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Substantiating the rock mass control parameters based on the geomechanical model of the Severny Katpar deposit, Kazakhstan

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Abstract

Purpose. The research purpose is to develop a geomechanical model for ensuring the safety of mining operations by determining the optimal slope angles and probabilistic assessment of the stability of the open-pit walls.

Methods. Three-dimensional geomechanical models for surface mining of deposits have been developed based on calculations of the stability factor (safety factor – SF) of the open-pit walls in the Rocscience program to determine the rock mass stress-strain state at the end of mining using the finite element method. The geological wireframe model (GWM) has been built on the basis of the available geological sections, horizon plans and the results of the engineering-geological surveys using the Surpac geoinformation system.

Findings. Strength reduction factor (SRF) has been determined taking into account the physical-mechanical properties of rocks that constitute the near-wall mass. An assessment of the stability of walls according to the selected geological sections is given, taking into account the projected contour of the Severny Katpar open-pit walls. The calculation of the projected contour stability of the open-pit walls by several different methods has revealed that the open-pit walls are generally stable. The open-pit parameters at the end of mining have been determined.

Originality. For the first time, it has been determined that in the Southern and South-Western area of the Severny Katpar open-pit wall in the horizons +700…+400, there is a decrease in SF from 1.18 to 1.41 due to the predominant occurrence of siltstones and tectonic disturbances of the walls.

Practical implications. The mathematical calculation results of the stability of the projected contour walls in the Severny Katpar open pit have been generalized. In addition, a geological and structural wire-frame model of the deposit has been developed, which makes it possible to ensure the safety of mining operations in the open pit.

Keywords: *open pit, stress-strain state, geotechnical model, slope*

1. Introduction

The history of surface mining indicates a trend towards increasing mining depths [1]-[3]. At the beginning of the 20th century, mining operations were carried out within sedimentary rocks; the maximum depth of open pits of that time did not exceed 100 m from the surface, but after a few decades, the maximum surface mining depth reached 200-300 m [4]-[7]. A further increase in the demand for mineral raw materials led to the improvement of equipment and technologies, the maximum surface mining depth began to reach 400 m in some cases [5]. Achieving such a depth is poorly consistent not only with the feasibility of mining, but also with the trends of green mining development [8]-[10].

Due to such characteristics as high efficiency and productivity of extracting minerals from the subsoil, the surface mining method remains the leader in terms of the percentage of minerals mined. According to the data given in the works of domestic and foreign scientists, about 80% of all mined minerals are accounted for by surface mining [11]-[15].

One of the main issues in the processing of minerals extracted by surface mining method is to ensure safety in mining operations and achieve rational development of deposits. An increase in the depth of surface mining usually leads to the pushing back of the open-pit walls and an increase in the volume of overburden [16], [17]. Another option for involving in mining of deep open-pit horizons without a significant increase in the cost of mining operations is to revise the ori-

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ginal project and increase the final angle of the wall inclination [18]-[20]. With this option, the problem arises of ensuring the stability of the open-pit wall and selecting parameters that are rational from the point of view of geomechanics of the newly projected ledges at deep horizons.

The main condition necessary for the revision of the initial mining projects is information on the rock mass geomechanical state, which, along with the stress-strain state parameters and geological-structural peculiarities of the deposit, also includes knowledge of the physical-mechanical properties of host ores and rocks [18], [21], [22].

The methods developed and adopted at the enterprises do not fully cover all the problems that arise when mining deep open pits [23]-[25]. According to these normative documents, the parameters of walls and ledges of open pits should be determined and substantiated by calculating the stability factor using classical methods of limit equilibrium. However, these methods do not take into account structural disturbances of the rock mass, which have a negative impact on stability. In addition, the existing theoretical approaches to substantiating the stable angles of open pit walls do not, as a rule, take into account the real stress-strain state (SSS) of rock masses, assuming that it is conditioned only by the own weight of the overlying rocks [26].

When calculating the stability of walls according to the method of 1972, only the own weight of the sliding triangle is taken into account in all schemes [25]. In rock masses, where horizontal stresses in most cases exceed vertical ones, neglecting the destress deformations predetermines the possible development of emergency situations at open-pit depths of more than 200-250 m. Destress deformations are manifested in the mass deformation and the occurrence of long fractures, subparallel slopes (fractures in the walls of repulsion). As a result of these processes, the mass splitting into steeply dipping "layers" begins which tilt and bend [27], [28].

The need to improve existing methods and ensure the sustainability of existing and planned open pits is studied in detail in [29]-[36]. The rationale for conducting research work is the need for mineral raw materials, which increases from year to year, leading to the need to increase the production capacity of mining industries [37]-[39]. The deposits with simple mining-geological conditions and a high content of a useful component in ores have already been mined out or are close to completion. Therefore, the present day mining industry development is characterized by a complication of mining conditions due to an increase in the mining depth and involving in the operation of deposits with difficult mining-geological conditions [40], [41]. With an increase in the depth of existing open pits, the issues of wall stability turn into problems of great economic importance for mining enterprises [42]. In this regard, substantiation of the stable parameters of the walls and ledges at deep open pits opens up new opportunities for mining deep-seated ores for existing enterprises. For this, computer modeling is most often used [43]-[47].

The task of computer modeling of geomechanical processes and phenomena is to obtain qualitative and quantitative assessments of the studied phenomenon using computer methods [48]-[50]. It should be noted that the use of computer methods in geomechanics makes it possible to adapt and spread mathematical modeling methods for studying complex geomechanical processes [51], [52]. The undoubted advantage of computer modeling is the ability to take into account and to vary many parameters involved in the mathematical formulation. The use of computer methods is effective and justified in the case of studying mechanical processes, the modeling of which is very laborious or almost impossible to implement using other scientific approaches. When developing a geomechanical model, analytical, experimental and numerical methods can be used, each of which has its own advantages [53].

Geomechanical modeling is a sequential process of determining the mechanical properties of the rock and its response to impacts during the deposit mining process [54]-[56]. In this paper, the authors study the development of three-dimensional geomechanical models for mining the deposits by surface method, which are based on the results of calculating the stability factor of the open-pit walls. The geomechanical model consists of four main components: geological, structural, hydrogeological and rock mass models. The models are built on the basis of geological, hydrogeological, geotechnical data of the deposit and from these positions allow optimizing the work of the entire enterprise, correctly assessing risks, and scientifically substantiating the parameters of deposit mining. The development of geomechanical models includes several stages: data collecting and processing, analyzing the results obtained, converting graphic documentation into digital one, working with digital data in specialized GIS.

The ultimate purpose of developing a geomechanical model is to ensure the safety of mining operations by determining the optimal slope angles and probabilistic assessment of the open-pit wall stability, based on studying the structure of the near-wall mass and its physical-mechanical properties [57].

The use of a geomechanical model provides a number of advantages for determining the open-pit wall stability and selecting rational mining parameters from the point of view of geomechanics, such as:

– in a short time, it is possible to obtain several options for designing and planning the mining operations;

– the use of a block model gives the advantage of taking into account the influence of different rock masses and rock lithology on the stability of the open-pit walls and other mining parameters;

– when obtaining actual data or changing some parameters according to the rock mass characteristics that can affect mining operations, it is possible to quickly enter or change data in the geomechanical model and calculate the optimal solutions in the deposit mining.

Thus, the purpose of this work is to ensure the safety of mining operations by determining the optimal slope angles and probabilistic assessment of the open-pit wall stability based on studying the structure of the near-wall mass and its physical-mechanical properties.

2. Mining-geological characteristic of the Severny Katpar deposit

This section presents the main mining-geological peculiarities of the Severny Katpar deposit. The deposit relief is plain- hilled. The deposit is located in an inter-hill depression with relative elevations of up to 5-10 m, with a general surface inclination from the south and west to the northeast and east (absolute surface elevations are 698.0-707.8 m). The mineralization depth is from 2 to 520 m. Ore bodies occur horizontally or obliquely; they are mostly steeply dipping. The thickness of the ore bodies varies from 10 to 370 m. The ore bodies are of the following shapes: sheet-like, ellipsoidshaped, twisty, upswell, half-moon-shaped and lenticular. Three genetic types of ores have been identified at the deposit: oxidized in clayey and clayey-detrital weathering crust, skarn-greisen and marmorized limestones and marbles, and quartz-greisen in granites. In structural and tectonic terms, the deposit area is located in the central part of the Uspensky synclinorium, within the Akamai-Katpar ore zone.

The deposit has a mainly two-level structure. Thus, the upper level is composed of non-cohesive and cohesive soils, and the lower one is composed of dislocated rocks (marmorized limestones, marbles, skarns, siltstones, sandstones, metasomatites, granites, diorites, diabases, porphyrites). The thickness of loose overburden deposits varies from 0 to 220 m, averaging 36 m. The area is non-seismic, and the possibility of landslides is excluded.

According to the engineering-geological type, geological structure, engineering-geological, hydrogeological conditions, the deposit belongs to type V (foredeeps in masses of rhythmically interstratified lithified rocks). By the degree of complexity of the study, the deposit is of medium complexity.

Due to the difficult engineering-geological conditions of mining, the deposit belongs to the category of medium complexity (it is confined to rocky dislocated fractured rocks, with the presence of zones of crushing, weathering, covered by cohesive and non-cohesive soils). The deposit is composed mainly of rocks that are covered almost everywhere by loose deposits. Sedimentary unconsolidated soils are represented by Quaternary and Neogene sediments and Mesozoic weathering crust formations.

Quaternary sediments are of limited distribution. Alluvial-proluvial modern loams, sandy loams occur in the eastern area of the deposit. Deluvial-proluvial loams and clays with gruss-rock, alluvial-deluvial gruss-rock and coarse medium gravels are found in the western area of the deposit. The thickness of these deposits is mainly up to 1-2 m, in rare cases up to 3 m.

Neogene sediments are confined to the depressions of the Paleozoic basement in the Southern and South-Eastern areas of the deposit. They are represented by green, greenish-brown and brown clays of montmorillonitic composition. Their thickness is up to 26 m.

Weathering crust formation is widespread. It is represented by loams and clays with gruss-rock and crushed stone content from 1 to 16%, as well as by gruss-rock soils with sand-clay aggregate. The weathering crust formation thickness varies from a few centimeters at rock outcrops to the surface up to 220 m in the junction of tectonic faults, averaging 36 m. The weathering crust formation thickness depends on the lithological composition of the primary rocks. Above the siliceous, clayey and carbonaceous limestones of the northern block, the weathering crust thickness is up to 5 m; above the skarn-saturated limestones, it is 18-60 m.

Based on the changes in the mineralogical and chemical composition, the weathering crust is divided into two zones (from bottom to top):

– a zone of disintegrated rocks with a subzone of flints and opalites, represented by gruss-rock and coarse medium gravels with sand-clay aggregate;

– a hydromicaceous-halloysite-montmorillonite zone represented by cohesive soils with different gruss-rock and crushed stone content.

The first zone thickness is 5-45 m. In the lower part, this zone is represented by decompacted rocks with initial weathering products. There are lenticular and nest-shaped bodies of quartz metasomatites 3-19 m thick. The hydromicaceous-halloysite-montmorillonite zone thickness is 3-45 m. This zone is characterized by deep mining of ore minerals. The soils are dark brown, gray and yellowish-greenish-gray. Their texture is spotty, massive, brecciated. Among minerals, montmorillonite, kaolinite, hydromica, halloysite and beidellite predominate.

Sedimentary cemented carbonate, silty and microfragmental, contact-metamorphosed and intrusive formations are found among the rocks. Sedimentary cemented soils are the main ore-bearing rocks. They are represented by siltstones and sandstones of the Upper Famennian and limestones of the Lower Tournai. Siltstones with sandstone interlayers are widespread in the Southern area of the deposit. They are carbon-bearing, from dark gray to black color. The cementing mass (70-90% of the rock volume) is of the basal type and is represented by siliceous, clayey or carbonaceous material. The siltstone texture is massive and schistose.

Fine and medium-grained sandstones occur as thin (up to 1-3 m) layers and lenses among siltstones. They also have a polymictic composition. The central and northern areas of the deposit are composed of limestones affected to varying degrees by metamorphic processes. Less metamorphosed limestones outcrop to the north of the deposit, forming a separate block. Here they are represented by dark gray carbonaceous-clayey, clayey-siliceous and banded limestones. In the central area of the deposit, the limestones are intensively marmorized. These are light-gray medium-coarse-grained limestones, composed mainly of calcite. Their structure is granoblastic, mosaic. The texture is massive, indistinctly-banded.

The metamorphic rocks of the deposit are mainly ore-bearing. They are represented by skarns, quartz metasomatites, hornfelses and marbles. The skarns are developed through limestones (marbles), to a lesser extent through hornfelses in the form of veins and veinlets of various thicknesses (up to 5 m). The skarns (calcareous) are mainly of garnetiferous (andradite), pyroxene-garnetiferous and less often vesuvian-garnetiferous composition with wollastonite capel. Ore-bearing skarn veins and veinlets are clustered to form a stockwork. In the central area of the deposit (profile 45-47), the stockwork is saturated with skarn veinlets and veins, having a significant vertical thickness (up to 400 m) and a maximum depth (up to 300 m). The stockwork as a whole is elongated in the sublatitudinal direction from profile 49 in the east to profile 42 in the west, and passes further into the Western Katpar ore occurrence. Towards the flanks, the stockwork acquires a lenticular and sheet-like shape, breaking up into separate bodies.

When approaching the center of the deposit and the granite mass, intense marmorization of limestones leads to the formation of monomineral medium-coarse-grained marbles. Their structure is granoblastic, mosaic. The texture is massive, indistinctly-banded. Quartz metasomatites within the ore field occur in the form of thin lenses and interlayers. The groundmass structure is microgranoblastic, mosaic; the texture is massive or spheroidal. Granites and dikes of dioritic and diabase porphyrites occur among the igneous formations of the ore field.

Granites at a depth of 400-600 m constitute the dome-shaped anticline part of the Akmainsky mass, complicated by a gently dipping apophysis. They are represented by massive fine-medium-grained varieties of leucocratic light-gray and pinkish-gray rocks of Upper Permian age with porphyritic and aplite inclusions. In the apical part of the dome, granites are greisenized and K-feldspathized, where quartz and quartz-feldspar veins and veinlets with a thickness of several mm to 5-10 cm are widespread. The dikes are distributed in the central part of the deposit (within profile 45-46) on a dome-shaped granite ledge. Their thickness varies from 3 to 20 m. The length of the dikes along strike does not exceed 200 m; to the dip, some of them are traced to a depth of 500 m.

The ore-bearing limestones in the central part of the deposit form a synclinal fold overturned to the north, which has unequal slope angles at different depth levels: in the upper part their dip angle to the south is 70-900, and lower, at a depth of 300-400 m – with a flattening up to 50-200. In the western part (profile 42), an anticline fold is assumed (on the upper horizons), the fold lock is strongly flattened and complicated by fine folded structures of a higher order with a general dip to the north at angles of 50-800. The synclinal fold limestones are overlain by flyschoid formations of the Upper Famennian, which also form complexly dislocated folds with steeply dipping (up to vertical) angles. The strike of these rocks along the azimuth is 60-900.

3. Methods

To assess the stability of ledge slopes and open-pit walls, the following calculation methods are most widely used in practice:

– the method of algebraic addition of forces;

– the graphical-analytical method (VNIMI).

When there are no weakening surfaces in the rock mass, dipping towards the ledge or horizontal ones, a calculation scheme is used, characterized by the fact that in this case the sliding surface can be taken as round-cylindrical, and the stability factor can be determined by the algebraic addition method of holding and shearing forces along this surface.

The graphical-analytical method for determining the stable slope parameters (VNIMI method) consists in determining the limiting slope parameters (height H, slope angle α and width of the possible sliding triangle) according to the graphs of G.L. Fisenko [25], [58]. When calculating the slope parameters, the weighted average values of the mass rocks C_{av}, ϕ_{av} and γ_{av} are used, into which the safety factor $n_з$ is preliminarily introduced.

$$C_n = \frac{C_{av}}{n_з}; \qquad tg\varphi_n = \frac{tg\varphi_{av}}{n_з}. \tag{1}$$

Firstly, H_{90} value is determined:

$$H_{90} = \frac{2k}{\gamma} \cdot ctg\left(45° - \frac{\rho}{2}\right). \tag{2}$$

If the wall height H is set, it is necessary to determine its slope angle α. To do this, the H' value is first determined:

$$H' = \frac{H}{H_{90}}, \tag{3}$$

and then, according to the calculated ϕ value, the slope angle α is found on the abscissa axis. If it is necessary to determine the slope height, according to the given slope angle of the wall, through the point on the abscissa axis corresponding to the value of the given angle, an ordinate is drawn to the curve corresponding to the calculated internal friction angle ϕ_n. On the ordinate axis, the conditional slope height is determined; the true height H' of the slope is determined by the Formula:

$$H = H' \cdot H_{90}. \tag{4}$$

The slope parameters are specified by stability verification calculations using the algebraic addition method of forces over the most stressed surface using specified values of each individual layer strength characteristics (without averaging).

The heterogeneous mass geomechanical model is used to calculate the stability of the open-pit walls of arbitrary shape in difficult mining-geological conditions.

The principal scheme for calculating the stability of heterogeneous mass slopes for all calculation schemes is as follows.

1. On the geological section, built across the open-pit wall strike, the open-pit wall projected contour and the groundwater level are plotted.

2. The rock contacts between layers, groundwater level, sliding surface and open-pit wall contour are described according to tabular given functions by local interpolation of polynomials of small degree or splines. To do this, an X/Y coordinate system is selected with the origin at the lower slope edge. In this case, the X-axis is directed deep into the mass, the Y-axis is directed vertically. On the section, characteristic (nodal) points are marked for each contour and contact; at the same time, this indicates which interpolation, linear or quadratic should be performed between the nodal points. Contacts are numbered from bottom to top, and nodal points within the contact are numbered as the abscissas of nodal points increase.

3. The sliding surface is approximately built (hereinafter, its position is specified by the method of successive approximations), for which the average calculated characteristics C_{av}, $tg\phi_{av}$ and γ_{av} are determined.

4. The average calculated characteristics are determined as weighted averages. After that, the stability factor is calculated.

The calculations are performed in the Rocscience and K-MINE programs for the full projected open-pit depth, which is about 385 m, using a round-cylindrical sliding surface.

These programs are designed to assess the stability of cylindrical and non-cylindrical failure surfaces in rock and earth slopes. The program analyzes the stability of sliding surfaces using the vertical block limit equilibrium method, also known as the Bishop (Cray's approach) method, as well as the Spencer, Yanbu and Fellenius methods. A single sliding surface can be taken for analysis, and the area of centers can also be used to determine the location of critical surfaces for a certain area of the studied object. When performing calculations, the geometric parameters of the open-pit wall, as well as the rocks composing the near-wall mass, are entered into the programs. The programs use methods that satisfy the equilibrium conditions of the sliding triangle and its elements in the limiting state, taking into account the rock mass stress state. The summary characteristics of the limit equilibrium methods for slope stability analysis are given in Table 1.

The Yanbu and Spencer methods are universal and can be used to calculate stability both on a round-cylindrical sliding surface and on a curved one, as well as on a straight-line contact. The most suitable methods for performing stability calculations for the Severny Katpar open-pit walls are the Bishop and Spencer methods. The Bishop simplified method uses the block method to find the stability factor for a rock mass. This method makes several assumptions. It is assumed that the failure occurs when the rock mass rotates along a round-cylindrical surface with a center at a common point.

Table 1. Characteristics of the limit equilibrium methods for slope stability analysis

Method	Use
The conventional method of blocks (Fellenius method)	Applicable for heterogeneous slopes and rock masses with cohesion and an internal friction angle, where the sliding surface can be approximated by a circle. It is suitable for complex calculations. Not accurate for high pore pressure acting stress analysis.
Bishop simplified method	Applicable for heterogeneous slopes and rock masses with cohesion and an internal friction angle, where the sliding surface can be approximated by a circle. It is more accurate than Fellenius method, especially for high pore pressure analysis. Calculations are feasible both manually and using tabular calculations.
Simplified Janbu method	Applicable for curved sliding surfaces, flat planar sliding surfaces that are not parallel to the earth's surface.
Generalized Janbu method	Applicable for sliding surfaces of any shape, as well as for accurate analysis.
Spenser method	Accurate method applicable to virtually any slope geometry and any type of rocks. The simplest complete equilibrium method for determining the stability factor.

Thus, the Bishop method should not be used when calculating SF for a curved surface, unless a frictional rotation center is used. It is assumed that the forces on the block sides are horizontal and therefore there are no shear stresses between the blocks. The total normal component of the force is considered to be acting on the center of the base of each block and is calculated by summing the forces in the vertical direction.

The Bishop simplified method does not satisfy the condition of complete static equilibrium, the procedure gives relatively accurate stability factor values. The Bishop simplified method is more accurate than the conventional block method, especially when analyzing the effective stress at high pore pressure, and is consistent within 5% with the factor calculated by the finite element method. The main limitation of the Bishop simplified method is that it is restricted to a round-cylindrical surface.

The Spencer method has originally been developed for the analysis of round-cylindrical sliding surfaces, but is also used for curved surfaces by applying a frictional rotation center. This method is based on the assumption that interblock forces are parallel, that is, they have the same inclination. Spencer summed the forces perpendicular to the interblock ones in order to obtain the force acting along the normal at the base of the block. Taking into account the general equilibrium of forces and moments, two values of the stability factor F_f and F_m are calculated. The stability factor (F_m) can be calculated from the general equilibrium of moments relative to a certain point. Using the Spencer assumption over the entire slope and in the absence of an external load, the equation for the stability factor in terms of forces is identical to the equation in the generalized Yanbu method. A trial and error procedure is used to solve the equation. However, Spencer tested the relationship between F_f and F_m for typical problems. At a certain angle of interblock forces, two SF are the same and both conditions for the equilibrium of moments and forces are satisfied.

Calculation of SF for both a local area and for the entire wall can be carried out by various methods (LEM – limit equilibrium method; FEM – finite element method, etc., depending on software), taking into account the lower and upper levels of the aquifer. The K-MINE software uses the limit equilibrium method and all cells of the block model are involved in the calculation, which makes the calculations as accurate as possible by eliminating the averaging of the physical-mechanical properties of the rocks composing the mass. Rocscience, Phase 2 and Midas GTS NX software use the above geomechanical model data to determine the stress-strain state by the finite element method, which has the advantage of simultaneously determining the sliding surface and the stability factor during the calculation process.

4. Results and discussion

According to the above methods, the calculations of the open-pit wall stability have been performed along the transverse, longitudinal and diagonal engineering-geological sections (Fig. 1), typical for the open-pit near-wall zone in the final position, taking into account the deepening to the absolute mark of +320 m, with the implementation of numerical mathematical modeling and identification of potentially hazardous areas.

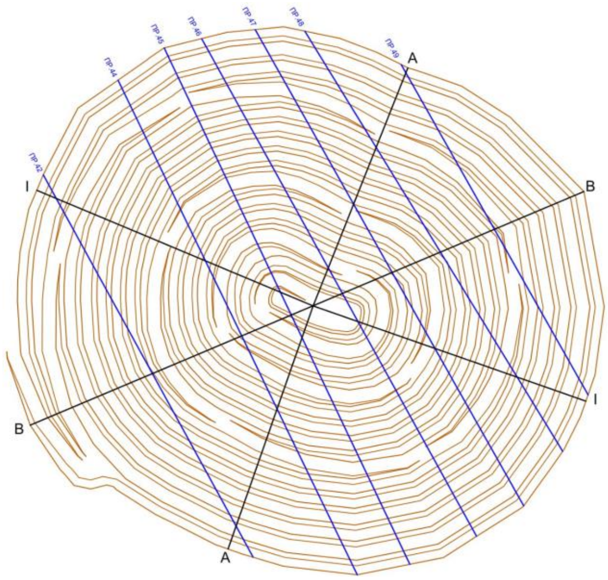


Figure 1. Location of calculated profiles

The open-pit wall projected contour and the near-wall mass geological structure have been plotted on the sections according to the prospecting borehole data. The calculated physical-mechanical properties of the host rocks in the Severny Katpar open pit have been previously studied and are the basis for this research.

For each section (open-pit profile), calculations have been made for several sliding surfaces. When predicting the slope stability, the problem is reduced to finding the weakest sliding surface in the mass and determining the stability factor from it. The stress-strain state of the open-pit projected contour at the end of mining has been analyzed using the finite element method in the Rocscience program (Fig. 2).

When calculating the SF, the load on the wall from the external rock dump has not been taken into account due to the fact that the nearest distance from the open-pit upper edge to the bottom of the existing dump in the area of profile lines No. 46 and 47 is 350 m (Fig. 3). There is also no initial information about the geology under the rock dump base.

(a) (b)

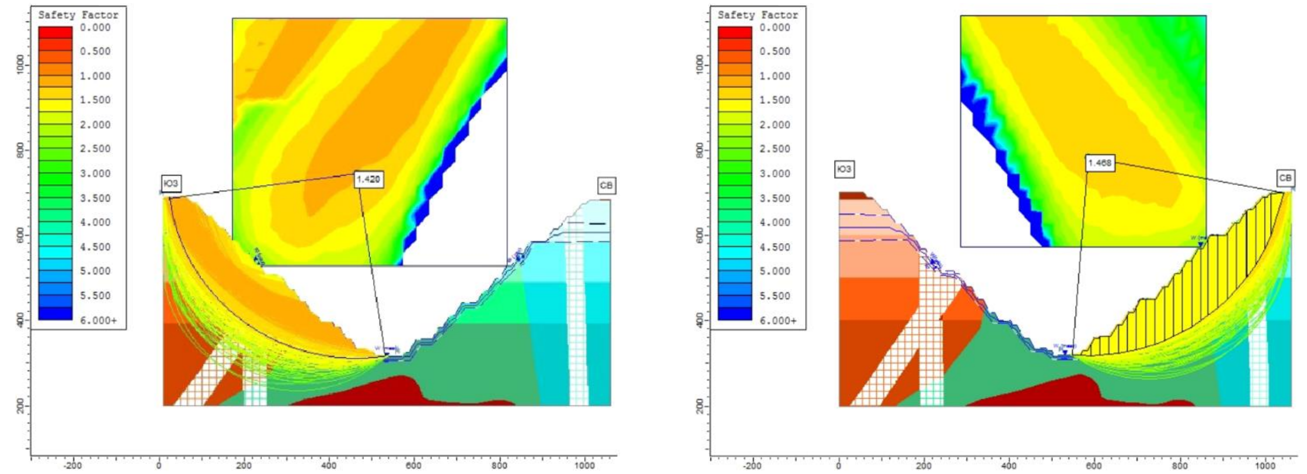


Figure 2. Predicting the slope stability (section along the line A-A SF = 1.4): (a) the South-Western wall; (b) the North-Eastern wall

(a) (b)

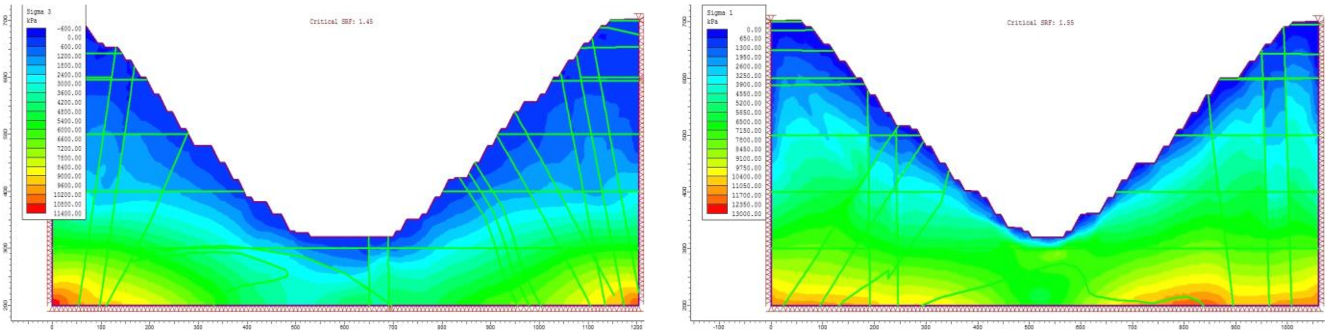


Figure 3. Determining the strength reduction factor (SRF) in the Rocscience program, taking into account the physical-mechanical properties of the rocks composing the near-wall mass: (a) section along the ∂ine I-I; (b) section along the ∂ine A-A

The calculations are carried out for the full projected open-pit depth, which is about 385 m, using a round-cylindrical sliding surface. The calculation results are presented in the form of curves in Figure 4. The mathematical calculation results of the stability of the projected contour walls in the Severny Katpar open pit are summarized in Table 2.

An assessment of the wall stability for the selected geological sections has been performed, taking into account the projected contour of the open-pit walls. Calculations have been made for geological sections: I-I, A-A, B-B, 45, 46. Based on the calculations, the following data have been obtained:

– line I-I: SE – the wall general angle 410, H = 381 m, SF_{av} = 1.31; SW – the wall general angle 380, H = 380 m, SF_{av} = 1.39;

– line A-A: SW – the wall general angle 400, H = 381 m, SF_{av} = 1.32; SW – the wall general angle 400, H = 378 m, SF_{av} = 1.41;

– line B-B: SW – the wall general angle 370, H = 381 m, SF_{av} = 1.51; SW – the wall general angle 370, H = 379 m, SF_{av} = 1.58;

– line 45: SE – the wall general angle 360, H = 383 m, SF_{av} = 1.52; SW – the wall general angle 380, H = 381 m, SF_{av} = 1.18;

– line 46: SE – the wall general angle 400, H = 381 m, SF_{av} = 1.26; SW – the wall general angle 340, H = 381 m, SF_{av} = 1.69, which are acceptable values for the stability factor.

The calculation of the projected contour wall stability in the Severny Katpar open pit by several different methods shows that the open-pit walls are generally stable, while the stability factors along the profile lines, at which the open-pit depth reaches its absolute limit mark of +320 m, vary from 1.18 to 1.41. However, there are areas with the stability factor value close to the maximum allowable (SF ≈ 1). These are the upper horizons of the Southern and South-Eastern open-pit walls in the 44, 46-47 profile line areas on horizons with an absolute mark of +700 and +660. This is explained by the fact that the rocks in these areas are represented by weathering crust with low physical-mechanical properties. For the same reasons, on the walls in the Southern area of the open pit, on +700 and +400 horizons, a decrease in the SF is observed due to the predominance of siltstones in the walls.

Taking into account the stability factor close to unity obtained in the calculations and the possible negative impact of certain factors (abundant atmospheric precipitation, drilling and blasting operations, etc.), it is necessary to ensure planned and preventive safety measures to exclude deformation processes of loose deposit ledges. Such measures include:

1. A properly selected optimal blasting technology (when mining a strong undamaged block, it should ensure the preservation of the natural structure of the abandoned mass, in order to improve the stability control of ledges in the limiting contour; the use of block blasting with the creation of a preliminary gap and ensuring the reversal of the total shock wave towards the mined-out space or using an additional locking crushing charge).

2. Artificial strengthening of ledges, separate areas with a very unstable or unstable state of rocks (developing of buttresses, combined, using self-retaining support).

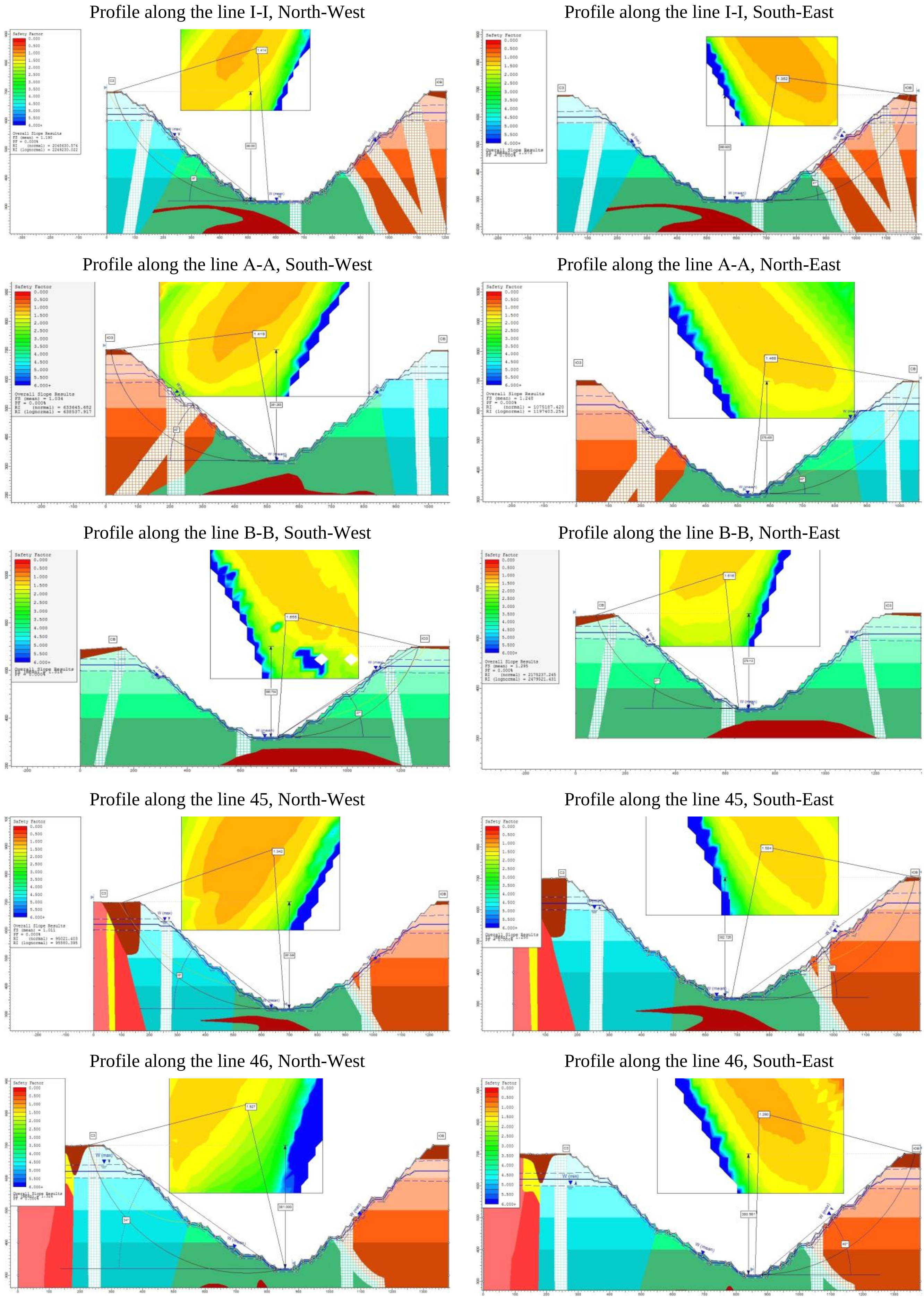


Figure 4. Results of calculating the stability factor according to the rational contour

Table 2. Results of mathematical calculations of the projected contour wall stability in the Severny Katpar deposit

Profile	I-I		A-A		B-B		45		46	
Wall	SE	NW	SE	NW	SE	NW	SE	NW	SE	NW
General angle, degree	41	38	40	40	37	37	36	38	40	34
Wall height, m	381	380	381	378	381	379	383	381	381	381
Bishop Simplified Method	1.35	1.41	1.42	1.46	1.53	1.61	1.58	1.20	1.29	1.78
Spencer Method	1.50	1.54	1.31	1.51	1.65	1.70	1.68	1.34	1.38	1.92
Felenius Method	1.35	1048	1.40	1.52	1.58	1.65	1.54	1.22	1.33	1.72
Yanbu Simplified Method	1.13	1.24	1.20	1.24	1.34	1.41	1.34	1.03	1.12	1.50
Generalized Yanbu method	1.21	1.32	1.29	1.33	1.43	1.50	2.44	1.09	1.19	1.61

3. To improve the hydrogeological conditions and ensure the stability of a group of ledges, it is necessary to provide for a decrease in water in the near-contour mass by laying inclined filtration wells connected to the most fractured and cavernous cavities located behind the shear plane of the group of ledges; to prevent clay rocks from sliding, do not allow wetting of the lower open-pit area (provide for the removal of melt water in the spring).

4. To prevent flooding of the open pit above the depth of occurrence of these rocks, etc.

Figure 5 shows the constructed three-dimensional model for the stability map of the Severny Katpar open pit.

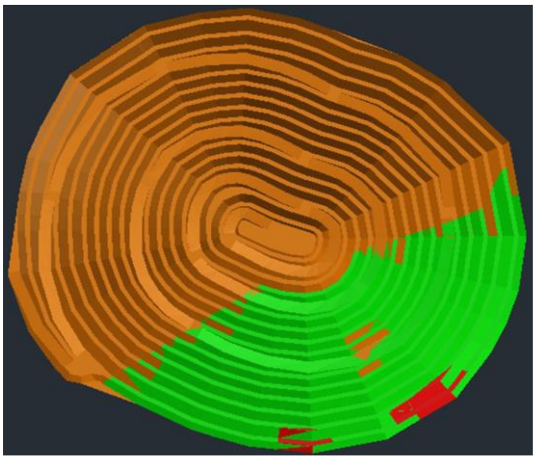


Figure 5. Three-dimensional model for the stability map of the projected contour in the Severny Katpar open pit: ≤ 1.0; 1.1-1.3; > 1.3

Thus, the following main technical parameters of mining the Severny Katpar open pit have been obtained: the mining depth is 385 m; surface dimensions – 970×1115 m; dimensions along the bottom – 60×170 m; the North-Western wall angle is 38°; the North-Eastern wall angle is 40°; the South-Eastern wall angle is 41°; the South-Western wall angle is 40°; the safety berms width is 10 m; the haulage berm width is 26 m. Additional open-pit parameters at the end of mining are presented in Table 3.

Table 3. Additional open-pit parameters at the end of mining

Horizon absolute mark	+710/+660	+630/+600	+570/+320
Project data:			
Ledge height, m	30	30	30
Ledge angle, deg.	50	55	60
Project data:			
Single ledge height, m	10-15	12-20	12-20
Double ledge angle, deg.	45-50	50-55	55-60

To ensure the stability of the Severny Katpar open-pit walls with the recommended parameters during mining, it is necessary:

– to study the impact of drilling and blasting operations on the open-pit near-contour mass deformations in order to develop adapted technological schemes for slopes of ledges on the projected contours;

– to carry out instrumental monitoring of the state of ledge slopes and walls on the open-pit projected contours;

– in the process of mining an open pit and in event of new research results of the near-wall mass state (physical-mechanical properties, geology, hydrogeology), update a single database represented by a geomechanical block model for subsequent adjustment of the safety factor of the walls.

The first step in developing a digital geomechanical model is to collect and prepare the necessary database. The second stage is the sequential transfer of the obtained data sets or their combinations into a three-dimensional model using the K-Mine modeling system. The deposit geomechanical model consists of four main components:

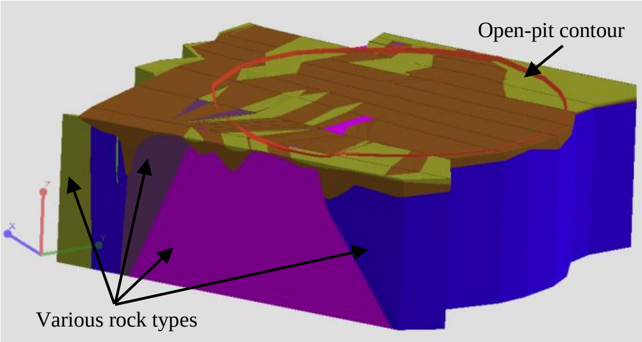
1) geological model;
2) structural model;
3) rock mass models (rock properties);
4) aquifer.

The geological model is represented by a three-dimensional distribution of rocks that form the open-pit walls. For the Severny Katpar deposit, 7 types of rocks have been identified (coal limestone, marmorized limestone, siltstone, fine-grained granites, medium-coarse-grained granites, tuffs, Late Permian porphyritic granites). Loose rocks are represented by clays, loams containing gruss-rock and crushed stone.

The geological wireframe model (GWM) has been developed on the basis of the available geological sections, horizon plans and the results of geotechnical studies performed using the Surpac geoinformation system. In general, the GWM is a three-dimensional triangulation created on the basis of string files (polylines), which are the contours of geological bodies. The deposit GWF elements are presented in the form of three-dimensional objects in Figure 6. The designations of the deposit geological model are also given here.

The geological wireframe model can be used as a basis for the following types of work: visualization of the spatial orientation of host rocks and ores, volume calculation, mining of geological sections in any direction and the basis for developing a geomechanical model of the deposit.

All the distinguished disturbances are included in the structural model of the deposit. The results of constructing a structural model are shown in Figure 7. The rock mass model is a database of the mass strength parameters (physical-mechanical rock properties), fracture frequency and the classification of the mass by ratings. The deposit block model is a set of three-dimensional blocks (cubic, of different sizes in space), with attributes inherent in blocks, which is based on a two-dimensional data table, where rows are numbered blocks, and columns are their attributes (characteristics).



No	Rock	
1	Weathering crust	
2	Carbonaceous limestone	
3	Marmorized limestone	
4	Siltstone	
5	Fine-grained granites	
6	Medium-coarse-grained granites	
7	Late Permian porphyritic granites	
8	Tuffs	

Figure 6. Geological wireframe model of the Severny Katpar deposit

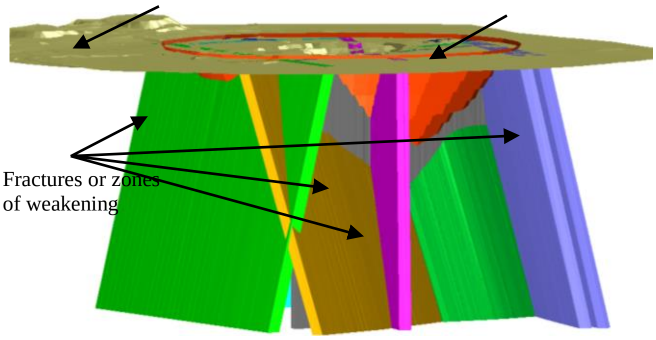


Figure 7. Structural model of the Severny Katpar deposit

The block model has been developed on the basis of wireframe modeling, that is, by direct filling closed solid-state three-dimensional structures: "solids"-frames of any bodies (for example, closed bodies of lithology). The dimensions of the BM cells are 10×10×5.

Having developed a geomechanical model of the deposit, the authors obtain a general pattern of the rock mass geomechanical state in the Severny Katpar open pit in 3D space. In the future, the geomechanical model can be used to solve such problems as:

– assessment of the stability of the open-pit walls at different angles of the open-pit slopes;

– the rock dump impact on the stability of the open-pit walls;

– the optimal drilling grid for drilling and blasting operations;

– the impact of surface mining on underground mine workings if a combined mining method is planned in the future, etc.

The use of programs such as Rocscience, K-MINE and their analogues, taking into account the mass structure, makes it possible for the geomechanical service of the mine, when working with the geomechanical block model, to quickly make adjustments, calculations, identify the least stable local areas and to make informed technical decisions to eliminate them directly in-situ without involvement of specialized organizations.

5. Conclusions

This paper presents the results of research on the stability of the open-pit walls along the transverse, longitudinal and diagonal engineering-geological sections, which are typical for the near-wall open-pit zone in the final position, taking into account the deepening up to an absolute mark of +320 m, with numerical mathematical modeling and identification of potentially hazardous areas. Methods for calculating the stability of the open-pit walls have been selected (A. Bishop, E. Spencer, Fellenius and Yanbu methods), as well as reliably tested in practice when substantiating the parameters of the walls in other open pits of Kazakhstan and neighboring countries.

For the selected geological sections, the wall stability has been assessed, taking into account the projected contour of the open-pit sides. Calculations have been made for the following geological sections: I-I, A-A, B-B, 45, and 46. The mathematical calculation results of the stability of the projected contour walls in the Severny Katpar open pit have been summarized. The calculations have been performed for the full projected open-pit depth, that is, about 385 m.

In the Southern and South-Western area of the Severny Katpar open-pit side, on horizons +700…+400, a decrease in the SF is observed due to the predominance of siltstones in the walls and the presence of tectonic disturbances. However, it varies from 1.18 to 1.41, which indicates that the walls are stable. On the upper horizons of the Southern and South-Eastern open-pit walls in the 44, 46-47 profile line areas, on horizons with an absolute mark of +700…+660, there are areas with a stability factor value close to the maximum allowable (SF ≈ 1).

Based on the available geological sections, horizon plans and the results of engineering-geological surveys, a geological wireframe model (GWM) of the Severny Katpar deposit has been constructed using the Surpac geoinformation system. This is a digital block geomechanical model to ensure the stable state of the walls and ledges of the open pit when mining up to 400 m.

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References

[1] Bozorgebrahimi, E., Hall, R.A., & Blackwell, G.H. (2003). Sizing equipment for open pit mining – A review of critical parameters. *Mining Technology*, *112*(3), 171-179. https://doi.org/10.1179/037178403225003591

[2] Wei, Z., Yin, G., Wan, L., & Shen, L. (2008). Case history of controlling a landslide at Panluo open-pit mine in China. *Environmental Geology*, *54*(4), 699-709. https://doi.org/10.1007/s00254-007-0839-y

[3] Dryzhenko, A., Moldabayev, S., Shustov, A., Adamchuk, A., & Sarybayev, N. (2017). Open pit mining technology of steeply dipping mineral occurences by steeply inclined sublayers. *International Multidisciplinary Scientific GeoConference*, *17*(1-3), 599-605. https://doi.org/10.5593/sgem2017/13/s03.076

[4] Rzhevsky, V.V. (1978). *Open pit mining processes*. Moskva, Rossiya: Nedra, 544 p.

[5] Cyedina, S.A. (2019). *Geomechanical support of the stability of the sides of a quarry during its deepening*. PhD Thesis. Almaty, Kazakhstan.

[6] Bejsebaev, A.M., Bitimbaev, M.Zh., Krupnik, L.A., & Tsekhovoj, A.F. (2001). The role of central Asian mining and industrial union in the development of mining and metallurgical complex in Kazakhstan. *Gornyi Zhurnal*, (11), 10-13.

[7] Tsirel S.V., & Pavlovich, A.A. (2017). Problems and ways of development of methods of geomechanical substantiation of the parameters of open pit sides. *Mining Journal*, (7), 39-45. https://doi.org/10.17580/gzh.2017.07.07

[8] Luo, H., Zhou, W., Jiskani, I. M., & Wang, Z. (2021). Analyzing characteristics of particulate matter pollution in open-pit coal mines: Implications for Green Mining. *Energies*, *14*(9), 2680. https://doi.org/10.3390/en14092680

[9] Bekbassarov, S., Soltabaeva, S., Daurenbekova, A., & Ormanbekova, A. (2015). "Green" economy in mining. *New Developments in Mining Engineering 2015: Theoretical and Practical Solutions of Mineral Resources Mining*, 431-434. https://doi.org/10.1201/b19901-75

[10] Bozhanova, V., Korenyuk, P., Lozovskyi, O., Belous-Sergeeva, S., Bielienkova, O., & Koval, V. (2022). Green enterprise logistics management system in circular economy. *International Journal of Mathematical, Engineering and Management Sciences*, *7*(3), 350-363. https://doi.org/10.33889/ijmems.2022.7.3.024

[11] Kovrov, A.S. (2013). *Stability of quarry walls in a complex-structured array of soft rocks*. Dnipro, Ukraine: National Mining University.

[12] Yang, Z., Gao, Q., Li, M., & Zhang, G. (2014). Stability analysis and design of open pit mine slope in China. *European Journal of Government and Economics*, (19), 10247-10266.

[13] 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

[14] Yanuardian, A.R., Hermawan, K., Martireni, A.T., & Tohari, A. (2020). The influence of discontinuities on rock mass quality and overall stability of andesite rock slope in West Java. *Rudarsko Geolosko Naftni Zbornik*, *35*(3), 67-76. https://doi.org/10.17794/rgn.2020.3.7

[15] Shpansky, O.V., Ligotsky, D.N., & Borisov, D.V. (2003). *Designing boundaries of open pit mining*. Saint Petersburg, Russian Federation.

[16] Bitimbaev, M.Zh., & Edygenov, E.K. (2001). Scientific and technological developments of the institute in the field of mining matter. *Gornyi Zhurnal*, (11), 86-89.

[17] Kalybekov, T., Rysbekov, K., Sandibekov, M., Bi, Y.L., & Toktarov, A. (2020). Substantiation of the intensified dump reclamation in the process of field development. *Mining of Mineral Deposits*, *14*(2), 59-65. https://doi.org/10.33271/mining14.02.059

[18] Panin, V.I., Rybin, V.V., & Konstantinov, K.N. (2013). New information about the physical properties of ores and rocks of the deposits of the Kola Peninsula and its use in projects for the development of mining enterprises in the region. Monitoring of natural and technogenic processes during mining. *Reports of the All-Russian Scientific and Technical Conference with International Participation*, 155-160.

[19] Gholamnejad, J., Azimi, A., Lotfian, R., Kasmaeeyazdi, S., & Tinti, F. (2020). The application of a stockpile stochastic model into long-term open pit mine production scheduling to improve the feed grade for the processing plant. *Rudarsko Geolosko Naftni Zbornik*, *35*(4), 115-129. https://doi.org/10.17794/rgn.2020.4.10

[20] Hussan, B., Takhanov, D., Kuzmin, S., & Abdibaitov, S. (2021). Research into influence of drilling-and-blasting operations on the stability of the Kusmuryn open-pit sides in the Republic of Kazakhstan. *Mining of Mineral Deposits*, *15*(3), 130-136. https://doi.org/10.33271/mining15.03.130

[21] Khomenko, O.Ye. (2012). Implementation of energy method in study of zonal disintegration of rocks. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (4), 44-54.

[22] Melnikov, N.N., Kozyrev, A.A., Reshetnyak, S.P., Kasparyan, E.V., Rybin, V.V., Svinin, V.S., & Ryzhkov, A.N. (2004). The concept of formation of non-working sides of deep quarries Kola Polar Region. *Mining Journal*, (9), 45-50.

[23] *Guidelines for monitoring the deformations of the sides, slopes of ledges and dumps in open pits and developing measures to ensure their stability*. (2008). Almaty, Kazakhstan: Ministry of Emergency Situations of the Republic of Kazakhstan.

[24] Krukovskyi, O., Bulich, Y., Kurnosov, S., Yanzhula, O., & Demin, V. (2022). Substantiating the parameters for selecting a pillar width to protect permanent mine workings at great depths. *IOP Conference Series: Earth and Environmental Science*, *970*(1), 012049. https://doi.org/10.1088/1755-1315/970/1/012049

[25] *Guidelines for determining the angles of inclination of the sides, slopes of ledges and dumps of open pits under construction and exploitation*. (1972). Leningrad, Russian Federation: VNIMI.

[26] Hussan, B., Takhanov, D.K., Oralbay, A.O., & Kuzmin, S.L. (2021). Assessing the quality of drilling-and-blasting operations at the open pit limiting contour. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (6), 42-48. https://doi.org/10.33271/nvngu/2021-6/042

[27] Zoteyev, O.V. (n.d.). *On the compliance of the current regulatory documentation with the tasks of geomechanical support for open pit mining*.

[28] Shustov, O.O., Haddad, J.S., Adamchuk, A.A., Rastsvietaiev, V.O., & Cherniaiev, O.V. (2019). Improving the construction of mechanized complexes for reloading points while developing deep open pits. *Journal of Mining Science*, *55*(6), 946-953. https://doi.org/10.1134/s1062739119066332

[29] Dyachkov, B.A., Bissatova, A.Y., Mizernaya, M.A., Zimanovskaya, N.A., Oitseva, T.A., Amralinova, B.B., Aitbayeva, S.S., Kuzmina, O.N., & Orazbekova, G.B. (2021). Specific features of geotectonic development and ore potential in Southern Altai (Eastern Kazakhstan). *Geology of Ore Deposits*, *63*(5), 383-408. https://doi.org/10.1134/S1075701521050020

[30] Rahim, A.F.A., Rafek, A.G.M., Serasa, A.S., Abdullah, R.A., Rahim, A., Harun, W.S.W., & Ern, L.K. (2022). Application of a comprehensive rock slope stability assessment approach for selected Malaysian granitic rock slopes. *Sains Malaysiana*, *51*(2), 421-436. https://doi.org/10.3390/buildings12030268

[31] Stupnik, M., Kolosov, V., Pysmennyi, S., & Kostiantyn, K. (2019). Selective mining of complex stuctured ore deposits by open stop systems. *E3S Web of Conferences*, (123), 01007. https://doi.org/10.1051/e3sconf/201912301007

[32] Zhang, F., Yang, T., Li, L., Bu, J., Wang, T., & Xiao, P. (2021). Assessment of the rock slope stability of Fushun West Open-pit Mine. *Arabian Journal of Geosciences*, *14*(15), 1-20. https://doi.org/10.1007/s12517-021-07815-8

[33] Belandria, N., Úcar, R., Corredor, A., & Hassani, F. (2021). Safety factor on rock slopes with tensile cracks using numerical and limit equilibrium models. *Geotechnical and Geological Engineering*, *39*(3), 2287-2300. https://doi.org/10.1007/s10706-020-01624-8

[34] Congress, S.S.C., Puppala, A.J., Kumar, P., Banerjee, A., & Patil, U. (2021). Methodology for resloping of rock slope using 3D models from UAV-CRP technology. *Journal of Geotechnical and Geoenvironmental Engineering*, *147*(9), 05021005. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002591

[35] Theocharis, A.I., Zevgolis, I.E., Deliveris, A.V., Karametou, R., & Koukouzas, N.C. (2022). From climate conditions to the numerical slope stability analysis of surface coal mines. *Applied Sciences*, *12*(3), 1538. https://doi.org/10.3390/app12031538

[36] Kavvadas, M., Roumpos, C., Servou, A., & Paraskevis, N. (2022). Geotechnical issues in decommissioning surface lignite mines – the case of Amyntaion mine in Greece. *Mining*, *2*(2), 278-296. https://doi.org/10.3390/mining2020015

[37] Krukovskyi, O., & Krukovska, V. (2019). Numerical simulation of the stress state of the layered gas-bearing rocks in the bottom of mine working. *E3S Web of Conferences*, (109), 00043. https://doi.org/10.1051/e3sconf/201910900043

[38] Demin, V.F., Yavorskij, V.V., Tutanov, S.K., Popov, S.N., & Popov, V.S. (2004). Investigation of stressed-strained state of rocks in contour zone of mining extraction working. *Gornyi Zhurnal*, (6), 58-63.

[39] Lewińska, P., Matuła, R., & Dyczko, A. (2017). Integration of thermal digital 3D model and a MASW (Multichannel Analysis of Surface Wave) as a means of improving monitoring of spoil tip stability. *Baltic Geodetic Congress*, 232-236. https://doi.org/10.1109/BGC.Geomatics.2017.29

[40] Kolapo, P., Oniyide, G.O., Said, K.O., Lawal, A.I., Onifade, M., & Munemo, P. (2022). An overview of slope failure in mining operations. *Mining*, *2*(2), 350-384. https://doi.org/10.3390/mining2020019

[41] Joshi, D., Paithankar, A., Chatterjee, S., & Equeenuddin, S.M. (2022). Integrated parametric graph closure and branch-and-cut algorithm for open pit mine scheduling under uncertainty. *Mining*, (2), 32-51. https://doi.org/10.3390/mining2010003

[42] Grishin, A.V., & Shevchuk, S.V. (2017). On the issue of organizing geomechanical monitoring in the development of mineral deposits by open pit mining at great depths. *Mine Surveying Bulletin*, (1), 51-55.

[43] Pivnyak, G., Dychkovskyi, R., Smirnov, A., & Cherednichenko, Y. (2013). Some aspects on the software simulation implementation in thin coal seams mining. *Energy Efficiency Improvement of Geotechnical Systems*, 1-10. https://doi.org/10.1201/b16355-2

[44] Singh, V.K., Prasad, M., & Dhar, B.B. (1994). Stability analysis of an open pit by numerical modelling. *Journal of Mines, Metals & Fuels*, *42*(3&4), 39-46.

[45] Singh, V.K., Prasad, M., Singh, S.K., Rao, D.G., & Singh, U.K. (1995). Slope design based on geotechnical study and numerical modelling of a deep open pit mine in India. *International Journal of Surface Mining and Reclamation*, *9*(3), 105-111. https://doi.org/10.1080/09208119508964729

[46] Arslan, A.T., Kahraman, B., Özfırat, M.K., Frühwirt, T., Yıldızdağ, K., & Köse, H. (2017). A parametric study using numerical modelling to assess the stability of marble quarries. *Procedia Engineering*, (191), 646-655. https://doi.org/10.1016/j.proeng.2017.05.228

[47] Mandalawi, M.A., You, G., Dahlhaus, P., Dowling, K., & Sabry, M. (2018). Modelling and analyses of rock bridge fracture and step-path fail-

ure in open-pit mine rock slope. *Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology*, 198-226. https://doi.org/10.1007/978-3-030-01935-8_15
[48] Ishchenko, K.S., Krukovskiy, A.P., Krukovskaya, V.V., & Ishchenko, A.K. (2012). Physical and numeral modeling of stressed-deformed state of the rock massif in the working face. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (2), 85-91.
[49] Zhussupov, K., Toktamyssova, A., Abdullayev, S., Bakyt, G., & Yessengaliyev, M. (2018). Investigation of the stress-strain state of a wheel flange of the locomotive by the method of finite element modeling. *Mechanics*, *24*(2), 174-181. https://doi.org/10.5755/j01.mech.24.2.17637
[50] Shults, R., Annenkov, A., Seitkazina, G., Soltabayeva, S., Kozhayev, Zh., Khailak, A., Nikitenko, K., Sossa, B., & Kulichenko, N. (2022). Analysis of the displacements of pipeline overpasses based on geodetic monitoring results. *Geodesy and Geodynamics*, *13*(1), 50-71. https://doi.org/10.1016/j.geog.2021.09.005
[51] Begalinov, A., Serdaliyev, Y., Abshayakov, E., Bakhramov, B., & Baigenzhenov, O. (2015). Extraction technology of fine vein gold ores. *Metallurgical & Mining Industry*, (4), 312-320.
[52] Nurpeissova, M., Bitimbayev, M.Zh., Rysbekov, K.B., Derbisov, K., Turumbetov, T., & Shults, R. (2020). Geodetic substantiation of the saryarka copper ore region. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *6*(444), 194-202. https://doi.org/10.32014/2020.2518-170X.147
[53] Shashenko, A., Gapieiev, S., & Solodyankin, A. (2009). Numerical simulation of the elastic-plastic state of rock mass around horizontal workings. *Archives of Mining Sciences*, *54*(2), 341-348.
[54] Petlovanyi, M., Ruskykh, V., Zubko, S., & Medianyk, V. (2020). Dependence of the mined ores quality on the geological structure and properties of the hanging wall rocks. *E3S Web of Conferences*, (201), 01027. https://doi.org/10.1051/e3sconf/202020101027
[55] Liu, Q., Fu, Q., Yang, K., Wei, Q., Liu, H., & Wu, H. (2022). Geomechanical modeling and inversion analysis of the in-situ stress field in deep marine shale formations: A case study of the Longmaxi aormation, Dingshan Area, China. *Frontiers in Earth Science*, (9), 808535. https://doi.org/10.3389/feart.2021.808535
[56] Yu, H., & Dahi-Taleghani, A. (2022). Advances in geomechanical modeling. *Unconventional Shale Gas Development*, 279-297. https://doi.org/10.1016/B978-0-323-90185-7.00011-X
[57] Nemova, N.A., Tahanov, D., Hussan, B., & Zhumabekova, A. (2020). Technological solutions development for mining adjacent rock mass and pit reserves taking into account geomechanical assessment of the deposit. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (2), 17-23. https://doi.org/10.33271/nvngu/2020-2/017
[58] Fisenko, G.L. (1965). *Ustoychivost bortov karerov i otvalov*. Moskva, Rossiya: Nedra, 378 s.

Обґрунтування параметрів управління гірським масивом на основі геомеханічної моделі родовища Північний Катпар, Казахстан

Б. Толовхан, В. Дьомін, Ж. Аманжолов, А. Смагулова, Г. Танєкєєва, Ш. Заіров, О. Круковский, Е. Кабана

Мета. Створення геомеханічної моделі для забезпечення безпеки ведення гірничих робіт за рахунок визначення оптимальних кутів укосів та ймовірності оцінки стійкості бортів кар'єру.

Методика. Створення тривимірних геомеханічних моделей розробки родовищ відкритим способом, виходячи з розрахунків коефіцієнта запасу стійкості (Safety Factor – SF) бортів кар'єру, здійснювалося у програмі Rocscience щодо напружено-деформованого стану гірського масиву наприкінці відпрацювання методом скінченних елементів. Геологічна каркасна модель (ГКМ) була побудована на основі наявних геологічних розрізів, планів горизонтів та результатів проведених інженерно-геологічних досліджень за допомогою геоінформаційної системи Surpac.

Результати. Визначено коефіцієнт зниження міцності (Strength reduction factor – SRF) з урахуванням фізико-механічних властивостей порід, що складають прибортовий масив. Дана оцінка стійкості бортів за виділеними геологічними розрізами з урахуванням проєктного контуру бортів кар'єру Північний Катпар. Розрахунок стійкості бортів проєктного контуру кар'єру декількома різними методами показав, що його борти загалом є стійкими. Визначено параметри кар'єру на кінець відпрацювання.

Наукова новизна. Вперше встановлено, що у південній та південно-західній частині борту кар'єру Північний Катпар на горизонтах +700…+400 спостерігається зниження КЗП (від 1.18 до 1.41) через переважання в бортах алевролітів та наявність тектонічних порушень.

Практична значимість. Узагальнені результати математичного розрахунку стійкості бортів проєктного контуру кар'єру Північний Катпар та побудована геологічна та структурна каркасна модель родовища дає змогу забезпечити безпеку ведення гірничих робіт на кар'єрі.

Ключові слова: *кар'єр, напружено-деформованого стану, геотехнічна модель, укос*