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© **Sh.K. Aitkazinova[1*], B.B. Imansakipova[1], O.O. Sdvizhkova[2], D.M. Kirgizbaeva[1], A.B. Imansakipova[1], 2025.**
[1]Kazakh National Research Technical University named after K.I. Satpayev, Almaty, Kazakhstan;
[2]Dnipro University of Technology, Dnipro, Ukraine.
E-mail: sh.aitkazinova@satbayev.university

LOCALIZATION OF THE SINKHOLE HAZARD OF THE EARTH'S SURFACE DURING UNDERGROUND MINING

Sh.K. Aitkazinova — PhD, Associate Professor of the Department of «Surveying and Geodesy», Kazakh National Research Technical University named after K.I. Satpayeva, Almaty, Kazakhstan,
E-mail: sh.aitkazinova@satbayev.university , orcid.org /0000-0002-0964-3008;
B.B. Imansakipova — PhD, Associate Professor of the Department of «Surveying and Geodesy», Kazakh National Research Technical University named after K.I. Satpayeva, Almaty, Kazakhstan,
E-mail: b.imansakipova@satbayev.university , orcid.org/0000-0003-0658-2112;
O.O. Sdvyzhkova — Doctor of Technical Sciences, Professor Dnipro University of Technology Dnipro, Head of the Department of Applied Mathematics, Dnipro, Ukraine,
E-mail: sdvyzhkova@gmail.com orcid.org/0000-0001-6322-7526;
D.M. Kirgizbaeva — PhD, Associate Professor of the Department of «Surveying and Geodesy», Kazakh National Research Technical University named after K.I. Satpayeva, Almaty, Kazakhstan,
E-mail: d.kirgizbaeva@satbayev.university , https:// orcid.org/0000-0002-5043-4275;
A.B. Imansakipova — PhD student, Kazakh National Research Technical University named after K.I. Satpayev, Almaty, Kazakhstan,
E-mail aimansakipova@bk.ru , https://orcid.org/0000-0001-6916-7130.

Abstract. *Relevance.* The problem of predicting the risk of failure of the Earth's surface during underground mining remains critically important for ensuring the safety of mining operations and minimizing environmental damage. Traditional estimation methods often do not take into account dynamic changes in the stress-strain state of the rock mass (MGP), which reduces their accuracy. In this regard, the development of new approaches based on energy criteria and real monitoring of the state of IHL is an urgent task. *Goal*. Development of a new method for zone zoning of the surface according to the degree of failure hazard based on the energy parameters of the IHL using dynamically updated data on its strength. *Methods.* Energy approach; Dynamic monitoring of IHL strength; Zone zoning; Mapping. *Results and conclusions.* A new criterion for the danger of destruction is proposed, based on the geoenergetic potential, taking into account gravitational and deformation processes. A method has been developed to refine the dynamic model using GSI and ultrasound tomography, as well as an algorithm for zoning the surface according to risk levels. Practical implementation has shown an increase in the accuracy of localization of areas with a risk of failure by 5-20%. The method makes it possible to reasonably plan the sequence of excavation, effectively manage risks and optimize field development. It can be integrated into digital mining management systems to improve the safety and economic efficiency of mining operations.

Key words: an array of rocks, sinkhole hazard, zone zoning, criterion, geoenergy, potential, situational maps

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© Ш.Қ. Айтқазинова[1*], Б.Б. Имансакипова[1], Е.А. Сдвижкова[2], Д.М. Қырғызбаева[1], А.Б. Имансакипова[1], 2025.

[1]Қ.И. Сәтбаев атындағы Қазақ Ұлттық техникалық зерттеу университеті, Алматы, Қазақстан;

[2]Днепр Технологиялық Университеті, Днепр, Украина.

E-mail: sh.aitkazinova@satbayev.university

ПАЙДАЛЫ ҚАЗБАЛАРДЫ ЖЕРАСТЫ ӨНДІРУ КЕЗІНДЕ ЖЕР БЕТІНІҢ ОПЫРЫЛУЫН ОҚШАУЛАУ

Ш.Қ. Айтқазинова — PhD, «Маркшейдерлік іс және геодезия» кафедрасының қауымдастырылған профессоры, Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университеті, Алматы, Қазақстан,
E-mail: sh.aitkazinova@satbayev.university, orcid.org /0000-0002-0964-3008;

Б.Б. Имансакипова — PhD, «Маркшейдерлік іс және геодезия» кафедрасының қауымдастырылған профессоры, Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университеті, Алматы, Қазақстан,
E-mail: b.imansakipova@satbayev.university, orcid.org/0000-0003-0658-2112;

Е.А. Сдвижкова — техника ғылымдарының докторы, «Қолданбалы математика» кафедрасының меңгерушісі, Днепр Технологиялық Университетінің профессоры, Днепр, Украина,
E-mail: sdvyzhkova@gmail.com orcid.org/0000-0001-6322-7526;

Д.М. Қырғызбаева — PhD, «Маркшейдерлік іс және геодезия» кафедрасының қауымдастырылған профессоры, Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университеті, Алматы, Қазақстан,
E-mail: d.kirgizbaeva@satbayev.university, https:// orcid.org/0000-0002-5043-4275;

А.Б. Имансакипова — PhD студенті, Қазақ ұлттық техникалық зерттеу университеті, Алматы, Қазақстан,
E-mail: aimansakipova@bk.ru, https://orcid.org/0000-0001-6916-7130.

Аннотация. *Өзектілігі.* Жер асты тау-кен жұмыстарының қауіпсіздігін қамтамасыз ету және экологиялық зиянды азайту үшін жер бетінің сәтсіздігін болжау мәселесі өте маңызды болып қала береді. Дәстүрлі бағалау әдістері көбінесе тау жыныстарының массивінің (МГП) кернеулі-деформацияланған күйіндегі динамикалық өзгерістерді ескермейді, бұл олардың дәлдігін төмендетеді. Осыған байланысты энергетикалық критерийлерге және МГП жай-күйінің нақты мониторингіне негізделген жаңа тәсілдерді әзірлеу өзекті міндет болып табылады. *Мақсат.* Оның беріктігі туралы динамикалық жаңартылатын деректерді пайдалана отырып, МГП энергетикалық параметрлері негізінде сәтсіздік дәрежесі бойынша бетті аймақтарға бөлудің жаңа әдісін әзірлеу. *Әдістері.* Энергетикалық тәсіл; МГП беріктігінің динамикалық мониторингі; аймақты аудандастыру; картаға түсіру. *Нәтижелер мен қорытындылар.* Гравитациялық және деформациялық процестерді ескере отырып, геоэнергетикалық әлеуетке негізделген жойылу қаупінің жаңа критерийі ұсынылды. GSI және ультрадыбыстық томографияны қолдана отырып, динамикалық модельді нақтылау әдісі, сондай-ақ тәуекел деңгейлері бойынша бетті аймақтарға бөлу алгоритмі жасалды. Тәжірибелік іске асыру сәтсіздік қаупі бар аймақтарды оқшаулау дәлдігінің 5-20% - ға өскенін көрсетті. Әдіс қазба кезектілігін негізді жоспарлауға, тәуекелдерді тиімді басқаруға және кен орындарын игеруді оңтайландыруға мүмкіндік береді. Тау-кен жұмыстарының қауіпсіздігі мен экономикалық тиімділігін арттыру үшін цифрлық өндірісті басқару жүйелеріне біріктірілуі мүмкін.

Түйін сөздер: тау жыныстарының массиві, опырылу қаупі, аймақты аудандастыру, критерий, геоэнергия, әлеует, ситуациялық карталар

©Ш.К. Айтказинова[1*], Б.Б. Имансакипова[1], Е.А. Сдвижкова[2], Д.М. Киргизбаева[1], А.Б. Имансакипова[1], 2025.

[1]Казахский Национальный исследовательский технический университет имени К.И. Сатпаева, Алматы, Казахстан;

[2]Днепровский технологический университет, Днепр, Украина.

E-mail: sh.aitkazinova@satbayev.university

ЛОКАЛИЗАЦИЯ ПРОВАЛООПАСНОСТИ ЗЕМНОЙ ПОВЕРХНОСТИ ПРИ ПОДЗЕМНОЙ ДОБЫЧЕ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Ш.К. Айтказинова — PhD, ассоциированный профессор кафедры «Маркшейдерского дела и геодезии» Казахского Национального исследовательского технического университета имени К.И. Сатпаева, Алматы, Казахстан,
E-mail: sh.aitkazinova@satbayev.university, orcid.org/0000-0002-0964-3008;
Б.Б. Имансакипова — PhD, ассоциирóванный профессор кафедры «Маркшейдерского дела и геодезии» Казахского Национального исследовательского технического университета имени К.И. Сатпаева, Алматы, Казахстан,
E-mail: b.imansakipova@satbayev.university, orcid.org/0000-0003-0658-2112;
Е.А. Сдвижкова — доктор технических наук, заведующая кафедрой «Прикладная математика», профессор Днепровского технологического университета, Днепр, Украина,
E-mail: sdvyzhkova@gmail.com, orcid.org/0000-0001-6322-7526;

Д.М. Киргизбаева — PhD, ассоциированный профессор кафедры «Маркшейдерского дела и геодезии» Казахского Национального исследовательского технического университета имени К.И. Сатпаева, Алматы, Казахстан,
E-mail: d.kirgizbaeva@satbayev.university, https:// orcid.org/0000-0002-5043-4275;
А.Б. Имансакипова — PhD студент, Казахского Национального исследовательского технического университета имени К.И. Сатпаева, Алматы, Казахстан,
E-mail: aimansakipova@bk.ru, https://orcid.org/0000-0001-6916-7130.

Аннотация. *Актуальность.* Проблема прогнозирования провалоопасности земной поверхности при подземной добыче полезных ископаемых остается критически важной для обеспечения безопасности горных работ и минимизации экологического ущерба. Традиционные методы оценки часто не учитывают динамические изменения напряженно-деформированного состояния массива горных пород (МГП), что снижает их точность. В этой связи разработка новых подходов, основанных на энергетических критериях и реальном мониторинге состояния МГП, является актуальной задачей. *Цель.* Разработка нового метода зонного районирования поверхности по степени провалоопасности на основе энергетических параметров МГП с использованием динамически обновляемых данных о его прочности. *Методы.* Энергетический подход**;** Динамический мониторинг прочности МГП**;** Зонное районирование**;** Картографирование**.** *Результаты и выводы.* Предложен новый критерий опасности разрушения, основанный на геоэнергетическом потенциале с учётом гравитационных и деформационных процессов. Разработан метод уточнения динамической модели с использованием GSI и ультразвуковой томографии, а также алгоритм зонального зонирования поверхности по уровням риска. Практическая реализация показала рост точности локализации зон с риском провала на 5–20%. Метод позволяет обоснованно планировать очередность выемки, эффективно управлять рисками и оптимизировать разработку месторождений. Может быть интегрирован в цифровые системы управления добычей для повышения безопасности и экономической эффективности горных работ.

Ключевые слова: массив горных пород, провалоопасность, зонное районирование, критерий, геоэнергия, потенциал, ситуационные карты

Introduction. Extraction of minerals during underground mining is accompanied by the formation of voids. Simultaneously with the loss of continuity, structural connections are disrupted, affecting the stability of the system. In response to man-made impacts, reactionary geomechanical processes are initiated aimed at relaxing the state of the RM or forming new structure-forming bonds that support its stability. The transience or inertia of the processes is determined by the rate of redistribution of the stress-strain state (SSS) and the physical and mechanical properties of the array. Critical stress concentrations at the boundaries of inhomogeneities with a high degree of curvature, such as peaks and edges of mine workings, dislocations, etc. can provoke the formation of foci of destruction, leading to the propagation of natural cracks, the appearance of zones of rock disintegration, initiation of displacement processes, as well as sudden uncontrolled collapse of rocks into workings. The spontaneity and avalanche-like evolution of the processes make it possible to achieve induced disturbances of the Earth's surface, which can lead to its failure in a local area. Such a development of the situation may result in the unpredictable occurrence of a crisis situation at an unexpected time, in an unspecified place on the earth's surface of the deposit in the form of its subsidence or failure (Fig.1).

a)

b)

Figure 1 - **Sinkholes of the Earth 's surface**
a) Ridder city (Ridder-Sokolnoye deposit, East Kazakhstan region), 2014;
b) Maykain mine (Pavlodar region), 2024.

Most of the known methods for predicting the risks associated with sinkhole formation are formed on the basis of an analysis of the mining and geological conditions of the deposit (occurrence of rocks, the specifics of their structure and texture, the presence of discontinuous geological disturbances in the form of discharges and thrusts, plicative disturbances, karst cavities, the specifics of the relief of the Earth's surface), as well as mining and technical conditions for mining minerals (method and procedure of mining, technological schemes, methods of protection of workings). The results of the analysis provide detailed information about the forms of genesis and patterns of placement of violations, about changes in the properties and condition of the mountain range, allow us to make quantitative and qualitative assessments of the conditions of formation and occurrence of violations, the degree of disturbance, and to make assumptions about the directions and intensity of such processes (Shustov et. al., 2012).

Studies of the risks associated with the development of deposits in conditions of probable sinkhole formation show that the assessment of the risk of sinkholes can be divided into three stages: forecasting (Gutiérrez et. al., 2008; Galve et. al., 2009), assessing the severity of the event (Gutiérrez et. al., 2008) and a retrospective analysis of previous failures (Theron et. al., 2017). The information obtained from the analysis of sinkholes and mapping of underground cavities can be used to identify high-risk areas (Andre Theron et. al., 2018).

Monitoring the condition of the earth's surface is a traditional way of preventing risks associated with the side-work of territories (Issabek et. al., 2019). However, instrumental methods with a fairly high accuracy have a significant disadvantage, since they do not allow simultaneous observation of the entire surface. The established cause-and-effect relationship between the conditions and processes in the mountain range and the daytime surface located in the zone of mutual influence determines the sites by the levels of failure hazard. Areas with a high level of sinkhole risk in the waiting stage of involvement in the sinkhole formation process may be in this state indefinitely. (Mutambo et. al., 2022) provides a unique example of the formation of sinkholes in our time on the territory of an abandoned mine more than a century ago.

A more effective tool for detecting signs of sinkhole formation is the methods of space radar interferometry (SRI), which can simultaneously cover the entire field with a satellite image. The paper (Guerrero et. al., 2021) presents innovative approaches to the detection of subsidence in karst areas using interferometric radar and InSAR methods, as well as the LiDAR platform for detecting shear deformations. The ability of these products to detect active karst craters in the evaporite karst of the Ebro Valley (northeastern Spain) has been demonstrated. The authors of (Hamdi et. al., 2020) also cite the results obtained using InSAR methods for large-scale monitoring of deformations of the Earth's surface and soil instability in two craters that collapsed and caused serious damage in the Cheria basin (Algeria). In (Muhagir et. al., 2021), the results of a study of the deformation of the earth's surface due to excessive exploitation of groundwater are presented. Based on the analysis of Sentinel-1 data, deformations of the earth's surface were revealed in the form of an extensive subsidence bowl (28.5 km in diameter) with a maximum sinking rate of 40 mm/year and a standard deviation inside the bowl of less than 2 mm/year.. The a uthors of (Zherong et. al., 2023) have shown that the multi-time synthetic aperture interferometric radar (InSAR) is an effective tool for measuring large-scale land subsidence, but requires automatic methods for detecting and classifying subsidence.

Radar interferometry makes mistakes due to atmospheric effects that can mask the actual displacements of the Earth's surface. Stable reflector methods and special smoothing filters are used to reduce atmospheric interference when processing a series of interferograms (Franck et. al., 2021). The use of numerical meteorological models has also shown its effectiveness in reducing atmospheric noise, which has been confirmed in tropical regions.

A common disadvantage of space technology is the loss of relevance of the data obtained due to the long-term processing of information to achieve the required accuracy, thereby limiting practical use in solving the problems of forecasting failure formation.

In Kazakhstan, based on the established causal relationship between processes in the massif and on the surface, the scientific and methodological base of methods for detecting weakened zones on the earth's surface of ore deposits has been developed (Spitsyn et. al., 2019).

These methods, unlike others, allow spatial localization of areas of the earth's surface with a high level of sinkhole risk throughout the field. The presence of voids leads to an excess of the geoenergy level relative to the level of the array in a stable state, thereby determining the metostability of the state of the RM. At the same time, under conditions of mass invariance, the basic principle of stability is violated, in which the system has a minimum value of potential energy. This determines the use of the amount of geoenergy between the two states as a criterion for zone zoning.

In (Sadykov et. al., 2019), the excess geoenergy is considered to be the potential gravitational energy of RM without taking into account the potential energy of elastic deformation. This leads to a loss of zoning accuracy. The most accurate results in the localization of areas with a high level of failure risk were obtained using two criteria (Imansakipova et. al., 2021), determined, respectively, by changes in geoenergy during the transition of the array from the initial state (stable) to the current and from the current (metastable) to the final (stable).

The disadvantages of this approach include the following: the calculation of criteria does not take into account changes in the GSI rating, in addition, when calculating the energy density of elastic deformation, only external pressures on the layer from the overlying rocks are used, but the internal pressure created by its own weight in the layer is not taken into account.

To improve the accuracy of zoning, a criterion is proposed that takes into account the internal pressure in the layer and the current values of the GSI rating, which is set according to the fracture parameters determined experimentally.

Materials and basic methods.

Energy is a universal measure of movement and a source of realization of processes. The greater the excess of geoenergy of the metastable state of the RM over the stable one, the greater the likelihood of the development of processes, the ultimate goal of which is failure formation. Geoenergy W is determined by the sum of the potential gravitational energies W_T and elastic deformation W_d and is therefore potential. It follows that the potential of geoenergy φ is equal to the sum of the gravitational potentials φ_d:

$$\varphi = \varphi_T + \varphi_d, \quad (1)$$

where $\varphi = \frac{W}{m}$, $\varphi_T = \frac{W_T}{m}$, $\varphi_d = \frac{W_d}{m}$, m – the mass of the rock mass.

For the effectiveness of the zoning method, it is proposed to use the potential of geoenergy as a criterion, taking into account the current values of the GSI rating of the array and the internal pressure in the layer. The criterion is calculated on the basis of a model common to all zoning methods (Spitsyn et. al., 2019), according to which the deposit is divided into mass elements in the form of a square column, a single area extending along the z axis from its lower horizon (z=0) to the daytime surface. The rock mass is divided into layers, within which the specific gravity (density) of the Young’s modulus and the Poisson’s ratio can be considered constant (Fig. 2).

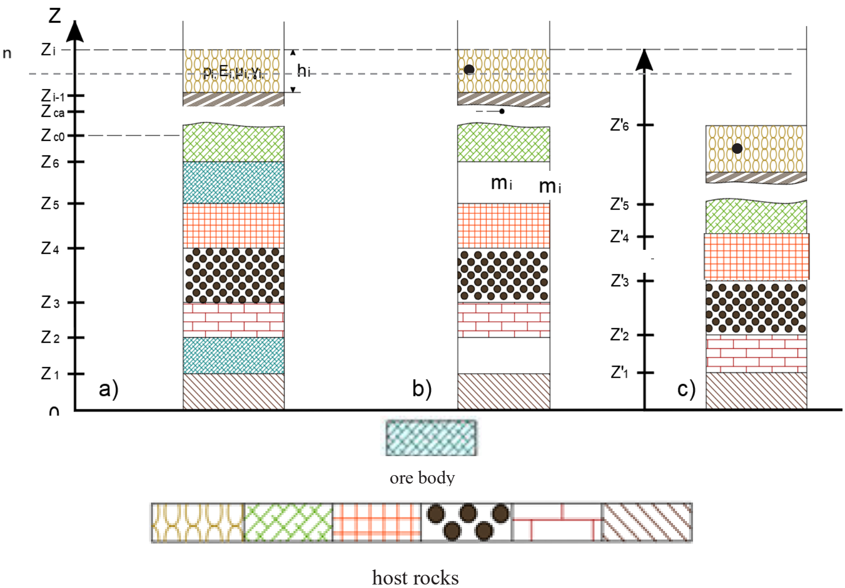


Figure 2 – Diagram for calculating the geoenergy potential of a mountain range a)-in the initial, b) in the current, c) in the final states z_i and z_{i-1}, z_{ci} – coordinates of the upper and lower boundaries, the center of mass, h_i=z_{i+1}-z_i – thickness, E_i – Young's module, μ_i – the Poisson's ratio, ρ_i – density, γ_i – specific gravity of the i-th layer, m_j – capacity of the j-th generation

Accordingly, the gravitational potential energy W_{T0} of the entire column in its initial state (Fig.2a):

$$\varphi_{TO} = \sum_{i=0}^{n} \varphi_{Ti} = \sum_{i=0}^{n} g(z_i + 0{,}5h_i) \tag{2}$$

As a result of mining, the continuity of the column is disrupted by mining operations (Fig.2b). The potential of the column's gravitational energies in this (current) state φ_{Tn} is determined by the sum of the potentials of the layers not affected by mining operations:

$$\varphi_{Tn} = \sum_{i=0, i\neq j}^{n} \varphi_{Ti} = \sum_{i=0, i\neq j}^{n} g(z_i + 0{,}5h_i) \tag{3}$$

where -j the index that defines the coordinate of the lower boundary of the mine.

Each layer experiences pressure from the overlying layers and internal pressure created by its own weight. The internal pressure varies from 0 upper part to $q\rho_i h_i$. In this regard, its average value of 0,5 $q\rho_i h_i$. Thus, the total pressure to which the layer is subjected will be equal to:

$$p_i = \sum_{k=i+1}^{n} \rho_i g_i + 0{,}5\, g\rho_i h_i. \quad (4)$$

According to A.Geim, the layer is subject to comprehensive hydrostatic compression. The equality of the initial stresses follows from this:

$$\sigma_{xi}=\sigma_{yi}=\sigma_{zi}=\sigma=p_i \quad (5)$$

As a result of comprehensive compression, the layer accumulates the potential energy of elastic deformation with an energy density ω_i equal to:

$$\omega_i=\frac{p_i^2}{2K_i}, \quad (6)$$

where K_i is the volumetric modulus of elasticity of the layer equal to:

$$K_i = \frac{E_i}{3(1-2\mu_i)}, \quad (7)$$

where E_i Young's modulus, μ_i is the Poisson's ratio.

Cracking processes have an impact on the GSI rating and elastic properties of the rock mass, thereby changing the energy of elastic deformation. In this situation, it becomes necessary to update data on fracture parameters.

The studies (Ma et. al., 2022) consider changes in the ultrasonic and mechanical properties of rock and identify the characteristics of fracturing and subcritical crack propagation of rocks with different lithologies.

The most effective methods are ultrasound tomography (Zubelewicz et. al., 2024). For the practical implementation of the method in mining conditions, a method has been developed, protected by the patent of the Republic of Kazakhstan (Patent na izobretenie RK No. 35795, 2024), in which the study of fracturing of a rock mass by ultrasonic waves is carried out from one well according to the delay time of receiving ultrasonic pulses reflected from cracks relative to those generated, for this piezoelectric transducers are installed at the vertices of a regular n-gon inscribed in the cross–section of the well - sensors, the input of which is connected to the ultrasonic pulse generator, the output – To a pulse analyzer to determine the delay time that converts electrical energy into acoustic energy and vice versa, the angle of the polygon is determined by the effective angle of the radiation pattern of the sensor.

According to experimentally determined parameters of the cracks in the massif, the geological strength index (GSI) is recalculated based on the Hawke-Brown elastoplastic deformation model, according to which the modulus of elasticity of the massif is calculated (Babets et. al., 2017):

$$E_i = E_{0i}\left(0{,}02 + \frac{1}{1+e^{(60-GSI)/11}}\right), \quad (8)$$

where, Ei and E_0i -the modulus of elasticity of the i-th layer in the current and initial states respectively.

The currently established modulus of elasticity Ei, determined by the current values of the GPI rating, leads to a change in the volumetric modulus of elasticity K_i.

Accordingly, the energy of elastic deformation of the column in the current state $W_{dn,}$ (Fig.2b) will be equal to:

$$W_{dn} = \sum_{i=1, i\neq j}^{n} W_{di} = \sum_{i=1}^{n} \frac{3\left(\sum_{l=i+1}^{n} \rho_i g h_i\right)^2 (1-2\mu_i) h_i}{2E_i \rho_i}, \quad (9)$$

where n is the number of layers.

From (9), for the potential, the energy of elastic deformations of the column in the current state φ_{dn} follows:

$$\varphi_{dn} = \sum_{i=1, i\neq j}^{n} \frac{3\left(\sum_{l=i+1}^{n} \rho_i g h_i\right)^2 (1-2\mu_i) h_i}{2E_i} \quad (10)$$

The potential of geoenergy in the final state φf is determined by:

$$\varphi_f = \sum_{i=0, i\neq j}^{n} g\left(z_i - \sum_{j=a}^{f} m_j + 0{,}5h_i\right) +$$

$$\sum_{i=1}^{n} \frac{3\left(\sum_{l=i+1-r}^{n} \rho_i g h_i\right)^2 (1-2\mu_i) h_i}{2E_i} \quad (11)$$

Potential energy is a relative quantity, determined with precision to a constant. The energy and potential in the final state are taken as the zero level.

According to this, the potential of geoenergy in the current state φ_{n0} will be equal to:

$$\varphi_{n0} = \sum_{i=0, i\neq j}^{n} g(z_i + 0{,}5h_i) + \sum_{i=1, i\neq j}^{n} \frac{3\left(\sum_{l=i+1}^{n} \rho_i g h_i\right)^2 (1-2\mu_i) h_i}{2E_i} +$$

$$+ \sum_{i=0, i\neq j}^{n} g\left(z_i - \sum_{j=a}^{f} m_j + 0{,}5h_i\right)$$

$$+ \sum_{i=1}^{n} \frac{3\left(\sum_{l=i+1-r}^{n} \rho_i g h_i\right)^2 (1-2\mu_i) h_i}{2E_i} \quad (12)$$

Results. A qualitative assessment of the influence of the parameters that determine the state of RM and are included in the basis of the criterion on the formation of the potential of geoenergy is carried out on a simplified model. According to which the array is considered homogeneous in physical and mechanical properties with values of density (p =2,7· 10^3 kg/m^3), Young's modulus (E=0,2· 10^{-3} MPa) and Poisson's ratio (μ=0,6· 10^{-3}).

Fundamentally differing in the physics of origin, gravitational energy and elastic deformation differ qualitatively and quantitatively in their contribution to the accumulation of geoenergy of the layer and the formation of the criterion. The exponential dependence of the elastic deformation energy on the depth of the layer, in contrast to the linear dependence of the gravitational energy, leads to an increase in its share and increased importance in the formation of geoenergy (potential, criterion). This is clearly seen from the dependence of the potentials of the elastic deformation energies φ_d, gravity φ_T and geoenergy φ on the depth of the layer following from (10) and (12) (Fig.3).

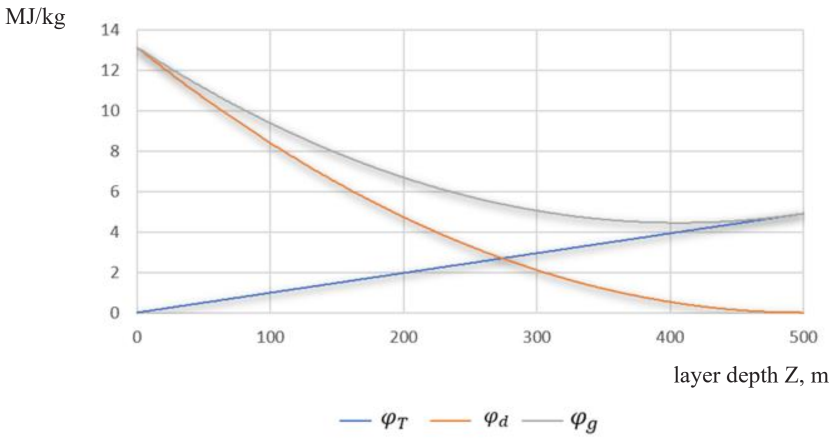


Figure 3 - Change in elastic deformation potentials φ_d, gravitational energy φ_T, and geoenergy φ_q of the layer with depth Z

The gravitational energy potential of the φ_T layer is determined by its position in the Earth's gravitational field, does not depend on its mass, and, in accordance with the selected reporting system, varies from the zero value of the lower part of the column to the maximum value in the upper one. The elastic deformation potential φ_d is determined by the amount of accumulated energy of the layer under the influence of external forces, which varies from the maximum value under the weight of the overlying rocks of the entire column to the value determined by the internal pressure in the lower part. Unlike the gravitational energy potential, the elastic deformation energy potential depends on the GSI rating (8, 10).

Figure 4 shows a graph of the dependence of the ratio of the specific energies of the layer in the initial state ω_{0i} and in the current ω_i states on the GSI rating (8).

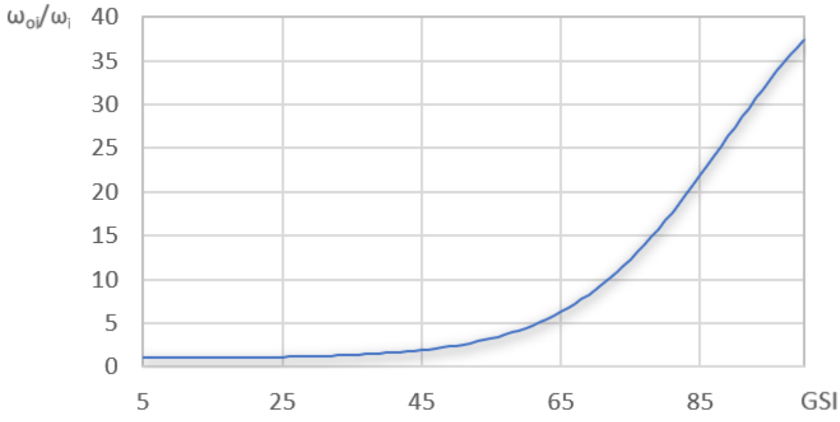


Figure 4 - Dependence of the ratio of the specific energies of the layer in the initial state ω_{0i} and in the current ω_i states on the GSI rating

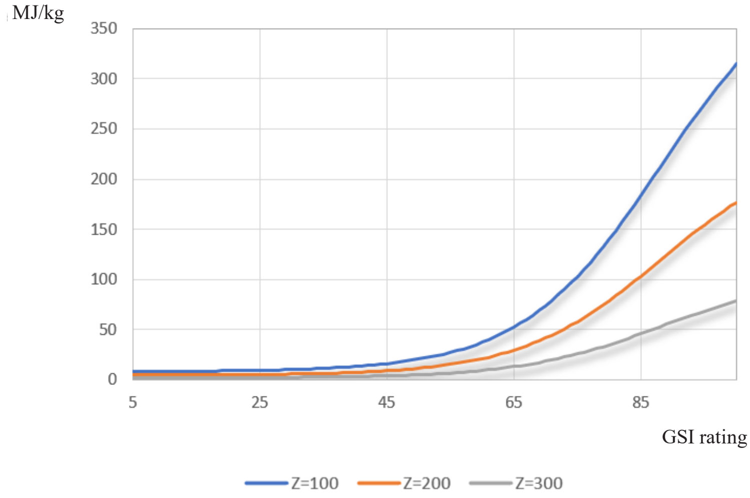


Figure 5 - Dependence of the elastic deformation potential φ_d on the GSI rating at a fixed layer depth

The influence of the GSI rating on the amount of elastic deformation energy indicates the need to use its current values in the calculations of the criterion based on the potential of geoenergy. For this purpose, fracture parameters were determined by ultrasonic sounding of the rock mass from a drilled well (Babets et. al., 2017).

An OPGS pulsed ultrasonic generator and CA-YD-187T piezoelectric transducers were used for the study. OPGS is a universal multichannel oscillator capable of exciting ultrasonic converters with a frequency of 50-500 kHz. The reception of the signal from the piezo sensors and their analysis was carried out on a personal computer using MatLab software. An acoustic probe with piezoelectric sensors was lowered into the borehole discretely with an interval of 15-20 cm. The probe was oriented so that the main axes of the lobes of the piezoelectric sensor pattern were orthogonal to the axis of the well. The position of the probe for each measurement was fixed by a pressure pneumatic system, which at the same time provided reliable contact conditions for the piezo sensors with the mountain range. As an example, Tables 1 and 2 show the fracture parameters from a well drilled at horizon 13 (Chamber 10, Panel 116, Block 03, K 42).

Table 1 – Angles of incidence of the slit plane on the borehole axis

Angle of incidence of the crack plane on the borehole axis, degrees (±5°)	15	30	45	60	75	90	105	120	135	150	165	180
The number of planes with the same angle of incidence	65	3	4	3	1	3	55	1	3	4	54	1

Table 2 – Fracture system for the borehole massif

Fracturing system	Elements of occurrence		The distance between the cracks, m.	Crack opening, mm
	Azimuth of the strike, deg.	Angle of incidence, deg.		
1	175±15	15±11	0,18±0,6	1
2	270±12	105±9	0,24±0,19	6
3	0±11	165±7	0,19±0,23	1

The distance between the cracks ranges from 0.18 to 0.24 m, the degree of crack opening ranges from 1 to 6 mm, the cracks are filled with a solid filler. Most cracks are steeply sloping with angles of inclination from 65 to 85 degrees.

According to the obtained fracture parameters, an assessment is carried out using the GSI rating indicators. For our example, the GSI index is 47, in contrast to the established value for core samples in laboratory studies - 65.

For convenience in practical use, comparing the results obtained by different methods, as a rule, a unified form of representation of the criterion in the form of a relative value is used. In the proposed method, the value γ is selected:

$$\gamma = \frac{\varphi_n - \varphi_f}{\varphi_n} \cdot 100\,\%, \qquad (13)$$

where φ_n and φ_f It is determined, respectively, from (11).

The boundary values of the criterion for the conditions of the Ridder-Sokolny deposit were established based on a retrospective analysis of the causes and parameters for nine sinkholes that occurred at different times and on different surface areas (Table 3).

Table 3 – Funnel parameters

№	Name of the excavation unit	Depth of development	Dredging capacity	Depth of the sinkhole	Loosening ratio
1	23 л.о. Blocks 12, 17, 21, panels 54, 15, 120, 90	254	70	21	1,19
2	17 л.о. Blocks 1, 9, 7, panels 18, 135, 2, 22, 23, 50	247	52	36	1,06
3	The fracture line, Blocks 7, 4-5, panels 45, 9, 113	211	37	19	1,09
4	23 л.о. Blocks 16, panels44	283	65	16	1,17
5	4 л.о. (20-24 л.ш.), panels 30, 31	99	55	20	1,35
6	5 л.о. (19-24 л.ш.), panels 30, 31, 41, 42	111	57	20	1,33
7	4 л.о. (11-16 л.ш.), panels 24, 16	91	40	24	1,18
8	5 л.о. (11-16 л.ш.), panels 4, 16	110	37	16	1,19
9	2 л.о. Blocks 5, 4, panels 15, 16, 24, 13	266	95	27	1,26

The depth of the sinkholes ranged from 16 to 36 m with a depth of development from 91 to 283, a dredging capacity from 37 to 95 and a loosening coefficient from 1.06 to 1.35. Based on archived data on the state of the RM preceding each event, the surface was zoned according to criterion γ (13) and its boundary values were set.

For the Ridder-Sokolny deposit, the zones are divided into three levels of failure hazard, which are determined by two boundary values of the criterion (Table 4).

Table 4 – Numerical values of boundary criteria

Fire hazard level	γ	
	More	Less
High (red)	13	
Medium (yellow)	8	13
Low (green)		8

Situational maps are created based on the results of zone zoning.

For a correct comparison of the zoning results using the proposed M_1 method obtained in (Zubelewicz et. al., 2024) and the M_2 method, the same site of the Ridder-Sokolny deposit was selected. The same parameters characterizing the state of RM were used to calculate the criterion, including its boundary values. The exception is the values of the Young's modulus, which in the new method are determined by the actual values of the GSI.

Figure 6 (b) provides the current situational map obtained from the results of zone zoning in accordance with the developed methods (M_2). For comparison, Figure 6 (a) shows a situational map from (Zubelewicz et. al., 2024) based on the method of zoning according to two criteria (M_1).

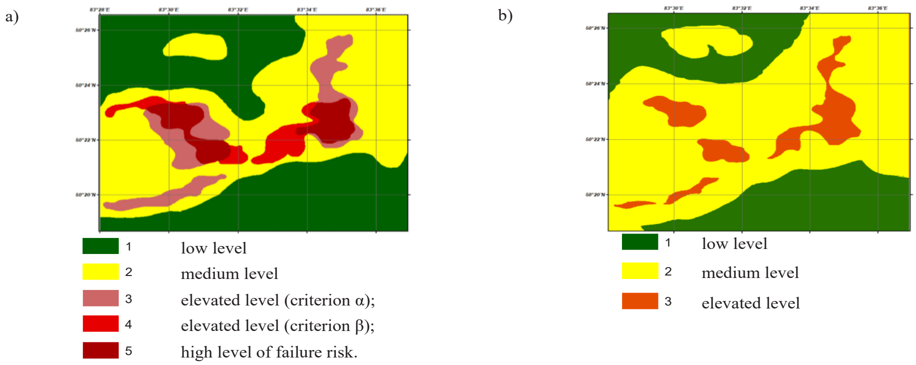


Figure 6 - Situational maps obtained by the M_1 (a) and M_2 (b) methods

For comparison, Figure 7 shows a histogram of the areas of zones with different levels of failure hazard for the results of zoning using the M_1 and M_2 methods.

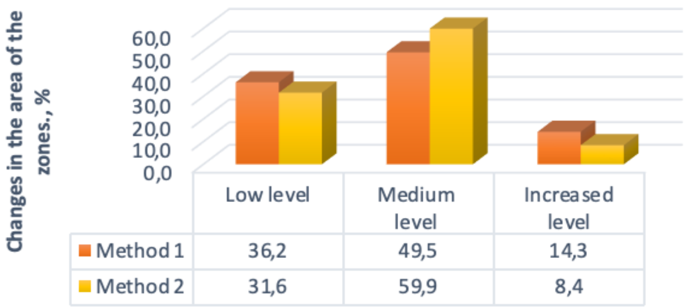
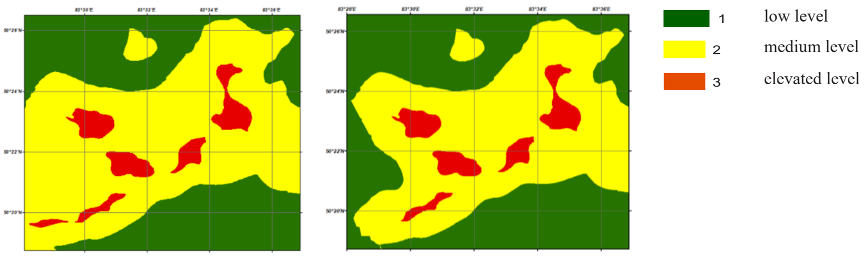


Figure 7 – Comparison of the areas of zones with different levels of failure hazard for the results of zoning using the M_1 and M_2 methods.

A comparative analysis of the figures shows that the use of a criterion based on the potential of geoenergy, which takes into account the current values of GSI and internal pressure, changes the boundaries of zones with different levels of failure hazard. Areas with a high level of sinkhole risk, defined by two criteria M_1, are represented by separate zones with M_2 that retain their sinkhole status. At the same time, the total area of zones with a high level of failure risk is reduced by 5.9%. This is a consequence of taking into account changes in the elastic properties of the RM in the M_2 criterion.

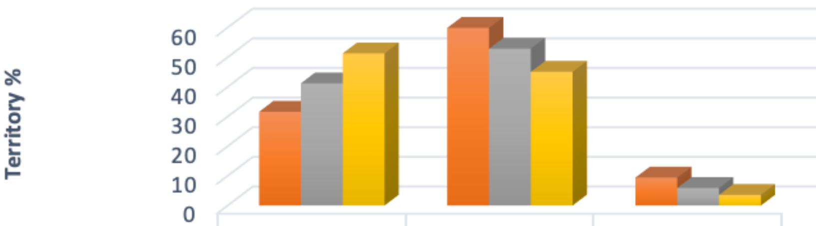
The main objectives of risk management are forecasting, taking preventive measures to prevent them and minimizing the consequences of their implementation. In this direction, the method is an effective tool for developing an optimal mining development plan based on an analysis of its implementation options based on the results of zone zoning, which does not allow the expansion of existing and the formation of new zones with a high level of failure risk.

The laying of voids formed during mining is the most effective method of restoring a mountain range to a stable state and is therefore an essential component of risk management related to sinkholes. In this situation, to prevent the realization of risks, it is necessary to establish the order of laying voids. In the absence of techniques that determine this sequence, the laying of mine workings is carried out without taking into account the potential danger of surface failure. At the same time, the dependence of the criterion of the proposed method on the total capacity Σm_j and the depth of their occurrence z_j (11,13) allows us to determine the degree of influence of the laying of certain voids on reducing the level of sinkhole. The voids with the greatest degree of influence should be laid first. The effectiveness of the laying works is largely limited by the problem of choosing the order of laying the mine workings. In solving this problem, based on a reasonable choice of the sequence of laying voids, the zonal zoning method has shown its effectiveness. As an example, the figure shows the results for two virtual options for laying voids on the 14th horizon (block 2, chambers 10, volume of voids 2217 m^3, chamber 12, volume of voids 7206 m^3) and the 16th horizon (block 25, chamber 1, volume of voids 3070 m^3, block 25, chamber 3, volume of voids 7146 m^3) and their effect on the surface condition (Figure 9). Horizon 18 (block 95, chambers 3, void volume 4789) (Fig.8).



a) b)

Figure 8 - Situational maps, after laying voids on horizons 14 (a) and 15 (b)



	Low level	Medium level	Increased level
Method 2	31,6	59,9	9,4
Horizons 14	41,2	52,9	5,9
Horizons 15	51,3	45,1	3,6

Figure 9 -Comparison of the areas of zones of different levels of failure hazard in the initial state and after the laying of voids on the 14th and 15th horizons

Obviously, in the current situation, in order to reduce the level of sinkhole risk of a surface area, it is a priority to lay the 15th horizon, in which the area of high-risk zones is reduced by 57%. For comparison, when laying the voids of the 14th horizon, this value decreases by 29%.

The known methods do not contain a justification for the number of observation stations and the choice of their position on the profile lines in relation to the current state of the array. At the same time, the results of zoning, obtained on the basis of a causal relationship between the state of the massif and the processes on the earth's surface, allow motivated management of these actions. In accordance with the physical representation of the potential of geoenergy, taken by the criteria of zoning, all points of the earth's surface located on the same equipotential line, in accordance with the principle of invariance, are in an identical state. This makes it possible to optimize ground-based instrumental observations.

Figure 10 shows, as an example, a plan for the location of observation stations with green areas (areas with a low level of sinkhole risk).

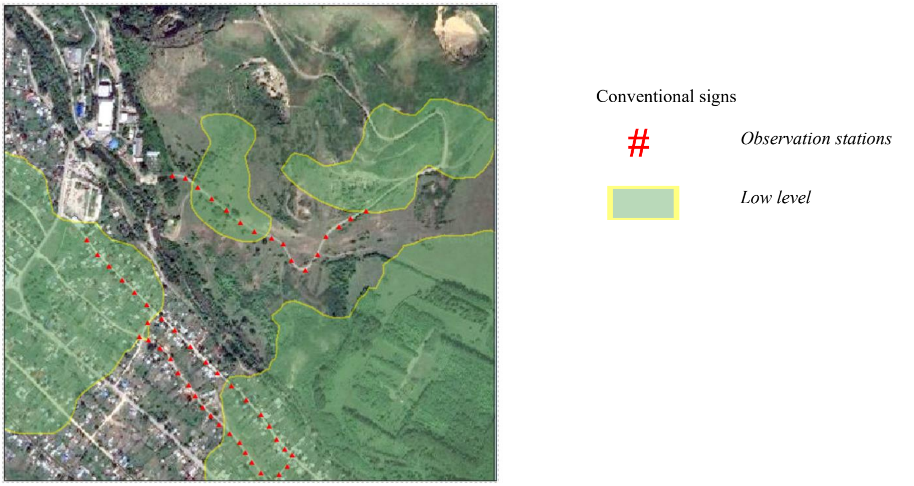


Figure 10 - Combined layout of observation stations and green areas

The green areas are covered by 28 observation stations. At the same time, in accordance with the principle of invariance of the method, monitoring of the territory of the green zone can be carried out at one station without loss of information content. The time saved for monitoring green areas can be used to increase the effectiveness of monitoring the condition of areas with a high level of failure risk.

Discussion.

The practical implementation of the method of zoning the earth's surface according to the level of collapse, the criterion of which is the potential of geoenergy, taking into account the internal pressure in the layer and the current values of the GSI rating, has shown its effectiveness. The method makes it possible to increase the accuracy of localization from a site with a high level of sinkhole risk by 5-20%, unlike the known ones, and can serve as an effective tool for developing an optimal mining development plan based on an analysis of its implementation options based on the results of zone zoning and a reasonable choice of the sequence of laying voids.

Conclusion.

The conducted research has confirmed its high practical effectiveness for predicting failures and managing risks in a changing state of the mountain range. Modeling of the geoenergy potential, a simplified model of a homogeneous array (p=2.7·103 kg/m3, E=0.2·10-3 MPa, m=0.6·10-3) made it possible to qualitatively assess the contribution of gravitational energy (linear dependence on depth) and elastic deformation (exponential dependence). The energy of elastic deformation dominates with increasing depth, which increases its importance in the formation of the criterion of failure hazard. The impact of the GSI rating. The elastic deformation potential depends on the GSI, which confirms the need for its current values. Ultrasound tomography (OPGS device, CA-YD-187T sensors) revealed a discrepancy between field (GSI=47) and laboratory (GSI=65) data, which is critical for the accuracy of the forecast. The criterion of failure risk. A dimensionless criterion γ (relative potential change) has been introduced, which is convenient for comparing different methods. Using the Ridder-Sokolny deposit as an example, it was found that taking into account GSI and elastic properties reduces the area of high-risk zones by 5.9%. Risk management. The method makes it possible to optimize the laying of voids: priority is given to the workings with the greatest impact on reducing the risk of failure (for example, laying the 15th horizon reduces the danger zone by 57% versus 29% for the 14th horizon).

Monitoring is optimized due to the principle of invariance: in homogeneous zones, one observation station is sufficient, which saves resources. Advantages of the method. Increase the accuracy of localization of hazardous areas by 5-20% compared to traditional methods. A tool for adaptive mining planning and a reasonable sequence of laying operations.

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