https://doi.org/10.33271/nvngu/2026-4/028

R. K. Zhanakova[1],
orcid.org/0000-0003-0845-8449,
T. M. Almenov[1],
orcid.org/0000-0001-9674-8598,
M. A. Sarybayev[*2],
orcid.org/0000-0003-4488-5659,
Ye. A. Koroviaka[3],
orcid.org/0000-0002-2675-6610,
M. Zh. Seksenbay[4],
orcid.org/0000-0002-6977-9169,
I. O. Vashchenko[3],
orcid.org/0009-0003-0697-544X

1 – Satbayev University, Almaty, Kazakhstan
2 – Al-Farabi Kazakh National University, Almaty, Kazakhstan
3 – Dnipro University of Technology, Dnipro, Ukraine
4 – Kazakh National University of Water Management and Irrigation, Taraz, Kazakhstan
* Corresponding author email: Sarybayev.Madiyar@kaznu.kz

WIREFRAME MODELING TO OPTIMIZE OPEN-PIT PARAMETERS OF BOGUTY TUNGSTEN DEPOSIT (KAZAKHSTAN)

Purpose. Comprehensive analysis of the mining-geological and technological conditions of the Boguty deposit (Kazakhstan) to develop science-based recommendations for enhancing mining efficiency through digital modeling methods.

Methodology. The research employs an integrated approach, including 3D wireframe modeling of ore bodies, GIS analysis of exploration data, and techno-economic optimization of mining parameters. Slope stability modeling and assessment were performed using Micromine, Surpac, and Rocscience (Examine2D) software suites, accounting for structural-tectonic features and the hydrodynamic regime of the rock mass.

Findings. It was established that optimizing drilling and blasting parameters – increasing bench height to 15 m and the working face angle to 75° – reduces operational losses to 2.9 % and the dilution coefficient to 6.4 %. Precision geometrization of the deposits was shown to ensure high mining selectivity and a 15–20 % reduction in oversize yield. Economic analysis confirmed the project's high profitability (NPV ~$320 million, IRR 18–20 %) while ensuring regulatory slope stability.

Originality. An integrated wireframe modeling methodology was developed, considering the synergistic impact of tectonic disturbances and ore body morphology on reserve recovery indicators. For the first time for this specific site, a mathematical relationship between the geometry of the working bench and the quality of the extracted raw materials has been substantiated.

Practical value. The proposed technological solutions enhance the completeness of mineral extraction, reduce ore production costs to $18–20/t, and minimize the environmental footprint. The developed methodological approaches can be adapted for open-pit design at deposits with similarly complex structural conditions.

Keywords: *wireframe modeling, open-pit mining, geoinformation technologies, open-pit design, sustainable development*

Received: 27 January 2026
Accepted: 23 June 2026
Available online: 27 August 2026

Introduction. The development of the mining industry in the modern world plays a key role in ensuring the energy, raw material, and economic security of countries. The mineral resource base is the foundation for the functioning of metallurgical, construction, energy, and other related industries. In this regard, the efficient and rational development of solid mineral deposits acquires not only economic but also strategic significance [1, 2].

Kazakhstan, possessing significant reserves of mineral resources, including non-ferrous and ferrous metals, is one of the leading participants in the global mineral market. In the structure of the republic's mineral resource complex, a significant place is occupied by deposits of copper, lead, zinc, gold, iron, and other metals that ensure the formation of the country's export potential. At the same time, under conditions of increasing competition and globalization of the economy, mining enterprises in Kazakhstan face the tasks of increasing the efficiency of deposit development, reducing production costs, minimizing environmental risks, and ensuring sustainable development [3].

Special attention in recent years has been paid to the improvement of open-pit mining technologies. The open-pit mining method is widespread due to its versatility, relative simplicity of production process organization, high productivity, and the possibility of using modern highly efficient machinery and equipment. However, open-pit mining involves a number of complexities: increasing volumes of stripping operations, the need to ensure the stability of quarry slopes, the safety of drilling and blasting operations, rational organization of transport flows, and the processing of large volumes of ore with varying quality [4, 5].

One of the promising objects for open-pit mining is the Boguty tungsten deposit, located in Central Kazakhstan. This object is characterized by favorable geological and mining-technical conditions, which makes it attractive for industrial development. At the same time, the specificity of the deposit requires a comprehensive

© Zhanakova R. K., Almenov T. M., Sarybayev M. A., Koroviaka Ye. A., Seksenbay M. Zh., Vashchenko I. O., 2026

scientific analysis, including the study of geological features, tectonics, hydrogeological conditions, the mineral and chemical composition of ores and rocks, as well as the evaluation of techno-economic development indicators [6, 7].

The relevance of the study of the Boguty deposit is determined by a number of factors.

In conditions of growing global demand for nonferrous and ferrous metals, the development of new deposits in Kazakhstan will strengthen the country's position in the global mineral resource market.

The deposit represents a unique object for studying geological and hydrogeological processes, patterns of ore body formation, and the influence of tectonic disturbances on the distribution of useful components.

The site's specific characteristics allow for the implementation of advanced techniques in ore processing, transport, and drill-and-blast operations, ultimately boosting overall operational productivity.

Modern approaches to deposit development require taking into account the principles of sustainable development, minimizing negative environmental impacts, and the rational use of natural resources.

Literature review. Increasing the efficiency of solid mineral deposit development and the rational use of the mineral resource base are priority tasks of modern mining science [8, 9]. In [8], development systems for steeply dipping thin ore bodies are substantiated, and dependencies of dilution and labor productivity on the thickness of the deposit are established for the first time. The study [9] is dedicated to the investigation of rare-metal mineralization in specific geological conditions of Kazakhstan using aerial photography for precise geometrization of objects.

Ensuring the stability of quarry slopes during their deepening requires a detailed study of the stress-strain state of the rock mass [7, 10]. Article [10] proposes a methodology for identifying vulnerable sections of slopes based on creating models of the stress-strain state of the near-pit rock mass using laser scanning data. The authors of study [7] conducted a numerical analysis of rock stability under tectonic fault conditions using the Examine 2D software, which allowed for the identification of potential instability zones around the workings.

The transition to intelligent design is based on the integration of geomechanical analysis and modern digital tools [11, 12]. In study [11], a basis for selecting optimal development systems during the transition from open-pit to underground operations was developed, taking into account the systematization of the rock mass by stability categories. In turn, the authors of article [12] proposed an intelligent approach to predicting surface subsidence based on the Sparrow Search Algorithm and gradient boosting (XGBoost), proving the high reliability of neural network models.

Optimization of drilling and blasting operations (D&B) parameters is a key factor in reducing losses and increasing safety [13, 14]. In study [13], the effectiveness of the sectional formation of cut cavities was experimentally proven, allowing for an increase in the blast hole utilization factor (BUF) from 0.88 to 0.97. In work [14], based on Chapo's law, the damping coefficient of the rock mass was determined to control and minimize the seismic impact of explosions on critical infrastructure.

The final stage of optimizing the quarry field parameters is a comprehensive account of economic indicators and the completeness of reserve extraction [6, 15]. Article [6] presents an assessment of the impact of losses and dilution on the profitability of gold deposits, proving the significance of these factors for the value-added chain. Article [15] substantiates the possibility of optimizing the design contours of deep quarries using 3D modeling in RS3 software to ensure maximum completeness of ore extraction while maintaining stability.

Unsolved aspects of the problem. The conducted analysis shows that despite the existence of fundamental research in the field of geomechanical modeling [10, 11] and digitalization of mining production [12, 16], the issues of their integrated application for the specific conditions of the Boguty deposit remain insufficiently studied. In particular, the literature lacks a unified methodology that allows for a comprehensive linkage of precision wireframe modeling of complex morphology ore bodies with the operational optimization of D&B parameters to minimize qualitative and quantitative ore losses [6, 13]. Thus, there is an objective need for the development of science-based recommendations that combine geological, technological, and economic factors into a single system for optimizing quarry field parameters specifically for the conditions of Central Kazakhstan.

The purpose of this study is to conduct a comprehensive analysis of the mining-geological and technological conditions of the Boguty deposit to develop science-based recommendations for enhancing the efficiency of its development using digital modeling methods.

To achieve the set goal, the following **tasks** are addressed in the work:

- study of the geological features of the deposit, including tectonics, mineral and chemical composition of ores;
- analysis of hydrogeological conditions and their influence on the development technology;
- construction of wireframe models of ore bodies to refine reserves and optimize quarry parameters;
- investigation of mining-technical conditions, including stripping ratios, development systems, and transport schemes;
- substantiation of drilling and blasting parameters and analysis of their influence on ore losses and dilution;
- determination of loss and dilution coefficients, identification of factors affecting their magnitude;
- assessment of techno-economic indicators of deposit development;
- formulation of practical recommendations for ensuring environmental and production efficiency.

Methods. The information base for constructing wireframe models was an array of exploration data, including the results of core drilling, well logging, as well as panning and lithogeochemical sampling data. Geometrization and verification of the spatial position of ore bodies were carried out based on a comprehensive structural-geological interpretation of the obtained materials to ensure the reliability of subsequent calculations [17].

The technological cycle for constructing wireframe models was implemented using specialized mining and geological information systems (MGIS) – Micromine and Surpac. The choice of these software suites is justi-

fied by their ability to provide high accuracy in the interpolation of geological data and their wide functionality for optimizing open-pit mining parameters [18]. The triangulation algorithms underlying the MGIS made it possible to create reliable geometric representations of ore bodies, providing a digital foundation for the subsequent design of the quarry field mining stages (Fig. 1).

Results. ***Mining-geological and hydrogeological characteristics of development conditions.*** The object of research – the Boguty tungsten deposit – is located within the Central Kazakhstan metallogenic zone, characterized by the wide distribution of non-ferrous metal formations and a diversity of geological structures (Fig. 2) [19, 20]. The area is distinguished by a complex geological structure, where the interaction of formations varying in age and composition determines the specifics of ore-forming processes and the variability of the mineral composition of ores.

The deposit is characterized by a developed transport infrastructure: the proximity of highways and railways significantly simplifies the material and technical support of mining operations. The specifics of the region's natural and climatic conditions (deficit of surface water and low winter temperatures) were taken into account when designing water supply systems and selecting mining and transport equipment to ensure its continuous operation.

The topography of the area is a plain with absolute elevations of 300–500 m above sea level. The absence of permanent surface watercourses near the site determines the leading role of groundwater in the hydrogeological

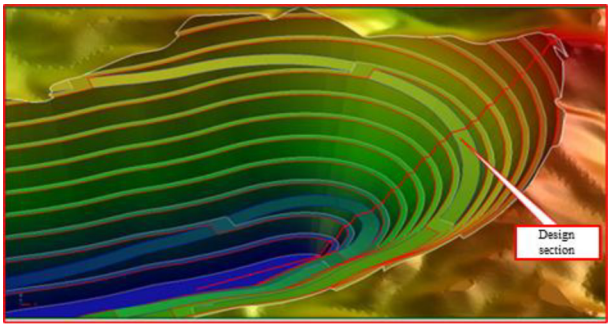

Fig. 1. Design variant in plan view with a calculated quarry cross-section

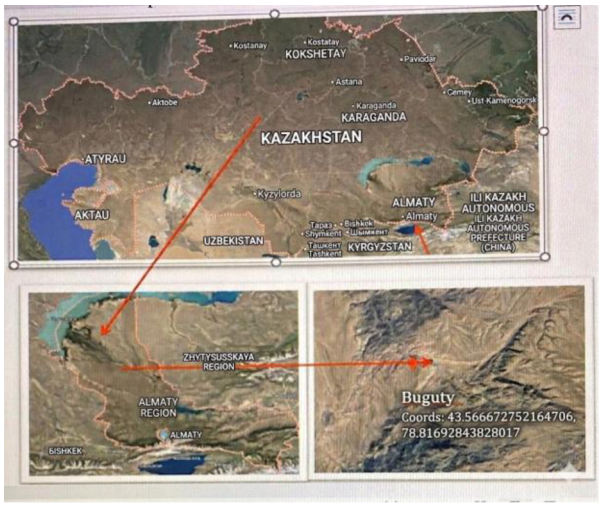

Fig. 2. Object of study

balance of the deposit, which is a decisive factor in the design of dewatering and technical water supply systems.

The geological basement of the area is represented by ancient metamorphic and igneous complexes, overlain by younger sedimentary strata. The structural heterogeneity of the deposit is due to the presence of several blocks separated by tectonic disturbances. It was established that specifically the zones of tectonic activity served as the main channels for ore-forming fluids, which determined the morphology of the ore bodies and the localization of useful components.

The high metallogenic potential of the area is due to a combination of intensive magmatism, metasomatic rock alterations, and the active functioning of hydrothermal faults. These factors determined the formation in Central Kazakhstan of a number of significant deposits of copper, polymetallic ores, gold, and iron, with which the Boguty deposit belongs to the same metallogenic series.

The Boguty deposit is of significant industrial interest as a promising object for open-pit mining. The favorable morphology of the ore bodies and their occurrence at a relatively shallow depth ensure high techno-economic efficiency of reserve extraction by the open-pit method (Fig. 3).

The characteristics of the material composition and structural-tectonic framework of the Boguty deposit are defined by high complexity and the presence of multiple ore-controlling factors. These geological conditions determine the patterns of spatial distribution of minerals and the specifics of the parameters for their industrial development.

The lithological section of the deposit is represented by several large geological complexes. The basement of the territory is composed of Archean and Proterozoic metamorphosed strata – gneisses, amphibolites, and quartzites. These rocks are characterized by the highest strength indicators and serve as a rigid foundation for the overlying formations [21].

The overlying horizons are represented by a Paleozoic complex of igneous (granites, diorites, granodiorites) and volcanic (andesites, dacites, and their tuffs) rocks. Carbonate formations – limestones and dolomites – play a special role in the structure of the deposit, acting in most cases as the host environment for the ore bodies.

The tectonic structure of the deposit is characterized by the presence of several systems of faults striking northeast and northwest. These zones act as the primary ore-controlling structures: intensive circulation of hydrothermal solutions occurred along them, which determined the localization and morphology of industrial ore bodies.

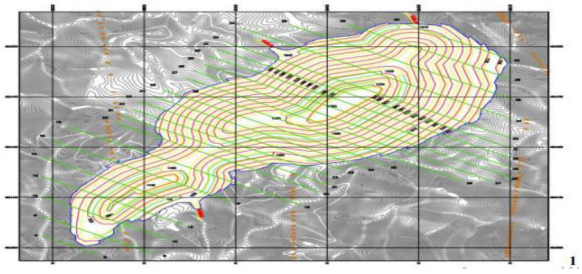

Fig. 3. Topographic map of the deposit

The choice of the open-pit mining method for the Boguty deposit is driven by the shallow depth of the primary ore zones, ranging from surface outcrops to a maximum depth of 80 meters. This surface extraction approach offers significant economic advantages by avoiding the high initial capital required for complex underground infrastructure and shaft sinking. The open-pit mining method allows for effective control of mining-technical parameters, the use of high-performance drilling and blasting equipment, and large-unit-capacity quarry machinery for the transportation of ore and overburden [22].

The local hydrogeology lacks any continuous surface streams or significant water basins. Consequently, groundwater recharge relies heavily on rainfall and snowmelt. Given the severe continental climate, water seepage into the rock mass is intermittent and extremely uneven, which determines the specifics of the groundwater regime formation.

Groundwater is confined to zones of increased fracturing in igneous and metamorphic complexes, as well as to carbonate strata, occurring at depths of 40–70 m. Borehole productivity remains minimal (between 0.5 and 2.5 l/s) under low-pressure conditions, suggesting that early mining phases will not encounter major water ingress issues. Chemically, the groundwater features moderate salinity levels (0.5 to 1.5 g/l) and is classified as sulfate-bicarbonate. Occasionally, the concentration of sulfates and iron requires preliminary purification before technical use. Given the risk of a drawdown reduction in the groundwater level and the potential impact on the ecosystem, the development project provides for a set of measures to monitor and protect water resources to maintain the hydrodynamic balance of the region.

The tectonic structure of the area determines the patterns of formation and spatial localization of the ore bodies of the Boguty deposit [23]. The main ore-controlling function is performed by systems of faults in northeast and northwest directions. These structures provided pathways for the intrusion of igneous melts and the subsequent circulation of hydrothermal fluids, which led to the formation of industrial mineralization.

The multi-stage nature of tectonic movements led to the superposition of mineralization stages of different ages, which determined the heterogeneous internal structure of the ore bodies and significant variability in their thicknesses. Despite the high geodynamic stability of the area, which favors open-pit mining operations, the presence of zones of increased fracturing requires the implementation of special engineering measures to ensure the stability of the pit walls, especially when mining deep horizons.

The qualitative indicators of the Boguty deposit ores are determined by the content of the main useful components and their technological properties, which dictate the choice of the processing scheme. The average tungsten content in the industrial contours is 0.178 %. The distribution of mineralization is characterized by a high degree of unevenness: both high-grade areas with content up to 0.25–0.30 % and low-grade zones (less than 0.1 %) are recorded. This variability necessitates the use of selective mining and enhanced operational geological quality control of the extracted rock mass. According to physical and mechanical properties, the ores are characterized by medium and high strength (the hardness coefficient on the M.M. Protodyakonov scale is 8–12), which requires high intensity of drilling and blasting fragmentation when preparing the rock mass for excavation [24, 25].

The oxidation zone, localized in the near-surface horizons of the deposit, is represented by secondary copper minerals: malachite, azurite, and cuprite. Despite the simplified technological schemes for processing these ores, their volume in the total reserve balance is limited. The results of technological tests for amenability to processing indicate high efficiency of the flotation method for sulfide ores: the recovery coefficient during enrichment reaches 60%.

The calculation of the recoverable value of tungsten and the ultimate stripping ratio for open-pit mining are given in Table 1.

Digital modeling of ore body morphology and geomechanical parameters of the quarry. The application of wireframe modeling methods allows for the complex optimization of the geometric parameters of the quarry field [26]. During the study, rational slope angles, bench heights, and working platform widths were determined, and a precision forecast of rock mass volumes, levels of technological losses, and dilution was performed. The high accuracy of the spatial coordination of the design contours of the workings with the morphology of the ore bodies allowed for minimizing the risks of geometric deviations and excluding excessive involvement of host rocks in the production cycle.

At the same time, the open-pit mining method is associated with a number of technological challenges. A key limitation is the necessity of moving significant volumes of overburden, which leads to an increase in the stripping ratio and requires substantial organizational and technical resources. As the quarry deepens, the importance of ensuring slope stability, organizing effective dewatering systems, and minimizing dust emissions increases [27]. Solving these tasks requires high-precision spatial analysis, which is implemented through digital modeling.

A key tool in preparing the Boguty deposit for industrial development is the construction of wireframe (three-dimensional) models of the ore bodies. Implementing 3D computer modeling enables accurate spatial evaluation of ore body shapes, depths, and thicknesses. Furthermore, these digital tools facilitate a comprehen-

Table 1

Indicators of recoverable ore value and ultimate parameters of open-pit mining

Indicator	Unit	Value (Quarry)
Cost of 1 t of tungsten concentrate	$	19,000
Amount of commercial ore	t	102,560,000
Average grade	%	0.178
Amount of metal in ore	t	182,557
Recovery rate during processing	%	60
Recovered amount of tungsten	t	109,534.2
Revenue from tungsten sales	thousand $	2,081,149.8
Recoverable value per 1 t of ore	$	29.43
Ultimate stripping ratio	t/t	7.85

sive visual representation of how mineralized zones interact with the surrounding geological and tectonic structures.

The analysis of the constructed wireframe models of the Boguty deposit allowed for the identification of a complex spatial configuration of the ore bodies, represented by a combination of lenticular, vein-like, and stockwork morphotypes. In certain areas, zones of junction and interference of several ore bodies were recorded, forming single complex-structured mineralized zones, which requires special attention when designing the mining contours.

Visualization of the results of the geometrization of the deposits is presented in Fig. 4: the integrated wireframe model reflects the spatial position of the balance ore bodies (Fig. 4, *1*) and the general structure of mineralization, taking into account off-balance reserves (Fig. 4, *2*). Such a comparison allows for evaluating the prospects for expanding the boundaries of open-pit mining and the feasibility of selective extraction of low-grade ores [28].

The use of the developed wireframe models allowed for an integrated approach to solving the following engineering tasks:

- refinement of industrial reserve volumes and predictive resource modeling within the design pit limits;
- geometric optimization of the quarry design parameters, taking into account the morphology of the ore bodies;
- technological planning of drilling, blasting, and mining-transport operations;
- scientific substantiation of decisions to minimize ore loss and dilution indicators when mining complex-structured zones.

To assess the geomechanical stability of the quarry's structural elements, modeling of the stress-strain state (SSS) of the rock mass was performed using the Rocscience software suite (Figs. 5, 6).

Based on the results of modeling the structural-tectonic situation in the Rocscience software suite, three hierarchical types of tectonic disturbances determining the stability and morphology of the object were identified:

1. Deep-seated regional-scale faults – form the structural framework of the deposit and determine the spatial position of igneous intrusions.

2. Second-order faults – act as the main migration channels for ore-controlling fluids; characterized by the development of intensive crushing and silicification zones.

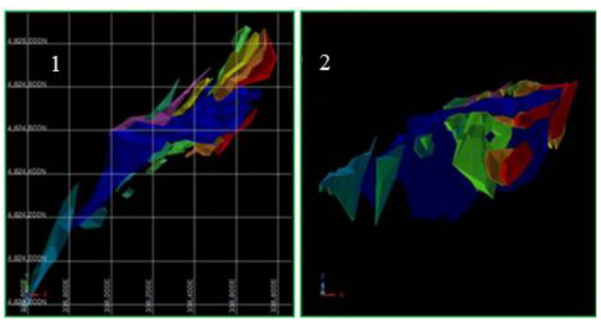

Fig. 4. Combined wireframe model of balance ores:
1 – plan view; 2 – north view at a –15° angle

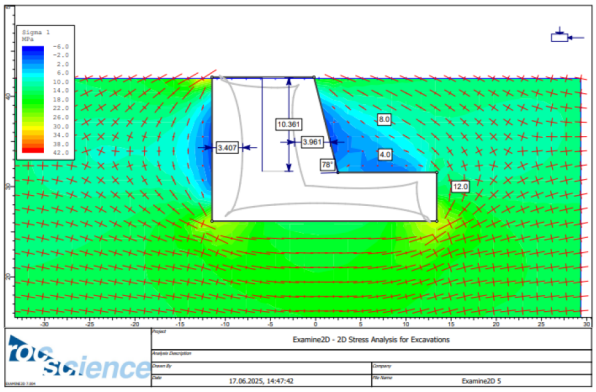

Fig. 5. Stability of the quarry contour of the Boguty tungsten deposit

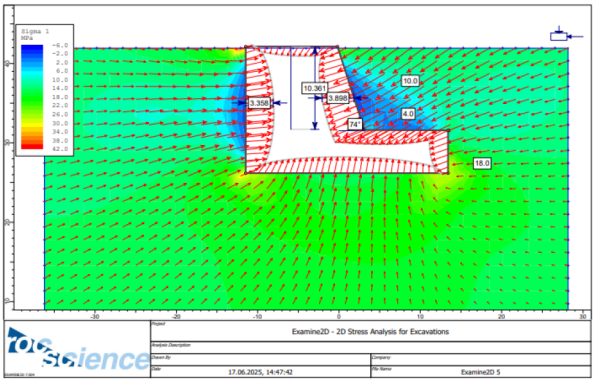

Fig. 6. Influence of tectonic disturbances on the quarry contour

3. Micro-fracturing and shear zones – play a decisive role in the localization of vein ore bodies and the formation of their internal morphology.

The average stripping ratio (the ratio of overburden mass to the mass of extracted ore) obtained as a result of the design contour optimization is 2.5–3.0. This indicator correlates with average industry values for similar deposits in Kazakhstan, confirming the high profitability and economic feasibility of the open-pit reserve development method within the identified boundaries.

The lithological composition of the overburden is represented mainly by granitoids, quartzites, and schists. The high strength properties of these lithotypes necessitate the use of the drilling and blasting method for preparing the rock mass for excavation at all stripping horizons. Minimizing the stripping ratio and increasing the overall efficiency of mining operations are achieved through geometric optimization of the opening-up schemes, rational tracing of transport communications and ramps, as well as the implementation of progressive technologies for external and internal waste dumping.

Based on the completed complex of design and analytical work, a science-based open-pit mining system using digital wireframe modeling has been formed for the Boguty deposit. The optimization of the quarry field parameters was implemented based on a multi-factor analysis of geological, mining-technical, and economic indicators.

A deepening mining system using motor transport and combined (external and internal) dumping was adopted as the primary system. The adopted technological

scheme provides for the phased deepening of the quarry with the extraction of the rock mass in horizontal layers (benches) 15 m high. The geometric parameters of the design contour are defined by the following values:

- working platform width – 25–30 m;
- working bench face angle – 65–70°;
- final pit wall angle – 45–50°.

The results of analytical calculations (Table 2) confirmed that with a bench height of 10 m and a working face angle of 75°, the minimum allowable working platform width is 45.6 m. This parameter fully complies with regulatory industrial safety requirements and provides conditions for the high-performance operation of the excavator-transport complex. Taking into account the dimensions of the excavation-loading and transport equipment used when loading rock mass into dump trucks, the working platform width is taken to be 46 m.

Reserve extraction provides for the application of selective mining: high-grade ores are transported directly to the processing plant, while low-grade raw material is stockpiled in specialized dumps to form a technogenic resource for subsequent involvement in processing.

The quarry transport scheme is based on the use of motor transport. As the primary fleet at the initial stage, mining dump trucks with a payload capacity of 55–90 t have been adopted. In the long term, as the quarry depth and transportation volumes increase, the introduction of equipment with a payload capacity of up to 130 t is justified, which will significantly reduce the unit production cost of rock mass haulage. The geometric parameters of in-pit roads with a longitudinal gradient of 8–10 % fully comply with industrial safety requirements.

The excavation and loading complex is represented by a fleet of hydraulic and electric excavators with a bucket capacity of 6–12 m³, providing the necessary technological flexibility and high productivity for the selective mining of various ore grades.

To optimize costs at deep horizons, the possibility of transitioning to in-pit crushing and conveying (IPCC) technology using conveyor transport is being considered. Despite significant capital investments, this solution will ensure a stable reduction in operating expenses and increase environmental safety by reducing exhaust emissions from mining equipment.

The drilling and blasting (D&B) method is the basic technological process for preparing ore and overburden for excavation at the Boguty deposit. As a result of optimization, the following drilling parameters have been established: borehole diameter: 165–250 mm; depth: 12–15 m. The drilling pattern is adopted differentially: 6 × 7 m for overburden and 5 × 6 m for ore bodies, due to the need for higher quality fragmentation of the mineral. For blasting operations, ammonium nitrate-based explosives (ANFO) and emulsion explosives are used in combination with electronic initiation systems. The implementation of short-delay blasting schemes with an interval of 17–25 ms ensures uniform fragmentation of the rock mass and minimization of seismic impact on the pit walls and engineering structures [29]. The average oversize yield is 3–5 % with a powder factor at the level of 0.4–0.6 kg/m³.

A comprehensive analysis of experimental data and calculated indicators confirmed the existence of a correlation dependence between the geometric parameters of the bench (height and slope angle) and the values of technological losses and ore dilution (Table 3). It was established that the optimization of these parameters during 3D modeling allows for achieving the minimum possible levels of dilution while maintaining the regulatory stability of the pit walls, which is critically important for the effective mining of the deposit's complex-structured zones.

Table 2

Parameters affecting the working platform width

Indicator	Unit of measurement	Value
Bench height	m	10
Working face angle	deg	75
Height (radius)	m	12.4
Excavator width	m	21.0
Distance from the toe to the road axis	m	2
Distance from the road axis to the potential collapse line (lower crest of the safety berm)	m	2
Width of the blasted rock mass	m	15.5
Safety berm width	m	5.1
Minimum working platform width	m	45.6

Table 3

Results of loss and dilution calculations for various slope angles and bench heights

Indicators	Working face angle, deg			Working face angle, deg	
	74	75	78	75	78
Horizontal thickness, m	286.2				
Dip angle, deg	80				
Height, m	10			15	
Density, t/m³	2.74				
Loss area, m²	123	115	120	188	177
Dilution area, m²	1.99	1.62	1.66	2.4	0.95
Absolute loss indicator	2.42	1.97	2.25	4.65	3.05
Absolute dilution indicator	583	517	560	51	45
Balance reserves, t	7,841.8	7,841.8	7,841.8	7,841.8	7,841.8
Regulatory loss rate, %	3.5	2.89	3.2	11.2	7.42
Regulatory dilution rate, %	7.9	6.4	6.6	9.5	6.4

The evaluated data demonstrates a clear correlation linking bench height and slope inclination with the final ore extraction rates. Relying on various simulation scenarios, the following values have been approved as design parameters: technological loss level – 2.9 %, dilution coefficient – 6.4 %. The obtained indicators testify to the high efficiency of the chosen geometric configuration of the quarry and allow for minimizing the economic damage from the loss of valuable components during the mining of complex-structured zones.

It was established that varying the working face angle in the range from 74 to 78° and increasing the bench height from 10 to 15 m leads to a significant improvement in recovery indicators: a reduction in technologi-

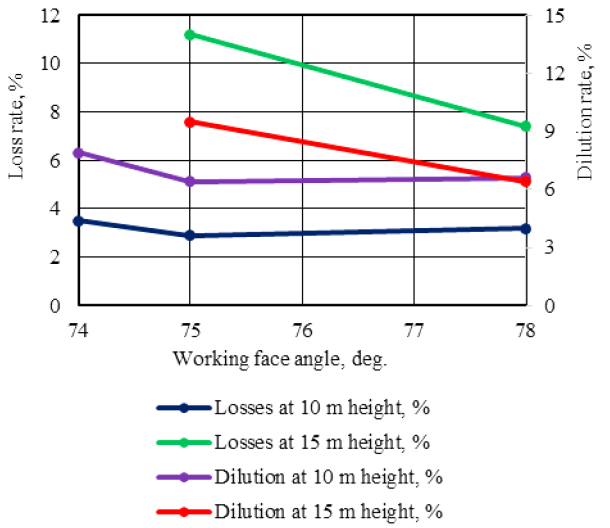

Fig. 7. Dependence of losses and dilution on working bench parameters

cal losses from 3.5 to 2.9 % and in the dilution coefficient from 7.9 to 6.4 % was recorded.

Based on the obtained data, the following parameters were determined as optimal for the conditions of the Boguty deposit: working bench slope angle – 75°, bench height – 15 m. These design values ensure not only the minimization of losses and dilution but also guarantee the stability of the slopes while simultaneously increasing the productivity of drilling and blasting (D&B) operations due to the increase in the volume of the blasted block (Fig. 8).

The grain-size distribution (fragmentation) of the blasted ore is characterized by a balanced distribution across size classes: the fine fraction (<20 mm) accounts for 25–30 %, the medium fraction (20–100 mm) – 45–50 %, and the coarse fraction (>100 mm) – 20–25 %. Such a distribution ensures high productivity of crushing and grinding equipment at subsequent processing stages and contributes to reducing specific energy consumption for comminution. The weighted average grade of the useful component in the extracted ore was recorded at 1.2–1.4 %, which fully complies with the established cutoff grade requirements and confirms the high reliability of the geological forecast and mining selectivity within the design pit limits.

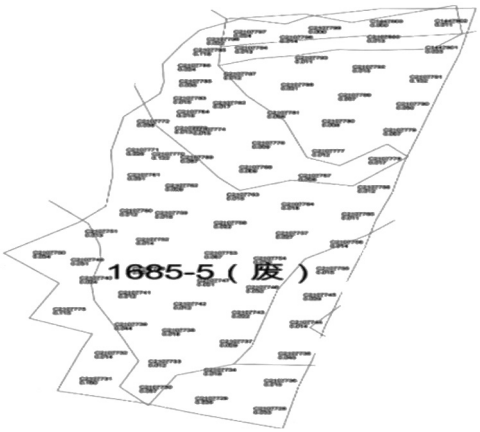

Fig. 8. Drilling and blasting pattern for block No. 5-1685

The integration of wireframe modeling into the design process has provided a significant increase in the economic and technological efficiency of mining operations. Optimized parameters guarantee regulatory slope stability and the achievement of minimum levels of ore loss (up to 2.9 %) and dilution (up to 6.4 %), which fully aligns with international mining standards. The results obtained confirm the methodological validity of the proposed approach and the possibility of its scaling to deposits with similar mining-geological and geomechanical conditions.

Optimization of mining parameters and techno-economic development indicators. The techno-economic indicators for the development of the Boguty tungsten deposit confirm the high efficiency of the proposed solutions. The annual design capacity of the quarry is 5 million tons of ore and 10 million tons of overburden, with an average stripping ratio of 2.0. Labor productivity is recorded at 500–600 t/person per month, and the ore production cost is $18–20/t, which guarantees the enterprise's competitiveness. According to predictive calculations, the project possesses high investment characteristics: the Net Present Value (NPV) is approximately $320 million, the Internal Rate of Return (IRR) is 18–20 %, with a payback period of 6–7 years and a total operational life of 25–30 years.

Model limitations and assumptions. The developed digital model of the Boguty deposit and the results of subsequent optimization of the quarry parameters rely on a number of methodological assumptions necessitated by the complexity of the natural-technogenic system and the discrete nature of the initial information.

The primary assumption of wireframe modeling is the hypothesis of the continuity of ore mineralization between exploratory drill hole intersections [30]. Given the significant variability in thickness and the complex internal structure of the ore bodies identified during the research, the actual position of "ore-host rock" contacts may differ from the model in zones of intense tectonic influence. The block model averages tungsten grade indicators within an elementary block, which, at the long-term planning stage, smooths the local heterogeneity of mineralization.

For pit wall stability simulations, the geological formations were treated as a continuous, isotropic material within specific rock types. Although fault zones were incorporated, the simulation cannot perfectly mimic the random distribution of micro-fractures across the site. Additionally, drainage system designs rely on a constant flow filtration regime that does not account for extreme peak loads associated with abnormal atmospheric precipitation or sudden changes in rock permeability at deep horizons.

Predicted metal recovery rates (60 % for tungsten) are adopted as constants based on the results of laboratory tests of representative ore samples. The model assumes the preservation of the ore's technological properties throughout the entire operational life of the quarry. However, a possible change in mineral associations with depth or an increase in the proportion of refractory oxidized varieties may require adjustments to the reagent regimes, which in the current version of the model is considered an external risk factor.

Long-term forecasting of economic indicators (NPV, IRR) for a 25–30-year period was performed based on current market conditions. The model assumes a stable tax burden and a fixed discount rate. The impact of global tungsten price volatility and inflationary processes on operating costs was accounted for through sensitivity analysis; however, the base scenario for optimizing the quarry contours remains deterministic and requires periodic recalculation in the event of significant changes in the macroeconomic environment.

Conclusions. The conducted comprehensive techno-economic and mining-technical analysis confirms that the industrial development of the Boguty tungsten deposit by the open-pit method is a highly efficient and technologically sound project. The main results of the study are as follows:

1. Digital Wireframe Modeling: The application of 3D modeling allowed for the adaptation of the design pit limits to the complex morphology of the ore bodies. Transitioning to a 15 m bench height and increasing the working face angle to 75° ensures a reduction in technological losses to 2.9 % and a dilution coefficient of 6.4 %, significantly exceeding the performance of traditional design methods.

2. Blasting Efficiency: Test results confirmed that using electronic initiation systems in combination with selective mining reduces the oversize yield by 15–20 %, ensuring uniform rock mass fragmentation and stable operation of the excavator-transport complex.

3. Economic Viability: The project demonstrates strong investment indicators (Net Present Value (NPV) of $320 million, Internal Rate of Return (IRR) of 18–20 %) with a payback period of 6–7 years, guaranteeing the long-term competitiveness of the enterprise in the global market.

An integrated approach to 3D modeling has been developed, which, for the first time for this site, accounts for the synergy of tectonic, hydrogeological, and mining-technical factors. The relationships between bench geometry and the completeness of reserve extraction in complex-structured deposits have been substantiated.

The applied significance of this study is that its methodological framework can be easily adapted for other comparable mining sites. Adopting these strategies leads to lower operational expenses while simultaneously shrinking the ecological footprint via optimized resource extraction.

Further improvement of the presented methodology is seen in the deep digitalization of subsurface resource management. A promising direction is the integration of wireframe models with Automated Fleet Management Systems (FMS) and the implementation of machine learning algorithms for dynamic, real-time refinement of ore quality indicators. This will enable the creation of a "Digital Twin" of the enterprise, providing a flexible response to changing mining-geological conditions.

References.

1. Kononenko, M., Khomenko, O., Sudakov, A., Drobot, S., & Lkhagva, T. (2016). Numerical modelling of massif zonal structuring around underground working. *Mining of Mineral Deposits*, *10*(3), 101-106. https://doi.org/10.15407/mining10.03.101

2. Pavlychenko, A. V., Ihnatov, A. O., Koroviaka, Y. A., Ratov, B. T., & Zakenov, S. T. (2022). Problematics of the issues concerning development of energy-saving and environmentally efficient technologies of well construction. *IOP Conference Series: Earth and Environmental Science*, *1049*(1). https://doi.org/10.1088/1755-1315/1049/1/012031

3. Ratov, B. T., Khomenko, V. L., Kuttybayev, A. E., Togizov, K. S., & Utepov, Z. G. (2024). Innovative drill bit to improve the efficiency of drilling operations at uranium deposits in Kazakhstan. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *4*(465), 224-236. https://doi.org/10.32014/2024.2518-170X.437

4. Ullah, S., Ren, G., Ge, Y., Burhan Memon, M., Kinyua, E., & Munene Ndayiragije, T. (2025). Dynamic slope stability assessment under blast-induced ground vibrations in open-pit mines: a pseudo-static limit equilibrium approach. *Sustainability*, *17*(14), 6642. https://doi.org/10.3390/su17146642

5. Pashchenko, O., Kamyshatskyi, O., Omirzakova, E., & Ratova, S. (2025). Development and optimization of hard alloy compositions for rock destruction. *Engineering for Rural Development*, *24*, 512-518. https://doi.org/10.22616/ERDev.2025.24.TF110

6. Almenov, T. M., Zhanakova, R. K., Askarova, G. E., Shautenov, M. R., & Amantayuly, K. (2025). Comprehensive assessment of ore losses and dilution impacting Vasilkovsky gold deposit profitability. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, (4), 27-46. https://doi.org/10.32014/2025.2518-170X.528

7. 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. https://doi.org/10.33271/mining14.03.028

8. Rysbekov, K., Bitimbayev, M., Akhmetkanov, D., Yelemessov, K., Barmenshinova, M., Toktarov, A., & Baskanbayeva, D. (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. https://doi.org/10.33271/mining16.02.064

9. Amralinova, B. (2023). Rare-metal mineralization in salt lakes and the linkage with composition of granites: evidence from burabay rock mass (Eastern Kazakhstan). *Water*, *15*(7), 1386. https://doi.org/10.3390/w15071386

10. Saik, P. B., Rysbekov, K. B., Kassymkanova, K. M., Lozynskyi, V., Meirambek, G., Moldabayev, S. K., Babets, D. v., & Salkynov, A. (2024). Investigation of the rock mass state in the near-wall part of the quarry and its stability management. *Frontiers in Earth Science*, *12*. https://doi.org/10.3389/feart.2024.1395418

11. Bekbergenov, D. K., Jangulova, G. K., Zeinullin, A., Zhanakova, R., Shagirova, K., Atalykova, N., & Kurmanbayev, O. (2025). Modeling of geomechanical processes from open pit to underground mining with complex morphology. *Civil Engineering Journal*, *11*(7). https://doi.org/10.28991/CEJ-2025-011-07-013

12. Xu, C., Zhou, K. P., Xiong, X., Gao, F., & Lu, Y. (2023). Prediction of mining-induced subsidence by sparrow search algorithm with extreme gradient boosting and TOPSIS method. *Acta Geotechnica*, 1-17. https://doi.org/10.1007/s11440-023-01830-7

13. Lozynskyi, V., Yussupov, K. A., Rysbekov, K. B., Rustemov, S., & Bazaluk, O. (2024). Using sectional blasting to improve the efficiency of making cut cavities in underground mine workings. *Frontiers in Earth Science*, *12*. https://doi.org/10.3389/feart.2024.1366901

14. Slimane, H., Berdoudi, S., & Hadji, R. (2024). Blast-induced vibration assessment in the Rouina open-pit mine: Impacts and measurements for the Ouled Mellouk Dam. *Mining of Mineral Deposits*, *18*(4), 1-9. https://doi.org/10.33271/mining18.04.001

15. 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. https://doi.org/10.33271/mining18.02.001

16. Ratov, B., Pavlychenko, A., Kirin, R., Pashchenko, O., Khomenko, V., Tileuberdi, N., ..., & Muratova, S. (2025). Using machine learning to model mechanical processes in mining: theory, practice, and legal considerations. *Engineered Science*, *33*. https://doi.org/10.30919/es1419

17. Yuan, J., Liu, G., & Chai, S. (2024). 3D geological fine modeling and dynamic updating method of fault slope in open-pit coal mine. *Scientific Reports*, *14*, 29906. https://doi.org/10.1038/s41598-024-81872-3

18. Lutsenko, S., Hryhoriev, Y., Peregudov, V., Kuttybayev, A., & Shampykova, A. (2021). Improving the methods for determining the promising boundaries of iron ore open pits. *E3S Web of Conferences*, *280*. https://doi.org/10.1051/e3sconf/202128001005

19. Bekbergenov, D. K., Jangulova, G. K., Zhanakova, R., & Bektur, B. (2024). Investigation of the block caving geotechnology at deep horizons. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *6*(468), 49-66. https://doi.org/10.32014/2024.2518-170X.460
20. Kuttybayev, A. E., Muratova, S. K., Khomenko, V. L., Pashchenko, O. A., & Meiram, G. (2025). Development and implementation of a program for monitoring the stability of quarry excavation slopes in the Almala area. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*, *25*(1.1), 379-386. https://doi.org/10.5593/sgem2025/1.1/s04.46
21. Ge, Z. P., Xu, J. N., Zhang, Z. Y., Liu, X. R., & Wang, B. L. (2024). Experimental study on the mechanical properties and energy evolution characteristics of sandstone under different stress paths. *Scientific Reports*, *14*, 2883. https://doi.org/10.1038/s41598-024-53227-5
22. Hang, Z., Xue, T., Chen, J., Shi, Y., Yin, Z., Cui, Z., & Zhou, G. (2025). A 3D geological modeling method using the transformer model: A solution for sparse borehole data. *Minerals*, *15*(3), 301. https://doi.org/10.3390/min15030301
23. Almenov, T., Zhanakova, R., Sarybayev, M., & Shabaz, D.-M. (2025). A novel approach to selecting rational supports for underground mining workings. *Civil Engineering Journal*, *11*(3), 1217-1241. https://doi.org/10.28991/CEJ-2025-011-03-022
24. Feng, Y., Wen, G., Shang, J., Wen, S., & Wu, B. (2024). Research on 3D geological modeling based on boosting integration strategy. *Ore Geology Reviews*, *171*, 106157. https://doi.org/10.1016/j.oregeorev.2024.106157
25. Ratov, B., Kuttybayev, A., Tileuberdi, N., Utepov, Z., Aliakbar, M., Zhanggirkhanova, A., ..., & Seidaliyev, A. (2025). Application of plasticizers octadecane to pentatriacontane and ethylene glycol in the manufacture of metaloceramic alloys. *ES Materials and Manufacturing*, *28*. https://doi.org/10.30919/mm1563
26. Zhou, J., Zhu, S. L., Qiu, Y. G., Armaghani, D. J., Zhou, A. N., & Yong, W. X. (2022). Predicting tunnel squeezing using support vector machine optimized by whale optimization algorithm. *Acta Geotechnica*, *17*(4), 43-66. https://doi.org/10.1007/s11440-022-01450-7
27. Mnzool, M., Almujibah, H., Bakri, M., Gaafar, A., Elhassan, A. A. M., & Gomaa, E. (2024). Optimization of cycle time for loading and hauling trucks in open-pit mining. *Mining of Mineral Deposits*, *18*(1), 18-26. https://doi.org/10.33271/mining18.01.018
28. Cheng, Y., & Hou, K. (2025). Open-pit slope stability analysis integrating empirical models and multi-source monitoring data. *Applied Sciences*, *15*(17), 9278. https://doi.org/10.3390/app15179278
29. Guo, J., Zhao, Z., Zhao, P., & Chen, J. (2024). Prediction and optimization of open-pit mine blasting based on intelligent algorithms. *Applied Sciences*, *14*(13), 5609. https://doi.org/10.3390/app14135609
30. Wang, S., Cao, B., Bai, R., & Liu, G. (2024). Dynamic optimization design of open-pit mine full-boundary slope considering uncertainty of rock mass strength. *Scientific Reports*, *14*, 19572. https://doi.org/10.1038/s41598-024-70902-9

Каркасне моделювання для оптимізації параметрів кар'єрного поля Богутинського родовища вольфраму (Казахстан)

Р. К. Жанакова[1], *Т. М. Алменов*[1], *М. А. Сарибаєв*[*2], *Є. А. Коровяка*[3], *М. Ж. Сексенбай*[4], *І. О. Ващенко*[3]

1 – Університет Сатпаєва, м. Алмати, Казахстан
2 – Казахський національний університет імені аль-Фарабі, м. Алмати, Казахстан
3 – Національний технічний університет «Дніпровська політехніка», м. Дніпро, Україна
4 – Казахський національний університет водного господарства та іригації, м. Тараз, Казахстан
* Автор-кореспондент e-mail: Sarybayev.Madiyar@kaznu.kz

Мета. Комплексний аналізу гірничо-геологічних і технологічних умов Богутинського родовища (Казахстан) для розробки науково обґрунтованих рекомендацій щодо підвищення ефективності його освоєння із застосуванням методів цифрового моделювання.

Методика. У дослідженні використано комплексний підхід, що включає каркасне 3D-моделювання рудних тіл, геоінформаційний аналіз даних розвідки й техніко-економічну оптимізацію параметрів видобутку. Моделювання й оцінка стійкості бортів виконувалися у програмних комплексах Micromine, Surpac і Rocscience (Examine2D) з урахуванням структурно-тектонічних особливостей і гідродинамічного режиму масиву.

Результати. Встановлено, що оптимізація параметрів буровибухових робіт – збільшення висоти уступу до 15 м і кута нахилу робочого борту до 75° – дозволяє знизити експлуатаційні втрати до 2,9 %, а коефіцієнт розубожування до 6,4 %. Доведено, що прецизійна геометризація покладів забезпечує високу селективність виїмки та скорочення виходу негабариту на 15–20 %. Економічний аналіз підтвердив високу рентабельність проєкту (NPV $320 млн, IRR 18–20 %) при забезпеченні нормативної стійкості бортів кар'єру.

Наукова новизна. Розроблена інтегрована методика побудови каркасних моделей, що враховує синергетичний вплив тектонічних порушень і морфології рудних тіл на показники вилучення запасів. Уперше для умов даного об'єкта обґрунтована математична залежність між геометрією робочого уступу й якістю сировини, що видобувається.

Практична значимість. Запропоновані технологічні рішення дозволяють підвищити повноту виїмки надр, знизити собівартість видобутку руди до 18–20 $/т і мінімізувати екологічне навантаження. Розроблені методичні підходи можуть бути адаптовані для проєктування кар'єрів на родовищах зі схожими складноструктурними умовами.

Ключові слова: *каркасне моделювання, відкрита розробка, геоінформаційні технології, проєктування кар'єрів, сталий розвиток*