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CURRENT STATE OF RESEARCH ON THE GEOMECHANICAL CONDITIONS OF ROCK MASSES DURING THE DEEPENING OF OPEN-PIT MINING OPERATIONS

Abstract. The paper assesses the geomechanical conditions affecting the stability of pit slopes and benches in a deep open pit mine using an iron ore deposit in the Kostanay Region of the Republic of Kazakhstan as a case study. Engineering-geological investigations included deep borehole drilling, geophysical surveys, laboratory testing of the physical and mechanical properties of rocks, and in situ investigation of rock mass fracturing. Based on the obtained data, engineering-geological units and design rock mass strength parameters were determined, and the probability of different bench failure mechanisms was evaluated. The results indicate that the least stable conditions occur on the eastern wall of the pit due to the unfavorable orientation of the major joint system relative to the slope.
Keywords: *pit slope stability, deep open-pit mine, rock mass fracturing, physical and mechanical properties of rocks, structural weakening coefficient, limit equilibrium method, finite element method, Sokolov-Sarbai deposit.*

Ашық тау-кен жұмыстарын тереңдету кезінде тау жыныстары массивтерінің геомеханикалық жағдайларын зерттеудің қазіргі күйі

Аңдатпа. Мақала Қазақстан Республикасының Қостанай облысындағы темір кен орны мысалында терең карьердің борттары мен кемерлерінің орнықтылығының геомеханикалық жағдайларын бағалауға арналған. Зерттеуде инженерлік-геологиялық ізденістердің нәтижелері, оның ішінде терең ұңғымаларды бұрғылау, геофизикалық зерттеулер, тау жыныстарының физикалық-механикалық қасиеттерін зертханалық анықтау және жартас массивінің жарықшақтылығын зерттеу қарастырылған. Статистикалық өңдеу нәтижесінде алты инженерлік-геологиялық элемент бөлініп, массивтің есептік беріктік сипаттамалары анықталды және карьердің сегіз учаскесі бойынша кемер деформацияларының пайда болу ықтималдығы бағаланды. Зерттеу нәтижелері карьердің шығыс бортында жарықшақтардың құлау бұрышы жобалық еңіс бұрышымен сәйкес келуіне байланысты орнықтылықтың ең қолайсыз жағдайлары қалыптасатынын көрсетті.
Түйінді сөздер: *карьер борттарының орнықтылығы, терең карьер, массивтің жарықшақтылығы, тау жыныстарының физикалық-механикалық қасиеттері, құрылымдық әлсіреу коэффициенті, шектік тепе-теңдік әдісі, соңғы элементтер әдісі, Сарыбай кен орны.*

Современное состояние исследования геомеханических условий массивов пород при углублении открытых горных работ

Аннотация. Статья посвящена оценке геомеханических условий устойчивости бортов и уступов глубокого карьера на примере железорудного месторождения, расположенного в Костанайской области Республики Казахстан. Представлены результаты инженерно-геологических исследований, включающих бурение глубоких скважин, геофизические исследования, лабораторное определение физико-механических свойств пород и изучение трещиноватости массива. На основе статистической обработки выделены шесть инженерно-геологических элементов, определены расчетные прочностные характеристики массива и выполнена оценка вероятности развития деформаций уступов на восьми участках карьера. Установлено, что наиболее неблагоприятные условия устойчивости характерны для восточного борта карьера вследствие совпадения угла падения основной системы трещин с проектным углом откоса.
Ключевые слова: *устойчивость бортов карьера, глубокий карьер, трещиноватость массива, физико-механические свойства пород, коэффициент структурного ослабления, метод предельного равновесия, метод конечных элементов.*

Introduction

The development of the modern global mining industry is characterized by a steady trend toward increasing the depth of open-pit mining. The depth of a number of operating open-pit mines worldwide (Bingham Canyon, Chuquicamata, Escondida, Grasberg, etc.) has already exceeded 500–1200 m from the earth's surface, making the justification of the maximum parameters of slopes and benches one of the most pressing issues in modern open-pit mining geomechanics.

The subject of this study is the Sarbay iron ore deposit, located in the northwestern part of the Kostanay region of the Republic of Kazakhstan. Open-pit mining has been conducted since 1960; The current quarry bottom elevation is minus 390 meters, and design documentation calls for a depth of minus 500 meters. The deposit has a two-tiered structure: a platform cover 150–230 meters thick, composed of loose Mesozoic-Cenozoic sediments, rests on a folded Paleozoic basement broken by a system of large faults (including a meridional reverse-slip fault with a vertical displacement amplitude of 1,100–1,350 meters).

The stability of the Sarbai quarry walls is affected by the presence of weakness surfaces (fracturing, layering, and schistosity), waterlogging of the massif, and the reduced strength properties of rocks in certain areas. The main destabilizing factor is the intense fracturing of certain sections of the near-wall massif. To further design stable slope parameters for the transition to deeper horizons, it was necessary to obtain up-to-date data on the geomechanical state of the rock mass at elevations from 0 to minus 660 m.

The objective of this study is to substantiate the stability of the Sarbai quarry slopes during its deepening based on a comprehensive geomechanical assessment, including an analysis of initial mining and geological data, the results of laboratory and in-situ studies, and an assessment of the likelihood of various bench deformation mechanisms [1–3].

To achieve this goal, the following tasks were completed: identifying the factors influencing the stability of the quarry slopes as the mining depth increases; conducting laboratory and in-situ studies of the rock mass with subsequent statistical processing of the obtained data; studying the structural and tectonic structure and fracturing of the rock mass at the edge; determining the estimated strength characteristics of rocks in the rock mass, taking into account the structural weakening coefficient; and assessing the likelihood of various types of bench deformation in characteristic sections of the quarry.

Materials and methods

Engineering and geological surveys

To study the geological and structural structure of the quarry walls, the engineering-geological and hydrogeological conditions of the massif, and the fracturing of the rock margins within the absolute elevation range of -200 to -500 meters, five deep vertical wells were drilled, totaling 2,195 linear meters, oriented along five profiles across the strike of the quarry walls. The geophysical survey included gamma-gamma density logging (GGK-P), resistivity logging (RL), gamma ray logging (GL), magnetic susceptibility logging, caliper logging, inclinometry, and flow logging. The logging data was used to identify intervals of fractured and unstable rocks, lithologically dissect the section, and determine zones of water absorption and influx.



Figure 1. Layout of geological boreholes at the Sarbai quarry. Determination of the physical and mechanical properties of rocks.
Сурет 1. Сарбай карьеріндегі геологиялық ұңғымалардың орналасуы. Тау жыныстарының физикалық және механикалық қасиеттерін анықтау.
Рис. 1. Схема расположения геологических скважин на Сарбайском карьере. Определение физико-механических свойств пород.

Samples of all identified lithological variations were collected from the borehole core. The following parameters were determined in the laboratory using standard methods: density (bulk density) γ, uniaxial compressive strength σc, tensile strength σp, elastic modulus E, Poisson's ratio μ, specimen cohesion C, internal friction angle φ, and longitudinal and transverse elastic wave propagation velocity V. Tensile test specimens were made with geometric dimensions of 1.0 x 1.0 cm and 1.5 x 1.5 cm (4.5 x 4.5 cm for weak and fractured rocks). The end surfaces were polished to ensure parallel contacts during load testing.

The density of regularly shaped specimens was determined by weighing and then calculated as the ratio of the specimen mass to the product of its cross-sectional area and height. The elastic modulus and Poisson's ratio were calculated using the propagation velocities of longitudinal ***(Vp)*** and transverse ***(Vs)*** ultrasonic waves, determined from the acoustic delay time ***(Δt)*** at a constant specimen length of $L = 100$ ***mm***. Cohesion and the angle of internal friction were determined by constructing a strength certificate based on the results of uniaxial compression and tension tests. For strong and medium-strength rocks at the studied deposit, a logarithmic relationship was established between the ultimate uniaxial compressive strength and the cohesion of rocks in the specimen [4].

Samples of all identified lithological variations were collected from the borehole core. Under laboratory conditions, standard methods were used to determine the density (bulk density) γ, uniaxial compressive strength σc, tensile strength σp, elastic modulus E, Poisson's ratio μ, specimen cohesion C, internal friction angle φ, and longitudinal and transverse elastic wave propagation velocity V. Tensile test specimens were manufactured with geometric dimensions of 1.0 x 1.0 cm and 1.5 x 1.5 cm (4.5 x 4.5 cm for soft and fractured rocks). The end surfaces were polished to ensure parallel contacts during load testing.

The density of regularly shaped specimens was determined by weighing and then calculating the ratio of the specimen mass to the product of the cross-sectional area and the height. The elastic modulus and Poisson's ratio were calculated using ultrasonic measurements of longitudinal ***(Vp)*** and shear ***(Vs)*** wave propagation velocities after an acoustic delay time of Δt at a constant specimen length of $L = 100$ ***mm***. Cohesion and the angle of internal friction were determined by constructing a strength certificate based on the results of uniaxial compression and tension tests. A logarithmic relationship between compressive strength and cohesion in the specimen was established for strong and medium-strength rocks of the Sarbayskoye deposit.

To assess the risk of deformations occurring on a bench scale, a classification of rock mass stability loss types adopted in international practice was used: block shear along the undercutting plane (*Planar Sliding*), wedge shear along the intersection of two fracture systems (*Wedge*), and rock block toppling toward the mined-out space, which occurs through direct toppling or flexural toppling. For eight representative quarry sections covering all the walls, the probability of each of these deformation mechanisms was determined based on data on the occurrence of fracture systems and the orientation of the bench slopes.

The calculated strength characteristics of the rock mass (adhesion Cm and internal friction angle) were determined taking into account the structural weakening coefficient λ using G. L. Fisenko's formula, which relates λ to the ratio of the side height H to the average size of the structural block l and the coefficient a, which depends on the rock strength in the sample and the nature of the fracturing. The specific adhesion in the rock mass was calculated as the weighted sum of the adhesion in the sample and along the weakening surfaces, taking into account λ.

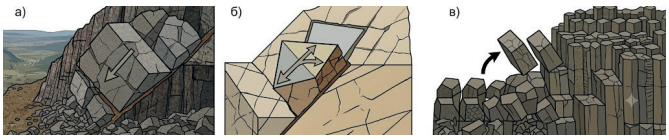


Figure 2. Main types of rock stability loss: *a) shear of a prismatic block; b) shear of a wedge-shaped block; c) collapse of a ledge with overturning of blocks.*

Сурет 2. Тау жыныстарының тұрақтылығының жоғалуының негізгі түрлері:
а) призмалық блоктың ығысуы; ә) сына тәрізді блоктың ығысуы; б) блоктардың аударылуымен қиғаштың құлауы.

Рис. 2. Основные виды потери устойчивости скальных пород: *а) сдвиг призматического блока; б) сдвиг клиновидного блока; в) разрушение уступа с опрокидыванием блоков.*

The stability factor (SF) for kinematically identified blocks was calculated using the limit equilibrium method using the lateral pressure method: a computational compartment, bounded below by the sliding surface (plane or line of intersection of fracture systems) and above by the slope surface, was divided by vertical lines into elementary columns less than one meter wide. For each column, the normal (N) and shear (E) components of the rock weight were determined using the force triangle, and the shear coefficient of the rock was calculated as the ratio of the sum of the holding forces (taking into account the angle of internal friction, cohesion, and lateral pressure coefficient) to the sum of the shear forces over the entire sliding surface. The calculations took into account the heterogeneity of the rock across layers with different physical and mechanical properties and the water content of the rock mass along the depression line.

Physical and mechanical properties of rocks by section depth

Analysis of laboratory test results revealed significant variability in the physical and mechanical properties of rocks, even within a single lithological type [5–8]. This is explained by differences in the intensity of fracturing, the degree of foliation, brecciation, and metasomatic alteration of the rocks. An additional factor contributing to variability in compressive strength is the heterogeneous mineralogical composition of the secondary minerals filling the fractures (for example, calcite is characterized by $\sigma \approx 16$ MPa, while pyrite has $\sigma \approx 128$ MPa).

Based on the statistical processing of core test data to a depth of minus 660 m, six engineering-geological elements were identified at the deposit: limestone (σcompression from 60 to 70 MPa, average 65 MPa), tuffs (from 30 to 230 MPa, average 113 MPa), tuffites (from 40 to 80 MPa, average 64.78 MPa), metasomatites (from 50 to 60 MPa, average 56.67 MPa), diorites (from 110 to 210 MPa, average 153.7 MPa) and ore (single intersection at a depth of 523.73–525.10 m, density 3.61 t/m³, σcompression = 160 MPa). The generalized physical and mechanical properties of rocks based on the survey results are presented in Table 1.

A pattern of growth in the strength characteristics of rocks with depth was established, as well as a practically directly proportional relationship between the adhesion in the sample and the uniaxial compressive strength, which is consistent with previously obtained results of foreign researchers for similar geological conditions.

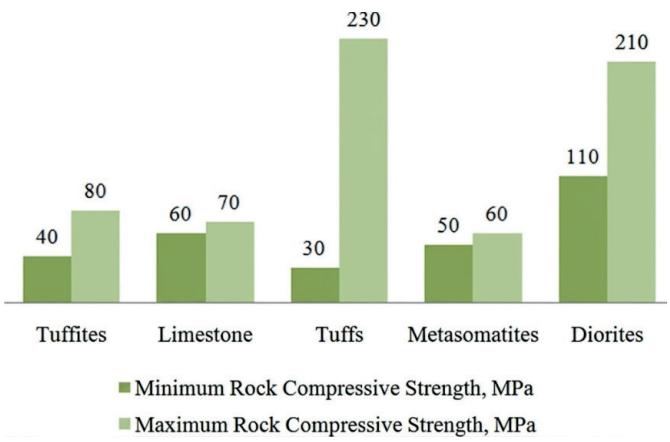


Figure 3. Minimum and maximum values of rock compressive strength based on the results of geotechnical surveys.

Сурет 3. Инженерлік-геологиялық зерттеулер нәтижелері бойынша тау жыныстарының сығылу беріктігінің минималды және максималды мәндері.

Рис. 3. Минимальные и максимальные значения прочности пород на сжатие по результатам инженерно-геологических изысканий.

Table 1

Generalized physical and mechanical properties of rocks and ores of the Sarbay quarry

Кесте 1

Сарбай карьерінің тау жыныстары мен кендерінің жалпыланған физикалық және механикалық қасиеттері

Таблица 1

Обобщенные физико-механические свойства скальных пород и руд Сарбайского карьера

Rock	γ, t/m³	$\sigma сж$, MPa	$\sigma р$, MPa	E·10⁻⁴, MPa	μ	C_0, MPa	φ, degrees
Limestone	2,82	65,0	8,00	5,94	0,22	18,0	35
Tuffs	2,75	113,0	8,15	6,06	0,21	30,0	37
Metasomatites	2,90	56,67	5,83	5,51	0,21	15,6	35
Tuffites	2,84	64,78	7,17	5,39	0,22	18,5	36
Diorite	2,84	153,7	11,5	7,79	0,21	43,5	35
Ore	3,61	160,0	13,5	5,90	0,21	20,6	38

Rock mass fracturing and structural survey results

According to drilling data, the average specific fracturing of the rock mass was 4.48 cracks/m, with a consistent trend of decreasing fracturing (increasing blockiness of the rock mass) with depth: from 21.33 cracks/m in the 0 to -100 m interval to 0.70 cracks/m in the -600 to -660 m interval. The proportion of unstable rock, according to well logging data, averages 7.4% of the total borehole length (maximum 10.7% for well #2, minimum 5.5% for well #4), increasing to 9.8% in the upper part of the section (down to a depth of 300 m). Most of the open cracks (more than 60%) are oriented subvertically with dip angles of 60–90°; the cavities of the closed cracks are filled mainly with calcite-chlorite material.

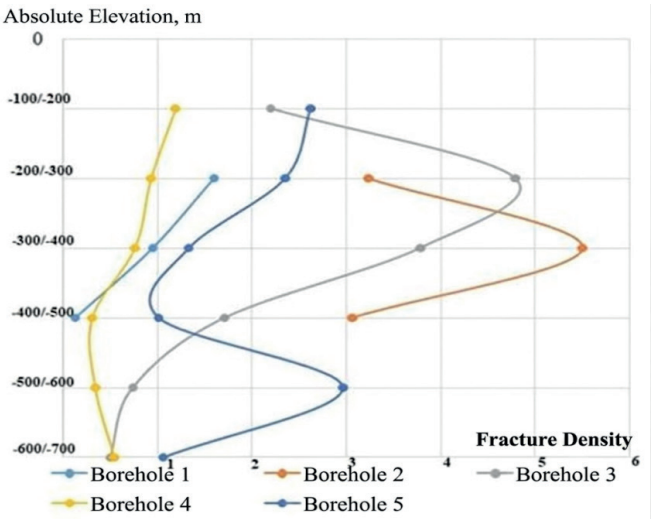


Figure 4. Change in rock mass fracturing with depth according to wells No 1–5.
Сурет 4. № 1–5 ұңғымалар бойынша тау жыныстарының массасының сынуының тереңдікке байланысты өзгеруі.
Рис. 4. Изменение трещиноватости массива горных пород с глубиной по данным скважин №№ 1–5.

Based on the results of the first series of measurements (processing of slope photographs, 2016), six systems of tectonic shear fractures were identified in four sections of the southern and eastern slopes; the fracture porosity coefficient varied from 0.21% (section III, eastern slope) to 0.60% (section I, southern slope), and the blockiness index ranged from 0.495 to 0.652 m, corresponding to moderately and highly fractured rocks. Based on the results of the second series of field measurements (2018, nine measuring stations), five fracture systems were identified; when comparing the two series, complete coincidence of the occurrence parameters was established only for the fracture systems associated with the natural layering of the massif (system 1/I).

Comparing the orientation of the identified fracture systems with the slope strikes allowed us to identify potentially hazardous (conformably dipping) weakness surfaces for each quarry wall: for the northern and northeastern walls — fracture system II-1; for the eastern and southeastern walls — system V; for the southern wall — system III; and for the southwestern and western walls — system I (with the probability of collapse prisms also forming along systems I', II-2, and III).

Conclusions

The engineering and geological conditions of the Sarbay quarry are characterized as complex, due to the significant thickness of loose rocks (up to 140 m), the presence of pronounced weakness surfaces (layering, fracturing, schistosity) [9–10], the tendency of the rocks to weather, and the high degree of water cut in both the loose and hard rocks of the massif. Based on the statistical processing of laboratory core test data from five deep boreholes at the deposit, six engineering and geological elements (limestone, tuffs, tuffites, metasomatites, diorites, and ore) were identified, for each of which generalized physical and mechanical properties were established. A trend of increasing rock strength with depth and a directly proportional relationship between specimen cohesion and uniaxial compressive strength were identified.

It was found that the average specific jointing of the rock mass decreases with depth from 21.33 joints/m (0 to -100 m) to 0.70 joints/m (-600 to -660 m). Based on the results of two series of structural measurements (2016 and 2018), six and five tectonic joint systems were identified, respectively. Of these, only those systems associated with the natural layering of the massif have completely consistent occurrence parameters. Potentially hazardous (congruently dipping) crack systems representing probable weakness surfaces have been identified for each quarry wall: System II-1 for the northern and northeastern walls, System V for the eastern and southeastern walls, System III for the southern wall, and System I (together with I', II-2, and III) for the southwestern and western walls.

An assessment of the probability of various deformation types (Planar Sliding, Wedge, Flexural Toppling, Direct Toppling) across eight characteristic sections revealed the greatest risk for the southern and southwestern/western walls of the quarry (probability up to 100%). However, a comparison with calculated safety factors shows that kinematically possible deformation does not always occur, confirming the need for a comprehensive consideration of the strength characteristics of the weakness surfaces, not just their geometric orientation. The most unfavorable conditions for ensuring stability when deepening the quarry to a depth of minus 500 m are predicted to be on the eastern wall due to the coincidence of the dip angle of the main layered fracture system (50–70°) with the design slope angle. This requires that this factor be taken into account when justifying the wall design at deep levels. The obtained calculated massif characteristics and the results of quarry zoning by types of potential deformations serve as the basis for further mathematical modeling of the stress-strain state of the edge massif.

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