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INTEGRATED MONITORING AND MODELING OF SLOPE STABILITY IN STRUCTURALLY COMPLEX ROCK MASS

The article focuses on the procedure for the integrated geodynamic monitoring. A new method is proposed for creating a geodynamic test site. The research used an integrated approach, including: geological engineering survey of structure and tectonics of rock mass with mapping of faulted areas and crushed rock zones; instrumental surveys using modern equipment and facilities developed by the authors for the stress–strain monitoring and analysis through modeling of structure and geometry of pitwall rock mass. The research results are introduced into production at operating mines, and into education and training at the Satbayev University.

Keywords: *mineral deposits, geology, jointing, physical and mechanical properties of rocks, stress state of rock mass, monitoring, geodynamic test sites, geodetic surveying, satellite systems, accuracy appraisal*

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Introduction

Induced seismicity is one of the severe issues of open mining of structurally complex rock masses. It only brings disastrous technical-and-economic effects, including triggered earthquakes, rock bursts and landslides but also entails fatalities, which is highlighted in the proceedings of the International Symposium on Rockbursts and Seismicity in Mines [1–3]. Control over these processes attracts heightened attention worldwide, which is proved by the increased number of publications on the topic [4–6].

Geodynamic supervision of solid mineral mining uses as a rule engineering approaches adapted to specific ground conditions. However, these approaches neglect structure of undermined strata and physical and mechanical properties of rocks, which impairs reliability of geomechanical estimation of real-life geotechnical situations [7–9]. These factors can be included in calculations through the analysis and introduction of the subsoil monitoring data.

The subject of this research are copper ore deposits of the Zhilandy group operated by the Kazakhmys Corporation in Kazakhstan. The proven copper ore reserves of the Zhezkazgan deposit are being gradually depleted, it is necessary to explore new resources to extend the life of this deposit for another 40–50 years, and to develop new deposits in the neighborhood of Zhezkazgan and Satbayev cities. Currently, conditions are created to increase mineral resources in Central Kazakhstan. These are the deposits of the Eastern and Western Saryoba, Kipshakbay, Karashoshak and Itauyz of the Zhilandy group (**Fig. 1**).

The Surveying and Geodesy Department of the Satbayev University carries out integrated research of the geodynamics of the specified area, to accurately estimate the behavior and parameters of tectonic stresses, especially in the zones of high-performance mining activities, and uses modern equipment and the monitoring facilities designed by the present authors. These activities are supported by the grant projects implemented by the authors: AP08053410 Innovative Prediction and Assessment of Rock Mass Behavior to Prevent Induced Accidents 2018–2020, AP08857097 Integrated Monitoring of Slow Ground Surface Deformations in Large-Scale Ore Mining in Central Kazakhstan 2020–2022 and AP14871828 High-Efficient Procedure of Geotechnical Monitoring of Rock Mass to Assess and Predict Deformation Processes in Mineral Mining 2023–2025.

The result of the work is the goal, concept and structure of integrated stress–strain monitoring and modeling in rock mass in Central Kazakhstan.

The ***geological and geotechnical conditions*** of the Zhilandy deposits are carefully examined. The Zhilandy field hosts 11 ore deposits with 109 proven ore bodies. The largest deposits adjoin the Taskuduk stratum. Their northeastward spread reaches 3200 m in length, their width ranges from 0.5 to 17 m, and their downdip size can be up to 1400 m. The rock mass is faulted, with many rock interfaces, and encloses mine openings of various configuration and size, which greatly complicates mining operations [10–12].

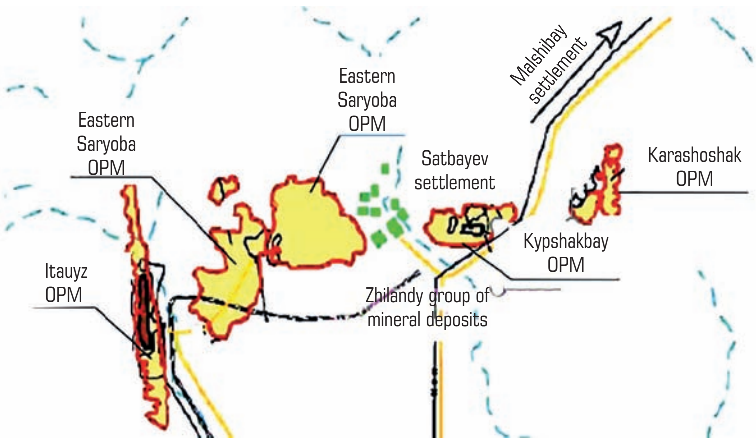

Fig. 1. Zhilandy group of mineral deposits (OPM—open pit mine)

Structural features of rock mass govern its geomechanics and geodynamics during mining. Movements of rock mass during underground mining, or slope stability of open pits are directly connected with the tectonics and structure of rock mass. Aimed at enhanced efficiency of jointing surveying, the authors used 3D Leica ScanStation scanner which allowed a detailed analysis of jointing and faulting (**Fig. 2**). The laser scanning data processing used software system Maptekl-SiteStudio with calculation of jointing parameters: trend azimuth, dip angles and sizes of rock blocks [13].

The study of the ***physical and mechanical properties*** of rock mass provided the analytical graphs of rock strength versus their occurrence depth and enabled the prompt revision of stability calculations per levels of rocks [14, 15].

a *b* *c*

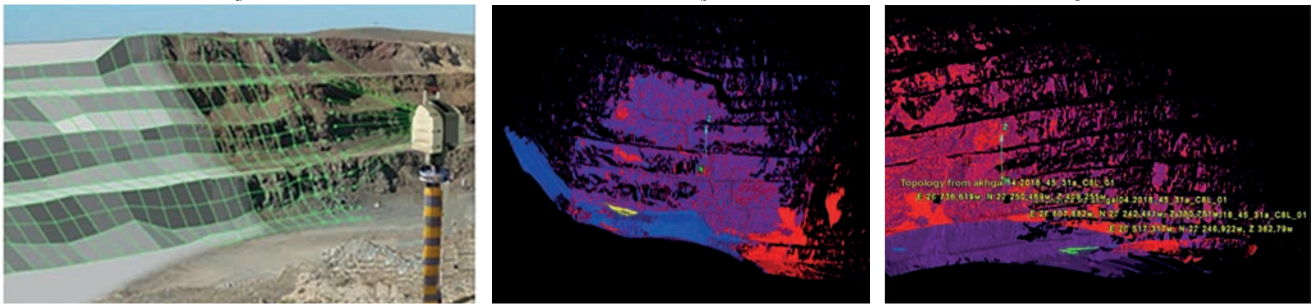

Fig. 2. Jointing surveying and results:
a – laser scanner is mounted on permanent ground bench mark; *b* – digital pitwall model; *c* – elements of jointing on computer display

a *b*

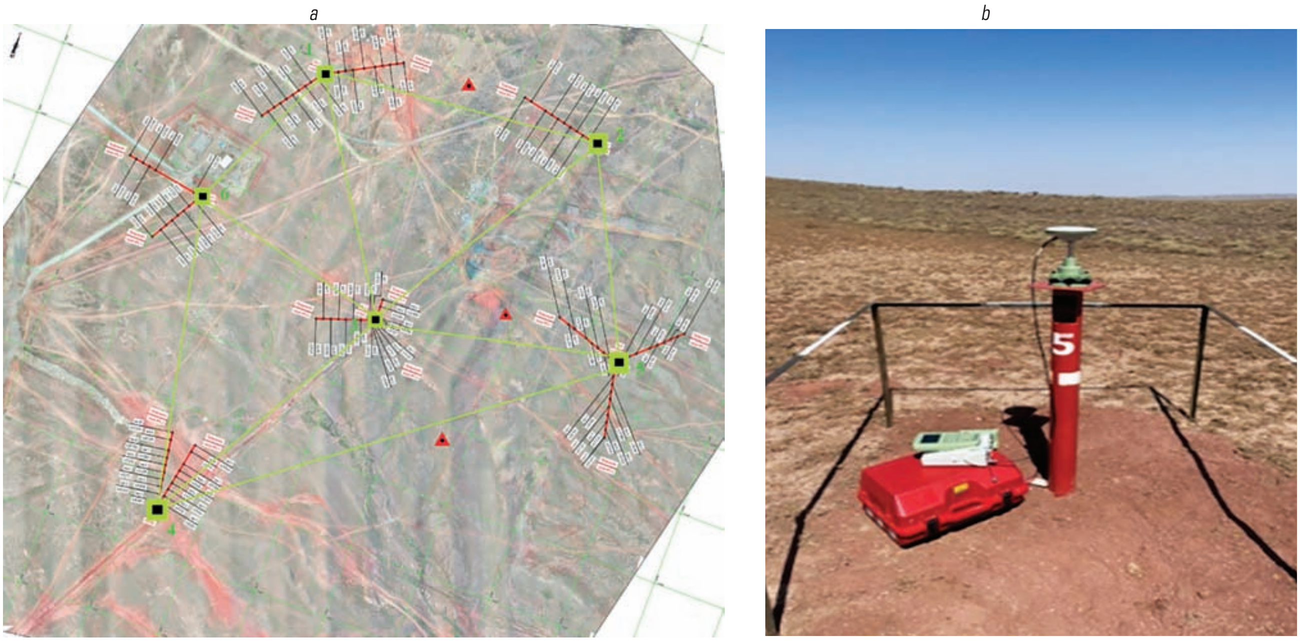

Fig. 3. Orthophotomap and layout of survey lines of geodynamic test site (green color—base points, red color—trig points) (*a*); GPS observations at permanent center adjustment points (*b*)

The research produced the quantitative and qualitative characteristics of rock properties at mineral deposits in Central Kazakhstan. These characteristics will be used in geotechnical problem solving at surface and underground mines: slope stability estimation of pitwall, design pillars and limit crowns, generalization of instrumental observations and understanding of physics of rock displacements.

The key geomechanical characteristic of rock mass is its ***stress–strain behavior*** (SSB). Many different methods are available to date for the SSB monitoring and control in rock mass. The present authors developed a seismoacoustic method for the SSB prediction in rock mass (Patent RK No. 35898) [16, 17].

Monitoring of rock mass in the course of mining of large mineral deposits comprising a number of mineral bodies at different deep levels requires creating *geodynamic test sites* (GTS). The visual inspection of the area of the Eastern Saryoba deposit and the mapping of survey lines of the local GTS involved aerosurveying using a TOPODRONE's unmanned aerial vehicle with an on-board satellite receiver. The orthophotomap is given in **Fig. 3**. For the more detailed and economic (no need to set out a survey grid covering the whole mining lease area) geodynamic investigations during mineral mining in Central Kazakhstan, with deep-seated and widely scattered ore bodies, the geomechanical school of the Satbayev University put forward and implemented a new approach to creating GTS. The survey grid contained branches with nodes representing *base points* and *displacement benchmarks* [18, 19]. Layout of all nodal points of GTS conforms with the layouts of ore lodes and with the trig points of the State Geodetic Survey (see Fig. 3*a*).

The base points of GTS are upgraded (see Fig. 3*b*). Invention of a permanent geodetic point with forced centering (PPFC) allows higher precision and enhanced operational efficiency of measurements, eliminates telescopic supports and ensures protection of the measurement facility from external impacts (rainfall, snowfall). The PPFC design is protected by the patent of the Republic of Kazakhstan (Patent RK. No. 35898. Seismoacoustic Method for SSB Prediction in Rock Mass).

The typical signs of tectonic movements show up in pitwall rock mass at the Eastern Saryoba. At this open pit mine, large sites of rock slides and rock falls form along the whole pitwall because of water saturation of clayey rock mass and due to the disagreement between the actual pitwall design and the stability standards.

Alongside with laser scanning of the Eastern Saryoba open pit mine, surveying was carried out using MATRICE 300 RTK UAV desinged with the help of an updated hardware/software platform and equipped with a wide range of functions on the basis of artificial intelligence. The surveying enabled 3D mapping of the Eastern Saryoba OPM for the purpose of an observation station design (**Fig. 4**).

Fig. 4. Landsliding on eastern (*a*) and southern (*b*) pitwall at the Eastern Saryoba

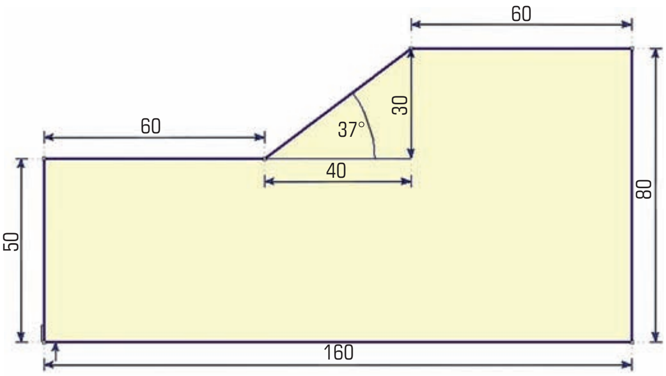

Fig. 5. Slope geometry

Modeling pitwall rock mass stability. Current geomechanical assessment of natural and manmade rock masses widely uses various specialized programs which practice numerical methods of deformable solid mechanics, for instance, the finite element method (FEM) and the boundary element method (BEM). The most efficient engineering program products are **Plaxis,** ScadStructureSlope, FLAC and Phase2.

Implementation of numerical modeling of pitwall slope stability at open pit mines of the Zhilandy, Kazakhmys Corporation selected Rocscience Phase2 program meant for the stability assessment of excavations and manmade bodies in surface and underground mineral mining. Phase2 enables modeling geomechanical and hydrogeological processes in rock mass, and determining factors of safety of slopes [20]. Verification of this program product through the comparison of modeling results with the main stress–strain patterns in rock masses, with the geomechanical principles and with the empirical data on landslides in civil engineering practice yields accurate and reliable results.

Applicability of failure criteria in geomechanical evaluations in Phase 2 was tested via numerical modeling of stability of a uniform slope. The elevation view of the slope is shown in **Fig. 5**.

Geometry is of key importance in the slope stability analysis. For the test open pit mines, factors of safety (FoS) were calculated at different angles (from 30 to 70°) and heights (from 15 to 40 m) of slopes with regard to structural features of rock mass.

The slope stability analysis using the Drucker–Prager criterion involves cohesion and internal friction angle in the form of the integral parameters q and k. The results of the stability estimation at different geometrical parameters of the slope in **Fig. 6** show that the slope is stable at the height $H \le 20$ m in a wide range of the slope angle $\alpha = 30\ldots70°$.

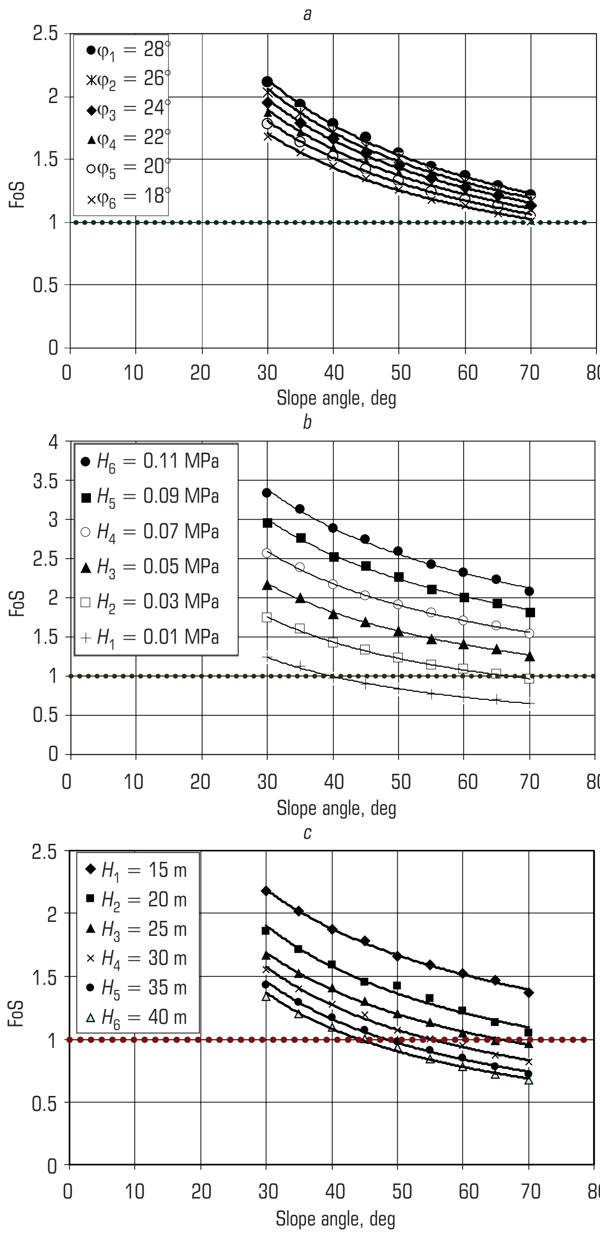

Fig. 6. Relationship of FoS with internal friction angle φ(*a*), tension strength σ_t (*b*) and geometry (Mohr–Coulomb criterion) (*c*)

Factor of safety as function of geometry of slope

Slope height H, m	FoS versus slope angle, deg								
	30	35	40	45	50	55	60	65	70
15	[1]2.18 [2]2.09 [3]1.96	2.02 1.81 1.82	1.87 1.59 1.67	1.78 1.52 1.61	1.66 1.31 1.52	1.59 1.23 1.44	1.52 1.17 1.37	1.47 1.01 1.33	1.37 0.90 1.23
20	1.86 1.86 1.66	1.71 1.66 1.54	1.59 1.48 1.44	1.45 1.34 1.33	1.42 1.19 1.25	1.32 1.08 1.19	1.22 0.96 1.13	1.13 0.90 1.06	1.05 0.83 1.00
25	1.67 1.69 1.47	1.52 1.53 1.39	1.41 1.39 1.27	1.30 1.19 1.19	1.20 1.08 1.11	1.13 0.96 1.04	1.05 0.90 0.98	0.99 0.84 0.92	0.96 0.71 0.88
30	1.55 1.51 1.42	1.40 1.42 1.28	1.28 1.25 1.17	1.19 1.12 1.08	1.07 1.01 1.00	1.00 0.93 0.94	0.95 0.88 0.88	0.87 0.81 0.82	0.82 0.67 0.79
35	1.43 1.46 1.31	1.29 1.35 1.20	1.17 1.21 1.07	1.07 1.08 1.00	0.98 0.97 0.94	0.91 0.88 0.87	0.85 0.78 0.82	0.78 0.72 0.76	0.72 0.62 0.74
40	1.34 1.45 1.23	1.20 1.28 1.13	1.09 1.14 1.04	1.00 1.01 0.94	0.93 0.90 0.88	0.84 0.81 0.82	0.78 0.73 0.77	0.72 0.66 0.74	0.67 0.58 0.67

**Comment*: Failure criteria [1]Mohr–Coulomb, [2]Hoek–Brown, [3]Drucker–Prager

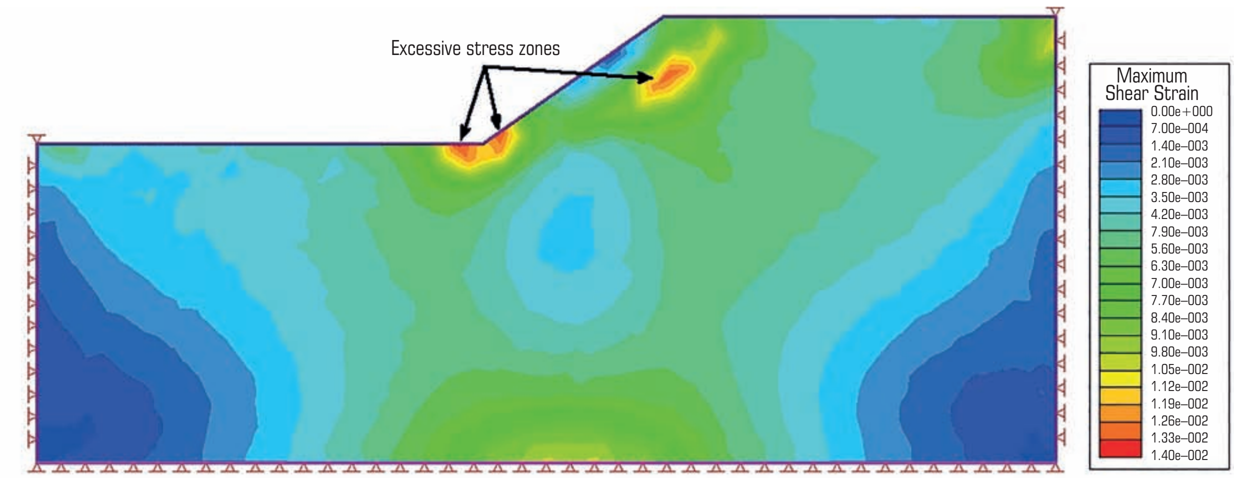

Fig. 7. Critical stress zones on slope

The analysis of the Drucker–Prager modeling allows a conclusion that a uniform slope with the above characteristics keeps stability at the height $H \leq 20$ m, slope angle $\alpha = 30\ldots70°$, loam cohesion $C = 0.04$ MПa, internal friction angle $\varphi = 18\ldots28°$ and uniaxial tension strength $\sigma_t \geq 0.04$ MPa. At the given geometry and strength of loam, the internal friction angle has no effect on the slope stability (Patent RK. No. 35798 Ground-Based Permanent Geodetic Point for Forced Centering of Instruments) [20].

Evaluation of the effect exerted by the internal friction angle φ on slope stability assumes that $H = 20$ m, the range of the slope angle $\alpha = 30\ldots70°$ and the loam cohesion $C = 0.04$ MPa. It follows from the FoS—φ relationship in **Fig. 6*a*** that the internal friction angle in the range of $\varphi = 18\ldots28°$, at the selected geometry and modeling conditions, has no influence on the slope stability.

At the slope height $H = 20$ m and slope angles $\alpha = 30\ldots70°$, the factor of slope safety is calculated as a function of the uniform tension strength σ_t. It is seen in **Fig. 6*b*** that slope is surely stable when $\sigma_t \geq 0.04$ MPa.

The Mohr–Coulomb criterion, according to the analytical results in **Fig. 6*c***, is advised as a priority for the numerical modeling of pitwall slopes composed of soft rocks. The FoS–geometry curves in **Fig. 6*c*** resemble the analytical results on FoS by the criteria of Hoek–Brown and Drucker–Prager.

The analysis of influence of the geometrical, physical and mechanical characteristics of rocks on the stability of rock mass revealed some specifics of rock movements. The slide curve follows a circular cylindrical surface. Depending on the slope geometry, the slide curve opens up on the slope surface at different distances from its upper and lower edges. For instance, on flatter slopes ($\alpha = 30\ldots45°$), the egress point of the slide curve is at a distance of 18.0 ± 2.5 m from the upper edge and at a distance of -3.0 ± 1.8 m from the lower edge; as the slope angle increases ($\alpha = 50\ldots70°$), the egress point of the slide line is spaced from the upper edge at 12.0 ± 2.1 m and is nearly at the lower edge at the slope bottom (**Table**).

A feature of the displacement mechanism in rock mass is the formation of critical stress zones on slopes, which initiates maximal deformations and a slide surface (**Fig. 7**).

Three such zones are identified and, as the multiple modeling shows, these zones are observed irrespective of variation in geometrical or mechanical characteristics of rock mass.

The major critical zone appears at the bottom of the slope, at a distance of 3.0 ± 1.5 m from its lower edge, and is 3.0–3.5 m in size. The other deformation zone, similar in size and in stress intensity, arises at the slope bottom, at a distance of 3.2 ± 0.8 m from the lower edge. The third zone forms deep in rock mass, at a distance of 10.0 ± 2.0 m beneath the lower edge, and is connected with the initiation of shearing processes.

The increase of the stresses in adjacent rock mass of slopes, because of the natural factors and external induced effects, conditions formation of a slide surface for landsliding. The slide line envelopes the three zones of critical stresses [21]. The maximum shear strains in these areas reach $\varepsilon_{max} = 1.4 \cdot 10^{-4}$, which is 2 times higher than in the rest slope-adjacent rock mass.

The final goal of any geomechanical research is safety; with that end in view, the authors developed a method of reinforcement of stationary pitwall slopes. The novelty of the method is proved by the patent of the Republic of Kazakhstan (Patent RK. No. 8408. Method for Strengthening Stationary Quarry Slopes).

Conclusions

The integrated monitoring of the ore deposits within the Zhilandy group in Central Kazakhstan has resulted in commercialization of some R&D outputs listed below:

—geospatial data base on ore deposits of Central Kazakhstan, studies of physical and mechanical properties and stress–strain behavior of rock mass at lower mining levels toward 3D modeling of geological objects with regard to variation in these characteristics of rocks in the course of mineral mining;

—clustered geodynamic test site for the regional purposes;

—permanent geodetic point with forced centering (PPFC) enhances precision and efficiency of observations;

—composition of reinforcement solution made of mining waste toward improved stability of damaged rock areas of pitwall slopes.

The novelty of the R&D outputs is proved by the patents of inventions of the Republic of Kazakhstan.

The stress state analysis of uniform rock mass using different failure criteria allows drawing a conclusion that the decrease in the geomechanical stability of a uniform slope composed of soft overburden rock down to the factor of safety of 1.05 … 1.15 results in formation of the excessive stress zones and, then, a slide surface which envelopes these zones. Identification of the excessive stress zones can help predict landslide-hazardous areas in open pit mines.

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