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DEVELOPMENT OF A SYSTEM FOR RANKING GEOMECHANICAL FACTORS, WHICH INFLUENCE THE STABILITY OF URANIUM MINES WORKINGS

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Abstract. The subject of research presented in the article are processes that take into account the influence of geomechanical factors on the stability of mining workings of uranium mines. The purpose of this work is development of a system for ranking geomechanical factors by the degree of danger based on the analysis of risk factors that affect the stability of uranium mines. The work uses critical analysis and generalization of both own research results and the results of domestic and foreign authors. The geomechanical factors that affect the stability of the mining workings of uranium mines have been determined. It is shown that their influence has both a direct and an indirect effects due to the connection with mining-geological and technological parameters. The stability of the workings is significantly influenced by mining and technical factors (outcropping time, working space length, floor height, compression properties and structure of the backfill mass, chamber width, dynamics of cleaning works progress), mining and geological factors (depth of mining, thickness of the ore body, strength (deformation)) and physical and mechanical properties of the rock mass. In addition, the engineering and technical conditions of mine construction have a significant impact, in particular, the form and size of the workings, their orientation in the massif, the method of carrying out and supporting, the design and technology of fastening, etc. It is practically impossible to simultaneously take into account all factors in an analytical way, so it is necessary to select one or two main factors that are of decisive importance for the description of a specific geomechanical process.

The originality of the work is the proposed ranking of geomechanical factors that affect the stability of mining workings of uranium mines. The ranking of geological, physical and mechanical factors on the stability of the chamber system elements at underground mining of uranium ores, according to the degree of attenuation of the influence, is as follows: strength of rocks → structure of the massif → angle of fall of the deposit → water content of the deposit → thickness of a seam. The ranking of the influence of support preparatory and capital workings on their stability, according to the degree of risk decrease, is as follows: no support → grid with anchors → sprayed concrete → wooden support → metal frame support with tightening → metal arches in concrete. Generalized ranking of the influence of the most significant factors on the stability of mining workings: geological, physical and mechanical factors → parameters of the development system → fastening technologies.

Keywords: uranium deposits, geomechanical factors, stability of workings, ranking, fastening of workings.

1. Introduction

Since uranium is the main component of fuel for nuclear energy, the issue of confirmed and forecast reserves and determination of trends in the production of uranium raw materials today is important for all countries of the world without exception. Ukraine ranks among the top ten countries in the world in terms of confirmed reserves and volumes of uranium mining and is the leader in Europe. However, in recent times, uranium mining in Ukraine has not been given the necessary attention.

About 100 000 tons of uranium are concentrated in the bowels of the earth of our country. All deposits are poor with uranium content of 0.1% or less, but they have a number of properties that support economic competitiveness for the production of uranium concentrate.

In the structure of electricity production in Ukraine, the share of nuclear power plants is high and as of 2020 was approximately 50%. In 2021, the production of electricity in Ukraine amounted to 156.576 billion kWh, which is 5.2% more than in 2020. This is stated in the data of the Energy Ministry. The main part in the total production in 2021 was nuclear power plants - 55.1%, thermal power plants - 29.3%, hydroelectric power plants and gas power plants - 6.7%. It should be noted that at the present time, taking into account the difficult situation in the world in connection with the aggression of the Russian Federation, demand is growing both for own needs and for the export of electricity from Ukraine to the countries of Western Europe. This means that Ukraine's need for uranium will constantly grow. Uranium mining in Ukraine is based on its large reserves, located within the Kirovohrad region. It allows, mainly, to provide its own needs in natural uranium. The construction of new modern mining enterprises and the intensification of work at existing mines presuppose the introduction of progressive mining technologies. First of all, it is aimed at reducing labor intensity and increasing work safety. One of the key links of such technologies, especially for the conditions of uranium mines developing deposits of a complex structure, is reliable, low-resource and safe fastening of mine workings [1–5].

At the end of 2021, the Cabinet of Ministers of Ukraine approved a program to make Ukraine self-sufficient in uranium by 2027. A significant expansion of nuclear energy beyond the 54% of electricity it already provides in Ukraine is planned.

The main purpose of this concept is to create conditions for increasing uranium production to fully meet the needs of the domestic nuclear power industry, and increase Ukraine's energy independence. Although its output has declined in 2020 and 2021, Ukraine's only uranium mining company "SkhidHZK" has historically produced up to 830 tons of uranium per year. According to the estimates of the World Nuclear Association, this is about 30% of the country's needs.

The plan of the Energy Ministry of Ukraine contains a number of measures to support and increase uranium production. Firstly, it is ensuring the functioning of the "Smolinska" mine until 2023 and the "Inhulska" mine until 2028. According to the World Nuclear Association, they have resources of about 66 000 and 5 000 tons of uranium, respectively.

The underground development of domestic uranium deposits has two main trends: the transition to the extraction of depleted ores and an increase in the depth of mining. At implementing the first trend, no special geomechanical problems arise. The main focus is on the implementation of new technologies for the enrichment of mined ore. Instead, increasing the depth of mining requires paying more attention to increasing the safety of mining operations. This requires the use of both operational and long-term monitoring of the geomechanical systems state. At the same time, there is a need to identify the most dangerous areas for timely monitoring [6, 7]. Therefore, the development of a ranking system of geomechanical factors affecting the stability of workings, according to the degree of their danger, is quite relevant.

It should be noted that an increase in the depth of mining leads to significant qualitative changes in the course of geomechanical processes in the near-contour zone of artificial cavities and in more remote zones of the rock mass, including the earth's surface. Mining technical and mining geological factors have a great influence on the stability of chambers and mine workings. The mining technical factors include the outcropping time, working space length, floor height, compression properties and structure of the backfill mass, chamber width, dynamics of cleaning works progress (the sequence of working out the chambers). Mining and geological factors include the depth of mining, the thickness of the ore body, strength (deformation) and physical and mechanical properties of the rock mass.

In the general case, the rock mass is a discrete heterogeneous anisotropic medium, the mechanical processes of deformation in which are of a non-linear temporal nature. In addition to geological factors, the engineering and technical conditions of construction and the shape and size of the workings, their orientation in the massif, the method of conducting and supporting them, the design and technology of fastening, etc., have a great influence. Thus, the purpose and novelty of this work is the development of a system for ranking geomechanical factors according to the degree of danger based on the analysis of risk factors affecting the stability of uranium working.

2. Methods

The work uses critical analysis and generalization of both own research results and the results of domestic and foreign authors.

3. Results and discussion

The issues of mine workings stability in the mining of mineral deposits are considered taking into account the influence of the most significant geological and geomechanical factors. These include the mining and geological conditions of the deposit, its watering, fracturing, layering, static and dynamic loads, rock strength, seismic actions. The classification of groups of phenomena and their attendant factors is presented in Table 1 [8].

Layering, fracturing, humidity and other factors have a significant impact on the stability of the rock outcrop. So, with the strength of the layers for uniaxial compression of 50–60 MPa and a thickness of more than 0.8 m, the rock outcrops of the roof remain stable for more than 2 hours. With a layer thickness of 0.1 to 0.4 m and rock hardness under compression up to 40 MPa, the steady state time is keep within one hour. When the thickness of the layers is less than 0.1 m, which is typical for a false roof, the time of their steady state is up to 10–20 minutes. In strongly fractured, disturbed rocks, with a distance between fractures from 0.01 to 0.20 m, their stability usually does not exceed 20 minutes. Rocks with fractures from 0.3 to 0.5 m and compressive strength of 20–40 MPa are stable for 0.5–1.5 hours. Rocks with a fracture of 0.6–1 m, with a strength of 40–50 MPa, are stable for 2.0–3.5 hours. Sandstones based on carbonate cement with increasing humidity lose their strength characteristics by about 5%, siltstones based on siliceous and carbonate-siliceous cement – by 14%, siltstones with clayey cement – by 20–30%, mudstones – by 40–60%. [9].

In addition, the stability of mine workings is greatly influenced by the initial stress state of the massif at the site of the working, the proximity of the earth's surface and other rock outcrops (neighboring workings), the presence of a load on the contour (supports reaction). The greatest influence among this group on the distribution of stresses is the value of the initial stress in the massif.

Table 1 – Classification of mining and geological conditions and geotechnical factors that arise during the mining of mineral deposits [8]

Groups of phenomena	Reasons of occurrence	Factors	Development optimization
1. Gravitational	The appearance of rock pressure	Different forms of rocks displacement Deformation of underground structures (workings, pillars, etc.) Fracturing of rocks Heaving of lithified clay rocks. Extrusion rocks in the zone of resistance pressure Rock shocks Sudden dynamic phenomena Deformation of rock layers	The need to adapt the shape and size of excavation site, technological schemes and optimal spatial position of workings to ensure their maximum stability
	Mechanical properties and structural-mechanical features of rock mass	Relation between stresses and deformations, anisotropy and heterogeneity of rocks	
II. Hydrodynamic	Disturbance of the hydrodynamic regime	Increased filtration Groundwater and floating water breakthrough Suffusion erosion of rocks Depressional deformation of rocks in the field of water drop	Carrying out mining works according to traditional schemes with the use of measures additional to the current regulatory documents. In difficult conditions, it is allowed to conduct mining operations based on the results of additional research and conclusions of specialized organizations
III. Hydrochemical	Disturbance of the wet regime of the chemical composition of pore moisture and mineral composition	Leaching of easily soluble rocks. Heaving of clay rocks Manifestations of thixotropic properties of floating water	The same as in II, or carrying out additional waterproofing works
IV. Technogenics	Formation of cavities	Stresses on the working contour Parameters of the seismic action of the explosion	Adaptation of mining technologies according to traditional schemes to actual conditions. Regular monitoring of workings state
	Landslides, rock impacts	Loosening, formation of a trough displacement of rocks	
	Intensive removal of groundwater (water-removal)	Formation of depression funnel	

It should be noted that humidity significantly affects the change in rock hardness. The practice of mining various ore deposits and similar deposits has shown that the rock strength coefficient varies widely: from 2 (chlorine-mineralized) to 13 (clay-silicon siltstone). Thus, in systems with hydraulic backfilling due to humidity, the rocks behave like rocks with a strength factor of 2.

It should be noted that samples of rocks with a strength factor of 8–12 in a dry state (with a natural humidity content of up to 2.0–2.5%) almost completely lose their stability even with slight humidity (up to 4–5%). With more humidity, the clay-like component of the rocks is washed out into the working. Thus, it is necessary to constantly monitoring the humidity and the corresponding strength of the rocks in the area where the workings are located [10].

The analysis of publications devoted to the study of the stability of workings [11–15] made it possible to establish the influence of geological, physical and mechanical factors on the stability of elements chamber system during underground mining of uranium ores (Table 2).

Table 2 – The influence of geological, physical and mechanical factors on the stability of elements of chamber system during underground mining of uranium ores

Geological characteristic	Hanging side, influence	Lying side, influence	Chamber ceiling, influence	Preparatory workings, influence
Strength of rocks	significant	moderate	significant	significant
Structure of the massif	significant	moderate	significant	significant
Water content of the deposit	moderate	moderate	moderate	moderate
Angle of fall of the deposit	significant	significant	moderate	insignificant
Thickness of a seam	moderate	moderate	significant	no influence

It should be noted that the geometric parameters of mine workings and various technological factors have a significant influence on the stability of mine workings during the development of ore deposits.

The analysis of the parameters of the chambers at one of the uranium mines of the "SkhidHZK" allows us to establish a number of regularities that connect the processes of manifestation of rock pressure with the dimensions of the cleaning chambers and the disturbance of the massif.

When determining stable parameters of ore massif outcrops and rocks in spent chambers, the function of the following type is used [16]:

$$(l^0)^n \cdot H = f(\sigma, R), \tag{1}$$

when l^0 – limit equivalent span of outcrop in chamber, m; H – depth of mining, m; σ – characteristic of the stressed deformed state of the massif, MPa; R – characteristic of strength, MPa; n –coefficient that takes into account the structural features of massifs (in solid massif n = 1, in thin layers with low adhesion and friction between layers n = 2).

At determining the width of the interchamber pillar and the thickness of the ceilings, a functional characteristic is used, which generally has the following form:

$$\frac{H}{A_p} = f(\sigma, R) \text{ i } \frac{H}{A_c} = f(\sigma, H). \quad (2)$$

Parameter values A_{p} i A_{c} – are determined by the following formulas:

$$A_p = \frac{C^2}{l_v(l_s + C)}, \quad (3)$$

$$A_c = \frac{d^2}{l_g(l_s + d)}, \quad (4)$$

when C –the width of the interchamber pillar, m; d – ceiling thickness, m; l_{v} – equivalent span of vertical outcrop of the ore massif, m; l_{g} – equivalent span of horizontal outcrop of the ore massif of the ceiling, m; l_{s} – equivalent span of a hanging-side outcrop in a chamber, m.

The degree of time influence is determined by the geological properties of the rocks that make up the marginal part of the mined rock mass [16]:

$$l_g^0 = l_g t^{-k}, \quad (5)$$

when l_{g}^0 l_{g} – limiting equivalent spans of horizontal outcrop, the duration of which is equal to t, month; k –coefficient reflecting the decrease in the stability of the outcrop in time due to rheological processes occurring in the massif.

The stability of workings and mined spaces depends on their size and largely determines the safe conduct of mining and the efficiency of the mineral deposits development. The generally accepted criterion for the stability of a horizontal and vertical outcrops is the equivalent span l. The geometrical parameters of the chambers are in the following dependence on the value of the maximum permissible equivalent span [16]:

$$l = \frac{L \cdot L'}{\sqrt{L^2 + (L')^2}}, \text{ m} \quad (6)$$

$$l_g = \frac{a \cdot b}{\sqrt{a^2 + b^2}}, \text{ m} \quad (7)$$

$$l_v = \frac{a \cdot h}{\sqrt{a^2 + h^2}}, \text{ m} \quad (8)$$

when L – the length of the mined space, m; L' –the size of the horizontal projection of the mined space on the section across the length, m; *a, b, h* –length, width and height of the camera, respectively, m.

The stability of the outcrops in the excavation blocks is ensured by the condition:

$$l_{ad} \leq l_f \leq l,$$

when l_{ad} – admissible outcrop span determined at the designing stage, m; l_f – actual equivalent span of the excavation block after its mined, m.

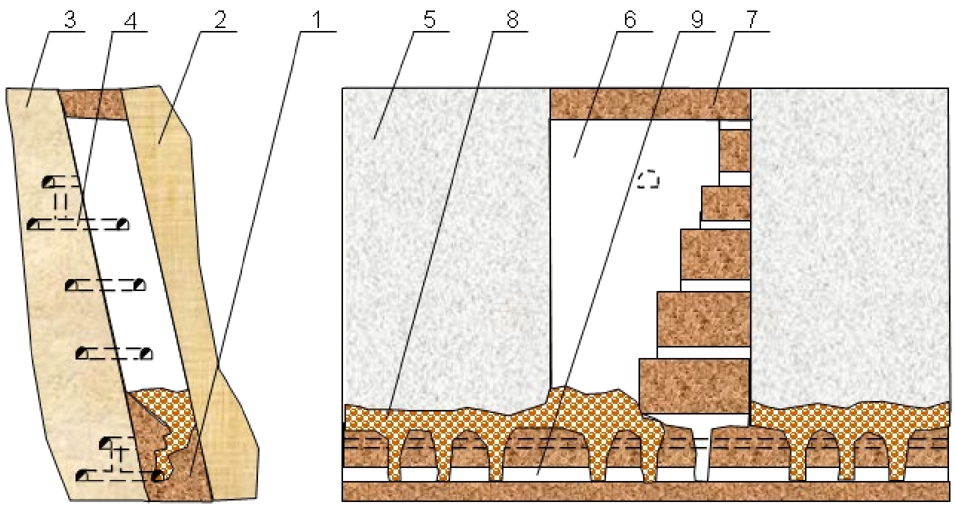
The maximum allowable equivalent span is significantly influenced by the mining and geological and structural features of the rock mass, the working time of the blocks, etc.

Studies of the chamber height influence on the massif stability during the development of ore deposits [17] established the lows of changes in the values of horizontal and vertical stresses for various parameters of the excavation chambers height and the development of the mining front. At ore body height up to 40 m, it is advisable to reduce the height of the excavation chamber to 20 m. This ensures the stable state of the chamber before filling with the backfill mixture. The development of the mining front is possible in a continuous manner, without leaving pillars, from the center of the chamber to the flanks. Mining of ore bodies can also be carried out according to the chamber-pillar scheme with the formation of pillars with a width equal to the width of the chamber and mined in the second turn.

Also, among the factors that determine the stability of working, the parameters of the selected ore deposit development system should be noted. It is known that ore deposits are mined both open and underground. It should be noted that the largest uranium deposits in the world Rössing, Husab, Langer Heinrich (Namibia), Kvanefjeld (Greenland), McClean Lake (Canada) open pit mining. This determines the relatively low cost of the final product, despite the low concentration of uranium in the ore. In the case of a deeper occurrence of the ore and favorable mining and geological conditions, in world practice there is an orientation towards underground leaching. According to estimates [18–22], about 50% of uranium is extracted by this method. The largest deposits developed according to the specified scheme include Four Mile, Beverley (Australia), Tort-Kudyk (Kazakhstan). Thus, the underground extraction of uranium ores using classical ore technologies accounts for much less than half of the extraction of this type of raw material. The expediency of extraction in this way is determined either by the high content of uranium in the ore, or by the concomitant extraction of a valuable product. These deposits include the Olympic Dam polymetallic deposit (Australia), powerful Cigar Lake and McArthur River deposits (Canada), Jaduguda, Turamdih (India), Akouta (Nigeria). But it is during underground mining that the greatest attention should be paid to supporting the stability of geotechnical systems.

In Ukraine uranium deposits are mined underground. The main way to mine uranium deposits is the chamber system of mining by sublevel drifts (orts) with alternate mining of blocks and filling the cavities with hardening mixtures. Based on the theoretical studies results, the parameters of the structural elements of the chamber system of mining were determined at mining complex-structural ore deposits for various mining and geological conditions [23]. It has been established that the span of the mined chamber outcrop depends not only on the chamber width of the second stage of mining and the period of its operation, but also on the physical and mechanical properties of the non-ore or ore inclusion. Thus, with a level height of 75–90 m, the stability of the mined chamber is ensured when its width does not exceed 15 m. In cases where the height of the sublevel is 25–30 m, on the stability of the mined chamber is affects the thickness and strength of the non-ore or ore inclusion. So, with the strength of a non-ore inclusion of more than 12 and their horizontal thickness of more than 10 m in stable ores, it is advisable to use the level variant of the chamber mining system.

An example of a system with mining by separate sublevels and alternate chamber backfilling is shown in Fig. 1.



1 –ore body, 2 – hanging side rocks, 3 – lying side rocks,
4 – sublevel drift, 5 – the backfill chambers of the first line, 6 – mined chamber,
7 – chamber ceiling, 8 – broken ore, 9 – rollback drift

Figure 1 – System for mining a steeply dipping ore body with sublevel drifts and full backfilling of the mined space

The stability of workings also directly depends on the quality and composition of the backfill mixture, its hardening time and solidity.

The great importance for the stability of the massif outcrops is the intensity of working and backfilling of chambers. The conducted studies [24] showed that the value of the stable equivalent span of outcrop (l) and outcrop time (t) are in the following relationship:

$$l^2 \cdot t = const \tag{9}$$

The lifetime of an outcrop is taken into account by the time coefficient (K_t):

$$K_t = \sqrt{\frac{t_1}{t_0}}, \tag{10}$$

when t_1 – the time during which the chamber can be worked out with intensive work, month; t_0 – initial estimated mining time, month.

For chambers that go under the backfilled space, the value of K_t varies from 0.76 to 1.10 and is determined based on the formula:

$$t_1 = 0.5t_2 + t_3 = 6\ month, \tag{11}$$

when t_2, t_3 –respectively, the time for working out the minerals reserves in the chamber and the time until its full backfilling, month.

For chambers that go under the ore massif, the value of K_t varies from 0.92 to 1.23 and is determined based on the formulas:

$$t_1 = 0.5t_2 + t_3 = 12\ month,\ \ t_0 = 0.5t_2 + t_3. \tag{12}$$

The conducted studies on the parameters of underground mining made it possible to generalize their degree of influence on the stability of the geotechnical system elements. The impact of these factors is given in Table 3.

Table 3 –The influence of the mining system parameters on the stability of the geotechnical system elements

Parameter of mining system	Hanging side, influence	Lying side, influence	Chamber ceiling, influence	Preparatory workings, influence
Floor height	significant	significant	insignificant	insignificant
Subfloor height	moderate	moderate	insignificant	insignificant
Chamber width	significant	moderate	significant	insignificant
Chamber form	significant	moderate	significant	insignificant
Working time	significant	significant	significant	moderate
Backfill strength	significant	moderate	moderate	insignificant

It should be noted that the influence of factors related to the parameters of the mining system can be regulated. Therefore, it can be reduced to an acceptable size and have a lower rank.

It should also be added that in addition to the mining and geological conditions and geometric dimensions of the workings, their stability can be determined by technological factors, namely, the method of fastening.

An approximate ranking of the impact of support on the stability of workings is presented in the Table 4.

Table 4 – The ranking of the influence of support preparatory and capital workings on their stability

The support influence rank	Support composition
1	No support
2	Grid with anchors
3	Sprayed concrete
4	Wooden support
5	Metal frame support with tightening
6	Metal arches in concrete

4. Conclusions

The geomechanical factors affecting the stability of the mining workings of uranium mines have been determined. It is shown that their influence has both a direct and an indirect effects due to the connection with mining-geological and technological parameters. According to various estimates, the degree of risks associated with the geomechanics of the production environment is about half of the total. That is, the consideration of geomechanical factors increases the production safety index by two or more times.

The stability of the workings is significantly influenced by mining and technical factors (outcropping time, working space length, floor height, compression properties and structure of the backfill mass, chamber width, dynamics of cleaning works progress), mining and geological factors (depth of mining, thickness of the ore body, strength (deformation)) and physical and mechanical properties of the rock mass. In addition, the engineering and technical conditions of mine construction have a significant impact, in particular, the form and size of the workings, their orientation in the massif, the method of carrying out and supporting, the design and technology of fastening, etc. It is practically impossible to simultaneously take into account all factors in an analytical way, so it is necessary to select one or two main factors that are of decisive importance for the description of a specific geomechanical process.

The ranking of geomechanical factors affecting the stability of mining workings of uranium mines was performed.

The ranking of geological, physical and mechanical factors on the stability of the chamber system elements at underground mining of uranium ores, according to the degree of attenuation of the influence, is as follows: strength of rocks → structure of the massif → angle of fall of the deposit → water content of the deposit → thickness of a seam.

The ranking of the influence of support preparatory and capital workings on their stability, according to the degree of risk decrease, is as follows: no support → grid with anchors → sprayed concrete → wooden support → metal frame support with tightening → metal arches in concrete.

Generalized ranking of the influence of the most significant factors on the stability of mining workings: geological, physical and mechanical factors → parameters of the mining system → fastening technologies.

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РОЗРОБКА СИСТЕМИ РАНЖУВАННЯ ГЕОМЕХАНІЧНИХ ЧИННИКІВ, ЩО ВПЛИВАЮТЬ НА СТІЙКІСТЬ ВИРОБОК УРАНОВИХ ШАХТ

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Анотація. Предмет досліджень, викладених в статті, це процеси, що враховують вплив геомеханічних факторів на стійкість гірничих виробок уранових шахт. Мета даної роботи: розробка системи ранжування геомеханічних чинників за ступенем небезпеки на основі аналізу факторів ризиків, шо впливають на стійкість уранових виробок. В роботі використано критичний аналіз та узагальнення як власних результатів досліджень, так і результатів вітчизняних та зарубіжних авторів. Визначено геомеханічні чинники, що впливають на стійкість гірничих виробок шахт з видобутку урану. Показано, що їх вплив має як пряму, так і опосередковану дію через зв'язок з гірничо-геологічними і технологічними параметрами. На стійкість виробок суттєвий вплив мають гірничо-технічні (час оголення, проліт виробленого простору, висота поверху, компресійні властивості та структура закладного масиву, ширина камер, динаміка просування очисних робіт) та гірничо-геологічні (глибина розробки, потужність рудного тіла, міцнісні (деформаційні) та фізико-механічні властивості масиву) чинники. Окрім того, суттєво впливають інженерно-технічні умови шахтного будівництва, зокрема, форма і розміри виробок, їх орієнтація в масиві, спосіб проведення та підтримки, конструкція та технологія зведення кріплення тощо. Одночасно врахувати всі фактори аналітичним способом практично неможливо, тому треба йти шляхом виділення одного-двох головних, що мають визначальне значення для опису конкретного геомеханічного процесу.

Новизною роботи є запропоноване ранжування геомеханічних чинників, що впливають на стійкість гірничих виробок уранодобувних шахт. Ранжування геологічних та фізико-механічних факторів на стійкість елементів камерної системи при підземному видобутку уранових руд, за ступенем згасання впливу, виглядає наступним чином: міцність порід → структура масиву → кут падіння покладу → обводненість родовища → потужність пласта. Ранжування впливу кріплення підготовчих та капітальних виробок на їх стійкість, за ступенем зменшення ризиків, виглядає наступним чином: кріплення відсутнє → сітка з анкерами → набризкбетон → дерев'яне кріплення → металеве рамне кріплення з затяжкою → металеві арки в бетоні. Узагальнене ранжування впливу найбільш вагомих чинників на стійкість гірничих виробок: геологічні та фізико-механічні фактори → параметри системи розробки → технології кріплення.

Ключові слова: уранові родовища, геомеханічні чинники, стійкість виробок, ранжування, кріплення виробок