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PROVIDING STABILITY OF QUARRY SLOPES AT COMBINED MINING OF MINERAL DEPOSITS

Purpose. To ensure the stability of quarry slopes during the combined development of mineral deposits by determining optimal slope parameters, ensuring their long-term stability while minimizing the volume of overburden operations, and reinforcing areas in case of detected fractures, both visible and hidden.

Methodology. The study employs a comprehensive approach that includes field geomechanical observations, mathematical modeling, and analytical calculations. Modern geodetic methods, such as laser scanning and Global Positioning System (GPS) navigation, were applied to identify instability zones and assess the impact of geotechnical factors. The Examine2D software was used to model stress and deformation distribution within the rock mass.

Findings. A zoning scheme of the stress-strain state of the rock mass was developed, taking into account the influence of tectonic faults and the load from waste dumps. Zones with low stability factor values (0.2–1.4), requiring additional reinforcement, were identified. Modeling showed that stress concentrations under the quarry bottom and near faults result in horizontal and vertical displacements of rock masses, affecting the stability of slopes and mining workings.

Originality. For the first time, a comprehensive study of the stress-strain state of the rock mass under combined mining conditions in Kazakhstan was conducted using modern geodetic and geomechanical technologies. Key factors affecting slope stability and their long-term stability were identified.

Practical value. The obtained results allow for the optimization of quarry slope parameters, a reduction in overburden operations, the prevention of emergency situations, the safe operation of underground workings, and improved mining efficiency. Recommendations for reinforcing unstable zones are provided.

Keywords: *slope stability, combined mining, rock mass, tectonic faults, geomechanical monitoring*

Introduction. Human activity in the use of subsurface resources causes the development in subsoil of geomechanical processes related to changes in the stress state, strain and shear of rocks [1]. These processes can both contribute to improved subsoil use efficiency and cause highly adverse technological and environmental consequences. As a consequence, on the territory of the Republic of Kazakhstan from negative manifestations of uncontrolled geomechanical processes suffer numerous objects of subsoil use, industrial regions and the earth's surface areas [2]. Therefore, with the exploration of new fields and reconstruction of old mines, the issues of managing geomechanical processes are now important for many mining enterprises. Monitoring of geotechnical processes is not a short-term activity, but systematic observation of mining safety, safety of underground mine workings and surface structures until the completion of field exploitation [3]. Additionally, the efficiency of subsurface resource development and geomechanical process management is closely linked to the optimization of transportation systems, including excavator-automobile methods [3], cyclic-and-continuous technologies [4], and the use of dump trucks [5] for material handling and waste removal.

Over the past 50 years, major geomechanical studies related to rock pressure and shear management have been conducted in Kazakhstan and abroad [6, 7]. However, a great variety of mining-geological conditions (presence of large tectonic faults, thickness of ore bodies, intense rock mass fracturing, heterogeneity and variability of mechanical properties of ores and rocks, etc.) of ore deposits requires special research in each specific case and the identification of patterns of rock shear and strain within the rock mass [8].

Issues related to strain, shear and failure, stability of rocks, namely the stress state of the rock mass in the presence of underground mine workings near the quarry slope, the formation of collapse sinkholes at the bottom of the quarry and some others have not been sufficiently studied [9, 10]. These circumstances predetermine the solution of the scientific problem – study the rock mass and on this basis to develop a methodology for geomechanical assessment and prediction of the shear process of hard-fractured rocks during open-pit and underground mining of ore deposits to protect structures and the environment from the harmful effects of mining operations [11].

To ensure safe and efficient combined field mining, it is necessary to regularly assess the geomechanical state of the rock mass, make a prediction of changes in this state, monitor the development of strain processes and manage them by regulating parameters, mutual position, order and organization of mining operations, as well as artificial strengthening of unstable rock mass areas. The results of the survey of mine workings in the East Saryoba field (quarry and underground levels) show that the largest number of rockfalls is confined to fractured rocks, with the volume of rockfalls increasing as the mine workings are exploited. Observations of the mine workings driven through fractured rock have revealed that they are stable for a month. After two to three months, cutter breaks up to 10–15 cm in size are formed. The formation of cutter breaks and rockfalls develop within half a year, roof caving occurs in the form of a dome. This sharply increases the volume and labor intensity of tunneling operations, as well as the cost of fastening and repairing mine workings.

To prevent the failure of mine workings driven through fractured rocks, roof-bolting supports with metal mesh and shotcreting are used. However, the cleavage of rocks from the haulage drift roof and significant destruction of rocks indicate that this support does not solve the problem of ensuring the stability of mine workings and does not prevent the process of strain development. As a result, after 2–3 years of exploitation of the mine workings, the support is destroyed and requires major repairs.

In the case of combined mining method and complex geomechanical situation, a fundamentally important aspect is the threat of flooding of underground mine workings, and especially the threat of dynamic water inrush into underground workings, leading to severe negative consequences [12]. An example of this is the water inrush that occurred in 2021 into the East Saryoba mine working of TOO Kazakhmys Smelting. This problem is relevant not only for Kazakhstan. So, in 2006, there was flooding of the mine face in Hongbei Province in China, in 2010 – in the Severnaya Mine of JSC Severokuzbassugol, in March 2013 – in the Osinnikovskaya Mine, in February 2013 – in the Krepenskaya mine in Ukraine, which resulted in death of people. All this is a direct consequence of the change in geodynamic and hydrogeological regime of the geological environment under the influence of large-scale mining operations, which is convincingly confirmed by the results of scientific research using the example of the East Saryoba mine.

It is now confirmed that the main factors determining the nature and values of the earth's surface and rock strains are the strength properties and structural peculiarities of the mass, its stress state, depth of mining operations, mining systems, sizes and dip angles of ore bodies. A significant contribution to the study of the degree of influence of various factors on the development of geomechanical processes in the context of a combined method of field mining is made by scientists from many countries of the world, where mineral deposits are mined. However, despite the existing individual research results, in general, the determination of patterns of manifestation of geomechanical processes in these conditions are performed using traditional methods. The rapid development of technologies in the mining industry causes the growth of mineral mining, which, in turn, leads to the need to create more advanced technologies for servicing mining operations and improving the safety of surveying. Technical progress has had a significant impact on the tasks of mine surveying over the last decade.

For specialists of the mining industry, it is becoming increasingly clear that the solution of such issues as pressure and shear of rocks, stability of the walls of quarries, is impossible without performing geomechanical monitoring of the mass state using modern geodetic methods. The described situation is typical for the Saryoba mine, where the authors conducted research into the earth's surface and rock mass shear under the influence of the undermined quarry and high-depth failure. Therefore, the introduction of satellite, electronic and laser devices into practice can be called the most significant technological innovation at the beginning of the *21st* century in mine surveying, geodesy and a number of related industries.

Literature review. Geomechanical processes occurring during combined open-pit and underground mining of ore deposits have been the subject of extensive research worldwide. Numerous studies have focused on understanding the behavior of rock masses under various stress and strain conditions, emphasizing the importance of monitoring and prediction to ensure operational safety and efficiency.

Several researchers have explored the interaction between open-pit and underground mining operations, highlighting the redistribution of stress and its implications on the stability of quarry slopes and underground workings. For instance, Portnov, et al. [13] studied the impact of surface properties of minerals on the disintegration of rebellious ores, concluding that the mechanical and chemical properties of rocks significantly influence the strain and failure mechanisms. Similarly, Issatayeva, et al. [14] emphasized the role of digital transformation in geological and economic assessments, providing insights into the integration of advanced technologies for better resource management.

In Kazakhstan, significant contributions have been made in geomechanical studies of rock pressure and failure mechanisms. Rysbekov, et al. [15] addressed mine planning issues related to ore reserve rationing, stressing the need for optimized resource allocation to mitigate stress concentrations in mining operations. Additionally, Nurpeisova, et al. [16] investigated deformation processes and radiation safety in mining environments, underscoring the importance of integrated monitoring systems.

A notable advancement in geomechanical monitoring involves the use of modern geodetic instruments, such as electronic total stations, GPS systems, and 3D laser scanning. The study by Kassymkanova, et al. [17] showcased the effectiveness of combining these tools for detailed spatial analysis of rock mass dynamics, enabling accurate prediction of subsidence and failure zones.

Despite these advances, unresolved issues remain, particularly in the context of combined mining operations. Key challenges include:

- limited understanding of the interaction between tectonic faults and mining-induced stresses, as highlighted by recent studies in the East Saryoba mine;
- insufficient methods for accurately modeling water infiltration and its impact on underground stability, as demonstrated by the catastrophic water inrush incidents in mines globally;

- gaps in the development of real-time monitoring systems that integrate seismic, hydrogeological, and geomechanical data to predict dynamic changes in rock mass behavior.

Recent works have also addressed the importance of sustainability in mining operations. Bazaluk, et al. [18] analyzed ground surface subsidence caused by underground coal mining, providing strategies for mitigating environmental impacts. Meanwhile, Alpysbay, et al. [19] reviewed the application of remote sensing in Kazakhstan, emphasizing its potential in enhancing resource exploration and environmental monitoring.

The above studies underscore the critical need for interdisciplinary approaches that integrate advanced geotechnical modeling, real-time monitoring, and data analysis to address the complex challenges associated with combined mining operations. The findings form the basis for the ongoing research aimed at improving safety and operational efficiency in the East Saryoba field.

Unsolved aspects of the problem. Despite significant advancements in understanding geomechanical processes during combined open-pit and underground mining, key challenges remain unresolved, particularly in the context of the East Saryoba field. These gaps underline the need for targeted research to address the unique conditions of this mining site. While previous studies have considered stress redistribution in mining operations, the influence of tectonic faults on the stability of the East Saryoba rock mass remains insufficiently studied. The lack of detailed modeling of fault zones limits the ability to predict localized displacements and strain concentrations.

Existing monitoring approaches lack the capacity to integrate data from seismic activity, hydrogeological processes, and geomechanical changes in real-time. In our study, we aim to address this by implementing advanced geodetic tools such as laser scanning and GPS technologies to improve prediction and management of rock mass behavior. Also, the long-term rheological behavior of fractured rocks under combined open-pit and underground mining operations is poorly understood. Our study focuses on analyzing the transition of rock masses from elastic to plastic states and their impact on the stability of sub-quarry layers and pillars.

Traditional geomechanical methodologies often fail to account for the unique mining-geological conditions of the East Saryoba field. Our study emphasizes the development of customized models and assessment techniques that incorporate these conditions, such as variability in rock strength and the influence of waste dumps.

Through our research, we aim to solve these gaps by developing a comprehensive geomechanical model tailored to the East Saryoba field. By integrating advanced monitoring systems, hydrogeological analysis, and customized modeling techniques, our study seeks to enhance the safety, efficiency, and sustainability of mining operations in this complex environment.

The purpose of this research is to develop effective methods for ensuring the stability of quarry slopes during the combined development of mineral deposits. This involves determining optimal parameters for slope design, implementing measures to ensure their long-term stability, and minimizing the volume of overburden operations. Additionally, the research aims to identify and reinforce areas with visible or hidden fractures to prevent potential failures, enhance the safety of mining operations, and improve the overall efficiency and sustainability of resource extraction processes.

Materials and methods. Research methodology includes laboratory and mine studies, analytical calculations, processing of observation results using methods of mathematical statistics and computer modeling successfully implemented in the previous research [20, 21].

The examined natural-technical system (NTS) East Saryoba consists of underground mine and quarry, beneficiation plant with tailings dumps and appropriate infrastructure with the geological environment containing all this, which is a part of a unified fold anticline system. A characteristic peculiarity of the field is that its veins are primarily mined by open-pit mining, with subsequent transition to underground method.

The possibility of rock shear process in the field is conditioned by the fact that under the applied mining system, mining is conducted in separate blocks with ore shrinkage, release of inter-block pillars and ceilings. In such a combined mining system, the rock stratum from the hanging wall side along the entire strike and at full depth loses support and will be forced to cave in, causing the process of shear of the host rocks. The problem of determining the boundaries of the influence of underground mining operations on the earth's surface in this case is considered as the identification of the wall sliding surface when deepening the quarry bottom. Therefore, to solve a number of mining-engineering problems, calculation methods should be corrected for specific conditions, and the influence of natural and mining-engineering factors should be taken into account, as well as the variability of values of rock strength properties in space and time, etc. [22, 23].

Analysis of the state of the methodology for conducting geodetic observations on the territory of NTS and interpretation of the data obtained in relation to geomechanical and hydrogeological impacts is primarily due to the lack of effective methods for determining the earth's surface subsidence (ESS) values [18, 24]. This necessitates improvement of the methodology of surveyor-geodesic observations of rock strains using modern electronic devices to increase reliability and efficiency in determining the ESS parameters for the safe mining of subsoil resources and taking measures to protect the mined objects.

Mining of the East Saryoba field of the Zhilandy Group of copper sandstones according to the scale of impact on the environment, and primarily on the stress-strain state of rocks, refers to the category of major technogenic impacts that can cause serious accidents, catastrophic events such as large landslides, local and large-scale failures in quarries, pressure and rock bursts at lower levels caused by imbalance in the earth's subsoil [25].

Mining operations of the East Saryoba quarry began in 2008, and underground operations began in 2016. The extent of influence of quarries, their dumps, tailings dumps, and underground mining is such that their impact overlaps each other, creating complex patterns of secondary stress field formation. One aspect of this phenomenon is isostatic vertical displacements. Therefore, the existing production scale in the area requires in-depth study and control of the processes that occur to

Fig. 1. East Saryoba quarry

avoid uncontrolled catastrophic manifestations of geomechanical processes (Fig. 1).

Under such conditions, effective and safe mining of ore veins is possible only by organizing the geomechanical monitoring of the state of rock masses, consisting: in systematic observations of spatial and temporal geomechanical processes occurring in the rock mass as a result of its mining; in the mathematical processing of observation results; comprehensive analysis and prediction of the state of rock masses, development of solutions for managing negative processes.

In 2020, based on a geomechanical study of mining-geological conditions of the field, projects for observation stations were developed: surface and underground. The projects deal with the creation of geomechanical monitoring system based on instrumental mine surveying and geodesic observations using electronic total station and GPS receivers of satellite positioning system [26].

The laser scanning method is used to examine the state of the near-wall mass in the quarries, which significantly increases the accuracy and specification of data on the geometry and structural peculiarities of the mass. Laser scanning is an advanced non-contact measurement technology that creates a detailed digital model of the entire surrounding space, using high-precision equipment to obtain a set of points with spatial coordinates. The resulting point model (or point cloud) contains data on the location of each surveyed surface element, which allows for a precise analysis of strains and changes in the mass.

A Leica HDS3000 scanner is used for the purpose of strain monitoring in this research. This type of equipment allows measurements to be made with high accuracy, which is especially important for identifying and monitoring changes in the near-wall mass stability. In addition, the Leica HDS4400 specialized mining scanner is used to explore the mass structure and analyze its internal configuration. This scanner is highly efficient and is equipped with special software designed to analyze the occurrence elements and structural mass patterns. This approach can not only create a highly accurate surface model, but also identify internal structure peculiarities, which is critical for the safe quarry operation [27].

To improve the accuracy and efficiency of laser scanning, the use of GPS systems is recommended, which allows the data to be integrated into a single geographically referenced model. Additionally, the integration of data obtained using a 3D scanner and GPS navigation contributes to improving the quality of spatial modeling and provides the possibility of more accurate tracking of changes in the mass dynamics [28].

The integration of GPS systems with laser scanning technologies has been widely recognized for its effectiveness in enhancing the accuracy and efficiency of geospatial data collection and analysis. By linking data collected using GPS systems and 3D scanners, researchers are able to create a unified, geographically referenced model that supports detailed spatial modeling and precise monitoring of mass dynamics. This approach is particularly useful in applications requiring high-resolution mapping and dynamic tracking, such as mining exploration, urban planning, and environmental monitoring.

The research [29] demonstrated the utility of integrating laser scanning and GPS systems in creating interactive 3D visualization maps, emphasizing its potential in developing detailed models within university campuses. Similarly, it is explored how resource visualization could benefit from advanced spatial modeling technologies, highlighting the role of geographic integration in supporting decision-making processes. Furthermore, the authors in research paper [30] showed how geophysical research, combined with advanced spatial data processing techniques, significantly enhances the efficiency of underground ore deposit development. Their findings underscore the importance of integrating high-precision technologies to improve the planning and execution of mining operations. Supporting this, [19] reviewed the application of remote sensing and mining mapping in Kazakhstan, highlighting the value of geospatial data integration for resource exploration and sustainable management practices.

In the realm of solving complex geophysical problems a simulated annealing approach to gravity direct problems is already applied, which showcased the benefits of combining computational methods with spatial data for modeling geological formations [31]. This research provides a robust example of how integrated geospatial technologies can contribute to advancing the accuracy and reliability of geophysical analyses.

The combined use of 3D laser scanning and GPS navigation systems not only improves the spatial resolution of geospatial models but also facilitates real-time data integration, allowing for more efficient monitoring of changes in mass dynamics and providing critical insights for industries such as mining, construction, and renewable energy planning.

The topology of mine workings of the East Saryoba mine (quarry and underground site) is taken as input data. In addition, the influence of tectonic faults of in-quarry waste dumps on underground mine workings is studied. A tectonic fault occurs in the northern part of the transportation corridor between profiles 10 and 18 in the field. The influence of this fault on underground mining has been calculated and modeled. The Examine2D program from the Canadian company RocScience is used to calculate the rock pressure with the following parameters: Poisson's ratio is 0.2; Young's modulus is 90.1–94.76; density is 2.7 tons/m^3. Since the specified program does not take into account the dump weight, the dump pressure is added manually (3 MPa).

Based on the comprehensive geomechanical monitoring, conducted in the East Saryoba field in the period of 2021–2024, the rock shear scheme has been compiled

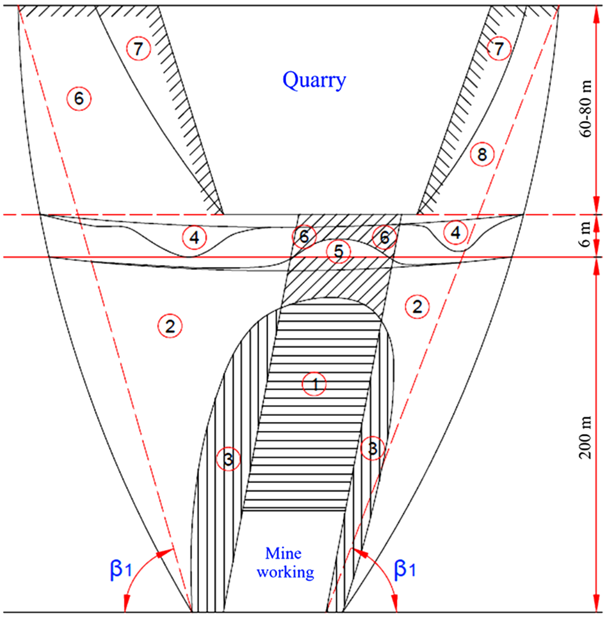

Fig. 2. Scheme of rock strain during combined mining of the East Saryoba field:

1 – failure zone; 2 – smooth deflection zone; 3 – ultimate stress state zone; 4, 5, 6 – tension and compression zones in the sub-quarry layer; 7 – landslide prism; 8 – near-wall mass

(Fig. 2). The scheme identifies two areas: de-stressing and increased rock pressure, and eight zones with specific characteristics, peculiar only to these zones.

The de-stressing zone is divided into zones characterized by different degrees of mass disturbance: failure, through and local fractures. According to this scheme, eight zones can be distinguished in the undermined stratum, which differ in terms of strain conditions and the degree of fracture formation.

To ensure the stability of quarry slopes during combined mining operations, the factor of safety (FoS) is a critical parameter for assessing the resistance of the slope against failure. The FoS is defined as the ratio of resisting forces (shear strength of the material) to driving forces (shear stress due to the applied loads). It is calculated using the following formula

$$FoS = \frac{c + (\sigma_n - u) \cdot \tan(\phi)}{\tau},$$

where c is cohesion of the material, representing the internal binding strength of the slope material, kPa; σ_n – normal stress, the perpendicular stress acting on the failure plane, kPa; u – pore water pressure, which reduces the effective normal stress by counteracting it, kPa; ϕ – the angle of internal friction, a measure of the shear strength due to frictional resistance, degrees; τ – shear stress, the stress tending to cause sliding along the failure surface, kPa.

The main focus is on the study of the load-bearing capacity of the quarry bottom (I^{st} level ceiling) and sublevel pillars. The pillars are initially in an elastic state, but over time the pillars may change to a plastic (or yield) state, for example, due to the development of rheological processes. The plastic state is characterized by a more than a tenfold increase in the yielding capacity of the pillars while maintaining their stress state.

The roof rock failure of the mine workings (sub-quarry layer) occurs after the ultimate tensile and compressive strength of the rocks is exceeded, as a result of which the mass is broken into blocks by a system of fractures. The mechanism of formation and development of technogenic fractures in the mass is presented in Fig. 3.

The diagram presented in Fig. 3 illustrates the formation of fractures in the sub-quarry layer during undermining, with three stages represented.

Critical tensile stress for fracture initiation (stage *1*), Pa

$$\sigma_t = \frac{M}{I \cdot y}, \tag{1}$$

where M is the bending moment, N · m; I – the moment of inertia of the bending layer, m^4; y – distance from the neutral axis to the outer surface, m.

Fracture propagation depth (stage 2), m

$$a = \frac{K_I^2}{\pi \cdot \sigma_t^2}, \tag{2}$$

where a is crack depth, m; K_I – stress intensity factor, Pa · m$^{1/2}$; σ_t – tensile stress at the crack tip, Pa.

Formula (1) helps estimate when fractures first appear due to bending stress in the layer when formula (2) evaluates how deep the fractures propagate as tensile stresses increase.

Layer failure due to alternating strains (stage 3)

$$\varepsilon = \frac{\Delta L}{L},$$

where ΔL is change in length due to deformation, m; L – original length of the layer, m.

Failure occurs when alternating tensile and compressive strains exceed the material's elastic limit. Alternatively, use Von Mises stress criterion for assessing failure, Pa

$$\sigma_v = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2},$$

where σ_1, σ_2 are principal stresses, Pa.

So, failure occurs if σ_v exceeds the material's yield strength.

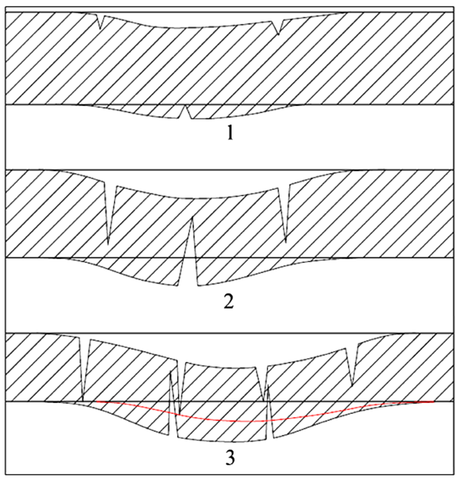

Fig. 3. Scheme of fracture formation in the sub-quarry layer during its undermining:

1 – first occurrence of fractures in the bending layer (stage 1); 2 – fracture depth opening (stage 2); 3 – layer failure under alternating strains (stage 3)

As a result of the layer deflection, tensile stresses appear in it and at a certain span size they reach the ultimate tensile strength of rocks, therefore transverse fractures begin to appear on the upper and lower surfaces of the layer. Further increase in span leads to a corresponding increase in tensile stresses and fracture development.

The mined mass state is analyzed from two positions. Firstly, the potential danger of developing a system of vertically oriented fractures in the water-protected zone (WPZ), which may become channels for groundwater penetration into the mined-out space of the mine, is assessed. Secondly, the possibility of formation of weakened zones on the upper part of the section under the influence of mining operations, which may pose a real danger to surface facilities and engineering structures, is considered. Mathematical modeling of geomechanical processes is performed in order to determine the distribution patterns of displacements, strains and stresses in the rock mass in the zone of mutual influence of open-pit and underground mine workings.

Results and discussion. To ensure safe and efficient combined field mining, the geomechanical state of the rock mass is regularly assessed, prediction of changes in this state is made, and measures to manage them by artificially strengthening unstable rock mass areas are developed. Combined open-pit and underground mining results in the redistribution of stresses, causing their increased concentration below the quarry bottom and displacement of rock masses towards the mined-out space. Deformations of quarry walls can change the stress state around the underground mine workings and complicate their mining.

In the course of modeling of the rock mass stability and displacements in the East Saryoba mine, data have been obtained to assess the influence of tectonic fault and load from the dump on the state of underground mine workings. The model demonstrates that dump pressure, applied with a value of 3 MPa, causes local stresses and strains in the quarry zone, especially near the fault line.

Fig. 4, *a* shows the modeling of the tectonic fault influence on an underground mine working within a quarry. The figure demonstrates the stress distribution caused by applied pressure from the dump (3 MPa) and the influence of the fault on the surrounding rock mass. The color scale represents the stress distribution: zones with more intense coloring (red and orange) indicate higher stresses, while green and blue zones represent relatively low stresses. The red and blue marks (Fig. 4, *a*) on the fault line indicate the values of maximum and minimum displacements calculated by the program.

The red mark corresponds to the highest displacement in the upper part of the fault, and the blue mark indicates the zone of minimum displacement in the lower part of the fault. The vector directions along the fault line demonstrate the direction of displacement, indicating a slight horizontal rock mass displacement towards the mine working. The modeling results show that the fault has insignificant impact on the mine working structure, and its influence on the mass stability in this area remains limited. Fig. 5 shows the rock mass safety factor distribution in the zone of dump and fault influence, measured by a strength factor scale.

The strength factor scale indicates the relative stability of rocks: the lower values (0.2 to 1.4), marked in red

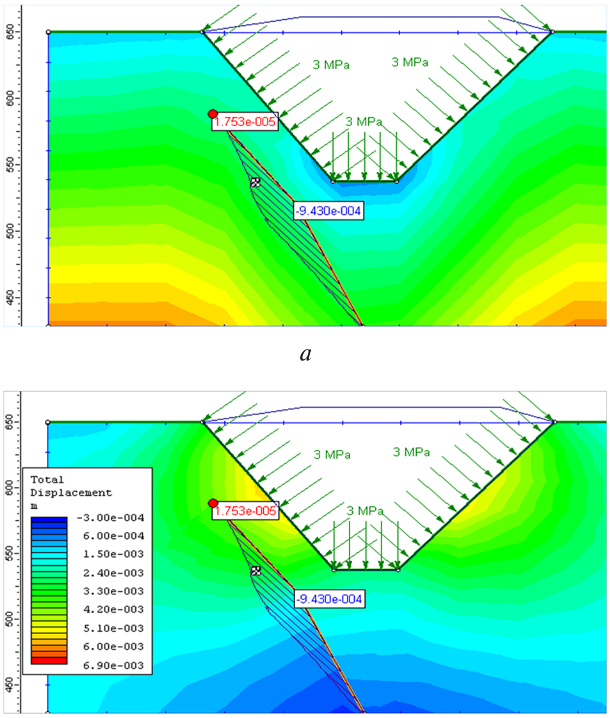

Fig. 4. Stress distribution curves:

a — influence of a fault on mine working; b — areas of potential shears

and orange, indicate zones where rock strength may be insufficient to resist applied loads, increasing the risk of strain and failure. On the contrary, higher values (3.0 to 4.2), marked in green and blue colors, indicate more stable zones capable of withstanding significant loads. The zone under the dump is marked with bright red shades, indicating a low safety factor and, consequently, an increased probability of the mass strains and displacements. The high stress in this area may be due to the concentration of loads caused by the dump and the proximity to the fault, which additionally influences the stability of the mass.

Different levels of stress and strength factors are observed in the zone of fault action. Low strength factor zones are visible in the immediate vicinity of the fault, indicating possible rock displacements and the need for stability control. Away from the fault and in the blue shaded areas, the safety factor is significantly higher, indicating more stable conditions. The results obtained suggest that the zone under the dump and near the fault needs additional stability control measures and possibly

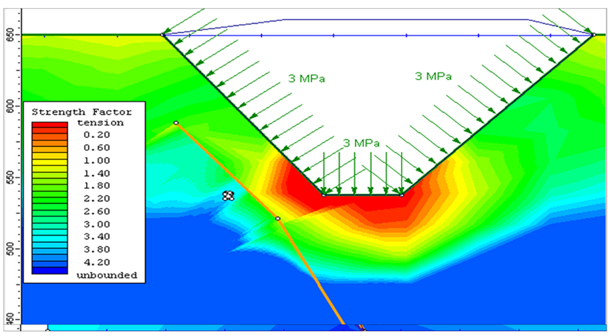

Fig. 5. Curves of safety factor distribution

mass strengthening to prevent undesirable strains and to ensure the safety of underground mine workings.

Based on Fig. 5, it is necessary to construct Fig. 6, which will provide a detailed representation of the distribution of the Strength Factor in the quarry slope under the load of 3 MPa. This figure is intended to complement the analysis and offer a deeper understanding of the instability zones identified within the rock mass.

A slope is considered stable if FoS > 1.0, where resisting forces exceed the driving forces. Conversely, if FoS ≤ 1.0FoS, the slope is at risk of failure. For the East Saryoba field, evaluating the FoS is crucial due to the complex interplay of geological factors, including the influence of tectonic faults, material heterogeneity, and groundwater conditions. High pore water pressures (u) and low cohesion values (c) can significantly reduce the stability of the slopes, necessitating careful monitoring and reinforcement strategies. The application of this method allows for the identification of critical zones along the quarry slopes where instability is likely to occur. By calculating the FoS for various sections of the slope, targeted measures such as slope angle optimization, drainage systems to reduce pore pressure, and the use of retaining structures can be implemented to ensure the long-term stability of the quarry and surrounding areas. This analytical approach forms the basis for designing safe and efficient mining operations while minimizing the risks associated with slope failures. Fig. 7 presents the analysis of the Strength Factor distribution along the quarry contour at depths 10 and 20 m.

Fig. 7 illustrates the Strength Factor (SF) distribution along the quarry contour at depths of 10 and 20 m. At a 10 m depth, the left and right slope sides exhibit relatively stable conditions, with SF values ranging from 1.5 to 2.5. However, a noticeable reduction in SF occurs near the quarry bottom, where values drop to between 0.0 and 0.5. This indicates a critical instability zone requiring immediate attention to prevent potential failures. The right slope side mirrors the stability of the left slope, with no significant stress accumulation detected.

At a depth of 20 m, the SF values decrease across all sections, reflecting the impact of greater stress at deeper levels. The left slope side shows SF values between 1.2 and 2.0, signaling a moderate reduction in stability compared to a 10 m depth. Similarly, the right slope side demonstrates a slight decline in stability, with SF values ranging from 1.0 to 2.0. The quarry bottom remains the most critical zone, with consistently low SF values below 0.5, confirming it as the area most vulnerable to stress concentration and deformation.

These findings highlight the need for targeted mitigation measures. Immediate reinforcement of the quarry bottom is essential, using methods such as retaining walls, ground anchors, or drainage systems to reduce pore water pressure. Monitoring systems should be installed to track stress and deformation in real-time, particularly in the quarry bottom and deeper slope sections. Adjustments to slope geometry and additional support for the lower slopes are recommended to ensure long-term stability and safe mining operations.

Further research in ensuring the stability of quarry slopes during the combined development of mineral deposits should focus on enhancing geomechanical modeling and monitoring methods. In particular, the development of adaptive models of the stress-strain state of the rock mass, which accounts for dynamic changes in the properties of the massif under varying mining and geological conditions, is a promising direction.

Another critical area involves refining methods for identifying critical instability zones using integrated monitoring systems in real time. These systems could combine data from geodetic, geomechanical, and hydrogeological sensors to comprehensively assess slope conditions and predict potential failures with higher accuracy. Finally, future work should investigate the influ-

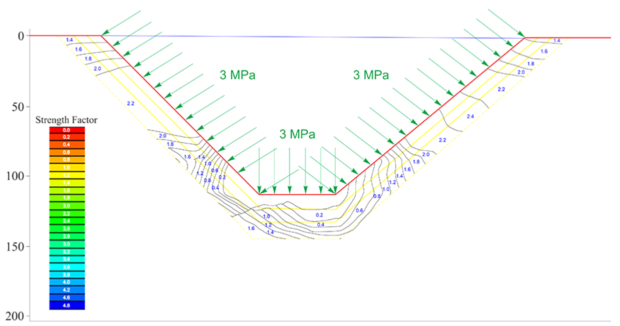

Fig. 6. Strength factor distribution in the quarry slope under the load of 3 MPa

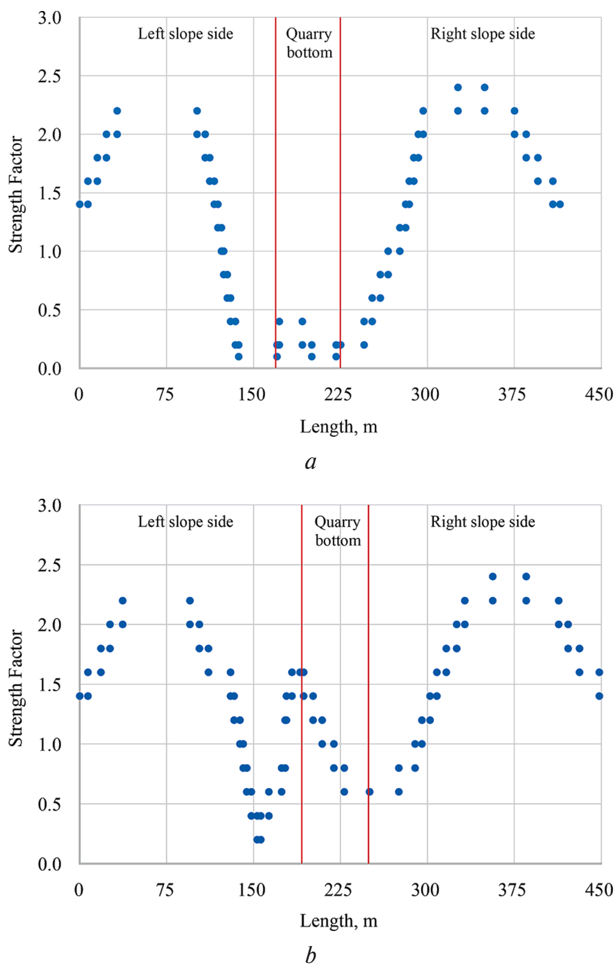

Fig. 7. Strength Factor distribution along the quarry contour:
a – at a depth of 10 m; b – at a depth of 20 m

ence of complex geological structures, such as fault zones and heterogeneous rock layers, on slope stability. Advanced numerical simulations and physical modeling could help to better understand these interactions, allowing for the optimization of quarry slope designs and ensuring safe and efficient mining operations.

Conclusions. Based on the results of modeling, it has been determined that the rock mass in the zone of influence of the trench experiences heaving and intense horizontal displacements towards the ore body areas located below the trench bottom, and the underground mine working is located in the zone of increased horizontal pressure. A preliminary stage of scientific basis for measures to predict signs of occurrence of strong strain processes at the early stage of their development has been developed to assess the occurrence of abnormal geodynamic phenomena, as well as their industrial and environmental consequences.

In the course of modeling of stability and displacements of the rock mass in the East Saryoba mine, data have been obtained to assess the impact of tectonic fault and dump load on the state of underground mine workings. The model demonstrates that the pressure from the dump causes local stresses and strains in the quarry zone, especially near the fault line.

The resulting data of the safety factor distribution made it possible to identify areas with low strength factor values (from 0.2 to 1.4), especially under the dump. This indicates that zones directly influenced by the dump and close to the fault have an increased risk of strains and require additional control and monitoring. In contrast, the safety factor is significantly higher in areas more distant from the fault and dump, indicating stable conditions and a minimal risk of failure.

Future research should focus on the development of advanced geomechanical models that incorporate dynamic factors such as seismic activity, water infiltration, and monitoring data further to enhance the accuracy of predictions regarding rock mass stability.

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Забезпечення стійкості укосів кар'єрів при комбінованій розробці родовищ корисних копалин

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Мета. Забезпечення стійкості укосів кар'єрів при комбінованій розробці родовищ корисних копалин шляхом визначення оптимальних параметрів укосів, надання їм довготривалої стабільності з мінімізацією обсягу розкривних робіт та укріплення у разі виявлення тріщин як видимих, так і прихованих.

Методика. У дослідженні використано комплексний підхід, що включає польові геомеханічні спостереження, математичне моделювання та аналітичні розрахунки. Застосовані сучасні геодезичні методи, зокрема лазерне сканування та GPS-навігацію, для виявлення зон нестабільності та оцінки впливу геотехнічних факторів. Для моделювання розподілу напружень і деформацій у гірському масиві використано програмне забезпечення Examine2D.

Результати. Розроблена схема зонування напружено-деформованого стану гірського масиву, що враховує вплив тектонічних розломів і навантаження від відвалів породи. Визначені зони з низькими значеннями коефіцієнта стійкості (0,2–1,4), що потребують додаткового укріплення. Моделювання показало, що концентрація напружень під кар'єрним дном і біля розломів спричиняє горизонтальні й вертикальні зсуви гірських порід, що впливає на стійкість укосів і гірничих виробок.

Наукова новизна. Уперше виконане комплексне дослідження напружено-деформованого стану гірського масиву при комбінованій розробці родовищ в умовах Казахстану із застосуванням сучасних геодезичних і геомеханічних технологій. Визначені ключові фактори, що впливають на стійкість укосів і їхню довготривалу стабільність.

Практична значимість. Отримані результати дозволяють оптимізувати параметри укосів кар'єрів, зменшити обсяги розкривних робіт, запобігти аварійним ситуаціям, запровадити безпечну експлуатацію підземних виробок і підвищити ефективність гірничих робіт. Запропоновані рекомендації щодо укріплення нестабільних зон.

Ключові слова: *стійкість укосів, комбінована розробка, гірський масив, тектонічні розломи, геомеханічний моніторинг*

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