Solid mineral mining in the permafrost regions: Geoeconomy and Geotechnology

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Abstract. The paper presents the review of geoeconomy and geotechnology of efficient solid mineral mining in the north and north-east of Russia. These areas feature harsh climate, predominant permafrost, vast areas of underdeveloped infrastructure and low population density, remoteness from processing and utilization hubs of produced minerals, high cost of goods and services, deficiency of skilled personnel, etc. The adverse and beneficial effects of the interior and exterior environment exert the direct and indirect influence on selection and adaptation of the existing and novel eco-friendly and efficient mining technologies, method and equipment to deposits in the permafrost regions. The authors describe some recent research findings of the Chersky Institute of Mining of the North, namely: integrated subsoil management in the permafrost region; thermophysics and geomechanics of permafrost rocks with regard to anthropogenic factors.

1. Introduction
In the recent decades, owing to obvious depletion of mineral resources and reserves in the central regions of Russia, mining operations permanently advance toward the underdeveloped north-east of the country. Modern Russia and its subjects, including the Republic of Sakha (Yakutia), in the current market environment, is challenged with enlarging and advancing the industries which replenish the state budget, including the mineral sector. In the vast territory of Yakutia (more than 3 Mkm²), given low exploration level, measured and proven mineral reserves unique in size and variety yet wait for being developed. By estimates, this area holds major Russia’s reserves of diamonds and antimony, 40% of tin, 20% of gold, 9% of measured and 15% of proven reserves of tungsten, 10% of commercial reserves of phosphate and iron ore, etc. Proven reserves of diamonds, antimony, tin, niobium, polymetals and silver feature very high and high quality; gold, phosphate, iron, coal and other minerals have comparable quality with the same minerals produced in other countries. Many mineral fields of proven but unmined reserves are the complex, unique and large deposits. However, more than 50% of proven reserves remain uninvolved in mining due to: poor geological study given obsolete economic-geological evaluation; underdeveloped transport and power supply infrastructure; remoteness from mineral processing and utilization hubs, expensiveness of goods and services; deficit of high-skilled personnel, etc. [1].

The natural environment (physicogeographic and geological conditions) in Yakutia exerts adverse effect on performance of the mining industry for many reasons (alongside with the above-specified factors): harsh continental climate (long and very cold winter and short and hot summer); an immense and low-populated territory of permafrost (64% of the territory of Russia); high labor cost at deficient human resources; need of using expensive mining equipment specially manufactured for operation in...
the north; elevated expenses connected with shipment of final products of the mining industry to consumers mostly situated in the central regions of the country; enhanced environmental requirements, etc. Consequently, it is immediately necessary to undertake and accomplish the integrated basic and applied research into geoeconomy and geotechnology of mineral mining in this area, into thermomechanics of permafrost rocks, as well as adaptation of the existing and novel, safe and efficient geotechnologies, methods and equipment to solid mineral mining in the permafrost regions.

At the same time, there are some beneficial effects of the permafrost environment, and these effects are studied by the Chersky Institute of Mining, in particular: availability of huge mineral resources of unique size and value; high fracture properties of frozen rocks and their ready disintegration under cyclic thermal treatment (freezing–thawing); length of the negative-temperature season which allows mining with frozen rock backfill in water rock masses; electrical conductivity of frozen rocks and ice expands the application range of the ground penetrating radar in investigation of rock mass structure and behavior; usability of underground openings as natural refrigerators at minimized consumption of energy sources, for long-term storage of various products and seed grains, including underground disposal of toxic substances, waste, etc. [2].

Within the R&D project supported by the Basic Research program of the Siberian Branch of the Russian Academy of Sciences IX.132.5: Integrated Research into Geomechanics and Thermal Physics of Geomaterials and Rock Masses under Natural Low Temperatures, and Development of Innovative Technologies, Techniques and Equipment for Permafrost Management, in 2017–2018 the scientists of the Chersky Institute of Mining of the North have obtained some basic research findings, which are the framework for the improvement and innovation in the mining science, technology and equipment, as well as for the recommendations on mineral mining and processing in the permafrost regions. Some of these research findings are presented below in this paper.

2. Geoeconomy and geotechnology

The modern concepts of efficient subsoil use and the methods of their adaptation to the varying external and internal conditions are synthesized into keystones of technological control over conversion of complex-structure solid minerals of the permafrost zones into products of the wanted quantity and quality, which assumes obvious monitoring of the variable environment of actual or novel mining systems. For example, coal ash content control in mining coal fields of complex structure and nonuniform quality is possible through monitoring and differentiation of natural and process-induced components of ash content, modeling of fractional variation in profit per a mining site or a coalbed within a single technological space integrating additional operating exploration, mine planning and implementation, and pretreatment. Such approach enables complete extraction and higher efficiency of mineral reserves.

Using an integrated approach to studying the coal supply chains in the polar regions of Yakutia as a single and people-centered system, some basic influences on the solid fuel supply in the region are estimated, and standard mining flow carts are developed for small open pit mines. The analysis of coal volume and equality transformation in production flows should take into account, among other things, segregation, oxidability, adfreezing ability, dilution and various kinds of loss in order to enhance efficiency of product quality management given sustainable utilization of coal by consumers. The developed recommendations on improvement of management and technology within production chains, as well as coal logistics and utilization in adverse terrains of the far north of Russia, with regard to consumers’ interests, enables efficient use of georesource potential of mineral deposit at reduced qualitative and quantitative loss of produced fuel.

The developed and tested package of programs and procedures for the radar monitoring of permafrost moisture content includes the dedicated humidity and nonuniformity detection algorithm which takes into account dynamics and kinematics of radar impulses, and allows systematization, storage (data bases ) and displaying of measurement and processing results (GIS), and provides reliable interpretation of the radar monitoring data based on revealed signs of wave fields associated with areas of higher moisture content, swelling and suffusion. The obtained results can be use in
prediction of adverse cryogenic processes in basements of engineering structures (protection dams, roadways, embankments, etc.). Two-dimensional radar monitoring models are developed for some geocryological objects of open pit mining planning and implementation, such as: thickness of seasonally thawed layer, ice pockets in beds and veins, unfrozen pockets and superpermafrost water in active soil, nonuniform distribution of moisture in rocks.

The new dragline productivity procedure takes into account secondary adfreezing of permafrost rocks after blasting in different seasons, geometry of dragline face area, digging sequence and the dragline work-cycle time versus rock temperature. The experimental tests of frozen geomaterial samples of nonuniform structure revealed the dependence of their shear strength, internal friction angle and structural cohesion on the grain size composition, temperature, moisture content and density. The frozen sample strength is mainly influenced by moisture content and grain size composition. In a range of average particle sizes from 10 to 40 mm, the internal friction angle decreases and the structural cohesion increase by 2 times as compared with the uniform structure samples. The obtained relationships assist in the analytical interpretation of the blasted frozen rock excavability in the moisture content range of 10–15% and temperature range of -5 to -15 °C.

The field research of sublevel caving process related the change in ore loss due to adfreezing with the broken layer sizes (width and height), distance between drill-and-haulage drifts, ore drawing rate and moisture content of broken rocks. When moisture content of ore increases from 0 to 1% while the broken layer height is decreased from 20 to 15 m, the ore loss jumps by 21%. When the broken layer thickness is reduced from 3 to 6 m, the ore loss increases by 9%. Within the same range of moisture content of frozen ore (-5 to -7 °C) and at the distance between drill-and-haul drifts, the loss of ore due to adfreezing also grows by 21%. Furthermore, at the same moisture content, the increase in the rate (batch) of ore drawing by 2 times (from 150 to 300 t/cm) leads to the decrease in the ore loss by 14% (from 33 to 19%), which is important for technological recommendations on ore drawing in safe and efficient mineral mining in the permafrost region.

3. Geomechanics and mining thermophysics

We experimentally investigated the elastic properties of enclosing carbonate rock mass of Botuoba diamond pipe in the conditions of low and moderate saturation with water. The new procedure is developed to determine the properties of a sample after the change of its state due to excessive moisture (as compared with air-dried state) and to eliminate errors associated with the scatter of properties of test samples. It is found that elasticity of samples changes essentially nonlinearly depending on water saturation. At the water saturation of limestone samples at the level of 20% of the maximum level, the change of the elasticity modulus and Poisson’s ration makes more than 90% of the maximal change in the water-saturated state against the air-dried state. New data on the static elastic properties of enclosing carbonate rocks of different moisture content are obtained in the tests under varied temperature from +20°C to -40°C. The modulus of elasticity increases in transition of a material from thawing to freeze condition at preserved Poisson’s ratio. With increasing moisture content of samples, the elasticity modulus decreases while Poisson’s ration increases in the whole range of the test temperatures.

The mathematical model and calculation procedure are developed for joint solution of problems on convective heat exchange, mass transfer and stress–strain behavior in rock mass during water–ice phase transformation under the action of alternating temperatures, with regard to surface infiltration of concentrated solutions in rock mass. The calculation programs are developed for concentration fields of solutions, ice content, moisture content, temperature and frost boil forces which affect mine stability in the permafrost rock mass. The new integrated mathematical model of concrete pile–rock interaction in basements in the conditions of freezing and infiltration of concentrated solutions shows that infiltration of mineralized solutions in basements along piles greatly decreases the load-bearing capacity of the piles.

The one- and two-dimensional mathematical models of heat transfer and mass exchange during permeation of liquids and gas in fractured permafrost rocks are developed to integrate thermal
conductivity, heat transfer and phase transformation of water (steam–water–ice). The models estimate the influence of geotechnical and climatic conditions of mineral mining in the permafrost regions on adfreezing capacity and mobility of broken ore, in particular, in safety cushion made under open pit bottoms. The recommendations are developed to ensure yielding of safety cushions in extraction of mineral reserves under bottoms of open pit mines using mining systems with caving in the permafrost regions, including requirements on safe operation of safety cushions at satisfactory seepage of rainfalls and groundwater; prevention of adfreezing in safety cushion with due regard to outdoor temperature during the year, rainfall density, temperature and depression of mine air, as well as salinity of geomaterials in the cushion.

4. Pretreatment, blending and processing

The dry pretreatment flow chart is developed and tested for Gurbey gold ore free gold using equipment designed at the Chersky Institute of Mining of the North, such as: crushers DKD-300, centrifugal grinder TSMVU-800 and pneumatic separator POS-2000, with total dissociation and extraction of gold more than 100 micron in size. Dry tailings containing fine gold smaller than 100 micron are subject to further processing using different methods, including flotation or cyanation. The experimental tests on disintegration of coarse geomaterials of different texture and phase composition based on quartz matrix (lode ore) under multiple impacts in crusher DKD-300 show that crushed products are usually distributed between two size grades. Fine class (-5+2 mm) is formed by the weakest textural components accumulated during crushing, including monomineral phases; large size (-20+10 mm) includes fragments of quartz matrix having more uniform composition. Based on the test results, the procedure is developed to determine efficiency of coarse geomaterial disintegration during impact crushing depending on the texture and phase composition of geomaterials.

The lab-scale tests of lignite conversion to humic substances and sorbents under the action of electromagnetic microwave radiation at a frequency of 2450 MHz have determined the optimized process parameters: moisture content and sizes of feed, weight of feed and treatment temperature. The EM microwave radiation treatment allows reduction in time of preliminary thermal processing of a lignite–alkaline mixture more than by 20 times in production of humic substances and sorbents of the same quality as compared with the materials produced after thermal pre-treatment in electrical drying box with capacity of 2 kW, as well as reduces thermolysis time by 4 times. The experimentally optimized parameters of single-stage steam-and-gas activation of coal eliminate the most energy-taking stage—carbonification (steam-and-gas agent flow rate 250–300 ml/h, temperature 800°C, isothermal curing time from, 60 to 90 min), and ensure production of sorbents of the same quality as commercial active carbon DAK.

5. Conclusions

The basic and applied research findings reported in this paper [3–13] are obtained with regard to both adverse and beneficial factors of solid mineral mining in the permafrost regions. All results are aimed at enhancement of safety and efficiency of the mining industry as the backbone sector of economy, which governs social development and economic advance in the north and north-east of Russia.

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