Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 07, July, 2025

Modeling of Geomechanical Processes from Open Pit to Underground Mining with Complex Morphology

Dossanbay Bekbergenov [1], Gulnar Jangulova [2], Abdikarim Zeinullin [3], Raissa Zhanakova [4*], Karlygash Shagirova [1], Nazym Atalykova [2], Olzhas Kurmanbayev [2]

[1] *Integrated Development of Colliery Resources, Mining Institute after D. Kunaev, Almaty, Kazakhstan.*

[2] *Department of Cartography and Geoinformatics, Al-Farabi Kazakh National University, Almaty, Kazakhstan.*

[3] *Kazakh University of Technology and Business named after K.Kulazhanov, Astana, Kazakhstan.*

[4] *Satbayev University, Almaty, 50013, Kazakhstan.*

Received 30 March 2025; Revised 11 June 2025; Accepted 17 June 2025; Published 01 July 2025

Abstract

The relevance of this study is the need to optimize the transition from open-pit to underground mining in mines with complex deposit morphologies, such as the Akzhal Mine. This is essential to ensure the safety of mining operations and to prevent adverse manifestations of rock pressure and mass cave-ins when changing the type of mining. This study aimed to develop a geomechanical basis for selecting an optimal mining system for the transition from open-pit to underground mining. Particular attention is paid to rock mass stability and its behavior during mining operations, which makes it possible to optimize the parameters of the mining system by considering the characteristics of a mine with a complex deposit morphology. This study used methods to assess the strength of the rock mass, including the concept of the geological structure of the natural environment, the methodology of determining the structural weakening coefficient, and the determination of the rock mass deformation modulus using the fracturing ratio and stability of the rock mass coefficient with an analytical functional relationship of geo-structural factors. The study results made it possible to systematize the rock mass by stability categories and proposed recommendations for the safe operation of deposits during the transition to underground mining, on the choice of mining system, and on the design of its elements. The novelty of this study lies in an integrated approach for predicting the behavior of rock mass and selecting the optimal mining system, which makes it possible to improve the safety and efficiency of production under difficult geological conditions.

Keywords: Modeling of Geomechanical Processes; Open Pit and Underground Mining; Complex Deposit Morphology; Geological Structure.

1. Introduction

The current stage of development in the mining industry of the Republic of Kazakhstan is characterized by a steady transition from open-pit to underground mining. This shift was driven by the depletion of near-surface reserves and the need to exploit deeper horizons while maintaining industrial safety and economic efficiency. In global practice, the depth of underground mining operations reaches 2.5–4.0 km (South Africa, India, Canada, Australia), while in European countries such as Russia, Sweden, and Finland, orebody exploitation typically begins at depths of 1.5–2.0 km [1, 2]. The premise of this study stems from the increasing depth of mine development under conditions of complex orebody morphology, where geomechanical risks significantly increase, the physical and mechanical properties of rocks change, rock pressure intensifies, and the likelihood of dynamic phenomena increases. These challenges necessitate a new

* Corresponding author: raissazhanakova@yandex.ru

http://dx.doi.org/10.28991/CEJ-2025-011-07-013

approach to the selection of mining methods and systems [3]. Recent studies underscore the need for stress–strain modeling of rock masses during the transition from open-pit to underground mining in deposits with complex structural and geological conditions [4].

The relevance of this study lies in the absence of comprehensive approaches for selecting underground mining systems that consider the morphological, structural, and geomechanical parameters of the deposit. Most existing studies treat stability, ore losses, and dilution factors in isolation without integrating these factors into engineering justification methods at the early design stages. Furthermore, there is a need to substantiate the transition to underground mining using quantitative evaluation methods based on actual deposit data. The main research gaps identified in the literature are the lack of a reliable algorithm for quantitative evaluation and the challenge of selecting suitable mining systems when the initial data are limited [5, 6]. Previous studies have insufficiently addressed the selection of mining technologies for orebodies with complex morphologies (stockwork, lens-shaped, and bedded). Additionally, existing stability models often lack applicability under dynamic, tectonic, and anthropogenic conditions, especially at great depths [7].

The aim of this study is to develop and test a combined methodological approach that includes geomechanical modeling (using Examine2D, FLAC3D, MIDAS GTS NX) and a multi-criteria analysis method (MSAHP – Modified Scale Analytic Hierarchy Process) implemented in Microsoft Excel™ to select the most rational underground mining system for deposits with complex morphology, using the Akzhal deposit as a case study [5, 6].

The Akzhal deposit, which has been in operation since 1935 initially via open-pit mining and since 2016 via underground mining, was selected as the object of study. According to the approved development plan until 2036 [8, 9], various classes of mining systems were considered, including caving, backfilling, and systems with permanent pillars. However, because of infrastructure constraints and limited exploitation timeline, systems with backfill and uniform chamber slicing were excluded [10, 11]. Accordingly, the selection of the optimal system is based on the numerical modeling of rock mass stability under various chamber configurations (accounting for fault TN-3, with dips of 57–71°) [7], analysis of ore losses and dilution, stability, rock structure, orebody geometry, and interpretation of the mining system using an AHP matrix based on expert evaluations [5].

The significance of this study is supported by the fact that similar methodologies have been applied to assess rock stability in underground workings in South Africa, China, Vietnam, and Morocco, using numerical modeling tools such as FLAC3D, UDEC, digital scattering techniques, and seismic orientation models [12-14]. For instance, Dintwe et al. [15] modeled the rock mass behavior during the transition from open-pit to underground mining. The developed approach fills a methodological gap in the selection of mining systems under complex morphological conditions, ensuring the stability of underground workings, reducing geomechanical risks, and increasing the efficiency of mineral resource development in Kazakhstan.

2. Literature Review

The modeling of geomechanical processes is crucial in experimental studies because the results significantly influence engineering decisions. In geotechnical engineering, natural materials such as rocks exhibit inherent variability that can lead to significant cave-ins [16, 17]. A study by Protosenya et al. [18] analyzed approaches to modeling the stress-strain state of a rock mass in the vicinity of a single mining excavation and the zone of influence of the rock console during the development of apatite nepheline deposits in Khibiny. The analysis of existing international engineering practice ideas about tectonic disturbances as a geomechanical element and experience in predicting the stress-strain state of a block rock mass shows that the formulation of core modeling problems requires a methodological approach for solving similar problems. Moroccan scientists [19] focused on the case of a rocky slope in the Ouarzazate area to analyze the effect of seismic impact orientation on the stability of mining operations. They determined the ranges of the values of the seismic impact orientations that led to the rock mass failure. This study of rock mass stability made it possible to determine the minimum values of the safety factor depending on seismic impact by studying its morphological features. However, according to the topic of our study, mining and geological and morphological conditions were considered [12].

Vietnamese scientists [20] determined the zones of rock mass shear by numerical modeling for mining a longwall face in a coal strip mine. Based on the UDEC software, the authors developed a simulation model of the mining process of longwall face 31104 of seam 11. Analysis of the simulation results showed the state of the shear zone of the surrounding rock mass. The authors defined the boundary of the shear impact on the topographic surface considering the depth of the shear vector of the rock mass [12-14].

Innovation in the mining sector can address the challenges of reduced access to resources and environmental impact, increased production, and improved mineral recovery. However, there are barriers to organizational innovation in the mining industry. Several studies [21-23] make an essential contribution to formulating and validating a three-stage innovation model adapted to the mining industry in terms of language, practices, and the nature of business and innovation.

Some studies devoted to the stress-strain state analysis of problem areas of the mine shaft include a comparative analysis of the residual bearing capacity of the mine shaft at different support parameters using computer modeling. The results made it possible to determine the bearing capacity of shaft No. 1 of mine No. 3 of JSC "Belaruskali" and offer recommendations for safe operation. These studies will be of interest after the final transition to underground mining [24-26]. The analysis of the global experience in the study of geomechanical processes during the transition from open-pit to underground mining with complex deposit morphology has shown that during the exploitation of ore deposits, there are not only simple but also distinctive characteristic features of ore deposits with complex morphologies with different formations, mining, and geological conditions [27-29].

Kazakhstan also contains ore deposits with complex morphologies and geological features, which require specific development methods. These deposits have variable thicknesses, interrupted mineralization, and varying dip and strike parameters of the ore bodies. The study of such deposits has attracted the attention of many foreign and domestic scientists working in geomechanics and geotechnical engineering [30-32]. Studies devoted to geomechanical modeling of mining processes in deposits with varying geometric parameters of ore bodies have considered numerical modeling methods to assess the stability of rocks under conditions of interrupted mineralization and variable thickness of ore bodies. These methods make it possible to predict the behavior of rock masses and optimize the development processes of deposits with nonstandard geometry [33-35].

Sdvyzhkova et al. (2022) [36] developed a methodology for predicting the geomechanical conditions during ore deposit mining in steeply dipping layers. They considered uncertainty in determining rock properties, which is a consequence of the heterogeneity of the rock mass. For the actual mining and geological conditions of a deep open pit, the dependence of the strength reduction factor on the slope angle of the open-pit side, which changes in the process of mining each steep layer, was determined. For each stage of mining operations based on stochastic modeling, the probability of reducing the stability of the pit side below the normative level was determined for the first time. However, because open-pit mining continues, some modeling aspects can be considered in the conditions of the Akzhal deposit [36-39]. In this context, Imashev et al. (2024) [38] revealed the regularities of stress distribution in layered rock masses depending on their slope angles. The study results provide new data on the mechanisms of rock interaction in complex mining and geologic conditions, and can be used in the design and operation of mine excavations under such conditions. Considering the changes in the stress zones caused by the changing slope angles of rocks, it is possible to increase the safety and efficiency of mining operations.

Many authors have devoted their studies to numerical modeling of the stability of pit sides when optimizing their boundaries to ensure the completeness of ore extraction. The finite element method for modeling enables the determination of the safety factor of the sides at the periphery of the open pit, where the potential sliding surfaces are localized within each of the selected sectors of the open pit based on the shear strength reduction procedure. The influence of the general slope of the pit side and the indicator of ore excavation completeness on the stripping ratio depend on each other during open-pit mining and the transition to underground mining [40-42].

In the development of deposits, the struggle to reduce ore dilution from mining thin ore bodies under various mining systems also requires geomechanical assessment. In this case, a three-dimensional block model was built using rating classifications of rocks based on the study of their strength properties and structural features. The inelastic deformation zones around the second mining were determined by numerical analysis using the finite element method in 2D. The experimental explosions were evaluated by varying the borehole-drilling scheme depending on the stability rating [8, 43, 44]. The determination of the parameters of the overlying bed caving zones during the reworking of intact rocks previously worked out by the open pit makes it possible to determine the parameters of overlying bed caving, such as the height of the cave roof and the condition of complete reworking of the overlying bed on the deposit. Such results can be used in normative document development to calculate the shear of the ground surface during the reworking of intact rocks in deposits with fractured rock masses. The obtained data are also helpful in reworking and predicting the ground surface shear to exclude the adverse effects of mining operations above the mining zone [40, 45, 46].

Some authors have proposed recommendations to reduce the stability coefficient of rock mass by adjusting the parameters of support, geometry of mining excavations, and control of rock deformation rate in studies modeling the displacement of the surrounding rocks of preparatory mining excavations. These studies are relevant to the transition to underground mining [30, 31, 47]. The assessment of the geomechanical condition of the main excavated space during the mining of deposits with complex morphology requires geomechanical substantiation and determination based on the analysis of rock condition parameters for specific geological and mining conditions to justify the safe operating conditions of the undermine network of the main excavations. Other studies have provided new knowledge about the distribution of stress components in a rock mass, characterized by its large thickness (approximately 100 m) but weak strength properties of all morphological features without exception, additionally reduced by the weakening factors of fracturing, layering, and moistening from many coal beds occurring at the height of the interlayer. To study the state of the interlayer, a spatial geomechanical model that considered all elements reflecting the mining situation was justified and constructed for the first time [11, 32, 48].

Tolovkhan et al. (2023) [40] studied rock-mass fracturing to ensure the stability of pit benches during the development of the North Katpar deposit in Kazakhstan. The results of their research can help determine and select parameters and conditions for safe mining under specific mining and geological conditions. They will help reduce the risk of accidents by providing a scientifically based approach to the choice of sequence, methods, and quarrying systems. The presented results of determining the fracturing in the pit boundaries and the stability of the pit sides for each section, considering the possible deformations on the sliding surface, can help the transition from open-pit to underground mining. Given the characteristic features and diversity of mining and geological conditions with complex morphology, representing ore bodies in the form of lenticular, veined, sheet-like, stockwork, nest-shaped, rod-shaped, and other massive configurations concentrated in a single ore field along the strike and dip of ore deposits, it is impossible to use the method of direct selection to choose the mining system when designing their mining. It is necessary to note that today, few authors in their scientific studies [40, 41, 46] have considered the morphological characteristics of ore bodies separately in technological decisions; that is, they have not considered the existing mining and geological complexities and the complex consideration of the morphological type of ore bodies of minerals in the underground mining of similar ore deposits isolated in one ore field.

In this paper, we consider geomechanical processes during the transition from open pit to underground mining with the complex morphology of the Akzhal deposit for the subsequent choice of mining system in the transition to underground mining.

The selection of the most suitable mining system was carried out using an exclusion method, which involved considering all existing systems and systematically eliminating those that did not meet the geological and mining conditions of the deposit [8, 9, 47]. During the initial stage of selection, certain mining system classes were excluded because of their incompatibility with site-specific geological and technical conditions. For example, supported stoping methods were ruled out because they are primarily used for thin ore bodies. Shrinkage stoping was also deemed unsuitable for the Akzhal deposit because it relies on low-capacity portable equipment and leaves interchambers and roof/floor intact rock, which typically cannot be economically recovered in subsequent operations [10, 11].

Consequently, the class of caving systems was adopted as the primary development approach. At Akzhal, ore is currently extracted using sublevel caving with an end-draw system. Sublevel caving with compensation chambers is also feasible under certain conditions. Filling systems were also evaluated, including subclasses with cemented backfill and dry or rockfill. However, cemented backfill systems are currently unfeasible at Akzhal because of the lack of necessary infrastructure and limited projected duration of mine operations based on available reserves and planned production volumes.

This research contributes to advancing applied science and enhancing the scientific-technical capacity in the field of mining engineering, particularly in the implementation of geotechnologies for underground mining of ore bodies with complex morphology. It focuses on developing methodologies and justifications for the technological, geomechanical, and structural parameters of efficient mining systems, with the aim of ensuring the comprehensive utilization of mineral resources. The Akzhal Mine serves as a case study for establishing technical guidelines for design and implementation [48, 49].

Achieving the intended research outcomes hinges on the accurate selection and justification of the geomechanical parameters. This will enable the identification of the most appropriate mining system for underground ore extraction, considering the various complexities of the orebody morphology. This study also aims to formulate design and application guidelines for mining operations under comparable geological and morphological conditions within Kazakhstan. The evaluation of mining systems enabled comparisons not only in terms of geotechnical parameters but also ore loss and dilution. Although block caving may be economically advantageous for large-scale extraction, the risk of uncontrolled subsidence and surface deformation makes it less suitable for conditions at Akzhal.

The results were interpreted in the context of the geodynamic characteristics of the Akzhal ore field. As indicated in the literature [50-52], during the transition from open-pit to underground mining, the rock mass demonstrates nonlinear deformation caused by both stress concentration and residual deformation following overburden removal. Our study provides recommendations on the direction of extraction and chamber orientation relative to regional fault systems based on successful examples such as the Nikolaevskoe deposit. Moreover, the slope deformation data, as presented by Shi et al. (2022) [52], were adapted to the conditions of the fractured rock mass at the Akzhal deposit. The findings suggest that in the absence of engineering control; progressive failure along weak zones may lead to cascading collapse. Our analysis proposes preventive measures, including phased mining and the local reinforcement of excavations. The MSAHP method does not replace engineering calculations but offers a systematic approach to substantiating the choice of mining technology by incorporating both qualitative and quantitative factors.

3. Material and Methods

Figure 1 presents the algorithm of the research method for modeling geomechanical processes with the transition from open-pit to underground mining, based on the analysis of geomechanical processes using the Akzhal mine as an example.

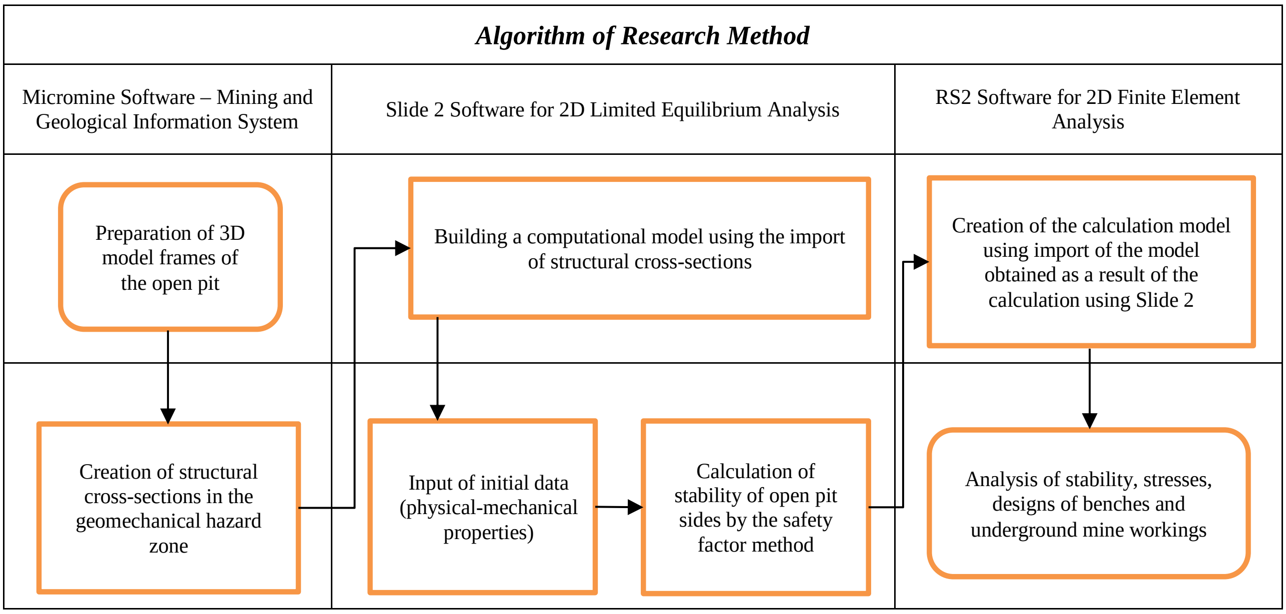


Figure 1. Algorithm of the research method

The methodology includes the following stages:

Stage 1

The micromine Software (Mining and Geological Information System) was designed for data processing, analysis, and modeling in the field of mining. A 3D pit-model frame is the basis for creating a digital representation of an open pit. It includes the geometric structure of the pit based on data such as the location of mineral layers, deposit geology, slope parameters, drilling and exploration data, and open-pit design decisions.

Structural cross sections are created in the geomechanical hazard zone to ensure the safety of mining operations, particularly when designing and operating open pits, mines, or other excavations in difficult geological conditions. Geomechanical hazard zones may include areas with possible cave-ins, shears, rock falls, or other adverse geomechanical processes. Structural cross-sections help assess and model such risks and develop measures to prevent anthropogenic emergencies. Slide2 software was then used to model and design the mining and geological processes.

Stage 2

The Slide2 software for 2D Limited Equilibrium Analysis provides powerful tools for geostatistical analysis, allowing the creation of models of the spatial distribution of minerals and predicting their behavior based on historical data. It helps in accurately estimating reserves and understanding geological structures.

This stage consists of building a computational model using imported structural cross sections, which is a key task in geomechanical and mining modeling that allows the creation of accurate 3D and 2D models of deposits for stability analysis, risk assessment, and mining optimization. The process involves using structural cross-sections as the primary tool to create a model that serves as the basis for numerical calculations and analysis of geomechanical processes. This model considers the physical, mechanical, and strength properties of rocks that determine their behavior under different loading conditions, environmental impacts, and mining processes, which are the basis for geomechanical calculations, mine excavation design, and mining safety. Subsequently, the stability of the open-pit sides and modeling of the geomechanical processes were performed according to the methodology.

Stage 3

RS2 Software for 2D Finite Element Analysis is designed for modeling of geomechanical processes and the stability analysis, including calculation of the stress-strain state of rocks, analysis of the stability of mine excavations, and design of underground and open pit mining operations, which are based on the finite element method; the compiled methodology specifies all processes.

Based on the evaluation of the initial data, the study areas were defined and the slip plane of the open-pit side, which determines the danger zone, was calculated. Further sections of this paper show all of the features separately in detail.

3.1. Study Environment

3.1.1. Representation of the Study Environment

The efficient development of ore deposits is justified by the correct choice of technology, the mining system of ore deposit reserves in the underground mining method, and the results of geomechanical process studies. Therefore, this study analyzes the geomechanical processes for the efficient application of geotechnology in the exploration of the underground reserves of the central area of the Akzhal deposit, which is operated by the Karagandy Region, Akzhal village.

Given the main geological and mining engineering characteristics of the Central area, with the recommendation to apply the system of development of ore reserves of the Eastern area of the Akzhal deposit by underground mining, it is necessary to substantiate the geomechanical processes occurring in the rock mass and representing its stress-strain state during ore mining. Therefore, it is necessary to analyze the existing materials for the study of geomechanical processes, represented by the physical and mechanical properties of the rock mass and ores during the development of the central area of the Akzhal deposit.

3.1.2. Physical and Mechanical Properties of the Surrounding Rocks and Ores of the Akzhal Deposit

According to surveying and geomechanical data of the Akzhal Mine, the developed lead-zinc ore deposits dip slightly ($m < 10$ m), and the average thickness of the ore bodies is 4.0÷5.5 meters. In the Eastern area of the Akzhal deposit, orebody no. 5 is represented by thick and steep deposits. To the north, the ridge gradually passes into the Kosdangol dry valley, which belongs to the watershed of the Zhamshi River. The average absolute surface elevations of the deposit areas are: in the eastern area, 615 m in the central area, and 635 m. Currently, the surface is disturbed as a result of the mining enterprise's economic activities (open pits, rock dumps, roads, industrial sites, and engineering facilities).

Administratively and territorially, the Akzhal polymetallic deposit is in the Shet District of the Karaganda region. At 90 km southwest of the deposit, there is the railway station Mointy, and at 110 km northwest, there is the railway station Agadyr. The Karaganda-Almaty highway runs 12 km northeast of the deposit. The nearest mining center is Balkhash Town, located 130 km southeast. Geographically, the region is a low ridge sharply expressed in relief, dissected into small hills with complex outlines and steep (30-40°) slopes. Hills are separated from each other by shallow trough-shaped ravines and gorges are less common. The relative elevations varied from 30 to 60 m. Figure 2 shows the location coordinates of the Akzhal deposit.

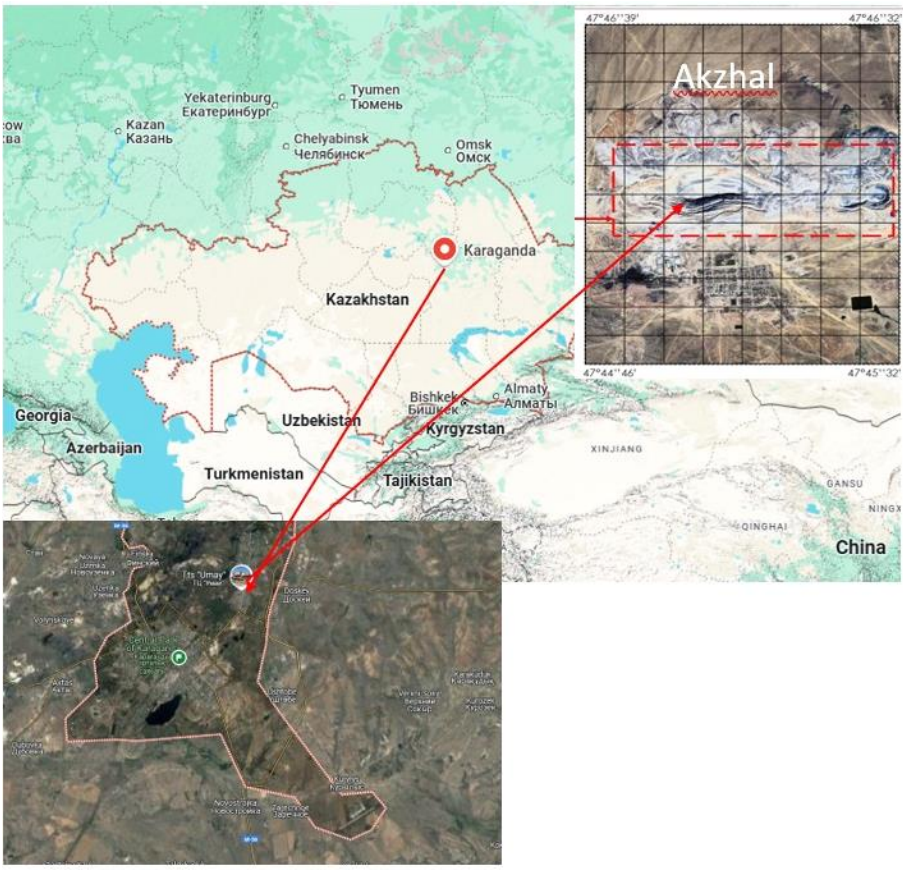


Figure 2. Location of the Akzhal deposit with coordinates 47°46'29''N, 73°59'22"E

According to geomechanical studies, clays have the following properties: average density is 1.9 t/m³, natural humidity is 20.4%, specific cohesion is 0.043 MPa, internal friction angle is 23°, the fragmentation index is 1.3, hardness coefficient, according to Protodyakonov, ranges from 1.5 to 2.0. Clays mainly have hard and semi-hard consistencies. Generally, the rock hardness coefficients on the scale of Protodyakonov vary from 6.0 to 15. The average density (bulk density) is: 2.7 t/m³ for ore-bearing rocks, 2.86 t/m³ for ores of the Central area, and 2.92 t/m³ for ores of the Eastern area. The natural humidity of the ores in the rock mass varied from 0.1% to 1.14%, with an average of 0.87%. These ores are not prone to compaction [9].

Industrial mineralization is localized in a pack of massive limestones, extending in a narrow ribbon in a sublatitudinal direction for 5-5.5 km. The width of the ore-bearing “ribbon” (strip) varies from 50-100 m to 300-350 m. Ore bodies and deposits do not have clear geological boundaries and are identified according to sampling data, depending on the accepted grade and other indicators of conditions [8, 9].

Table 1 lists the physical and mechanical properties of the rocks in the central part of the deposit.

Table 1. Physical and mechanical properties of surrounding rocks and ores of the Akzhal deposit (Centergeoanalit LLP, 2009)

Indicators	Units	Rocks and ores						
		Massive limestones		Limestones with lead-zinc mineralization	Siliceous-clayey limestones	Intensively scarified limestones and scars	Fine-grained diorites	tuff sandstones
		ore-free	Ore-bearing					
Number of samples	pcs.	2	2	3	3	2	1	1
Average Values								
Hardness coefficient according to Protodyakonov		6.5	9.0	7.6	10.0	10.1	12.9	8.6
Strength								
Compressive	MPa	60.53	89.8	76.1	98.43	107.65	129.0	85.5
Tensile	MPa	5.63	6.7	7.5	6.96	9.4	16.5	7.3
Normal compressive stress, σ								
σ at 30°	MPa	4.6	4.2	4.3	6.13	-	-	3.7
σ at 35°	MPa	17.7	20.0	19.15	30.6	-	-	21.0
σ at 45°	MPa	41.27	38.7	39.35	59.4	-	-	37.4
Shear strength, τ_{share}								
τ_{share} at 30°	MPa	7.93	7.3	7.45	10.6	-	-	6.4
τ_{share} at 35°	MPa	25.27	28.5	27.4	43.73	-	-	30.0
τ_{share} at 45°	MPa	41.27	38.7	39.35	59.4	-	-	37.4
Abrasion index	mg	22.93	38.5	34.27	39.3	37.55	39.1	40.3
Longitudinal wave velocity (P)								
Parallel to the axis	m/s	6225	6403	6043	6082	6650	6186	5405
Perpendicular to the axis	m/s	5837	6181	5884	5775	6159	5767	5362
Transverse velocity	m/s	3787	3944	3700	3716	3920	3778	3192
Acoustic stiffness of rock	A×10^{-6} MPa	1.71	1.77	1.79	1.65	2.05	1.73	1.50
Poisson's ratio	-	0.20	0.19	0.21	0.20	0.24	0.20	0.23
Young's modulus	E×10^{-4} MPa	9.48	1.03	9.52	9.01	11.17	9.60	6.91
Shear modulus	G×10^{-4} MPa	3.94	4.30	3.94	3.76	4.76	3.99	2.82
Bulk compression modulus	K×10^{-4} MPa	5.38	5.60	5.54	5.04	7.35	5.37	4.30
Humidity	%	0.06	0.08	0.11	0.14	0.3	0.15	0.35
Porosity	%	1.1	0.7	1.03	0.97	1.9	1.4	1.5
Density (bulk density)	t/m^3	2.69	2.70	2.87	2.66	3.12	2.72	2.70
Particle specific gravity	t/m^3	2.74	2.76	2.98	2.72	3.08	2.79	2.75

The area seismicity is less than six points, which eliminates additional requirements for building structures. The radioactivity of the ores and rocks of the deposit was low and did not exceed the background values of the area. Therefore, no additional radiation requirements are necessary, and no measures to protect against radioactive impacts are required. In 2006, the ores and rocks of the deposit were subjected to radiological tests at the Research Center of

Ecoexpert LLP. According to the conclusion of the Department of Sanitary and Epidemiological Control of Karaganda Region, the safety of overburden rocks and ores of the deposit has radionuclide activity less than 300 Bq/kg, and they are classified as materials that are not dangerous in terms of radiation background.

The ore sulfur content ranged from 0.3% to 13%, and the ores and rocks were not prone to spontaneous combustion. According to the "Methodological guidelines on preventive siltation and extinguishing of underground endogenous fires at copper and cobalt mines of the Republic of Kazakhstan," the deposit is classified as Type 3, non-fire hazardous. This deposit is not dangerous to sulfide dust explosions in underground workings.

According to Isabek et al. [8], the following is established:

- Dynamic manifestations of rock pressure on deposits can arise when conducting mine workings at depths of 400 m and below, predominantly when these processes are subject to massive (ore-free) limestones.
- Areas of the rock mass around mine workings at the level of 250 m and below belong to the category "Dangerous" due to the possibility of accumulation of high-stress concentration;
- The elimination of high stresses in the rock mass and the transfer of some areas from the category 'Dangerous' to the category "Not dangerous" is possible when providing compliance with specific parameters of intact rocks and volumes of overlying formations above the mined-out space.

The average fragmentation index for the ores and rocks of the deposit is 1.5.

The ores of the deposit have an abrasion index of 0.7 mg and are very low abrasive (abrasion class I); surrounding rocks with an abrasion index from 5-10 mg to 30-5 mg belong to abrasion class II (from low abrasion to above average abrasion).

Therefore, the concept of the geological structure of the natural environment, the presence of cracks, their spatial orientation, and morphological features can be selected when assessing the strength of the rock mass. For the conditions under consideration, the most common indicator for evaluating the strength of a rock mass is the structural weakening coefficient k_w, which represents the ratio of the strength of the rock mass to the compressive strength of the rock in the specimen. Some researchers have proposed an assessment of the structural weakening coefficient k_w using the crack angle with respect to the acting load direction and fracturing intensity. Others recommend a calculation method that considers the parameters of the structural blocks, according to which k_w is determined from the ratio [35, 44, 47]:

$$k_w = k_r \cdot k_{\mathrm{rb}} \tag{1}$$

where k_w is structural weakening coefficient of the rock mass; k_r is strength reduction coefficient of rock mass on outcropping of size ℓ and average linear size of structural block d, k_{rb} is strength reduction coefficient of a structural block with average linear size d due to its fracture disruption by cracks into more elementary blocks of size d_o.

$$k_r = 0{,}1 + \frac{0{,}9}{1+0{,}1(\ell/d)^{1{,}5}} \tag{2}$$

$$k_{rb} = 0{,}4 + \frac{0{,}66}{1+0{,}1(d/d_o)^{1{,}5}} \tag{3}$$

According to the geo-structural description of the rock mass in the area under consideration, k_w was calculated, and the compressive strength of the rock mass was calculated as follows:

$$\sigma_c^m = k_w \cdot \sigma_c^s \tag{4}$$

here σ_c^m is compressive strength of the rock mass; and σ_c^s is compressive strength of rock in the specimen.

The analysis of the methodological techniques for determining the strength of the rock mass and the results of testing rock specimens with different degrees of fracturing demonstrated the possibility of practical calculations to assess the state of the rock mass using the structural weakening coefficient. According to laboratory tests, the structural weakening coefficient varies between 0.10 and 0.20 for the conditions of the Akzhal deposit. Considering the sufficiently high variation of indicators when determining them and the impossibility of completely considering all factors weakening the rock mass, the structural weakening coefficient in engineering calculations is assumed to be equal to k_w = 0.1 for rock masses as a whole, which is confirmed by the calculations of the authors considering structurally disturbed rock masses [8-10].

The assessment of the deformation properties of a rock mass is a rather complicated task because its total deformation is composed of the deformations of the primary material and fracture interlayers, predominantly filled with secondary material, considering the spatial orientation of structural damages. The solution to this problem is based on previously conducted experimental and analytical studies under similar conditions, using the methodological approach outlined in this paper. The main objective was to determine the deformation parameters of the base material, fracture interlayers, and total deformation of a structurally heterogeneous rock element. The deformation properties of the primary material were determined by processing tests previously conducted on monolithic specimens of a particular material. The deformation properties of the fracture layer were determined by testing a complex specimen with a sufficiently well-defined fracture layer. The total absolute deformation of such a specimen is the sum of the deformations of the primary material and the crack filler material.

The deformation moduli E_2 of the crack filler and E_0 of the entire rock mass were determined using data from laboratory tests and a structural picture of the rock mass [53, 54].

Thus, we have:

$$\mathrm{E}_0 = \frac{\mathrm{E}_1}{1+2\sum_1^{n}\eta_i \cos^2\theta_i} \tag{5}$$

where E_0 is complex modulus of the deformation of the complex specimen (modulus of deformation of the rock mass); E_1 is modulus of deformation of the primary material, E_1 is modulus of the deformation of the primary material, $\eta_i = \frac{m\cdot E_1}{\square\cdot E_2}$, E_2 is the modulus of the interlayer deformation, h is the specimen height; m is the interlayer thickness; θ_i is the angle formed by the i-th crack system to the dip; n is the number of cracks; i is the index of the fracture system. The modulus of the interlayer deformation is calculated from the expression:

$$\mathrm{E}_2 = \frac{mE_1\cdot E_0}{h(E_1-E_0)}\cdot 2\cos^2\theta \tag{6}$$

subsequently, based on the experimental studies, it was possible to obtain the averaged calculated indices of the rock mass deformability. m–0.7 cm is averaged fracture thickness; φ– 70° is averaged crack slope angle;E_1 – 1.6□⊙10^4 MPa is deformation modulus of the primary material; E_2 – 0.015□10^4 MPa is deformation modulus of the crack filler; E_0 – 0.57□10^4 MPa at φ =70° is deformation modulus of the rock mass; E_0 – 0.11□10^4 MPa at φ =20°.

Calculations were performed to assess the deformability of the rock mass depending on its deformation modulus, that is, on the general parameter characterizing the complete structural picture. Table 2 lists the calculation results.

Table 2. Deformability of the rock mass depending on its deformation modulus

E_0, MPa	$\sigma\gamma H$				
	0.3 γH	0.6 γH	0.8 γH	1.0 γH	2.2 γH
$0.78\cdot10^4$	1.31	0.30	0.40	0.49	1.09
$0.69\cdot10^4$	0.17	0.34	0.45	0.56	1.23
$0.57\cdot10^4$	0.20	0.41	0.54	0.68	1.50
$0.30\cdot10^4$	0.39	0.78	1.04	1.30	2.90
$0.1\cdot10^4$	1.17	2.34	3.10	3.90	8.60

The obtained deformation characteristics make it possible to assess the nature and degree of deformability of structurally heterogeneous rock masses and the individual structural elements of deposits with the complex morphology of the Akzhal Mine deposit.

Table 3 summarizes the results of the study of the physical and mechanical properties of rocks and ores for the additional exploration of deep horizons.

Table 3. Physical and mechanical properties of rocks considering fracturing

No.	Rocks	Compressive strength σ_c, t/m^2	Tensile strength σ_t, t/m^2
1	Reddish-brown sandy clays and clay loams	262.4	16.64
2	Acidic tuffs, brownish-reddish, greenish-reddish, fractured, with calcite veins	272	21.76
3	Siltstones, mudstones, tuff siltstones brown greenish-brown, greenish-reddish, layered, fractured	262.4	16.64
4	Sandstones fine short-grained, brown, greenish-red, layered, slightly fractured	265.6	18.24
5	Upper siliceous-clayey limestones, dark gray, black, nodular-layered, with brachiopod fauna	256	25.6
6	Ore-bearing massive limestones of gray, light gray color, medium-grained, with calcite veins	287.36	21.44
7	Lower siliceous-clayey limestones of gray and dark-gray color, with veins of calcite	256	25.6

It is necessary to introduce appropriate corrections to the values of σ_c and σ_t to determine the strength of the rocks in the rock mass for different fracturing intensities. The calculation was performed using the formulae given above to assess the fracturing effect on rock mass strength under the conditions of the Akzhal deposit.

3.1.3. Geomechanical Evaluation of the Stability Coefficient in the Vicinity of Mine Workings and Working Excavations

The assessment of the mechanical condition of a rock mass containing a mine or underground facility involves determining the probability of rock failure in the vicinity of the mine and quantifying the resulting processes and phenomena. It is necessary to evaluate the sizes of the resulting zones of the limit states, ruin destruction, and displacements of the rock contour.

A methodology was developed to evaluate the stability of fractured rocks by analyzing their susceptibility to rockfalls [35, 37]. These developments provide a scheme for the systematization of rock masses and the evaluation of their engineering conditions (quality). The proposed classification is based on a comprehensive assessment of the influence of numerous factors on rock mass stability. The functional relationship between geo-structural factors and rock mass stability is described by the following analytical dependence.

$$k_s = \sigma_c^s \frac{10 \cdot m_1 \cdot m_3 \cdot m_4}{m_2 \cdot m_5 \cdot m_6 \cdot m_7} \tag{7}$$

where k_s is stability criterion; σ_c^s is compressive strength of the rocks in the specimen; and $m_1 ... m_7$ and coefficients characterizing the geostructural situation of the rock mass. Coefficients $m_1 ... m_7$ depending on the structural picture of the rock mass, take the following values:

m_1 is the coefficient (relative fracturing ratio) characterizing the influence of rock fracturing and depends on the relative fracturing module *n*, where;

$$п = 2a/\ell' \tag{8}$$

where; 2a is excavation span; and $\ell'$is average distance between the cracks.

The value of m_1 is found from the graph $m_1 = f(n)$ (Figure 3, Table 4).

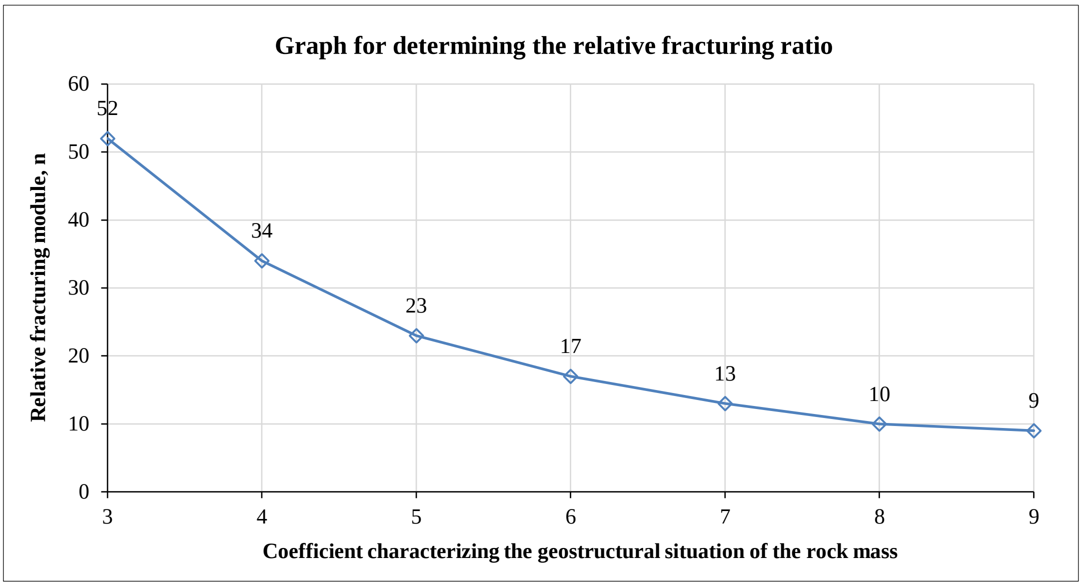


Figure 3. Determining the relative fracturing ratio

These indicators indicate that the rocks of the Akzhal deposit belong to rocks of medium stability. At a specific level of stress acting in the rock mass, as a result of mining excavation, the rocks begin to fracture and lose some or all of their bearing capacity. The analytical calculation method provides a more accurate description of the degree of loading of horizontal mining excavations, considering geomechanical and technological factors.

To enhance the methodological transparency and reproducibility of the results, a detailed explanation of how the structural weakening coefficient of the rock mass (k_s) was calibrated was provided as part of the geomechanical assessment of the Akzhal deposit. The calibration of the $k_s$coefficient was based on a series of laboratory tests conducted on rock samples collected from various sections of the Akzhal deposit, characterized by high fracturing and structural heterogeneity. Sample collection was carried out to ensure representative coverage of geological variability, particularly in terms of natural jointing, block character, and the presence of fault systems. The tests involved determining the uniaxial compressive strength (UCS) of both the relatively intact and highly fractured samples. The $k_s$value was calculated as the ratio of the strength of the fractured mass to that of the intact rock samples [44], which accounted for both the inclination angle of the joints relative to the loading direction (τ) and the size of the structural blocks.

Table 4. Estimation of stability coefficient in the vicinity of mine excavations and working excavation

Coefficient characterizing the geo-structural situation of the rock mass	Coefficient description	Coefficient value
m_2	Coefficient considering the influence of the number of fracture systems	1.0 - practically unfractured rocks 2.0 - one fracture system 5.0 - two fracture systems 10.0 - three fracture systems 15.0 - four fracture systems
m_3	Coefficient considering the fracture face roughness	1.0 - practically unfractured rock mass 0.6 - interrupted cracks 0.4 - uneven undulated cracks 0.2 - undulated cracks with slickensides 0.15 - smooth cracks filled with secondary material 0.1 - flat cracks with slickensides
m_4	Coefficient considering the wetting of rocks	0.1 - dry rocks 0.7 - wet rocks 0.5 - water drip 0.3 - jet water inflow
m_5	Coefficient considering the opening of unfilled cracks	1.0 – closed or filled cracks 2.0 - opening width t = 3-15 mm 4.0 - opening width t > 15 mm
m_6	Coefficient considering the filling of cracks	1.0- absence of filler, crack walls are closed 2.0 - sand and crushed rock filler (without clay) 3.0 - clay filler 4.0 - kaolinite, mica, talc, graphite, graphite filler 5.0 - sandy-clay filler
m_7	Coefficient considering the orientation of the excavation	1.0 - at angle = 70-90° 1.5 - at angle = 20-70° 2.0 - at angle e = 0-20°

During testing, the samples were classified based on the intensity of fracturing, spatial orientation of the joints, and average linear dimensions of the blocks. The experimental data reveal consistent patterns of strength reduction with respect to these parameters. As a result, it was established that the k_s values ranged from 0.10 to 0.20, which aligns with similar findings for structurally disturbed carbonate rocks, and confirms the applicability of this coefficient as an engineering indicator of rock mass weakening.

Given the observed variability in k_s values, a conservative approach was adopted in the engineering calculations. For $k_s = 0.1$ the lower bound of the experimental range was selected, reflecting the worst-case scenario for structural weakening. This is particularly relevant for high-risk zones of rock masses with significant disturbances.

Furthermore, the selected values were verified through a back analysis of the stress–strain behavior of the rock mass. Numerical models incorporating this coefficient produced stress and deformation patterns consistent with field observations, confirming their validity under the geological conditions of the Akzhal deposit.

The k_s value used in this study was not hypothetical or averaged; rather, it was derived through targeted laboratory calibration and confirmed via engineering calculations. Its application ensures a justified, safe, and reliable assessment of the rock mass stability in the context of underground mining at Akzhal. Based on this rationale, specific modifications were made to improve the methodological clarity and interpretability of the applied procedures. We also refined the criteria parameters and weighting principle for ranking alternatives in the application of the MSAHP (Modified Scale Analytic Hierarchy Process) method.

4. Results

4.1. Modeling of Technogenic Risk of Underground Mining Excavation Cave-in Considering Deformation Properties of the Sides of Central Open Pit

Geomechanical modeling revealed the adverse effect of the displacement of structural blocks from the sides of the open pit by the sudden caving of rocks and loss of rock mass stability. Changing the current system for the development of underground deposits is recommended (Figure 4).

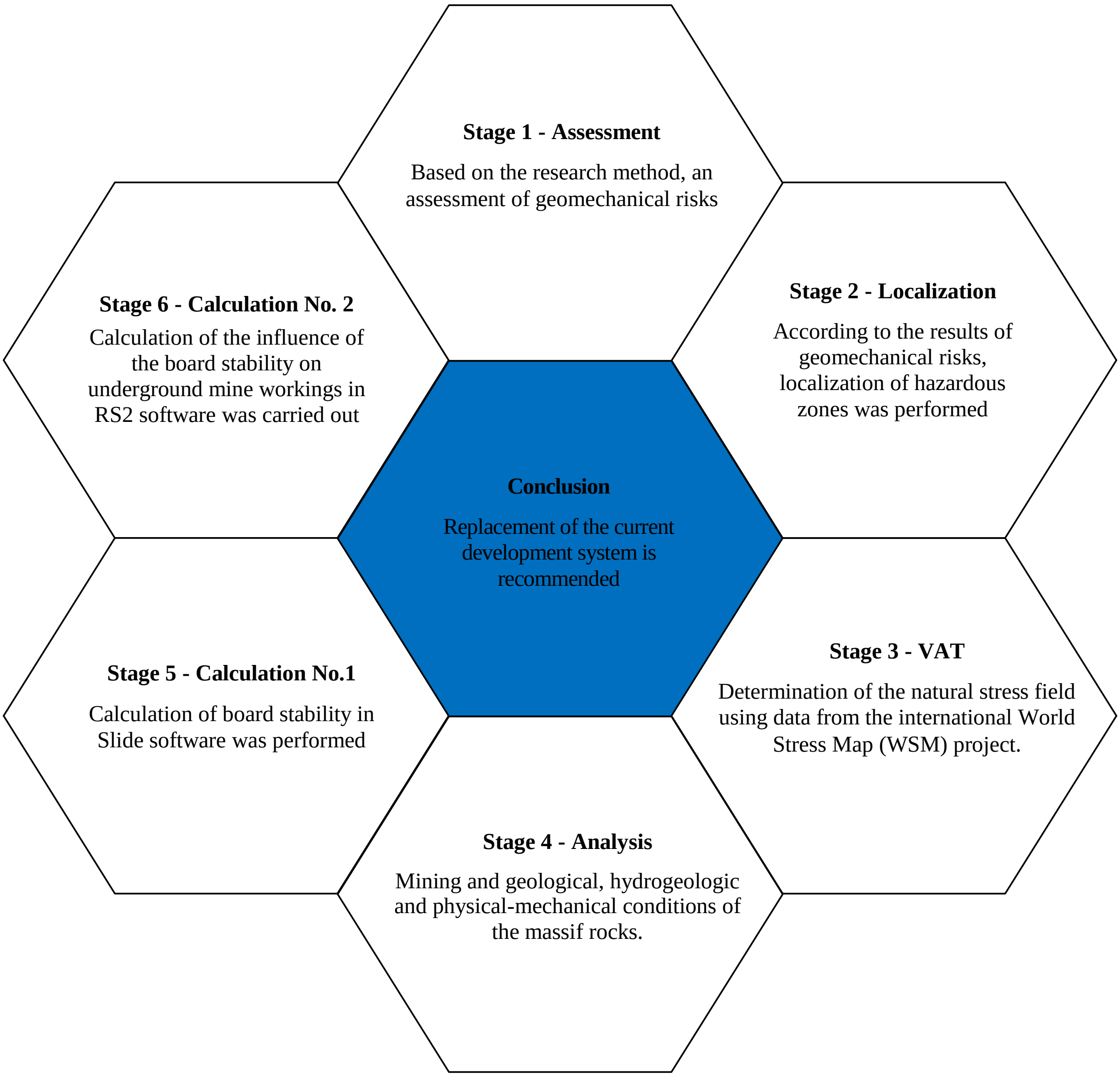


Figure 4. Stages of geomechanical modeling and determining the influence of deformation zones

Currently, the development of pit reserves in the central open pit of the Akzhal deposit reveals the following geomechanical risks:

a) Risk of sudden cave-ins on the southern side of the central open pit.

- The stability assessment in the interval of the geologic profiles of the southern side of the central open pit showed that the side was in a limiting condition. There is a high potential for cave-ins of the side slope; mining operations (mining systems with caving of the overlying strata) have led to a high risk of rock mass shearing.
- Possible consequences of the shearing of the open-pit sides include loss of transportation slope and, consequently, reduced mine productivity, damage to machinery, injury, and death of personnel.

b) Risk of air shock waves in underground excavations; during the survey of previously processed working excavations, a direct aerodynamic connection between the working excavations and the day surface is observed in all existing geological cross-sections (Figure 5).

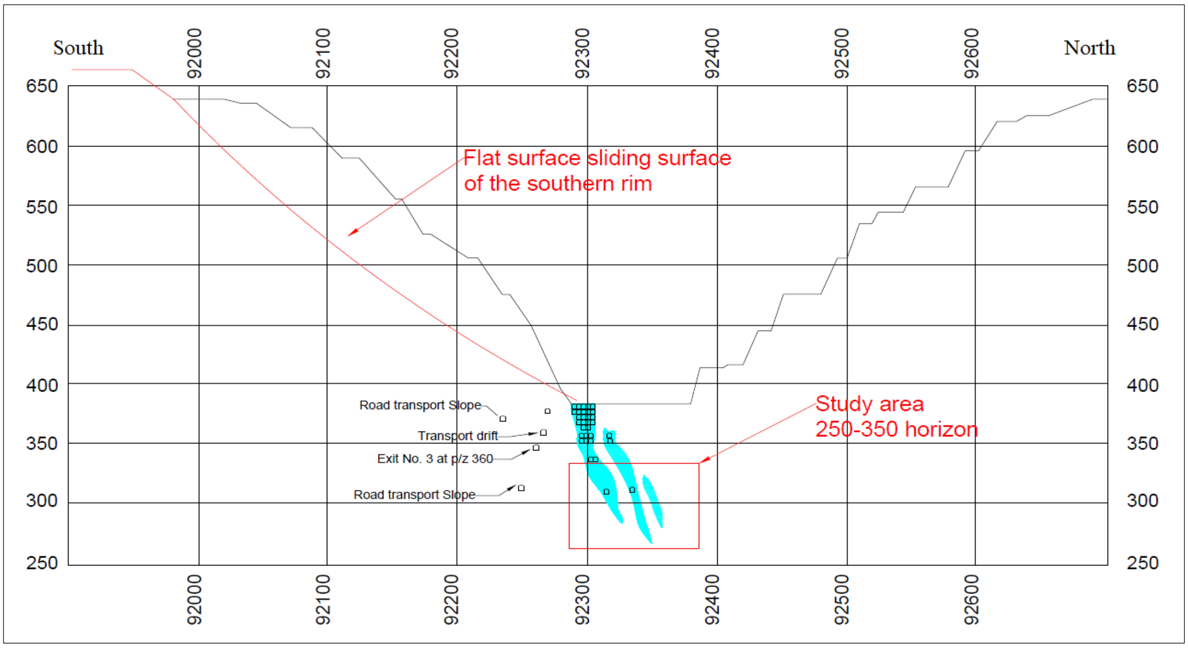


Figure 5. Geological cross-section of the Central area along profile V

There have been no in situ measurements of the natural stresses on the Akzhal deposit. Therefore, their assessment can use data from the World Stress Map (WSM) International Project. According to the WSM database, the natural stress condition of the rock mass in the Akzhal area is characterized mainly by the strike-slip (SS) tectonic mode (shear). Along the strike of the ore body, the value was 1.9 gamma-N, and across the strike of the ore body, the value was 1.4 gamma-N.

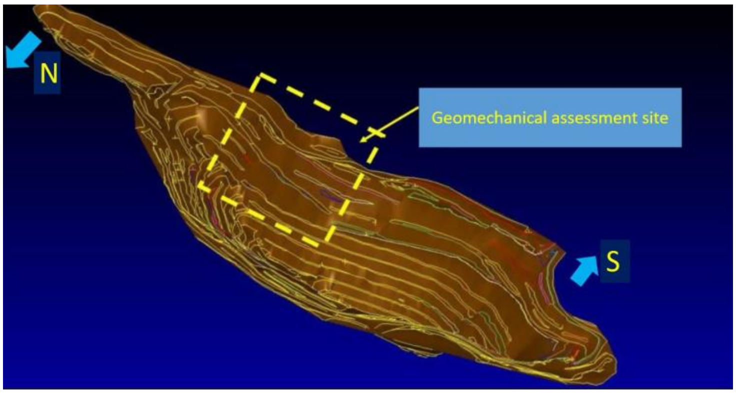


Figure 6. Geomechanical assessment site

The southern section was modeled using three profile lines (A, B, and C) because the available geological profiles have an inclined vector. The Micromine software program constructed profile lines with a straight dip and elevations from +660 m to +400 m (Figures 6 and 7).

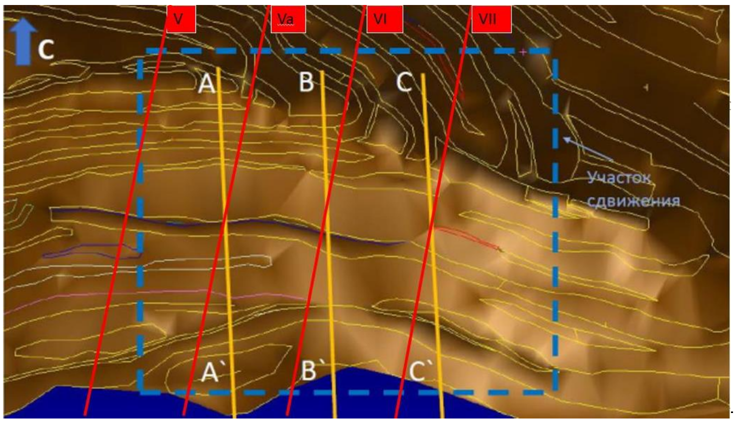


Figure 7. Geomechanical assessment site with cross-sections

As a result of the consideration of the factors influencing the state of the rock mass (mining and geological conditions, hydrological, physical, and mechanical properties of the rock mass, technological factors, and others), the stability of the side local section was analyzed (in Slide2 software). After entering the initial data into the Slide2 software, the stability of the sidewall along profile A-A (cross-section V-Va) was analyzed (Figures 8 to 10).

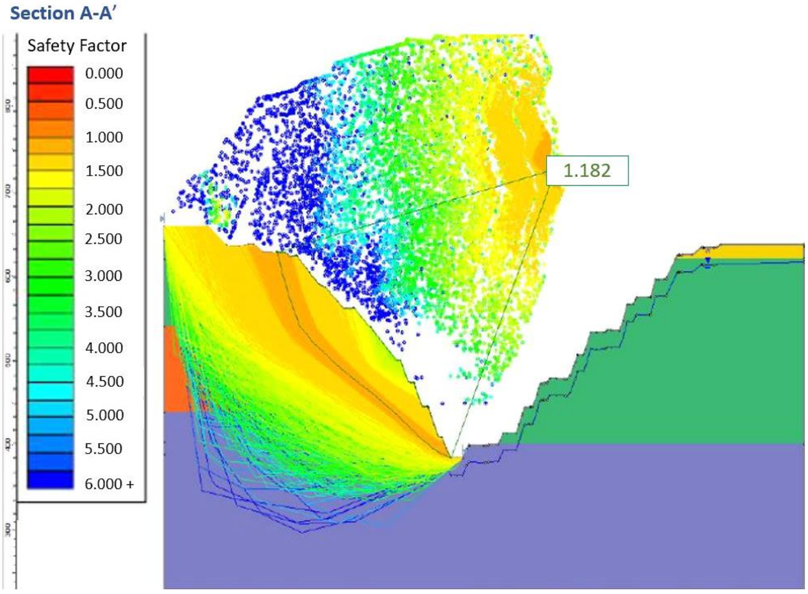


Figure 8. Side stability analysis. Profile A-A

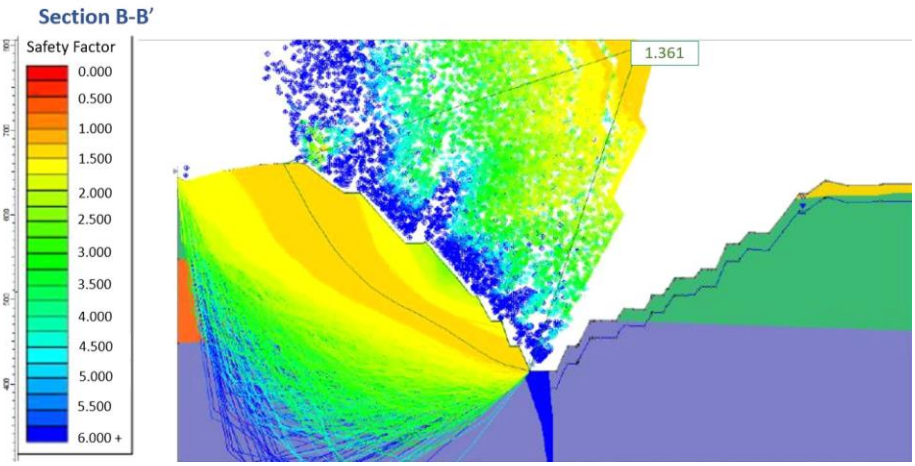


Figure 9. Side stability analysis. Profile B-B

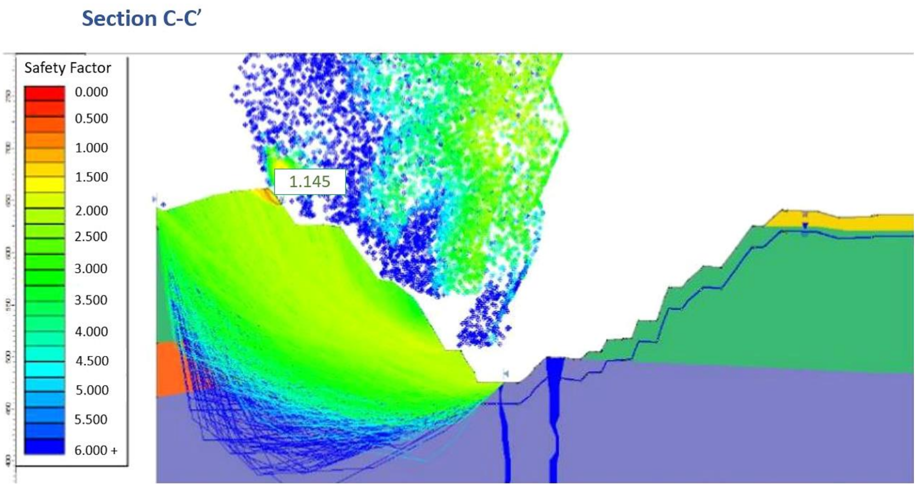


Figure 10. Side stability analysis. Profile C-C

According to the general criteria of acceptability of the factor of safety (FoS) established in the Design Acceptance Criteria (DAC), the minimum value of the FoS for the inter-ramp slopes was 1.20, and for the overall slope angles was 1.30. According to the results of calculations by the methodology, the safety factors for local sections of the southern side of the central open pit are as follows: along profile A-A – 1.18, along profile B-B – 1.36, and along profile C-C – 1.14.

Geomechanical modeling conducted using Slide2 software showed that on the site along profile A-A (V), the FoS was 1.18, indicating instability of the rock mass according to the specified criteria of the DAC. Along the B-B profile, the FoS was 1.36, corresponding to an acceptable level of stability. However, when analyzing the section of the upper benches, starting from an elevation of +620 m, consisting of loams, the FoS was 1.14, which corresponds to the parameter along profile C-C (VII) equal to 1.14, indicating that an unstable state of the rock mass is also observed in this section.

The obtained lines of the plane of failure are projected onto the existing geological profiles V-VII, highlighted by the red dotted line, and are a program of actions to ensure safe operations at the underground mine Akzhal in the presence of a geomechanical hazard risk from the deformation properties of the sides of the central open pit.

The stress-strain state (SSS) assessment of the investigated object was divided into several stages, corresponding to the sequence of rock mass development. This approach provides a more detailed and consistent model of the transition from open-pit to underground mining, which allows a more accurate prediction of changes in the state of the rock mass at each stage. The model considered the specifics of each stage, starting with the analysis of the initial state of the rock mass, then moving to the phased development of its parts and the final transition to underground mining, which makes it possible to consider the impact of changes in the rock mass and mining operations on the SSS at different development stages. Figure 11 shows the gradual transition from open-pit to underground mining.

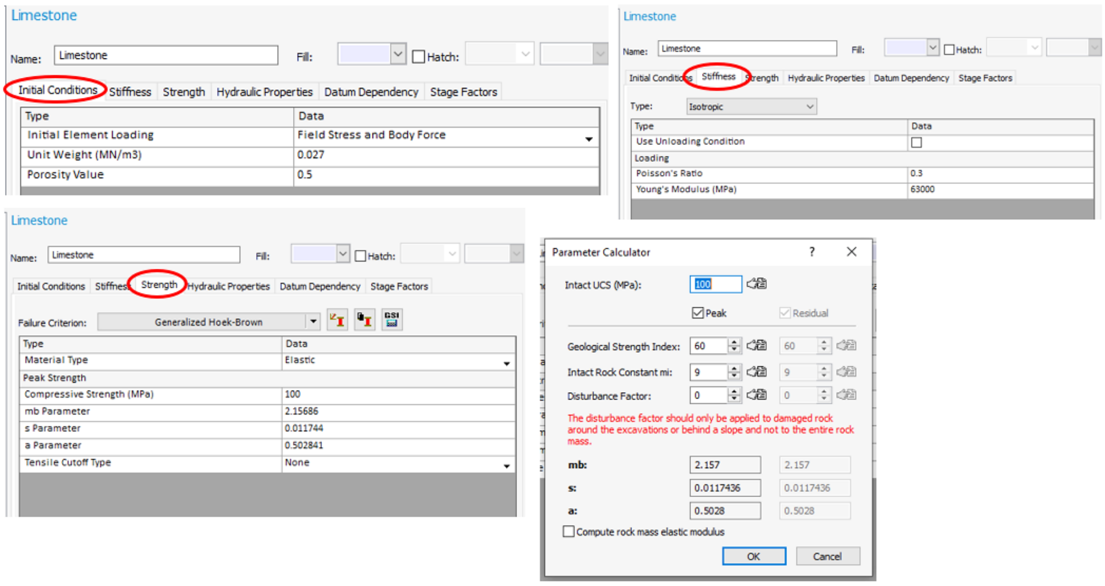


Figure 11. Database for modeling the SSS of the object under study

Modeling of the stress–strain state (SSS) of the rock mass at the Akzhal deposit was carried out in stages, taking into account the transition from open-pit to underground mining. The main geomechanical risks were identified, including pit wall collapse and rock mass displacement, in relation to underground excavations. The calibrated rock mass parameters, including the structural weakening coefficient k_s, were used in the calculations.

The zones related to the mining operations zones were designated and increased by three times compared with the actual size of the corresponding areas on the deposit, thus creating the computational boundary of the model. This approach is necessary to consider possible changes in the geometry of the rock mass and clarify its stability at different stages of development, which makes it possible to consider the impact of mining operations on the stability of the rock mass in wider zones. This is essential for risk assessment and the choice correctness of the development methods. It is important to note that before the start of mining operations, the rock mass is already in a stressed condition, which is the natural state of rocks in this area. This stress state is the baseline for modeling and serves as a starting point for assessing subsequent changes in the rock mass due to mining. The pre-mining rock stress state must be considered when predicting rock mass behavior because this state can significantly affect its stability and response to the impact of mining operations. The physical and mechanical characteristics of massive limestones and the ore body properties represented by mineralized massive limestones were used as input data for model building. These data are key to the accuracy of the calculations and adequacy of the model because the physical and mechanical characteristics of rocks affect the strength and deformation properties of the rock mass and their behavior during mining (Figures 12 to 15).

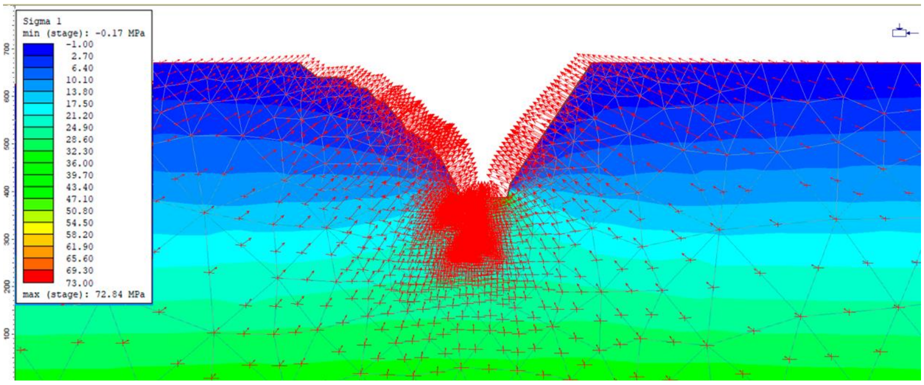


Figure 12. Impact of Sigma 1 on the sides of the Central open pit

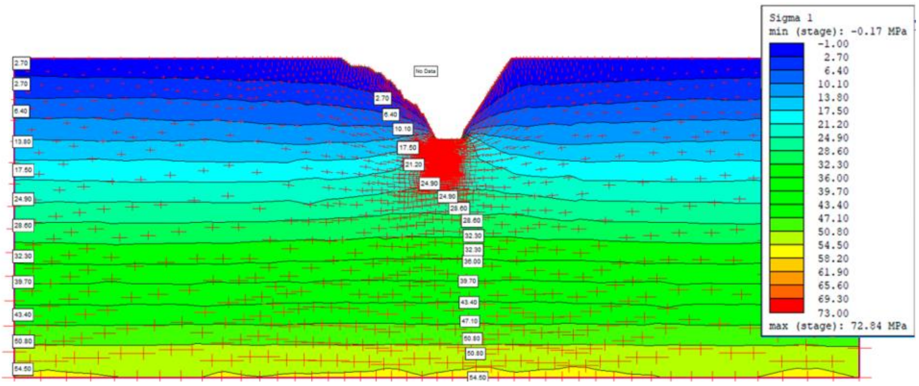


Figure 13. Dynamic change of the natural stress field concerning bathymetric elevations

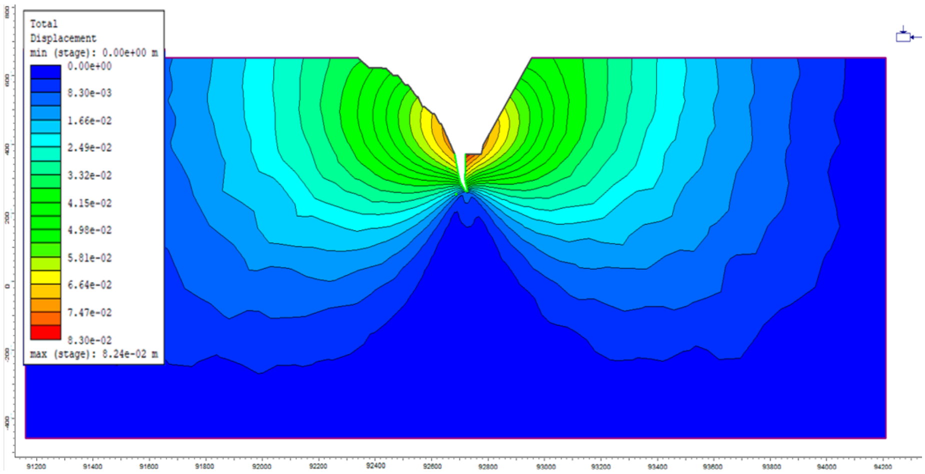


Figure 14. Stage of pit transition to underground mining system

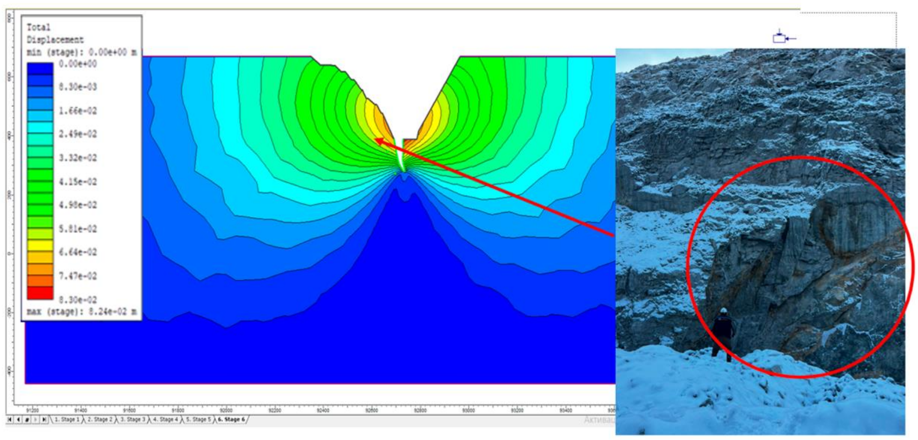
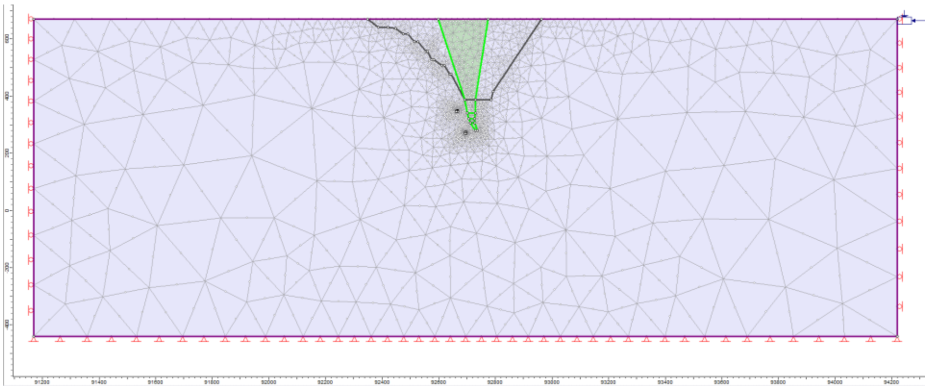
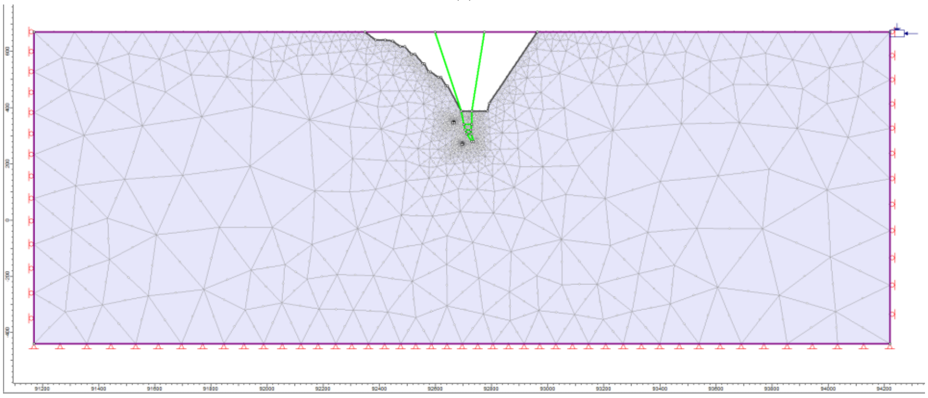


Figure 15. Exit of the working excavation to the ground surface

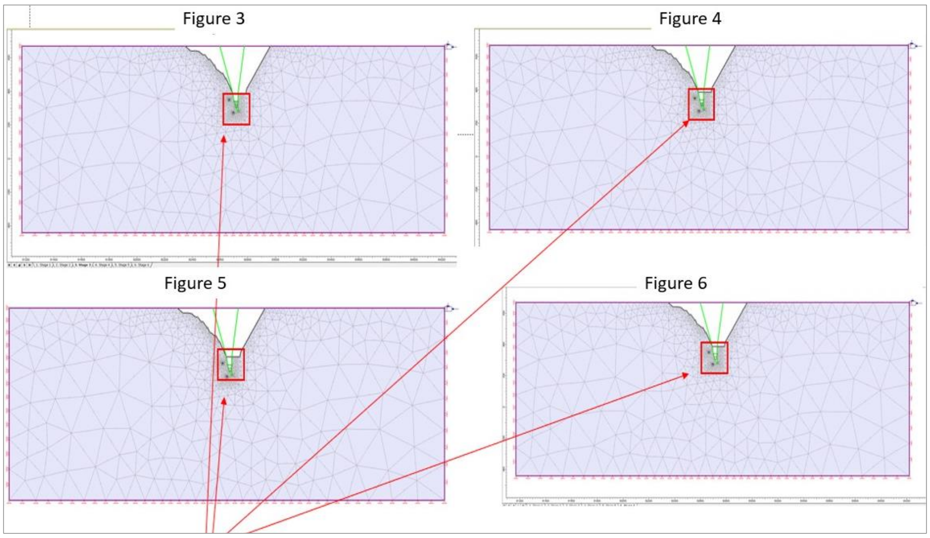
Figures 16-a to 16-c shows the model of the intact rock mass without considering the mining operations. In the natural state, the upper boundary of the model was at an elevation of +670 m, and the lower boundary was at an elevation of +400 m.



(a)



(b)



(c)

Figure 16. (a) Model of the intact rock mass without considering mining operations. In the natural state, the upper boundary of the model is at +670 m, and the lower boundary is at +400 m; (b) Boundaries of the Central pit mining (surface mining) specified at the second stage of the program; (c) Stages of the deposit development by underground mining method, stage-by-stage deepening of underground works with application of the sublevel mining system.

4.2. Mining Systems Used on the Akzhal Deposit

On the polymetallic deposit Akzhal, the following variants of mining systems meet the geological and mining conditions. The variant of the sublevel caving system with the end discharge in the areas of ore bodies with a thickness of more than 6 m and different dip angles was mainly applied (Figures 17 and 18). In addition to the abovementioned system, a variant of the sublevel caving system with compensation chambers in the areas of ore bodies with a thickness of more than 15 m and a dip angle of less than 60° and a variant of the sublevel-chambered mining system with rock filling and ascending order of mining in the areas of ore bodies with a thickness of up to 20 m and a dip angle of more than 60° are considered. The last variant of the mining system used the central section at elevations below +265 m.

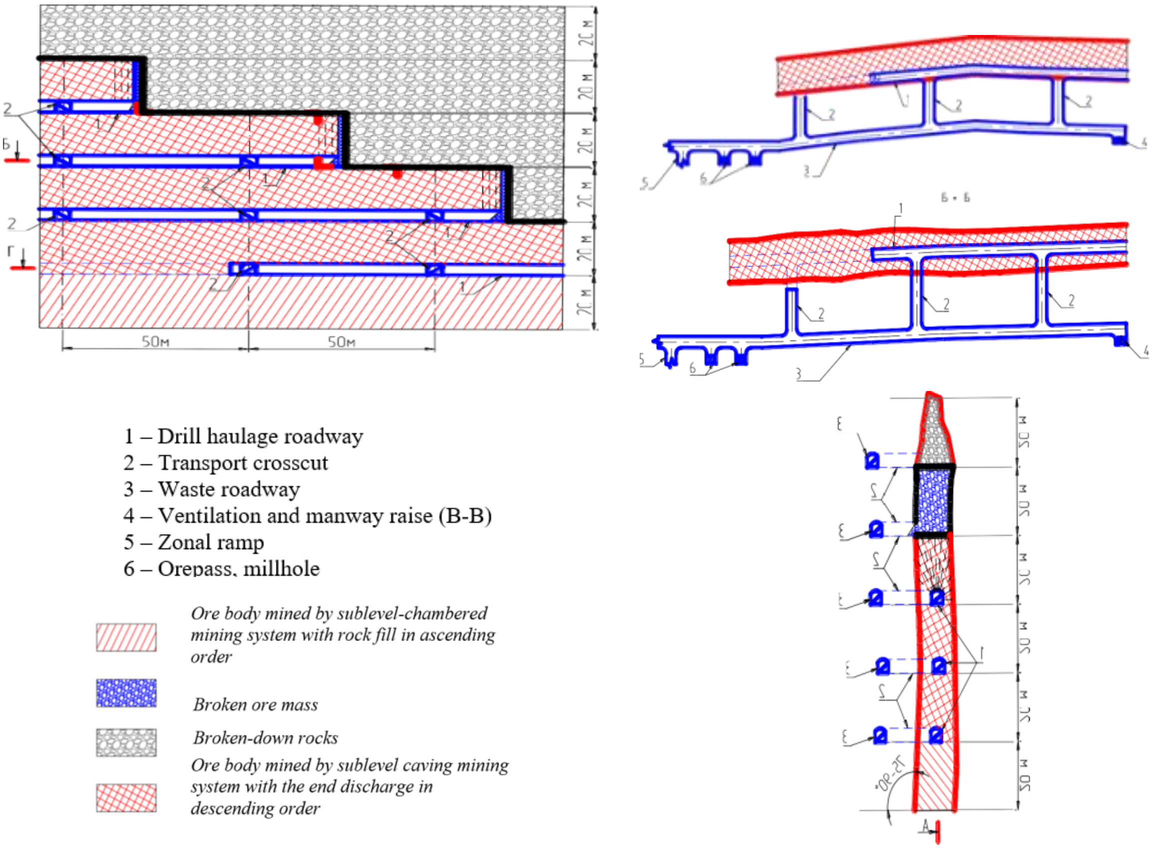


Figure 17. Sublevel caving system with the end ore discharge when passes are located along the strike of the ore body. Variant for the ore body areas with a dip angle of 75-90°

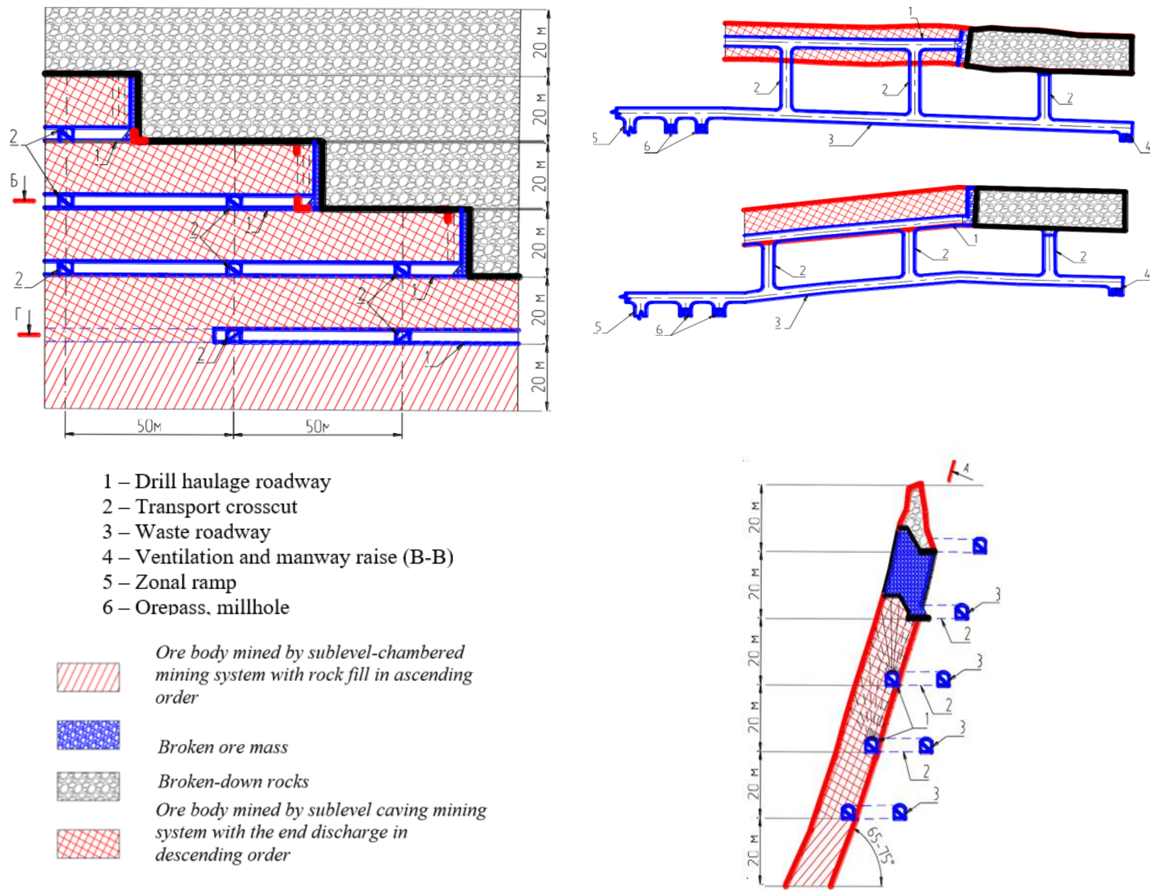


Figure 18. Sublevel caving system with the end ore discharge when passes are located along the strike of the ore body. Variant for the ore body areas with a dip angle of 65-75°

The geotechnical analysis involved two mining excavations, namely, the transport roadway at an elevation of +265 m and the entrance to the sublevel at an elevation of +355 m, because the daily geomechanical inspection revealed cleavage on the roof parts of the excavations. In addition, a crack opening in the rock mass occurred along the side of the workings. The contours of the mining excavations were deformed under the influence of the rock pressure. As a result of intensive cleavage, geotechnical risks for the movement of underground mine personnel and difficulties in conducting mining and tunneling operations have emerged. Figures 19 to 22 show the axonometry of the central open pit with a haulage roadway at an elevation of +265 m (highlighted in yellow).

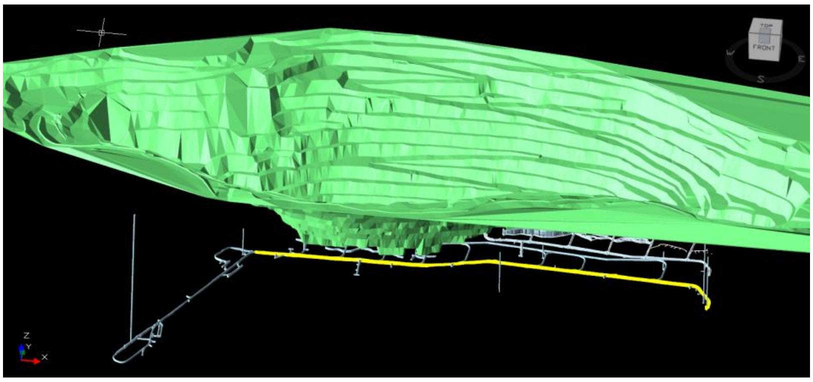


Figure 19. 3D model of the Central open pit with interpretation of the haulage roadway at the elevation of +265 m

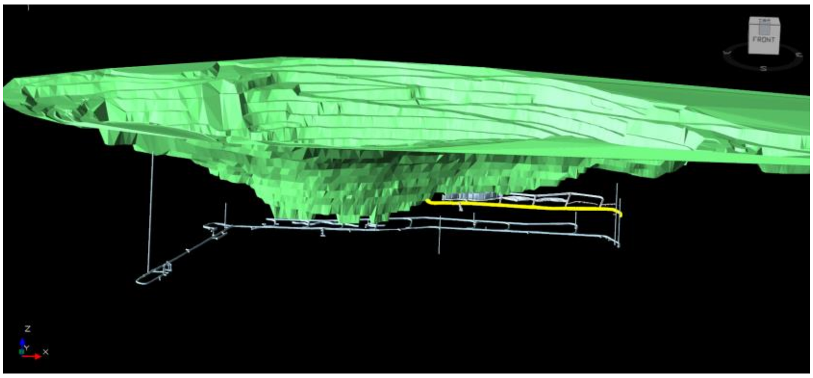
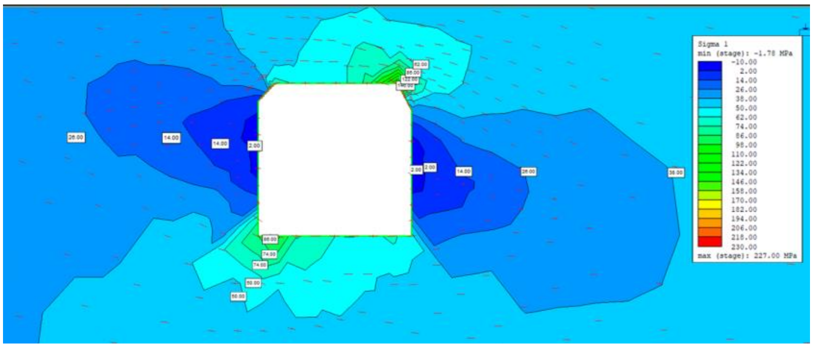


Figure 20. 3D model of the Central open pit with interpretation of the entrance to the sublevel at the elevation of +355 m



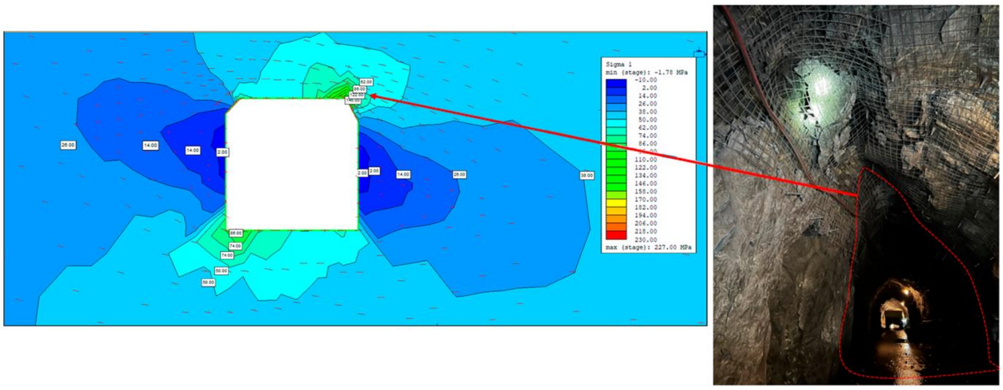


Figure 21. Caving zones around the haulage roadway at horizon +265 m

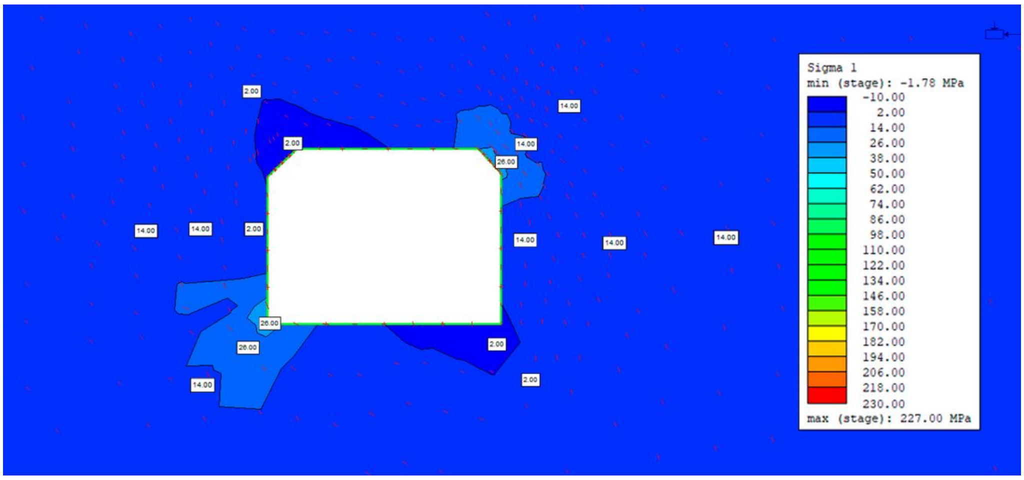


Figure 22. Caving zones around the transport slope at the horizon +355 m

Figure 20 presents a 3D model showing the central quarry with an interpreted ramp connected to the polygon at the +355 m horizon, where the quarry is opened, and when moving to the lower horizon, a motor transport stoop road is shown, which has not yet been completed, and the future working stress-strain state is investigated.

The proposed algorithm is not merely a conceptual framework that has been implemented in the software. All stages from the construction of the geomechanical model to the selection of the mining system were carried out using Micromine, MIDAS GTS NX, and Slide2 environments, employing the Mohr Coulomb failure criterion and parameters calibrated based on laboratory data. This approach allowed for a quantitative assessment of the rock mass stability and enabled the proposal of a specific mining system tailored to the identified geomechanical conditions.

For the geomechanical assessment of the southern side of the central open pit around the road transport slope, the choice of the type of support according to rock stability categories (Table 5) and computer modeling in the Slide2 software of the local section of the side in the area of geological disturbance in the interval of geological profiles V-VII were performed.

Table 5. Choice of the type of supports according to rock stability categories

Rock stability category	Type of support	Nature of interaction with rocks	Fastenings
Stable enough (I)	Without supports	No loads on the support	Fastenings are absent when the excavations exist for 5 years or less but are required when the excavations fall within the zone of influence of mining operations.
Stable (II)	Isolating	No loads on the support, local rock failures are possible	A thin insulating coating of shotcrete for the continued operation of the excavation.
Stable (II) and mean stable (III)	Enclosing	No regular loads, or loading because of accidental cleavages	Shotcrete, metal mesh lacing, and others.
Mean stable (III)	Strengthening	Strengthening of rocks surrounding the excavation, ensuring joint displacement of disturbed rocks	Shotcrete. Various types of anchor (rod) support. Combined fastening (anchor + shotcrete or mesh)
Unstable (IV)	Supporting	Operation in the set load mode (rockfalls, rock cleavages)	Arched metal, combined fastening (anchor + mesh + shotcrete)
Unstable (IV) and very unstable (V)	Supporting in the support-rock system	Operation in the mode of joint deformation with rock mass, the mode of interdependent deformation	Specific tunneling methods are required to move the rocks to a higher stability category, i.e., compressible supports in combination with advanced and safety supports, or rock injection is necessary.

5. Discussion

Despite the high accuracy and predictability of rock behavior, geological risks, and mechanical characteristics under different conditions, modeling geomechanical processes does not always directly lead to economic benefits. The reasons for this may be as follows:

- High initial cost and impossibility of direct application. Although the model can provide essential information for long-term projects, the results may not noticeably impact on the economy in the short term when the dynamics of the processes are uncertain or complex calculations are required to obtain the results [55, 56].
- Modeling may not be sufficiently integrated with economic and production processes, leading to insufficient decision-making efficiency based on the data obtained.

Long-term control of geomechanical processes, which have significant economic potential for predicting and preventing disasters, can be efficient in the short term. Therefore, to achieve cost advantages, proper data interpretation, integration with other technologies, and long-term benefits must be considered. Mineral extraction is a primary focus of mining. Therefore, the area of estimation of reserve recovery and the assay of commercial components, such as zinc and lead, became a subject for comparative analysis. A comparison was conducted between the extraction of reserves using the proposed modeling methodology of geomechanical processes without considering the mining system as a whole.

The calculations provide a forecast of the behavior and condition of the surface of the day above the working excavation, which makes it possible to objectively assess the risk of anthropogenic disasters, both during the mining of the ore deposit and after the completion of mining operations (Table 6).

Table 6. Comparative analysis of reserves recovery and zinc and lead content in ore bodies

Category of reserves	Category of reserves	Ore, kt	Mineral resources		
			Lead, kt	Zinc, kt	Cadmium, t
Extraction of reserves with the application of the methodology	C_1	7283.066	164.367	288.051	2579.710
	C_2	8376.463	107.160	347.077	2818.864
Extraction of reserves without application of the methodology	C_1	6520.23	135.36	189.066	2055.23
	C_2	7230.12	95.22	288.023	2566.12

The results showed that the application of the methodology provided a significant increase in the indicator values for all categories. In category C_1, increases were observed for ore (11.7%), lead (21.43%), zinc (52.35%), cadmium (25.52%); in category C_2: for ore (15.86%), lead (12.54%), zinc (20.5%), and cadmium (9.85%). These results confirm the high efficiency of modeling applications, including selective excavation, reduction of mineral resource losses, and improvement in the accuracy of geological and technical calculations.

The developed methodology for calculating the coefficient characterizing the geostructural situation of the rock mass is distinguished using an integrated approach that considers the strength characteristics and structural parameters of the rock mass at the transition stage from open-pit to underground mining operations. The calculations included the following data.

- Number of fracture systems;
- Fracture roughness;
- Crack opening and filling;
- Orientation of excavations in the rock mass.

The calculation characteristics are taken from data corresponding to actual geomechanical conditions.

Many known methodologies [35, 38, 55] involve stability calculations based on individual rock mass parameters such as rock strength, depth of occurrence, angles of cleavage slope, and stress concentration. However, this does not consider their complex mutual influence, which can lead to significant errors in the engineering estimates. In contrast to such approaches, our developed methodology uses a multiparametric analysis that reflects the actual geomechanical behavior of the rock mass under the conditions of a particular deposit.

For example, a method for determining the stability coefficient of mining excavations is based on the strength properties of rocks at the depth of their occurrence, as well as on the calculation of stress concentration along the contour. However, this method does not consider significant factors, such as the number of fracture systems, their orientation, opening, filling, and structural inhomogeneities of the rock mass [57].

Similarly, the studies on excavations provided earthquake resistance and mechanical properties of rocks, but they modeled the influence of fracturing and tectonic disturbances only in a generalized way. Barchak's studies emphasize the importance of analyzing the stress-strain state of the rock mass; however, the calculations are based on simplified linear-elastic models that do not reflect the entirety of geomechanical conditions [58].

Terentyev's methodologies, focused on assessing the stability of underground chambers, also do not cover the full range of parameters, particularly in transition zones from open-pit to underground mining operations, where the risk of caving is much higher [59].

The model based on the Mohr Coulomb failure criterion, implemented in Slide2 and Micromine software environments, plays a key role in planning and managing the stress–strain state of the rock mass. In particular, it is used for work scheduling, where the model enables early identification of potentially unstable zones. This allows for the optimization of the excavation sequence: high-risk areas are either reinforced before extraction begins or postponed to later stages, thereby reducing the impact of hazardous technogenic events.

Determining the extraction sequence using stability assessments along profile lines A, B, and C enables mining to commence in more-stable zones. This approach helps reduce secondary stress redistribution and minimizes the likelihood of deformation or collapse.

The support system design provides quantitative recommendations regarding support type, anchor length, and spacing, as well as the need for temporary or permanent reinforcement. These data are incorporated into the design documentation to enhance safety and reduce construction costs.

To assess the effectiveness of the proposed methodology, a comparative mineral extraction analysis (lead, zinc and cadmium) from categories C1 and C2 ore bodies was performed. Two options were considered, with and without the use of developed technology [1]. The main criterion was the economic return, expressed in US dollars based on average world prices (as of 2024–2025): lead \$2,000/t, zinc \$2,500/t, and cadmium \$20,000/t.

The obtained data demonstrate (Figure 23) that the proposed method application allows achieving significant economic growth: for category C1 — + \$315.97 million (+40.3%), for category C2 — + \$176.57 million (+18.4%). The total effect was \$492.54 million. As a result of applying the proposed methodology, not only does the extraction of all target components increase, but the geomechanical environment stability also improves, reducing the surface displacement deformation probability. This confirms that the method has a significant advantage over the traditional approaches described in recent literature.

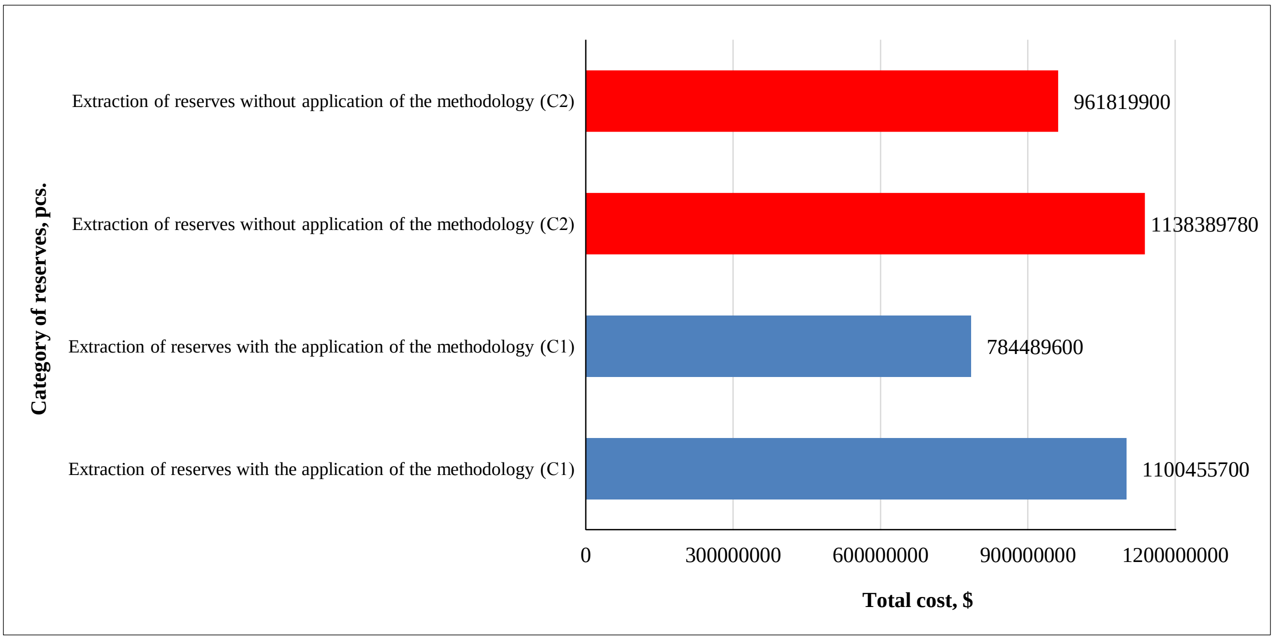


Figure 23. Component extraction cost-effectiveness

Thus, our methodology is distinguished by the comprehensive integration of strength, structural, and fracture characteristics; direct use of engineering and geological research data; accurate modeling of actual rock mass conditions; consideration of the orientation of excavations; and applicability in conditions of combined field development [39, 60]. These advantages make this methodology an effective tool for predicting and preventing the risks of caving open-pit sides and underworked zones, which have engineering and economic significance. Modeling can avoid losses measured in tens of millions of dollars, prevent infrastructure destruction, and significantly reduce the threat of human casualties. Our modeling method allows for a more accurate calculation of geomechanical parameters such as the stability of ceilings between open and underground excavations, risks of pit wall cave-ins, and parameters of safe deposit mining. This is particularly important for assessing the risks associated with existing excavations, which can lead to cave-ins, loss of access to unexcavated ore deposits, and damage to transportation infrastructure.

The cave-in of open-pit sides and ceilings can cause significant material losses of tens and hundreds of millions of dollars and, more importantly, endanger the lives and health of workers. Modeling can significantly reduce these risks even if precise quantification is impossible. Production losses, infrastructure damage, and direct losses from downtime are strong arguments in favor of advanced geomechanical analysis. Thus, the integration of complex modeling into the process of designing and conducting mining operations is a key element in improving the sustainability, safety, and economic efficiency of deposit development.

6. Conclusions

6.1. Research Novelty

This study proposes a new approach for modeling geomechanical processes under the complex morphology of the Akzhal deposit. Given the specific conditions of rock interaction during the transition from open-pit to underground mining, the proposed method allows for a more accurate prediction of the behavior of rock masses under such conditions, significantly improving the efficiency and safety of mining.

The feature of this study is modeling under the conditions of the complex morphology of the deposit, creating a model capable of considering the complex geometric shape of the deposit, characteristics of mines with rugged terrain, and unstable geological structure. Models that consider such features are rare, and provide a more realistic view of the development process.

As for predicting the stability of mine excavations and ensuring safety, it is essential that modeling geomechanical processes aims to optimize the scheme of transition from open pit to underground mining by considering potential risks and opportunities for their minimization. Methodologies for assessing the strength of the rock mass that accounts for the structural weakening coefficient and the analytical functional relationship of geostructural factors with the stability of the rock mass have been developed. This allows for the early identification of possible problems with the stability of excavations, and proposes methods to prevent them.

6.2. Theoretical Contribution

The developed theoretical model improved the prediction of deformation and rock failure mechanisms during the transition from open-pit to underground mining at the Akzhal deposit. The model considers complex geomorphological and geological conditions, the initial stress state of the rock mass, and dynamic changes throughout the mining process.

A step-by-step assessment of the stress–strain state (SSS) of the rock mass significantly enhances the accuracy of predicting changes in rock mass conditions at various stages of deposit development. One of the key advantages of the model is its ability to simulate geomechanical processes, specifically during the transition between mining methods, which ensures a more accurate forecast of rock mass behavior under complex morphological operating conditions.

The model also contributes to identifying potentially hazardous zones, optimizing development methods, and supporting the rational selection of underground mining systems, which directly affects the stability of mine workings and operational safety. The shape and physical–mechanical properties of the rocks were incorporated into the calculation framework to ensure a high modeling accuracy. These parameters play a crucial role in minimizing geotechnical risks and improving the overall efficiency of mining operations.

6.3. Practical Significance

The practical significance of this study lies in the development of a comprehensive methodological approach aimed at improving the efficiency and safety of the transition from open-pit to underground mining under complex geomorphological conditions of the Akzhal deposit. The implementation of the proposed geomechanical modeling system enables highly accurate predictions of rock mass behavior in response to changing mining conditions. This, in turn, supports informed engineering decisions to reduce geotechnical risks, such as rock mass collapse or deformation of underground workings, thereby significantly enhancing the stability of mining operations and ensuring worker safety.

6.4. Research Limitations

This study has a number of limitations arising from both the initial conditions and the applied methodological approaches. The geomechanical justification of the proposed mining systems is based on mathematical calculations developed considering the orebody morphology, sequence of mining and preparatory operations, and physical and mechanical properties of ores and host rocks. However, in real-world conditions, deviations from the assumed parameters may occur because of geological, technological, and morphological factors.

One of the key limitations is the quality and availability of geological and geophysical data related to the deposit structure, geomorphological features, and physical and mechanical properties of the rock mass. Insufficient accuracy or completeness of these data may reduce the reliability of numerical modeling and, consequently, the validity of engineering decisions.

Moreover, the accuracy of modeling depends on the selected computational models, discretization parameters, available computational resources, and level of approximation used to simulate internal and external impacts on the rock mass. It is also important to note that modeling assumptions embedded in software packages do not always fully reflect the complex natural and man-made conditions of mining excavations.

These limitations should be carefully considered when interpreting results and applying them in practice. This highlights the need for further research aimed at refining input data, increasing the accuracy of models, and developing adaptive methodologies for selecting mining systems under geomechanical uncertainty at each horizon during transitions to greater depth.

6.5. Future Research Directions

Further research will aim to substantiate and develop geotechnology parameters that ensure sustainable and efficient ore extraction during underground mining of reserves in geological and mining conditions with complex deposit morphology and a comprehensive ore recovery rate from the subsurface.

7. Declarations

7.1. Author Contributions

Conceptualization, D.B., G.J., and A.Z.; methodology, R.Z.; software, K.Sh.; validation, D.B., G.J., and R.Z.; formal analysis, N.A. and O.K.; investigation, G.J. and R.Z.; resources, G.J. and R.Z.; data curation, D.B., G.J., and A.Z.; writing—original draft preparation, G.J. and R.Z.; writing—review and editing, G.J. and R.Z.; visualization, D.B., G.J., and R.Z.; supervision, D.B., G.J., and R.Z.; project administration, D.B.; funding acquisition, D.B. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding and Acknowledgments

The authors acknowledge the financial support provided by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan under research Grant No. AP23488767, which funds the project Development and substantiation of effective systems for mining ore deposits of complex morphology.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] Kozyrev, A. A., Batugin, A. S., & Zhukova, S. A. (2021). Influence of water content on seismic activity of rocks mass in apatite mining in Khibiny. Gornyi Zhurnal, 2021(1), 31–36. doi:10.17580/gzh.2021.01.06.

[2] Fedorov, E., Bekbergenov, D., & Jangulova, G. (2020). Modeling and methodology for calculating the strength of a man-made bottom in a system with self-destruction of ore for ecologically safe mining. E3S Web of Conferences, 192, 3018. doi:10.1051/e3sconf/202019203018.

[3] Yakovlev, V. L. (2022). Key Stages and Results of Research to Formulate Methodological Basis for the Strategy to Develop Mining Systems for Deep Seated Deposits of Solid Minerals. Gornaya Promyshlennost, 2022(1s), 34–45. doi:10.30686/1609-9192-2022-1S-34-45.

[4] Akishev, K. M., Aryngazin, K. S., Tleulessov, K., Bulyga, L. L., & Stanevich, V. T. (2024). The Use of Simulation Modeling in Calculating the Productivity of the Technological System for the Production of Building Products with Fillers from Man-Made Waste. News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 2024(4), 22–32. doi:10.32014/2024.2518-170X.422.

[5] Balt, K., & Goosen, R. L. (2020). MSAHP: An approach to mining method selection. Journal of the Southern African Institute of Mining and Metallurgy, 120(8), 451–460. doi:10.17159/2411-9717/1072/2020.

[6] Lyashenko, V., Khomenko, O., Chekushina, T., & Topolnij, F. (2020). Justification of safe underground development of mountain deposits of complex structure by geophysical methods. Technology Audit and Production Reserves, 5(3(55)), 9–18. doi:10.15587/2706-5448.2020.215737.

[7] Rybak, J., Khayrutdinov, M. M., Kuziev, D. A., Kongar-Syuryun, C. B., & Babyr, N. V. (2022). Prediction of the geomechanical state of the rock mass when mining salt deposits with stowing. Journal of Mining Institute, 253(1), 61–70. doi:10.31897/PMI.2022.2.

[8] Isabek, T., Orynbek, Y., Kozhogulov, K., Sarkulova, Z., Abdiyeva, L., & Yefremova, S. (2022). Geomechanical substantiation of the parameters for the mining system with ore shrinkage in the combined mining of steep-dipping ore bodies. Mining of Mineral Deposits, 16(4), 115–121. doi:10.33271/mining16.04.115.

[9] Suimbayeva, A. (2020). Geotechnological Research to Justify the Parameters of Stability of the Rock Mass During Combined Mining (on the Example of the Akzhal Field). Ph.D. Thesis, Karaganda State Technical University, Karaganda, Kazakhstan.

[10] Rysbekov, K., Bitimbayev, M., Akhmetkanov, D., Barmenshinova, M., Toktarov, A., Baskanbayeva, D., & Yelemessov, K. (2022). Substantiation of mining systems for steeply dipping low-thickness ore bodies with controlled continuous stope extraction. Mining of Mineral Deposits, 16(2), 64–72. doi:10.33271/mining16.02.064.

[11] Yussupov, K., Aben, E., Akhmetkanov, D., Aben, K., & Yussupova, S. (2023). Investigation of the solid oxidizer effect on the metal geotechnology efficiency. Mining of Mineral Deposits, 17(4), 12–17. doi:10.33271/mining17.04.012.

[12] Mussin, A., Kydrashov, A., Asanova, Z., Abdrakhman, Y., & Ivadilinova, D. (2024). Ore dilution control when mining low-thickness ore bodies using a system of sublevel drifts. Mining of Mineral Deposits, 18(2), 18–27. doi:10.33271/mining18.02.018.

[13] Xing, Y., Kulatilake, P. H. S. W., & Sandbak, L. A. (2018). Investigation of rock mass stability around the tunnels in an underground mine in USA using three-dimensional numerical modeling. Rock Mechanics and Rock Engineering, 51(2), 579-597. doi:10.1007/s00603-017-1336-6.

[14] Kashan, A. J., Lay, J., Wiewiora, A., & Bradley, L. (2022). The innovation process in mining: Integrating insights from innovation and change management. Resources Policy, 76, 102575. doi:10.1016/j.resourpol.2022.102575.

[15] Dintwe, T. K. M., Sasaoka, T., Shimada, H., Hamanaka, A., Moses, D. N., Peng, M., Fanfei, M., Liu, S., Ssebadduka, R., & Onyango, J. A. (2022). Numerical Simulation of Crown Pillar Behaviour in Transition from Open Pit to Underground Mining. Geotechnical and Geological Engineering, 40(4), 2213–2229. doi:10.1007/s10706-021-02022-4.

[16] Mazraehli, M., & Zare, S. (2020). An application of uncertainty analysis to rock mass properties characterization at porphyry copper mines. Bulletin of Engineering Geology and the Environment, 79(7), 3721–3739. doi:10.1007/s10064-020-01758-2.

[17] Han, L., Wang, L., & Zhang, W. (2020). Quantification of statistical uncertainties of rock strength parameters using Bayesian-based Markov Chain Monte Carlo method. IOP Conference Series: Earth and Environmental Science, 570(3), 32051. doi:10.1088/1755-1315/570/3/032051.

[18] Protosenya, A. G., Belyakov, N. A., & Bouslova, M. A. (2023). Modelling of the stress-strain state of block rock mass of ore deposits during development by caving mining systems. Journal of Mining Institute, 262, 619–627.

[19] Bennouna, R., Ouadif, L., Akhssas, A., Senhaji, A. S., & Boulaid, G. (2024). Wedge stability analysis in fractured soft rock slopes for different orientations of seismic components. Mining of Mineral Deposits, 18(1), 1–8. doi:10.33271/mining18.01.001.

[20] Vu, T. T., & Do, S. A. (2023). Determination of the rock mass displacement zone by numerical modeling method when exploiting the longwall at the Nui Beo Coal Mine, Vietnam. Mining of Mineral Deposits, 17(1), 59–66. doi:10.33271/mining17.01.059.

[21] Stemn, E., & Krampah, F. (2022). Injury severity and influence factors in surface mines: A correspondence analysis. Safety Science, 145, 105495. doi:10.1016/j.ssci.2021.105495.

[22] Joe-Asare, T., Stemn, E., & Amegbey, N. (2023). Causal and contributing factors of accidents in the Ghanaian mining industry. Safety Science, 159, 106036. doi:10.1016/j.ssci.2022.106036.

[23] Diulin, D. A., Prushak, V. Y., & Gegedesh, M. G. (2023). Analysis of the stress-strain state of problematic sections of the shaft of the mine using computer simulation. Doklady of the National Academy of Sciences of Belarus, 67(4), 322–330. doi:10.29235/1561-8323-2023-67-4-322-330.

[24] Susilo, A., Zulaikah, S., Pohan, A. F., Fathur Rouf Hasan, M., Hisyam, F., Rohmah, S., & Adhi, M. A. (2024). Vulnerability Index Assessment for Mapping Ground Movements Using the Microtremor Method as Geological Hazard Mitigation. Civil Engineering Journal (Iran), 10(5), 1616–1626. doi:10.28991/CEJ-2024-010-05-017.

[25] Elbshbeshi, A., Gomaa, A., Mohamed, A., Othman, A., & Ghazala, H. (2022). Seismic hazard evaluation by employing microtremor measurements for Abu Simbel area, Aswan, Egypt. Journal of African Earth Sciences, 196, 104734. doi:10.1016/j.jafrearsci.2022.104734.

[26] Ma, C., Lafrance, B., & Montreuil, J. F. (2025). Polyphase formation of a Neoarchean auriferous fault zone network in the Michipicoten greenstone belt, southern Superior craton. Canadian Journal of Earth Sciences, 62(2), 171–191. doi:10.1139/cjes-2023-0120.

[27] Jellicoe, K., Ciufo, T. J., Lin, S., Wodicka, N., Wu, N., Mercier-Langevin, P., & Yakymchuk, C. (2022). Genesis of the Island Gold Deposit, Ontario, Canada: Implications for Gold Mineralization in the Wawa Subprovince of the Superior Province. Economic Geology, 117(7), 1597–1612. doi:10.5382/econgeo.4963.

[28] Zhienbayev, A., Zharaspaev, M., Balpanova, M., Nurkasyn, R., Asanova, Z., & Zhakupov, B. (2023). Analysis of the roof span stability in terms of room-and-pillar system of ore deposit mining. Mining of Mineral Deposits, 17(1), 129–137. doi:10.33271/mining17.01.129.

[29] Kaiser, P. K., & Cai, M. (2012). Design of rock support system under rockburst condition. Journal of Rock Mechanics and Geotechnical Engineering, 4(3), 215-227. doi:10.3724/SP.J.1235.2012.00215.

[30] Begalinov, A., Almenov, T., Zhanakova, R., & Bektur, B. (2020). Analysis of the stress deformed state of rocks around the haulage roadway of the beskempir field (Kazakhstan). Mining of Mineral Deposits, 14(3), 28–36. doi:10.33271/mining14.03.028.

[31] Begalinov, A., Shautenov, M., Almenov, T., Bektur, B., & Sakhipova, K. (2024). Research of Gravity Concentration of the Gold Placer of Eastern Kazakhstan. News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 2024(3), 17–34. doi:10.32014/2024.2518-170X.407.

[32] Begalinov, A., Peregudov, V., Tretyakov, A., Almenov, T., Bektur, B., Sakhipova, K., & Shautenov, M. (2023). Polygenic gold mineralization in quartz-pebble formations on the Takyr-Kaljir site of the Southern Altai, East Kazakhstan Region. Mining of Mineral Deposits, 17(3), 32–41. doi:10.33271/mining17.03.032.

[33] Akhmetov, N. B. (2020). Satpayev Readings. Kazakh National Technical University named after K.I. Satpaev, Almaty, Kazakhstan. Available online: https://official.satbayev.university/download/document/15654/Сатпаевские%20Чтения%202020%20-%202%20том.pdf (accessed on July 2025) (In Kazakh).

[34] Begalinov, A., Shautenov, M., Almenov, T., & Bektur, B. (2022). Leaching process intensification of gold-bearing raw materials. Mining of Mineral Deposits, 16(2), 42–48. doi:10.33271/mining16.02.042.

[35] Sazanbayeva, A., Jangulova, G., & Levin, E. (2024). Theoretical Substantiation and Technology of Geodetic Support of Chromite Deposits on the Case of Kazakhstan: Literature Review. Acta Montanistica Slovaca, 29(3), 525–534. doi:10.46544/AMS.v29i3.01.

[36] Sdvyzhkova, O., Kuldeyev, E., Moldabayev, S., Sultanbekova, Z., Bascetin, A., Amankulov, M., Babets, D., & Issakov, B. (2022). Probabilistic assessment of slope stability at ore mining with steep layers in deep open pits. Mining of Mineral Deposits, 16(4), 11–18. doi:10.33271/mining16.04.011.

[37] Han, S., Zhuang, X., Yao, Q., Zhou, Q., & Hu, X. (2023). Understanding the Role of Rock Heterogeneity in Controlling Fault Strength and Stability. doi:10.48550/arxiv.2311.16879.

[38] Imashev, A., Suimbayeva, A., Zhunusbekova, G., Adoko, A. C., & Issakov, B. (2024). Assessing stability of mine workings driven in stratified rock mass. Mining of Mineral Deposits, 18(1), 82–88. doi:10.33271/mining18.01.082.

[39] Sdvyzhkova, O., Moldabayev, S., Babets, D., Bascetin, A., Asylkhanova, G., Nurmanova, A., & Prykhodko, V. (2024). Numerical modelling of the pit wall stability while optimizing its boundaries to ensure the ore mining completeness. Mining of Mineral Deposits, 18(2), 1–10. doi:10.33271/mining18.02.001.

[40] Tolovkhan, B., Smagulova, A., Khuangan, N., Asainov, S., Issagulov, S., Kaumetova, D., Khussan, B., & Sandibekov, M. (2023). Studying rock mass jointing to provide bench stability while Northern Katpar deposit developing in Kazakhstan. Mining of Mineral Deposits, 17(2), 99–111. doi:10.33271/mining17.02.099.

[41] Orlóci-Goodison, R. A., Lafrance, B., Beaudoin, G., & Côté-Mantha, O. (2024). The structural setting and evolution of the Upper Beaver gold–copper deposit, Ontario, Canada. Canadian Journal of Earth Sciences, 62(2), 401–425. doi:10.1139/cjes-2024-0027.

[42] Dehghan, A. N., & Khodaei, M. (2022). Stability analysis and optimal design of ultimate slope of an open pit mine: a case study. Geotechnical and Geological Engineering, 40(4), 1789-1808. doi:10.1007/s10706-021-01993-8.

[43] Seredkin, M., Zabolotsky, A., & Jeffress, G. (2016). In situ recovery, an alternative to conventional methods of mining: Exploration, resource estimation, environmental issues, project evaluation and economics. Ore Geology Reviews, 79, 500-514. doi:10.1016/j.oregeorev.2016.06.016.

[44] Neverov, A. A., Konurin, A. I., Neverov, S. A., Vasichev, S. Y., & Shchukin, S. A. (2024). Geomechanical Justification of Ground Control Method Using Pillars and Roof Caving in Mining Inclined Thin and Medium-Thick Orebodies. Journal of Mining Science, 60(5), 808–818. doi:10.1134/S1062739124050107.

[45] Genbach, A. A., Bondartsev, D. Y., & Beloev, H. I. (2021). Studies of integrated natural capillary-porous coatings. IOP Conference Series: Materials Science and Engineering, 1032(1), 12038. doi:10.1088/1757-899X/1032/1/012038.

[46] Demina, T., Zhumabekova, A., Medeubayev, N., Meiram, D., Sherubayev, S., Abdrasheva, Z., & Gabitova, A. (2024). Simulation of the enclosing rock displacements around the development mine workings. Mining of Mineral Deposits, 18(4), 153–161. doi:10.33271/mining18.04.153.

[47] Bekbergenov, D. K., Jangulova, G. K., Nasyrov, R. S., Aiymbetov, M. M., Bektur, B. K., & Abakanov, A. T. (2022). Applicability of manmade bottoms in extraction panels toward sustainable stoping with caving at deep levels in mines. IOP Conference Series: Earth and Environmental Science, 991(1), 12047. doi:10.1088/1755-1315/991/1/012047.

[48] Genbatch, A. A., & Bondartsev, D. Y. (2018). Experimental method of investigation of the heat transfer crisis in a capillary-porous cooling system. News of the National Academy of Sciences of the Republic of Kazakhstan-Series of Geology and Technical Sciences, (2), 81-88.

[49] Guo, Y., Luo, L., Ma, R., Li, S., Zhang, W., & Wang, C. (2023). Study on Surface Deformation and Movement Caused by Deep Continuous Mining of Steeply Inclined Ore Bodies. Sustainability (Switzerland), 15(15), 11815. doi:10.3390/su151511815.

[50] Shaojie, F., Chen, G., & Wenbo, L. (2021). Study on failure law of rock mass and slope stability by open-pit combined mining. E3S Web of Conferences, 248, 3013. doi:10.1051/e3sconf/202124803013.

[51] Xie, Z. H., Xie, R. Y., & Lu, X. Y. (2015). Stability Analysis on High and Steep Slope of Open-Pit Based on Limit Equilibrium Method. Applied Mechanics and Materials, 777, 106–111. doi:10.4028/www.scientific.net/amm.777.106.

[52] Shi, S., Guo, Z., Ding, P., Tao, Y., Mao, H., & Jiao, Z. (2022). Failure Mechanism and Stability Control Technology of Slope during Open-Pit Combing Underground Extraction: A Case Study from Shanxi Province of China. Sustainability (Switzerland), 14(14), 8939. doi:10.3390/su14148939.

[53] Baloyi, V. D., & Meyer, L. D. (2020). The development of a mining method selection model through a detailed assessment of multi-criteria decision methods. Results in Engineering, 8, 100172. doi:10.1016/j.rineng.2020.100172.

[54] Konyukhov, D. S. (2022). Analysis of mechanized tunneling parameters to determine the overcutting characteristics. Mining Science and Technology (Russian Federation), 7(1), 49–56. doi:10.17073/2500-0632-2022-1-49-56.

[55] Nemova, N. A., & Belsh, T. A. (2019). Geomechanical estimation of stability parameters of pit slope scale and batters when developing the apatitebnepheline ore deposit «Oleniy Ruchey». Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering, 330(11), 109–120. doi:10.18799/24131830/2019/11/2355.

[56] Pospehov, G. B., Norova, L. P., & Izotova, V. A. (2024). Comparing the methods of grain size analysis of gypsum-containing sulfuric acid wastes neutralized with limestone. Sustainable Development of Mountain Territories, 16(4), 1729–1742. doi:10.21177/1998-4502-2024-16-4-1729-1742.

[57] Driouch, A., Ouadif, L., Lahmili, A., & Belmi, M. A. (2022). Evaluation of the Compression Potential of Serpentine Rock Masses of the Bou Azzer Mining District in the Central Anti-Atlas of Morocco. Mining, Metallurgy & Exploration, 39(1), 189–200. doi:10.1007/s42461-021-00517-5.

[58] Badakhshan, N., Shahriar, K., Afraei, S., & Bakhtavar, E. (2023). Evaluating the impacts of the transition from open-pit to underground mining on sustainable development indexes. Journal of Sustainable Mining, 22(2), 155–168. doi:10.46873/2300-3960.1382.

[59] MacNeil, J., Dimitrakopoulos, R., & Peattie, R. (2022). A stochastic mine planning approach to determine the optimal open pit to underground mining transition depth–case study at the Geita gold mine, Tanzania. Mining Technology: Transactions of the Institute of Mining and Metallurgy, 131(3), 181–190. doi:10.1080/25726668.2022.2072559.

[60] Siad, L. (2003). Seismic stability analysis of fractured rock slopes by yield design theory. Soil Dynamics and Earthquake Engineering, 23(3), 21–30. doi:10.1016/S0267-7261(02)00213-0.