Geomechanical and geotechnical features of solid mineral deposits in the Russian North

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Abstract. The author analyzes geomechanical and geotechnical features of solid mineral mining in the north of Russia, and their positive, as well as their beneficial effect and adverse impact on safety and performance of mines. The research performed at the Chersky Institute of Mining of the North, SB RAS is aimed at development and improvement of eco-friendly and efficient innovative geotechnologies, methods and equipment for mineral mining and processes with regard to the specificity of the permafrost zone.

1. Introduction
The efforts made recently by the Russian Government toward national economy diversification to evade the resource curse have failed. The weight of non-resources in Russia’s GDP decreases while the weight of resources grows in the industry and in the whole economy alike. Russia’s State Statistics Service informs that percentage of mineral production, including oil, gas, coal, metals and primary mineral in the country’s GDP experienced the record increase up to 13.2% in 2018 [1]. This fact however means no imbalanced development of the resource and non-resource sectors of economy. Progressive advance of the non-resource industries is impossible without sufficient supply of hydrocarbons and other minerals, which lays emphasis on the part of the mining industry in sustainable social and economic development, and in welfare gain in the country.

Due to the steady mineral depletion in the regions possessing well-developed infrastructure, mining operations creep to the east and north-east of Russia, where the territory is vast but underdeveloped, underpopulated and lies far from the sites of mineral mining and processing, which elevates the cost supplies and services, hunger for higher skilled personnel, etc. [2]. Physiographic and geologic conditions naturally affect the mining efficiency in such areas. This is particularly valid for the permafrost zone (which covers 64% of the territory of Russia). A demonstrative example of such regions in Russia is an immensely wide (more than 3 million square kilometers) area of the Republic of Sakha (Yakutia) one third of which lies in the Arctic zone. Local population numbers somewhat 970 000 people as of January 1, 2020.

Geomechanically and geotechnically, mining efficiency in the permafrost zone is governed by: permafrost; high production costs; special standards imposed on reliability of equipment to operate in the harsh climate conditions; exclusive standards of operational safety and vulnerable environment protection; complex and expensive logistics, including delivery of equipment, expendables and finished products. The subsoil singularity defines the challengers to be met by mining sciences and practices to improve geotechnologies and make them adaptable to the mining conditions in the North.

Dynamic mineral production at a commercial scale in the northeast of Russia, including Yakutia,
dictates scientific supervision of mining operations in the extreme climatic conditions. To reach the goal, the Institute of Mining of the North was founded in 1980 in Yakutia (named after its founder N.V. Chersky later on). Since the inception, the Institute addresses the aspects of geomechanics and geotechnology which exert influence on the subsoil management in the North [2–4].

In the framework of the basic and applied research (integrated mineral mining and use in the permafrost zone, thermal physics and geomechanics of permafrost rocks with regard to anthropogenic effects), the Chersky Institute’s scientists have obtained worthwhile results in geomechanics and mining thermophysics, surface and underground mineral mining in the permafrost zone, mineral processing and deep conversion, geophysical explorations of soil add rocks, geoecology of the subsoil management in the North. These results produced novel machine engineering and geotechnologies, concepts and guidelines. Many of them were implemented and successfully applied in difficult conditions of the Northern areas [5].

This paper continues the reporting [2, 6] and announces some new results obtained by the Institute in 2019 under state contracts in three areas of research: efficient structure and technology for underground and surface mining in the permafrost areas, strength and physical and mechanical properties of geomaterials, as well as thermophysics and geomechanics of rock mass under naturally low temperatures; innovative technologies and equipment for efficient processing and deep conversion of minerals in the North [7–14].

2. Geoeconomy and geotechnology

The methodological framework is developed for the integrated quality management in the coking and thermal coal supply chains as a case-study of Yakutia coal deposits described with nonuniform structure and properties. The framework is base on: the systemic approach to general and particular concepts of quality management; competitive marketing requirements; data bases and 3D models of the deposits; analyses of coal properties in seams and in process flows; developed procedure for the assessment of produced coal ash content and its division into natural and induced components; resource-saving technologies and management aimed to ensure the coal quality to conform with the use standards at the reduced coal loss in the supply chains.

The quality control system is justified for deep-buried gold placer at the Bolshoi Kuranakh River, including statistics and patterns of gold inside the producing strata limits, combination of draglines, shovels and bulldozers, mining sequence, grain-size composition and reduction in volume of processable sand at minimized loss of the useful component, which can enable sustainable gold extraction and processing, and selectivity and completeness of resources extraction.

In the course of development of a measurement procedure and the radio detection data processing for the real-time analysis of rock mass structure with detection of zones of watering and icing, the radio detection signs of in-pace ice are found. The difficulty of underground ice detection is conditioned by the ice image similarity in radio wave field with any intact frozen rock strata. These signs are found for the radio detection model represented by frozen sand (relative permittivity \( \varepsilon = 4 \)) with ice pockets (\( \varepsilon = 3.2 \)). For the identification of radiogram sites fitting all signs, the radio detection data algorithm is developed. In this algorithm, the continuous events of radar impulse, located one under the other are identified. For each couple of the events, oppositions are checked, and \( N \) maximums are counted in the Fourier spectra of paths in the radargrams. Then, the ratio of amplitudes \( \gamma \) of the events is calculated (for ice, \( \gamma < 1 \)). The algorithm result is location of in-place ice, calculated using the events which satisfy all signs.

The experimental research determines the influence of pore water mineralization on loss of broken ore in sublevel stoping under negative temperatures. In particular, after ore treatment by 10% \( \text{CaCl}_2 \) solution in quantity of 2.5 l per 1 t of broken ore having wetness of 1.0% at the temperature minus 5 deg C, the ore loss grows considerably because of adfreezing (by 20.7%). The use of 15% \( \text{NaCl} \) solution under the same conditions enables the adfreezing-caused loss decrease by 16.5% at the solution consumption of 5 l/t. The increased consumption of the solution results in degradation of flowability of ore and in increase loss in ore drawing in both cases (up to 48%).
The mathematical model and calculation program are developed for the technology of mining with direct internal dumping of regulating overburden with regard to temperature behavior of permafrost rocks in rock mass and in muck, mining sequence in excavation block and blasting performance. This program enables prediction of dragline capacity at all operating stages in excavation block under varied temperature conditions along its depth.

3. Geomechanics and mining thermophysics
The mathematical modeling based on linear elasticity is implemented for deformation of surrounding permafrost rock mass around long singular underground openings with circular and square cross-sections, and the critical sizes of thawing envelopes are determined. The thawed zone is found to contribute to the reduction in the stresses at the boundary of the openings first, and later on the stresses increase with expansion of the thawing envelope. When the thawed / frozen zone strength limit ratio is lower than the ratio of the adequate elastic moduli, there exists a critical size of the thawing envelope, such that the opening becomes unstable as per the Mohr–Coulomb failure criterion.

Some new fracture criteria are developed, physically justified and experimentally proved. The application domain of these criteria extends to quasi-brittle materials containing a large pre-fracture zone. The criteria contain minimum number of additional constants and are convenient for the engineering analysis. The use of the criteria allows strength assessment in materials and structures containing stress raisers and predicting catastrophic failures connected with the viscosity to brittleness transition in geomaterials and rocks.

The experimental research of the alternating temperature effects (+20 to -20 °C) on energy content of fracture in carbonate rocks of different salinization (NaCl) in nival conditions finds out that the maximum decrease in the energy content of failure in dolomite samples having porosity of 14% in Internatsionalnaya pipe is 6% after five freezing–thawing cycles at NaCl solution concentration of 0%. The increase in the solution concentration decreases the impact of the freezing–thawing cycles on the fracture energy content, and at the concentration of more than 10%, no effect of 10 freezing–thawing cycles is observed.

The recommendation are developed for the optimized thermal conditions in pit wall rock mass in the permafrost zone (prevention of thawing), including the seasonal temperature changes, thermophysical and permeation properties of rocks, pit wall slope and height, thermophysical properties and geometry of heat insulation, which can essentially improve pit wall slope stability and, consequently, mining safety for the whole period of mining.

In the field of air and gas dynamics in mines, mathematical modeling has determined the influence of the main mine fan reverse duration on the thermal conditions in ventilation shaft, concrete lining and enclosing rock mass as a case-study of diamond mines in Yakutia. At the ambient air temperature of -45 °C and ventilation air flow velocities more than 2 m/s, concrete lining is totally frozen in 24 h of reverse. At the air flow velocities to 10 m/s, the thickness of frozen rocks around the shaft will be less than 7 cm. After reverse for 48 h, the maximum depth of freezing reaches 30 cm. At the shaft mouth, when ventilation flow velocity in the shaft is 5 m/s and ambient air temperature is -45 °C, freezing of rocks (with swelling and deformation of lining) takes place 48 and 96 h after reverse beginning in the damping layer 0.5 and 1 m thick, respectively.

4. Pretreatment, blending and processing of minerals and hydrocarbons
The lab-scale tests of vertical centrifugal disintegrator VTSI-12 designed at the Chersky Institute determined effective parameters of a vertical mill (clearance between discs—3 mm, dumping angle—150 deg). The optimization improved control over milling in the mode of multiple impacts and abrading effects (with elimination of blowout of under-ground particles from the grinding zone) and enabled setting of check size for disintegration products. The engineering documentation is worked out for the vertical centrifugal disintegrator model VTSI-1 having capacity to 12 t/h.

The design and mode procedure is developed for an air separator with external and internal diameters of 500 and 60 mm, respectively, for a screw chamber with two different purpose screws.
The procedure takes into account fractional makeup, density of minerals and gangue, air flow velocity for mineral separation by their migration capacity. The procedure enables determining rational design and mode for a screw work chamber (pitch, tilt angles of the internal and external walls, shape and parameters of cross-section) toward efficient separation of different size grades of high- and medium-density minerals (above 3.2 g/cm³) from barren rocks with density to 2.7 g/cm³.

The method is proposed for the production of high-quality carbonic sorbent using the combination of chemical and steam gas activation, and the optimized parameters of production of sorbents having iodine adsorbability more than 1000 mg/are experimentally determined. In particular, carbon raw material should be treated with potassium hydroxide at a ratio of 1:1 before thermal shock at 800 °C and subsequent isothermal curing for 60 min with steam-gas reagent feed (250–300 ml/h).

5. Conclusions

Rapid development of solid mineral fields in Russian East and North East, in the zones of permafrost and far distant from processing factories and consumers needs that the mining sciences and practices apply maximum efforts to meet relevant objectives with regard to geomechanical and geotechnical features of the geographic area. The research findings of the Institute of Mining of the North presented in this paper are aimed at development and modernization of eco-friendly and efficient geotechnologies, methods and means for mining, processing and deep conversion of minerals.

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