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Rock mass management to ensure safe deposit development based on comprehensive research within the framework of the geomechanical model development

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Abstract

Purpose. To create and study a three-dimensional geomechanical model in order to determine the parameters of the open-pit walls and benches, ensuring safe and economically feasible mining, as well as predicting unstable zones within the open pit.

Methods. A comprehensive methodological approach is used, including a systematic analysis of scientific, normative and methodological literature; analyzing the results of previously performed studies on the object; engineering-geological surveys in the near-edge rock mass of the Kurzhunkul' deposit; laboratory testing of rock strength properties; determining the rock mass rating according to the MRMR classification; kinematic analysis of bench faces; calculating the stability of the Kurzhunkul' deposit final boundary using the limit equilibrium method; numerical modeling of the rock mass stress-strain state at the Kurzhunkul' deposit using the finite element method.

Findings. The paper represents the results of data collection and analysis for the development of a geomechanical model of an operating iron-ore open pit in the Republic of Kazakhstan. Comprehensive geomechanical studies to substantiate the optimal parameters of the Kurzhunkul' deposit walls and benches on the limiting contour, as well as calculations to determine the degree of the open-pit walls and benches stability have been performed. Based on the results of studying the geological-structural configuration of the deposit, as well the mathematical modeling data of stability and acting stresses, subsequently entered into a unified digital database, weakened zones have been identified.

Originality. For the first time, the geomechanical model has been created for the conditions of the Kurzhunkul' deposit, which makes it possible to combine in one database all the parameters that affect the safety of mining operations. The model takes into account structural disturbances of the rock mass that have an adverse impact on stability.

Practical implications. The developed model gives a visual representation of the rock mass state at various sites of the deposit, simplifies the selection of design sections for stability calculations, facilitates the choice of optimal technical solutions and analysis, especially for complex geological structures with multiple geotechnical or geological units with different texturing and inclination.

Keywords: *geomechanical model, open pit, fracturing, stability, stress-strain state, rock mass classification, rocks*

1. Introduction

With the development of open-pit mining, deposits with more difficult mining-geological conditions are put into operation, which leads to the need to solve new, more complex problems in assessing the stability of open-pit walls [1]. Currently, various problems of geomechanics are solved using information technologies and computer modeling of geomechanical processes at various stages of deposit development.

At present, digital technologies are introduced into all areas of activity, including the mining industry [2]-[4]. Initially, geologists used modern digital technologies to create three-dimensional geological models that helped to solve many problems, such as localization and calculation of reserves, creating a technological scheme for mining operations, support by drilling, hydrodynamic studies, planning of geological exploration, search and development of residual reserves, monitoring of mining and predicting of production.

The developed three-dimensional geological models make it possible to understand how to mine a deposit correctly, how to avoid mistakes that can lead to serious problems and even ruin the deposit, how to draw up a technological scheme for mining operations, to track the physical processes that occur within the deposit during its development [5]-[6].

Next, three-dimensional models are used by miners and mine surveyors for planning and designing mining operations, for processing data from various surveys and mine surveying support for mining operations [7], [8].

To date, the digitalization of mining production has led to the need to create three-dimensional geomechanical models that can improve the efficiency and safety of mining opera-

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tions, monitor and assess the effectiveness of measures for a rational mining method.

The relevance of creating geomechanical models is beyond dispute, since solving real geomechanical problems requires more than having a prepared classification of rock masses and knowing the patterns of stress distribution in the mining system elements. It is necessary to have a clear understanding of the mutual spatial occurrence of certain rock types with the corresponding deformation-strength properties [9], [10]

In other words, to solve geomechanical problems, it is necessary to develop various situation models. This methodological approach is gradually gaining general recognition [11].

Consequently, the geomechanical model has become the main source of information for the geomechanical engineer to perform all the necessary calculations. Such a model is relevant for deposits mined both by open-pit and underground methods. On its basis, the geomechanical service can identify the main weakened zones and perform all the necessary calculations to assess the stability of both open-pit walls and underground mine workings [12]-[15].

Modern software tools provide modeling of the deposit development process using three-dimensional models of the surrounding rock mass. The most widely spread is the block method of deposit modeling.

The purpose of developing a block geomechanical model development is to ensure the safety of mining operations, reduce production costs, prevent accidents during the subsoil development and visualize the rating indicators of the mass quality in three-dimensional space.

The research purpose is to manage the rock mass on the basis of the integrated geomechanical model of the deposit.

To achieve this purpose set, the following tasks are supposed to be solved:

– processing and analysis of the collected geotechnical data on strength and structural properties of the rock mass, estimation of the rock mass quality rates, identification of the main joint set systems, determining the effect of fracturing on stability, substantiating the calculated parameters for physical-mechanical properties of the host rocks;

– identification of potentially unstable zones based on kinematic analysis;

– mathematical modeling of the rock mass stress-strain state and calculation of the stability of the open-pit walls and benches;

– development of an algorithm for grouping the collected and processed geotechnical data on a rock mass into a unified digital database;

– creating the geological model for the deposit according to the data on sections, plans and geological databases;

– completing a block geomechanical model.

2. Research method

Modern methods involve the creation of a three-dimensional geomechanical model of the rock mass, which includes detailed and reliable information about the geological and structural configuration of the deposit. It also includes the distribution of the strength properties of rocks, their changes as well as the hydrogeological model of the groundwater pore pressure distribution. On the basis of the geomechanical model, a kinematic analysis of slope stability is performed using the methods of limit equilibrium and numerical modeling [16].

The object of the study is the operating mining enterprise which is a part of JSC "SSGPO." The Kurzhunkul' magnetite ore deposit, which is located in the Kostanay Region of the Republic of Kazakhstan. The Kurzhunkul' deposit has been developed by the open-pit mining method since 1983. At present, the open-pit depth has reached -28 m (the depth is 240 m). The development of open-pit mining at the Kurzhunkul' deposit implies an increase in its depth to an absolute mark of -290 m. To solve the problem, research has been conducted to study the main actual rock mass characteristics and their influence on its stability [17].

The open-pit field of the Kurzhunkul' deposit is transversed by premineral faults of northeast strike (NE) with a northwest dipping (NW) at angles of 80-85°, as well as fault zones of northwest strike (NW) with a southwest dipping (SW) at the same angles. That is, it is a small- and medium-block rock mass. Reverse faults with a vertical amplitude of 15-20 m predominate [17]. The whole modeling process consists of the following main stages (Fig. 1).

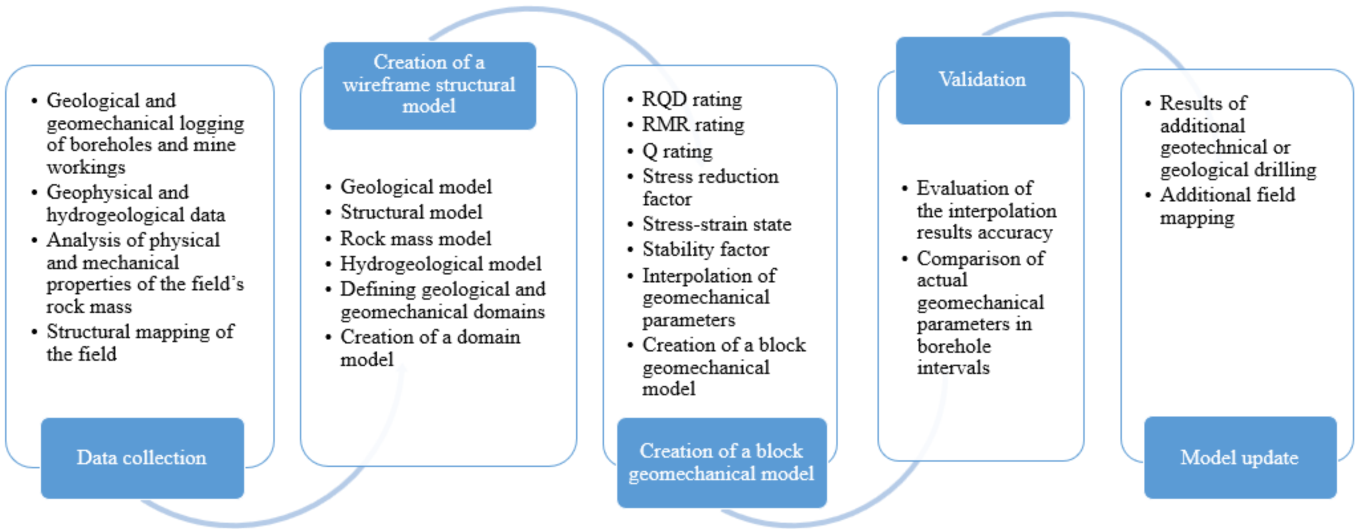


Figure 1. Stages of creating a geomechanical model

The collection of source data includes complete geological and geomechanical documentation based on the results of in-situ and laboratory studies of the peculiarities of the open-pit walls and benches. During this stage, data on the geological and geomechanical structure are collected, and the necessary parameters are determined for calculating the rock mass rating indicators [18].

The list of source information obtained for integrated stability modeling on the example of the Kurzhunkul’ deposit:

– study of geological and geotechnical documentation for boreholes, analysis of historical studies previously performed at the enterprise. As part of the research work, results have been obtained for 17 geotechnical boreholes located along the main projected section;

– hydrogeological data such as aquifer depth and thickness, flow pressure and rate, which are important parameters included in the RMR and MRMR rating systems;

– physical-mechanical rock properties. Laboratory tests have been conducted to determine the density, moisture content, elastic modulus, Poisson's ratio, ultimate strength in uniaxial tension and compression, cohesion and internal friction angle [19];

– survey of the rock mass fracturing by measuring it with a mining compass to determine the angle and azimuth of joint dip, its filler, roughness, length, distance along the normal to the nearest joint set of this system [20];

– study of the borehole core in order to determine the direction and pattern of the main weakness surfaces, as well as the spatial orientation of the main joint set systems [20];

– classification of a rock mass according to RQD, MRMR ratings;

– in-situ studies and mathematical modeling of the stress-strain state (SSS);

– multivariate calculation of the stability factor (SF).

The next stage is based on the collected data transfer into the three-dimensional model. Table 1 shows a summary of the geomechanical model database.

Table 1. Database description

Deposit	Input data	Source of data
ROCK	Rock lithotype code	According to drilling records of exploration boreholes
ZONE	Classification by zones: ore bodies, tectonic faults, mine workings, etc.	
RQD	Rock quality designation [21]	
FF	Fracture frequency	
FRAC	Fracturing modulus	
HW	Underground water level, m	
JN	Parameter characterizing the number of joint set systems	
JR	Parameter characterizing the joint roughness	
JA	Parameter characterizing the joint filler	
JW	Parameter characterizing the water cut of the mine working	
UCS	Ultimate uniaxial compression strength, MPa	According to laboratory studies
UTS	Ultimate tensile strength, MPa	
E	Elastic modulus, hPa	
NU	Poisson’s ratio	
COH	Cohesion in the rock mass, MPa	The rock mass mechanical properties are assessed using both the Coulomb-Mohr and the Hoek-Brown criteria [22], [23] and other non-linear failure criteria. The failure envelope can be used as source data.
PHI	Angle of internal friction, degree	
RMR	Bieniawski rating	According to the RMR rock mass quality rating system (Bieniawski, 1989) [24]
MRMR	Laubscher classification	According to [25]
SRF	Stress reduction factor	The indicator that takes into account the relationship among the stresses acting in the rock mass and the rock strength. It is determined based on the results of numerical modeling
FS_IRA	Factor of safety	According to the results of calculations using the methods of limit equilibrium and numerical modeling
FS_BFA	Stability factor of bench face angle	
FS_OVA	Stability factor of overall wall slope angle	
BH	Bench height, m	
BFA*	Bench face angle	
IRA*	Inter-ramp angle, degree	
OVA*	Overall wall slope angle, degree	

The wireframe structural model is created by bringing together all the available information (database containing the geological description of the core of exploration boreholes, geological plans and sections, topo-surface) obtained at various research stages and deposit development. The heterogeneity of the Kurzhunkul’ deposit rocks is represented by different host rock types, structural and geometric heterogeneity, which is taken into account when dividing the rock mass into several geomechanical (geotechnical) areas – domains. Each domain is supposed to have a clear boundary and a certain recognizable texturing and material properties. The average values of physical-mechanical properties, obtained as a result of rock sampling for each area, are assumed as characteristics of rock properties in this area. Additional parameters in the form of non-averaged values are also introduced for the areas located in the immediate vicinity of geotechnical boreholes with possible outcrops during subsequent open pit development.

3. Results

Based on the results of the deposit geological structure analysis, the lithological codes are corrected to create a reliable geological model (Table 2).

Table 2. Distribution of lithological units

Geological domain	Domain code in the model
Meso-Cenozoic deposits	CLY*
Limestones	LST
Porphyrites	TUF
Metasomatites	MET
Andesites	AND
Weathring crust	WEAT
Ore	ORE
Weakness zone	WEAK

*Note: In previous studies, there was no division of loose deposits according to geological varieties

The combination of differently oriented tectonic faults plays the main role in the formation of unstable blocks of the Kurzhunkul' deposit near-edge rock mass. Figure 2 shows the positions of the main tectonic faults of northwest strike (NW) from the 1st to the 6th, as well as the faults (in the horizontal plane) of northeast strike (NE). The existing disturbances and faults give the rock mass at the Kurzhunkul' deposit a hierarchical-block structure. The sizes of blocks into which the rock mass is divided by tectonic faults range from tens to a few hundreds of meters.

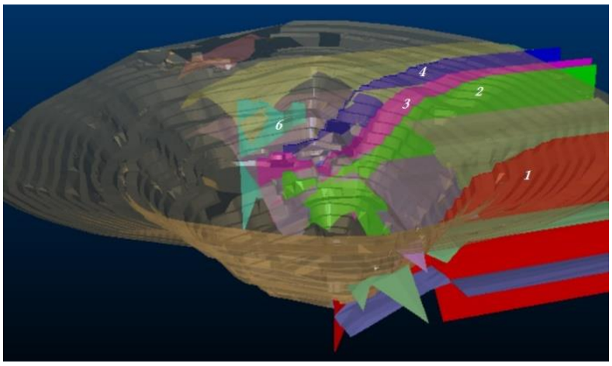
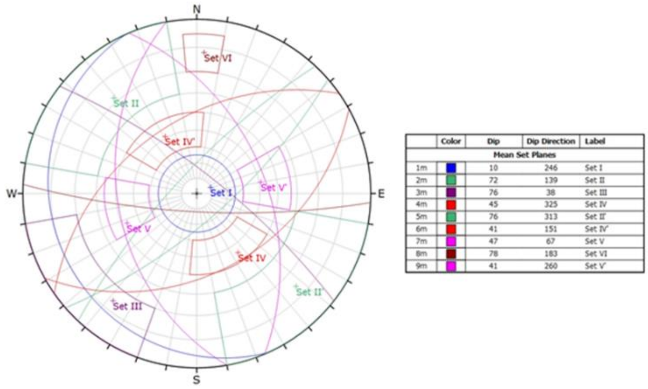


Figure 2. Main tectonic disturbances and faults transversing the Kurzhunkul' deposit final boundary (view from the south)

To determine the MRMR rating of the Kurzhunkul' deposit rock mass and to preliminarily assess the slope angles of the open-pit walls, the ratings of the rocky part benches of walls on the final boundary have been calculated according to the structural documentation of the borehole cores obtained during the engineering-geological surveys. Based on to the calculated parameters, according to the D. Laubscher rock classification method, the rocky part of the open pit belongs to the 2nd class and is characterized by medium and high stability with the following ranges of values: southeastern (SE) wall – 63.0-71.7; southwestern (SW) wall – 64.0-80.4; northwestern (NW) wall – 62.0-76.5; northeastern (NE) wall – 60.5-62.2.

On certain benches, the MRMR values have a wide scatter, which is explained by various structural disturbances of the near-edge rock mass represented by zones of tectonic crushing and increased fracturing. According to the results of statistical processing of structural data on the SW, SE, and NW walls, six joint set systems have been distinguished in the near-edge rock mass of the Kurzhunkul' deposit (Fig. 3). Some joints that are not included in the systems form nonsystematic chaotic fracturing, which is observed in the crushing and weathering zones [17].

(a)



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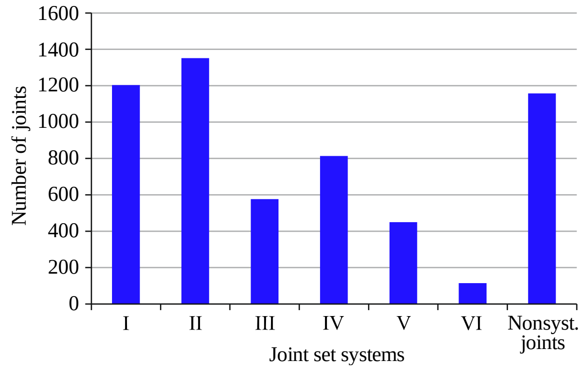

Figure 3. Kurzhunkul' deposit joint set systems: (a) stereogram; (b) distribution bar chart

Of the identified joint set systems of the studied areas, those have been localized that, individually or in combination with each other, most likely determine the deformations of the benches. Based on the kinematic analysis results, it has been determined that on the SE and SW open-pit walls, wedge failures of benches (the percentage of critical intersections of joint set systems reaches 50 and 25%, respectively) and planar failures (the percentage of critical intersections of joint set systems reaches 30 and 5%, respectively) are possible [26].

The stability of the Kurzhunkul' deposit walls is assessed according to six profiles built across the strike of the slopes. The location and direction of the calculated profiles have been chosen based on the principle of maximum danger (probability of the open-pit wall failure).

When calculating the stability of Kurzhunkul' deposit benches and walls, the following factors are taken into consideration:

– physical-mechanical properties of rocks and weakness surfaces;

– influence of fracture zones;

– water cut of the rock mass;

– technogenic impact is not taken into account, since the seismic rating of the Kurzhunkul' deposit is $\mu = 0$ (according to survey data, it is 6 points) according to the RK Code of Rules 2.03-30-2017 [27].

In the immediate vicinity of the southern and northern open-pit walls, there are external dumps No. 3 and No. 4.

The stability in this area is calculated for a unified "open pit-dump" system. By calculating the stability on the deposit final boundary with the seabed level (-290 m) and the actual strength characteristics of the rock mass, it has been revealed that the open-pit walls, with the accepted design parameters, are characterized by a minimum stability factor (SF) value in the range of 0.99-1.23 and meet the regulatory requirements on stability. However, the northeastern part of the open pit has lower values of SF = 0.89.

The weakened zone in the northern and northeastern open-pit wall is a zone of concentrated large tectonic faults, which have a significant extent to the dip, strike, and to a depth of open-pit walls, dividing it into blocks (Fig. 2). The unfavorable occurrence in combination with the weak physical-mechanical properties of fillers in fault joints can cause the blocks to shift during the development of the northeastern wall middle horizons. The technogenic impact and the rock mass water cut contribute to the deformation of the wall sections confined to the zones of faults and tectonic disturbances, which is confirmed by calculations.

On the northeastern open-pit wall, an in-pit dump is designed in the area of the weakened zone (Fig. 4). Based on the mathematical modeling results, it has been proposed to make a change in the design geometry of the in-pit dump. Calculations show that surcharge of the weakened zone with the in-pit dump contributes to its stability (Figs. 5 and 6).

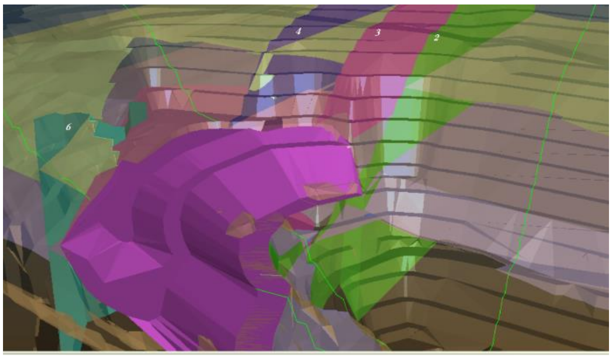

Figure 4. Visualization of the in-pit dump location on the limiting contour of the Kurzhunkul' deposit northeastern wall

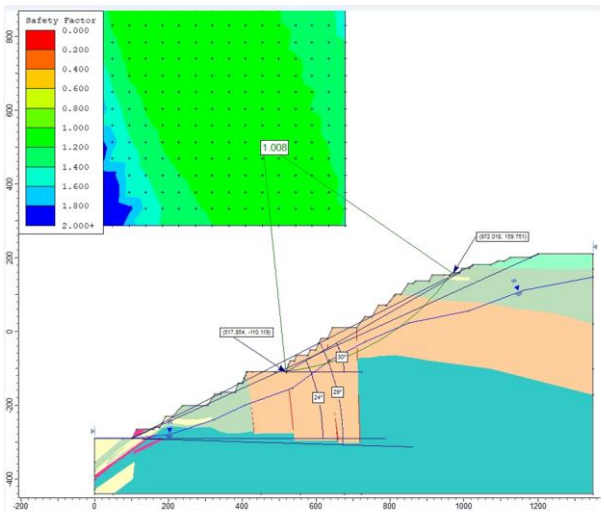

Figure 5. Estimation of the weakened zone stability of the northeastern wall along the final boundary (without in-pit dump)

Numerical modeling of the rock mass stress-strain state at the Kurzhunkul' deposit is performed within the framework of a two-dimensional problem.

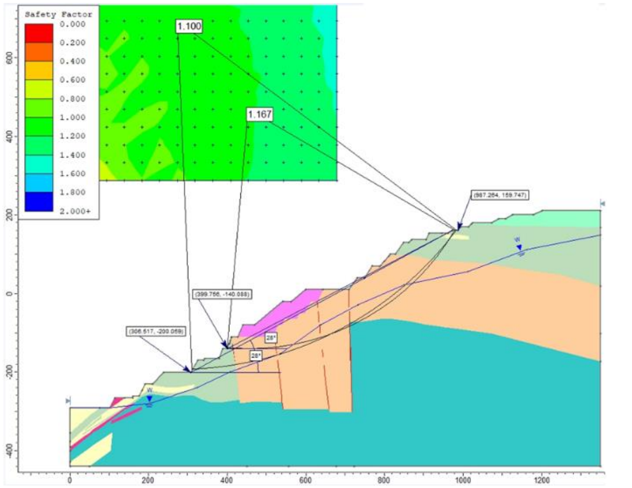

Figure 6. Estimation of the weakened zone stability of the northeastern wall along the final boundary (with in-pit dump)

To construct a finite element grid, the design models use sections of the Kurzhunkul' deposit final boundary in the direction of the SE and NW walls, as well as the SW and NE walls. The minimum linear size of the finite element based on the minimum geological layer thickness is 1-2 m, the maximum is 10-20 m. The calculation models contain 96866-119935 elements.

The Mohr-Coulomb model of an elastoplastic medium is used to model the rock properties of the near-edge rock mass [28]-[30]. Based on the modeling results, the main normal stresses σ_{max} (Max), σ_{min} (Min), maximum shear stresses τ_{max} (XY), vertical stresses σ_{vert} (YY) and stresses due to the weight of the overlying rock mass σ_x (XX) and σ_y (ZZ) have been determined.

For the NW wall, the values of the maximum stress component σ_{max} (Max) first decrease to the level of -100…-130 m, at the absolute value from 9.07 to 7.04 MPa, due to the surcharge with the external dump, and then gradually increase to 9.42-9.51 MPa. Then at the level of -400 m, the maximum component of horizontal stresses is equal to the gravitational stress σ_{max} (Max) = σ_{vert} (YY).

Minimum tensile stresses σ_{min} in the open-pit walls are observed at contacts of geological layers with different deformation properties and at the surface of slope benches. The values of minimum tensile stresses σ_{min} are 0.37 MPa, which is much less than the estimated values of tensile stresses σ_p in the model and generally do not affect the stability of the walls.

The SE wall benches down to the design depth of 500 m are under the force of low compressive stresses at the absolute stress values σ_{max} = 6.5-10.64 MPa. In the SE wall, at -400…-450 m levels, the maximum component of horizontal stresses is equal to the gravitational stress σ_{max} (Max) = σ_{vert} (YY).

Based on the modeling results of the SE-NW walls, the areas have been revealed, where there is an adverse effect of maximum shear stresses on the near-edge rock mass. It is possible here that the maximum shear stresses (τ_{max}) exceed the shear strength. In the NW wall, at the levels of -20…-230 m and in the SE wall at the levels of -20…-250 m, the maximum shear stresses τ_{max} act exceeding the shear strength. On these horizons, rock blocks can shift along natural and technogenic fractures (Fig. 7).

Calculation of stability and modelling of the stress-strain state using the Slide3 and RS3 software is possible on the basis of the created geotechnical model, taking into account all input parameters.

Figure 7. Distribution of maximum shear stresses τ_{Max} in the SW and NE directions of the Kurzhunkul' deposit walls in the virgin near-edge rock mass and the open pit

However, according to the requirements of the software (at the time of performing the works), the block sizes should be uniform throughout the model (i.e. of the same size). At the same time, taking into account the rather small thicknesses of contacts between rocks with faults 1-2 m, the model blocks should also have the approp-riate sizes, which makes the model quite complicated, thereby complicating further work and calculations. Therefore, to calculate the stability and simulate the SSS in Slide3 and RS3 software, it was decided to use wireframe models and the created database of physical-mechanical properties, which are the geomechanical model basis.

4. Conclusions

To substantiate the optimal parameters of the Kurzhunkul' deposit walls and benches, comprehensive geomechanical studies and calculations have been performed on the limiting contour to determine the stability of the open-pit walls and benches. The weakened zones, identified by the results of studying the geological and structural configuration of the deposit, the data of mathematical modeling of stability and acting stresses, are included into a unified digital database.

The research results make it possible to ensure the safety of mining operations when the wall is placed in the final position, while having a positive impact on the economics of mining production by reducing the volume of overburden and maintaining the stability of slope benches at their maximum permissible angles of slope.

Further research can be aimed at additional study of the northwestern open-pit wall, where, according to historical data, the main structural disturbances are located and the dip of host rocks is the most unfavorable. A small amount of reliable data in the framework of performed studies did not allow a detailed study of this area, since the available data on boreholes in this area do not include geotechnical characteristics of the border rock mass. However, the current mining-geological situation requires increased attention to this part of the open pit, given the close proximity of the main external dump to the wall.

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Управління гірничим масивом для забезпечення безпечного відпрацювання родовища на основі комплексних досліджень у рамках створення геомеханічної моделі

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Мета. Створення та дослідження тривимірної геомеханічної моделі для визначення параметрів бортів та уступів кар’єру, що забезпечують подальше безпечне й економічно обґрунтоване відпрацювання, та прогнозування нестійких зон у межах кар’єрної виїмки.

Методика. Використано комплексний методичний підхід, що включає системний аналіз наукової, нормативно-методичної літератури; аналіз результатів раніше виконаних досліджень за об’єктом; інженерно-геологічні дослідження у прибортовому масиві Куржункульського кар’єру; лабораторні визначення властивостей міцності порід; визначення рейтингу масиву за класифікацією MRMR; кінематичний аналіз укосів уступів; розрахунок стійкості проектного контуру Куржункульського кар’єру шляхом граничної рівноваги; чисельне моделювання напружено-деформованого стану породного масиву Куржункульського кар’єру шляхом скінченних елементів.

Результати. Наведено результати щодо збирання та аналізу даних для створення геомеханічної моделі діючого залізорудного кар’єру в Республіці Казахстан. Виконано комплексні геомеханічні дослідження для обґрунтування оптимальних параметрів бортів та уступів Куржункульського кар’єру на граничному контурі, а також розрахунки щодо визначення ступеня стійкості уступів і бортів кар’єру. Виявлено ослаблені зони за результатами вивчення геолого-структурної будови родовища, даними математичного моделювання стійкості та діючих напружень, що внесені в єдину цифрову базу даних.

Наукова новизна. Для умов Куржункульського кар’єру вперше створено геомеханічну модель, що дозволяє об’єднати в одній базі даних усі параметри, що впливають на безпеку відпрацювання родовищ, яка відрізняється врахуванням структурних порушень масиву гірських порід, які негативно впливають на стійкість.

Практична значимість. Розроблена модель дає наочне уявлення про стан масиву гірських порід різних ділянок родовища, спрощує вибір розрахункових перерізів для проведення розрахунку стійкості, полегшує прийняття оптимального технічного рішення та проведення аналізу особливо для складних геологічних структур, де є більше геотехнічних чи геологічних одиниць з різною орієнтацією та ухилом.

Ключові слова: *геомеханічна модель, кар’єр, тріщинуватість, стійкість, напружено-деформований стан, класифікація масиву, гірські породи*