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ҰЛТТЫҚ ҒЫЛЫМ
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«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

ХАБАРЛАРЫ

ИЗВЕСТИЯ

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DEVELOPMENT OF METHOD FOR ASSESSING QUARRY SLOPE STABILITY USING SIDE MASSIF MAPPING

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Abstract. The article presents the results of ensuring the stability of the slopes of the quarry, which is solved using the developed methodology for mapping stability, which takes into account and analyzes all natural and technological factors based on GIS. The work uses an integrated approach, including: engineering and geological rock formations with mapping of disturbed areas, instrumental surveying observations using modern instruments. Implementation of the developed methodology for creating stability maps of quarry sides in production at the Aktogay copper ore quarry. As a result of the research, they have been developed, studied and implemented: – methods and means of monitoring the condition of the sides of the quarry in the Republic of Kazakhstan; – a methodology for monitoring instrument arrays, taking into account all natural and man-made factors; – the technique of geoinformation mapping of slope stability based on geomonitoring data; – the composition of a strengthening solution from mining waste to increase the stability of disturbed sections of ledges. The novelty of the developed solutions

is confirmed by the patent and copyright certificate of the Republic of Kazakhstan. The methodology for creating quarry side stability maps is used in other quarries, as well as in the educational process by master's and doctoral students at the Kazakh National Research University named after K.I. Satpayev.

Keywords: ore deposits, quarry, rock edge stability, monitoring, physical and mechanical properties of rock, stability maps, modeling.

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АСПАПТЫҚ МАССИВТЕРДІҢ КАРТАЛАРЫН ЖАСАУ АРҚЫЛЫ КАРЬЕР БОРТТАРЫНЫҢ ТҰРАҚТЫЛЫҒЫН БАҒАЛАУ ӘДІСТЕМЕСІН ӘЗІРЛЕУ

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Аннотация. Мақалада геоақпараттық (ГАЖ) технологиялар негізінде барлық табиғи және технологиялық факторларды жан-жақты есепке алу мен талдауды көздейтін тұрақтылықты картаға түсірудің әзірленген әдістемесін қолдану арқылы шешілетін карьер беткейлерінің тұрақтылығын қамтамасыз ету нәтижелері келтірілген. Зерттеу әдістемесі. Жұмыста интеграцияланған тәсіл қолданылады, оның ішінде: бұзылған аймақтарды картаға түсіре отырып, тау жыныстарының массасының құрылымдық-тектоникалық құрылымын инженерлік-геологиялық зерттеу, заманауи аспаптардың көмегімен аспаптық маркшейдерлік бақылаулар, сонымен қатар аспаптар массивінің кернеулі-кернеулі күйін модельдеу. Зерттеу нәтижелері. Геодинамикалық

мониторингтің кешенді жүйесін жүргізу әдістемесі әзірленді. Ақтоғай мыс кен орны карьер борттарының тұрақтылығы карталарын жасаудың әзірленген әдістемесін өндіріске енгізілді. Жұмыстың ғылыми жаңалығы. Жүргізілген жұмыстың нәтижесінде мыналар зерттелді, әзірленді және өндіріске енгізілді: — Республикадағы және одан тысқары жерлердегі карьерлерді бақылау әдістері мен құралдары; — барлық табиғи және технологиялық факторларды кешенді есепке алуды қамтамасыз ететін жақын маңдағы массивтерді бақылау әдістемесі; — геомониторинг мәліметтері бойынша карьер беткейлерінің орнықтылығын геоақпараттық картаға түсіру әдісі; — карьер беткейлерінің орнықтылығын арттыру үшін тау-кен кәсіпорындарының қалдықтарынан бұзылған учаскелерді нығайту ерітіндісінің құрамы. Әзірленген құжаттардың жаңалығы Қазақстан Республикасының патенті және ғылыми шығармаға берілген авторлық құқық куәлігімен расталады. Практикалық құндылығы. Аспаптық массивтердің карталары негізінде Карьер борттарының тұрақтылығын бағалаудың ұсынылған әдістемесі басқа Карьерлердегі өндірістік қауіпсіздік деңгейін арттыру үшін, сондай-ақ Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университетінің магистранттары мен докоранттарының білім беру процесінде пайдаланылуы мүмкін.

Түйін сөздер: кен орындары, карьерлер, тау жыныстарының жиектерінің тұрақтылығы, тау жыныстарының мониторингі, физикалық-механикалық қасиеттері, тұрақтылық карталары, модельдеу.

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РАЗРАБОТКА МЕТОДИКИ ОЦЕНКИ УСТОЙЧИВОСТИ БОРТОВ КАРЬЕРА ПУТЕМ СОЗДАНИЯ КАРТ ПРИБОРТОВЫХ МАССИВОВ

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Аннотация. В статье приведены результаты обеспечения устойчивости откосов карьера решается с применением разработанной методики картографирования устойчивости, предусматривающей комплексный учёт и анализ всех природных и технологических факторов на основе геоинформационных (ГИС) технологий. Методика исследования. В работе использован комплексный подход, включающий: инженерно-геологическое изучение структурно-тектонического строения массива горных пород с картографированием нарушенных участков, инструментальные маркшейдерские наблюдения с использованием современных приборов, а также моделирование напряжённо-деформированного состояния прибортового массива. Результаты исследования. Разработана методика ведения комплексной системы геодинамического мониторинга. Внедрение разработанной методики создания карт устойчивости бортов карьера в производство на меднорудном карьере Актогай. Научная новизна. В результате НИР разработаны, изучены и внедрены: — методы и средства мониторинга состояния бортов карьера в Республике Казахстан и за рубежом; — методика мониторинга прибортовых массивов с учётом всех природных и техногенных факторов; — методика геоинформационного картографирования устойчивости откосов по данным геомониторинга; — состав укрепляющего раствора из отходов горного производства для повышения устойчивости нарушенных участков уступов. Новизна разработанных решений подтверждена патентом и авторским свидетельством патентного ведомства Республики Казахстан. Практическая значимость. Предложенная методика оценки устойчивости бортов карьера на основе карт прибортовых массивов может быть использована для повышения уровня производственной безопасности на других карьерах, а также в образовательном процессе магистрантов и докторантов Казахского национального исследовательского технического университета имени К.И. Сатпаева.

Ключевые слова: рудные месторождения, карьер, устойчивость кромки породы, мониторинг, физико-механические свойства породы, карты устойчивости, моделирование.

Introduction. Mining globally is predominantly conducted through open-pit methods, which account for 75% of the mineral products extracted from the Earth's subsurface, trend that is expected to continue in the future. Among these are the copper ore deposits of Kazakhstan, such as Aktogay, Bozshakol, and Aidarly, as well as gold ore deposits like Akbakay, Bakyrchik, Vasilkovsky, and others.

These deposits have estimated service life of over 50 years. As open-pit mining progresses, there is a continual increase in the depth, volume, and production

capacity of quarries. Critical requirement for ensuring safety of mining operations is maintaining stability of quarry walls.

Deformations of quarry slopes can lead to significant material damage to mining enterprises, disrupting safe and efficient mining operations and resulting in mineral losses, which become particularly critical in a market economy. As a result, ensuring stability of quarry slopes is one of the most pressing issues in mining.

Main content. Current stage of mining industry development is marked by significant geomechanical processes, including changes in the stress state and deformation of quarry walls. These processes introduce uncertainty during deposit development and can lead to serious technological, environmental, and economic consequences, sometimes resulting in catastrophic technical failures, financial losses, and even human casualties (Rockburst, 2005; John, 2012; Melnikov, 2010; Trubetskoy, 2020; Oparin, 2013).

In this context, priority research areas in the field of industrial safety include: development of methodologies for studying and forecasting geomechanical processes; implementation of innovative geomonitoring techniques; and establishment of scientific foundations and practical approaches for managing geomechanical processes during subsoil development. Significant contributions to development of field geomechanical research methodologies have been made by scientists from the Moscow, Leningrad, and Kazakhstan schools of geomechanics (Pevzner, et al., 2005; Fisenko, 1975; Kozyrev, et al., 2006 Mashanov, et al., 1981; Popov, et al.,1986; Nizametdinov, 2014).

Despite the progress made, challenge of studying geomechanical processes and ensuring industrial safety remains unresolved. Modern research on geomechanical processes has gained new momentum with the widespread adoption of the hierarchical structure concept for the fracture-block composition of rocks at various scales (Nurpeissova, et al., 2015). This approach is closely linked to variability of tectonic disturbance parameters as mining operations reach greater depths.

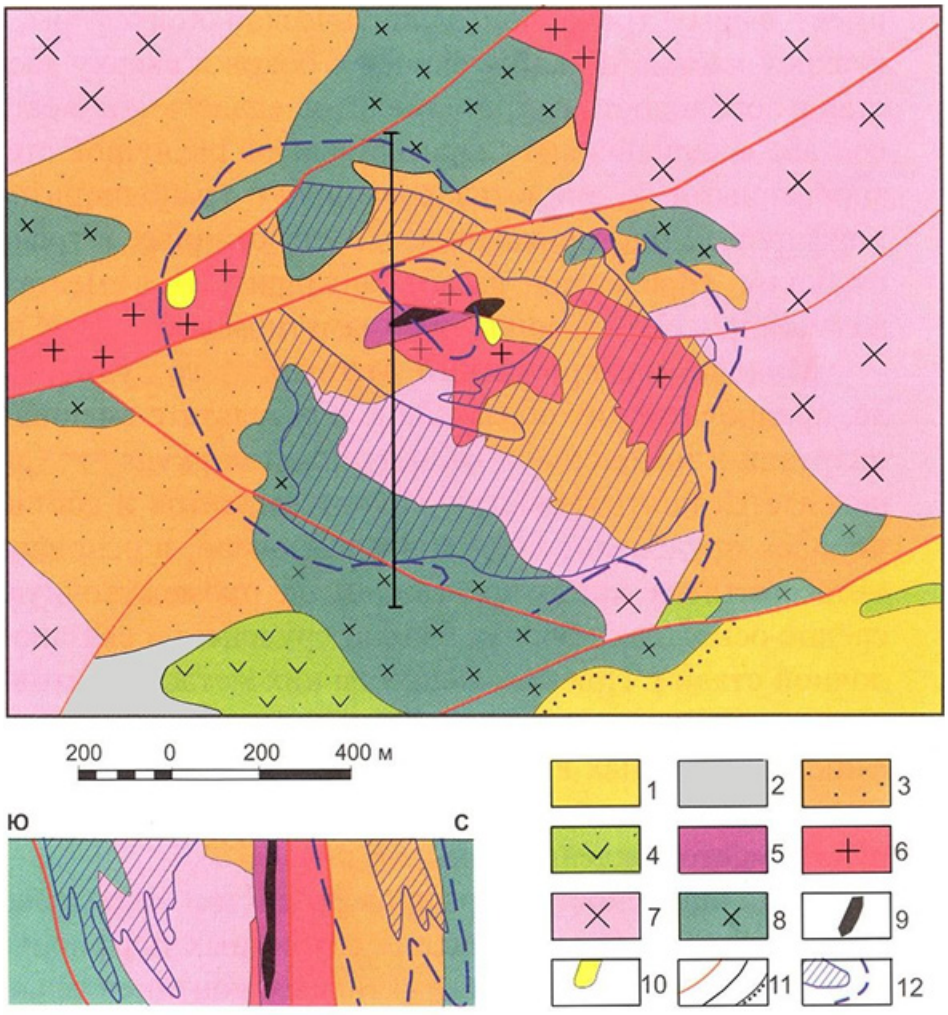
Methods and scope of research. The work used a complex method, including engineering-geological study of the structural-tectonic structure of the rock mass with mapping of disturbed areas, instrumental surveying observations using modern instruments and assessment of changes in the stress-strain state of the rock mass by creating zoning maps of the edge massifs. In world practice, to solve this problem, a variety of specialized programs are widely used, based on the use of numerical solution methods borrowed from the mechanics of solid deformable bodies, for example, the finite element method (FEM) and the boundary element method (BEM).

Application of innovative geomechanical data recording techniques, along with modern software tools for processing this data, enables creation of detailed models of the stress-strain state of the massif.

The object of the study is the Aktogay copper ore deposit, located in the Abay region of the Republic of Kazakhstan. The ore development project is part of the

state program for industrial and innovative development and the KAZ Minerals group.

Results. The Aktogay deposit is an ore stockwork, which is a semi-closed thick-walled ellipse with a barren core, elongated in the submeridional direction by 2500 m with a width of 50-830 m. Mineralization pinches out at a depth of over 800 m (Figure 1).



Legend*: 1 – sandstones with interlayers of tuffs and dacites of the Koldar suite; 2 – tuffs of dacites and andesidacites of the Keregetas suite; 3 – hornfels and hornfelsed porphyrites and tuffs of the Keregetas suite; 4 – stock- and dike-shaped bodies of andesidacite porphyrites; 5-8 rocks of the Koldar intrusion: 5 – granodiorite porphyries, 6 – porphyritic granites and granodiorites with aplite groundmass, 7 – uniformly crystalline granodiorites, 8 – diorites, gabbro-diorites; 9 – breccia bodies on tourmalinized cement; 10 – quartz bodies; 11 – tectonic contacts, intrusive and unconformable; 12 – boundaries of ore bodies and dispersed ore mineralization*

Fig. 1 - Geological structure of the Aktogay field (Copper, 2014)

The shape of the ore stockwork and the depth of the ores predetermined the development of the deposit by open-pit mining to a depth of 585 m. In the process of developing the open-pit mining method, an increase in the depth, volume and production capacity of quarries has been observed. A prerequisite for safe mining operations in quarries is to ensure the stability of the quarry sides.

Given the objectives and functions of managing stability of rock massifs -particularly quarry slopes - during development of mineral deposits with diverse and variable geological structures, it is essential to continuously conduct research to obtain reliable information on structural characteristics of rock massif, its strength properties, hydrogeological conditions, and other factors. Such research should be carried out at all stages of quarry slope development (including quarry construction, capacity design, initiation of permanent quarry slope design at the marginal contour, and quarry refinement) as part of integrated system.

Validity of previously made technological decisions regarding quarry slope parameters is assessed through geotechnical monitoring of quarry slope condition. Therefore, it must be integrated into a unified system of observations and research.

Instrumental mine surveying and geodetic observations are primary methods for obtaining information on deformations of quarry and dump slopes, providing the most reliable basis for predicting their stability (Fig. 2).

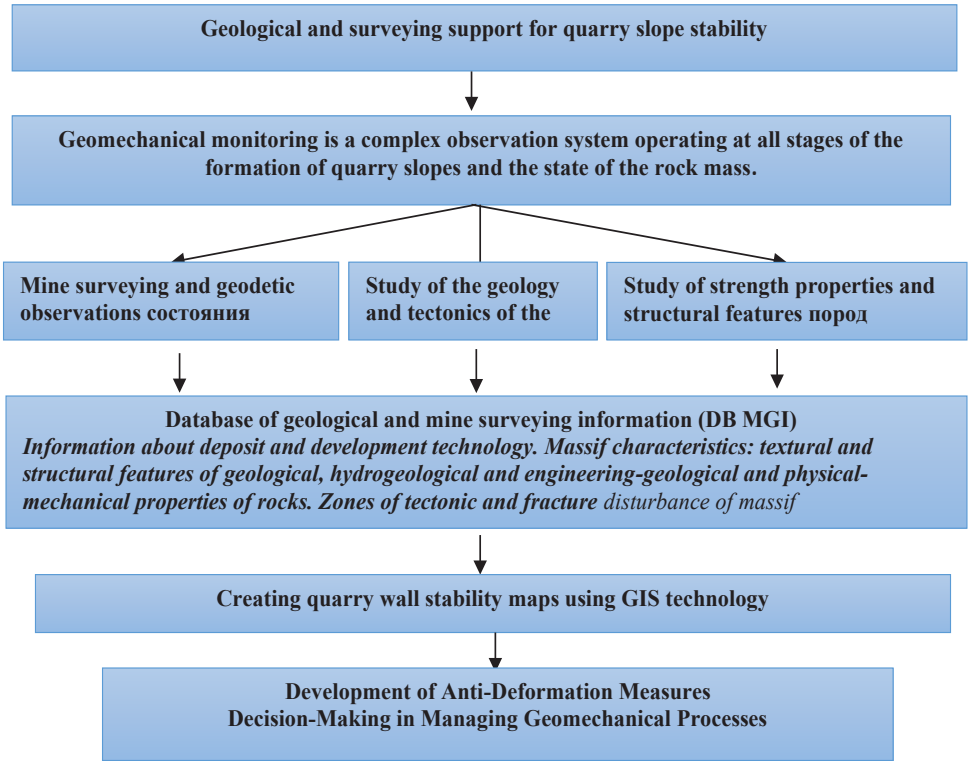


Fig. 2 - Methods of observing stability of quarry sides

Currently, open-pit mining of mineral deposits is marked by integration of new technological advancements in mineral extraction, which leads to intensification of mining operations. In this context, reliable implementation of geomechanical monitoring using modern high-precision geodetic equipment and software tools plays a critical role. To achieve this objective, the following tasks are planned:

1. Conduct study of mining and geological conditions at sites, identify the main factors influencing slope stability.

2. Create comprehensive methodology for monitoring state of quarry slopes using modern technologies (sensors, geophysical methods, etc.).

3. Develop mathematical models for assessing slope stability considering various mining and geological conditions and influencing factors.

Analysis of methods for instrumental observation of quarry slope conditions reveals need for further enhancement through use of modern geodetic technologies, including laser scanning, electronic tacheometry, photogrammetry, global satellite systems, advanced information technologies, and radar interferometry.

Discussion. The widespread adoption of electronic tacheometers and satellite GPS devices (Fig. 3) in mine surveying and geodetic work offers a unique opportunity to rapidly and accurately determine rock mass displacement parameters. This technology also enables regular, continuous monitoring of changes in these parameters over time (Aitkazinova, et al., 2020).

Fig.3 - GPS observations at the quarry

Among modern methods of mine surveying observations, laser scanning has become widely adopted, with two key types: terrestrial laser scanning and airborne scanning. Laser scanning enables creation of digital model of surrounding environment, represented as collection of points with spatial coordinates. For deformation monitoring, use of architectural scanner such as the Leica HDS3000, which offers a scanning accuracy of 6 mm, is recommended. To study structure, the

Leica HDS4400 mining scanner, known for its high performance and specialized software for analyzing bedding elements, is preferred. To enhance observation efficiency, GPS systems and 3D scanners can be used in combination (Nurpeissova, et al., 2023).

In addition to laser scanning at the Vostochny quarry, survey was conducted using MATRICE 300 RTK UAV, which is built on advanced hardware and software platform and equipped with a wide range of AI-powered functions. Survey results were used to create 3D model of the Vostochny quarry, which will be utilized for designing observation station (Fig. 4).

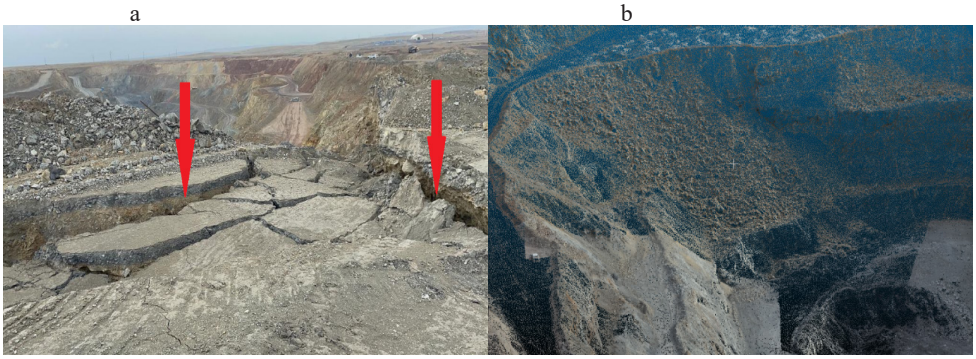


Fig. 4- Landslides on the Eastern (a) and Southern (b) Slopes of the Aktogay Quarry

In parallel with instrumental observations, calculations are performed to create a three-dimensional model of quarry, assess stability, draw horizons, and develop a situational plan. Quarry stability map is generated using the 'Bort' software package, which supports 3D object modeling and allows for graphical representation of interpolation results (Author, 2025).

To calculate slopes stability , fan of sections with constant rotational angle relative to each other is used, ensuring uniform representation across entire quarry. Sections are marked across slope extension wherever possible. Sections selected for calculation in the 'Bort' software package are shown in Fig. 5.

For each section, azimuth of the section's direction relative to quarry floor and the overall slope angle in corresponding section are indicated as a fraction. These sections were then sequentially loaded into the software package for processing.

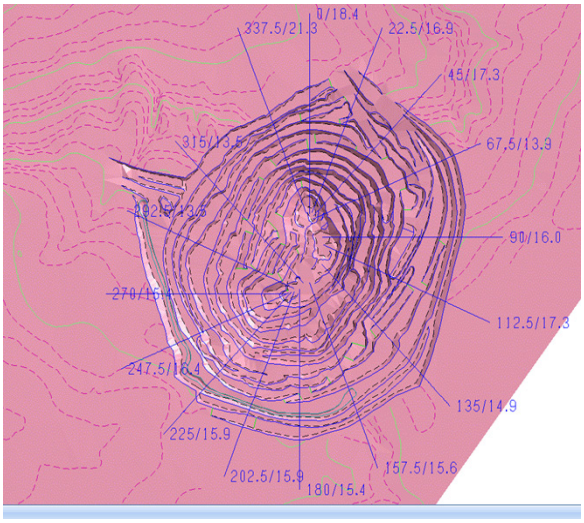


Fig.5 - Calculated sections for constructing a stability map

During calculations, results from studies on physical and mechanical properties (PMP) of rocks and ore from the Aktogay quarry, presented in Tables 1 and 2, were used, accounting for structural weakening of massif (Amanzholuly, et al., 2024; Rysbekov, et al., 2022).

Table 1 – Calculation parameters for assessing the stability of the quarry side

Types of rocks and ores	Density γ 10-3, kgf/m^3	Angle of internal friction φ, degree	Adhesion in the sample C, MPa	Adhesion on weakening surfaces k', tf/m^2	Structural weakening coefficient λ	Adhesion in the array C_M, kgf/cm^2
Massive limestones	2,81	36°	16	7	0,0409	7,209
Porphyrites	2,78	37°	22	7	0,0276	6,757
Ore	4,73	37°	22	7	0,0276	6,757
Weighted average calculation parameters	3,44	36,7°				6,91

For each section, the calculation results were displayed in graphical and text form. The final information on the calculated sections is summarized in Table 2.

Table 2 – Summary of calculation of quarry wall section stability

№	Position of the calculated section and its azimuth	General angle of inclination of the quarry side in section	Line of displacement with minimum safety factor		Minimum coefficient of stability margin
			from the mountains, m	to the mountains, m	
1	N; 0°	18,4°	+ 70	+ 131	1,686
2	NE; 22,5°	16,9°	+ 42	+ 145	2,179
3	NE; 45°	17,3°	+ 70	+ 88	1,940
4	NE; 67,5°	13,9°	+ 71	+ 87	2,353

5	E; 90°	16,0°	+ 59	+ 116	1,501
6	SE;1 12,5°	17,3°	+ 59	+ 115	1,247
7	SE; 135°	14,9°	+ 59	+ 170	2,050
8	SE;157,5°	15,6°	+ 57	+ 105	1,433
9	S; 180°	15,4°	+ 58	+ 90	2,166
10	SE; 202,5°	15,9°	+ 100	+ 162	1,891
11	SE; 225°	15,9°	+ 85	+ 150	2,431
12	SE; 247,5°	16,4°	+ 70	+ 100	2,032
13	E; 270°	15,4°	+ 70	+ 100	2,050
14	NE; 292,5°	13,5°	+ 116	+ 145	3,003
15	NE; 315°	13,5°	+ 130	+ 160	2,781
16	NE; 337,5°	21,3°	+ 72	+ 132	1,712

Next, these sections were sequentially loaded into the BORT software package, where they were processed. The calculation results of the Bort software package for all sections of the quarry are exported to the Surpac geographic information system. The resulting combined model of the quarry with the results of calculations in the Bort software package is presented in Figure 6.

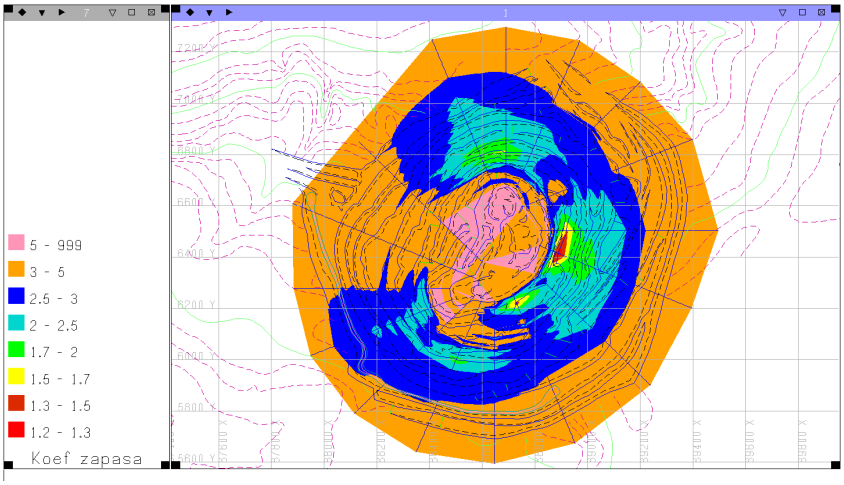


Fig.6 - Quarry stability map

Analysis of results and quarry stability map show that as of September, 2019 quarry wall was in a stable state, which is confirmed by absence of serious collapses in the real quarry. Safety factor for all calculated sections exceeds $\eta > 1.3$. Only on the south-eastern side of the quarry was minimum value obtained ($\eta = 1.24$) falls on the south-eastern side of the quarry (azimuth section 112.5°).

Development of the 'Bort' software package involved creation of several technologies for its integrated use with the Surpac GIS. These advancements facilitated both preparation of high-quality initial data for software and collaborative processing of calculation results for individual sections. Similar work has been

carried out for the quarries of JSC SSGPO, including the Sokolovsky, Kacharsky, Sarbaysky, Akzhal, and Vasilkovsky quarries. For each quarry, two stability maps were developed: one for current state of mining operations and another for the planned quarry contour.

As the ultimate goal of all geomechanical studies is to ensure industrial safety and prevent further collapses of quarry slope benches, we have developed method for reinforcing stationary quarry slopes. Technical novelty of this method is confirmed by a patent from the Republic of Kazakhstan (Patent, 2023; Aitkazinova, et al., 2022:112 p).

Conclusions.

1. Implementation of high-performance instrumental observation methods for assessing condition of quarry edge massifs-utilizing global satellite positioning systems, electronic tacheometers, and 3D scanners-ensures safe working conditions and uninterrupted operations at mining enterprises.

2. A method has been developed for assessing the stability of quarry sides, which makes it possible to identify deformations at an early stage based on the creation of zoning maps of edge massifs, the novelty of which is confirmed by the author's certificate of the Republic of Kazakhstan for a work of science. Developed stability maps enabled identification of potentially hazardous zones in terms of stability and provided recommendations to mitigate risk of quarry wall collapses.

3. Since the ultimate goal for all geomechanical studies is to ensure industrial safety, to prevent further collapse of quarry side benches, the authors have developed a method and composition of a strengthening solution from mining waste to increase the stability of disturbed sections of quarry benches, the novelty of which has been confirmed by the Pentent of the Republic of Kazakhstan.

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