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Predicting the magnitude of technogenic earthquakes during underground mining of the Zhezkazgan ore field

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Abstract

Purpose. Determining a relationship between the shear/failure of the rock mass and the technogenic earthquakes caused by them during underground mining of ore deposits with the derivation of an equation for the dependence of the technogenic earthquake indicators for the conditions of the Zhezkazgan copper-ore field.

Methods. The research methodology consists of studying and analyzing early research on technogenic earthquakes by the method of statistical data processing. Calculation of rock mass deformation distribution in the study area is based on numerical modeling in the Comsol Multiphysics 5.6 and MATLAB 2020 software package environment. Calculations are performed based on solving a plane problem using the Finite Element Method (FEM).

Findings. Based on the transition from the failure area to subsidence and shear values of the overlying rock mass stratum, an equation for the dependence of the earthquake magnitude on the numerical values of the mass subsidence or shear has been obtained.

Originality. For the first time, based on the physics and geomechanics of rock mass shear processes, empirical-analytical formulas have been obtained that make it possible to predict the technogenic earthquake magnitude during underground mining of ore deposits in the conditions of the Zhezkazgan copper-ore field.

Practical implications. Preliminary predictive calculations made by the obtained formulas for the conditions of the active mine No. 31 of the East-Zhezkazgan mine, TOO Kazakhmys Smelting, show acceptable results of magnitude value, comparable to in-situ measurements during field mining. This prediction makes it possible to pre-calculate the technogenic earthquake magnitude at the stage of designing mining operations and make appropriate scientifically sound decisions during further mining of the field.

Keywords: *ore deposit, underground mining, mine, failure, rock mass shear, technogenic earthquake*

1. Introduction

Kazakhstan's mining industry plays a key role in the country's economy, due to its vast natural resources and significant contribution to the formation of domestic and global markets for raw materials [1], [2]. In light of modern challenges and technological innovations, the mining sector is becoming a fundamental element of Kazakhstan's sustainable development strategy. However, along with the positive aspects of mining industry development, attention should also be paid to the potential risks that accompany its activities [3]-[5]. A particularly important aspect in underground mining of solid minerals is the impact on the geodynamic mass state, leading to undesirable consequences, such as technogenic earthquakes that can pose a threat to underground and surface structures [6]. In light of these challenges, particular attention is paid to research into geodynamic processes and development of control measures to ensure safe and sustainable mining operations [7].

In underground mining of solid minerals, in particular ore deposits, one of the geodynamic consequences is the occurrence of technogenic earthquakes, which pose a hazard to both underground geomechanical structures and surface life-support facilities. The causes of such forms of mass reaction during technological intervention in its equilibrium state are mainly two [8]-[10]. These are massive blasting operations during the preparation and mining of ore bodies and/or instantaneous failure of overhanging rock stratum into mined-out spaces [11], [12]. While the action of massive explosions can to some extent be controlled (by the amount of explosives, shielding slots, etc.), spontaneous failure over large outcrop areas is almost uncontrollable [13]. In massive explosions, short-term fluctuations of varying intensity in underground and surface structures occur, and in the case of failure, there is also surface shear [14]-[17]. Both of these consequences of intervention are characteristic of an earthquake, one of the most severe catastrophic events.

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The impact of technogenic earthquakes is particularly dangerous for the life-support facilities of built-up areas, which are often formed within the field on the surface of the ore bodies. These include residential buildings of various number of floors and duration of use, water supply and sanitation networks, outdoor and buried storage facilities for fuels and lubricants, railways and highways, high-voltage power transmission lines, production sites and buildings, and religious objects [18]-[20]. Mining operations for the completion of reserves and mining-induced technogenic earthquakes necessitate difficult and sound decisions on the relationship between mining enterprises, local authorities and communities [21]. In connection with the above, along with others, there is a difficult task of predicting and assessing the degree of hazard of technogenic earthquakes during the full mining of ore deposits, especially those with a high thickness of 10 m or more.

Natural earthquakes have limited impact on underground mining operations, but can cause instability in open-pit mines and tunnel portals [22]. However, the presence of underground mine workings near faults can significantly influence the initiation of tectonic earthquakes [23], [24]. Mining-induced seismic events can lead to step changes in rock mass shear and excavation closures, making the excavation less stable and more susceptible to seismic impacts [25]. The impact of earthquakes on open-pit slopes, particularly at non-homogenous and varying slope angles, can trigger instability and failure [26].

Anthropogenic earthquakes, induced by activities such as underground mining, can have significant magnitudes, with the imbalance between extraction and injection volumes being a key factor [27]. These earthquakes can occur in previously aseismic regions and are often triggered by stress state rearrangement due to human activity [28]. The impact of these earthquakes on the earth movement can be substantial, and the use of satellite radar interferometry has proven effective in monitoring and analyzing these effects [29], [30].

The term “technogenic” or “anthropogenic” refers to the diverse in nature, mechanism, duration and intensity of influence on lithosphere objects resulting from human economic activity. The size and extent of anthropogenic impact on the geological environment are quite comparable with the natural processes of exogenous geodynamics [31], [32]. The main difference is the speed of the process deployment. While geological processes are usually slow and can extend over hundreds of thousands or millions of years, human impacts on the environment occur much more quickly, over decades. This rapidity of impact processes represents one of the characteristic features of anthropogenic activity [33].

Studying the nature and consequences of technogenic earthquakes has been the subject of scientific research, especially in the last few decades [34], [35]. For a long time, there was no consensus that seismic activity in mining is related specifically to underground or open-pit mining operations. At the same time, natural and technogenic earthquakes, as well as rock-tectonic bumps, are considered dangerous for life-support facilities. According to the authors in [10], [36], they may occur not only during mining of solid minerals, but also in oil and gas mining, as well as during the construction of hydrotechnical structures.

The difference is, as the authors note [37], [38], that technogenic seismicity, to some extent, is controllable, as opposed to natural seismicity. For example, in mines or open pits, measures for de-stressing can be planned or triggered artificially at the required safe time.

As for rock-tectonic bumps and technogenic earthquakes, the foci of the former are located directly in mine workings, causing significant destruction of underground geomechanical structures – pillars and mine workings [39]-[42]. Tectonic earthquake, like any other earthquake or rock-tectonic bump, may well result in seismic vibrations on the surface. Moreover, the intensity can reach 5-6 points on the MSK-64 scale in the nearest settlements or at the industrial sites of open pits or mines. According to long-term observations, the magnitude of technogenic earthquakes does not exceed 1-4, although some may reach a magnitude of 4.5-5 on the Richter scale [43].

In general, magnitude is a conventional dimensionless value, characterizing the total energy of elastic vibrations caused by an earthquake, including technogenic one [44]. Magnitude is not measured in points, so it is correct to call “an earthquake of magnitude”. Sometimes an empirical formula is used, obtained by different methods of measuring the energy class and earthquake magnitude [43]:

$$M = \frac{2}{3}\left(\lg E - 4.8\right), \quad (1)$$

where:

E – earthquake energy, J.

Given that predicting technogenic earthquakes is part of the general problem of safe development and mining of mineral deposits, including in social terms [7], scientists have focused on solving this problem. Such studies have mainly been conducted for the conditions of solid mineral deposits in the north of the Asian continent, in Kazakhstan and Kyrgyzstan [45].

The above publications examined the complex relationship between technogenic seismicity and the shear of the overlying rock stratum in open pits and mines, and the mechanism of seismic process development in underground and open-pit mining methods. It is noted in [46] that the technogenic seismic process develops simultaneously, that is, in parallel with subsidence and failure of the rock stratum into the mined-out space. However, it has been observed that there is a decrease in seismic activity during periods of greatest subsidence and an increase when shear ceases or decreases.

It can therefore be argued that in addition to predicting seismic events, it is also necessary to assess seismic activity in order to timely develop anti-seismic measures. Here the authors propose to use a methodology developed on the basis of certain empirical indicators of seismic events. There are known studies aimed at determining the relationship between the rock failure area and the Richter magnitude of a seismic event [47], as well as seismic event severity depending on the depth of mining.

The analysis of publications on technogenic seismicity has shown that, despite the successes achieved, there is no simple and accessible method for predicting such a formidable and hazardous phenomenon, as the consequences of intervention in the rock mass [48]-[51]. A famous scientist in the field of seismic exploration and geophysics [43] notes that “for the 150-year history of its existence, engineering geology has not made a single prediction of a technogenic disaster”.

The author of [9], pointing to the conditions for the formation and manifestation of technogenic earthquakes, claims that there are still few achievements in the field of predicting rock-tectonic bumps, including technogenic earthquakes. At present, no methodology for predicting rock-tectonic bumps and technogenic earthquakes has been developed.

Repeated mining of thick ore deposits by excavating the pillars left for various technological purposes leads to formation of extensive (in area and height) mine-out spaces and the creation of conditions for spontaneous failure. It seems to us that the seismic hazard assessment may and should be determined by implementing scientifically based safety decisions for both underground and surface life-support facilities in the mining area. Miners assess underground mining hazards by the energy of rock shear from a system of installed sensors. Firstly, such systems are not available everywhere. Secondly, they cannot be used to assess the risk of technogenic earthquakes for surface facilities.

Based on the analysis of previous studies, this paper aims to substantiate the method for predicting the magnitude of technogenic earthquakes in the conditions of the Zhezkazgan copper-ore field. To achieve the purpose set, the authors, based on previously conducted and published research results, conduct an analysis of physical processes and use modern software products for modeling geomechanical processes.

2. Methods

In our research we primarily use the information on technogenic earthquakes caused by rock failure in open pits mining flat-dipping deposits using open stope systems (longwall workings, board-and-pillar mining and similar) given in the paper [46]. Table 1 presents the indicators of technogenic earthquakes during rock failure in the fields of foreign countries, Table 2 – during rock failure in the fields of Kazakhstan.

Table 1. Indicators of some technogenic earthquakes during rock failure in the fields of foreign countries

Fields	Year	Mine, country	Failure area, thousand m^2	Earthquake strength	
				magnitude	energy class
Potassium	1938	Varengeville, France	100	2.3	8.3
	1940	Krugershall, Germany	600	3.8	10.5
	1943	Klein Schiersted Germany	300	3.1	9.5
	1975	Marx-Engels, GDR	3400	5.2	12.6
	1989	Merkers, GDR	6000	3.6	13.2
	1995	Solvey, USA	1900	5.3	12.8
Gold	1962	Champion Reef, India	135	4.5-5.0	11.9
	1982	Welkom, South Africa	180	4.6	11.7
	1985	Klerksdorp, South Africa	30	3.6	10.2
	1987	Klerksdorp, South Africa	750	4.9	12.2
	1988	Klerksdorp, South Africa	300	4.3	11.3
	1986	Klerksdorp, South Africa	500	4.7	11.9
Iron ore	1991	Umbozero, USSR	80	2.2-2.6	8.7
	1987	Lubin, Poland	2000	4.3	11.3
	1980	Belchatow, Poland	2000	4.6	11.7
	1984	SUBR, USSR	30	2.3	8.1
	1993	Beech Cliffs, USA	15	3.6	10.2
	1990	SUBR, USSR	450	3.5-4.0	10.5

Table 2. Indicators of some technogenic earthquakes during rock failure in the Zhezkazgan field in Kazakhstan

Field	Year	Mine	Failure area, thousand m^2	Earthquake strength	
				magnitude	energy class
Iron ore	1994	Mine 57 bis	480	4.7	11.8
	1996	Mine 42-47	474	3.7	6.1
	1996	Mine 42-51	135	3.7	10.7
	1998	Mine 42-51	42	1.3	6.8
	1998	Mine 42-52	93	1.2	6.6
	2001	Adit to old mines	102	3.7	7.6
	2002	Mine 57 bis	117	1.2	6.5
	2002	Mine 57 bis	184	4.4	6.5
	2005	Mine 45 south of the village	153	3.9	7.0
	2005	Mine 45	150	1.5	7.0
	2007	Mine 31 north of the village	96	3.7	5.6

Using a special software package for scientific-engineering research, empirical equations for the relationship between earthquake magnitude and energy class with the failure area can be obtained [52]:

– for foreign fields:

$$M = 4.418e^{-4.03310^{-6}F} - 1.379e^{-0.003098F}; \quad (2)$$

$$K = 11.56e^{-2.19510^{-5}F} - 2.417e^{-0.002598F}; \quad (3)$$

– for the Zhezkazgan field in Kazakhstan:

$$M = -4.78710^{-5}F^2 + 0.0154F + 0.061; \quad (4)$$

$$K = 6.768e^{(0.000588F)} - 0.7166e^{(-0.01705F)}. \quad (5)$$

Formulas (2)-(5) are empirical equations that describe the relationship between the earthquake magnitude (M), energy class ($K = \lg E$) and failure area (F) for the fields in foreign countries and the Zhezkazgan field in Kazakhstan. There is no direct mathematical correlation between these formulas, but they can be used to model different types of earthquake energy class dependences on failure area F. These equations provide a tool for assessing the magnitude and energy class of earthquakes in the Zhezkazgan field depending on failure area. It is important to remember that these equations are empirical and based on statistical data rather than on fundamental physical principles, making it necessary to apply and interpret them carefully in the context of specific research and practical problems [53]-[55].

Figure 1 presents the dependence of the energy class of technogenic earthquakes on the failure area according to source [47]. The graph illustrates the relationship between energy class and failure area size, providing a visual representation of how changes in failure area relate to different energy activity levels of technogenic earthquakes.

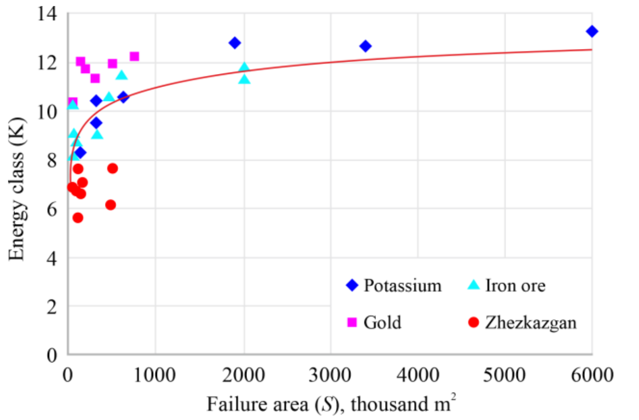

Figure 1. Relationship between the energy class of technogenic earthquakes and failure area (according to [47])

Based on Figure 1, the relationship of energy class of technogenic earthquakes can be approximated by the Formula:

$$K = 0.89 \ln F + 4.76 . \tag{6}$$

The expediency of transition from failure area to mass shear is grounded in that the vertical subsidence values and full shear of the mass are determined by numerical modeling of the mass stress-strain state (SSS) according to research and scientific substantiation of safe mining of ore deposits. By the value of magnitude, it is possible to proceed to corresponding MSK-64 scale scores and predict the possible hazardous consequences.

Then numerical modeling of the mas SSS is performed. Calculation of rock mass deformation distribution in the study area is based on numerical modeling in the Comsol Multiphysics 5.6 and MATLAB 2020 software environment. Calculations are performed based on solving a plane problem using the finite element method. The modeling methodology is shown below.

The study of stresses and strains in a rock mass under the action of external loads and internal (mass) forces can be solved using the finite element method (FEM) [56]-[58]. Usually, a plane problem is solved, in which the stress state parameters are calculated in given or some presumably most hazardous sections. Stresses under the influence of external forces are related to deformations and physical-mechanical properties of the medium by known elasticity theory relations [59], [60].

Numerical values of stresses and strains in the mass are calculated in the environment of the integrated MATLAB software package, which implements the finite element method and is specifically focused on scientific-engineering research.

When modeling the elastic-plastic rock mass medium state, physical-mechanical properties of rocks characteristic of a particular field area are used: rock elasticity static modulus, Young's modulus (E), MPa; Poisson’s ratio (ν); internal friction angle (φ), deg.

As a result of numerical solution of the elasticity theory equations, the MATLAB software package calculates and outputs the complete list of parameters characterizing the rock mass stress-strain state: vertical, horizontal, principal and tangential stresses, as well as shear, vertical, horizontal and resultant strain and displacements.

Development of the working scheme and formation of a triangulation area for calculations by the finite element method is conducted in stages in the COMSOL Multiphisics software package environment.

The initial data when developing a working scheme are geometric parameters of the studied mass area: depths of location of technological facilities, their linear dimensions, thickness of ore bodies (coal seams), incidence angles. After analyzing these data using the Structural Mechanics module, an initial rock mass model, including the geomechanical structures located within it, is built using coordinates. The model is then adjusted to the location of mined-out stopes, pillars, decommissioned or backfilled areas, etc. The final formation of the triangulation area then occurs. The first step is to input data on physical-mechanical mass properties, taking into account lithological varieties, physical state (caved – not caved, etc.). The second step is to input the calculated pressure values (taking into account the lateral pressure coefficient), the required calculation accuracy due to the dimensions of the grid area elements. In the end, we have a rock mass fragment formed and ready for SSS modeling.

Figure 2 shows the computational scheme for SSS numerical modeling using the finite element method on profile line No. 21 of VZhR mine No. 31.

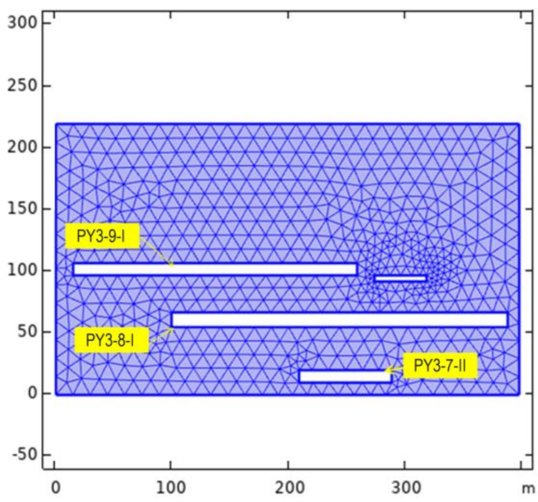

Figure 2. Computational scheme for the section of profile line No. 21

Figure 2 shows that three deposits are fully depleted, which is highly likely to result in a large mass shear and a significant technogenic earthquake.

This research studies the plane-stress mass state under the action of the weight of the overlying rocks γH in the vertical plane along the Y axis and the volumetric force of the studied mass area weight Q. The lower part of the mass above the mined-out space is assumed to be free, that is, not influenced by the action of external forces. Stresses, deformations and displacements act predominantly in the Y-axis direction (perpendicular to the roof mass plane) and insignificantly in the X-axis direction (along the mined-out space span line). It is assumed that there are no stresses and deformations in the semi-bounded rock mass plane along the Z-axis direction (perpendicular to the XOY plane). The mass dimensions along the X and Y axes are finite and are determined by the modeling conditions.

3. Results and discussion

To predict the magnitude, it is reasonable to switch from area to the value of shear during mass failure, because, in our opinion, this transition reflects more the physics of a technogenic earthquake. To determine the relationship between the mass shear and the magnitude of the earthquake it causes, use information about the earthquake energy. It is determined by the parameter K, which by the formula $E = 10^K$ J, expresses the physical earthquake energy value. Bearing in mind that Joule is a unit of work (or energy) measurement determined as the product of force and distance, it is possible to calculate the mass shear value from the failure energy value. Based on the work formula $A = P \cdot L$ and the unit of measurement (J = N·m) of the failure energy, the caving (or shear) force can be determined from the known failure area using the Formula:

$$P = 10 \cdot F \cdot h \cdot \gamma \,, \tag{7}$$

where:

h – thickness of caved rock stratum, m;

γ – unit specific gravity of rocks, kg/m^3;

10 – approximate conversion factor of kg·Force to Newton.

Then the shear value L (or displacement) of the mass part during failure can be calculated by the Formula:

$$L = \frac{E}{10 \cdot F \cdot h \cdot \gamma} \,. \tag{8}$$

In the conditions of the Zhezkazgan field, the following can be assumed: average unit specific gravity of the rock stratum is 2600 kg/m^3, caved stratum thickness is within 3-8 m [61]. Further we will use empirical Formula (6) and using the data of Table 2, calculate the energy class K by Formula (1) and the corresponding magnitude value M. Using Formula (8), taking the average thickness of the caved rock stratum as h = 5 m, the shear value L is determined. Table 3 presents the technogenic earthquake indicators and the corresponding calculated rock shear values, depending on the failure area and taking into account the conditions of the Zhezkazgan field.

By processing the data, the equation for the relationship between magnitude and shear value during overlying rock stratum failure has been obtained:

$$M = 4.851 \cdot L^{0.268} \,. \tag{9}$$

As can be seen from the calculation results in Table 3, the calculated shear value of overhanging rock stratum at full mining of the ore body, depending on the area, can range from 20 mm to 2.6 cm. In this case, the calculated magnitude of technogenic earthquake takes values from 2.19 to 3.64.

Figure 3 shows a dependency graph of the technogenic earthquake magnitude on the rock mass shear during failure. The graph in Figure 3 shows that the earthquake magnitude increases as the rock mass shear value increases. With a mass shear value of 0.05 m, the earthquake magnitude is about 2.5.

Table 3. Technogenic earthquake indicators and calculated rock shear values for the conditions of the Zhezkazgan field

Area, thous. m^2	Energy class (K)		Earthquake magnitude (M)		Calculated shear (L), m
	measured	calculated	measured	calculated	
480	11.8	10.2	4.7	3.64	0.251
474	6.1	10.1	4.7	3.63	0.263
184	6.5	9.4	4.4	3.07	0.105
153	7.0	9.2	3.9	2.96	0.081
150	7.0	9.2	1.5	2.95	0.080
135	10.7	9.1	3.7	2.38	0.070
117	6.5	9.0	1.2	2.80	0.066
102	7.6	8.9	3.7	2.72	0.080
96	5.8	8.8	3.7	2.68	0.051
93	6.6	8.8	1.2	2.66	0.055
42	6.8	8.1	1.3	2.19	0.021

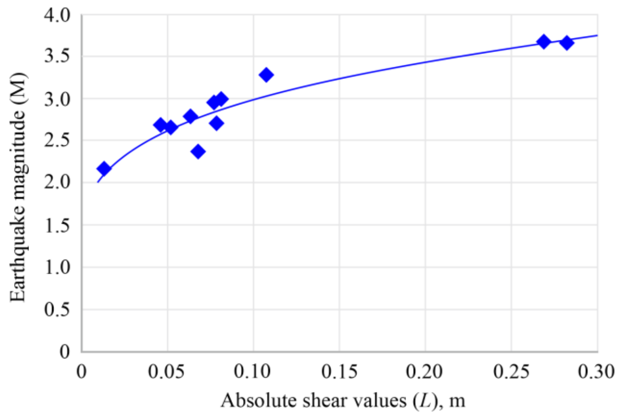

Figure 3. Dependency graph of the technogenic earthquake magnitude on the rock mass shear value

With a mass shear value of 0.10 m, the earthquake magnitude is about 3.0. Thus, it can be concluded that the mass shear value is one of the main factors influencing the technogenic earthquake magnitude. The greater the mass shear value, the greater the earthquake magnitude. The obtained data can be used to assess the potential risk of technogenic earthquakes. For example, if it is known that work is planned in a particular area that may cause a mass shear, then this pattern can be used to assess the potential earthquake magnitude. It is important to note that the earthquake magnitude is also influenced by other factors, such as the rock type, the depth of the rock mass occurrence, and the presence of fractures in the mass. However, the rock mass shear value is one of the most important factors. Calculated by Formula (8), the magnitude of the technogenic earthquake caused by vertical mass subsidence of 0.45 m is 3.95.

Figure 4 shows the dependency graph of energy classes of technogenic fields on the rock failure area. The graph is based on two data sets: measured data (1) and calculated data (2). The graph shows that both data sets show a similar relationship. Energy class increases as the rock failure area increases. It can be concluded that the rock failure area is one of the main factors influencing the energy class of a technogenic field. The larger the rock failure area, the higher the energy class of the field.

A comparative analysis of measured and calculated data shows that the calculated data are generally consistent with the measured data. However, if the failure area is of about 500 thousand m^2, the calculated data slightly underestimate the energy class.

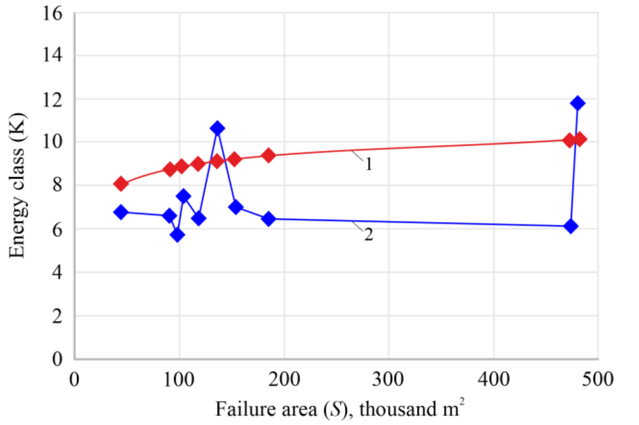

Figure 4. Indicators of energy classes of technogenic fields depending on the area of rock failure : 1 – measurement data; 2 – calculated data

This may be due to the fact that the calculated data does not take into account all factors influencing the energy class. In general, the obtained dependence is a reliable tool for assessing the potential hazard of technogenic fields.

In accordance with the presented methodology (Section 2 of the paper), the vertical trough surface subsidence has been calculated for profile line No. 21 of VZhR mine No. 31 (Fig. 5).

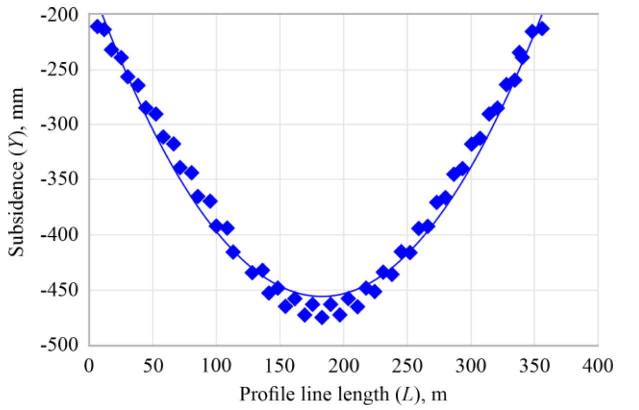

Figure 5. Graph of absolute vertical trough surface subsidence along the length of the profile line

Table 4 shows the calculated vertical subsidence and total shear values of the rock mass after full mining of the ore deposits at different distances from the shear trough boundary. Table 4 shows that the subsidence and shear values almost coincide and take values from 1.96 to 2.73 m (the "–" sign of vertical subsidence is related to the choice of coordinate axis directions). Calculations by Formula (8) show that at such instantaneous mass shears, the technogenic earthquake magnitude is predicted to be from 5.8 to 6.4.

Table 4. Calculated values of surface subsidence and displacements

Surface subsidence and shears	Distance from the left trough boundary, m					
	140	160	180	200	220	240
Vertical subsidence, m	-2.48	-2.63	-2.72	-2.76	-2.73	-2.65
Total shear, m	1.96	2.14	2.29	2.40	2.48	2.52

Analyzing Figure 6, it can be concluded that the principal normal stresses decrease with increasing distance from the face since the face influences on the redistribution of stresses in the rock mass.

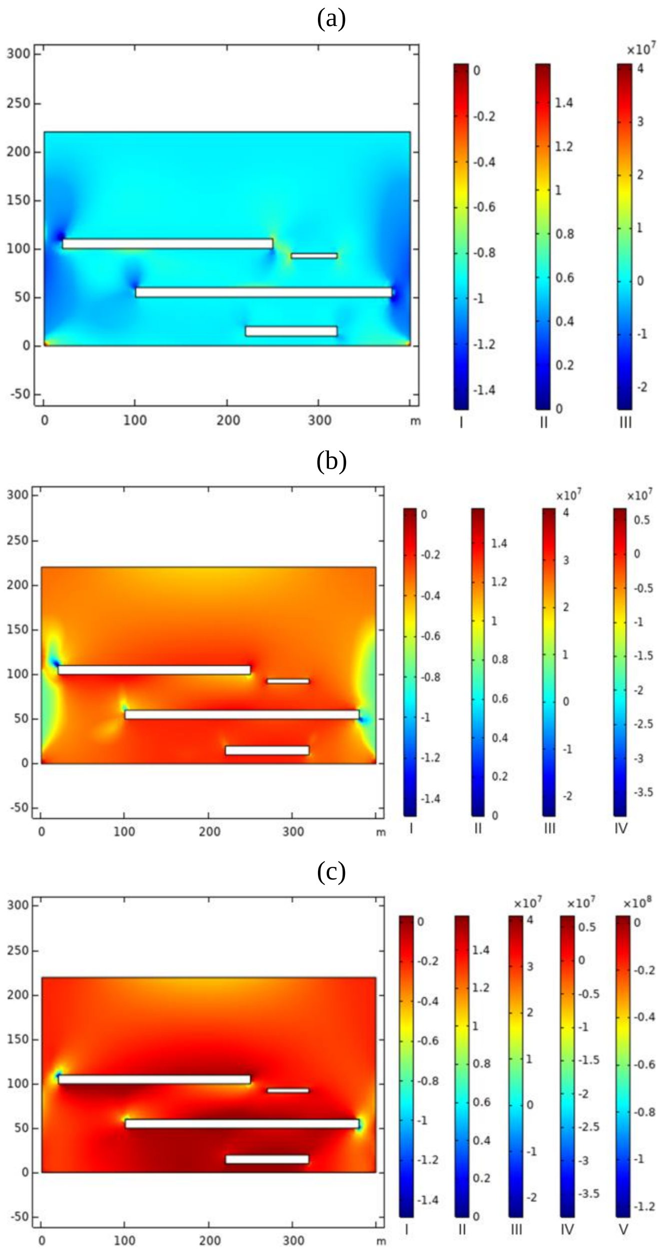

Figure 6. Graphical fields of principal normal stresses: (a) σ_1; (b) σ_2; (c) σ_3; I – displacement field Y component, m; II – displacement magnitude, m; III – first principal stress, N/m²; IV – second principal stress, N/m²; V – third principal stress, N/m²

Near the face, the principal normal stresses have higher values and are orientated towards the face itself, causing tensile stresses in the rocks. As the distance from the face increases, the principal normal stresses decrease and become compressive stresses. In addition, the principal normal stresses vary in direction. Near the face, the principal normal stresses have one direction, and as the distance from the face increases, the principal normal stresses may have two or three directions. The change in the direction of the principal normal stresses is primarily due to the rock mass heterogeneity. Figure 6 also shows that the principal normal stresses can have critical values, which can lead to deformations and failures in the rock mass. Displacement field *Y* (Fig. 6, I) near the face has high values and is directed towards the face. As the distance from the face increases, the *Y*-axis displacement decreases and becomes equal to zero.

Displacement magnitude (Fig. 6, II) also varies depending on the distance from the face. Near the face, the displacement magnitude has high values and decreases with increasing distance from the face.

First principal stress (Fig. 6, III) is the greatest of the three principal normal stresses. Near the face, the first principal normal stress has higher values and is directed towards the face. As the distance from the face increases, the first principal normal stress decreases and becomes compressive stress.

Second principal stress (Fig. 6, IV) is the average of the three principal normal stresses. Near the face, the second principal normal stress has low values and is directed perpendicular to the first principal normal stress.

Third principal stress (Fig. 6, V) is the least of the three principal normal stresses. Near the face, the third principal normal stress has low values and is directed perpendicular to the first and second principal normal stresses. As the distance from the face increases, the third principal normal stress decreases and becomes equal to zero.

The scientific value of the conducted research is to determine empirical relationships between the energy class, the technogenic earthquake magnitude and the failure area, including for conditions of the Zhezkazgan copper-ore field. As part of the practice of two-stage complete mining of ore deposits, it is necessary to determine the vertical subsidence and complete mass shear above the mined-out ore deposits from geological sections. These parameters provide the basis for developing measures to protect surface life-support facilities.

It is important to anticipate the quantitative characteristics of a possible technogenic earthquake, its energy class and magnitude, in order to ensure the safe mining operations and assess the possible destruction of industrial and civil facilities, especially with limited information about the area of failure. In this paper, based on the physics of technogenic earthquake energy, an empirical equation has been derived that relates the magnitude to the absolute rock mass shear.

The set tasks are solved by using numerical modeling of the stress-strain state of the mass by the finite element method in modern software packages. The results of subsidence and shear calculations obtained by modeling the stress-strain state make it possible to assess the risk of such phenomena and calculate the strength of possible technogenic earthquakes using magnitude ratios with MSK-64 scores.

Prospects for further research in this direction cover a number of key aspects that can significantly expand our understanding of the relationship between mining operations, technogenic earthquakes and their environmental impacts.

In subsequent studies, an in-depth analysis of the factors influencing the energy class of technogenic earthquakes seems necessary. Achieving this goal requires the development of more detailed and integrated models, taking into account different parameters of mining operations, ore types, geological peculiarities and other important factors. This approach will significantly improve the accuracy of determining the relationships between failure area and energy class of technogenic earthquakes. Such an analysis may include a detailed examination of the impact of each of these factors on the processes leading to the occurrence of technogenic earthquakes. It is also important to take into account their interaction and cumulative impact on the energy potential of earthquakes. In parallel, additional aspects, such as the influence of geological conditions on earthquake characteristics and energy potential should be addressed. Additional data on ore types and their characteristics can also have a significant impact on the research results.

4. Conclusions

Based on the conducted research, the following conclusions have been formulated:

1. Underground mining of thick ore deposits leads to the occurrence of technogenic earthquakes that pose a significant threat to both underground geomechanical structures and surface life-support facilities in the built-up areas of the fields.

2. The analysis of the conducted research has confirmed that at present there is no effective method of predicting indicators that allow at the stage of development of projects for full mining of ore deposit reserves to assess the degree of possible hazardous consequences of technogenic earthquakes.

3. The adoption of a methodology based on mass shear measurement, as an alternative to assessing the failure area, is a strategically important step in understanding the physical mechanisms leading to technogenic earthquakes. The transition from assessing the failure area to the mass shear value represents a more complete reflection of the physics of technogenic earthquake occurrence.

4. The resulting equation makes it possible to calculate the magnitude based on the ore-rock mass shear value, providing a tool for more accurate prediction of the strength of technogenic earthquakes.

5. Numerical modeling of the mass SSS in preparation of scientific-engineering design solutions makes it possible to effectively solve the problems: to assess the risk of surface subsidence in case of full mining of thick ore deposits and to calculate indicators of possible technogenic earthquakes.

Author contributions

Conceptualization: NK, SA; Data curation: TK, KA; Formal analysis: NK, GN, AA; Investigation: NK, SA, ZA, KA; Methodology: TK; Project administration: NK; Resources: NK, TK; Software: NK, SA; GN, AA; Writing – original draft: NK, SA, TK, ZA, KA; Writing – review & editing: NK, GN, AA. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

References

[1] Issatayeva, F.M., Aubakirova, G.M., Maussymbayeva, A.D., Togaibayeva, L.I., Biryukov, V.V., & Vechkinzova, E. (2023). Fuel and energy complex of Kazakhstan: Geological and economic assessment of enterprises in the context of digital transformation. *Energies*, *16*(16), 6002. https://doi.org/10.3390/en16166002

[2] Rudko, G.I., Myatchenko, A.V., Isataeva, F.M., & Portnov, V.S. (2018). Geological-economic estimation of Kazakhstan deposits. *Sustainable Development of Mountain Territories*, *10*(4), 471-480. https://doi.org/10.21177/1998-4502-2018-10-4-471-480

[3] Umarbekova, Z.T., Zholtayev, G.Z., Zholtayev, G.Z., Amralinova, B.B., & Mataibaeva, I.E. (2020). Silver halides in the hypergene zone of the Arkharly Gold Deposit as indicators of their formation in dry and hot climate (Dzungar Alatau, Kazakhstan). *International Journal of Engineering Research and Technology*, *13*(1), 181-190. https://doi.org/10.37624/ijert/13.1.2020.181-190

[4] Togizov, K., Issayeva, L., Muratkhanov, D., Kurmangazhina, M., Swęd, M., & Duczmal-Czernikiewicz, A. (2023). Rare earth elements in the Shok-Karagay Ore Fields (Syrymbet ore district, Northern Kazakhstan) and visualisation of the deposits using the geography information system. *Minerals*, *13*(11), 1458. https://doi.org/10.3390/min13111458

[5] Sarybayev, O., Nurpeisova, M., Kyrgizbayeva, G., & Toleyov, B. (2015). Rock mass assessment for man-made disaster risk management. *New Developments in Mining Engineering 2015: Theoretical and Practical Solutions of Mineral Resources Mining*, 403-409. https://doi.org/10.1201/b19901-70

[6] Kalybekov, T., Rysbekov, K., Nauryzbayeva, D., Toktarov, A., & Zhakypbek, Y. (2020). Substantiation of averaging the content of mined ores with account of their readiness for mining. *E3S Web of Conferences*, *201*, 01039. https://doi.org/10.1051/e3sconf/202020101039

[7] Bekbergenov, D., Jangulova, G., Kassymkanova, K.K., & Bektur, B. (2020). Mine technical system with repeated geotechnology within new frames of sustainable development of underground mining of caved deposits of the Zhezkazgan field. *Geodesy and Cartography*, *46*(4), 182-187. https://doi.org/10.3846/gac.2020.10571

[8] Nurmagambetov, A. (2010). Tekhnogennye seysmicheskie yavleniya, svyazannye s razrabotkoy i ekspluatatsiey mestorozhdeniy tverdykh poleznykh iskopaemykh, nefti i gaza. *Geologiya i Okhrana Nedr*, *1*(34), 1-12.

[9] Lovchikov, A.V. (2016). Nekotorye voprosy proyavleniya gorno-tektonicheskikh udarov i tekhnogennykh zemletryaseniya na rudnikakh. *Prognoz i Preduprezhdenie Tektonicheskikh Gornykh Udarov i Zemletryaseniya: Izmerenie Deformatsiy, Ostatochnykh i Deystvuyushchikh Napryazheniy v Gornom Massive*, 39-49.

[10] Sokolova, I.N., Mikhaylova, N.N., Velikanov, A.E., & Poleshko, N.N. (2017). Tekhnogennaya seysmichnost' na territorii Kazakhstana. *Vestnik NYaTs RK*, *2*, 47-56.

[11] Fedko, M.B., Muzyka, I.O., Pysmennyi, S.V. & Kalinichenko, O.V. (2019). Determination of drilling and blasting parameters considering the stress-strain state of rock ores. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *1*, 37-41. https://doi.org/10.29202/nvngu/2019-1/20

[12] Kyelgyenbai, K., Pysmennyi, S., Chukharev, S., Purev, B., & Jambaa, I. (2021). Modelling for degreasing the mining equipment downtime by optimizing blasting period at Erdenet surface mine. *E3S Web of Conferences*, *280*, 08001. https://doi.org/10.1051/e3sconf/202128008001

[13] Lawal, A.I., Kwon, S., Hammed, O.S., & Idris, M.A. (2021). Blast-induced ground vibration prediction in granite quarries: An application of gene expression programming, ANFIS, and sine cosine algorithm optimized ANN. *International Journal of Mining Science and Technology*, *31*(2), 265-277. https://doi.org/10.1016/j.ijmst.2021.01.007

[14] Askaripour, M., Saeidi, A., Rouleau, A., & Mercier-Langevin, P. (2022). Rockburst in underground excavations: A review of mechanism, classification, and prediction methods. *Underground Space*, *7*(4), 577-607. https://doi.org/10.1016/j.undsp.2021.11.008

[15] Qiu, Y., & Zhou, J. (2023). Short-term rockburst prediction in underground project: insights from an explainable and interpretable ensemble learning model. *Acta Geotechnica*, *18*(12), 6655-6685. https://doi.org/10.1007/s11440-023-01988-0

[16] Ren, F., Zhu, C., He, M., Shang, J., Feng, G., & Bai, J. (2023). Characteristics and precursor of static and dynamic triggered rockburst: insight from multifractal. *Rock Mechanics and Rock Engineering*, *56*(3), 1945-1967. https://doi.org/10.1007/s00603-022-03173-3

[17] Lapin, V., Makish, N., Kassenov, K., Omarov, Z., & Kassenov, D. (2022). Spectral response characteristic of local earthquakes according to instrumentation readings of the engineering-seismometrical service. *International School on Neural Networks*, 1437-1446. https://doi.org/10.1007/978-3-031-11051-1_147

[18] Shepetov, A., Kryakunova, O., Mamina, S., Ryabov, V., Saduyev, N., Sadykov, T., & Zhukov, V. (2021). Geophysical aspect of cosmic ray studies at the Tien Shan mountain station: Monitoring of radiation background, investigation of atmospheric electricity phenomena in thunderclouds, and the search for the earthquake precursor effects. *Physics of Atomic Nuclei*, *84*, 1128-1136. https://doi.org/10.1134/S1063778821130330

[19] Lapin, V., Makish, N., Kassenov, K., Omarov, Z., & Kassenov, D. (2021). Instrumental records received in 11 storey steel frame building during a remote earthquake. *E3S Web of Conferences*, *258*, 09078. https://doi.org/10.1051/e3sconf/202125809078

[20] Sydykov, A., Sadykova, A.B., & Siylkanova, A.O. (2021). Diurnal periodicity of weak earthquakes in the Zhongar North Tian Shan region. *Surveys in Geophysics*, *42*, 21-41. https://doi.org/10.1007/s10712-020-09622-4

[21] Tolovkhan, B., Demin, V., Amanzholov, Zh., Smagulova, A., Tanekeyeva, G., Zairov, Sh., Krukovskyi, O., & Cabana, E. (2022). Substantiating the rock mass control parameters based on the geomechanical model of the Severny Katpar deposit, Kazakhstan. *Mining of Mineral Deposits*, *16*(3), 123-133. https://doi.org/10.33271/mining16.03.123

[22] Lenhardt, W.A. (2009). The impact of earthquakes on mining operations. *BHM Berg-und Hüttenmännische Monatshefte*, *154*(6), 249-254. https://doi.org/10.1007/s00501-009-0470-1

[23] Kocharyan, G.G., Budkov, A.M., & Kishkina, S.B. (2018). Initiation of tectonic earthquakes during underground mining. *Journal of Mining Science*, *54*, 561-568. https://doi.org/10.1134/S1062739118044014

[24] Pysmennyi, S., Chukharev, S., Peremetchy, A., Fedorenko, S., & Matsui, A. (2023). Study of stress concentration on the contour of underground mine workings. *Inżynieria Mineralna*, *1*(1(51)), 69-78. https://doi.org/10.29227/IM-2023-01-08

[25] Hsiung, S.M., Blake, W., Chowdhury, A.H., & Williams, T.J. (1992). Effects of mining-induced seismic events on a deep underground mine. *Pure and Applied Geophysics*, *139*, 741-762. https://doi.org/10.1007/BF00879961

[26] Srikrishnan, S., Porathur, J.L., & Agarwal, H. (2014). Impact of earthquake on mining slopes – A numerical approach. *Arabian Journal of Geosciences*, *7*(12), 5193-5208. https://doi.org/10.1007/s12517-013-1144-6

[27] Mitchell, J.K., & Green, R.A. (2017). Some induced seismicity considerations in geo-energy resource development. *Geomechanics for Energy and the Environment*, *10*, 3-11. https://doi.org/10.1016/j.gete.2017.01.001

[28] Adushkin, V.V. (2016). Tectonic earthquakes of anthropogenic origin. *Izvestiya, Physics of the Solid Earth*, *52*, 173-194. https://doi.org/10.1134/S1069351316020014

[29] Malinowska, A.A., Witkowski, W.T., Guzy, A., & Hejmanowski, R. (2018). Mapping ground movements caused by mining-induced earthquakes applying satellite radar interferometry. *Engineering Geology*, *246*, 402-411. https://doi.org/10.1016/j.enggeo.2018.10.013

[30] Owczarz, K., & Blachowski, J. (2020). Analysis of the geometry of surface deformations caused by induced tremors in the area of underground copper mining. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *3*, 149-156. https://doi.org/10.5194/isprs-annals-V-3-2020-149-2020

[31] Nurpeissova, M., Rysbekov, K., Levin, E., Derbisov, K., & Nukarbekova, Z. (2021). Study of slow motions of the earth surface. *Engineering Journal of Satbayev University*, *143*(5), 3-9. https://doi.org/10.51301/vest.su.2021.i6.01

[32] Nurpeissova, M., Bitimbayev, M.Zh., Rysbekov, K.B., Derbisov, K., Turumbetov, T., & Shults, R. (2020). Geodetic substantiation of the Saryarka copper ore region. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *6*(444), 194-202. https://doi.org/10.32014/2020.2518-170X.147

[33] Khozyaykina, N.V., Soldatova, B.S., & Khozyaykin, A.V. (2014). Tekhnogennye seysmicheskie yavleniya pri ekspluatatsii mestorozhdeniy tverdykh poleznykh iskopaemykh. *Geomekhanika i Geotekhnika*, 104-110.

[34] Shkolnik, V.S., Rogov, E.I., Karabalin, U.S., Ogay, E.K., & Rogov A.E. (2015). Sposob isklyucheniya tekhnogennykh katastrof pri dobyche nefti zavodneniem plastov s yacheistymi skhemami. *Nauchno-Tekhnicheskoe Obespechenie Gornogo Proizvodstva*, *87*, 357-362.

[35] Kozhogulov, K.Ch. (2015). Obespechenie bezopasnosti pri kombinirovannoy razrabotke rudnykh mestorozhdeniy Kyrgyzstana. *Nauchno-Tekhnicheskoe Obespechenie Gornogo Proizvodstva*, *87*, 45-48.

[36] Velikanov, A.E., Mikhaylova, N.N., Sokolova, I.N., Aristova, I.L., & Mukambaev, A.S. (2013). Izuchenie istochnikov promyshlennykh vzryvov na territorii Kazakhstana. *Vestnik NYaTs RK*, *2*, 77-85.

[37] Bekbergenov, D.K., & Tolysbaev, A.K. (2015). Zarubezhnaya praktika i podzemnaya razrabotka Zhezkazganskogo mestorozhdeniya kamerno-stolbovoy sistemoy. *Nauchno-Tekhnicheskoe Obespechenie Gornogo Proizvodstva*, *87*, 1-14.

[38] Pihulevskyi, P.G., Anisimova, L.B., Kalinichenko, O.O., Panteleeva, N.B., & Hanchuk, O.V. (2021). Analysis of natural and technogenic factors on the seismicity of Kryvyi Rih. *Journal of Physics: Conference Series*, *1840*(1), 012018. https://doi.org/10.1088/1742-6596/1840/1/012018

[39] Adushkin, V.V., & Oparin, V.N. (2013). Ot yavleniya znakoperemennoy reaktsii gornykh porod na dinamicheskie vozdeystviya k volnam mayatnikovogo tipa v napryazhennykh geosredakh. *Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh*, *2*, 3-46.

[40] Nurpeisova, M.B., & Kurmanbaev, O.S. (2016). Laws of development of geomechanical processes in the rock mass Maykain mine. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *6*(420), 109-115.

[41] Stupnik, M., Kalinichenko, V., & Pismennyi, S. (2013). Pillars sizing at magnetite quartzites room-work. *Annual Scientific-Technical Collection – Mining of Mineral Deposits 2013*, 11-15. https://doi.org/10.1201/b16354-3

[42] Yakovlev, D.V., Tsirel', S.V., & Mulev, S.N. (2016). Laws of spreading and operational evaluation procedure for induced seismicity in mines and in mining areas. *Journal of Mining Science*, *52*(2), 233-244. https://doi.org/10.1134/S1062739116020369

[43] Zhou, J., Zhang, Y., Li, C., He, H., & Li, X. (2023). Rockburst prediction and prevention in underground space excavation. *Underground Space*, *14*, 70-98. https://doi.org/10.1016/j.undsp.2023.05.009

[44] Tsai, C.H., Abdrakhmatov, K., Mukambayev, A., Elliott, A.J., Elliott, J.R., Grützner, C., & Wilkinson, R. (2022). Probing the upper end of intracontinental earthquake magnitude: A prehistoric example from the Dzhungarian and Lepsy Faults of Kazakhstan. *Tectonics*, *41*(10), e2022TC007300. https://doi.org/10.1029/2022TC007300

[45] Tazhibaev, K.T. (2016). Nauchno-tekhnicheskie osnovy prognoza p preduprezhdeniya tektonicheskikh gornykh udarov i zemletryaseniy. *Prognoz i Preduprezhdenie Tektonicheskikh Gornykh Udarov i Zemletryaseniya: Izmerenie Deformatsiy, Ostatochnykh i Deystvuyushchikh Napryazheniy v Gornom Massive*, 25-37.

[46] Batugin, A.S., & Shermatova S.S. (2016). K otsenke maksimalnoy magnitudy tekhnogennogo zemletryaseniya v gornopromyshlennom rayone. *Prognoz i Preduprezhdenie Tektonicheskikh Gornykh Udarov i Zemletryaseniya: Izmerenie Deformatsiy, Ostatochnykh i Deystvuyushchikh Napryazheniy v Gornom Massive*, 12-13.

[47] German, V.I., & Mansurov, V.A. (2010). Prognoz obrusheniy na Zhezkazganskom mednom mestorozhdenii. *Gornyy Informatsionno-Analiticheskiy Byulleten*, *1*, 95-105.

[48] Rysbekov, K.B., Toktarov, A.A., & Kalybekov, T. (2021). Technique for justifying the amount of the redundant developed reserves considering the content of metal in the mining ore. *IOP Conference Series: Earth and Environmental Science*, *666*(3), 032076. https://doi.org/10.1088/1755-1315/666/3/032076

[49] Baibatsha, A.B., Bekbotayeva, A.A., & Bekbotayev, A.T. (2015). Ore minerals of Carboniferous copper sediment-hosted Zhezkazgan deposit (Central Kazakhstan). *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, *1*, 329-335.

[50] Portnov, V.S., Yurov, V.M., & Maussymbayeva, A.D. (2016). Applied problems of thermodynamic approach to the analysis of geophysical information. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *1*, 5-11.

[51] Shoimuratov, T.H., Hajitov, N.Sh., & Kurbanyazov, S.K. (2022). The role of hydrodynamic and structural-tectonic factors in the formation of hydrocarbon deposits in the Jurassic sediments of the Bukharo-Khiva region. *Engineering Journal of Satbayev University*, *144*(4), 41-45. https://doi.org/10.51301/ejsu.2022.i4.06

[52] Dashchenko, A.F., Kirillov, V.Kh., Kolomiets, L.V., & Orobey, V.F. (2003). *MATLAB v inzhenernykh i nauchnykh raschetakh*. Odesa, Ukraina: Astroprint, 216 s.

[53] Baibatsha, A.B., Bekbotayev, A.T., & Bekbotayeva, A.A. (2013). Ore-bearing strata lithology of the Zhezkazgan copper sandstones deposit. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, *1*, 135-140.

[54] Aidarbekov, Z.K., Istekova, S.A., & Glass, H. (2021). Complex of geophysical research for studying geological structure of Zhezkazgan ore region in Kazakhstan. *Engineering and Mining Geophysics*, *1*, 1-9. https://doi.org/10.3997/2214-4609.202152070

[55] Aidarbekov, Z.K., & Istekova, S.A. (2022). Classification of geophysical fields in the study of geological and structural features of the Zhezkazgan ore district. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *2*(452), 33-48. https://doi.org/10.32014/2022.2518-170X.158

[56] Baymakhan, R.B., Muta, A.N., Tileikhan, A., & Kozhogulov, K.C. (2023). On the use of the finite element method in the study of the stress-strain state of the contour of the Annie Cave on Mount Arsia. *Engineering Journal of Satbayev University*, *145*(2), 31-36. https://doi.org/10.51301/ejsu.2023.i2.05

[57] Wang, S., Zheng, H., Li, C., & Ge, X. (2011). A finite element implementation of strain-softening rock mass. *International Journal of Rock Mechanics and Mining Sciences*, *48*(1), 67-76. https://doi.org/10.1016/j.ijrmms.2010.11.001

[58] Mao, H., Xu, N., Zhou, Z., Sha, C., Xiao, P., & Li, B. (2024). Failure mechanism and deformation forecasting of surrounding rock mass in an underground cavern based on engineering analogy method. *Tunnelling and Underground Space Technology*, *143*, 105497. https://doi.org/10.1016/j.tust.2023.105497

[59] Imansakipova, B.B., Baygurin, Z.D., Soltabaeva, S.T., Milev, I., & Miletenko, I.V. (2014). Causes of strain of buildings and structures in areas of abnormal stress and surveillance terrestrial laser scanners. *Life Science Journal*, *11*(9s), 165-170.

[60] Uzbekov, A.N., & Poleshko, N.N. (2022). Stress and strain state of the Kazakh shield from the earthquake focal mechanisms data. *Geodynamics and Tectonophysics*, *13*(1), 571. https://doi.org/10.5800/GT-2022-13-1-0571

[61] Akhanov, T.M. (2010). Tekhnologicheskie osobennosti podzemnoy razrabotki zhezkazganskogo mestorozhdeniya. *Marksheyderiya i Nedropolzovanie*, *1*, 38-41.

Прогнозування магнітуди техногенних землетрусів при підземній розробці Жезказганського рудного родовища

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Мета. Встановлення зв’язку між зрушенням і обваленням масиву гірських порід і викликаними ними техногенними землетрусами при підземній розробці рудних покладів з отриманням рівняння залежності показників техногенних землетрусів в умовах Жезказганського родовища мідних руд.

Методика. Методика досліджень полягає у вивченні та аналізі ранніх досліджень щодо техногенних землетрусів методом статистичної обробки даних. Розрахунок розподілу деформацій гірського масиву в районі, що розглядається, заснований на чисельному моделюванні в середовищі програмних продуктів Comsol Multiphisics 5.6 і MATLAB 2020. Обчислення виконуються на основі рішення плоскої задачі методом скінченних елементів.

Результати. На основі переходу від площі обвалення до величин осідань і зрушень налягаючої товщі порід масиву отримано рівняння залежності магнітуди землетрусу від чисельних величин осідань або зрушень масиву.

Наукова новизна. Вперше на основі фізики та геомеханіки процесів зсуву масиву порід отримано емпірико-аналітичні формули, що дозволяють прогнозувати магнітуду техногенних землетрусів при підземній розробці рудних покладів в умовах Жезказганського родовища.

Практична значимість. Попередні прогнозні розрахунки, виконані за отриманими формулами для умов діючої шахти № 31 Східно-Жезказганського рудника ТОВ “Корпорація Казахмис», показали прийнятні результати величини магнітуди, які можна порівняти з натурними вимірами при розробці родовища. Такий прогноз дає можливість заздалегідь розрахувати магнітуду техногенних землетрусів на етапі проєктування гірничих робіт та прийняти відповідні науково-обґрунтовані рішення під час подальшої розробки родовища.

Ключові слова: *рудний поклад, підземна розробка, рудник, обвалення, зсув масиву, техногенний землетрус*

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