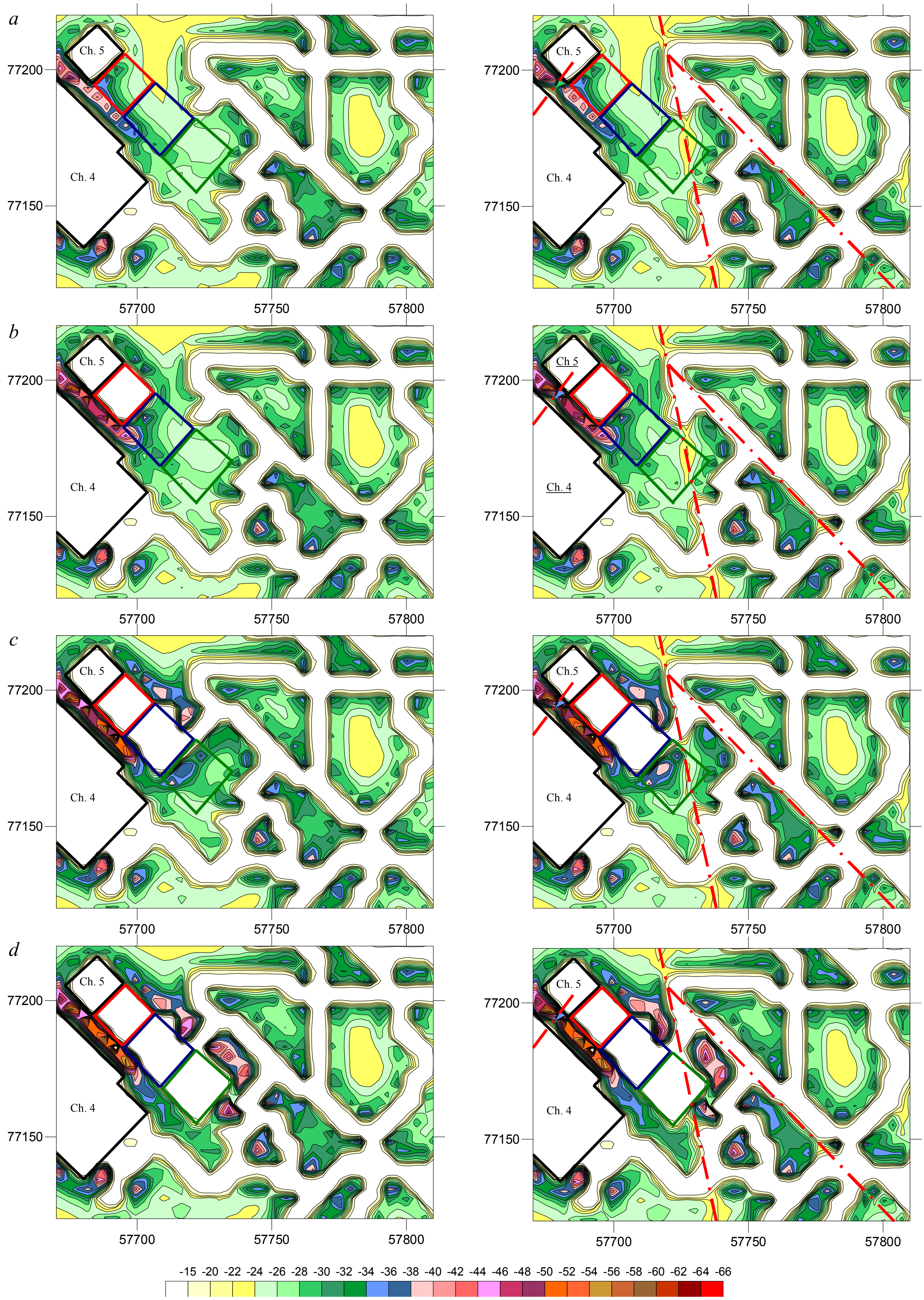

Fig.3. Distribution of normal stresses in ore-rock elements during heading at hor. –323 m, MPa: not considering TS influence (on the left) and with TS impact (on the right): *a-d* – stages I-IV respectively

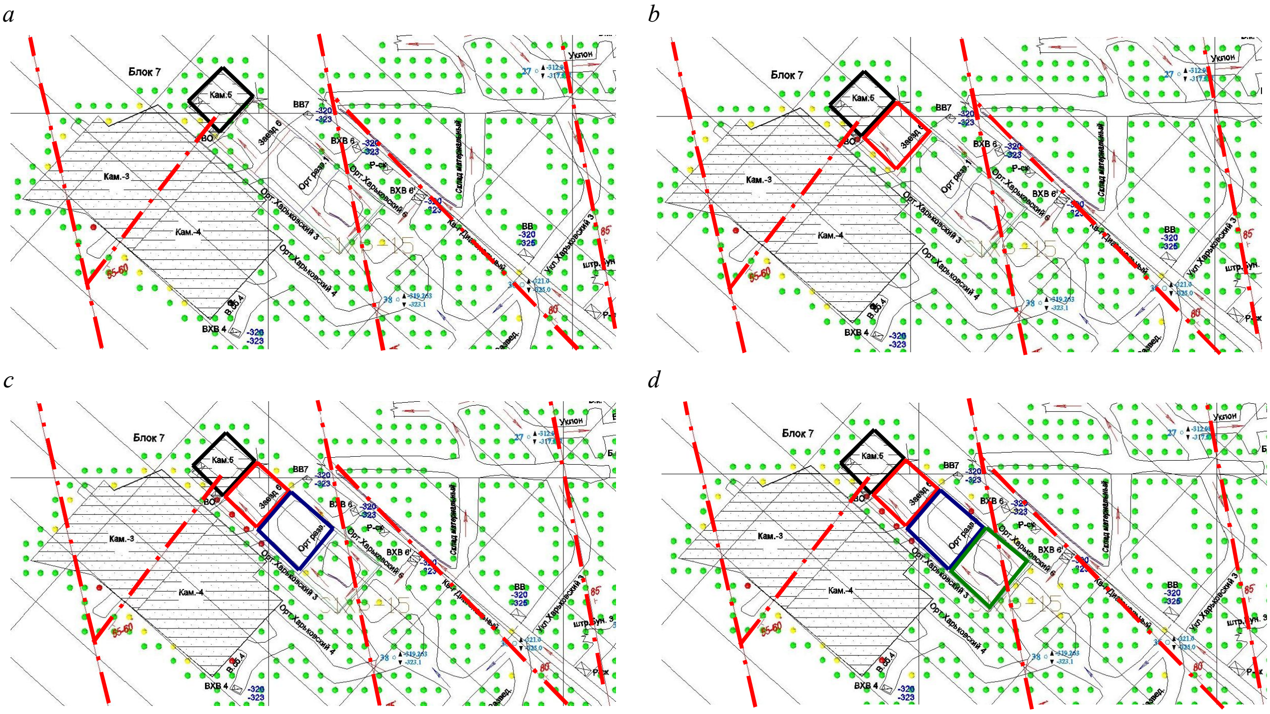

Fig.4. Forecast for distribution of rock burst hazard during mining of chamber N 5 in ore-rock elements on a plane of hor. –323 m (considering TD influence):
a-d – stages I-IV respectively

The results of the study. For the most efficient and safe planning of mining operations during mining of block 7 of the Kharkovskoe ore deposit, volumetric geodynamic modeling was performed on the floor –323 m; also, the potential impact of the structural elements of the applied development system in this area.

Research results. For the most efficient and safe planning of mining of the block 7 of the Kharkovskoe ore deposit, volumetric geodynamic modeling was performed on the floor –323 m; the obtained data were used to assess the effect of the TS the stress level during the sequential mining of chamber 5 of block 7, also the potential rock burst hazard of structural elements of the applied development system on this section.

When constructing a volumetric geodynamic model of the studied area, a base of initial data of mining and TD objects was formed in several stages: linking the mine plan to surveying coordinates; setting the size of the cells of the electronic grid (sizes of the calculated elements); covering the area with a grid of calculated elements; selection of elements belonging to the ore-rock massif (green color – Fig.2). Elements belonging to the mine workings (access crosscuts, drifts, stopes, etc.) are not highlighted (transparent). Then a database of calculated elements is formed in several stages: ore-bearing elements for calculating SSS; elements belonging to workings for various purposes with confinement conditions in the form of stress values taken from floor; tectonic disturbances.

The change in the nature of the distribution and additional normal compressive stresses acting in the calculated elements belonging to the horizon –323 m as the heading works advance, without taking into account the influence of the TD, showed that the presence of TD in the massif leads to a qualitative change in the SSS of the rock mass. Along the TD there is a decrease in stresses by 20 % from the original, and stresses in the nearby pillars, on the contrary, increase by 4-6 MPa (Fig. 3).

Analysis of the results of numerical simulation in the form of the distribution of the rock burst hazard during the sequential development of the chamber 5 of block 7 on the horizon –323 m made it possible to identify the sections of the massif with high stress concentrations. Before the development of chamber 5, an area of high stress concentrations is formed from the southwest side of chamber 3 between the heading space of chamber 3 and tectonic disturbances (Fig. 4, *a*)

Sequential mining of the chamber leads to the formation of the interchamber pillar, the concentration of stresses in which increase proportionally to the increase of mined space and reach critical values at the final stage of development (Fig. 4, *a*). In addition, the developing entry along the developed – cross cut Kharkovsky 3 and Kharkovsky 6 also overlap with the zone of high stress concentrations. After the third stage of development, in the area where the air room 4 and stope 4 intersect, the rock burst hazard indicator is more than one, this signals the potential rock burst hazard in this area (Fig. 4, *c*).

Conclusion. The volumetric geodynamic model based on the developed PRESS 3D URAL software complex allowed to establish the peculiarities of the formation of the technogenic stress field in the ore-bearing massif as the Kharkovskaya ore deposit, it considers the complex configuration of the ore deposits, the developed space and tectonic structure. Sequential mining of the chamber 5 of the stope 7 leads to the formation of potentially rock burst hazardous areas, which include the interchamber pillar between the developed chamber 5 and the mined space of chamber 3 and 4, developing entries along the currently developed chamber – cross-cut Kharkovsky 3 and Kharkovsky 6, the intersection of air room 4 and stope 4.

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