Analysis of the Geomechanical Conditions at the Kalmakir Porphyry Copper Ore Deposit (Uzbekistan)

E N Esina¹, A E Kirkov², A I Doskalov¹

¹Peoples’ Friendship University of Russia, Russia, 117198, Moscow, 6 Miklukho-Maklaya str.
²Institute of Complex Exploitation of Mineral Resources of RAS, Russia, 111020, Moscow, 4 Kryukovsky tupik

E-mail: esina555@list.ru

Abstract. The parameters of the open-pit mining of the Almalyk deposit of porphyry copper ores of the Kalmakir open-cast are analyzed. Three-dimensional model of the quarry is constructed by means of modern geoinformation modeling method. Basic factors affecting the deformation processes of the rock mass are identified. The zones of potential deformations of the quarry-sides with the depth increase are determined, recommendations for effective deformation processes monitoring to provide safe mining operation process are developed

1. Introduction
One of the basic challenges at mineral deposits development by the open method is to ensure mining operations safety and increase efficiency of the development of the field's reserves. A depth increase in the open-pit mining makes it necessary to broaden the sides of the open-cast and increase the overburden volume [1-3]. Another option for deep horizons engaging in the quarry development without significant increase in the cost of mineral extraction is to change the initial design solutions and increase the inclination angle of the quarry side. At the same time, to ensure the open-cast side stability, a geomechanical validation of the rational parameters of the newly designed ledges at deep horizons is mandatory.

The principal condition necessary for the revision of the initial field development projects is the analysis of the geomechanical state of the rock mass, including the parameters of the stress-strain state, the physical and mechanical properties of ores and host rocks, as well as geologic and structure features of the deposit.

2. Succinct engineering-geologic and hydrogeologic information on the research object
The Kalmakir mine is one of the ten largest copper mining enterprises in the world. On its basis, a copper processing plant and a copper smelter were created. The key industrial value of the ores of this deposit is copper, molybdenum, precious metals, as well as sulfur, selenium, tellurium, rhenium. Kalmakir is a unique deposit and is strategically valuable for the Republic of Uzbekistan [4-9].

The Almalyk copper-porphyry deposit is located in the South-Eastern part of the Tashkent region. The industrial center is the city of Almalyk, which is 65 km away from Tashkent. The history of the field development begins in 1954. The originary project was developed by the Giproruda Institute with application of an open development system. The Giprotsvetmet Institute in 1960 upgraded design
solutions based on updated geological exploration data. The climate of the district is severely continental, maximum temperatures in summer are +35–40°C, in winter temperature drops to −25°C.

The Kalmakir deposit is being worked out as an open-cast, the development transport system with external dump formation (Figure 1) is design-implemented. The location of the deposit in the mountainous part demanded the use of special overburden removal method. The upper section up to the level of +680 m was opened by single semi-trenches, which were subsequently grouped and brought to railway stations, which are located at different elevations. Ledges above the +780 m horizon are being developed with loading to autotruck transportation of rocks and removal to a separate overburden dump located on the Eastern side of the open-cast.

![Image](image.jpg)

Figure 1. Satellite image of the Kalmakir open-cast.

The quarry in total has a pear-shaped form with a thickening in Eastern direction. The sections above the mark +680 m have an L-shaped form, and below this mark – a U-shaped form.

Currently, 24 ledges have been cut at the open-cast, including 16 operational and 8 non-operational ones. The operational ledges height is 15.0–22.5 m. The minimum width of the operational platforms is 40–60 m, and the length of the excavation operational front on the upper horizons is 80–100 m, and 60–80 m on the lower ones.

Currently, the quarry is deepening by 8–11 m per year, and the value of advancing the operational front is 100–120 m. The average rail line distance is 13.7 km to the ore and 6.2 km to the overburden.

The productivity of the ore quarry (according to the project engineering documentation) is equal to 32 million m³ per year. The open-cast is divided into 3 sections: Central, Eastern and Overburden quarries. The essential design parameters of the Kalmakir quarry are shown in Table 1.

| Parameter                               | Value              |
|-----------------------------------------|--------------------|
| Absolute marks                          | 700–940 m          |
| Maximum depth                           | 580 m              |
| Inclination angles of the operational side | 32–38°            |
| Inclination angles of the non-operational side | 40–60°         |
| Operational ledges height               | 15.0–22.5 m        |
| Surface length of the side              | 4250 m             |
| Surface width of the side               | 2500 m             |
3. Geology and structure patterns
On the deposit territory there are more than 10 local tectonic faults, which play an important role in the development of geomechanical processes at the open-cast (Figure 2).

![Figure 2. Geological model of the fault zone.](image)

The geomechanical state of the Kalmakir open-cast is characterized by:

- strength properties. The strength properties of the rock mass determine the displacement process parameters. Strength coefficient of the host rocks by the Protodyakonov scale is more than 14;
- tectonic disruptions. The largest tectonic disruptions are revealed on the Northern Side. These include dikes that dissect ore bodies along the strike into local areas, as well as large tectonic disruptions that cause sliding when angles of incidence exceed the values of the friction angle of rocks;
- considerable thickness of loose rocks. The Eastern side of the quarry is composed of loose sediments with thickness of up to 80–100 m, represented by clays, loams, sandstones. The ledge slopes slide and collapse due to large thickness;
- weakening of the Earth's surface on the North-Western side (stratification in loose rocks, presence of cracks, cleavage shale in rocks).

4. Essential factors affecting the deformation processes progress
To determine the areas exposed to deformations and to identify the origins of the deformation occurrence, an extensive analysis of the deposit' geologic and tectonic structure and hydrogeological conditions is carried out, as well as observations of deformations of the quarry sides and ledges are also performed (Figure 3).

The initial data analysis made it possible to identify basic factors affecting the deformation processes progress, namely:

- The mining conditions of the loose and hard rocks of the open-cast within the North-Western side generate the risk of the side catastrophic collapse (involving several ledges) with the movement of the collapse mass over considerable distances.
- The risk of ledges collapse with the movement of collapsed and landslide rocks on one or two horizons is considerably high both on the North-Western and on the Eastern side. Extremely collapse-affected areas are the horizons located in the boundary zone of chalk sands and the weathering crust of Paleozoic rocks.
- Landslide processes in Mesocainozoic rocks are widely developed on the Eastern side due to the waterlogging of the massif.
- In the North-Western section of the quarry, deformation processes occur in the weathering crust in
the form of the collapse of ledges composed of the weathering crust clays.

Figure 3. The Kalmakir open-cast three-dimensional model developed using QGIS 3.4.7 with GRASS 7.6.1 software.

5. A project of observing station at the quarry

To determine the stability of the position of the North-Western quarry side, an observing station is laid. This station consists of three profile lines starting outside the displacement zone and ending at the bottom of the open-cast. The general layout of the profile lines is shown in Figure 4.

Figure 4. The observing station profile lines layout.

To observe the position of the North-Western side of the open-cast, 25–30 working reference points are laid, located along three profile lines. The measurements are carried out by the Leica GS08 GNSS receiver.

The in-plane and altitude displacements along the profile lines are determined (Figures 5-10). The geomonitoring data analysis along three profile lines allow to find out that the greatest displacements along this lines occur mainly in the middle part of the side and at the bottom of the quarry [10]:
- average displacement rate ranges at 60–84 mm/month on the horizon 640;
- average displacement rate varies at 76–116 mm/month on the horizon 535;
- average displacement rate ranges at 85–141 mm/month on the horizon 475 (bottom of the open-cast).

The analysis of the dynamics of vertical and horizontal displacements rates shows their high intensity. To ensure the safe conduct of further work at the open-cast, it is necessary to perform continuous comprehensive geomechanical monitoring, which allows to quickly determine the signs preceding the occurrence of emergency situations and to take preventive measures to stabilize the geomechanical state of the mining system [11-17].

Figure 5. Altitude displacements of reference points of the profile line 1-1.

Figure 6. In-plane displacement of reference points of the profile line 1-1.

Figure 7. Altitude displacements of reference points of the profile line 2-2.

Figure 8. In-plane displacement of reference points of the profile line 2-2.

Figure 9. Altitude displacements of reference points of the profile line 3-3.

Figure 10. In-plane displacement of reference points of the profile line 3-3.
To ensure the safety and increase the efficiency of the quarry mining at deep horizons, the use of automated technologies for geomechanical monitoring of the rock massif state near the quarry space is recommended, the positive experience of using which has been accumulated at many open-casts and excavation plants.

To improve the forecast quality, the rules and mechanisms of the deformation processes development in the considered mining and geological conditions are identified in advance with an assessment of the critical values of the deformation rates of the massif in the selected most characteristic control points [18-20]. The probability of side collapse is determined by the dynamics of changes in the displacement rates of representative elements of the massif. The onset of critical deformation rates is a criterion for the collapse to be predicted.

The prompt data acquisition over significant area of the section surface allows to assess the probability of the development of critical displacement rates of the near-side massif in real time, to prognosticate the slopes collapse in software mode and to timely remove mining and transportation equipment from potentially dangerous zones, which generally ensures safety during the development of deep horizons of the quarry.

6. Conclusion
On the basis of systematization and analysis of mining and geologic conditions and mining engineering parameters of the open-pit mining of the Almalyk copper-porphyry ore deposit, a three-dimensional model of the open-cast is designed. The model allows to identify basic factors determining the evolution of deformation processes pattern in the rock mass. The zones of potential deformations of the sides are discovered, recommendations for the effective detection of deformation disruptions to ensure safe mining operations are developed. To procure the safe pursue of further work at the open-cast, it is recommended to organize and perform continuous comprehensive geomechanical monitoring. Monitoring allows to quickly determine the signs preceding the emergency situations occurrence and to take preventive measures for the stabilization geomechanical state of the mining system. As practice has shown, the most progressive solution is the use of automated geomonitoring systems that allow to credibly prognosticate the development of critical deformations of ledges and sides of the quarry in advance.

7. References
[1] Trubetskoy K N 2008 Handbook of Open Mining Operations (Moscow: Gornoe Buro) 428 p
[2] Reznichenko S S, Sytenkov V N, Naimova R S 2017 Organization of a complex system for monitoring the stability of the sides and ledges of deep quarries using modern geodetic equipment Rational Development of the Subsoil 2 pp 56-67
[3] Cheng Zhiguo, Zhaochong Zhang, Fengmei Chai, etc. 2017 Carboniferous porphyry Cu–Au deposits in the Almalyk orefield, Uzbekistan: the Sarycheku and Kalmakir examples International Geology Review 60(46) pp 1-20
[4] ‘Kalmakir’ mining administration https://www.agmk.uz/en/manufacturing/mining-section/606-kalmakir-mining-administration
[5] Dabizha S I, Shumskaya E N, Mikhailova A V 2010 Technology of enrichment of copper-molybdenum off-balance ores of the kalmakyr mine Gornyi Zhurnal 10 pp 31-33
[6] Ramme V Yu, Yaroshevich V V 2009 Kalmakyr quarry: formation, development, prospects Gornyi Zhurnal 1 pp 30-35
[7] Turesebekov A Kh, Vasilevsky B B, Khametburov R M, Nizamova A T, Ashirmatov D Kh 2007Rare metal minerals in the copper-porphyry and gold deposits of Kalmakyr and Muruntau Obogashchenie Rud 3 pp 29-33
[8] Makhmudov D R, Petrosov Yu E 2017 Technology of production of drilling and blasting operations in deep quarries of Uzbekistan Mining information and analytical bulletin (scientific and technical journal) 5 pp 331-336
[9] Rakhimov V R, Mingbaev D I, Murzaykin I Ya 2009 Investigation of the influence of engineering
and geological factors on the stability of the sides of the Kalmakyr quarry *Gornyi Zhurnal* 1 pp 116-118

[10] Iofis M A, Neguritsa D L, Esina E N 2020 Displacement of Rocks During the Development of the Earth's Interior (Moscow: RUDN) 287 p

[11] Basahel H, Mitri H 2017 Application of rock mass classification systems to rock slope stability assessment: A case study *Journal of Rock Mechanics and Geotechnical Engineering* 9(6) pp 993-1009

[12] Mohammadi M, Hossaini M F 2017 Modification of rock mass rating system: Interbedding of strong and weak rock layers *Journal of Rock Mechanics and Geotechnical Engineering* 9(6) pp 1165–1170

[13] Makarov A B, Livinsky I S, Spirin V I, Pavlovich A A 2018 Comparison of limit equilibrium and finite element methods to slope stability estimation *Geomechanics and Geodynamics of Rock Masses* 2 pp 845-850

[14] Memon Y 2018 A comparison between limit equilibrium and finite element methods for slope stability analysis *Slope Stability Analysis* pp 1-17

[15] Bishop A W 1955 The use of slip circles in stability analysis of slopes *Geotechnique* 5(1) pp 7-17

[16] Chowdhury R N 1978 Slope analysis *Development in Geotechnical Engineering* 22 pp 137-53

[17] Griffiths D V, Lane P A 1999 Slope Stability analysis by finite elements *Geotechnique* 49(3) pp 387-403

[18] Rylnikova M V, Vladimirov D Ya, Fedotenko V S, Esina E N 2018 The application of intelligent systems and technologies in surface mining of coal deposits with high overburden benches *Gornyi Zhurnal* 1 pp 32-36

[19] Klebanov D A, Makeev M A 2012 Robotic technology mining are born in the depths of the innovative center *SKOLKOVO Mining Industry* 4 p 132

[20] Fedotenko V, Esina E 2018 Substantiation of the Technology of Efficient Transition to High Bench Stripping of Thick Coal Seams *E3S Web of Conferences* 41(01044) pp 1-7