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PATTERNS OF DEVELOPMENT OF GEOMECHANICAL PROCESSES DURING HYBRID OPEN PIT/UNDERGROUND MINERAL MINING

This article deals with the determination and analysis of patterns of geomechanical processes in hybrid open pit/underground mineral mining.

The domestic and foreign practices of mineral mining gravitate increasingly more toward the hybrid open pit/underground technologies. An illustration of such operations in Kazakhstan is the Saryoba copper–gold ore deposit which needs individual engineering solutions and reliable geomechanical justification of production with regard to the standards of subsoil protection and industrial safety.

Hybrid open pit/underground mining creates a complex geomechanical system featuring repeated loading of the same rock mass areas during open pit and underground mining operations implemented concurrently or sequentially. The problem of geomechanical assessment of rock mass in such conditions is complicated by many internal and external influences, and by variability of rock mass behavior in time and space.

Aiming at safe and efficient mining of gold ore lodes at the test deposit, the authors analyze the influence of natural and geotechnical factors on deformation processes, which enables estimating controllability of these effects on rock mass and its surroundings.

This article describes the studies accomplished by the authors in the course of the research in the framework of the Project on Integrated Monitoring of Slow Crustal Motions in Central Kazakhstan. Furthermore, the article contains the geomechanical monitoring results obtained by the authors using up-to-date survey and geodesy equipment which ensures high accuracy and efficiency of surveying.

The novelty of the research consists in evolvement of a concept about deformation mechanism in bedded rock masses and fracturing of a pillar established between the open pit and underground mine, as well as in determination of displacement patterns in rocks mass subjected to the hybrid open pit/underground method of mineral mining, which enables selecting ways of control over geomechanical processes.

Keywords: *mineral mining, rocks, geomechanical processes, monitoring, methods, patterns*
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Introduction

The mining industry in Kazakhstan is currently facing some difficulties connected with depletion of the subsoil as the best part of mineral reserves occurring in the most favorable conditions of economic geology is extracted, and the rest part (round 45%) lies at deep levels — for example, the Zhilandy group of deposits such as Saryoba, Karashoshak, Kypshakbay and others. New deposits, when introduced into operation, are incapable to fully compensate diminishing capacity of copper ore production at the listed mines since these resources have much worse quality. Therefore, toward sustainability and high efficiency of the gold mining industry, it is necessary to change from the open pit to underground mining.

The safety standards in the modern mining industry require having reliable information on the behavior of rock masses in seismically active areas. The review of the studies focused on major geomechanical problems served as a framework for the new procedures of geomonitoring, stress–strain modeling and mining and metallurgy waste utilization aimed at reduction of risk of technological disasters and at enhanced economic efficiency of mineral mining in whole.

Prediction of geomechanical processes is still a high-priority problem in all countries possessing developed mining industry. This fact was confirmed once again at the 6th Symposium on Rockburst and Seismicity in Mines held in Australia in 2005 [1]. Geomechanical control commonly attracts great attention, which is proved by the ever-growing number of publications on this topic objects [2–4].

In hybrid mining in difficult geomechanical situation, a matter of principal is the risk of flooding of underground roadways, particularly, the risk of sudden water inrush in mines, which leads to calamitous consequences. An illustrative example to that effect is water inrush happened in a roadway in Saryoba mine, Kazakhmys in 2021. This problem is topical not only in Kazakhstan. For instance, in 2006 longwall flooding took place in a mine in Hubei province in China, in 2010 — in Severnaya Mine, Severokuzbasugol and in March 2013 — in Osinniki Mine, Kuzbass in Russia, in February 2013 — in Krepenskaya Mine in Ukraine. The disasters caused a great number of fatalities. Such events are the direct consequence of alteration of geodynamic and hydrogeological regimes induced in the geological environment by large-scale mining, which is conclusively proved by scientific findings obtained in Saryoba Mine [5–7].

Furthermore, the practice of surveying lacks a common procedure of geomonitoring using up-to-date geodetic equipment. Accordingly, introduction of geodetic monitoring methods for the assessment and prediction of rock mass behavior is an urgent and challenging objective as a basis of mineral mining safety and efficiency.

The main factors assumed currently as determinants of the nature and size of ground surface and rock mass deformation are the strength and structure of rock mass, its stress–strain behavior, mining depth, mining systems, as well as dimensions and dip angles of ore bodies. Considerable contribution to the investigation of different effects on the geomechanical processes in rock mass in the course of hybrid mining was made by such scientists as K. N. Trubetskoy, A. A. Borisov, D. M. Kazikaev, Yu. A. Kashnikov, M. V. Kurlenya, M. A. Iofis, G. I. Cherny and many others.

Research procedure

Despite some isolated scientific findings, geomechanical patterns in the behavior of rock mass during hybrid mining are determined using conventional methods. Onrush of technologies in the mining industry conditions growth of mineral production, which, in its turn, calls for even more advanced technologies for the maintenance and higher safety of mining and surveying. The technical progress of the recent decade has greatly assisted surveying maintenance in open pit mining.

It is getting more clear for the mining engineers that dealing with the issues connected with rock pressure and displacements, or pit wall stability is impossible without geomechanical monitoring using up-to-date surveying methods.

The said is incidental to Saryoba Mine where the authors have investigated displacement of ground surface and underground rock masses under the influence of an undermined open pit and deep sinks. In this respect, practical application of satellite, electronic and laser equipment can be called the most epoch-making technological innovations in surveying, geodesy and in some allied industries in the 21st century.

The investigation included the lab-scale and full-scale tests, analytical calculations and processing of the results using the methods of mathematical statistics and computer-aided modeling.

Research object characteristics, operation description and results

The natural-and-technical facility of Saryoba consists of an underground mine and an open pit, a concentration plant with tailings ponds and a certain infrastructure within a geological environment folded in the system of an anticline [8, 9].

This lode deposit features first implementation of open pit mining and then transition to underground mining. Displacements in rock mass are governed by the fact that this hybrid mining is carried out by separate extraction blocks, with ore shrinkage, and with ore drawing from inter-block pillars and crown pillars.

In such hybrid mining, the hanging wall rock mass along its whole strike and thickness loses support and has to cave, which causes displacement of rocks. The problem connected with identification of influence zone of underground mining relative to ground surface is in this case assumed as the determination of slickensided surface of the pit wall when deepening the existing pit.

To this end, regarding many geotechnical problems, the calculation methods need adjustment to specific conditions, with taking into account the influence of natural and geotechnical factors, variability of rock strength in space and time, etc.

Despite numerous studies [1–9], the problem connected with prediction and management of risk of technical disasters yet remains to be solved because of complexity and wide variety of geological conditions.

The analysis of the surveying procedure adopted at the test natural-and-technical system and the survey data interpretation in correlation with the local geomechanical and hydrogeological effects exhibits the lack of efficient methods to determine ground surface subsidence (GSS), which necessitates improvement of the geodesy and surveying procedure for observation of deformations in rock mass using up-to-date electronic devices toward the higher reliability and efficiency of GSS determination for the safe subsoil use and protection of the objects being mined.

By the scale of environmental impact and, first and for most, by the level of influence of the stress–strain behavior of rock mass, the mining operations at the Saryoba deposit are attributed to the large technical impacts capable to cause severe accidents and disasters such as large landslides, local and massive rock falls in open pit mines, and overpressure zones and rock bursts initiated by disequilibrium at deep levels in underground mines [10, 11].

The largest fault is the Central Saryoba reverse fault between the East and West Saryoba sites (**Fig. 1**). This zone of crushing 300–400 m thick consists of numerous thrust shears that split the area into separate tectonic blocks. The zone is traced for more than 10 km in azimuth of 20–25°. The zone has a westward dip at the angles of 25–30°.

The southwest part of the deposit holds the second fault which is an extension of the latitudinal Kipshakpai normal fault stretched across the west of the northern branch of the Jezkazgan syncline. The fault is traced in azimuth of 230–260° and links in the southwest to the master Saryoba reverse fault.

Mining operations at Saryoba started as open pit mining in 2008 and changed to underground mining in 2016. Over this period of time, the access is gained to the mineral reserves on the levels of 300 and 500 m, and heading and actual mining are in progress.

The overlapping effect of the open pit, dumps, tailings pounds and underground mine creates complex patterns of secondary stress field. One of the aspects of this phenomenon is the isostatic vertical displacements. Accordingly, the existing scale of mining requires an in-depth study and control of the intervening processes with a view to eliminating wild disastrous geomechanical events (**Fig. 2**).

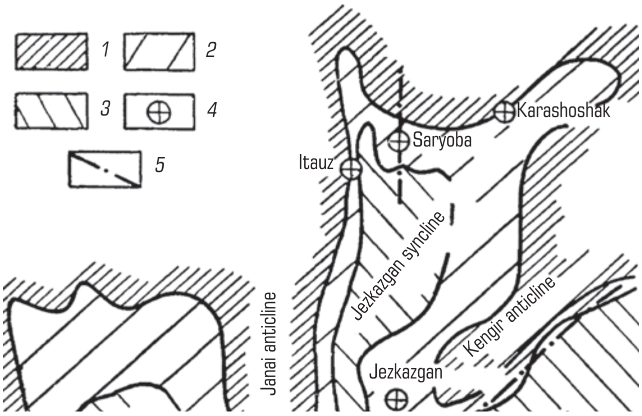

Fig. 1. Structural map of Jezkazgan copper ore province:
1 – lower-level bituminous deposits; *2* – productive Jezkazgan series; *3* – Permian deposits; *4* – cupriferous sandstone deposits and occurrences; *5* – faults

Fig. 2. Saryoba open pit mine

In such conditions, safe and efficient mining of ore lodes is only possible with the geomechanical monitoring by way of: systematic observations over time–spatial geomechanical processes induced in rock mass by mining operations; mathematical processing of observation results; comprehensive analysis and prediction of rock mass behavior; decision-making on the adverse activity control.

In 2020 on the ground of geomechanical research of geological conditions at the test deposit, design projects were developed for surface and underground observations. The projects covered the issues of creation of a geomechanical monitoring system including instrumental land surveying and geodetic measurements using an electronic tachometer and satellites of the Global Positioning System (GPS).

The wide introduction of electronic tachometers and GPS satellites into surveying and geodesy practice offers a unique opportunity to determine displacement parameters in rock masses fast and more accurately, and to carry out continuous observation of these parameters in time.

The first observational station composed of five observation lines was laid in 2020 and embraced all ore-bearing lodes. In 2020–2023 six series of observations were accomplished using robotic electron tachometer TCA 1202 (Leica Geosistems, Switzerland). The use of the device made it possible to automate the measurement process, to eliminate the error of guidance on reflecting prisms, as well as to cut the time of field operations, while generation of an electronic data base essentially simplified office processing of measurement results [12].

The transmission accuracy of a height mark by an electronic tachometer device is governed by the exceedance error of trigonometric leveling values calculated from the formula:

$$m_h^2 = L^2 \cos^2\delta \frac{m_\delta^2}{\rho^2} + m_L^2 \sin^2\delta + 2m_v^2, \text{ mm},$$

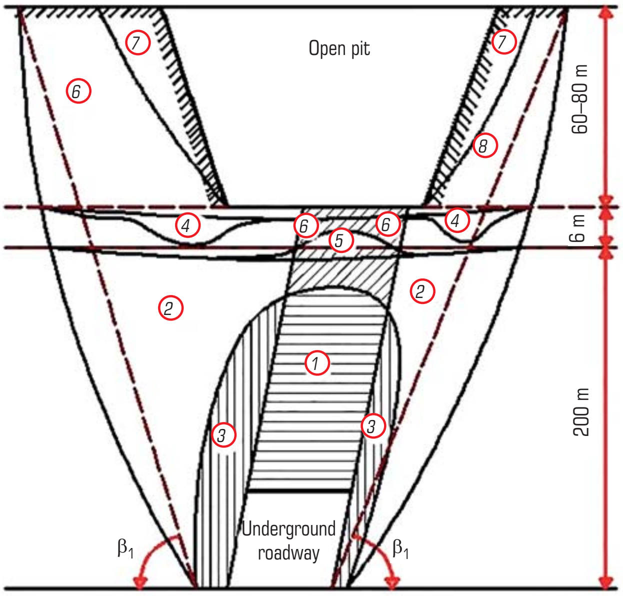

Fig. 3. Rock mass deformation chart for Saryoba deposit during hybrid mining Zones:

1 – rockfalls; *2* – smooth sag; *3* – limit stress state; *4*, *5*, *6* – compression and tension under pit bottom; *7* – landslide wedge; *8* – pit wall rock mass; *A–B* – boundary between zones 7 and 8 – slickenside surface

where m_δ, m_L and m_v are the average square errors of the vertical angle, distance and height of the tool and reflector, respectively; *L* is the shoulder length, km.

For electronic tachometer Leica TC1201, these average square errors are: $m_\delta = 1^{//}$; $m_L = 2$ mm $\pm 0.5L$ mm/km; $m_V = m_i = 1$ mm.

The pit wall rock mass was studied using the method of laser scanning. Laser scanning allows creating a digital model of the vicinity by representing it by a set of points with spatial coordinates. Deformations were examined using a scanner of the type of Leica HDS3000, and the rock mass structure analysis used scanner Leica HDS4400, having a high capacity and a special software to survey the bedding. For making observations more efficient, it is possible to use jointly the GPS systems and 3D scanners [13].

Based on the integrated geomechanical monitoring of the Saryoba deposit in 2020–2023, a rock displacement chart was drawn (**Fig. 3**). The chart includes two domains: *relaxation from stresses* and *high rock pressure*, and eight zones having inherent peculiarities.

The domain of relaxation from stresses is divided into the zones of different rock mass quality: rockfalls, through and local fractures [14, 15].

According to the given chart, the test rock mass contains eight zones with different conditions of deformation and fracturing.

Key attention is payed to the load-bearing capacity of the pit bottom (crown pillar of level 1) and sublevel pillars. The pillars are initially in the elastic state but the salt rock pillars can pass into the plastic state (or state of yielding) with the course of time, for instance, as a result of rheological processes.

The plastic state features a more than tenfold increase in the yield of the pillars at their stress state being preserved.

Rockfalls in the roof of the underground roadways (the layer under the open pit bottom) occur when the compressive and tensile strengths of rocks are exceeded, and the rock mass is split into blocks by a system of cracks as a result. The mechanism of induced fracturing of rock mass is depicted in **Fig. 4**.

As a result of sagging, tensile stresses appear in the layer and, at a certain value of the span, they reach the tensile strength limit of rocks, and cross fractures appear on the top and bottom surfaces of the layer. The further increase in the span leads to the increase in the tensile stresses and to the fracture propagation [16–19].

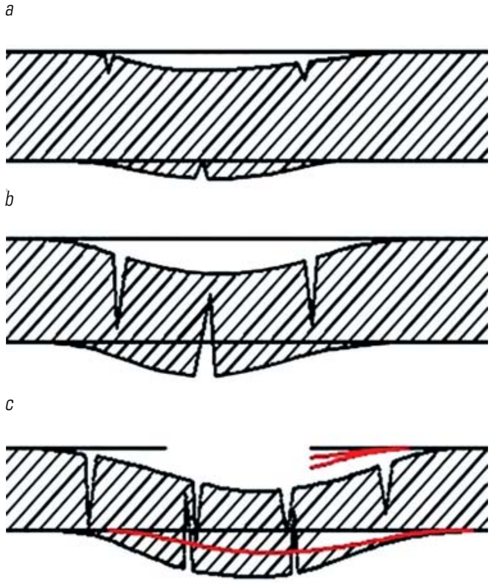

Fig. 4. Chart of fracturing under open pit bottom during its undermining:
a – initiation of cracks in bending layer; *b* – opening of cracks; *c* – fracture with alternating deformations

The analysis of the undermined rock mass behavior had two courses. First, the authors estimated the risk of vertical fracturing in the impermeable stratum as such fractures could be conductors of water to the mined-out space in the mine.

Second, the researchers considered potential formation of weak zones induced by mining in the upper portion of the cross-section, which was hazardous for the facilities and engineering infrastructure on ground surface.

The subsequent mathematical modeling of geomechanical processes aimed to determine the distribution patterns of displacements, strains and stresses in rock mass, in the zone of cross-effect of the open pit and underground mining operations [20, 21].

The source data were the topology of roadways in the East Saryoba ore site (open pit and underground mine). For another thing, the influence of tectonic faults on the internal dumps in the pit and on the underground roadways was investigated. In the north of a haulage passage between profile lines 10 and 18, a tectonic fault occurs. The influence of the fault on the underground mining operations was modeled and calculated. The rock pressure computation used Canadian RocScience Examine2D software and the following parameters: Poisson's ratio 0.2; Young's modulus of 90.1–94.76; density of 2.7 t/m^3. The software neglects the weight of a dump, and the pressure applied by the dump is added manually therefore — 4 MPa.

Figures 5*a* illustrates potential influence of the fault in the neighborhood of the actual open pit mining operations on the stress–strain behavior of the enclosing rock mass.

Figure 5*b* depicts the average probability of displacements (m) in the zone of the pit, and **Fig. 6** shows the factor of safety.

The modeling results imply that rock mass in the influence zone of the open pit experiences upheaval and intensive horizontal displacements toward ore sites located beneath the open pit bottom, and the underground roadway occurs in the zones of the increased horizontal earth pressure.

Conclusions

1. Evaluation of rock mass behavior allows taking into account the features of geological structure of undermined strata and, thereby, improving the quality of the geomechanical supervision of mining operations. Geomechanical prediction makes it possible to detect the most hazardous areas subject to regular geophysical and geodetic observations and surveying aimed at location of zones of manmade damages.

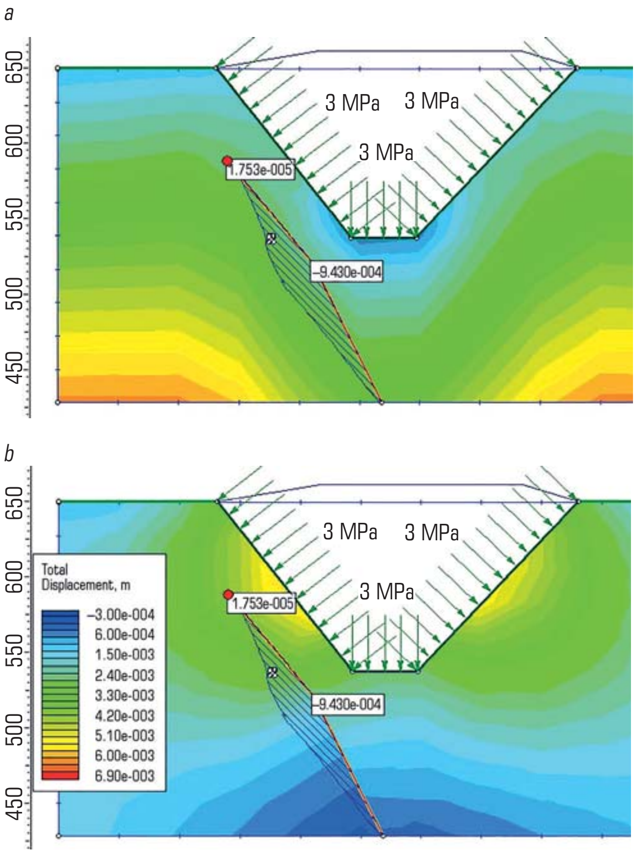

Fig. 5. Probable impact of fault on open pit (*a*) and zone of probable displacements (*b*)

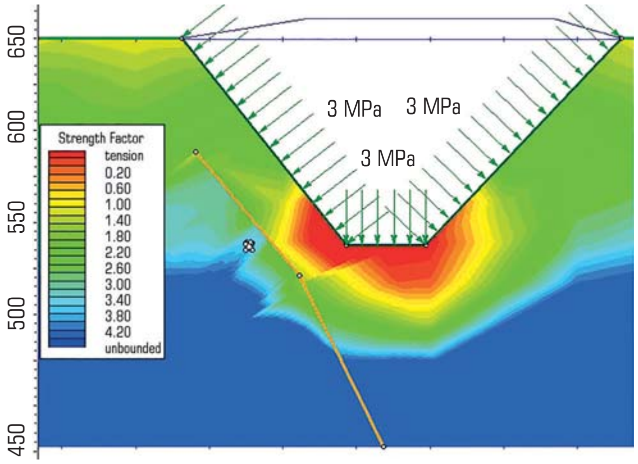

Fig. 6. Factor of safety

2\. Toward safe and efficient hybrid mining, regular geomechanical assessment is carried out in rock mass, the geomechanical prediction of the rock mass behavior is performed, and the ground control measures with reinforcement of unstable rock mass areas are developed.

3\. The hybrid open pit/underground mining induces redistribution of stresses, which leads to a higher concentration of stresses beneath the open pit bottom and the displacement of rock mass toward the mined-out void. Deformations and strains in the pit wall rock mass can change the stress state in surrounding rock mass around underground roadways, and can complicate the underground mining operations.

4\. The preliminary scientific framework is evolved for the prediction of signs of strong deformation processes at their early stages toward the assessment of abnormal geodynamic events as well as their environmental and industrial consequences.

5\. The research findings are introduced into production and education processes.

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STUDY OF GRAVITY PRETREATMENT OF REFRACTORY GOLD-BEARING ORE FROM AKTOBE DEPOSIT

Extraction of gold from refractory gold-bearing ores in processing with combined flow charts is higher if more gold is extracted by gravity methods before flotation and hydrometallurgical circuits. The article presents the results of gravity beneficiation of refractory gold-bearing ore from the Aktobe deposit with the cyanidation-recoverable gold content of 46.47%. Assessment of the gravity separation efficiency used the GRG-test which found that 35.93% of gold could be extracted in centrifugal concentration. Two flow charts of gravity concentration of ore in the grinding circuits with jigging and centrifugal concentration were tested. The studies find out that the main amount of Aktobe gold has a size less than 0.1 mm, and it is recommended to recover such gold by combining grinding and centrifugal concentration in the integrated processing circuit.

Keywords: *Aktobe deposit, gold, gold-bearing ore, recoverability by gravity*
DOI: *10.17580/em.2024.01.03*

Introduction

At present the world gold mining industry due to depletion of easily dressable mineral resources is forced to master technologies of processing of refractory gold-bearing raw materials characterized by fine dispersion of gold in sulphide minerals, which complicates direct cyanidation of beneficiation products. Processing of refractory gold-bearing ores has a variety of technological schemes, the choice of which is influenced by many factors. The main influences are: the chemical composition of initial ore, the location and distribution of gold in ore, the properties of accessory minerals, the presence of other components that complicate beneficiation. In addition, the presence of adhesive films and coatings on the surface of gold significantly worsens the process of gold recovery.

Modern experience of refractory gold-bearing ore processing is based on the combination of gravity separation and flotation technologies with cyanidation of gold-containing concentrates.

One of the refractory gold-bearing deposits is the Aktobe deposit explored in 2017 by Mynaral Gold and Mynaral Resources, which holds 4.7 tons of gold according to the JORC system estimate, is located in the Zhambyl region of Moyinkum district and is a part of the Mynaral ore field [1].

In connection with the above-said, it is impossible to use ready-made technical solutions on enhanced gold recovery, and it is required to improve processes and high-efficiency technologies via physical and chemical treatment of mineral raw materials. Remoteness of deposits, reduction of quality of extracted materials leads to the necessity of preliminary concentration of valuable components [2].

The review of the work of gold extraction plants show that the total recovery of gold from ores in combined processing schemes is higher when more gold is separated by gravity methods before the main circuits.

This takes place because neither flotation nor cyanidation provide recovery of all forms of free gold.

So flotation fails to recover:

1. Rounded coarse gold of 0.2 mm;
2. Gold covered with films of iron and manganese hydroxides;
3. Gold covered with oxide films of copper, silver and silicate;
4. Rolled-up gold (covered with small particles of rock minerals embedded in the surface layer of gold particles during grinding).

Cyanidation misses:

1. Densely coated gold particles (dense sulphide and silicate films);
2. Coarse gold particles of 0.2 mm (which have no sufficient time to dissolve).

For gravity extraction of gold, the most common processes are sedimentation, concentration on tables, centrifugal separators, enrichment in screw and cone jet separators, as well as on sluice devices of various kinds [3–5].

Gold recoverability by gravity is estimated using the GRG-test (Gravity Recoverable Gold Test) improved by Nelson (Knelson) company in centrifugal concentrators [6–14].

This article is devoted to the study of gravity concentration of refractory gold-bearing ore of Aktobe deposit in order to develop a rational technology of its processing.