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MAINTENANCE OF UNDERGROUND MINING DEVELOPMENTS IN SEISMIC-TECTONIC ACTIVE AREAS

Abstract. In this article we consider the results of studying the conditions for the construction and maintenance of underground mine workings in regions characterized by seismic and tectonic activity. Output of mineral deposits in the Central Asia is carried out in the difficult conditions characterized by high seismic and tectonic activity of region, considerable geological infringement deposits, danger of rockbursts. Long-term practice of mining works shows, what difficulties create tectonic fields of tension at working out of a mineral deposits. Modern mathematical methods and technical computing means allow obtaining qualitatively new and multivariate solutions of problems with subsequent evaluation of the degree of their identity to real processes. The authors developed computer application programs for the quantitative evaluation of the strength of underground workings, taking into account the features of their design, piecewise inhomogeneous physical and mechanical characteristics of the surrounding rock mass for the accepted calculation schemes and numerical models.

Keywords: underground mining, seismotectonic activity, rock massif, earthquake, mine support, rockbursts.

Introduction

In the world practice of mining there is a steady tendency of a natural increase in the depth of mining of mineral deposits. Along with the desire to increase the volume of mining, strict requirements are put forward to improve the working conditions of miners, to ensure the safety of work, the use of new more efficient technologies (Gattinoni, Pizzarotti, & Scesi [12]).

The countries of Central Asia are rich in minerals, they traditionally develop the extraction of gold, uranium, oil, gas, copper, coal and a number of other types of mineral raw materials. More than 3.000 deposits of about 100 kinds of minerals have been identified in Uzbekistan, more than 1,400 deposits containing more than 70 types of mineral raw materials, including more than 50 noble deposits, more than 40 deposits of non-ferrous, rare and radioactive metals, etc., have been discovered (Abdykaparov, Imaraliyev, & Mambetov [7]; Aytmatov, & Kozhogulov [6]; Golovanov [14]; Mambetov Sh., Abdiyev, & Mambetov, A. [21]; Sanakulov [29]; Ulomov [29]).

With the development of deposits with favorable geological conditions, as well as lying at shallow depths, the depth of field development increases, mining and geological conditions become more complicated, rock pressure and water cut of the massif increase, which requires additional costs for maintaining underground workings during the required time of their operation (Ageenko, & Baklashov [3]; Brady, & Brown [7]; Wang, & Hagan [33]; Wittke [34]; Zhu, Chen, Zhao, & Niu [36]).

A special feature of the Central Asian region is the complex geodynamic situation and seismotectonic activity, which is accompanied by the action of additional stress fields in the surrounding massif, which in magnitude exceed the traditionally taken calculated stresses from the gravitational field (Ulomov [32]). Many deposits of minerals in this region are located in the territory of sites, the seismicity of which is estimated up to 7–9 points. In some earthquakes, the fields fell into a zone with the maximum intensity of seismic vibrations, which led to disturbances in the stable operation of mines, deformations and destruction of the support of mine workings, and the disabling of stationary equipment (lifting and drainage installations, main ventilation fans). To eliminate the consequences, additional funds are spent, which undoubtedly affects the cost of production, and a significant part of the damage is accounted for the restoration and repair of underground workings (Melikulov, 1993; Pletnev, Rakhimov, Tadzhibayev, Melikulov, 1983).

As is known, the period between earthquakes is characterized by the accumulation of the elastic energy of deformation of the rock mass, that is, the growth of the acting stresses. Obviously, the field of tectonic stresses, the magnitude of which varies relatively slowly (as a quasi-static process), also has a fairly tangible effect on the state of mine workings.

Particular attention from the point of view of underground mining technologies attracts stress fields that are formed under the influence of tectonic forces as a result of uneven movements and deformations of the earth's crust. Such stresses in an array of rocks caused by tectonic processes, according to experts in various mining regions of the world, can exceed 10 to 20 times the tension from the total weight of the rock column. Under the action of these forces acting in the subhorizontal plane, qualitatively new conditions arise both in studying the natural stress field and in calculating the steady state of the rocks around the workings (Kearey, Klepeis, & Vine [18]; Khloptsov, & Baklashov [20]; Markov [22]).

Relationship of seismotectonic processes and fields of stresses

One of the characteristic features of mineral deposits in the countries of Central Asia is their location in the highlands or even in high mountains. For example, the polymetallic deposit Khandiza (Uzbekistan) is located in the spurs of the Tien Shan at the level of 1300–1800 m above sea level; coal deposit Shargun – at a mark over 1550 m; mercurial deposit of Khaidarkan (Kyrgyzstan) – at the level of 1500–2350 m. The well-known railway tunnel Angren-Pap, which is the longest in Central Asia, was built in the mountains at 1320–1420 meters, the elevation points on the surface of this mountain pass reach a mark of 2,845–3,476 meters above sea level (Aytmatov, & Kozhogulov [6]; Golovanov [14]; Mambetov, Sh., Abdiyev, & Mambetov [21]; Markov [22]; Zhou, Aripov, Guo, Zang, & Melikulov [35]).

It is easy to interpret the state of the array, when in the coving zone of anticlines the effective stresses are less than in synclines. However, in some cases, on the contrary, fold locks are compression points. The same is also observed in fault zones: in some cases, the zones of decomposition do not exert a noticeable effect on the differentiation of stress fields, while in others the stress state in the zones of decomposition increases sharply. It is especially noted that the tectonic forces on the scales of long geological time vary in both magnitude and direction (Aydan [5]; Hunt, [16]; Markov [22]).

In areas covered by active new tectonic movements, the change in tectonic forces over time is of interest for the problems of rock mechanics. For example, in the Carpathians, the Caucasus and the Kurile-Kamchatka region (Russia), according to the records of strong earthquakes in 6 to 12 years, a qualitative change in the directions of the axes of stresses (Adushkin & Turuntayev [2]).

Estimation of the constant "feeding" of tectonic stresses due to modern movements and deformations of the earth's crust is based on the analysis of the following experimental data. According to the results of geodetic survey and deformometers, the rate of accumulation of tectonic deformations of 10^{-7}/ year is typical for aseismic zones, and 10^{-5}/year for high seismic zones. The magnitude of the deformation change in the case of a catastrophic earthquake was obtained on the basis of a survey near the epicenter. Deformations – forerunners of the shock in catastrophic earthquakes have a magnitude of the order of 10^{-5}. Deformations from tidal effects in the earth's crust are estimated at 10^{-8} (Markov [22]; Ohnaka [25]).

Monitoring of the conditions of underground mine and mine works

The results of long-term observations of the state of mine workings located in the zone of influence of elevated tectonic stresses are known. Survey of preparatory workings of a number of coal mines in Central Asia showed that the conditions for maintaining them are complex, despite frequent repairs. Attention is drawn to the amount of work to maintain the workings, when individual sites on average were repaired after 1–1,5 years, although there are areas on which repair mine supports were made even 2–3 times within one year. The state of the excavations fixed by a metal arch support was studied. This support for structural features should work reliably enough in a compliant mode, i.e. to provide the specified design strains without destruction. In fact, in the zone of tectonic stresses, the mounting frame is compressed by lateral loads, and the development is narrowed as a result of this action, the nodes of compliance are no longer functioning in the supporting construction. Often, the destruction or loss of load-bearing capacity of the support is preceded by the deviation of the fixing frame from the given design position, i.e. loss of stability. Moreover, the reason for the loss of stability of the fastening frame can be different: the unevenness of the load along the contour due to the anisotropy of the properties of the rock massif, the uneven distribution of the load from the rock pressure to the neighboring fixing frames, the spread of the rigidity of the fastening frames, the loads acting on the frame outside the plane of its location, dynamic loads, etc. It is only natural that the loss of stability of the mounting frame leads to a reduction in its load-carrying capacity, as a result of which such workings are deformed over time and need to be repaired (Melikulov, & Dzhangiyev [23]).

Observations have shown that the magnitude of tectonic stresses can change noticeably when passing from the mine to the mine. Even within the same mine and on the same horizon (for example, in the 600 m of the Rasvumchorrsky mine, Russia) tectonic stresses change more than twice in magnitude. Thus, against the background of the general pattern of excess of horizontal tectonic stresses over gravitational verticals, a statistically significant change in the tectonic stresses at different sites is observed (Markov [22]; Sashurin [30]).

Such factors are the reason that some of the coal mines (Shurab in Tajikistan, Sulukta and Kizilkiya in Kyrgyzstan, etc.), signs of rockbursts have a depth of about 200 m development. The case was observed in the construction of an inclined mine for the transportation of coal by a conveyor on Angrensky coal mine (Uzbekistan), when the deformation of the array curved the axis of production and made it impossible to equip it with a conveyor.

The unfavorable manifestation of tectonic processes together with the stress concentration in the massif (increased rock pressure), which resulted in the formation of a wide zone of disturbed rocks in the Kayragach gold mine (Uzbekistan), led to difficulties in the construction stage of the gallery, and subsequent frequent repairs of the site forced to abandon its further exploitation and build a new gallery around this tectonically unfavorable zone.

In connection with the technological peculiarities of the repair conditions for the damaged support or the working site in underground cramped and dangerous conditions of the threat of continuing collapses, the cost of repairing each meter of the emergency site of underground mining may even exceed the cost of constructing a meter of new gallery.

Analysis of the information basis on the seismic activity of the region

In order to quantify the impact of seismotectonic processes, extensive studies are carried out at geodynamic polygons. Experts based on long-term observations compiled a map of young and modern geological movements of the territory of Uzbekistan. At the Central Kyzylkum geodynamic range, the vertical displacement rate is from (–4) to (+2) mm per year, and in the zone of tectonic faults the displacement module reaches up to 18–22 mm per year. In the narrower part of this region in the zone of Marjanbulak earthquake on May 26, 2013 (Uzbekistan, there are several gold mines here), the displacement speed in the flat zone is up to 10 mm per year, in the foothills – up to 20–30 mm per year, in the mountains – up to 50 mm per year; as a result of this earthquake, the magnitude of stress relief is estimated at 12 MPa (Khamidov, & Shukurov [19]).

In modern geomechanics methods for assessing the influence of acting factors through the probabilities of events (Glaser [16]). Especially relevant is the probabilistic approach to the evaluation of random events scattered in space and time, such as earthquakes. In addition, earthquakes vary greatly in intensity, depth of manifestation, distance from the epicenter to the object, engineering-geological conditions of the environment, etc. (Gasanova, Salyamova, & Melikulov [11]; Hencher [15]; Ismail-Zadeh, & Tackley [17]).

For the probabilistic estimation of the effect of seismic phenomena, statistical studies of the field of events were carried out, which took the region of Central Asia and Kazakhstan, located within the parallels of 35–45 degrees North latitude and meridians 63–82 degrees East longitude. For ease of use, information on earthquakes registered in this region with a magnitude $M \geq 2.8$ based on the annual earthquake bulletins is registered as an electronic database.

The collected database covers on average more than 2800 events (earthquakes) occurring annually within this region, each of which is represented by 7 main features: date, time, geographic coordinates, depth of focus, accuracy class of the epicenter coordinates, energy class (Gasanova [9]).

Technogenic-tectonic or induced seismicity in mining operations

The induced seismicity in the mines takes place both in the areas of active modern mountaineering movements, and in the areas of old folded systems, and on platforms and shields. The average depth of the work at which seismic phenomena occur is about 600 m in areas of modern orogenesis in Central Asia (Aytmatov, & Kozhogulov [6]).

Dangerous are mining and mining-tectonic rockbursts, which in the mining industry lead to major accidents, significant material damage and human casualties. The damage from one mining rockburst reaches 100 million rubles, restoration work in a number of cases lasts for months.

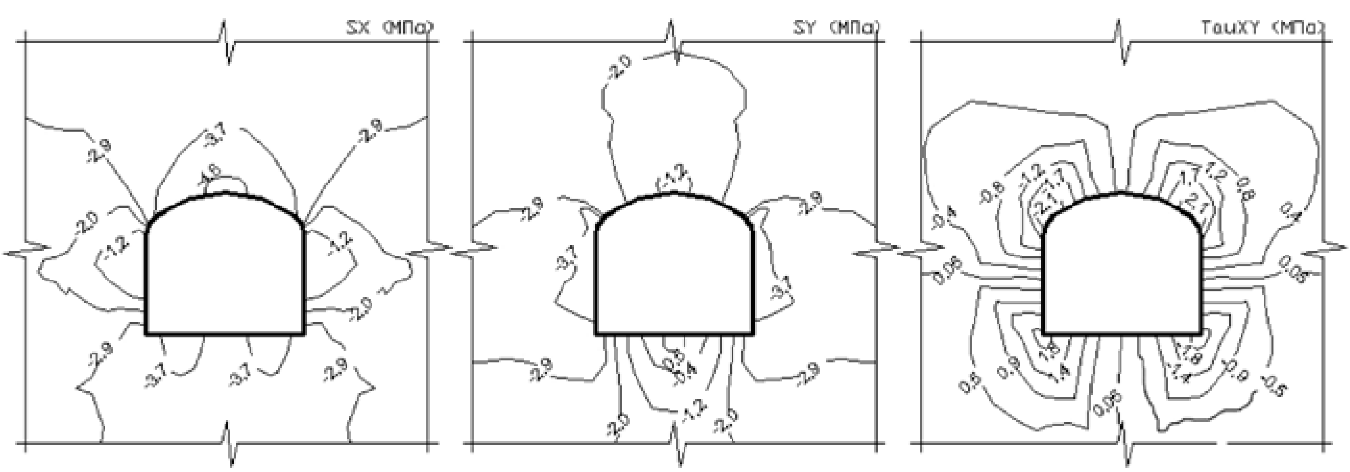
More than half of the Russian mines are experiencing seismic phenomena, the practical manifestation of which is associated with mining operations. Severouralskiy bauxite mines, Tashtagolsky mine, Kuznetsk coal basin mines, Khibiny, and Talnakh mines in Russia, the system of Witswatersrand mines, South Africa, Palabora, Kolar gold deposit, India, Solvay mine, USA (Adushkin, & Turuntayev, [2]; Glaser [16]).

As the strongest (in Russia) seismic events induced by mining operations were noted: Bachatsky earthquake on June 18, 2013 ($M = 6.1$) in Kuznetsk coal basin (epicenter on the territory of the Bachatsky open pit); mining -tectonic rockburst on the Kirov mine of OJSC "Apatite", which occurred on April 16, 1989, with an energy of ~10^{12} J ($M = 4.8$–– 5.0); a rockbursts at the mine Kurbazakskaya of the Yuzhnouralsk bauxite mine, which occurred on May 28, 1990, with an energy of 1010–1011 J ($M = 3.5$– –4.0); a powerful mining and tectonic impact at the Umbozero mine of the Lovozero rare earth metals deposit, which took place on August 17, 1999, with an energy of 1011–1012 J, equivalent to the initiated earthquake with a magnitude of 4–4.4 and destroyed more than 6.0 × 105 m^2 of mine workings.

On the basis of the analysis of manifestations of technogenic seismicity, specialists prioritized the maximum magnitude M_{max} of the technogenic earthquakes that arose in the world. According to this criterion, the marked catastrophic seismic events in different industries are distributed as follows: A) development of oil and gas fields (Gazli, Uzbekistan, $M_{max} = 7.3$); B) filling of reservoirs (Koina River, India, $M_{max} = 6.5$); C) underground mining operations (Kuznetsk coal basin, Russia, $M_{max} =$ $= 6.1$); D) underground nuclear explosions (polygon in Nevada, USA, $M_{max} = 4.5$) (Adushkin, & Turuntayev [2]).

Computational experiment: modeling of processes of sustainability of underground mine workings

Modern mathematical methods and technical computing means allow obtaining qualitatively new and multivariate solutions of problems with subsequent evaluation of the degree of their identity to real processes. The authors developed computer application programs for the quantitative evaluation of the strength of underground workings, taking into account the features of their design, piecewise inhomogeneous physical and mechanical characteristics of the surrounding rock mass for the accepted calculation schemes and numerical models (Gasanova, Salyamova, & Melikulov [10]; Jaeger [18]; Salyamova, & Melikulov [27]).



a) b) c)

Figure 1. Stress diagrams in an rock mass around the underground gallery: a) isolines of horizontal stresses; b) isolines of vertical stresses; c) isolines of tangential stresses

A flat task in the study of the stress-strain state of a rock mass around underground mine workings

For the numerical solution of the problem, the infinite region surrounding the underground mine is replaced by a finite region, at the boundaries of which the corresponding boundary conditions are put or loads are applied (Salyamova, & Melikulov [28] Sultanov, Salyamova, Khusanov, & Melikulov [31]).

Figure 1 shows stress plots in an rock mass around the mine, constructed on the basis of calculations using this technique for the case when the lateral (tectonic) pressure coefficient is 1.38.

Solution of the problem using the COSMOS/Works software complex with the example of the given mining and geological conditions

COSMOS/Works is a finite element analysis system integrated into 3D SolidWorks. The combination of design systems and finite element analysis has made it possible to obtain a tool for calculating and optimizing designs consisting of a large number of elements (Alyamovskiy [4]). In the rock massif with the accepted average physical-mechanical properties (modulus of elasticity, Poisson's ratio, volume weight, angle of internal friction, coefficient of adhesion), a mining with design parameters is constructed at a given depth. Based on the results of calculations of the state of the array, the acting stresses are set (Melikulov, Salyamova, & Kaygarodov [23; 24]).

In assessing the stability of rocks, the limiting state is described by the well-known Coulomb law. In the practice of designing the construction of underground structures to assess the permissible level of stress or strength, the safety factor is widely used, defined as the ratio of the tangential stress acting at the considered point to the magnitude of the limiting tangential stress. As an example, we determine the stresses σ_x, σ_y, τ_{xy}, at various arbitrarily taken points of the array around the underground gallery, as shown in (Fig. 2). Here, for example, 3 rows of 12 points in each row are taken. The first row (points 1–12) passes along the left contour of the axis of symmetry of the development, the second row of points (13–24) is displaced from the first into the depth of the massif by a distance of 0.6 m. Similarly, the third row of points (25–36) is located at a distance of 0.6 m from the second row into the depth of the array.

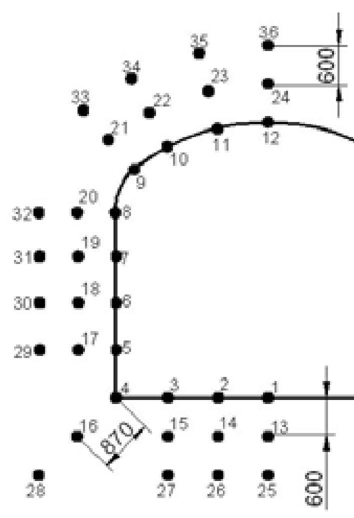


Figure 2. Scheme of the location of points for calculating stability

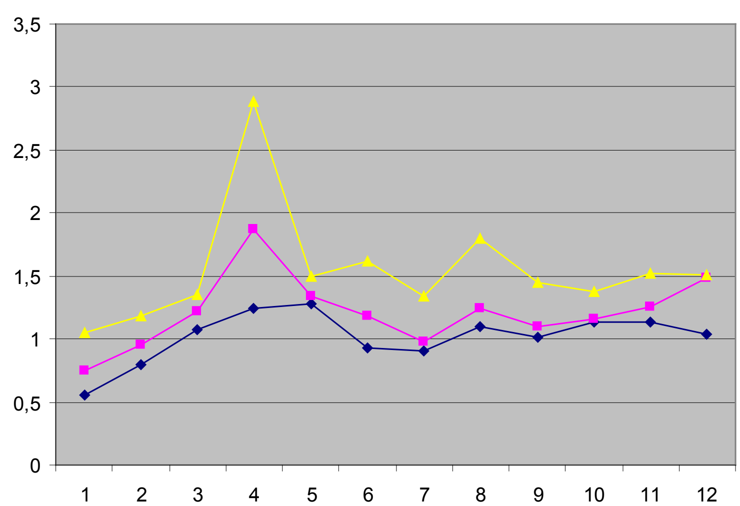


Figure 3. Graph of the change of stability coefficient at some points of the massif around the underground gallery

Figure 3 shows a graph of the change in the values of the coefficient of stability in each of the 36 points.

Figure 4 shows another example, when rock massif around the gallery is reinforced by an artificial method, for example, by cementation (in the figure, this area is shaded). The finite elements of this zone of the array in the design model are given the appropriate values of physical and mechanical properties: the modulus of elasticity, the Poisson's ratio, the angle of internal friction, the coefficient of adhesion.

Figure 5 shows the graph of the change in the stability factor of the points of the massif around the mine, constructed from the results of solving the problem, taking into account the artificial strengthening of the massif.

In the graph of the change in the coefficient of stability (Fig. 3), the points having coefficient values less than 1.0 are potentially unstable points, i.e. the rocks in this part of the massif is prone to destruction. The graph (Fig. 5) of the change in the stability coefficient of the same points of an artificially fortified rocks shows that there are no points with a coefficient of stability below 1.0.

Finite-element computational modeling of blasting operations in a vertical shaft

Analogously to the problems of estimating the stress state of a rocks around the gallery, we solved the task of calculating the stress-strain state of rocks during the production of blasting operations at the construction of a vertical shaft. The condition of this problem is to study the stress state of the array with successive short-delayed blasting of several groups of charges in order to ensure the quality destruction of rocks by an explosion within the contour with minimal damage to the rocks behind the design contour.

In solving this problem, the following basic parameters of objects and processes are taken into account in the developed model: the physical and mechanical properties of rocks, the depth of the holes and the scheme of their location in the face, the design of charges, the length of the charge in each hole, the energy of blasting, the rate of detonation in the charge, the speed of propagation of elastic waves and the process of crack formation in the array, the parameters of intrahole retarders, the wave interaction of simultaneously exploded charges in each group of the explosion series.

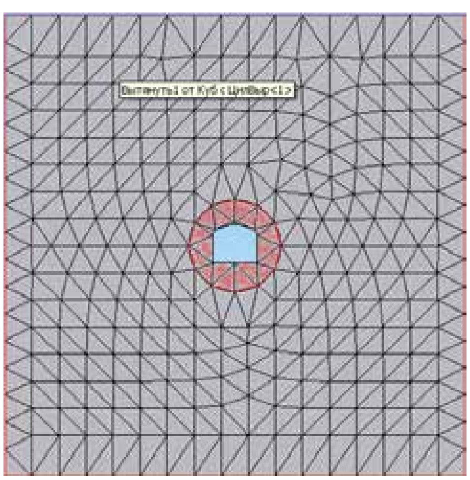


Figure 4. Scheme of partitioning an strengthened array into elements

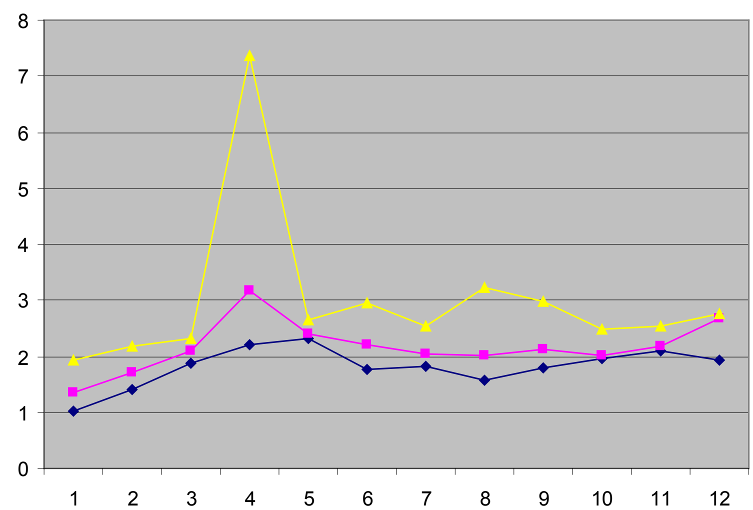


Figure 5. Graph of the change of stability coefficient at points of strengthened array around gallery

Figures 6 and 7 show horizontal and vertical displacements of points as a result of successive explosions of the central cut hole (single charge), then in a group of cut holes that are disposed around a 1.5 m diameter circle.

The duration of the explosion of the first charge in the central hole is 10^{-3} s, the duration of its action on the array continues for 10^{-2} s, after which its influence on the rocks dies out. Then, at a time of 12×10^{-3} s, detonation occurs in two symmetrically located boreholes of the next series, the duration of explosion of which is also 10^{-3} s, the duration of the action of this explosion on the array also continues for 10^{-2} s, i.e. up to the moment 23×10^{-3} s.

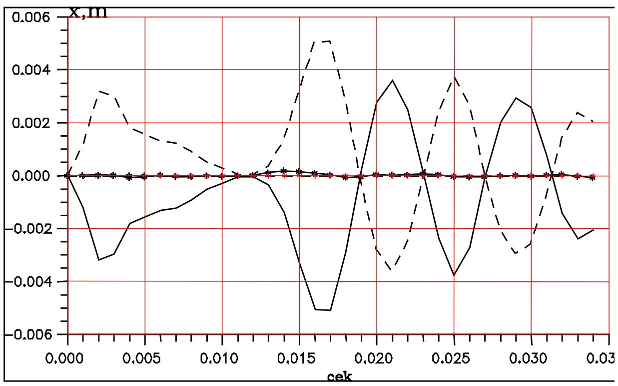


Figure 6. Horizontal displacements of points on the face of shaft at consecutive blasting of cuttings

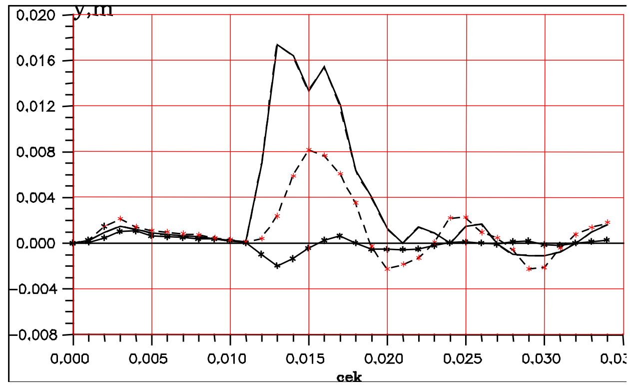


Figure 7. Vertical displacement of points on the face of shaft at consecutive blasting of cuttings

The results of solving this problem make it possible, on the basis of the wave interaction of simultaneously exploded charges in each group of the exploded series, to select the optimal range of the following parameters for blasting operations: the mass and number of charges in each series of deceleration, the sequence and the delay of the explosion of charge explosions both within each series, and between series of explosive charges (Davison [8]). The control of the action of explosive charge during the construction of the mine makes it possible to achieve a qualitative and uniform fragmentation of the blasted rock mass in the shaft. At the same time, the maximum integrity of the rock massif behind the design outline of mine workings is ensured, which is one of the measures to preserve the stability of the rock massif and the constructing underground gallery (Polukhin, Kaloyerov, Gryadushchiy, & Goryanskaya, [26]). This quality of blasting operations will also prevent negative impact on the surrounding massif without causing unnecessary cracking and deformation, including the avoidance of dynamic (induced) manifestations of rock pressure in the tectonically tense zone of the rock massif.

It should be noted that such broad opportunities to manage the process and the result of blasting when constructing underground mine workings arise using modern means of non-electric initiation of charges of explosives.

Conclusions

The permanently movement of our planet and the natural processes taking place in the Earth's crust are the cause of the emergence of vast areas of seismic activity, where thousands of earthquakes of various energy occur every year, which complicate the conditions for the development of mineral deposits. In addition, with the depletion of reserves of deposits with favorable geological conditions, mining works continue to develop for more complex natural conditions.

The Central Asian region and many areas of modern orogenic processes are characterized by the manifestation of seismotectonic processes, the results of which, on the one hand, complicate engineering conditions of work, and on the other become a powerful engine for the further development of mining technologies. As a result of anthropogenic activity, in the solution of global regional problems, there are cases of creating additional sources of danger leading to the stimulation of technogenic-tectonic or induced seismicity.

The human need to solve the problems that have arisen, has led on the basis of study of Earth's physics and engineering mathematics to the intensive development of modern methods of geomechanics, tectonics, geophysics, and geodynamics.

Numerical methods of modeling mining-geological objects and processes of any complexity with the use of modern technical and software tools offer new opportunities in solving technological problems, especially in areas where physical experiments in the traditional view are difficult – in underground mining facilities, processes of destruction and mining of minerals using explosive technologies.

Modern investigations in the discussed field of science and mining production gives an instrument for preliminary substantiated evaluation of technical solutions, the forecast of possible adverse consequences, the threat of catastrophic events, the safety of objects and people, and material and economic losses. The original development of the methodology for calculations with the use of models allows us to solve the modern tasks in a new way using computer programs developed, as well as to offer technological measures for managing the state of the array in the production of blasting operations in underground workings, taking into account the safety and prevention of the dynamic manifestations of the mountain pressure.

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