ABSTRACT

Dissertation for the Degree of Doctor of Philosophy (PhD) in the Educational Program 8D07202 – "Mining Engineering"

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RESEARCH AND DEVELOPMENT OF A SYSTEM FOR MANAGING TECHNOLOGICAL RISKS IN THE PERFORMANCE OF MINING OPERATIONS IN MINES

Relevance of the Study – The management of any process within an enterprise is inherently linked to a variety of risks, which stem from a range of factors. It is crucial to highlight that the mining industry is particularly exposed to such risks due to its complex and high-risk nature.

The support of underground workings is one of the key processes involved in the development and maintenance of mining excavations and other underground structures. The current state of underground support during excavation at mining enterprises can be described as a step-by-step process, which involves a series of operations for the construction of rock support (and, if necessary, their maintenance, repair, restoration, etc.) during underground mining operations. Determining the most rational type of support, developing measures to prevent rock bursts, collapses, falls, and detachment of rocks are among the main strategies for establishing a system of management of natural and technological risks at underground mines during the performance of mining operations, including the development, maintenance, and support of preparatory and main workings.

To ensure the safety of mining operations and the efficient development of ore deposits, it is essential to take into account the physico-mechanical and strength properties, fracturing, and the natural stress field of the rock mass. This will enable the determination of stress distribution and the identification of zones with elevated stress levels that may pose a threat to the stability of the workings and the safety of workers. An analysis of the current state of excavation operation and mining activities at underground mines reveals deficiencies in the existing types of support and their insufficient reliability.

Technological risks are the hazards of industrial accidents, fires, explosions, etc., that threaten not only the lives and health of people but also cause damage to the environment. This paper considers the sources of technological risks associated with geomechanical processes, such as violations of the stability of the side rocks of excavations, including falls, collapses, and delamination's of roof and side rocks, the formation of rock mass collapses and consoles due to poor execution of blasting works, and others.

The objective of this study is to identify the patterns of stress variation around underground excavations with the aim of minimizing the likelihood of technological risks associated with the disruption of the structural and strength properties of the rock mass, as well as the deterioration of the stability of mining

excavations. This will be accomplished through the application of methods that integrate combined steel-polymer anchoring systems and shotcrete reinforced with high-performance chemical additives.

The primary aim of this dissertation is to improve the efficiency and safety of operations involved in the excavation and maintenance of mining workings by reducing technological risks. This is accomplished through the implementation of combined support systems (steel-polymer anchoring and shotcrete) with chemical additives applied via the wet method, utilizing highly effective setting accelerators and superplasticizers to enhance performance and stability.

The primary objectives of the research undertaken to achieve the stated goal are as follows:

- Identification and analysis of the key factors influencing the selection of support parameters and the safeguarding of mining excavations, as well as a comprehensive evaluation of the feasibility and effectiveness of incorporating chemical additives in wet-shotcreting techniques under underground mining conditions;
- Numerical analysis of the stress state of the rock mass using the finite element method in the RS2 software (Rocscience) to determine zones of stress relief and concentration, areas of rock mass disintegration, and the safety factor of the rock. The analysis also includes determining the magnitude of the principal stresses, zones of elastic and inelastic deformations, and the optimal support parameters based on excavation depth and the stability rating of the rock mass.
- Performing a comparative analysis of the finite element modeling results, applying the Hoek-Brown failure criterion, and constructing the dynamic evolution of failure zones as a function of the Geomechanical Strength Index (GSI) and excavation depth, with a focus on the correlation between rock quality rating and stability;
- Establishing scientifically substantiated optimal support parameters for mining excavations, tailored to the specific stability ratings of the rock mass;
- Carrying out experimental and pilot-scale industrial testing of the proposed scientific and applied technological solutions, to validate their effectiveness and practical applicability.

The subject of the research is the rock mass surrounding underground excavations during the exploitation of ore deposits.

Research Methodology: Assessment of the scientific and practical expertise in the field of research and development of technological risk management systems for mining operations at underground mines, with an emphasis on the identification and mitigation of key risk factors. Execution of pilot-scale industrial trials in real-world mining conditions to evaluate the effectiveness of the proposed technological interventions for the reinforcement and stabilization of mining excavations.

Scientific Novelty of the Dissertation:

- Empirical relationships for the stress threshold at which rock mass failure initiates, expressed through a relatively convex logarithmic function, providing a novel approach to predicting failure in the rock mass under varying conditions.
- Identification of the governing patterns in the variation of the rock mass

safety factor in relation to the Geomechanical Strength Index (GSI) when utilizing a combined support system (anchor + mesh + shotcrete), offering a deeper understanding of the interaction between rock mass properties and support systems.

- For combined support systems involving anchors and shotcrete with a minimum thickness of 0.05 m, the stability of the surrounding rock mass is achieved with a safety factor of no less than 1.2. This represents a significant improvement over the use of steel-polymer anchors alone, which results in a lower strength reserve of the rock mass.

- A probabilistic analysis of rock mass failure at the intersection of multiple fractures, conducted using UnWedge software, with a focus on determining the optimal support parameters for combined anchoring and shotcrete, while factoring in the rock mass's safety reserve. This provides a novel and comprehensive methodology for enhancing the stability of mining excavations under complex geological conditions.

Key Scientific Propositions to be defended:

The dynamics of the collapse zone evolution around mining excavations, as a function of the GSI rating and excavation depth, is characterized by an increase in maximum stresses with increasing depth, showing a growth of 35-40% for every 100 meters of excavation depth, while maintaining the stability of the excavation boundaries. The minimization of rock mass failure risks is directly related to the stresses acting within the rock mass surrounding mining excavations.

These stresses follow a gently increasing logarithmic functional dependence and lead to the failure of the excavation contour as the depth of mining operations increases, with a quantitative increase in failure risk by 12-14% in the 300-500 meter depth range. The pattern of variation in the safety factor of rock mass stability with respect to the GSI rating indicates that the zone of destructive (inelastic) deformations in the host rock above the excavation extends up to 1.0 meter. When applying combined support (anchor + mesh + shotcrete) with the installation of metal reinforcing rods of 2.4 meters in length, the stability of the rock mass in this zone can be ensured.

The practical significance of the work lies in the development of:

- A wet shotcreting technology utilizing a non-alkaline setting accelerator, MasterRoc SA 167, and a superplasticizer, MasterGlenium UG 3553.
- A shotcrete mixture incorporating chemical additives produced by Normet.
- A rock mass thermal map for managing technological risk levels.

The results of this research can be applied in underground mines in Kazakhstan, as well as in mining enterprises across Central Asia and Russia, particularly those involved in the extraction of gently dipping ore deposits. The findings provide a basis for the selection and justification of steel-polymer anchoring and shotcrete support systems aimed at reducing technological risks associated with rock falls and collapses during installation.

The final outcomes of the scientific and experimental research, numerical modeling, and testing of the developed technological solutions presented in this dissertation are as follows: the formulation of progressive technological concepts, reinforcement schemes, and material solutions designed to enhance the strength of the rock mass, with a focus on ensuring its stability and safety in proximity to excavation boundaries. Furthermore, the implementation of these innovations at underground mining enterprises for the optimization of operational safety and efficiency.

Personal Contribution of the Author. The author has independently formulated the research objectives, upon which the scientific and experimental work was based, including the execution of pilot-scale industrial trials and testing in accordance with the results of analytical studies. The principal scientific propositions and recommendations have been developed. The author conducted a comprehensive analysis of rock mass stability using advanced numerical modeling techniques, aimed at the prognostic evaluation of stress distribution and the identification of fundamental physical relationships influenced by external factors. Additionally, a comprehensive mining risk management map was developed and implemented to effectively monitor and mitigate technological risks associated with mining operations.

Publications and Dissertation Validation. The results of the scientific research are presented in six scientific publications, including one article published in peer-reviewed journals indexed in the international Scopus database, and five articles in journals included in the list of recommended publications by the KOKSONVO. Additionally, four abstracts were presented at scientific conferences, and the findings were incorporated into implementation reports for educational and industrial processes. The author completed a scientific internship focused on the study of mining pressure phenomena, utilizing equipment and research facilities at the Tashkent State Technical University named after I. Karimov (Tashkent, Uzbekistan). Furthermore, the technological developments were validated at the mining enterprises "Zhilyandy" and "Zhomart" for practical application.

Structure of the Dissertation. The dissertation research consists of an introduction, four chapters, 60 illustrative materials, 30 tables, a list of references with 52 entries, and four appendices. The total length of the work is 116 pages.

Acknowledgements. The doctoral candidate expresses sincere gratitude to the scientific advisors for their guidance and recommendations during the research and experimental work, as well as for their assistance in the preparation of dissertation chapters. Special thanks are extended to the faculty members of the Department of "Development of Mineral Deposits" at Karaganda Technical University named after Abylkas Saginov, and to the engineering and technical staff of the mining enterprises "Zhilyandy" and "Zhomart" for their support in conducting experimental work under industrial conditions and facilitating the scientific research.