
GEOMECHANICS

Maly Tulukui Deposit in Southeastern Transbaikalia: Geomechanics and Geodynamics

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Received August 8, 2021

Revised September 9, 2021

Accepted September 10, 2021

Abstract—The article presents the integrated research into geomechanics and geodynamics of the Maly Tulukui uranium ore deposit in southeastern Transbaikalia. The studies into tectonic structure and the terrain morphometry in the area of the Steltsovka ore field reveals the modern geodynamics features and their correlation with the stress–strain behavior of rock mass. The stress field parameters and the physical/mechanical properties of rocks point at potential of dynamic fracture in the edge area of the deposit. The numerical stress–strain modeling and in-situ observation data prove the tendency of rock mass to rockbursting, and the bottom levels of the deposit (at the depth of 500 m and downward) are assessed as rockburst-hazardous. A package of measures aimed to prevent rock bursts and to reduce geodynamic risk is developed for the mining safety.

Keywords: Geodynamic zoning, stress–strain behavior, physical and mechanical properties, geomechanical control, rockburst hazard.

DOI: 10.1134/S106273912105001X

INTRODUCTION

Mineral mining is carried out under worsening geomechanical and geological conditions at the moment. Essential nonuniformity of natural stress fields, governed by the complex geology and tectonics of mineral deposits, grows under the manmade impact of mineral mining on rock mass. The natural stress redistribution in time and space, as well as concentration of stresses in certain areas is one of the main causes of hazardous dynamic fracture of rocks [1–9]. The key influences in geomechanics of rock masses are the growing sizes of mined-out voids and increasing depth of mining.

The manmade risks in underground mining is the critical problem worldwide, including the Far East of Russia. The geomechanical research implemented in rockburst-hazardous mines, such as Antey in Transbaikalia, or Nikolaevsky and Yuzhny Mines in Primorye, etc., shows that rockburst hazard is in many ways governed by the high level of the effective tectonic stresses. The horizontal compressive stresses exceed the vertical stresses, due to their geodynamic positioning within the limits of the tectonically active Amur Plate characterized with the high structural nonuniformity, tectonic subdivision and the availability of higher stress areas [4, 10–16].

The earlier rockburst hazard analysis in the mines in the East Primorye and Transbaikalia revealed geotechnical complication and increased geodynamic risk of mineral mining due to enlargement of mined-out voids and greater depth of mining. Geodynamic processes get activated and represent restructuring and self-organization of block rock mass in the natural-and-induced stress field. These processes are accompanied with displacements and slippage along various scale faults, with essential elastic energy release and induced seismicity events [13, 17].

In this respect, the most effective approach to studying natural and induced processes in rock masses is the integrated multi-level monitoring investigations in the upper crust using some complementary methods. Understanding the mechanisms of natural and induced stress fields is critical for the safety and efficiency of mineral mining [18].

1. SUBJECT AND METHODS OF RESEARCH

The object of research is the Maly Tulukui uranium ore deposit in the south-eastern Transbaikalian area, within the Streltsovka ore field in the same-named volcano-tectonic depression of the South Argun bending fold [19]. The bottom and walls of the depression are composed of the Archaean-Proterozoic gneissic granite, and Early- and Late-Paleozoic metasomatic granite containing inclusions of amphiboles, gneiss, dolomite, shale and other metamorphic rocks. The Mesozoic volcanic sediments, which make the upper structural level, have thickness of 400–700 m, and even 1400 m in the most dropped places of the depression. They gently dip at 5–15° and are complicated by tectonic discontinuities.

In plan view, the deposit is stretched north westward to 3 km, with the width to 600 m in the north and to 100–150 m in the south. The blind mineralization is initially found at the depth of 200 m and spreads to 450 m all in all. The average elevation of ground surface of the mine is 810 m. In the latest 5 years, mining has covered ore levels VII, VIII, IX, X at the depth of 500–700 m below ground surface.

A feature of this deposit is the absence of visible geological contacts between the ore bodies. The ore and enclosing rock interfaces are winding, hold many apophyses at intersections of tectonic faults of various direction. The ore bodies, both down dip and along the strike, contain alterations of very thick sites (ore pillars—to 20 m and more, first tens meters long), with twitches 0.2–0.1 m thick. In plan, the subparallel ore bodies are spaced at 3–10 m, intersect and link, are displaced by tectonic fractures, and form bodies of complex internal structure and various shapes.

The geological and geotechnical features of the ore field include three types of ore run (flat, lodes and stockwork) mineable using different technologies.

The rockburst hazard investigation at the Maly Tulukui deposit used a set of techniques, including the geodynamic zoning, the stress–strain analysis, determination of physical and mechanical properties of ore and rocks, the numerical modeling and the field studies.

The geodynamic zoning of the deposit, with identification of active faults and nature of deformations in the block rock mass, with the later integrated analysis of the data and their comparison with the seismicity and neotectonics studies used the methods of morphometry and Earth remote sensing [1, 10]. The digital terrain models SRTM30 and GTOPO90 were visualized in OGIS and represented the images with hill shading in WGS84 [20, 21].

The stress–strain behavior of rock mass was assessed using the bore slotting technique [22, 23]. The stresses effective in perpendicular to the slot plane:

$$\sigma = \frac{U_{AB} E}{1.034 \cdot 2L - l(1 - K_{\perp(\perp)} + \mu K_{\parallel(\perp)})},$$

where U_{AB} is the displacement after the distress slot initiation, cm; E is the elasticity modulus of rocks, MPa; μ is Poisson's ratio; L is the slot width, cm; l is the distance between the measurement tools, cm; $K_{\perp(\perp)}$, $K_{\parallel(\perp)}$ are the stress concentration factors at the boundary of the distress slot in parallel and in perpendicular to the slot, respectively.

The induced stress patterns in different phases of mining were studied using the finite element method in FEM and PRESS 3D URAL. The rockburst hazard was assessed using the known criteria of brittle and shear fracture, and the energy-based indicator including the modulus of decay in the post-limiting deformation curve [24–27]. The rock mass quality was monitored in situ, using portable equipment Prognoz L [28, 29].

2. GEODYNAMIC ZONING

The geological, tectonic and geodynamic studies of the Maly Tulukui deposit shows that it occurs in the mobile and geodynamically hazardous knot of the north–southward and north–westward zones of faulting. The morphometry results were used to plot the map of stiff tectonic blocks of the Russian Far East region using the digital terrain models GTOPO30 [10, 20]. The analysis of the obtained charts allows assuming that the horizontal displacement of the tectonic flow south to east shapes a representative wave pattern. It is generated by alternation of torsional–separation waves of the ensembles of tectonic flakes. Hypsographically, it represents alteration of crests and intermountain troughs which are extended south eastward. The velocity vectors of the modern horizontal movements of blocks in the lithosphere orient in the same direction as per the GPS data in the modern geodynamic map of Asia [11].

Figure 1 shows a ground surface subimage after decoding of Earth remote sensing data. We clearly see stiff blocks and a rather sparse and, probably, older network of regional tectonic faults. Three different-scale blocks surround the Streltsovka ore field and create conditions for movements of the ore field blocks along these faults. The general tectonic drift is overlapped with its local abnormalities. In the east, the tectonic flow rotates clockwise. This is proved by the change in the stretch of the lineaments which are reflective of the positions of the extended elements of the terrain. The rotation center is situated nearby the Streltsovka ore field. Probably, this is the location of a structure which has a maximal decelerating effect.

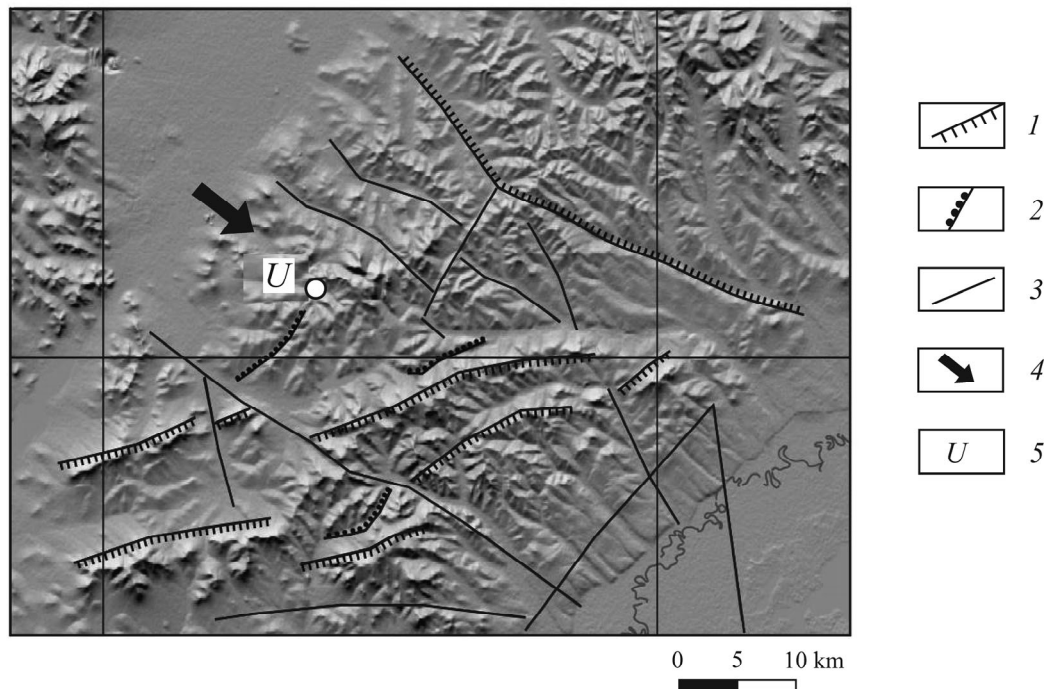


Fig. 1. Morphotectonic chart of Streltsovka ore field: 1—overthrusts (hachures are directed in the line of the upthrown side); 2—downthrusts; 3—disjunctive dislocations of different kinematics; 4—direction of tectonic flow; 5—Maly Tulukui uranium ore deposit. The basis is the anaglyph of terrain in SRTM03 (SRTM30).

Rank II faults represent the zones of northwestward faulting (Tulukui). They activated earlier than the north-southward faults. Rank III faults stretch north-eastward and east-westward. This allows assuming the high horizontal stresses of the tectonic nature. Within the Streltsovka ore field, the main structural inhomogeneity of the crystalline basement is the north-eastward Argun zone of long-term tectonomagnetic activity which is in charge of the physical layout of volcanism centers (Krasnokamensk volcano) [19]. Inside the deposits localized in the basement granite (for example, Antey), this zone represents lodes of high-temperature K-feldspar–albite metasomatic rocks.

The high geodynamic activity in the test regions is proved by the GPS data obtained at the Institute of the Earth's Crust SB RAS [30, 31]. It is found that the point IRKT (Irkutsk), which is a stable part of Eurasia, in absolute coordinates (ITRF 2009), displaces southward at the velocity of 6.8 mm/yr and eastward at the velocity of 25.0 mm/yr, and undergoes slight subsidence at the velocity of 0.2 mm/yr. at the same time, the continuous measurements at the point ULAZ (Ulan-Ude) in 1999 show its south-eastward displacement at the velocity of 8.3 mm/yr and very slow upheaval. The difference in the displacement velocities of IRKT and ULAZ is reflective of a tensile component located in-between these points, in the Baikal depression. The measurements at the permanent point CHIT (Chita), on the area of the Arakhley lakes, show the horizontal displacements at the velocities of 10.9 mm/yr and 39.9 mm/yr to the south and to the east, respectively. The displacement measurements at the point KRNK (Krasnokamensk) in the territory of the Streltsovka ore field, show the horizontal displacements at the velocities of 5.8 mm/yr and 25.6 mm/yr to the south and to the east, respectively, as well as the upheaval at the velocity of 1.12 mm/yr. The geodesy survey points arranged on the walls of the Urulyungui depression displace horizontally toward the east and east-southeastward in the coordinate system ITRF 2009 at the velocity ranging from 20 to 25 mm/yr.

The earthquake mechanisms in the area of Krasnokamensk are analyzed. On average, this is a shearing mechanism. The axes of compression and tension are close to a horizontal line, are directed from the east to the northeast and from the north to the northwest [32].

3. RESULTS AND DISCUSSION

The laboratory tests of rock samples from the Maly Tulukui deposit have found out that their strength and elasticity vary in wide ranges: the uniaxial compression strength 17.1–116.3 MPa (average 48.1 MPa); uniaxial tension strength 1.2–8.7 MPa (average 3.0 MPa); Young's modulus 7.1–30.2 GPa (average 26.0 GPa). The strongest and most brittle rocks (potentially rockburst-hazardous) are coarse- and fine-grained granite. Light-grey brecciated granite is quasi-brittle. Brittleness factor of 1 (potential rockburst hazard) belong to 25% of native samples and to 11% of water-saturated samples. In some test holes, core dinking is observed, which is a sign of increased stresses and potential rockburst hazard.

The stress measurement in the Maly Tulukui deposit using the method of borehole slotting is performed at 9 stations on levels V, VI, VIId and IX at the depths of 368–616 m¹.

The resultant stress–strain behavior analysis shows that the rock mass experiences the nonuniform gravitational–tectonic stress field, with the maximal compressive stresses oriented along the strike of the ore body, south–southwestward, in the line of the azimuth 155–180° and exceeding the vertical gravitational stress 1.7–2.1 times (Table 1). The maximal stresses increase with growing depth from 33.3 MPa on Level V (depth of 370 m) to 49.9 MPa on Level IX (depth of 620 m).

¹The stress–strain analysis of the Maly Tulukui deposit was performed with the participation of R. V. Krinitsyn and S. V. Sentyabov from the Institute of Mining, Ural Branch, Russian Academy of Sciences.

Table 1. In-situ stress measurements in rock mass of the Maly Tulukui deposit

Stress	Stress by Dinnik, MPa	Average stress, MPa	Stress ratio	
			Strike-line stress to vertical stress	Dip-line stress to vertical stress
Level V, depth of 368 m				
Vertical	-9.5	-20.2	—	—
Strike-line	-3.7	-33.3	2.10	—
Dip-line	-3.7	-26.2	—	1.30
Level VI, depth of 428 m				
Vertical	-11.1	-20.3	—	—
Strike-line	-4.3	-33.8	1.67	—
Dip-line	-4.3	-27.1	—	1.33
Level VIId, depth of 512 m				
Vertical	-13.4	-24.0	—	—
Strike-line	-5.2	-43.4	1.80	—
Dip-line	-5.2	-34.8	—	1.45
Level IX, depth of 616 m				
Vertical	-16.0	-26.0	—	—
Strike-line	-6.2	-49.9	1.90	—
Dip-line	-6.2	-41.6	—	1.60

The influence of the stress state on the rock mass is studied using the FEM-base mathematical modeling of section 93 as the best reflective of the structural geology of the deposit (Table 2, Fig. 2a). The modeling results are depicted in Fig. 2b.

Extraction of ore reserves from the complex-morphology bodies under conditions of the gravitational–tectonic stresses promotes an increase in the natural stresses 1.8–2.2 times in some areas (Fig. 2b). In enclosing rock mass and above the cemented-backfilled mined-out void, the higher stress zones are revealed (depth of 600 m, $\sigma_x = -76$ MPa, $\sigma_z = 59$ MPa). Along the granite and trachydacite interface, the stress concentration is observed and keeps for the whole period of mining.

Table 2. Boundary conditions of FEM-based stress–strain modeling for Maly Tulukui deposit

Boundary conditions	Depth from ground surface, m	Stress, MPa	
		Horizontal	Vertical
Intact rock mass in projection to section 93	368 (Level V)	-26.2	-20.2
	616 (Level IX)	-41.6	-26.0
Structural elements of slicing system in stoping panel on Level IX	556	-37.9	-26.0
	616	-41.6	-26.0

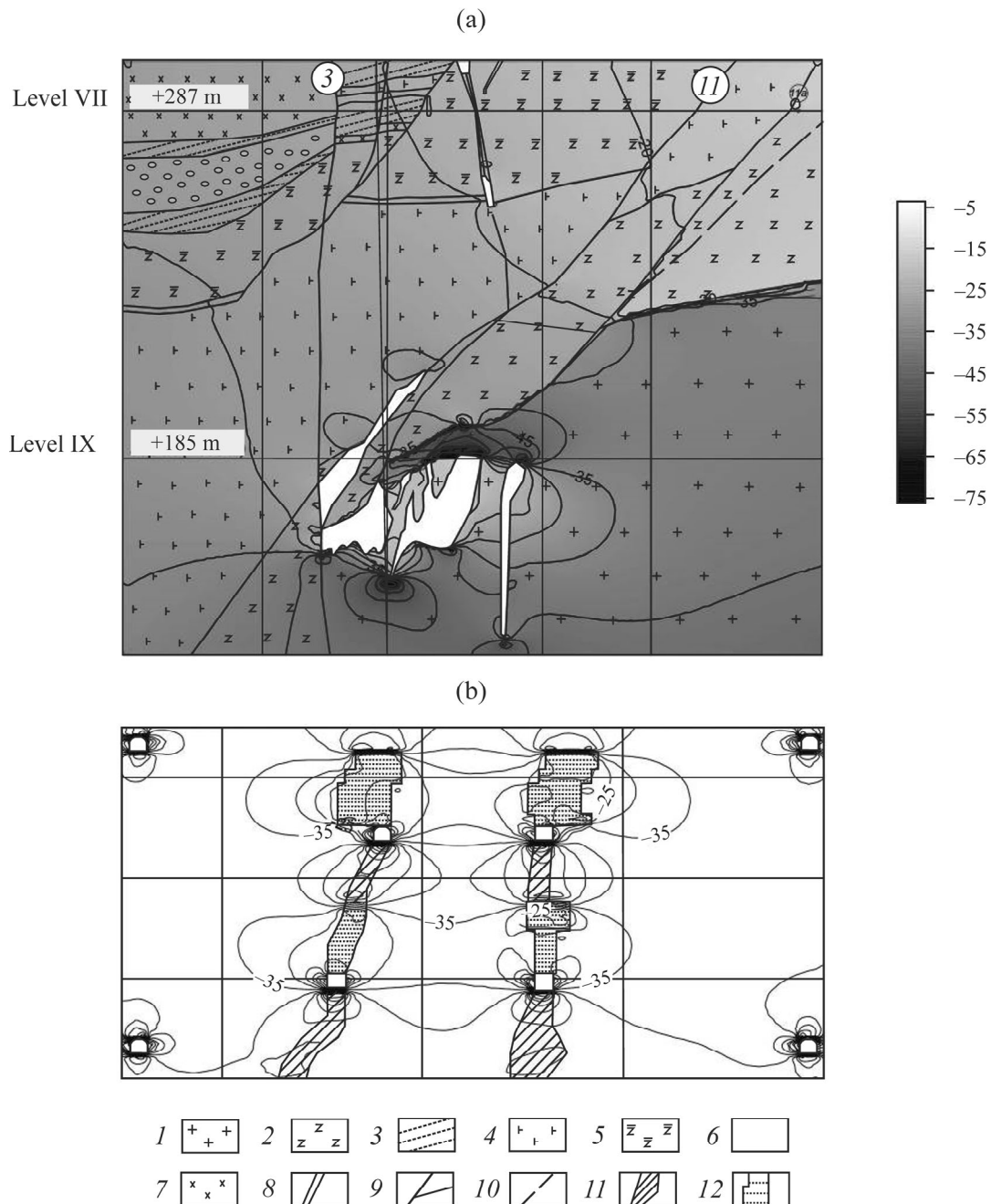


Fig. 2. (a) Geological chart of Maly Tulukui deposit and (b) horizontal stress pattern dip-line of ore bodies after stoving completion: 1—granite; 2—fluidal trachydacite; 3—sandstone; 4—massive basalt; 5—trachydacite; 6—tuff; 7—conglomerates; 8—ore bodies; 9, 10—faults of ranks I and II; 11—mined-out area; 12—cemented backfill.

The modeling with regard to the technology and sequence of mining, with division of the ore body into two subpanels meant for the underhand cut-and-fill with layers 3.0–3.5 m high has determined the highest stressed in the rib pillars which are diminished as stoving proceeds. At the final stage of operations in a stoving pane, the maximal concentration of the horizontal compressive stress σ_x in the decreasing ore pillar 12 m high reaches 93 MPa, which exceeds the compression strength of enclosing rocks by 83%. The stress–strain analysis data on the ore pillars at the final stage of stoving are given in Table 3.

Table 3. Stress–strain behavior of rib pillars versus average pressure concentration factors and maximal compressive stresses, MPa

Natural stress field		Maximal stress in ore pillars		Concentration factor	
Average pressure	Maximal compression	Average pressure	Maximal compression	Average pressure	Maximal compression
31.20	37.90	58.00	92.60	1.86	2.44

The maximal concentration factors of average pressure and horizontal compression at the final stage of the pillar formation are 1.86 and 2.44, respectively. In mining at the bottom of the deposit, the stresses in some areas of ore and rock mass (rib ore pillars, high-stress areas composed of granite at the top and bottom of stoping panels) exceed the limiting values, which points at the potential of these structural elements of mining system.

The full-scale monitoring and local geoaoustic control at the boundaries of stopes revealed some rockburst-hazardous events such as spalling and roof fracturing, with separation of flat pieces with torn edges in 8-902 drift drivage on Level IX. Nearby panels 8-903 and 8-703, increased acoustic activity is found. On Level IX, at the juncture of cross-cut 8-905 and drift 8-902, the number of AE pulses was 127 and 126 in channels N_1 and N_2 of instrument Prognoz L. The pulse-height distribution is 0.008, which conforms with the category Hazard [27, 28].

The implemented research determines that the Maly Tulukui deposit is prone to rockbursting while the bottom of the deposit, down from the depth of 500 m (beneath Level VIId) is assessed as rockburst-hazardous. The safety regulations to prevent hazardous events include the validated scope and measures of ground control and dynamic risk reduction. For the efficient assessment and management of rock burst hazard, it is required to implement the integrated geomechanical monitoring using appropriate instrumentation and facilities, including the multi-channel automated ground control equipment, such as Prognoz ADS.

CONCLUSIONS

Sufficiently high geodynamic activity is determined in the Streltsovka ore field and in the Maly Tulukui deposit. The effective horizontal tectonic flow is directed south-eastward, which complies with the orientation of the velocity vectors of the modern horizontal movements in the lithosphere according to GPS data. In the area of the Streltsovka ore field, the tectonic blocks displace horizontally from the east to the southeast at the velocity of 20–25 mm/yr.

It is found that the strength and the elastic characteristics of rock samples from the Maly Tulukui deposit vary in wide ranges: uniaxial compression strength—from 17 to 116 MPa, Young's modulus—from 7.1 to 30.2 GPa). The strongest and most brittle rocks are coarse- and fine-grained granite. Brittleness factors of 1 characterize 25% of native test samples and 11% of water-saturated samples.

The stress measurement using the method of borfehole slotting shows that the deposit is subjected to the nonuniform gravitational–tectonic stress field. The maximal compressive stresses are directed along the strike of the ore bodies, along the azimuth of 155–180°, and exceed the vertical gravitational stress 1.7–2.1 times.

Extraction of ore reserves from the complex-morphology bodies under the action of the gravitational–tectonic stresses induces the natural stress increase by 1.8–2.2 times in some areas. The enclosing rock mass above and under the cemented backfilled mined-out void holds the higher stress zones, particularly in the rib pillars which are reduced as mining operations proceed. At the final stage of stoping, the maximal concentration of the horizontal compressive stresses in the ore pillar 12 m high reaches 93 MPa, which is much higher than the ultimate compression strength of the enclosing rock mass.

The numerical modeling results and preliminary estimates were proved by the full-scale monitoring and local geoaoustic control of adjacent rock mass. The rockburst-hazardous events and increased level of acoustic activity are detected in some areas of enclosing rock mass.

The geomechanical studies prove that the Malu Tulukui deposit is prone to rockbursting while its bottom below the depth of 500 m is assessed as the rockburst-hazardous. With a view to preventing hazardous events, the scope and measures of the ground control and geodynamic risk reduction are substantiated, and the recommendations are given for the integrated geomechanical monitoring arrangement.

FUNDING

The studies used the assets of the Shared-Use Center for Scientific Data Processing and Storage of the Far East Branch of the Russian Academy of Sciences, under financial support of the Ministry of Science and Higher Education of Russia, agreement no. 075-15-2021-663.

ACKNOWLEDGMENTS

The authors highly appreciate participation of V.G. Kryukov, M.I. Rasskazov, A.A. Tereshkin, D.I. Tsoi and M.I. Lomnv from the Institute of Mining, Far East Branch, Russian Academy of Sciences, in these studies.

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