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Forecast for the formation of zones of high rock pressure in the conditions of mining ore deposits in a combined way

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Abstract. The prospect of mining the majority of deposits in the Far Eastern region is associated with the need to switch from the open-pit to the underground method of developing deep-lying ore bodies. Ensuring the safest conditions for the combined development of the field is possible only after comprehensive studies have been carried out that make it possible to establish the peculiarities of the formation of the stress state in the rock mass taking into account the influence of various natural and technogenic factors. An assessment of the stability of structural elements of the proposed development systems at the deposits will allow identifying potentially impact hazardous areas and developing measures to maintain and protect mine workings, which will reduce the risk of dynamic manifestations of rock pressure.

1 Introduction

The prospect of developing most of the ore deposits in the Far Eastern region is associated with the need to switch from the open to the underground mining method. The complexity of this transition is associated with the possible formation of zones of increased rock pressure in individual sections of the rock massif, in the structural elements of the applied development systems, as well as in the pit pillars, which are high stress concentrators [1-3].

One of the deposits where the need arose for conducting comprehensive geomechanical studies, is the Malomyr ore gold deposit (Quartzite site), located in the Selemdzhinsk district of Amur Region. The ore mineralization of the Quartzite site occurs in the form of medium-sized (length from 70-90 m to 200-240 m, thickness from 1-3 to 15-25 m) lenticular and stockwork bodies, quite well sustained in dip and strike. Ore bodies controlled by sub-latitudinal structures fall to the north at an angle of about 70-85º, by submeridional – mainly to the east at angles of 60-80º, in circular faults they have a centroclinal abrupt bedding.

Based on the geological and geomechanical conditions at the deposit, a chamber development system with borehole breaking of the ore was proposed as the main one for mining

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ore bodies. As an additional option in some areas with low-grade ore bodies, it is possible to use systems with ore shrinkage with shallow blast-hole blasting.

In the territory of Amur Region in Zeya district, there is another Pioneer gold ore deposit, where the prospect of development in the Andreevskaya ore zone is also associated with the deepening of mining and the transition to the underground mining method. The total length of the ore bodies along the strike in this section is up to 150 m. The thickness of the ore bodies is from 0.3 to 1.9 m. The structure falls to the south at angles of about 80º. For mining the Andreevskaya ore zone, sub-floor drifts with a descending order of extraction of reserves and chamber development system with an ascending order of extraction were adopted [4].

For the early identification of potentially impact hazardous areas in the elements of the proposed systems for the development and reduction of the risk of dynamic manifestations of rock pressure, an integrated approach to research and assessment of the geomechanical state of the rock massif in the area of developed deposits is required.

2 Materials and methods

To establish the degree of impact hazard of the proposed technologies, mathematical modeling was carried out using the finite element method, which is widely used to solve various geomechanical problems [5, 6]. The implementation of this method was carried out using the FEM software package, which consists of three modules: FEM1 (for the volumetric problem – FEMV1), FEM2-3 (FEMV2-3), and FEM4 (FEMV4), enabling to solve the problems of the theory of elasticity and plasticity using the finite element method both in flat and in volumetric settings. The software allows specifying homogeneous and non-uniform arrays with any kind of heterogeneity: ore bodies with different angles of inclination, workings of various configurations [7].

To justify the boundary conditions when calculating the stress state of the massif, a set of special studies was preliminarily performed, including detailed laboratory studies of the physicomechanical properties of rocks composing the lithological complex of the area of planned mining (Table 1). The features of the regional stress field, which is formed in the upper part of the section of the Earth’s crust in contemporary times, were also identified. It is here that modern natural geodynamic processes take place, with which the mining engineering system will interact, formed during the mining of quarry reserves in the Quartzite and Andreevskaya areas. To date, numerous materials have been published [8–11], which indicate that the lithosphere of the region of deposits is in a state of stress.

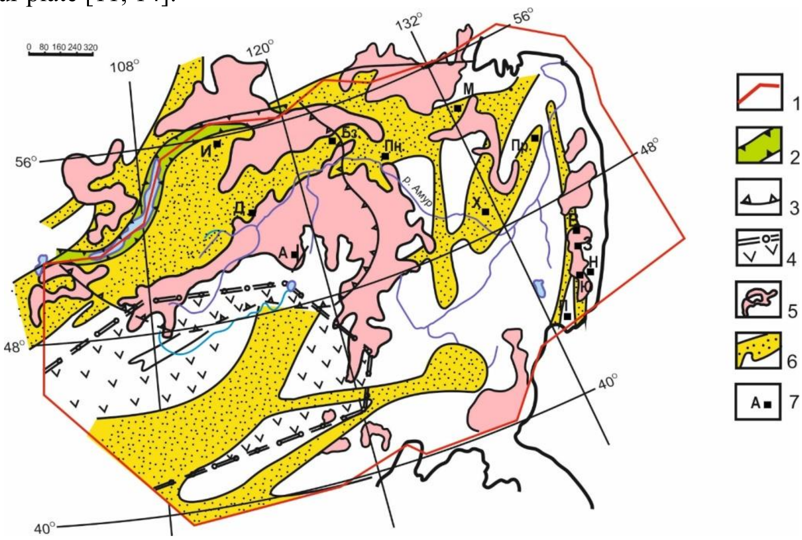
Table 1. Rock properties used in modeling

Rocks	Density, kg/m^3	Deformation modulus	Poisson’s ratio	Tensile strength	Angle of internal friction	Coherence
Malomyr Quartzite deposit						
Quartz-biotite shale with feldspar*	2,677	37,610	0.2	1.9	40	15
Desintegrated rocks	2,677	376	0.45	0	10	0.5
Fine-grained massive and banded berezites**	2,691	49,770	0.18	3.2	41	11.5
Pioneer deposit Andreevakaya ore zone						
Granite-porphyry*	2623	44.31	0.16	5.93	36	9.5
Diorite-porphyrite*	2638	58.38	0.2	5.93	37	10.4
Sandstones with intercalations of siltstones*	2644	21.89	0.21	2.07	40	4.8
Mineralized zones with vein-mesh silicification *	2622	48.26	0.22	5.56	37	9.9
Ore bodies	2700	30	0.2	5	39.8	4.5

Note: * – host rocks, ** – ore bodies

However, to differentiate this territory by the degree of change in the internal state of the upper part of the Earth's crust is possible only by additional specifications, according to the totality of indirect signs, various-scale zones of "extension – compression". An analysis of the geodynamic position of the Malomyr and Pioneer deposits in the modern structure of the Amur Plate showed that they are confined to the shear compression region [4, 11].

According to the results of morphometric analysis of the relief according to satellite geodesy and seismic data [11-13], it has been established that the compression mode is generally characteristic of the field of deposits and the vector of the modern main horizontal compression on the site is directed SWW. The expected value of the main horizontal stress at the deposits was estimated based on the position in the modern structure of the Amur plate [11, 14].



1-5 – main elements that determine the current intraplate geodynamic mode: 1 – modeled seismic-generating faults of the Amur plate framing; 2 – the Baikal rift zone; 3 – external contour of the Baikal tectonic flow; 4 – a relatively stable area of the plate with a weak manifestation of late orogenesis; 5-6 – areas with different values of compression stresses: 5 – areas of intense modern compression with a predicted intensity of more than 50 MPa, manifested by an increased density of minimum lineament of relief of the Earth's surface (strokes), 6 – areas of relative tectonic disturbance of the Earth's surface with a predicted compression rate of 10 up to 50 MPa, manifested by increased density of lineaments; 7 – position of impact hazardous ore deposits (N – Nikolaevsk, Yu – Yuzhnoe, P – Partizansk; Z – Zabytoe, V – Vostok-2, Pr – Perevalnoe, Kh – Khinganskoe, A – Antey, D – Darasun, I – Irokindinsk, Bz – Berezitovoe, Pn – Pioneer, M – Malomyr

Fig. 1. Current stress-strain state of the upper part of the Earth's crust of the Amur Plate according to the interpretation of materials of radar satellite imagery of the Earth's surface

As follows from the figure, the studied deposits are located within the region, which is characterized by increased tectonic disturbance of the upper part of the Earth's crust, where the predicted intensity of maximum horizontal compression (σ_1) varies from 10 to 50 MPa, and $\sigma_2=\sigma_3$. Judging by the geomechanical study materials of the Khinganskoye and Berezitovoye deposits, located in the same zone (Fig. 1), the probable ratio of the main stresses at the Pioneer and Malomyr deposits is expected to be $\sigma_1:\sigma_2:\sigma_3 = 1.2 – 2.0:1:1$.

When setting loads along the boundaries of the finite element model, the authors used the results of an experimental estimation of stress state parameters using the acoustic emission memory effect [15, 16], as well as the fact that the natural stress field of the upper (upland) part of the massif is determined by the influence of the modern relief of the Earth's surface and at a depth below the bottom of the valleys tectonic forces that form the tectonic component of the stress tensor begin to act. Therefore, the deep and upland parts of the massif were differentiated according to the level of initial stresses, assuming that in the upper part of the deposits a gravitational stress field acts, described in accordance with the well-known Dinnik hypothesis. In the rock mass of the studied deposits at a depth of up to 320 m, a gravitational stress field is predicted, the parameters of which are determined by the weight of the overlying rock mass.

3 Results and discussion

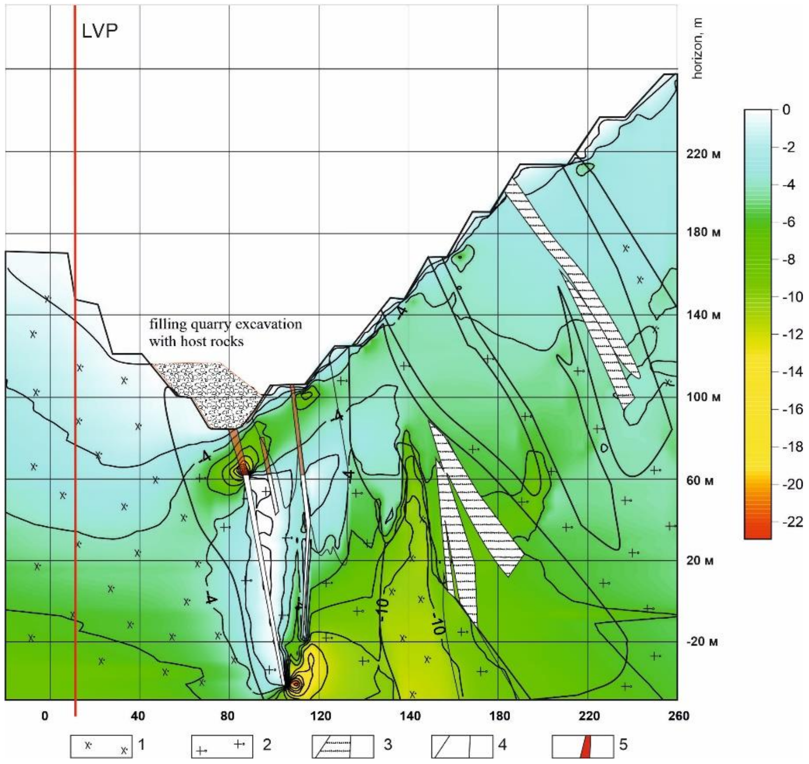
The study of the stress state of the rock massif in the area of deposits consisted of the following: the change in the stress level at individual points of the massif was determined as the power of the quarry pillars decreases in the process of mining ore bodies, and the applied mining system was evaluated from the position of impact hazard.

To justify the optimal parameters of the quarry pillars in the process of mining ore bodies: 55 in the Quartzite area and 3, 3Ap-1, 3-1b in the Andreevskaya ore zone a modeling in a two-dimensional formulation of the problem was carried out and it was found that the extraction of reserves leads to the formation of discharge areas (mainly on the sides of the quarry), and zones of increased stress concentrations in the guard pillars, the marginal parts of the massif, as well as on the rocks contacts. The level of stress increases with increasing volumes of worked out space.

On the plot of *the Andreevskaya ore zone* when reaching a pillar with a capacity of 6 m, the maximum compressive stresses in it reach 25 MPa, the level of intensity of the tangents is 11 MPa. In the area between the treatment chambers of waste ore bodies 3-1 and 3 at -20 m ÷ -40 m at the final stage of mining, stresses reach rather high values (σ_1 and τ_{int} are 33 and 16 Mpa, respectively). But the areas of tensile stresses practically do not change, the value increases slightly. Fig. 2 shows the distribution of the maximum compressive stresses σ_1 in the rock massif at an intermediate stage of ore reserves mining when the pillar reaches a thickness of 20 m. An assessment of the stability of pillars at the Pioneer deposit according to the criteria of brittle and shear failure [17, 18] showed that their stability is ensured at a thickness of at least 20 m.

According to the results of volumetric modeling of the process of sequential mining of treatment blocks at the deep horizons of the Andreevskaya ore zone, it was established that under the application of the chamber system of mining, the main elements of mining structures will remain stable at all stages of mining. The use of the system of sublevel drifts leads to the formation of an interblock pillar in the upper sublevel, where the level of compressive and tangential stresses exceeds the maximum design values, which indicates a possible loss of stability in this section (Fig. 3).

The use of the chamber mining system *at the Quartzite site* results in maximum stress concentrations in the edge part of the ore substage massif after mining 2/3 of the treatment block's reserves with mining of ore bodies at deep horizons (floor 165÷210 m). The values of the maximum compressive σ_{max} and the intensity of the tangents τ_{int}, reaching 50 and 23 MPa, respectively, approach the ultimate values for compression and shear. After complete mining of the ore block, stress redistribution and concentration in the interblock pillars along the uprising occurs, but the level of maximum compressive stresses σ_{max} in them does not exceed 40 MPa.



1 – diorite porphyrites, 2 – granite porphyries, 3 – mineralized zones with vein-mesh silicification, 4 – sandsones with intercalating siltstones, 5 – ore bodies

Fig. 2. Distribution of maximum compressive stresses σ_1 in a rock mass at an intermediate stage of mining ore reserves along the profile line 205A+5 (pillar thickness 20 m)

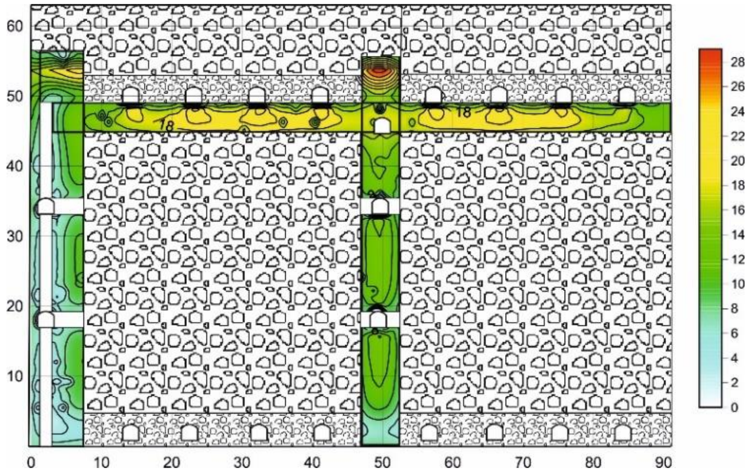


Fig. 3. Distribution of the intensity of the tangential stresses τ_{int} in the rock massif after complete extraction of ore reserves in a projection onto a vertical plane

The use of a mining system with ore shrinkage leads to the formation of a region of increased stresses in the region of the decreasing ore ceiling. Upon reaching the ore ceiling thickness of 15 m, the maximum values of compressive and shear stress intensities are reached, 40 and 27 MPa, respectively. In general, the results of modeling (Table 2) showed that the main elements of the mining structures of the applied mining systems at the Malomyr field (Quartzite site) will remain stable according to the criteria of the operating maximum compressive and tangential stresses at all considered stages of the treatment block's mining.

Table 2. Calculation of the ultimate stress state of structural elements of applied mining systems

Section considered	Ultimate value of compressive stresses / effective maximum compressive stresses, MPa			Coherence in massif, MPa	Angle of internal friction, deg.	Ultimate value of ultimate tensile strength / effective tangential stress, MPa		
	1 stage	2 stage	3 stage			1 stage	2 stage	3 stage
Chamber system of mining								
Sublevel's rock ore	56.5/28	56.5/50	56.5/40	6.9	27.5	21.5/10.2	30.8/22	31.8/23
Selvage of sublevel's rock ore	56.5/30	56.5/55	56.5/50	6.9	27.5	22.5/18	32.9/20	27.7/19
Ore shrinkage system of mining								
Ore pillar of a neighboring waste block	56.5/35	56.5/37	56.5/42	6.9	27.5	25.1/15	26.2/19	28.8/26
Edge of the decreasing ore ceiling	56.5/39.5	56.5/40	56.5/46	6.9	27.5	27.4/18	27.7/**27**	30.8/28
Rock ore of a neighboring unmined block	56.5/39.5	56.5/40	56.5/43	6.9	27.5	27.4/14	27.7/18	29.3/24

Note: 1 stage – initial mining stage, 2 stage – intermediary mining stage, 3 stage – final mining stage

But in case of complication of geological and geomechanical conditions, it is possible that the ore massif of the upper sublevel is unstable at the final stage of mining using the chamber mining system and an ore ceiling with a thickness of 10-15 m in the case of the ore shrinkage mining system (Table 2).

4 Conclusion

1. The performed geomechanical calculations and modeling results made it possible to substantiate the safe parameters of the security guard pillars formed during the mining of the Pioneer deposit (the Andreevskaya ore zone) as being 20 m. The use of the chamber mining system will allow for the most safe mining of underground ore reserves and maintaining the stability of the main elements of mining structures. The extraction of reserves by the system of sublevel drifts will lead to the formation of an interblock pillar in the upper sublevel, where the level of compressive and shear stresses will exceed the maximum design values and there is a high probability of the destruction of this section in a dynamic form.

2. The main elements of the mining structures of development systems with the use of which it is proposed to develop the Quartzite section of the Malomyr deposit will remain stable according to the criteria of the current maximum compressive and tangential stresses at all stages considered. The ore reserve of the upper sublevel at the final stage of mining using the chamber system and the ore ceiling when the thickness reaches less than 15 m in the case of the mining system with ore shrinkage will have a minimum margin of stability.

3. The results of the comprehensive geomechanical studies made it possible to substantiate the parameters of quarry pillars and other structural elements of the mining

systems and to work out some recommendations on the rational procedure for mining ore bodies and effective methods of protecting and maintaining mine workings at the deposits.

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