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GEODETIC MONITORING OF GROUND SURFACE MOVEMENT DURING RE-EXTRACTION OF ORE RESERVES AT THE ZHEKAZGAN DEPOSIT

Introduction

Through the whole service life of a mine, movement and deformation of ground surface remain one of the critical problems. At present the scale and rate of mining operations in the Republic of Kazakhstan are very high and induce movement of ground surface, which conditions the need of geodetic monitoring of mining areas.

Movement of ground surface and rock mass at ore deposits drastically differ from these processes in ore fields since ore bodies within the same deposit feature a large variety of shapes, sizes and geometrics of occurrence. One of such deposits is Zhezkazgan which contains both steeply and gently dipping bodies of copper ore.

Long-term mining at the Zhezkazgan deposit results in formation of very many mined-out voids, which has a significant influence on ground surface within the limits of mining areas and on engineering structures in the near vicinity. Despite many pillars left in the mine to ensure safety of mining operations, uncontrolled caving of overlying rocks is recorded recently in the mine.

The review and generalization of studies in this field of research identified the main mechanisms of rock mass movement, the factors influencing displacements of ore bodies and ground surface, as well as the main parameters of ground surface movement: boundary angles, angles of displacement, maximal values of subsidence, horizontal displacements, slopes, curvature, compression, tension, etc.

Movements in rock masses under influence of underground mining, in particular, re-extraction of mineral resources, is specific at certain ore deposits and, also, in certain areas of one and the same deposit. The growing depth of mining operations, or the changes in shapes and geometric parameters of ore bodies can induce stress redistribution in rock mass. The physical and mechanical properties of rocks, the structure of rock mass, as well as the shapes of mineral bodies and faults have a substantial influence on deformation of rock mass [1].

The conventional method of instrumental observation over movement and deformation of ground surface, though sufficiently accurate, involves much labor and time to be spent. This problem can be solved by means of development of digital geodetic monitoring using the up-to-date leveling equipment. The advanced technologies allow curtailing time of geodetic measurements, accelerating data processing and creating visual models of ground surface.

To sum up, digital geodetic monitoring of movement and deformation of ground surface in the course of mineral mining can enable well-timed prediction of critical deformations.

This study aims at integrated geodetic monitoring of movement of ground surface and rock mass at a copper ore deposit with regard to re-extraction of ore from old pillars. The results have a particular

The research aimed at the analysis of influence exerted by re-extraction of ore reserves at the Zhezkazgan deposit on the condition of ground surface. The research involved the analysis, comparison and generalization of measurement data. The research findings revealed the features of impact of re-extraction on ground surface stability, and allowed prediction of deformations and substantiation of safety measures.

Improvement of the high-precision leveling procedure with digital monitoring of ground surface displacements enables early and reliable prediction of ground surface condition under adverse effects of mining operations. Recommendations on design and deployment of geodynamic test sites in study areas can further help acquire information on rock mass and ground surface condition, and provide safety of mining thereby.

During re-extraction of mineral reserves at the Zhezkazgan deposit, the values and velocities of subsidence along the survey profiles are constant and stable, which is ensured by backfill of mined-out voids. The geodetic survey results make it possible to create 3D images of ground surface in the test areas, which, in its turn, enables comparing the series of observations.

Keywords: re-extraction, hydraulic fill, ground surface movement, profiles, geodetic monitoring, geodynamic test site, high-precision leveling

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applied significance for the mining industry, and contribute to efficient and effective management of mineral resources.

Research procedure

The research used various methods to obtain a complete picture of movement of ground surface in the zone of mining operations. The modern approaches to instrumental ground-based monitoring were discussed. A great many published materials and regulatory documents were carefully reviewed.

The analyses revealed the impact of re-extraction on ground surface movement, defined advantages and disadvantages of the existing methods, as well as justified application of integrated monitoring to solving the test problem. The geomechanical assessment of rock mass and ground surface during re-extraction of ore reserves at the Zhezkazgan deposit traced the immediate effects on local deformations [2].

The investigation of ground surface movement needs implementing a set of studies aimed at determination and control of displacements and deformations both in horizontal and vertical planes. The instrumental observations of movement of ground surface and rock mass show that the stress–strain changes induced in rock mass by underground mineral mining propagate to great distances, much greater than sizes of mined-out areas.

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The instrumental observations (surveying, geodesy, photogrammetry, airborne photography, geophysical research) and visual inspection of movements in rock mass and on ground surface are carried out using observation stations composed of benchmarks arranged on ground surface, in stopes and in permanent and development drifts, in boreholes, as well as at operating facilities and guarded structures [3].

The main parameters of movement induced in rock mass and on ground surface under the impact of underground mining are the absolute or relative magnitudes of ground surface subsidence (vertical and horizontal deformations), angles of movement, subsidence velocities and displacement durations.

In the course of long-term development of various ore deposits, it is found that sizes of mined-out voids along the strike and the depth of mining are the key determinants of movement process and its parameters. For underground mines, scattering of ore bodies, both laterally and vertically, events induced by rock pressure at depths greater than 400 m below ground surface, as well as worsening of mine ventilation are also complications for mining operations [4].

For monitoring, evaluation and prediction of condition of critical facilities, the observations of movement are organized in rock mass and on ground surface. The observations of ground surface movement and condition of protected facilities can be instrumental and sometimes visual. And both types of observations are implemented in conformity with the effective guidelines and standards [3, 5, 6].

Orderly elimination of voids, safe sequence of ore extraction from pillars, ground control and substantiated operational techniques require obligatory backfilling.

For solving problems connected with movement and deformation of ground surface, it is necessary to analyze basic displacement patterns in rock mass and on ground surface, to reveal the causes of the adverse after-effects, as well as to calculate the values of displacements and deformations of ground surface immediately above the mined-out voids and at engineering facilities arranged in the undermined area.

The analysis of geodetic survey data is an important stage of research as they are directly related with the practical geodetic backup of mineral mining. The objective of all stages of the research is the geomechanical assessment of rock mass, acquisition of geospatial data and improvement of geodetic backup of copper ore mining and production.

For revealing the weakest points in the Zhezkazgan mine field, it is recommended to carry out extraction of ore on unstable sites, with rock mass zoning with respect to the degree of hazard and to the rate of mining advance [7].

Improvement of high-precision leveling procedure with digital monitoring of ground surface movement enables well-timed and reliable prediction of rock mass behavior under adverse effects of mining operations. Guides on design and deployment of geodynamic test sites allow getting information on ground surface and rock mass condition in the areas of interest, and promote safety of mining thereby [8].

The Zhezkazgan copper ore deposit adjoins the Zhezkazgan sedimentary strata composed of alternating beds of grey and red sandstone and siltstone, with interbeds and lentils of conglomerates and hornstone. The Zhezkazgan mine field is divided into a number of sites: Pokro-South-west, Pokro-North, Akchi-Spas, Zlatoust, Annen and Kresto [9].

The main physical and mechanical properties of rocks, which govern stability of pillars and exposures and are used in design of mine systems and in stability evaluation of mined-out stopes, are: specific weight of overlying rock mass, compression and tension strengths, adhesion,



Fig. 1. Hydraulic fill of mined-out voids at safety pillar under the northern areas of the Zhezkazgan town

internal friction angle, elasticity modulus and Poisson's ratio. These properties of rocks were determined by lab-scale testing of core samples using the known procedures. The properties of rock mass, with regard to the weakening effect of fractures, were determined from in-site testing of rock wedges, and by means of introduction of a structural weakening coefficient found from the analysis of failure causes in pillars [10].

Old pillars become stress concentration points in the course of time, and cause rock pressure phenomena. Stress concentration increases with growing depth of mining operations. The long-term use of the room-and-pillar system of mining resulted in formation of a great volume of mined-out voids.

The setting of ore re-extraction includes: the primary mining system; stopes remained after the first mining phase; the shapes and parameters of ore sites intended for re-extraction; amount and commercial value of ore; condition of mined-out stopes [11].

The earlier theoretical studies and lab-scale tests of models made of equivalent materials found out that backfill, even to the full height of mined-out stopes, failed to provide the maximal load-bearing capacity of pillars because of the lower stiffness of backfill as compared with ore. The tangible geomechanical effect of backfill shows up only after failure of rib pillars and consists in the following:

- backfill prevents exfoliation and sloughing of walls of pillars, and as well as reduction of their area;
- backfill limits lateral deformation of pillars, creates side support for them and suspends their failure [12].

Failure of rib pillars stops after lateral deformations, when the post-limit load-bearing capacity of pillars recovers to the level of its limit value. The hydraulic fill of the pre-backfilled stopes can prevent propagation of large-area uncontrolled caving in mines. Hydraulic fill of mined-out voids ensures smoother subsidence of ground surface. Another important effect of hydraulic fill is reduction of mineable thickness. The mineable thickness reduction leads to a decrease in the intensity of displacements and deformations in rock mass and on ground surface, which, in its turn, is beneficial for the safety of engineering structures and facilities arranged on the undermined ground areas [13].

In 2002–2007, hydraulic fill was carried out on weak underground sites under the northern and southern areas of the Zhezkazgan town, which were earlier supported with rock fill (Figs. 1 and 2).

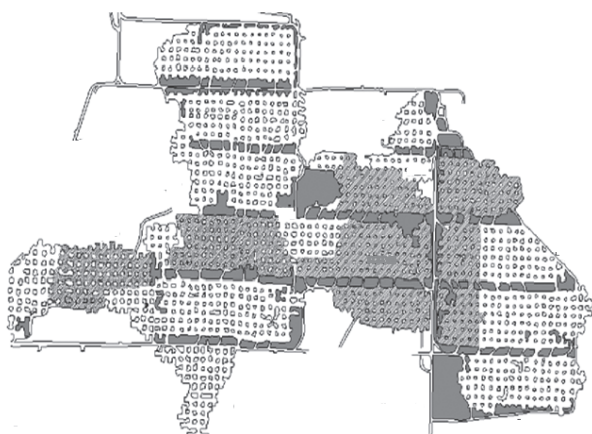


Fig. 2. Hydraulic fill of mined-out voids at safety pillar under the southern areas of the Zhezkazgan town

Backfill operations conformed with the project developed by the ZhezkazganNIPItsvetmet Institute in accord with the KazNIMI's recommendations. Hydraulic fill of mined-out voids at the Zhezkazgan deposit is made of tailings of the Satpayev Mining and Processing Plant located in the near vicinity of the operating mine fields [13].

It is worthy of mentioning that such geomechanical processes as failure of pillars, displacement of rocks, caving of overlying strata with the formation of sinkholes on ground surface, as well as bumps and induced earthquakes are intrinsic to the Zhezkazgan deposit.

Despite an individual approach with regard to specific geological conditions of each area, selection of an optimized mining system and implementation of activities aimed at stability of rock strata, re-extraction of the remaining ore reserves at the Zhezkazgan deposit is carried out in difficult geomechanical and geotechnical conditions.

The geomechanical situation in the other areas of the Zhezkazgan town is estimated as quiet. Subsidence values measured over the period of 2012–2017 are mostly within the accuracy limits and go beyond them only in some cases. Subsidence higher than accuracy of measurement is local. Such events take place mostly at the guarded boundary of the residential area, and the zones of multiple overlap of mined-out ore bodies.

In the conditions of mining at great depths, the influence exerted by re-extraction on ground surface mostly within the limits of safety standards of public utilities. In this connection, decision-making on feasibility of re-extraction should include estimation of mining impact on ground surface by the criterion of safe mining depth and, also, prediction of ground surface deformations in the mining influence zone with comparison with the admissible deformation values for public utilities on each individual site.

Instrumental observations of ground surface movement along survey profiles arranged in the Zhezkazgan and Lermontovo towns are executed annually upon requisition of an authorized governmental agency—Department of Intraindustry Supervision and Control of Energy Saving and Energy Efficiency in the Zhezkazgan Region [14].

Ground surface subsidence at the Zhezkazgan deposit is monitored by geodetic leveling using a network of profiles with a total length of 48 km (148 profile lines). The monitoring data base was collected for more than 20 years. Thus, information is complete and allows reliable



Fig. 3. High-precision leveling with DNA03

estimation of the geomechanical situation at the deposit under impact exerted by underground mining on ground surface and public utilities.

Class I leveling uses high-precision digital level DNA03 and bar-coded invar leveling staff (**Fig. 3**).

The instrumental observations consisted in leveling of reference ground points of profile lines nos. 78, 79, 80 and 81 set along the strike of ore bodies, above the overlapped mining operations, and oriented along the main streets in the center and in the south of the town [15]. Geodetic leveling of vertical movement of ground surface involves obligatory monitoring and determination of values of vertical displacements.

Unlike optical levels, digital counts are read out automatically. Digital levels use unique counting devices. With the help of special bar-coded invar leveling staff, these devices identify excess values at the wanted accuracy. Digital processing eliminates errors of reading and interpretation, which are often in optical leveling. So, instrumental observation of ground surface subsidence in the areas of the towns of Zhezkazgan and Lermontovo was implemented as geodetic leveling using a network of profile lines [16].

The scope of the research embraced the analysis of the subsidence of benchmarks in profile lines nos. 76, 77, 78, 79, 80, 81, 169, 33bis and 166 in the area of the Zhezkazgan town and in profile lines nos. 64, 195, 60 and 115 in the area of the Lermontovo town from observations over the period from 2014 to 2020 (**Fig. 4**).

In profile line no. 79, the greatest subsidence (to 21.5 mm) is demonstrated by benchmark Rp36 in 2014–2020. In profile line no. 81, the greatest subsidence (to 38.6 mm) is demonstrated by benchmark Rp6 in 2014–2020. In profile line no. 115, the greatest subsidence (to 50 mm) is demonstrated by benchmark Rp10 in 2018–2020.

The paths of the geodetic leveling in this research conform with precision classes I and II. The analysis of the instrumental observation data obtained from the profile in the towns of Zhezkazgan and Lermontovo over the period from 2014 to 2020 reveals the highest subsidence of benchmarks in profile line no. 115: up to 50 mm. This is conditioned by the fact that the area of the Lermontovo town is mostly undermined, and in the neighborhood, according to mining plans, the first and secondary mining operations are carried out at different ore bodies, and there are also zones of multiple overlap of mined-out stopes.

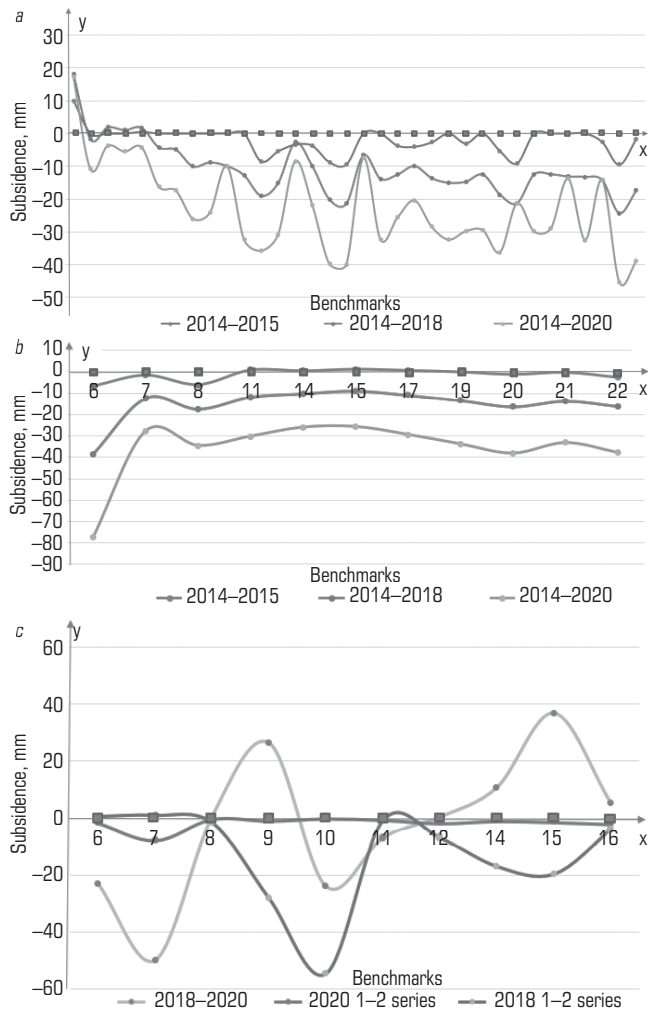


Fig. 4. Subsidence of benchmarks in profile lines nos. 79 (a), 81 (b) and 115 (c)

Based on the comparative analysis of the ground subsidence plots along all the survey profiles, the most stable benchmarks occur above the mine sites with rock backfill and hydraulic fill of mined-out stopes, and above rib pillars. Furthermore, subsidence of ground surface takes place mostly above overlapping of stoping operations on a few levels.

Discussion

The research findings demonstrate the necessity of systematic geodetic monitoring of ground surface movement to detect parameters of benchmarks in order to determine the values of ground surface subsidence. The best reliable data are only provided by integrated monitoring.

The integrated monitoring implemented on a geodynamic test site area using a network of profile lines allows determining both horizontal and vertical displacements of the control points [17]. Along with conventional observations along profile lines, the up-to-date geodetic survey equipment is commonly and widely used for detecting ground surface subsidence parameters and designing geodynamic test sites.

The long-term observations over condition of rock mass and ground surface using various methods reveal highly probable deterioration in the geomechanical behavior of rock mass, which, in its turn, can adversely affect movement of ground surface and initiate zones of possible failure.

In order to ensure safety of mining operations, it is required to reveal promptly the most hazardous zones to prevent accidents, which advises creation of a geodynamic test site in a study area.

Development of observation programs and the analysis of errors and their sources are the key points of accuracy and reliability of data in geodetic leveling and measurement along preset profile lines. The results obtained by the authors highlight the necessity of a systemic and integrated approach to monitoring and analysis of subsidence of benchmarks, particularly, in the zones of highly active tectonics and geological changes [18, 19].

Conclusions


The implemented research has shown that:

—from the geodetic monitoring of ground surface movement in the undermined areas of the Zhezkazgan and Lermontovo towns, the values of subsidence of benchmarks along survey profiles over the period from 2018 to 2020 reach 50 mm, which points at complex and potentially hazardous geomechanical situation in the test areas; —from the comparative analysis of data obtained using the ground surface subsidence plots along all profile lines, the most stable condition of benchmarks is recorded in the sites of preliminary rock backfill and hydraulic fill of mined-out stopes, and above rib pillars;

—in the complicated geomechanical conditions of mining at the Zhezkazgan deposit, the high-precision instrumental observations are to be combined with the other methods of ground surface subsidence monitoring; moreover, it is required to create a geodynamic test site using GPS technologies.

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ASSESSMENT OF DEFORMATION AND RADIATION SITUATION AT THE SEMIPALATINSK TEST SITE

Introduction

The Semipalatinsk Test Site (STS) was the test site for 456 nuclear explosions which led to significant deformation of the earth's surface and extensive radionuclide contamination of soil, water and air across large areas [1, 2]. Contaminated lands, along with adjacent areas exposed to radioactive fallout, require continuous monitoring and evaluation to determine their suitability for agricultural, industrial and other forms of economic use.

As portions of the STS are currently being analyzed with a view to commercial land use, a key priority is to carry out comprehensive research and develop measures to ensure safe implementation of economic activities in these areas [3, 4]. An illustration of such activity is development of the Karazhyra coal deposit situated within the Balapan test site, where 106 underground nuclear explosions were conducted in deep boreholes (**Fig. 1**). [5–7].

Near the Karazhyra deposit, the Atomic Lake was formed as a result of an excavation-type nuclear explosion. Geological exploration, coal extraction and subsequent transportation to consumers are currently being carried out at this site. The deposit is developed by open-pit mining, with overburden placed in external and internal waste dumps. Stripping operations disturb the upper soil layer, which contains radionuclide contaminants. During extraction and transport of coal along haul roads, dust is generated directly within the open pit area. In addition, the long-distance transportation of coal beyond the boundaries of the

The article describes the research results obtained by the authors in geodetic monitoring of ground surface deformation with zoning and cadastral valuation of contaminated land. The primary analysis of the geodetic monitoring results is performed in terms of the Balapan site, where subsidence of ground surface reaches 5–6 mm. The findings are used in impact assessment of contamination generated at the Semipalatinsk Test Site (STS), and in development of recommendations on the use of the land in terms of radiation safety. The procedure of creation of a geodynamic test site is proposed, which allows efficient tracing of changes in ground surface deformation and adjusting cadastral valuation of land depending on its contamination level.

Keywords: Semipalatinsk Test Site, Atomic Lake, Karazhyra deposit, geo-information systems, geodetic monitoring, radioecological monitoring, analysis of results, ground surface deformation, radioactive contamination maps

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test site contributes to the dispersion of radionuclides, leading to secondary contamination of adjacent area.

The relevance of this research is defined, first, by need to monitor radioactive contamination level in certain areas of the test site, including the Karazhyra deposit, where geodetic and mine surveying operations are underway, and second, by the necessity of applying obtained data to cadastral assessments both within the deposit and in adjacent area, including transport routes. These factors highlight significance of