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ANALYSIS OF DESTRUCTION AND DEFORMATION PROCESSES IN THE ROCK MASSES OF QUARRIES IN UZBEKISTAN

Purpose. A comprehensive analysis of the deformation processes occurring in the quarries of the Republic of Uzbekistan, such as Muruntau and Kalmakyr, with the aim of identifying the key factors influencing the stability of rock masses. Development of practical recommendations and effective measures to ensure the long-term stability of quarry slopes, prevent collapses, and minimize risks to worker safety and the environment.

Methodology. The study involves a comprehensive analysis of geological, tectonic, and climatic factors affecting the stability of quarries. For this, data from long-term monitoring (1979–2024) is used, allowing the identification of trends and patterns in deformation processes. Additionally, the method of modeling the stress-deformed state of rock masses is applied to assess risks and develop predictive models of quarry behavior under various conditions.

Findings:

- the main types of deformations have been identified: collapses (82 %), landslides (18 %);
- key destabilizing factors have been identified: tectonic faults, fracturing, drilling and blasting operations, and geodynamic activity;
- critical slope angles have been determined (for the northern slope of Muruntau – 38°);
- measures to improve stability have been proposed: geomechanical modeling, dynamic monitoring, optimization of drilling and blasting operations, and rock reinforcement.

Originality. The interrelation between tectonic disturbances and the mechanisms of slope failure has been identified. Parameters of residual deformations after blasting operations have been determined. Recommendations have been developed for adjusting slope angles depending on lithology and fracturing.

Practical value. The developed methods of monitoring and geomechanical modeling can be successfully integrated into quarry stability control systems, providing more accurate diagnostics of rock mass conditions. Optimizing drilling and blasting operation parameters, such as drilling grid, type and amount of explosives used, as well as the sequence and timing of detonations, will significantly reduce the risk of damage and increase the efficiency of mining operations. The use of innovative technologies, such as intelligent fiber-optic sensors, ensures continuous real-time monitoring of the rock mass condition, facilitating prompt responses to changes and preventing emergency situations.

Keywords: *deformation processes, slope stability, landslides, collapses, geomechanical modeling, monitoring systems, geodynamic activity*

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Introduction. A comprehensive analysis of deformation processes in open-pit slopes [1–3], based on modern geomechanical modeling methods, monitoring systems, and engineering solutions, is a key factor in ensuring slope stability, preventing catastrophic failures, and improving the efficiency of mineral extraction. The implementation of an integrated forecasting and control system, including geodetic monitoring, geophysical surveys, mathematical modeling, and automated observation systems, enables the early identification of critical deformation zones, the development of adaptive slope stabilization measures, and the optimization of mining operations. Thus, the application of a comprehensive approach to the analysis and management of deformation processes in open-pit mines not only minimizes accident risks and economic losses but also establishes a sustainable framework for the rational and safe exploitation of mineral deposits.

Literature review. Studies [2–4] provide a systematic review of existing technologies for monitoring slope stability in open-pit mines. The research covers both remote sensing methods (InSAR, UAV surveying) and ground-based measurements (GNSS, TLS), as well as IoT technologies and machine learning algorithms. The authors of [2] emphasize the importance of integrating these approaches into a unified monitoring system to improve the efficiency of analysis and the timeliness of response to potential hazards.

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Modern engineering safety systems are based on the principles of RES and STPA. The methodology involves a step-by-step identification of vulnerable zones and the design of a monitoring architecture in such a way that the system is capable of predicting risks and initiating automated response measures before failure occurs. This approach has been successfully tested in several pilot open-pit mines [3].

Studies [4, 5] employed comprehensive geomechanical analysis methods, including laboratory testing of rock samples, laser scanning of pit slopes, and numerical simulations to calculate the stress-strain state of the rock mass. This approach made it possible not only to assess stability conditions but also to develop localized engineering stabilization measures.

Slope behavior modeling that accounts for geological anisotropy, structural discontinuities, and blasting operations enables the development of dynamic 3D risk models. One such study published in 2024 demonstrated the effectiveness of modeling for real-time adaptive design of engineering solutions [6].

D-InSAR technology, widely used in inaccessible and seismically active regions, has demonstrated high accuracy in detecting subtle deformations well before they become visible on the surface. The method shows the greatest effectiveness when combined with ground-based measurements and high-resolution satellite imagery [7].

Recent studies demonstrate a high level of accuracy in slope stability prediction when applying neural networks and machine learning algorithms. In combination with wireless sensor networks (IoT, WSN), this enables real-time assessment of changes in moisture content, stress conditions, and displacements within the rock mass [8, 9].

Slope stability can vary depending on a range of uncertain parameters, from the dip angle of strata to the degree of weathering and rock fracturing. The use of stochastic models makes it possible to account for the full spectrum of potential failure scenarios and to precalculate safe slope angle ranges, particularly at the design stage [10].

Integration of remote sensing, ground-based, and intelligent methods into a unified monitoring and modeling system enables early detection of hazardous open-pit slope deformations, supports informed engineering decisions, and allows adjustment of mining operations. This approach improves safety and economic efficiency by optimizing overburden removal and production. The future of sustainable mining lies in digital, integrated, and adaptive solutions.

The mining industry of the Republic of Uzbekistan is actively developing, extracting gold, copper, uranium, coal, and other minerals [11]. However, open-pit mining is accompanied by destructive deformation processes that can reduce the efficiency of deposit exploitation and create serious safety risks [12, 13].

Uzbekistan lies within the Tien Shan and Pamir-Alay geosynclinal zones, resulting in high tectonic activity and fault systems. The region has diverse lithological formations, from granites and sedimentary rocks to clay shales, along with highly fractured rock masses, zones of weakness, and karst processes that contribute to subsidence and rock failure.

Climatic conditions also play a significant role: an arid climate with high summer temperatures promotes rock cracking, while sharp diurnal temperature variations accelerate physical weathering processes. Spring floods and heavy rainfall trigger rock weakening and landslide development, whereas wind erosion in desert areas (Kyzylkum) contributes to the degradation of pit slopes.

Destructive deformations in open-pit mines in Uzbekistan are caused by a combination of geological, tectonic, and climatic factors. Common phenomena include collapses, erosion, landslides, karst subsidence, and seismically induced failures [2, 3].

The purpose of the study is to analyze typical failure and deformation processes in rock masses at open-pit mines in the Republic of Uzbekistan, with an emphasis on the influence of tectonic disturbances, geomechanical properties of rocks, and the impact of blasting operations.

Methodology. The study involves the development and implementation of modern monitoring, modeling, and engineering approaches for the effective management of open-pit slope stability. The integrated approach includes the use of advanced technologies to reduce the risk of accidents, enhance mining safety, and optimize mineral extraction. This method enables the integration of various monitoring systems, detailed modeling of mining processes, and the development of engineering solutions aimed at improving the stability of open-pit mines.

Methods for deformation monitoring include the classification of deformation types, such as displacements and collapses, using observational data and monitoring systems to identify critical zones within the open-pit mine. An assessment of the impact of blasting operations is also carried out, examining how blasting activities affect rock masses and pit slopes, and analyzing stress changes and deformation risks.

Results and discussion. The Muruntau open pit is one of the largest gold mines in the world and is characterized by complex geological and mining conditions, including a wide range of physical and mechanical properties of rocks [14]. The diversity of lithological complexes, structural features of the rock mass, and significant stress redistribution induced by open-pit mining create favorable conditions for the development of deformation processes in pit slopes and walls.

The evolution of deformation phenomena is observed in different parts of the mine, where systematic monitoring records cases of rock falls, collapses, and landslides. The rock mass is composed of heterogeneous formations, including [15]:

- high-strength rock formations (granites, quartzites, and siliceous shales, characterized by a high degree of fracturing);
- medium-strength sedimentary rocks (limestones, dolomites, and siltstones, with variable stability depending on moisture content and weathering degree);
- clayey rocks and loose deposits (with low shear resistance and high susceptibility to landsliding, especially in fault zones).

Structural discontinuities within the rock mass include major tectonic faults controlling the position of ore bodies and forming weakened zones that are highly prone to deformation.

Changes in the stress state of the rock mass induced by mining operations extend over a large area and significantly influence the nature of deformation. The main contributing factors include:

- depth of excavation;
- slope angle of pit walls;
- structural anisotropy of the rock mass;
- geodynamic activity of fault zones.

These conditions lead to an increased likelihood of slope instability under limit equilibrium conditions.

Systematic monitoring of the pit slopes has been conducted since 1979 [14]. In total, 32 deformation events have been recorded, including:

- landslide processes – 18 %;
- collapses – 82 %.

The volume of displaced rock ranges from 900 m³ (deformation event No. 30) to 230,000 m³ (southwestern slope, deformation event No. 24).

The deformation events are concentrated in two main zones [15]:

1. Southern Fault Zone – 7 recorded cases of collapses and landslides.

2. Second Northeastern Fault Zone – 18 cases of slope failures.

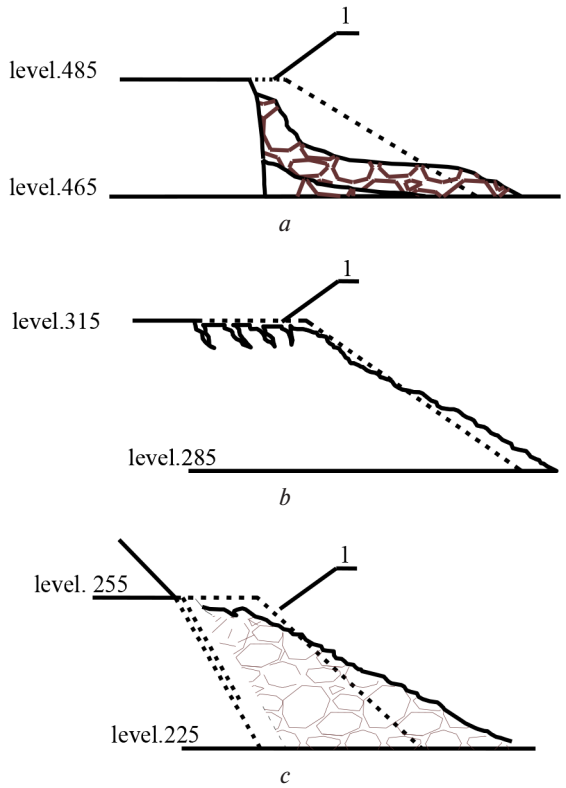

Fig. 1. Types of slope deformation within the Muruntau open-pit mine:

a – rock collapse one month later along the plane of the latitudinal fault and along a weak contact of water-saturated carbonaceous-micaceous schists (northwestern slope; deformation No. 38); b – formation of tension cracks extending 185 m along the bench face during slope trimming using short-hole vertical blasting (southern slope; deformation No. 39);c – rock collapse two months later along a steeply dipping tectonic fracture inclined toward the pit, filled with fault gouge with slickensides (northern slope; deformation No. 35). 1 – slope surface prior to failure

Landslides and collapses predominantly develop vertically within one to two benches, while along the pit face they may extend up to 40–60 m, with deformation depths of 3–5 m (Fig. 1) [15].

Collapses occur in zones of intense rock fracturing, where the presence of weak contacts and bedding planes contributes to loss of stability. The block size (collapse spacing) typically ranges from 1 to 3m.

Landslides are typically contact-type failures and develop in layered rocks dipping toward the pit. The main causes include weakened slope foundations affected by tectonic disturbances, low internal friction angles of rocks-especially in clay interlayers-and additional loading of the slope by waste dumps.

The largest landslide (230,000 m³) occurred on the southwestern slope of the open pit in 1991 within the influence zone of the Southern Fault (Fig. 2) [15].

Blasting operations exert a strong dynamic impact on the rock mass, leading to the formation of zones of residual deformation [16]: deformation No. 41 (2000) developed after bench slope trimming using blasting operations, while deformation No. 43 (2001) was associated with rock loosening induced by blasting. In these zones of residual deformation, rock cohesion decreased several times.

During large-scale blasting, the tension crack zone extends over 5–40 m, while the zone of residual deformation reaches 60–70 m. Insufficient protection of the perimeter rock mass during blasting contributes to intense fracturing and loss of stability.

The main causes of bench deformation include:

- unfavorably oriented tectonic discontinuities filled with fault gouge, characterized by low shear resistance;
- developed rock fracturing reducing cohesion;
- blasting operations inducing residual deformations;
- bench height and slope angles exceeding critical values;
- anisotropy of the near-slope rock mass influencing the formation of slip surfaces.

For the northern slope of the pit, the critical slope angle was adjusted to 38°, based on an analysis of rock cohesion and internal friction angle ($\varphi = 26°$ in weakened zones).

To reduce the risk of slope instability in open-pit mines, it is necessary to [15]:

- develop a geomechanical model of the near-slope rock mass accounting for fracturing and weak zones;

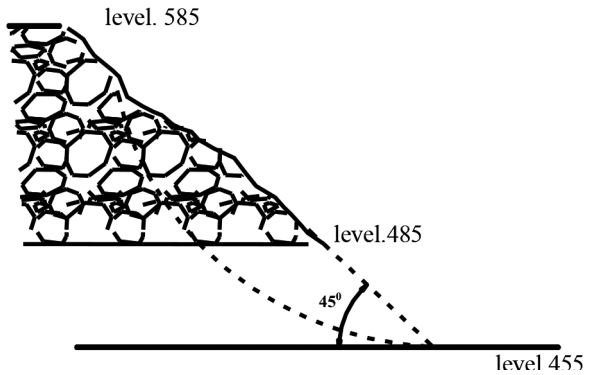

Fig. 2. Initial stage of landslide formation on the slope of the Muruntau open-pit mine

- implement dynamic monitoring of seismic effects to predict the impact of blasting operations.

- optimize slope angles by reducing inclination in weak zones and reinforcing stable rock masses where appropriate;

- apply rock bolting and reinforcement in areas of intensive deformation;

- modernize blasting techniques to minimize the destructive impact of explosions on the perimeter rock mass;

- conduct in-situ shear tests to accurately determine rock mass stability parameters.

Thus, the Muruntau open pit is characterized by complex geological and mining conditions that promote the development of deformation processes. The main causes of collapses and landslides include tectonic disturbances, intense rock fracturing, and the impact of blasting operations. The analysis of monitoring data indicates that critical slope angles require refinement with consideration of the engineering-geological properties of the rock mass. The implementation of modern geomechanical monitoring and forecasting methods will enhance mining safety and minimize the risk of pit slope failures.

The Kalmakyr ore field is one of the largest porphyry copper deposits in Central Asia, developed by open-pit mining [17]. Its unique geological and structural features, significant mining depths, and intensive blasting operations create complex geotechnical conditions that contribute to the development of destructive slope deformations.

Slope failure processes include rock falls, collapses, and landslides resulting from changes in the stress state of the rock mass, tectonic activity, and mining operations. This analysis considers the main types of deformation processes, their causes and mechanisms, as well as measures to improve slope stability in the open pit.

The geological structure of the deposit is represented by a variety of rock types, including [18]:

- hard rocks (granites, porphyrites, quartzites), which have high strength but are characterized by intense fracturing;

- medium-strength rocks (limestones, siltstones, sandstones), whose stability varies depending on hydrological conditions and the degree of weathering;

- clayey rocks and loose deposits, which have low strength characteristics and are prone to weakening and landslide processes.

Tectonic disturbances within the deposit include systems of deep-seated faults that create weakened zones within the rock mass [19].

Changes in the stress state of the rock mass are associated with mining activities and include an increase in stresses along pit slopes with increasing excavation depth, weakening of the rock mass due to fracturing and faulting, and the influence of blasting operations that generate dynamic loads. These processes increase the likelihood of slope failure and destructive deformations.

Rock fall processes develop in zones of intense fracturing and are manifested as local sliding of small rock fragments. Slope collapses occur due to loss of stability of rock masses. They are caused by high fracturing of competent rocks, blasting activities that promote rock mass loosening, and the influence of unfavorably oriented tectonic discontinuities. Landslides represent the most hazardous type of deformation, as they involve the movement of large rock volumes. Landslides at the Kalmakyr deposit are predominantly contact-type and develop in fault-weakened zones with low internal friction angles [20].

The dynamic impact of blasting operations is one of the key factors in the formation of destructive deformations. The tension crack zone extends over 5–50 m, while the zone of residual deformation reaches 80–90 m. In areas of intensive blasting, rock cohesion decreases, and fracturing increases.

Insufficient protection of the perimeter rock mass during blasting operations contributes to slope instability.

The main causes of bench deformation include [21]:

- tectonic discontinuities weakening the rock mass;

- intense fracturing reducing rock cohesion;

- blasting operations inducing residual deformations;

- high slope angles exceeding critical values;

- presence of clay interlayers reducing overall rock mass stability.

For the northern slope of the pit, the critical slope angle was adjusted to 39°, taking into account an internal friction angle of 25° in weakened zones [22].

Fig. 3. Geological and structural scheme of the Kokpatas ore field:

1 – Kokpatas Formation: microquartzites, dolomites, limestones, shales, sandstones; Karashakh Formation: 2 – sandstones, siltstones, shales (Member 3); 3 – sandstones, shales, microquartzites (Member 2); 4 – shales, siltstones, sandstones with conglomerates at the base (Member 1); 5 – Tubabergen Formation: polymictic sandstones and siltstones, shales, tuff breccias, spilites; 6 – Dzhuskuduk Formation: limestones; 7 – dikes of granite porphyries, diorites, diorite porphyries, lamprophyres; 8 – aplites; 9 – biotite granites; 10 – porphyritic granites; 11 – adamellites; 12 – granodiorites; 13 – quartz porphyries, albitophyres; 14 – gabbros, gabbro-diabases; 15 – ultramafic rocks; 16 – faults; 17 – thrust faults; 18 – bauxite-bearing horizon; 19 – gold ore bodies; 20 – quartz veins with gold; 21 – quartz–antimonite veins with silver and gold

The geological structure of the Kokpatas ore body is shown in Fig. 3 [23].

Thus, the Kalmakyr deposit is characterized by complex geological and mining conditions that promote the development of destructive deformations. The main causes of slope instability are associated with tectonic disturbances, high rock mass fracturing, and blasting operations. Monitoring data analysis has indicated the need to adjust slope angles and implement additional stability measures. The application of modern geomechanical monitoring and forecasting methods will improve mining safety and minimize the risk of pit slope failures.

The Kokpatas ore field represents a complex geological structure characterized by significant variability in bedding angles and strike directions [23]. These features, together with the presence of carbonaceous material within the rocks, have a direct impact on slope stability, requiring comprehensive geotechnical analysis.

The Kokpatas ore field is confined to a large brachyanticlinal structure with a meridional strike. The core of the structure is composed of Lower Carboniferous limestones, which have high strength but may exhibit a well-developed system of fracturing. The limbs of the anticline are formed by volcanogenic-sedimentary rocks of the Karashakh Formation and siliceous–carbonate–shale deposits of the Kokpatas Formation, which are characterized by high variability in their physical and mechanical properties. The widespread presence of carbonaceous material in the rock composition significantly affects their mechanical strength and may contribute to the formation of weakened zones [24].

The region is subject to active tectonic processes, resulting in the formation of numerous faults and zones of rock mass weakening. Tectonic discontinuities cause variations in bedding dip angles even within a single open pit, which complicates the design and prediction of slope stability [25].

Results of engineering-geological investigations at the Yuzhny-I open pit confirm that all geological and lithological units forming the pit slopes are characterized by significant variability in mechanical properties. Laboratory testing of rock samples did not allow for obtaining fully representative characteristics for all lithological varieties present in the rock mass. Significant variations in strength parameters make it difficult to determine critical slope angles. During the studies, key parameters such as rock cohesion, internal friction angle along discontinuity surfaces, and structural weakening coefficients of the rock mass were not determined. In-situ shear tests, which are critically important for assessing rock stability under seismic-blasting loads from large-scale blasts, were not conducted [25].

Due to the uncertainty in geotechnical parameters, the design slope angles of the pit walls were adopted with a significant safety margin. The construction slope angles (including haul road berms) were set at 33–35°. A survey of 31 open pits showed that in all cases the slopes exhibit a high degree of stability, confirming the safety of the adopted parameters. Based on geological and mining conditions, the ultimate slope angles of open pits range from 38 to 47°, indicating the possibility of operating the pit with steeper slopes [26].

A comparison of design and actual data indicates that the adopted slope angles include a considerable stability margin; therefore, they can potentially be increased to optimize pit geometry and reduce overburden stripping volumes.

One of the factors affecting slope stability is the impact of seismic–blasting loads during mining operations. Blasting activities may trigger local collapses in zones of fracturing and faulting. In areas containing carbonaceous inclusions, rock weakening may occur, increasing the likelihood of slope deformation.

To improve the accuracy of slope stability calculations at the Kokpatas open pit and optimize slope angles, detailed geomechanical investigations are required, including laboratory testing of all rock types to determine cohesion and internal friction along discontinuities, in-situ shear tests to assess rock strength under field conditions and blasting effects, and geophysical monitoring using ground-penetrating radar to identify hidden weak zones. Laser scanning should also be applied for real-time slope stability control. Based on experience from similar open pits, slope angles may be increased to 38–47° to reduce stripping volumes without compromising safety.

Thus, the analysis of engineering-geological data from the Kokpatas ore field shows that the existing pit slope angles were adopted with an excessive safety margin. Based on analytical calculations and comparisons with other open pits, it has been established that mining operations are feasible at steeper slope angles, which would improve mining efficiency.

To further improve the accuracy of slope stability predictions, additional research is required, including laboratory and in-situ testing, as well as detailed monitoring of the rock mass using modern geophysical technologies.

The Angren coal strip mine is one of the largest in Uzbekistan and is developed by open-pit mining as part of the Angren kaolin–coal deposit.

The layout of the open pits is shown in Fig. 4. Complex geological and geotechnical conditions lead to various destructive deformations, including landslides, rockfalls, and collapses. Landslides at the mine pose a serious risk to mining operations, especially to railway transport used for overburden and ore removal. The largest deformations include the “Central” and “Old Substation” landslides, along with smaller failures on waste benches and working pit slopes.

The Jurassic sedimentary section of the pit includes the following main rock groups:

- sandy-clayey rocks (Suzak horizon, Paleogene), characterized by low shear resistance and representing the main zone of landslide development;
- montmorillonite clays, water-saturated rocks with low bearing capacity that form weak horizons beneath working benches;
- water-bearing interlayers of coal-bearing sequences, which promote rock mass weakening and reduce slope stability.

Tectonic discontinuities such as thrusts and faults create zones of weakness that act as natural slip surfaces for landslide formation.

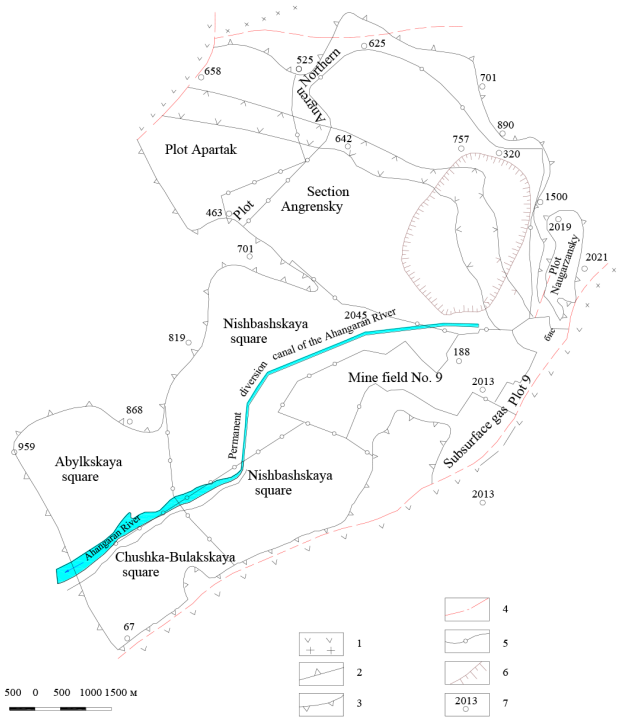

Fig. 4. Layout scheme of the Angren deposit mining areas:
1 – Paleozoic; 2 – boundary of coal deposit distribution within the field; 3 – boundary of coal dilution zone; 4 – tectonic faults; 5 – boundary of the area along the coal seam floor; 6 – benches of the coal open pit; 7 – boreholes and their identification numbers

The Angren open pit is located within an active subsurface groundwater flow zone directed into the mine through fault structures. The main groundwater inflows originate from the Sayaksay and Baksuksay streams, contributing to the weakening of clay interlayers and the formation of landslide bodies.

Observations show that the rate of rock mass displacement increases with rising water inflows, as well as during periods of intensive snowmelt and seasonal rainfall.

The "Central" landslide is located in the middle section of the pit slope (PK 9–PK 23). It formed in May 1987 and is still active. Its total volume is 58 million m^3, with 45 million m^3 already removed. The landslide is controlled by tectonic discontinuities and groundwater inflows. Average annual displacement ranges from 0.8 to 6.3 m/year, reaching up to 8.5 m/year during peak activity. After unloading the head scarp and reducing water inflow, movement decreased to 15–16 mm/day, but increased again to 22–23 mm/day with rising groundwater. Nine monitoring benchmarks are used to track deformation. Geodetic data show the most intensive horizontal displacement at 960 m elevation, reaching 16 m over two years.

The "Old Substation" landslide is located in the upper part of the working slope (PK 21–PK 30). It formed in May 1993 and is still active. It covers an area of 700 × 300 m with a volume of 3.5 million m³. The landslide is moving toward the "Central" landslide, which may lead to their merging. Studies by the HYDROINGEO Institute show that the main Sayaksay groundwater flow is directed toward the landslide zone, contributing to its activation. GPS and topogeodetic monitoring indicate that after periods of acceleration, the displacement rate decreased but later increased again to 2.0 mm/day.

Deformation on benches 6–11 (PK 13–PK 15) was triggered by the collapse of a production bench. The bench is 60 m high with a 60° slope angle. The failure zone is 180 m long and 30 m wide, with a displaced rock volume of 300,000 m^3. The collapse occurred two days after tension cracks (10–20 cm wide) appeared on the berm, highlighting the need for intensified monitoring.

To minimize the risk of slope instability in the open pit, it is necessary to expand the geodetic monitoring network, systematize water drainage control and reduce groundwater inflows into the pit, optimize slope angles considering lithological conditions, implement slope reinforcement in active landslide zones, and regularly analyze the stress state of the rock mass using numerical modeling. It is also recommended to limit railway transport speed in deforming areas and carry out regular maintenance of railway tracks.

Trends and regularities of deformation processes. Long-term observations of the largest open pits in Uzbekistan (Muruntau, Kalmakyr, and Angren) have revealed stable patterns in the development of deformation processes. In the Muruntau open pit, collapses dominate (approximately 80 % of cases) in fractured rock masses, while landslides (approximately 20 %) occur in zones of tectonic disturbances and weak interlayers. Deformations most often develop within one to two benches, with displacement fronts reaching 40–60 m and depths of 3–5 m.

The Angren coal strip mine is characterized by large-scale landslides with volumes reaching tens of millions of cubic meters, which are activated by rising groundwater levels and during the spring–summer season. In the Kalmakyr open pit, block failures dominate in fractured rock masses; however, with increasing depth of mining, mixed-type slope deformations begin to develop.

Overall, a general trend can be observed: with increasing depth and more complex tectonic conditions, the probability of combined failure mechanisms increases.

Systematization of observations allows identification of the main types of deformation, which are presented in the Table below.

Table

Deformation process types and their manifestations in open-pit mines

Deformation type	Formation conditions	Manifestation example
Caving	Fractured granites and quartzites	Muruntau, northern slope
Rockslides	Argillaceous shales, siltstones, tectonic contacts, water saturation	Angren, Southern Fault
Talus	Small-scale fragmentation processes, precursors of large rockfalls	All open pits
Block displacements	Active faults and fractures, seismic activity	Kalmakyr, eastern slope

Such a classification makes it possible to relate specific deformation forms to geological and mining conditions and to take them into account in the design of slope angles.

Influence of blasting operations on stability. The studies showed that blasting operations exert a significant dynamic impact on open-pit slopes. Seismic loading from production blasts leads to:

- formation of new cracks at distances of 50–100 m from the pit boundary;
- residual deformations up to 80–90 m from the blast center;
- rock slabbing at depths of 5–50 m within the rock mass.

As a result, the internal friction angle of the rocks in the blast-affected zone decreases by 10–15 %. Conditions involving alternation of competent and weak layers are particularly hazardous, where vibrations accelerate the formation of sliding surfaces. Optimization of blasting parameters (reducing the drilling pattern, dividing blasts into delays, and limiting charges near the pit wall) can significantly reduce rock mass damage and help maintain slope stability.

Modeling of the stress-strain state of the rock mass. Numerical methods based on the finite element method and limit equilibrium approach are used to predict slope stability. Software packages such as PLAXIS, FLAC3D, and Rocscience (Slide, RS2) are applied. The models account for the physical and mechanical properties of rocks (cohesion, internal friction angle, Young's modulus, Poisson's ratio), the presence of tectonic faults, groundwater conditions, and dynamic effects (seismic loading, blasting).

Calculations show that, for the Muruntau open-pit rock mass, the safe slope angle in fault zones should not exceed 38°, whereas in more competent rock units a permissible angle of up to 47° can be adopted. Such models enable refinement of design parameters, control of the factor of safety, and identification of potential sliding zones.

Predictive models of slope behavior. Predictive models of slope behavior are developed through the integration of monitoring data (geodetic surveys, GNSS, InSAR, and laser scanning) with the results of geomechanical modeling. This approach enables the construction of forecasting models describing slope response over time.

Based on the analysis of displacement velocities, it is possible to predict the onset of landslide activation. For example, an acceleration exceeding 5 mm/day in Angren has been identified as a precursor to developing instability.

The application of machine learning methods and neural networks trained on historical datasets allows for real-time assessment of the probability of failure occurrence.

Stochastic models account for the variability of natural conditions and enable risk assessment using a probabilistic approach.

Thus, predictive models not only provide analysis of the current state of a rock mass but also enable forecasting of hazardous process development, thereby improving industrial safety in the operation of deep open-pit mines.

Conclusion. Thus, the analysis of failure-related deformations in open pits shows that the main factors triggering landslides and slope collapses are the geological structure of the rock mass, hydrogeological conditions, and blasting operations.

The Muruntau open pit is characterized by high tectonic activity, complex engineering-geological conditions, and intensive development of deformation processes driven by the interaction of natural and anthropogenic factors. Analysis of monitoring data has shown that the main causes of slope instability include adversely oriented tectonic faults, high rock mass fracturing, residual deformations induced by blasting, and exceedance of allowable bench slope angles. The implementation of a dynamic geomechanical model based on integrated hydrogeological, structural-geological, and seismodynamic data will enable accurate delineation of risk zones, adjustment of slope design parameters, and development of adaptive engineering solutions to improve slope stability.

The Kalmakyr deposit, one of the largest porphyry copper deposits in Central Asia, has complex geological and mining conditions, including highly fractured rock mass, strong tectonic structures, and significant blasting impacts. Monitoring data show that slope instability is mainly caused by failure of near-contour rock mass, residual blast-induced deformations, and weak zones within the rock mass. Improving slope stability requires an adaptive geomechanical model considering stress changes, blasting effects, and hydrogeological factors. Optimizing slope angles, using improved contour blasting, and strengthening landslide monitoring can reduce failure risks and enhance mining safety.

The Kokpatas ore field has a complex geological structure, variable rock properties, and strong seismic-blasting impacts, requiring optimization of pit slope parameters based on detailed geomechanical studies. Analysis shows that existing slope angles were set with an excessive safety margin, and increasing them to 38–47° would reduce stripping volumes, improve mining efficiency, and lower costs without reducing safety.

The Angren coal open pit has complex engineering-geological conditions and is affected by active landslide and rockfall processes caused by tectonic faults, clay interlayers, high groundwater saturation, and blasting impacts. The most hazardous landslides, "Central" and "Old Substation," continue to develop, threatening slope stability, infrastructure, and mining safety. Stable mine operation requires an integrated deformation management approach, including expanded geodetic monitoring (GPS, UAVs, laser scanning), optimization of slope angles based on rock properties, slope stabilization, drainage systems, and numerical modeling for prediction and prevention of hazardous events.

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Аналіз процесів руйнування й деформації гірських масивів кар'єрів Узбекистану

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Мета. Комплексний аналіз деформаційних процесів, що відбуваються в кар'єрах Республіки Узбекистан, таких як Мурунтау й Кальмакир, з метою виявлення основних факторів, які впливають на стійкість гірських масивів. Розробка практичних рекомендацій та ефективних заходів щодо забезпечення довготривалої стійкості бортів кар'єрів, запобігання обвалень і мінімізації ризиків для безпеки працівників і навколишнього середовища.

Методика. У рамках дослідження проводився комплексний аналіз геологічних, тектонічних і кліматичних факторів, що впливають на стійкість кар'єрів. Для цього використані дані багаторічного моніторингу (1979–2024 рр.), що дозволяє виявити тенденції й закономірності в деформаційних процесах. Крім того, застосовано метод моделювання напружено-деформованого стану гірських масивів для оцінки ризиків і розробки прогностичних моделей стійкості кар'єрів в різних умовах.

Результат:

- ідентифіковані основні типи деформацій: обвалення (82 %), зсуви (18 %);
- виявлені ключові фактори дестабілізації: тектонічні розломи, тріщинуватість, буропідривні роботи, геодинамічна активність;
- визначені критичні кути нахилу бортів (для північного борту Мурунтау – 38°);
- запропоновано заходи щодо підвищення стійкості: геомеханічне моделювання, динамічний моніторинг, оптимізація буропідривних робіт, армування порід.

Наукова новизна. Виявлено взаємозв'язок тектонічних порушень і механізмів руйнування укосів. Визначені параметри залишкових деформацій після вибухових робіт. Розроблені рекомендації щодо коригування кутів нахилу укосів у залежності від літології та тріщинуватості.

Практична значимість. Розроблені методи моніторингу й моделювання геомеханічних процесів можуть бути успішно інтегровані в системи контролю стійкості кар'єрів, забезпечуючи більш точну діагностику стану гірських масивів. Оптимізація параметрів буропідривних робіт, таких як сітка буріння, тип і кількість застосовуваних вибухових речовин, а також послідовність і час підриву, дозволить істотно знизити ризики руйнувань і підвищити ефективність гірничих робіт. Застосування інноваційних технологій, таких як інтелектуальні волоконно-оптичні датчики, забезпечує безперервний моніторинг стану масиву в реальному часі, що сприяє оперативному реагуванню на зміни й запобіганню аварійних ситуацій.

Ключові слова: *деформації порід, стійкість схилів, зсуви, обвалення, геомеханічне моделювання, моніторинг, геодинаміка*