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ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
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Satbayev University

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ
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NAS RK is pleased to announce that News of NAS RK. Series of geology and technical sciences scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of geology and technical sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

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MULTIVARIANT GEOMECHANICAL ESTIMATION OF THE DESIGN PARAMETERS' STABILITY OF SLOPE AND BENCH IN SOUTH SARBAI MINE

Abstract. The article presents the results of a multivariate geomechanical assessment the design parameters stability of the South Sarbai open pit's slopes and benches.

According to the project of «Giproruda» JSC, the final pit depth during the development will be 600 m. The main complication of increasing the depth of mining is the increased risk of large-scale destruction of the overall slope. For the planned significant deepening of the South Sarbai pit, an integrated approach was used during the analysis, which included a geomechanical assessment the stability of final pit walls by various methods:

- limit equilibrium methods in the plane and volume task statement;
- probabilistic method to more accurately take into account the influence of the uncertainty factor of strength properties;
- numerical simulation methods to take into account the effects of stress fields using the shear strength reduction (SSR) method.

The base model of the South Sarbai pit for use in calculations was created in the Datamine software in form of a digital wireframe geological and structural model.

To date, the most accurate calculation of slope stability is possible with the help of modern software systems. The assessment of the stability of the South Sarbai pit by the methods of limit equilibrium was carried out using the Slide2

and Slide3 programs (Rocscience). Prediction of the destruction of the near-edge mass under the action of tectonic stress fields was performed by numerical methods using the RS2 Rocscience program.

Based on the results, a geomechanical substantiation of the permissible parameters of the slopes of the South Sarbai pit was carried out during the development of a project for its mining to a depth of 600 m.

Key words: stability calculation, limit equilibrium methods, probabilistic method, numerical simulation methods, safety factor.

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ОҢТҮСТІК САРЫБАЙ КАРЬЕРІНІҢ БОРТТАРЫ МЕН КЕМЕРЛЕРІНІҢ ЖОБАЛЫҚ ПАРАМЕТРЛЕРІНІҢ ТҰРАҚТЫЛЫҒЫН КӨП НҰСҚАЛЫ ГЕОМЕХАНИКАЛЫҚ БАҒАЛАУ

Аннотация. Мақалада Оңтүстік Сарыбай карьерінің борттары мен кемерлерінің жобалық параметрлерінің тұрақтылығын көп нұсқалы геомеханикалық бағалау нәтижелері келтірілген.

“Гипроруда” АҚ жобасына сәйкес Оңтүстік Сарыбай карьерін игеру кезінде борттар еңісінің соңғы биіктігі 600 м құрайды. Тау-кен қазу тереңдігін арттырудың негізгі асқынуы – карьердің борттар еңісінің көлбеу қирау қаупінің жоғарылауы. Оңтүстік-Сарыбай карьерін айтарлықтай тереңдету үшін талдау кезінде олардың соңғы контурларының тұрақтылығын әртүрлі әдістермен геомеханикалық бағалауды қамтитын кешенді тәсіл қолданылды:

- мәселенің жазықтық және көлемдік орналасуындағы шекті тепе-теңдік әдістері;
- беріктік қасиеттерінің белгісіздік факторының әсерін дәлірек есепке алудың ықтималдық әдісі;
- ығысу күшін азайту (SSR) әдісін қолдана отырып, кернеу өрістерінің әсерін есепке алу үшін сандық модельдеу әдістері.

Есептеулерде пайдалану үшін Оңтүстік Сарыбай карьерінің базалық моделі Datamine бағдарламалық жасақтамасында сандық қаңқалы геологиялық-құрылымдық модель түрінде жасалған.

Бүгінгі таңда заманауи бағдарламалық кешендердің көмегімен беткейлердің тұрақтылығын дәл есептеуге болады. Оңтүстік Сарыбай карьерінің тұрақтылығын шекті тепе-теңдік әдісімен бағалау Slide2 және Slide3 (Rocscience) бағдарламаларын қолдана отырып жүргізілді. Тектоникалық кернеулі өрістердің әсерінен шеткі массивтің жойылуын болжау RS2 Rocscience бағдарламасының көмегімен сандық әдістермен орындалды.

Нәтижесінде 600 м тереңдікке дейін игеру жобасын әзірлеу кезінде Оңтүстік Сарыбай карьер борттары еңістерінің рұқсат етілген параметрлерін геомеханикалық негіздеу орындалды.

Түйін сөздер: тұрақтылықты есептеу, шекті тепе-теңдік әдістері, ықтималдық әдісі, сандық модельдеу әдістері, тұрақтылық қорының коэффициенті.

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МНОГОВАРИАНТНАЯ ГЕОМЕХАНИЧЕСКАЯ ОЦЕНКА УСТОЙЧИВОСТИ ПРОЕКТНЫХ ПАРАМЕТРОВ БОРТОВ И УСТУПОВ ЮЖНО-САРБАЙСКОГО КАРЬЕРА

Аннотация. В статье приведены результаты многовариантной геомеханической оценки устойчивости проектных параметров бортов и уступов Южно-Сарбайского карьера.

Согласно проекту АО «Гипроруда» конечная высота откоса бортов при разработке Южно-Сарбайского карьера составит 600 м. Основным осложнением при увеличении глубины добычи является повышенный риск крупномасштабных разрушений откосов бортов карьера. Для планируемого значительного углубления Южно-Сарбайского карьера при проведении анализа применялся комплексный подход, который включал геомеханическую оценку устойчивости их конечных контуров различными методами:

- методами предельного равновесия в плоской и объемной постановке задачи;
- вероятностным методом для более точного учета влияния фактора неопределенности прочностных свойств;

- методами численного моделирования для учета воздействия полей напряжений с использованием метода снижения прочности на сдвиг (SSR).

Базовая модель Южно-Сарбайского карьера для использования в расчетах была создана в ПО Datamine в виде цифровой каркасной геолого-структурной модели.

На сегодняшний день наиболее точно произвести расчет устойчивости откосов возможно с помощью современных программных комплексов. Оценка устойчивости Южно-Сарбайского карьера методами предельного равновесия проведена с использованием программ Slide2 и Slide3 (Rocscience). Прогнозирование разрушения прибортового массива под действием тектонических полей напряжений было выполнено численными методами с использованием программы RS2 Rocscience.

По итогам выполнено геомеханическое обоснование допустимых параметров откосов бортов Южно-Сарбайского карьера при разработке проекта его отработки до глубины 600 м.

Ключевые слова: расчет устойчивости, методы предельного равновесия, вероятностный метод, методы численного моделирования, коэффициент запаса устойчивости.

Introduction. The South Sarbay deposit is located 0.3 km south of Sarbay deposit in the same skarn-ore zone. In fact, it is a continuation of the Sarbay deposit and is actually one of its sections. It was discovered in 1961 during the well-boring control of a magnetic anomaly to the south of the explored Sarbay deposit.

According to the project of JSC "Giproruda," the final height of pit slopes at the development of the South Sarbay deposit is 600 m. It is expected that the pit will mainly expand in the western and northern directions. The project defines that the slope angles are within 40^{o} to 55^{o} at a bottom elevation of minus 400 m. The fundamental factor influencing the slope angle is its stability which is estimated by the stability factor.

The main complication of increasing the depth of mining is the higher risk of large-scale destruction of the pit slopes. The analysis performed for the planned significant deepening of the South Sarbay deposit involved an integrated approach including a geomechanical assessment of the stability of its final contours using various methods:

- Limit equilibrium methods in two and three-dimensional formulation of the problem using Slide 2 and Slide 3 software (Rocscience);
- Probabilistic method for a more accurate account for the influence of uncertainty of strength properties;
- Numerical simulation methods to account for the impact of stress fields in the RS2 Rocscience software using the shear strength reduction method (SSR).

Characteristics of the researched object. The exploitation of the deposit as an open pit began in 2008. To date, the eastern side of the South Sarbay deposit has been opened up to a 137 m horizon (practically to the bottom of loose sediments). Within the studied area of the eastern side, there are deformation sloughing of the sand-clay strata, and suffusions most likely caused by a change in the hydrological conditions of the field in the absence of drainage and the impact of precipitation. On the day surface, the pit has not reach the design contours.

The deposit is characterized by a block structure due to numerous rupture anomalies. Zones of tectonic faults within the studied area are zones of crushing, without clay gouge, along with zones of increased fracturing.

Two complexes of rocks compose the geological structure of the deposit: highly deformed sedimentary-volcanic rocks of the Paleozoic age and horizontally occurring, mostly loose, Meso-Cenozoic deposits overlapping the latter.

To assess the structural disturbance of the rock mass, the RMR (Bieniawski) rating system for quality assessment was used (Momeni E., 2015: 50). The calculated geological strength index of the rock mass of the South Sarbay deposit (GSI=RMR_{89}-5, for $RMR_{89} > 23$ according to the Hook-Brown strength theory (Eberhardt E., 2012: 45), which describes the influence of blockiness and fracturing, varies within 53÷63 (except for the weathering crust and weathered rocks, GSI=22÷38). This characterizes the rock mass as highly blocky and cemented, partially disturbed with polyhedral, angular blocks, formed by 4 and more fracture systems; in the weathering crust and weathered rocks, as a small block rock mass.

The hydrogeological conditions of the researched area are characterized by the absence of upper aquifers drained by the dewatering system of the Sarbay and South Sarbay open pits. The main share of water inflows into the open pit is formed by rocks of the Cretaceous and Paleozoic aquifer complex. At the development of reserves on all sides of the open pit, it is necessary to take into account the presence of watered strata of loose rocks and clays due to the threat of sloughing and collapse of slopes composed of chalk sands, Neogene clays and Quaternary loams.

The method of research of stability of the open pit slopes. A multivariant geomechanical assessment of stability of final pit contours was performed using the following methods:

- Limit equilibrium methods in two and three-dimensional formulation of the problem;
- Probabilistic method for a more accurate account for the influence of uncertainty of strength properties;
- Numerical simulation methods to account for the impact of stress fields.

Today, the most accurate calculation of slope stability is possible with the help of modern software systems. The stability of the South Sarbay open pits was assessed using the Slide 3 program (Rocscience), which ensures a three-dimensional (3D) analysis of stability of the pit slopes using methods of limit equilibrium with due account for its geometry (Soto J.G., Romanel C., 2018:746). Confirmatory calculation was also done in a standard two-dimensional formulation using the Slide 2 program (Rocscience). The Spencer, GLE and Morgenstern-Price methods were used for calculating the limit equilibrium that ensure more accurate results (Fomenko I., Jıtınskaıa O., 2018: 76).

The base model for the Slide 3 program was created in Datamine software as a digital wireframe geological and structural model. The wireframe geological and structural model (Figure 1) was created by bringing together all the available information (geological horizon plans and sections, topo-surface) obtained at various stages of the study of the South Sarbay field.

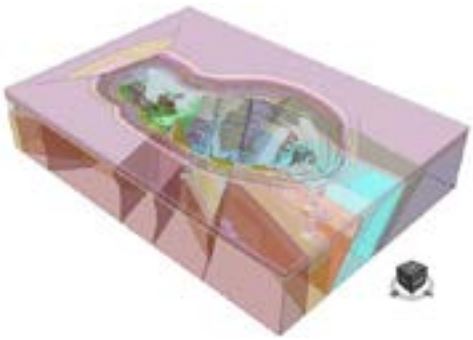


Figure 1. General view of the 3D geological and structural model of the South Sarbay open pit according to the design at the end of mining.

To analyze the stability of the South Sarbay open pit in 3D formulation, this wireframe geological and structural model (Figure 1) was imported into the Slide 3 program.

Next, at the creation of a geotechnical model, the following characteristics of the mining and geological conditions of the open pit were taken into account:

1) Strength parameters of the main overburden rocks and weakening surfaces.

The calculated physical and mechanical properties of the identified lithotypes of the geological section, which determine the initial stress field and elastic-plastic deformation of rocks, included: specific gravity of rocks, deformation characteristics (Young's modulus and Poisson's ratio) and strength characteristics.

2) Ground water conditions.

Due to incorrect information in the calculations regarding the level regime of observation wells at the Paleozoic horizon, the possible deviation of the ground

water level of the Paleozoic aquifer is assumed to be ≈200 m from the base of the deposits of the Cretaceous aquifer complex (up to absolute elevation minus 50 m), according to survey data.

3) Seismicity. Stability was calculated for static conditions. The seismicity coefficient μ=0 (according to survey data, it was determined as 6 points), according to the RK Code of Rules 2.03-30-2017 (SP RK 2.03-30, 2017).

4) Lamination (orientation of inhomogeneities). Within sections 33-53, lamination structures for tuffites were added to the calculation model for the final contour. The parameters of the average orientation of the layers are (55°(±10) /158°) for the eastern slope (heterogeneities coincide with the direction of potential sliding), and for the western slope, reverse lamination with the orientation of (55°(±10) /338°) was considered.

n=1.3 (Rylnıkova M.V., Zoteev O.V., 2018., Mochalov A.P., Popov V.N., Eremın G.M., 2016:224) was assumed as an acceptable value of the standard (design) stability factor in the calculations, which was introduced into the initial strength characteristics of the host rocks of the pit slopes.

Results of stability calculation. Three-dimensional analysis of stability using the methods of limit equilibrium of the South Sarbay open pit with the actual strength characteristics of the rock mass revealed that the pit slopes, with the accepted design parameters in the rocky part, are stable. The lowest stability factor n'=1.115 is noted on the eastern slope (Figure 2).

Most of the rocks of the loose part of the pit slopes, according to the design, are beyond the stability limit. The most critical areas with the lowest total calculated stability factor are observed in the loose part of the western slope (n'=0.646) with the boundaries of the wedge of failure at elevations (+200 m) ÷ (+108 m).

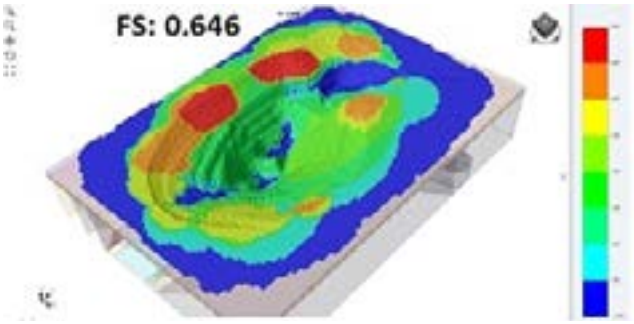


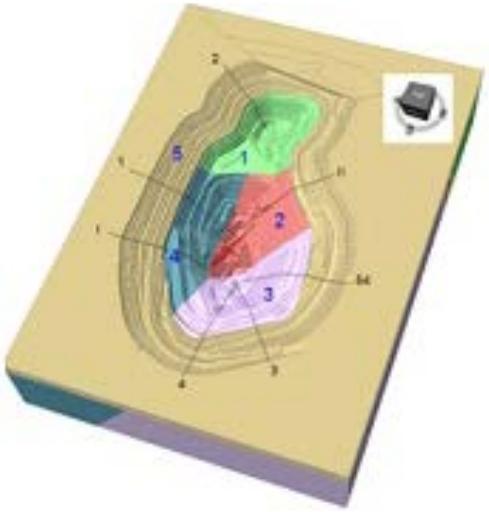
Figure 2. The results of calculation of the overall (global) stability of the South Sarbay open pit in a 3D formulation (Slide3 Rocscience program).

The results of three-dimensional (3D) analysis are considered more realistic because they take into account the influence of large faults on the stability of the pit walls, the anisotropy of the rock mass, and the actual geometry of the pit.

The main goal of slope stability analysis is to find the critical fracture surface - the surface along which the rock mass will fail. When calculating the stability factor, an optimized sliding surface search option was used in the RocScience Slide program (the "cuckoo method") (Wu A., 2012, Levın E.L., Serdıýkov A.L., 2017), which allows finding the shape and location of the most critical fracture surface in the model (global minimum).

To determine the optimal design parameters of the pit slopes, the quarry field was divided into 5 sectors, within which the properties of rock masses and ore are considered similar (Figure 3). At the division into sectors, the lithologies of the host rocks, their strength characteristics, the boundaries of the main faults documented during the operation of the open pit, and the orientation of the pit slopes were taken into account (Shamganova, L.S., Syedina, S.A., Berdinova, N.O., 2021:30).

The stability of the South Sarbay open pit walls was assessed on 7 significant sections built across the strike of the slopes (Figure 3). The calculated sections of the open pit were extracted from a 3D wireframe geological and structural model of the deposit.



Notation:
3 - Sector number
II - Number of the calculated section
Figure 3. Location of calculated sections on the 3D plan of the South Sarbay open pit.

The stability factors of the most critical sliding surfaces of the rocky part of the slopes of the South Sarbay open pit calculated using the methods of limit equilibrium (Figure 4) at the accepted design parameters equaled n'=0.962-1.177.

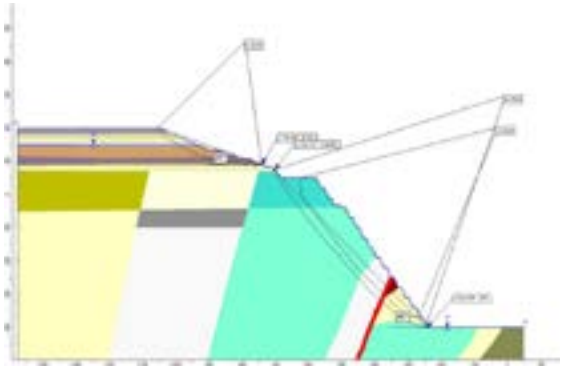


Figure 4. An example of stability calculation for section I using limit equilibrium methods (FoS=0.962)

The effects of high stresses in rocks at great depths cannot be fully accounted for by the traditional stability analysis using limit equilibrium methods. To predict deformations, the mechanism of displacements and destruction of rocks in deposits with due account for the impact of stress fields, numerical methods are used to model the trend of changes in the stress-strain state (SSS) of the rock mass. Numerical simulations were performed using the RS2 RocScience software (Sedina S.A., Berdinova N.O., Abdikarimova G.B., Altayeva A.A., Toksarov V.N., 2021:110, Griffiths D.V., 2012), where slope stability is quantified using the shear strength reduction (SSR) method. The main estimated indicators in assessing the stability of the rock mass at the application of numerical modeling methods in the RS2 RocScience program are the strength factor and the total displacement.

The stability factors of the calculated sections in numerical simulation were SRF=0.98-1.16 (Figure 5).

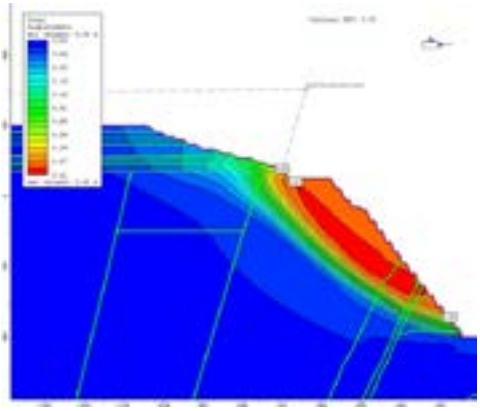


Figure 5. Contours of maximum shearing strain and distribution of total displacement along section I (SFR=0.98).

The calculation of slope stability of the design contour of the South Sarbay open pit using the numerical simulation methods in the RS2 Rocscience program revealed that:

- In section I (+120) m - (-360) m, a displacement of about 0.40 m towards the gob area is predicted. The estimated strength factor SRF is 0.98 (using the limit equilibrium methods n'=0.962).

– In section II (-280) m - (-370) m, a slight displacement of about 0.04 m towards the gob area is predicted. The estimated strength factor SRF is 0.99 (using the limit equilibrium methods n'=1.034).

Additionally, an alternative calculation of the pit slopes stability was done using the probabilistic method for more accurate account for the influence of the uncertainty factor of strength properties (Hadjigeorgiou J., 2019:159, Spırın V.I., Lıvınskıı I.S., Hormazabal E., 2019, Hideki Shimada, Takashi Sasaoka, Akihiro Hamanaka, Tumelo K. Dintwe, Sugeng Wahyudi, 2020). In the world practice, in addition to the stability factor, the standard criteria for assessing the reliability of a pit slope design is also the probability of failure (PoF). For the most significant sections (high slopes with large structures, areas that affect the technological process), an additional calculation of the probability of failure (PoF) was also done for the rock part in order to be able to take into account potential changes in the initial strength characteristics. The calculation of the probability of failure shows the variability of the adhesion parameter within ±30%. The probability of slope failure (PoF) depends on the proportion of calculation results with a stability factor less than 1 to the entire volume of calculations.

According to the results of the probabilistic analysis of stability of the estimated sections, their strength factors were FS > 1, namely FS=1.005-1.161 (Figure 6).

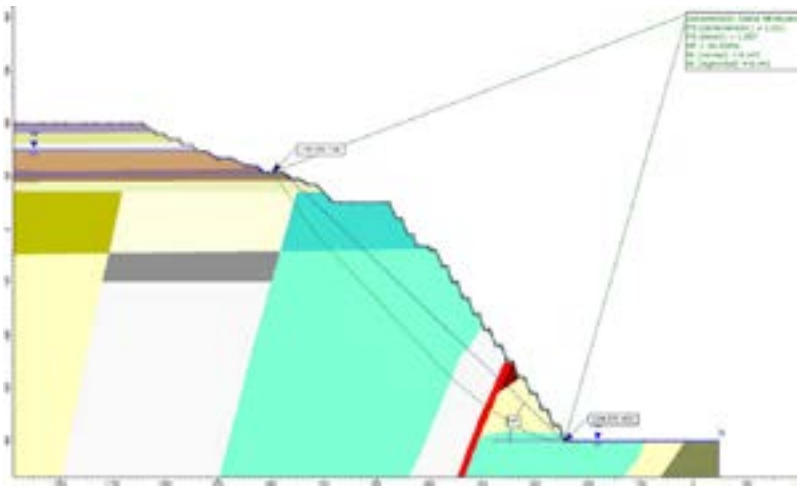


Figure 6. Calculation of the probability of failure in section I (FS=1.007).

A summary table of the results of stability factor calculation using various methods for the estimated sections is represented in the Table 1.

Table 1. Stability factors of the design contour of slopes of the South Sarbay open pit calculated using various methods

Sector	Slope orientation	Estimated sections	Resulting slope angle, degree	Slope angle in the rocky part, degree	Stability factor calculated using the method of		
					Limit equilibrium	Numerical simulation	Probabilistic calculation
					FoS	SFR	FS
1	North	2	33	50	1.083	1.03	1.108
2	East	II	32	40	1.034	0.99	1.008
3	South	3, 4, 54	28	35	0.99,1.17	1.03-1.16	1.005,1.161
4	West	1, I	37	46	0.96,1.12	0.98-1.01	1.007,1.074

Conclusion. Based on the results of a multivariant geomechanical assessment of design stability parameters of the slopes and benches of the South Sarbay open pit using the methods of limit equilibrium and numerical modeling, the following was determined (Table 1):

- The calculated minimum stability factors of the estimated sections of the South Sarbay open pit using the methods of limit equilibrium (FoS) and numerical modeling (SFR) do not differ from the design stability factors by more than 5% and, according to the instructions of the VNIMI, no adjustments are required to the slope parameters.

- The slopes of the open pit in the rocky part, with the accepted design parameters, are characterized by a minimum margin of stability and meet the regulatory requirements in terms of stability.

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