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## ENSURING THE STABILITY OF SLOPES AND LEDGES AT THE VASILKOVSKY QUARRY (REPUBLIC OF KAZAKHSTAN)

**Purpose.** To comprehensively assess the stability of the walls and ledges at the Vasilkovsky quarry, located on a gold-bearing deposit in the Republic of Kazakhstan, taking into account the geomechanical characteristics of the rock mass structure, the presence of multidirectional fractures, and tectonic disturbances.

**Methodology.** To achieve the set goals, a comprehensive approach was used, including mining-geological and geomechanical analysis of the structure and massif of rocks, as well as the study of their fracturing and tectonic faults.

**Findings.** The study resulted in a comprehensive assessment of the stability of the northern slope at the Vasilkovsky quarry on a gold-bearing deposit in the Republic of Kazakhstan using numerical modeling in Rocscience and DIPS software packages. It was found that the presence of tectonic disturbances and fracturing has a significant impact on the stability of the slopes. The relationships between the slope height and the width of the collapse prism were determined. A fracture propagation model was developed.

**Originality.** The scientific novelty lies in the development of a comprehensive geomechanical approach to assessing the stability of the sides and ledges at the Vasilkovsky quarry based on the integration of numerical modeling of the stress-strain state and spatial analysis of the rock mass fracturing. Critical directions of the sidewall with reduced stability have been established, and dependencies between the geometry of the slopes and the parameters of the collapse prism have been determined. The influence of microstructural disturbances on the strength characteristics of rocks has been substantiated.

**Practical value.** The developed geomechanical model, which takes into account the fracturing of the massif and tectonic disturbances, provides the ability to accurately predict unstable zones. Numerical modeling of the stress-strain state of rocks allows for the justification of quarry planning and design parameters.

**Keywords:** *slope stability, fracturing, tectonic faults, stress-strain state, numerical modeling*

**Introduction.** Modern developments in open-pit mining are characterized by the exploitation of deposits with complex mining and geological conditions, as well as by an increase in production volumes and the impact of climatic factors. This is especially true for the development of complex gold deposits, where there is a tendency toward increasing the depth of quarries and the duration of their operation. The intensification of mining operations, the concentration of efforts on individual sections of the quarry, as well as the use of high-performance equipment and advanced development technologies require more accurate and reliable methods for assessing the stability of sides and benches.

The diversity of geological and geomechanical conditions in open pits necessitates the development and application of a variety of methods for calculating the stability of pit slopes. It is important to select the optimal calculation scheme corresponding to the specific conditions of the deposit, which will ensure the accuracy and safety of mining operations. With the current level of development of mining equipment and technol-

ogies, there is a tendency to increase the depth of mineral extraction, which significantly complicates the development process and requires a more accurate determination of the stability parameters of benches and sides at various stages of mining operations. Despite a significant number of studies devoted to the issues of the limiting parameters of stability of benches and sides, in practice, cases of slope deformation are still recorded, which leads to a decrease in the safety of mining operations and an increase in financial costs for eliminating the consequences of emergency situations. One of the factors that is not sufficiently taken into account in the development of gold-bearing deposits is the presence of megafaults or faults in the rock mass, which have a significant impact on the stability of slopes.

Domestic and foreign scientific research pays considerable attention to analyzing the causes of collapses of ledges and quarry walls, as well as methods for assessing their stability parameters. Despite the progress made in assessing the condition of contour rock masses, no reliable methods have yet been developed for calculating slope stability that take into account tectonic disturbances in the form of megafaults and faults. The lack of a methodology for assessing the influence of the spa-

tial location of megafractures or faults in the quarry relative to the slope surface leads to the adoption of suboptimal stability parameters [1].

Thus, research aimed at ensuring the stability of slopes and quarry walls operating in conditions of complex rock fracturing and the presence of megafractures and faults in the contour zone is a relevant and important task. The aim of this work is to develop a method for assessing the stability of quarry benches and walls, taking into account the presence of a system of megafractures and faults in the rock mass, which will improve the safety of mining operations and optimize the stability parameters of slopes at all stages of deposit development.

Therefore, research aimed at ensuring the stability of the slopes and sides of the Vasilkovsky quarries in the conditions of mining in rocks with complex fracturing in the presence of megafractures and faults in the contour zone allows for improving the completeness of comprehensive development of deposits and the safety of mining operations, and is a relevant task.

The aim of the work is to develop a method for assessing the stability of quarry benches and walls in the presence of a system of megafractures and faults in the deposit, ensuring safe conditions for quarry development.

**Materials and methods.** The idea of the work is to take into account the influence of megafractures on the parameters of stable quarry benches and walls [2]. Modern developments in technology and techniques for open-pit mining of gold-bearing ores are characterized by a trend toward deeper pits and higher benches. This necessitates a more accurate and detailed determination of the stability parameters of slopes and pit walls, which is an important condition for ensuring the safety of mining operations. Deformations of benches, which lead to a decrease in their stability, not only pose a threat to the safety of mining operations, but also cause significant financial costs to eliminate the consequences of emergency situations [3].

Despite the progress made in assessing the stability of contour masses, the problem of accurately accounting for the influence of fracturing and faults on the stability coefficient of the quarry wall remains unresolved. The lack of reliable rapid methods for assessing the degree of fracturing and accounting for geological disturbances, such as faults, in calculation schemes for refining stability parameters leads to the use of suboptimal stability coefficient values, which in turn reduces the accuracy of forecasts and increases risks. These problems are particularly acute in the development of gold-bearing deposits, where rock masses are often affected by both natural and man-made fractures and faults. These factors significantly complicate the task of developing effective methods for assessing the stability of slopes and walls, requiring approaches that can accurately account for the geomechanical characteristics of rocks. To calculate the stability of quarry walls, a method based on the theory of limit equilibrium is traditionally used, which is standard practice in mining. Recent studies [4] present developments based on the results of numerous experiments (in particular, those conducted at our university), in which the coefficients of structural weakening of rocks were determined. However, existing methods require a detailed study of a specific rock mass and analysis of its fracturing to accurately determine the desired coefficient.

The proposed approach involves the use of photographs of rock outcrops to refine the strength characteristics of rock masses, which will subsequently allow for more accurate solutions to the problems of quarry slope stability based on the analysis of data on fracturing and geological disturbances. The study of the physical and mechanical properties of rocks also plays a key role in assessing the stability of slopes, which is only possible through a thorough study of rock samples.

Thus, the research aimed at improving methods for ensuring the stability of slopes and quarry walls, especially in conditions of complex fracturing and geological disturbances (megafractures and faults), is not only relevant but also extremely important. This will significantly improve the safety of mining operations and increase the efficiency of gold deposit development.

The rock mass is a system with a complex hierarchy, where larger-scale volumes are less durable and more susceptible to deformation because they include larger weak surfaces. There is a tendency for deformability to increase and strength to decrease with an increase in the area of the rock mass under study. This dependence is called the scale effect in the massif. The presence of structural inhomogeneities significantly complicates the task of determining the physical and mechanical parameters in the massif. To solve this problem, it is necessary to increase the size of rock samples, but not beyond the dimensions determined by the technical characteristics of the power plants. At the same time, rock mass samples of the maximum possible size (usually no more than 0.1 m<sup>3</sup>) in laboratory tests remain smaller than an elementary block even for relatively homogeneous masses, and therefore, as a result of laboratory experiments, it is not possible to evaluate the mechanical properties of the mass. The stability index of rock should reflect the strength of adhesion not in a piece, but in the massif. This can be comprehensively accounted for by the attenuation coefficient, which expresses the ratio of cohesion in the mass to cohesion in the elementary structural block (in the sample) or the ratio of compressive strength in the mass to compressive strength in the sample. The strength characteristics of a fractured or faulted mass are influenced by the fracture intensity factor, which is expressed by the number of fractures per unit length. To refine the parameters of the stable edge, photographs are first taken with overlapping images of the exposed fracture area [5]. In order to scale the images obtained, a ruler (folding meter, stake, etc.) is placed within each photograph. Processing is performed using software products such as AutoCad and Rocscience to measure the horizontal distances between the traces of cracks in the fault, and the data obtained is averaged. Remote study of the structure of a mountain massif has a number of advantages over traditional methods of direct visual observation and sketching: photographic images can be easily enlarged, scaled, transformed, and reproduced, allowing the photographed phenomenon to be shown to a large number of geographically dispersed viewers; photography allows a large number of objects to be accurately and objectively recorded in a very short time, i.e., the entire picture of the observed phenomenon as a whole, with all its details and nuances [6].

**Experimental procedure.** The object of the study is the persistent gold-bearing Vasilkovskoye deposits. As a

result of the study, it was established that all faults of this open pit are clearly detected by magnetometric surveying. Along the tectonic dislocations, secondary smaller fractures with inherited bedding elements were formed at all stages of their activation, commonly accompanied by zones of intense rock fragmentation. The most active development of higher-order dislocations and fragmentation zones was observed within the block bounded by major faults and stock-like diorite bodies. In the south-western part of the ore field, the faults occur in a disjointed manner, whereas in the northeastern direction their convergence is observed. These structures are generally accompanied by additional zones of disturbance. The Vasilkovskoye deposit is spatially associated with the intersection node of one of these zones with a similar northeast-trending structure, where large areas of rocks were intensely fractured. This deposit is characterized by a high degree of tectonic disturbance, manifested during pre-ore, ore, and post-ore stages, as well as by the multidirectional nature of tectonic faults. Consideration of these structural and geological features is essential for addressing the issues of slope and bench stability in the Vasilkovsky open pit” [7, 8].

The Vasilkovskoye deposit, located 17 km north of Kokshetau in Akmola region, is one of Kazakhstan’s and the world’s 20 largest gold deposits. It is bordered by Riphean and Ordovician formations, with Early-Middle Riphean rocks present in the northwest and southwest. The open pit measures 1,210 by 1,290 m and reaches 450 m depth. A modern plant processes up to 8 million tons of ore annually, yielding about 400,000 troy ounces of gold.

This is what determined the overall structural pattern of the Vasilkovskoye deposit (53.434031, 69.251791 Vasilkovskoye gold-bearing Deposit) the type of ore bodies, and the features of their spatial distribution, with faults being particularly visible. Displacements and deformations of rock masses during open-pit mining significantly diminish the key advantages of the open-pit mining method.

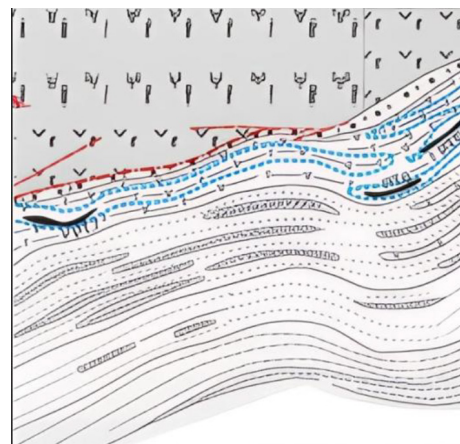
They lead to considerable material losses for the mining enterprise, disrupt the regulated and safe progress of mining operations, and result in unproductive losses of mineral resources (Fig. 1). In this regard, ensuring the stability of pit walls and benches becomes a critical factor for improving the efficiency and safety of mining operations at the Vasilkovskoye deposit. Currently, about 80 % of all mining in the Republic is carried out using the more economical and safer open-pit method, and this industry is developing through the use of high-performance technology and an increase in the depth of quarries using new technological solutions [9, 10]. When assessing the stability of quarry walls and ledges, the reliability of the calculation method depends, first of all, on the correspondence of the selected calcu-



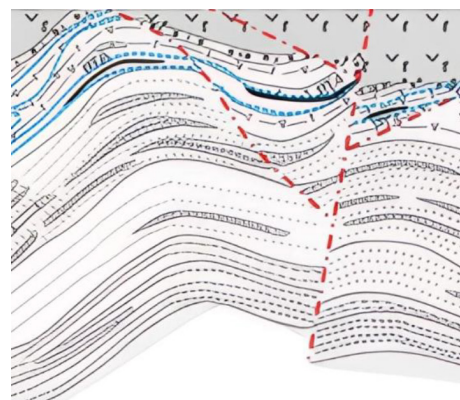
Fig. 1. Republic of Kazakhstan, (Vasilkovskoye field)

lation model to the actual stress distribution pattern in the wall massif, as well as the pattern of its destruction. Today, the stability analysis method has two directions: the development of limit equilibrium methods and the development of numerical methods. Due to the high development of the open method of deposit development in the USSR, a scientific school of quarry wall stability was formed, founded by such scientists as N. V. Melnikov, K. N. Trubetsky, G. P. Demidyuk, V. V. Rzhnevsky, V. V. Adushkin, M. A. Sadovsky, M. A. Lavrentyev, E. I. Shemyakin, V. Biletsky, N. Bakka, Yu. Vilkul, G. Gaiko, A. Gribov, Istomin V., Ilchenko I., Kasimov M., Kozlovsky E. N., V. V. Rzhnevsky, N. V. Melnikov, G. L. Fisenko, S. I. Popov, Yu. M. Maluyshitsky, P. M. Tsimbarevich, I. I. Popov, M. E. Pevzner, A. B. Fadeev, A. I. Arsentiev, V. N. Popov, A. M. Demin, R. P. Okatov, A. M. Galperin, E. L. Galustyan, P. S. Shpakov, B. V. Nesmeyanov, A. B. Makarov, V. A. Gordeev, F. K. Nizametdinov, G. G. Poklad, A. M. Mochalov, M. B. Nurpeisova, Zh. D. Baigurin, Kh. M. Kasymkanova, B. R. Rakishev, A. B. Begalinov, S. K. Moldabaev, K. A. Yusupov, and many other scientists [11, 12]. Fig. 2 shows the geological section of the field under development.

Stability calculations using limit equilibrium methods are a key tool for assessing the stability of slopes composed of various types of soil and rock. Among the



a



b

Fig. 2. Geological cross-section of the rock types being mined at the Vasilkovsky quarry:

a – geological cross-section in moderate fault zones (along block IV-IV); b – geological cross-section in intensified fault zones (along block IIV-IIV)

engineering methods for calculating the stability of quarry slopes based on the principles of limit equilibrium theory, a widely used method involves calculating and comparing the shear and retaining forces on a circular cylindrical slip surface. This method is based on the assumption that the sliding surface is circular-cylindrical, and the possible collapse prism is a solid “rigid” wedge.

Given the large-scale impact of modern quarries on the environment and man-made massifs, as well as the increase in the depth and volume of open-pit mining, there is a clear need to develop a qualitatively new approach to ensuring the stability of deep quarry slopes. The increasing complexity of the engineering-geological conditions of deposit development requires a more detailed consideration of all factors affecting slope stability.

In the context of rock mass stability management tasks, in particular quarry slopes during the development of mineral deposits characterized by highly variable geological structures, it is extremely important to conduct regular studies aimed at obtaining accurate and reliable information about the structural features of the rock mass near the slope. Particular attention should be paid to assessing the strength characteristics of rocks, hydrogeological conditions, and other factors that affect slope stability [13]. A key criterion for verifying the validity of previously adopted technological decisions regarding pit slope parameters is the geodetic instrumental monitoring of the condition of pit walls and benches, which should be regarded as an integral component of the unified system of mine surveying observations and studies. The implementation of comprehensive geomechanical investigations enables the assessment and prediction of processes occurring within the near-slope rock masses of the open pit, as well as the development of scientifically grounded recommendations for pit slope parameters aimed at enhancing the stability, efficiency, and safety of mining operations at the Vasilkovskoye deposit.

Fig. 3 shows the main stages of ore body geometrization and volume calculation, which form the basis for analyzing the stability of quarry slopes and benches. In the upper left part, a three-dimensional shape of the ore body is presented with contours by levels, as well as its projection onto horizontal planes with thickness isolines. The scheme in the upper right illustrates the division of the ore body into blocks based on the drilling grid for reserve estimation. The lower part shows longitudinal and transverse sections, which make it possible to trace the layered structure and geometry of the rock mass. In the lower right corner, the principle of volume calculation by the method of average cross-sections is

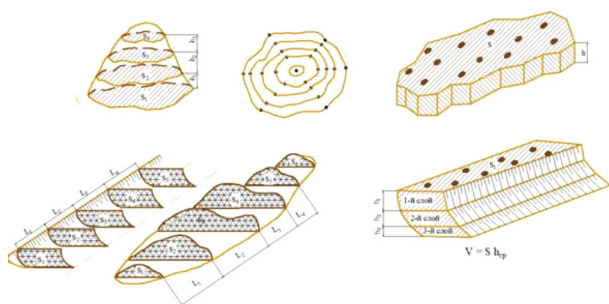


Fig. 3. Determination of volumes

demonstrated, where the volume is defined as the product of the cross-sectional area and block height.

This geometrical modeling is directly related to the assessment of slope and bench stability at the Vasilkovsky quarry, since accurate determination of the geometry and volumes of ore and host rocks makes it possible to identify potentially unstable zones and optimize the parameters of open-pit mining.

The stability of the slopes of the planned quarry was assessed using specialized GeoStab software. The program is designed to determine the stability of slopes and inclines in circumstances of complex geological structure of rock mass. The basis for analyzing the stability of rock masses in a quarry is a comparison of their actual calculated stress state with the maximum possible stress state. In accordance with this definition, under the guidance of professors from our university B. R. Rakishev, A. B. Begalinov, Zh. Baigurin, S. K. Moldabaev, K. A. Yusupov, T. M. Almenova, R. K. Zhanakova, and M. B. Nurpeisova, geomechanical monitoring should be regarded as a comprehensive system of measures that includes periodic mine surveying and engineering-geological observations of slope conditions, a thorough investigation of the engineering-geological characteristics of the composition and properties of rocks, as well as the study of the structural features of the near-slope rock mass. Within the framework of monitoring, the assessment and prediction of geomechanical processes developing in the pit rock mass are carried out, along with the determination of stable slope parameters based on the construction of an adequate geomechanical model of the rock mass. In addition, recommendations are developed for the operational adjustment of pit wall and dump parameters with the aim of enhancing slope stability, as well as ensuring the efficiency and safety of mining operations at the Vasilkovskoye deposit as well as the determination of stable slope parameters based on the creation of an adequate geomechanical model of the massif and the development of recommendations for the operational change of quarry sidewall and dump parameters in order to increase the efficiency and safety of mining operations in gold-bearing deposits [14]. Fig. 4 shows the graph of the relationship between the height of the flat slope  $H$  and its angle of inclination  $\alpha$  at  $k = 0$  and 8. The graph of the relationship between the height of the slope and the width of the collapse prism.

Fig. 4 presents graphical dependencies used to assess slope stability. Graph (a) illustrates the relationship between slope height  $H$  and its inclination angle  $\alpha$  at a stability coefficient of  $k = 0$ , which makes it possible to determine the limiting parameters at which the probability of shear deformations increases. Graph (b) shows the dependence between slope height and the width of the collapse prism formed in case of stability loss. These dependencies are of great practical importance for analyzing the stability of benches and pit walls at the Vasilkovsky quarry, as they make it possible to justify safe slope parameters, identify critical values of angles and heights, and develop engineering measures to prevent collapses and optimize the parameters of open-pit mining operations.

**Results and discussion.** Currently, methods for determining stable parameters of quarry slopes must be improved in line with scientific and technological developments, as well as through the introduction of computer

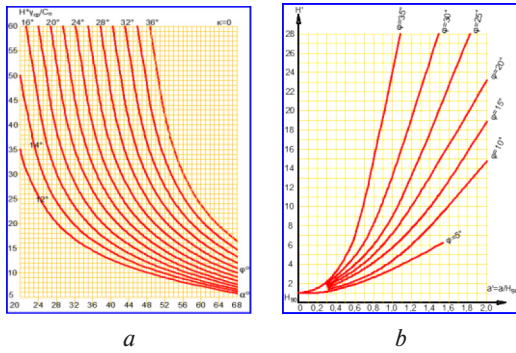


Fig. 4. Dependence of slope height on inclination angle and collapse prism width:

a – graph showing the relationship between the height of a flat slope  $H$  and its angle of inclination  $\alpha$  when  $k = 0$ ; b – graph showing the relationship between slope height and width of the collapse prism

innovations. In this regard, managing the stability of quarry masses in complex-structured deposits based on a unified comprehensive system for monitoring the stability of quarry slopes is becoming a very important and relevant scientific and practical problem. Mathematical modeling of tectonic disturbances should begin with the study of geological data. The assessment and analysis of geological data, including data on the structure of rocks, faults, fractures, folds, and other tectonic disturbances, allows us to understand exactly what disturbances are present in the study area. Geological disturbances are taken into account by introducing various coefficients that reduce the strength of the rock mass, such as the structural weakening coefficient or the use of the Geological Strength Index (GSI) in conjunction with the Hock-Brown empirical strength criterion. Creation of a simulation geological model. Based on geological data, a geological model is constructed that reflects the structure of rocks and tectonic disturbances in them [15]. The model is then integrated into numerical models, such as finite element models, using numerical modeling software that allows us to take into account various types of faults and their impact on the mechanical behavior of rocks. One such software program is RS3 from Rocscience. It is important to consider the impact of tectonic faults on the boundary conditions of the model. For example, the redistribution of stresses arising from faults can significantly affect the behavior of rocks. After constructing the model, it is necessary to validate it using available observations and data reflecting the actual conditions of the mine workings. This stage is necessary to verify the accuracy of the modeling and the correctness of the accounting for geological faults [16]. Accounting for tectonic disturbances is an important aspect of geomechanical modeling. As an example, a digital geological model was developed for a complex-structured soil-rock mass, including a deep open pit (540 m deep) at a gold-bearing deposit. Discontinuous faults and tectonic fractures were recorded in various parts of the quarry, which were discovered during the exploration stage of the deposit.

The digital geological model was created using SURPAC software. It was then integrated into Rocscience's RS2 calculation module for finite element analysis via AutoCAD files. This made it possible to simulate vari-

Table 1  
Geometric parameters of fracture systems in the rock mass

System crackiness	Deposit elements		Length, m	Distance, m
	Azimuth simple	angle of incidence		
1	$147 \pm 10$	$48 \pm 15$	10–168	$0.51 \pm 0.39$
2	$170 \pm 18$	$68 \pm 12$	10–35	$0.44 \pm 0.39$
3	$2 \pm 19$	$36 \pm 9$	0.2–4	$18 \pm 0.33$

ous types of tectonic disturbances and assess their impact on the mechanical behavior of rocks, which is key to ensuring the accuracy of geomechanical modeling and assessing the stability of the quarry.

Table 1 makes it possible to characterize the orientation, intensity, and spatial development of fracturing, which is important for assessing rock mass stability and determining the parameters of mining operations. The results of previous studies of rock fractures at the Vasilkovskoye deposit have shown that a gently sloping system of cracks in the form of a schistosity fracture, intersected by the slopes of the ledges and sides of the quarry, can be clearly traced along the entire eastern edge of the quarry (Fig. 5) [17].

Previous studies conducted on rock fractures at the Vasilkovskoye deposit have shown that a clearly defined gently dipping fracture system is observed along the entire eastern edge of the quarry, representing a schistosity fracture undercut by ledges. In general, five main fault systems can be distinguished in the rock mass, mainly characterized by submeridional and sublatitudinal extension, as shown in section No. 1. Horizon +55 m. Bench height 20 m (Fig. 6). Bench slope angles: 220, 320. A system of fractures with strike azimuths of 150,

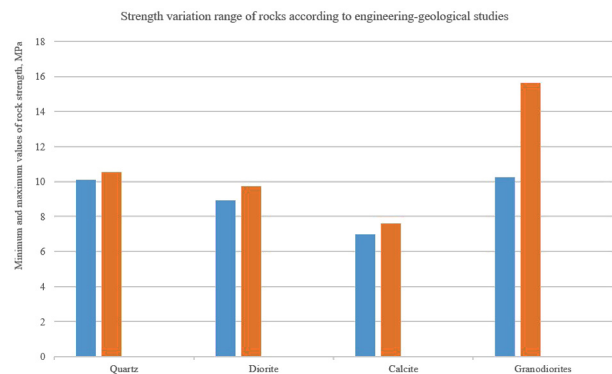


Fig. 5. Strength range of rocks according to engineering-geological studies

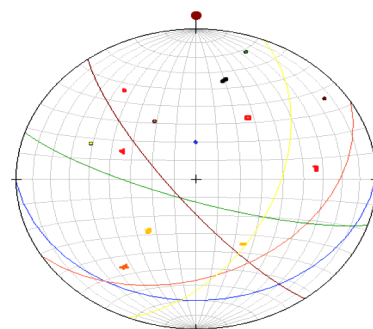


Fig. 6. Extent of fracture systems

150, 132 and dip angles of 350, 350, 400, respectively, is observed in the section [18].

Section No. 2. Horizon +45 m. The height of the ledge is 20 m. The angle of the ledge slope is 380. A collapse occurred on the section under consideration, as shown in Fig. 8, forming a collapsed part of 2/3 of the slope. The ledge is dominated by slope collapses shown in Fig. 8.

Figs. 8–10 shows how the array shifts according to the location of the fractures as shown in the DIPS program. This system has identified four systems of discontinuous faults (submeridional, sublatitudinal, north-south, and northwest directions). The most developed system is the north-west fault system, which we will investigate. Generalized circular point diagram of the fracturing of the Vasilkovsky quarry walls.

We used the Rocscience program to study the length of the deformable walls of the quarry slope. This approach provides a clear picture of the structural and tectonic features of the rocks along all sides of the quarry. Analysis of the polygonal curve using the Rocscience program shows the predominance of fracture systems with strike azimuths from 10 to 70°, from 210 to 250°, and from 300 to 340°. The quarry under study extends from southeast to northwest. On the western side of the



Fig. 7. Scheme of directions and spatial location of tectonic faults in the territory of the study area

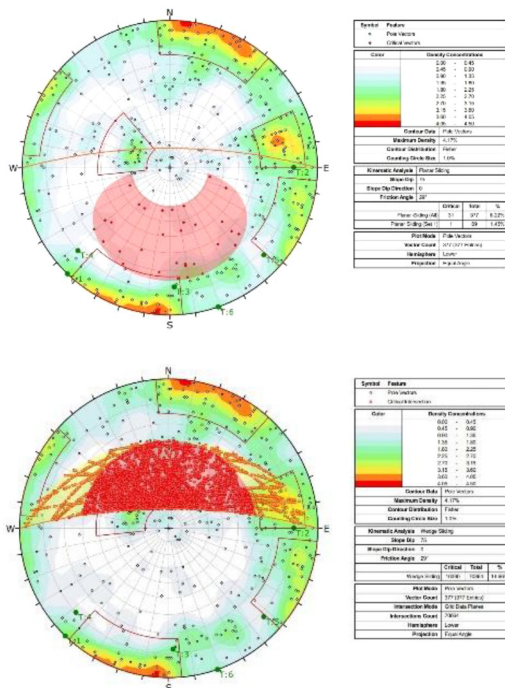


Fig. 8. Fracture diagram in the DIPS program DIPS

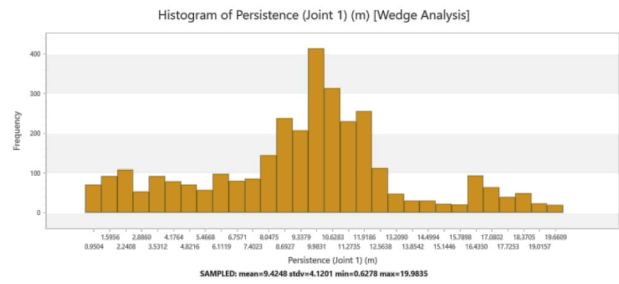


Fig. 9. Polygonal curve of crack system distribution by their azimuth of extension according to the Rocscience program

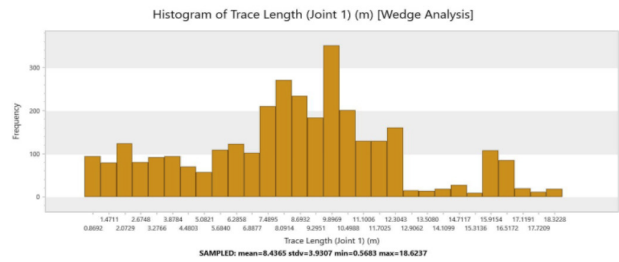


Fig. 10. Result of determining the fracturing of the rock mass based on the results of geological surveys using the Rocscience program

quarry, systems with strike azimuths of 300–340° will be dangerous, and on the eastern side, systems with strike azimuths of 140–160° will be dangerous [19].

The presence of areas hazardous to humans, as well as the lack of access to some areas, means that traditional methods do not allow for sufficient study of the geometry of the quarry's sidewall massif. For this reason, in order to obtain reliable data on the geometry of the slopes, we investigated a remote measurement technology using a digital tachymeter with a non-reflective measurement mode on the opposite side.

We also studied the loss of slope stability by tipping rock blocks toward the slope when the rock strata steeply dip into the depths of the slope. The destruction process can develop in two ways: direct tipping and tipping with bending.

Direct overturning of blocks develops in layered rocks that have a system of fractures conjugate to the direction of the strata, breaking the strata into blocks. The second overturning with bending occurs when the rock mass strata reach the surface of the slope, with the main normal compressive stresses parallel to the surface of the ledge [20]. Fig. 12 shows the trajectory of the ledge failure.

Figs. 11–12 illustrates the scheme of rock mass geometry modeling. On the left (a), a block discrete model is shown, where the rock mass is conditionally divided into separate parallel blocks, allowing the structural framework to be clearly represented. In the center (b), a prismatic model is presented with an inclined plane (highlighted in orange), indicating a potential weakness zone or slip surface within the rock mass. On the right (c), a similar model is shown, demonstrating the spatial intersection of the rock mass with the highlighted plane, which provides a clearer visualization of potential boundaries of deformation or failure.

The modeling results demonstrated the impact of changes in the geometry of the sides and ledges on their

Classification of fracture systems in relation to the slope face

Plot number	Probability influencing systems	Type of deformation			
		Planar Sliding	Wedge	Flexural Toppling	Direct Toppling
1	Probability, %	78.79	32.55	100	78.79
	Systems	III	III, V, I', II'	IV	III
2	Probability, %	65.0	52.0	0	65.0
	Systems	III	I+III	–	III
3	Probability, %	42.84	26.81	0	42.82
	Systems	I	I, II-2, III	–	I
4	Probability, %	78.65	22.26	0	78.75
	Systems	I	I, II-1, IV	–	I

stability. Correlations between the slope height and the width of the collapse prism were identified, which allows for a more accurate assessment of the potential stability of the sides and ledges of the quarry.

**Conclusion.** In modern conditions, there is a tendency toward increasing the depth of quarry mining, which, in turn, has a negative impact on the stability of the sides and ledges of the Vasilkovsky quarry. For the effective and safe operation of gold-bearing mining enterprises, reliable, timely, and comprehensive information about the subsoil within the quarry is necessary.

This paper presents scientifically based results of geomechanical support for the stability of quarry slopes using the example of the operating Vasilkovsky enterprise with the use of modern software complexes.

The analysis of the stability of the walls and benches of the Vasilkovsky open pit mine is a key task, since the safety and economic efficiency of the mine's operation directly

depend on the stability of its walls. The results of the study provided significant benefits for the enterprise, including the determination of the critical stability of the submeridional, sublatitudinal, northeast, and northwest directions of the slope, the characterization of the physical and mechanical properties of rocks, and the performance of 3D modeling in Rocscience and DIPS software. The results obtained are of high practical value, as they provide the necessary basis for assessing the safety and stability of the northern slope, which is a key element of the quarry. The purpose of this work is to conduct a comprehensive assessment of the stability of critical areas of the northern side. Using numerical modeling, a detailed analysis of the condition of the northern side was performed, possible scenarios of deformation and collapse were identified, and measures to strengthen stability were proposed.

This article presents an integrated approach to assessing the stability of quarry walls and benches based on the application of a set of methods, including numerical modeling of the stress-strain state of rocks in the vicinity of the quarry. The simulation results demonstrated a significant influence of changes in the geometry of the sides and benches on their stability. The study revealed dependencies between the slope height and the width of the collapse prism, which allows for a more accurate and objective assessment of the potential stability of the sides and benches of the quarry.

Based on the integration of geological, mining, and geomechanical data, a model of the rock mass fracture density was constructed, which made it possible to determine the directions of fracture propagation and identify potentially unstable zones, including areas located within the design contours of the quarry. These results serve as the basis for the development of preventive measures aimed at increasing the stability of the sides and ledges as the quarry deepens. This is critical for ensuring the safety of mining operations and minimizing the risk of collapses, which in turn contributes to the stable and safe operation of the quarry.

The following significant results were obtained, reflecting the scientific novelty and practical significance of the research conducted:

1. The analysis of the current state of research into the geomechanical conditions and mining and geological characteristics of the Vasilkovsky quarry showed that the stability of the sides and ledges is significantly influenced by factors such as the presence of weak surfaces and the strength properties of the rock.

2. The host rocks of the Vasilkovsky quarry are characterized by differences in physical and mechanical prop-

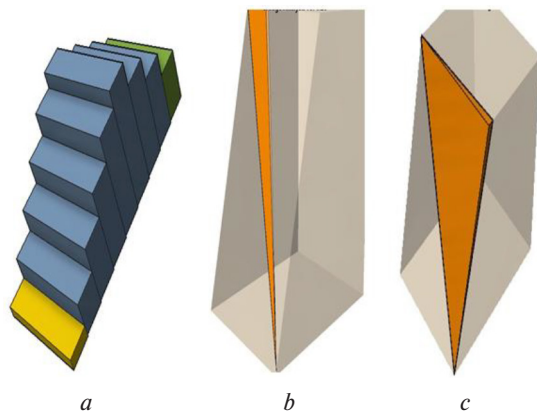


Fig. 11. Geometric representation of rock mass modeling: a – block discrete model; b – prismatic model with an inclined plane; c – spatial intersection of the rock mass with the highlighted plane

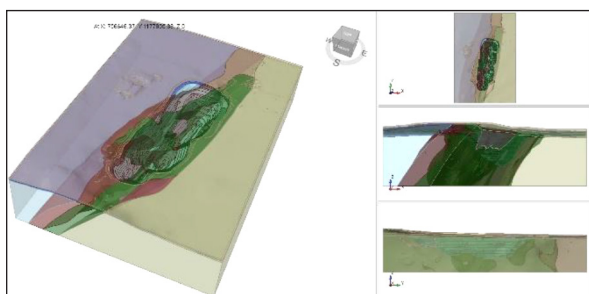


Fig. 12. Geometric representation of 3D rock mass models for the Vasilkovsky quarry

erties, with a significant variation in parameters such as adhesion and uniaxial compressive and tensile strength. This indicates a high spatial variability of rock properties both in terms of area and depth, which is associated with the presence of fractures and faults in the massif.

3. As a result of studying the structural composition of the rock mass, a system of fractures was identified, which are slip planes that have an adverse effect on the stability of the quarry benches.

These conclusions are an important contribution to improving the safety of mining operations and the stability of quarry benches, and also serve as a basis for further research and development in the field of geomechanics and mining.

The article also presents an integrated approach to assessing the stability of quarry walls and benches using a set of methods, including numerical modeling of the stress-strain state of rocks in the vicinity of the quarry. The modeling results demonstrated the influence of changes in the geometry of walls and benches on their stability. Dependencies between the slope height and the width of the collapse prism were identified, which allows for a more accurate assessment of the potential stability of the sides and ledges of the pit.

Based on geological, mining, and geomechanical data, a system of cracks was constructed, which made it possible to determine the directions of their propagation and identify potentially unstable zones, including within the design contours of the quarry. These results form the basis for the development of preventive measures aimed at increasing the stability of the sides and ledges as the quarry deepens, which is critical for ensuring the safety of mining operations and minimizing the risk of collapse.

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#### References.

1. Liu, X., Wang, Y., & Li, D. (2019). Investigation of slope failure mode evolution during large deformation in spatially variable soils by random limit equilibrium and material point methods. *Computers and Geotechnics*, 111, 301–312. <https://doi.org/10.1016/j.tust.2021.104203>
2. Shiyi, L., Zhenning, S., Ming, L., & Longtan, S. (2020). Slope stability analysis using elastic finite element stress fields. *Engineering Geology*, 273, 105673. <https://doi.org/10.1016/j.enggeo.2020.105673>
3. Sezgin, J.-G., Bosch, C., & Montouchet, A. (2019). Coupled hydrogen and phosphorous induced initiation of internal cracks in a large 18MnNiMo5 component. *Engineering Failure Analysis*, 104, 422–438. <https://doi.org/10.1016/j.engfailanal.2019.06.014>
4. Pivnyak, G., Dychkovskiy, R., Smirnov, A., & Cherednichenko, Yu. (2013). Some aspects on the software simulation implementation in thin coal seams mining. Energy Efficiency Improvement of Geotechnical Systems. *Proceedings of the International Forum on Energy Efficiency*, 1–10. <https://doi.org/10.1201/b16355-2>
5. Ratov, B. T., Chudyk, I. I., Fedorov, B. V., Sudakov, A. K., & Borash, B. R. (2023). Results of production tests of an experimental diamond crown during exploratory drilling in Kazakhstan. *SOCAR Proceedings*, (2), 023–029. <https://doi.org/10.5510/OGP20230200842>
6. Sudakov, A., Dreus, A., Ratov, B., Sudakova, O., Khomenko, O., Dziuba, S., ..., & Ayazbay, M. (2020). Substantiation of thermome-

- chanical technology parameters of absorbing levels isolation of the boreholes. *News of the national academy of sciences of the Republic of Kazakhstan*, 2(440), 63–71. <https://doi.org/10.32014/2020.2518-170X.32>
7. Babets, D. (2018). Rock Mass Strength Estimation Using Structural Factor Based on Statistical Strength Theory. *Solid State Phenomena*, 277, 111–122. <https://doi.org/10.4028/www.scientific.net/SSP.277.111>
  8. Rong, H., Wang, Y. J., Zhao, X. Y., & She, J. (2019). Research on fracture characteristics of rock-concrete interface with different roughness. *Gongcheng Lixue. Engineering Mechanics*, 36(10), 96–103. <https://doi.org/10.6052/j.issn.1000-4750.2018.09.0485>
  9. Sakhno, I., Sakhno, S., & Vovna, O. (2020). Assessing a risk of roof fall in the development mine workings in the process of longwall coal mining in terms of Ukrainian mines. *Mining of Mineral Deposits*, 14, 72–80. <https://doi.org/10.33271/mining14.01.072>
  10. Babets, D., Sdvyzhkova, O., Shashenko, O., Kravchenko, K., & Cabana, E. (2019). Implementation of probabilistic approach to rock mass strength estimation while excavating through fault zones. *Mining of Mineral Deposits*, 13(4), 72–83. <https://doi.org/10.33271/mining13.04.072>
  11. Kožar, I., Torić Malić, N., Simonetti, D., & Smolčić, Ž. (2019). Bond-slip parameter estimation in fiber reinforced concrete at failure using inverse stochastic model. *Engineering Failure Analysis*, 104, 84–95. <https://doi.org/10.1016/j.engfailanal.2019.05.019>
  12. Seitl, S., Rfös, J. D., & Cifuentes, H. (2017). Comparison of fracture toughness values of normal and high strength concrete determined by three point bend and modified disk-shaped compact tension specimens. *Frattura ed Integrità Strutturale*, 11(42), 56–65. <https://doi.org/10.3221/IGF-ESIS.42.07>
  13. Rakishev, B. R., Kuzmenko, S. V., Sedina, S. A., & Tulebaev, K. K. (2018). Analysis of the influence of mining and geological factors on the stability of sides using the example of the Sarbaysky quarry. *Reports of the National Academy of Sciences of the Republic of Kazakhstan*, 3, 19–25. <https://doi.org/10.25018/0236-1493-2019-07-0-123-131>
  14. Lyashenko, V. I., Dudar, T. V., & Shapovalov, V. A. (2024). Research and assessment of mineral reserves based on automated geoinformation system support using the example of the Novokostiantyniv uranium ore deposit. *Heolohichnyi Zhurnal*, (3), 61–78. <https://doi.org/10.30836/jgs.1025-6814.2024.3.304036>
  15. Stupnik, M., Kalinichenko, V., Fedko, M., Kalinichenko, O., Pukhalskiy, V., & Kryvokhin, B. (2019). Investigation of the dust formation process when hoisting the uranium ores with a bucket. *Mining of Mineral Deposits*, 13(3), 96–103. <https://doi.org/10.33271/mining13.03.096>
  16. Shcherbakov, P., Tymchenko, S., Bitimbayev, M., Sarybayev, N., & Moldabayev, S. (2021). Mathematical model to optimize drilling-and-blasting operations in the process of open-pit hard rock mining. *Mining of Mineral Deposits*, 15(2), 25–34. <https://doi.org/10.33271/mining15.02.025>
  17. Shcherbakov, P., Klymenko, S., & Tymchenko, D. (2017). Statistical research of shovel excavator performance during loading of rock mass of different crushing quality. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (1), 49–54.
  18. Nazerigivi, A., Nejati, H. R., Ghazvinian, A., & Najjigivi, A. (2018). Effects of SiO<sub>2</sub> nanoparticles dispersion on concrete fracture toughness. *Construction and Building Materials*, 171, 672–679. <https://doi.org/10.1016/j.conbuildmat.2018.03.224>
  19. Sukhov, R. P. (2013). Establishment of the main relationships between the energy intensity of the roller drilling process and the strength parameters of the mass being destroyed. *Mining Journal of Kazakhstan*, 9, 8–12. <https://doi.org/10.31643/2022/6445.20>

## Забезпечення стійкості бортів і терас Васильківського кар'єру (Республіка Казахстан)

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**Мета.** Комплексна оцінка стійкості бортів і терас Васильківського кар'єру, розташованого на золоторудному родовищі Республіки Казахстан, з урахуванням геомеханічних характеристик структури гірського масиву, наявності різноспрямованих тріщин і тектонічних порушень.

**Методика.** Для досягнення поставлених цілей застосовано комплексний підхід, що включає гірничо-геологічний і геомеханічний аналіз структури та масиву порід, а також дослідження їхньої тріщинуватості й тектонічних порушень.

**Результати.** У результаті дослідження виконана комплексна оцінка стійкості північного борту Васильківського кар'єру золоторудного родовища Республіки Казахстан із використанням чисельного моделювання у програмах Rocscience і DIPS. Встановлено, що наявність тектонічних порушень і тріщинуватості має суттєвий вплив на стійкість укосів. Визначена залежність між висотою укосу й шириною призми обвалення. Розроблена модель поширення тріщин.

**Наукова новизна.** Полягає в розробці комплексного геомеханічного підходу до оцінки стійкості бортів і терас Васильківського кар'єру на основі інтеграції чисельного моделювання напружено-деформованого стану та просторового аналізу тріщинуватості масиву. Визначені критичні напрямки борту зі зниженою стійкістю й залежності між геометрією укосів і параметрами призми обвалення. Обґрунтовано вплив мікроструктурних порушень на міцнісні характеристики порід.

**Практична значимість.** Розроблена геомеханічна модель, що враховує тріщинуватість масиву й тектонічні порушення, забезпечує можливість точного прогнозування нестійких зон. Чисельне моделювання напружено-деформованого стану порід дозволяє обґрунтувати параметри планування та проектування кар'єру.

**Ключові слова:** *стійкість укосів, тріщинуватість, тектонічні порушення, напружено-деформований стан, чисельне моделювання*

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