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THE ANALYSIS OF GROUND SURFACE DISPLACEMENTS AND DEFORMATIONS IN RE-WORKING OF PILLARS ON THE BASIS OF INTEGRATED MONITORING OF ROCK MASS

In the modern mining industry, the room-and-pillar mining system, previously characterized by non-extractable pillars to ensure stability of rock mass, transforms into the methods of complete and partial extraction of ore reserves from pillars. This allows essential enhancement of mining safety and efficiency in the conditions of depletion of ore reserves, and also requires integrated monitoring of ground surface displacements and rock mass assessment above re-worked pillars. To this effect, this article analyzes mining conditions in re-working of the Zhezkazgan deposit in the Republic of Kazakhstan. For the assessment of workability of re-extraction of ore reserves from pillars, and toward ground control and mining safety, the integrated monitoring of ground surface was carried out. The article describes the visual inspection control of the room-and-pillar system components. The presented results of satellite monitoring determined the ground surface displacement parameters at the Zhaman-Aibat and Zhezkazgan deposits, including areas unequipped with survey lines. The comparison of the data of interferometric synthetic aperture radar and instrumental levelling results over the same period of time proved the accuracy of the developed technology to a few millimeters. This made a framework for a new displacement calculation procedure aimed at preserving safety of transportation routes and engineering facilities at the Zhaman-Aibat deposits.

Keywords: *pillar, room-and-pillar mining, mining system, monitoring, ground surface deformations*
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Introduction

The room-and-pillar system was considered an efficient solution for mining flat and gently dipping ore bodies of moderate thickness [1–3]. For the fruitful extraction of mineral reserves from the subsoil in the room-and-pillar mining, it is necessary to use all available technologies and to understand the stress–strain behavior of rock mass. An insufficient study in this regard may lead to high expenditures connected with room support, which makes mineral production unsafe and uneconomic [4, 5].

At flat ore deposits operated by Kazakhmys Corporation in the Karaganda Region in Kazakhstan using the room-and-pillar mining, rib pillars that separate ore bodies into extraction panels at medium and great depths weaken abutment pressure applied by overlying rock mass, which ensures safe and maximum extraction of ore reserves from rooms owing to re-distribution of loading to the rib pillars [6]. Temporary and permanent pillars, including safety and rib pillars, serve for the purpose of optimization: the former are kept until total extraction of ore reserves from the rooms and the latter ensure long-term stability of the mined-out voids [7].

The current research shows at the at the Sayak, Solikamsk, Eastern Zhezkazgan and Annenka Mines, where there are known events of failure of rib pillars and caving of roof rocks up to ground surface [6], the main conditions of room-and-pillar mining safety are the gradual advance of the mining front, stability of support pillars and the predicted caving of overlying rocks as it is impossible to support them for a long time [8, 9].

Practice shows that safety and efficiency of mining operations requires adherence to certain principles when planning and implementing stoping and caving. One of the key aspects is straightness of mining fronts and their continuous advance [10]. This enables enhanced safety and makes it possible to reduce ore losses [11] owing to the reduction of pillar sizes.

Re-working operations at the Southern Zhezkazgan Mine reveal grave difficulties connected with failure of rib pillars. The major cause of the difficulties is re-distribution of loads from mined-out pillars to the remaining pillars, which leads to the excessive loading and cascaded failure of the latter. **Figure 1** illustrates the problem. In this case, after extraction of ore reserves from 24 pillars, cascaded failure of the remaining pillars started and continued until caving of the entire stoping space. As a result, mining operations were suspended.

According to the study [12], the room-and-pillar stoping greatly alters initial stresses in rock mass, which leads to continuous dynamic changes in the fields of stresses and displacements in rock mass above the stoping front, in time and space relationship with the operations. Majority of the previous

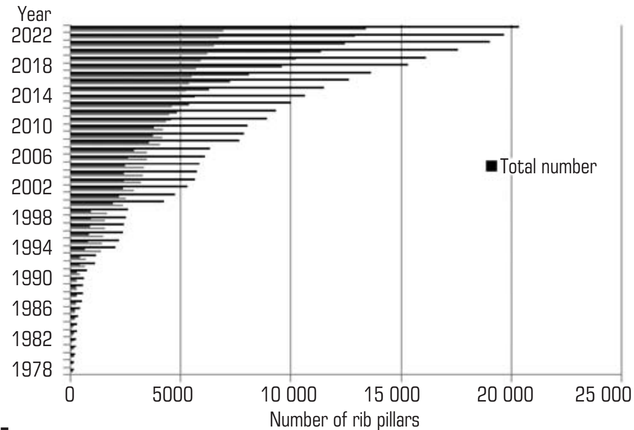

Fig. 1. Partial and total failure of rib pillars

investigations of ore and coal fields focused on flat mineral bodies of an average thickness of 5–12 m [13–15]. These investigations took into account patterns of deformation and failure of overlying rock mass because of improper parameters of stoping space, as well as sizes of rooms and pillars, which proved the importance of careful design of these parameters for the safety of underground mining operations and protection of ground surface infrastructure [12, 16]. The load-bearing capacity of a pillar is definitely connected with its dimension [17]. G. Y. Zhao et al. [18] thoroughly investigated the influence of the occurrence depth of an ore body and used the Platts theory to derive a theoretical formula of an optimized size of an ore pillar, which allowed taking into account features of phosphate rocks. X. F. Wang et al. [19] carried out numerical and physical modeling to analyze stresses and deformations in roof rocks, and supported their conclusions with the actual data on laws of failure of overlying rock mass. Similarly, S. A. Guan et al. [20] examined flat gold ore bodies using the same methods of estimating displacement and subsidence of ground surface above mined-out areas. However, cupriferous sandstone deposits, such as Zhaman-Aibat, greatly differ from phosphate and coal fields not only by morphology but also by metallogeny, structure and tectonic stresses. Moreover, softer rocks feature higher swelling, which, together with high rheology, substantially elevates probability of roof failure around pillars under the influence of mining operations and groundwater impacts. Thus, the main objective of this study is to analyze displacement and deformation of ground surface during re-working of ore pillars using the data of integrated monitoring of rock mass. Another objective is to develop a procedure to calculate displacements for the accurate prediction of safety of transportation and engineering infrastructure on ground surface.

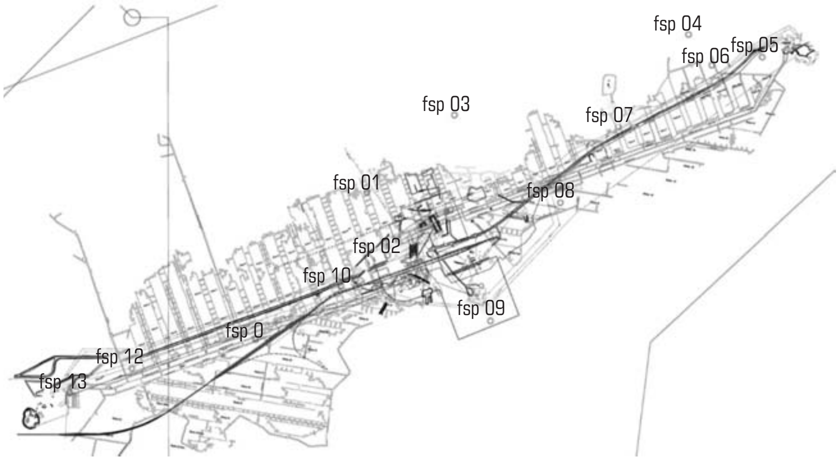

Fig. 2. Survey lines at the Zhomart Mine (fsp — field survey point)

Operating experience of the Zhezkazgan deposit shows that insufficient stability of pillars complicates repeated extraction of mineral reserves in case of large spans of mined-out voids [21]. Re-working in extraction panels was successful in stopes with small spans and risky and difficult in stopes with large spans. The major cause was the chain reaction of failure of rib pillars without rigid support. This fact emphasizes necessity of an integrated approach to the problem, including monitoring of adverse effects on underground openings and on ground infrastructure. Deficiency of the current techniques of ground control shows up in failure dynamics of support pillars (see Fig. 1). Consequently, in order to ensure safety of underground and surface infrastructure, it is required to develop an integrated monitoring approach to cover all potential risks and adversities [22].

During caving in mined-out spaces, rock pressure changes jump-wise, which activates displacements in overlying rock mass. High strength of rocks conditions both intense and sudden failure capable to provoke local seismic activity in rock mass [23, 24].

Industrial safety regulations adopted in Kazakhstan obligate the integrated monitoring of rock mass and rock pressure in order to ensure operating safety during re-working of mineral deposits [25–27].

Materials and methods

Safety and efficiency of mining requires a multi-component approach to geomechanical monitoring. The Zhomart Mine implemented a full engineering solution including three basic components described below.

Visual inspection of deformations

The Mine carries out a thorough visual inspection, on a regular basis, aimed at detection of changes in the structure of stopes. The procedure includes:

—the analysis of changes in the shape and size of cross-sections of pillars;

—the evaluation of size and configuration of roof and sidewall falls;

—the rockbolting control and detection of fractures in rocks.

Special attention is paid to the time history of the listed changes for the prompt adjustment of safety measures.

Instrumental monitoring

Every year since 2010, the mining field of the Zhomart Mine is subjected to integrated geodetic surveying along six survey lines of 156 benchmarks, which enables efficient monitoring of the subsidence trough above the mining operations and ensures prompt detection of potential deformations on ground surface. The obtained data greatly improve prediction accuracy of possible risks because of change of the earth's surface owing to the regularity of such monitoring. The layout of the survey lines is shown in **Fig. 2** [6].

Between 2010 and 2015, no subsidences were observed during extraction of reserves from rooms in extraction panels and in the course of re-working of some local areas in extraction panels 2, 4 and 5 [6].

Growing deformation of ground surface in Zhomart-1 site started in 2015 after re-working of pillars in 16 extraction panels and was accompanied by strong seismic events with the energy E = 6000–100 000 kJ, which greatly exceeded the energy of blasting using granulated explosive Granulit A-6 (E = 0.1–10 kJ). The event was recorded as an induced earthquake with a magnitude higher than 2.5 (**Table 1** and **Fig. 3**) [6].

Since 2019 subsidence dynamics of ground surface slowed down essentially to a level of a few millimeters per year. This implies stabilization of the situation connected with the suspension of re-working operations on Zhomart-1 site [6] including extraction of reserves left in the rib pillars [28–30]. The suspension facilitated deactivation of rock falls [31]. However, at the end of 2022, the re-working operations were resumed with integrated preparatory activities (heading of drilling-and-loading drifts, ore chutes under pillars) in the neighborhood of extraction panels 45–50. This can re-activate geomechanical processes and require extra measures of safety.

Satellite monitoring

A jump of the seismic activity in 2019 at the Zhomart Mine required immediate measures to ensure safety both of underground and surface infrastructure. An integrated program of geomechanical supervision of all mining operations was developed for all mines within the Zhezkazgantsvetmet Production Association. An important trend became the recommencement of investigations of ground surface displacements around the Zhomart Mine and Zhezkazgan deposit using advanced space radar monitoring techniques. The investigations included the detailed study of the area while the conventional displacement control with levelling was impossible because of the features of the terrain or due to remoteness. The details of the investigations aimed at determining key displacement parameters, including velocity and direction, are given in the study [32].

The source information for the analysis were the unique images of remote earth sounding. Emphasis was laid on interferometry and data from COSMO-SkyMed satellite system. This equipment possesses a unique ability of surveying at the intervals from one to twenty days, which drastically enhances accuracy of detecting super high velocities of subsidence—up to 1 m per year and more.

In this manner, owing to data from COSMO-SkyMed, accurate patterns and trends of vertical displacement were revealed in the area of the Zhomart Mine. The results described in **Fig. 4** and in **Tables 2** and **3** [6] offer a distinct

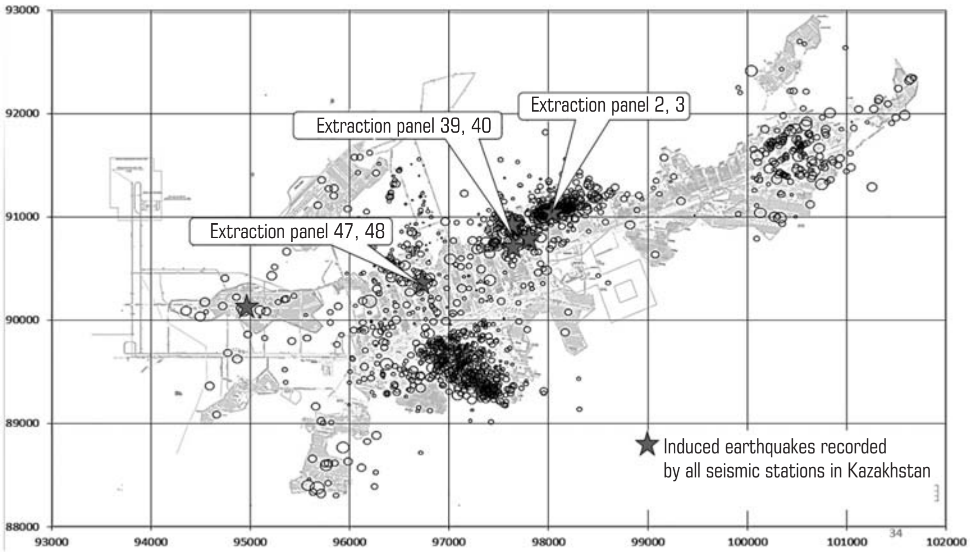

Fig. 3. Seismic events at the Zhomart Mine

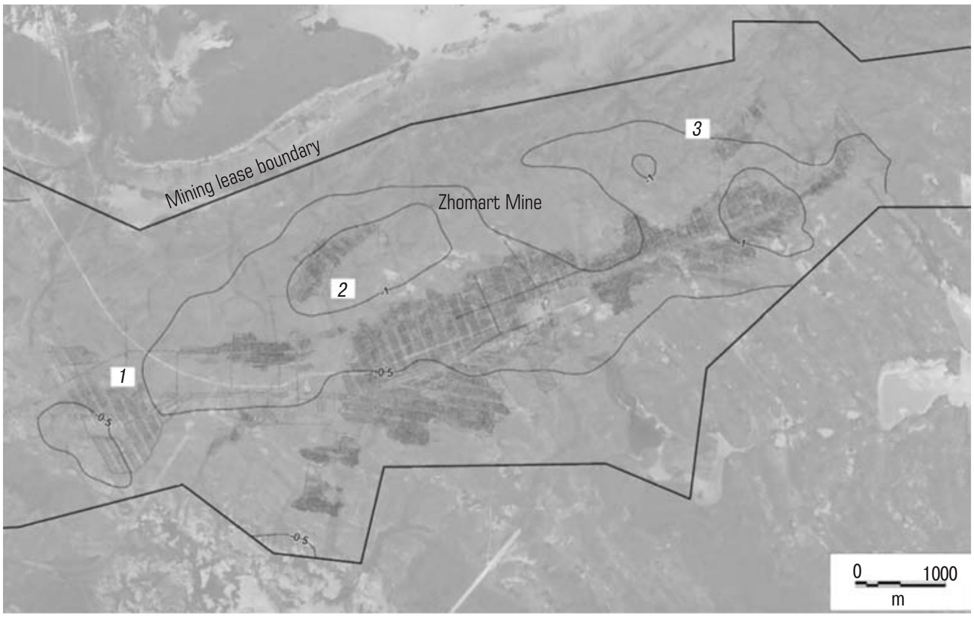

Fig. 4. Subsidence velocity map at the Zhomart Mine

distribution pattern of deformations, which enables real-time adjustment of possible accident precautions.

From the analysis of the interferometric synthetic aperture radar data of 2020 and 2021, the level of subsidence on site 2 greatly changed. The maximal subsidence recorded in 2020 was 6.7 mm while in 2021 this value dropped to 1 mm. A deeper insight of subsidence dynamics requires comparing these data with the instrumental levelling information.

The instrumental survey along line 1 fitting site 2 recorded the maximal subsidence of 7.4 mm in 2020 and 1.9 mm in 2021. The comparison of the quoted data shows that the satellite method provides more stable values in the last months of 2021 while the instrumental levelling points at more pronounced fluctuations. This may be declarative of the need to carry out an integrated monitoring including both techniques to improve completeness and accuracy of evaluation of changes on ground surface.

Calculations of ground surface displacements during re-working of pillars

For the enhanced safety of extraction of mineral reserves from pillars and for the improved accuracy of ground surface displacements during the re-working on site No. 1 of the Zhomart Mine, a specialized computational method of horizontal deformation determination method adapted to the conditions of the Zhezkazgan deposit was used [21, 33–35]. The area of the Mine is put into protection category III, which is marked on the superimposed layout showing the surface infrastructure: roads, railway tracks, power lines and communications [36] (**Fig. 5**). The re-working area colored red covers a site of 2.8 Mm, with the perimeter length of 9 Km, and the excavation thickness is 6.7–7.2 m.

Table 1. Induced earthquakes recorded at the Zhomart Mine

Date, dd.mm.yy	Magnitude	Site/ extraction panel
24.08.17	2.1	Zhomart 1/2
12.09.17	2.3	Zhomart 1/3
28.11.18	3.4	Zhomart 1/47
21.07.18	2.8	Zhomart 1/48
30.04.18	3.2	Zhomart 1/39
21.03.18	2.3	Zhomart 1/ 40
25.03.18	2.9	Zhomart 1/ 41
28.11.18	2.7	Zhomart 1/97
28.11.18	2.7	Zhomart 1/98
09.03.19	3.5	Zhomart 1/2

The equivalent values of a span of an irregular-shape mined-out space can be calculated using the mined-out void area and perimeter from the formula:

$$l_{eqv} = 3S/P, \text{ m}; \tag{1}$$

Then

$$l_{eqv} = 3 \cdot 2800000/9000 = 933.3 \text{ m}.$$

From the formula:

$$\eta_m = \frac{m}{\left[1 + \left(\frac{H}{l_{eqv}}\right)^{4,5}\right]},$$

Table 2. Maximal ground surface subsidence on site 1 of the Zhomart Mine in 2020

Observation time		Zone 1: center		Zone 2: east		Zone 3: west	
Date, dd.mm.yy	Days	Max.subs., mm	Velocity, mm/month	Max.subs., mm	Velocity, mm/month	Max.subs., mm	Velocity, mm/month
29.03.2020	0	0	0	0	0	0	0
22.04.2020	24	0.1	0.1	2.1	2.7	1.6	2
04.05.2020	36	1.6	3.8	1.0	–	2.6	2.5
16.05.2020	48	2.5	2.3	3.3	5.8	3.5	2.3
28.05.2020	60	3.5	2.5	3.6	0.8	3.5	0
09.06.2020	72	4.2	1.8	2.7	–	3.3	–
21.06.2020	84	3.1	–	3.1	1	3.5	0.5
03.07.2020	96	1.5	–	4.6	3.8	3.1	–
15.07.2020	108	2.6	2.8	3.7	–	2.3	–
27.07.2020	120	3.0	1	4.0	0.8	2.5	0.5
08.08.2020	132	3.1	0.3	5.0	2.5	3.6	2.8
20.08.2020	144	4.3	3.1	5.0	0	4.6	2.5
01.09.2020	156	3.8	–	4.9	–	3.3	–
13.09.2020	168	3.4	–	5.3	1	3.3	0
25.09.2020	180	3.5	0.3	5.1	–	2.9	–
07.10.2020	192	3.4	–-	5.8	1.8	3.1	0.5
19.10.2020	204	4.1	1.8	6.1	0.8	3.7	1.5
31.10.2020	216	4.0	–	6.4	0.8	4.1	1
12.11.2020	228	3.9	–	6.7	0.8	4.4	0.8

Table 3. Maximal ground surface subsidence on site 1 of the Zhomart Mine in 2021

Observation time		Zone 1: center		Zone 2: east		Zone 3: west	
Date, dd.mm.yy	Days	Max.subs., mm	Velocity, mm/month	Date, dd.mm.yy	Days	Max.subs., mm	Velocity, mm/month
05.04.2021	0	0	0	0	0	0	0
11.05.2021	36	0.8	0.7	0.8	0.7	1.0	0.8
23.05.2021	48	1.5	1.9	1.2	1.0	1.6	1.6
04.06.2021	60	2.3	2.0	1.1	–0.3	1.9	0.7
16.06.2021	72	2.4	0.1	1.5	1.0	2.2	0.9
28.06.2021	84	2.0	–1.0	1.8	0.8	2.5	0.5

Fig. 5. Superimposed layout of the Zhomart Mine

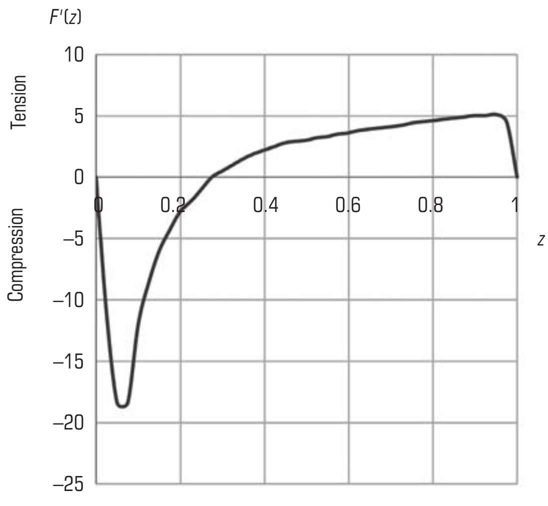

Fig. 6. Function F'(z) characterizing horizontal compressions–tensions at the Zhomart Mine

$$\eta_m = \frac{7}{\left[1+\left(\frac{600}{933.3}\right)^{4,5}\right]} = 6.157\ m, \qquad (2)$$

where m is the excavation thickness, m; H is the overlying rock thickness (depth), m; l_{eqv} is the equivalent span, m.

The horizontal compressions–tensions are found from [38]:

$$\varepsilon_x = 0{,}5 \cdot a_0 \cdot \frac{\eta_{max}}{L} \cdot F'(z)\ , \qquad (3)$$

where a_0 is the relative maximal horizontal thickness to be assumed to equal 0.3 for ore bodies overlaid with layered rock mass as is recommended by VNIMI; $F'(z)$ is the function characterizing the horizontal compressions–tensions in the conditions of the Zhezkazgan deposit (**Fig. 6**) [38]; η_{max} is the maximal value of the ground surface subsidence, m; $L = leqv/2 + H \cot \delta$ is the half-trough length, m; $\delta = 73°$ is the displacement angle [6].

The calculated values of the maximal horizontal compression and tension on the test site of the Zhomart Mine equal 26.21 mm/m and 7.26 mm/m, respectively.

According to the guideline [39], for railways with the freight traffic to 3 Mt-km annually and for the tangent suspension supports of 200–400 kV, the allowable deformations of compression and tension are limited to 7 mm/m [6]. This means that the calculations yield the values critical for the surface infrastructure at the Zhomart Mine.

For the purpose of prevention of critical ground surface deformations, it is required to ensure controllable overlying rock caving. The appropriate action plan includes:

—strict compliance of the design parameters of a mining system can help avoid excessive deformations of ground surface;

—in case of roof arching in the course of extraction of reserves from a number of rib and safety pillars, roof rock torpedoing is required. This will help induce roof caving and prevent massive spontaneous caving. This approach can reduce risk of ground surface deformations and avoid potentially hazardous consequences for people and environment;

—regular monitoring of ground surface and infrastructure can reveal problems and help decide on appropriate precautions in timely manner.

Results

Re-working of pillars in underground mineral mining requires an integrated monitoring including obligatory monitoring and evaluation of potential adverse effects on mining facilities both underground [40, 41] and on ground surface. The comparative analysis of two monitoring techniques—interferometric synthetic aperture radar (InSAR) and instrumental levelling along survey lines—yields a few conclusions. First, tiny (millimeter) differences between the two techniques can be explained by the difference in the measurement periods, errors in data processing and inaccuracy of instrumentation. These differences are usually uncritical and can be taken into account as allowable. However, InSAR possesses some advantages over the conventional levelling. In particular, InSAR allows covering a wider area, which greatly expands the application range of the technology, especially in an industrial region with a dense production infrastructure.

Furthermore, the radar surveying allows more often measurements as against the conventional levelling limited to annual observations. This enables more sensible tracing of time history of ground surface displacements and ensures prompt responding to potential problems. Thus, InSAR provides major advantages in subsidence monitoring at the enhanced accuracy and speed of data processing.

The calculations for the repeated extraction of reserves from pillars on site No. 1 of the Zhomart Mine predict critical maximal compressions and tensions for the surface infrastructure.

Discussion

The discussion of the research findings on re-extraction of ore reserves from pillars as a case-study of the Zhezkazgan deposit contains a number of key aspects which emphasize relevance of the research and its contribution to the development of mining science and practice. The research focuses on the exigence of integrated monitoring of rock mass and ground surface displacements to ensure safety and efficiency of mining. The use of advanced technologies such as interferometric synthetic aperture radar allows precise recording of changes in rock mass, which can promote efficient ground control and risk reduction in re-extraction of ore reserves from pillars. The research also demonstrates that insufficient attention to rock mass stability can lead to high expenditures connected with mine support and can create unsafe working environment. This emphasizes importance of development of new methods for the ground surface control and geomechanical stabilization, which is a relevant challenge for the mining industry.

It is worthy of mentioning that the research rests on the practical experience of re-mining operations at the Zhezkazgan deposit, which makes the results particularly valuable for application. Examples of effective and ineffective re-working depending on the conditions and methods of application accentuate the need of an individual approach to each specific case. The novelty of the research is integration of advanced monitoring, analysis and design techniques, which enhances safety and economic efficiency of re-extraction of mineral reserves from pillars.

Conclusions

In summary, the research of re-working of pillars as a case-study of the Zhezkazgan deposit emphasizes the crucial nature of integrated monitoring and ground control in mining safety and efficiency. The analysis of rock mass and ground surface displacements using advanced technologies such as interferometric synthetic aperture radar reveals critical variables of stability of mined-out areas. A key aspect of efficient re-working is application of the room-and-pillar mining method with regard to specifics of geomechanical behavior of rock mass. The need of new methods of ground control and geomechanical setting stabilization in rock mass becomes evident, especially in rock masses of high hardness and stiffness which may lead to seismic events.

The research findings show that insufficient attention to the stress–strain behavior of rock mass can result in high expenditures connected with the support of the remaining rooms and pillars, and in unsafety of working environment. Efficient extraction of mineral reserves should take into account all possible risks and adversities, which requires an integrated approach to planning and implementation of mining operations. Using the method being developed, an improved flowsheet will be proposed for extraction of mineral reserves from rooms and for re-extraction of mineral reserves from pillars in gently dipping ore bodies to ensure preservation of structures and communications on ground surface at the stage of re-working (after backfill of mined-out voids).

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