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# RESEARCH OF STRENGTH AND FEATURES OF DEFORMATIONS OF ROCKS IN URANIUM DEPOSITS

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**Abstract**. The subject of the research was physical and mechanical properties of rocks from uranium deposits in Ukraine. The purpose of the work was to study the strength characteristics and features of deformation of rocks of uranium deposits beyond their strength limit to ensure the stability of mine workings at great depths. Research methods were experimental with using stationary laboratory equipment and special recording equipment. The studies were carried out within and beyond the strength limits. The rock specimens were made of material taken from a uranium mine. The complex of the studies included determination of general physical properties of rocks (density, specific gravity, porosity, humidity and adhesion coefficient); basic strength parameters (compressive and tensile resistance depending on humidity and layering, angle of internal friction, elastic modulus, Poisson's ratio, modulus of decrease and residual strength) and deformation characteristics. Calculations of the scale strength factor were made. The results were analyzed. It is shown that the rocks of uranium deposits in Ukraine are considered strong and very strong, according to the Protodyakonov scale. However, structural and textural features lead to the occurrence of a scale effect of strength of rocks. The complex structure of uranium deposits, the steep angle of dip of the rocks, their lamination, as well as the significant size of the mine workings further reduce the strength of the massif. It is also shown that when calculating stability of mine workings and choosing parameters for their support, the strength of rocks in the massif should be reduced by half from the value obtained by standard laboratory tests. The characteristics of rock samples within and beyond their strength limit indicate that they have almost no plastic properties. The ratio of the modulus of decrease to the static elastic modulus for all studied types of rocks of uranium deposits is greater than one. This indicates the tendency of rocks to accumulate potential energy and cause brittle failure of the massif beyond its compressive strength. That is, at great depths, the main problems in mine workings associated with rock deformation processes will manifest themselves in the form of rock bumps, collapses or other dynamic phenomena. This does not exclude the possibility of deformation or destruction of rock support due to static loads.

**Keywords**: uranium deposit, rock, laboratory research, extreme stress, physical properties, strength, elasticity, scale factor.

## 1. Introduction

The main sources of force impacts on the rock massif are rock pressure and other geomechanical processes occurring around the mine workings due to the violation of the integrity of the rock massif. The nature of these forces is different: gravity, geotectonics, hydrostatics, gas pressure, temperature, etc. The tendency of rocks to resist pressure and fracture is a priori inherent in their strength characteristics and deformation. Numerically, these characteristics are described by such parameters as temporary compressive and tensile strength, adhesion coefficient, angle of internal friction, elasticity, displacement and collapse modulis, Poisson's ratio and residual strength. From the point of view of the stability of underground structures, another important characteristic is fracturing of the massif. This characteristic is so important that modern continuum mechanics increasingly uses the concept of crack resistance to describe fracture processes.

In rock mechanics, a set or group of the listed parameters makes it possible to refer an individual lithotype of a rock to a specific class. This is very important for calculating stability of mine workings and is associated with the diversity of rock structure, a wide range of types and values of effective stresses and deformations. There are several types of classification of rocks and massifs: by origin, structure, texture and physical and mechanical properties. The latter classification is the most important. At the same time, classification by strength is the most objective, since it is based solely on quantitative indicators obtained by standardized mechanical testing methods.

Rocks can be prone to elastic, brittle or plastic deformations depending on their deformation properties. However, this division is somewhat arbitrary since rock samples are deformed differently depending on the speed and magnitude of their loading. Unlike the classical test for the strength of a specimen, rocks in a massif are in a volumetric stress-strain state, and therefore have the ability to bear a load beyond their strength limit.

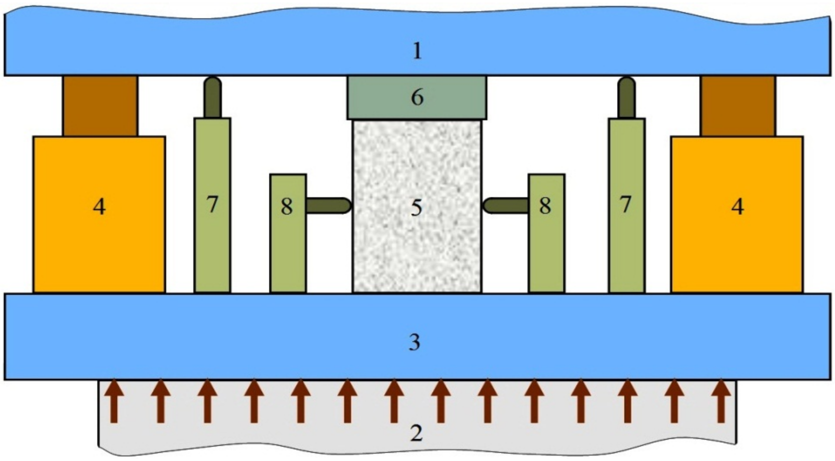
It is known that the uniaxial compressive strength of rock is not the same in geometrically similar specimens of different sizes. This phenomenon is called a large-scale effect, and the causes of its occurrence are called a scale factor. As a rule, the dependence of the strength of the specimen on its volume is inversely proportional. This is caused by the scale effect of strength. It consists in the fact that for real structurally inhomogeneous bodies, the probability of a defect (crack, weak inclusion, etc.) appearing is higher for larger bodies. Therefore, the strength of the rock specimen will always be higher than the strength of the rock massif. This phenomenon is characterized by the coefficient of structural weakening.

A sufficient number of works are devoted to the study of physical and mechanical parameters of rocks [1–16]. However, interest in such research does not decrease. This is explained by the huge diversity of rocks and their properties, even within the same lithotype. In addition, the increase of the depth of mineral development and, accordingly, rock pressure requires research of rocks beyond their strength limit. Note that the bulk of the work is devoted to rocks of low and medium strength categories. As for hard (firm) rocks, especially rocks from uranium deposits, information on their mechanical properties is very limited. Therefore, the purpose of this work is to study the strength characteristics and features of deformation of rocks of uranium deposits beyond their strength limit to ensure the stability of mine workings at great depths.

## 2. Methods

Studies of the deformation properties and strength of rocks were carried out in laboratory conditions on a testing machine of increased rigidity. The installation consists of a press with a force of 5MN (PSU-500), two anti-compression hydraulic jacks and a system for continuous synchronous recording (or photo recording) of the load on the specimen, longitudinal and transverse deformations. The diagram of the testing machine is shown in Fig. 1. The machine is designed in such a way that during testing, up to 90% of the load can be taken by the counter-action jacks. This allows you to control the “load-deformation” process even beyond the strength limit of the specimen.

The tests were performed on specimens shaped like a parallelepiped with an edge ratio of 1.0 : 1.0 : 1.5, where the larger size is the height of the sample. The specimens were made from samples taken at the Novaya mine (Zhovti Vody city, Ukraine). The choice of this mine is due to its accessibility, since uranium mining there was completed more than twenty years ago, so there are no restrictions on access to the mine workings and selection of rock material. In addition, the rocks that form the massif of this mine are characteristic of most uranium deposits in Ukraine.




1 – upper thrust plate of the press, 2 – press piston, 3 – lower movable press plate,
4 – anti-compression hydraulic jack, 5 – specimen, 6 – strain gauge force meter,
7, 8 – longitudinal and transverse strain meters

Figure 1 – Schematic illustration of a high-rigidity testing machine

The size of the specimens for deformation studies was 40×40×60 mm. The choice of sizes was determined by technical capabilities of the testing equipment. With a nominal maximum compressive force of the press of 5 MN, the real possibilities are limited by the hydraulic system and range from 3.5 MN to 4,0 MN. The maximum compressive load under severe test conditions ranges from 35 kN to 40 kN. Based on this, the base area of a specimen with an expected strength of 250 MPa cannot exceed 16 cm$^2$.

To prevent inertia in recording deformations, a device specially developed for the synchronous photographic recording of compressive force and deformations was used (Fig. 2).


Figure 2 – Appearance of an inertia-free stress and strain recorder for testing rock specimens

To identify the scale effect and determine the scale strength factor of rocks of uranium deposits, two series of specimens (four in each) measuring 30×30×30 mm, 50×50×50 mm and 100×100×100 mm were made from two large pieces of rock of different lithotypes (magnetite-amphibole schist and pegmatite). The specimens were tested at an approximately constant slow loading rate (50 kN/s). This made it possible to limit the influence of loading speed on the parameter - temporary compression resistance.

## 3. Results and discussion

Table 1 provides information about the rocks which were tested.

Table 1 – Information about samples according to the geological service of the Novaya mine

| Sample number | Name of the rock and its geological description | Strength $R_c$, MPa |
|---|---|---|
| 1 | Magnetite-amphibole shales (poor) dark gray in color, medium to coarsely banded texture, fine-grained structure | 130-150 |
| 2 | Magnetite-amphibole schists (rich), dark gray, finely striped texture, fine-grained structure | 130-150 |
| 3 | Mica schists are dark gray in color, massive in texture, and have a finely scaly structure | 80-100 |
| 4 | Ferrous quartzites are dark gray in color, striped texture, fine-grained structure | 130-150 |
| 5 | Pegmatites are light pink to dark brown, massive texture, medium crystalline structure with quartz and feldspar | 110-130 |

The obtained research results are shown in table 2-4.

Table 2 – Physical characteristics of rocks

| Sample number | Density range $\rho\cdot10^{-3}$, kg/m$^3$ | Average specific gravity $\gamma\cdot10^{-2}$, N/m$^3$ | Average porosity $p$, % | Average natural humidity $W$, % | Coefficient of adhesion $K$, MPa |
|---|---|---|---|---|---|
| 1 | 3.25-3.35 | 3.7 | 10.8 | 0.2 | 42.3 |
| 2 | 3.60-3.70 | 4.0 | 8.5 | 0.5 | 77.7 |
| 3 | 2.65-2.70 | 3.8 | 29.7 | 0.6 | 42.5 |
| 4 | 3.60-3.75 | 4.3 | 14.4 | 0.4 | 47.2 |
| 5 | 2.60-2.65 | 3.3 | 21.2 | 0.3 | 32.7 |

Table 3 – Strength characteristics of rocks (rounded values)

| Sample number | Temporary resistance $R_c$, MPa: | | | | | | |
|---|---|---|---|---|---|---|---|
| | compression (orthogonal to laminations) | | | stretching | | | |
| | Moisture-saturated | With natural humidity | | Orthogonal to laminations | | Parallel to laminations | |
| | | Average | Interval | Average | Interval | Average | Interval |
| 1 | 170 | 162 | 83-263 | 11 | 9-12 | 19 | 19-20 |
| 2 | 272 | 265 | 123-316 | 14 | 7-18 | 48 | 47-48 |
| 3 | 115 | 135 | 135-136 | 133 | 8-16 | 29 | 17-29 |
| 4 | 139 | 172 | 112-203 | 11 | 9-12 | 28 | 20-34 |
| 5 | 148 | 145 | 120-169 | 10 | 10-11 | 14 | 12-17 |

Table 4 – Average values of mechanical and deformation characteristics of rocks

| Sample number | Decay modulus *M*, GPa | Angle of internal friction *φ*, degree | Dynamic modulus of elasticity *E*, GPa (parallel / orthogonal to laminations) | Poisson's dynamic ratio *μ* (parallel / orthogonal to laminations) | Relative deformation value at ultimate strength, % | |
|---|---|---|---|---|---|---|
| | | | | | longitudinal $\varepsilon^{\parallel}$ | transverse $\varepsilon^{\perp}$ |
| 1 | 42.0 | 40.0 | 54.8 / 52.4 | 0.42 / 0.41 | 1.00-1.15 | 0.40-0.55 |
| 2 | - | 29.5 | 66.3 / 56.0 | 0.44 / 0.43 | 0.90-0.95 | 0.30-0.35 |
| 3 | 23.0 | 25.5 | 45.9 / 36.0 | 0.44 / 0.42 | 1.10-1.45 | 0.40-0.55 |
| 4 | - | 32.5 | 55.9 / 52.8 | 0.43 / 0.41 | 1.05-1.20 | 0.35-0.40 |
| 5 | 21.5 | 41.0 | 32.0 / 29.9 | 0.43 / 0.42 | 1.25-1.40 | 0.55-0.65 |

A significant discrepancy is identified in the tables and geological exploration data used by the mine's technical services. This is especially true for such important characteristics as the strength and density of the rock.

As an example, Fig. 3 and Fig. 4 show the stress-strain relationships smoothed and constructed by points obtained by photographic recording for two rock samples (the strongest, iron-rich magnetite-amphibole schist, and the least strong, micaceous schist).

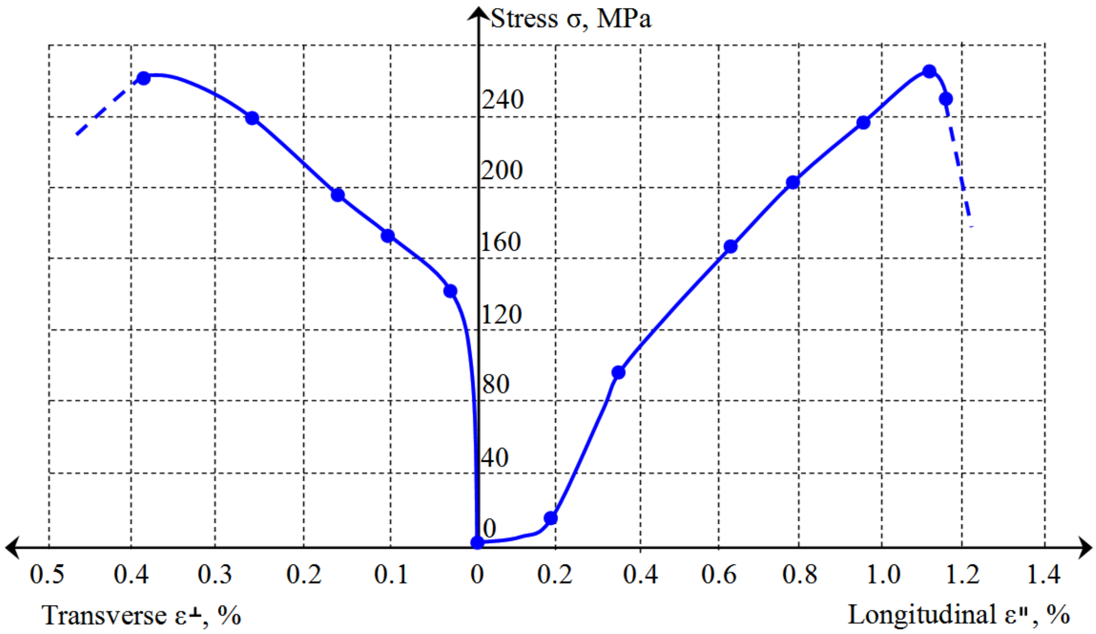



Figure 3 – Dependences of "stress – relative deformations" of sample No. 4

Note that the dynamic elastic moduli given in table 4 were obtained by ultrasonic research. Therefore, they are on average twice the value of the static moduli determined from the stress-strain relationships. Thus, it can be stated that all the tested rocks satisfy the condition $M / E > 1$ by their characteristics, that is, they have a tendency to brittle fracture.

The results of the studies of the scale effect of strength are given in table 5 and in Fig. 5.

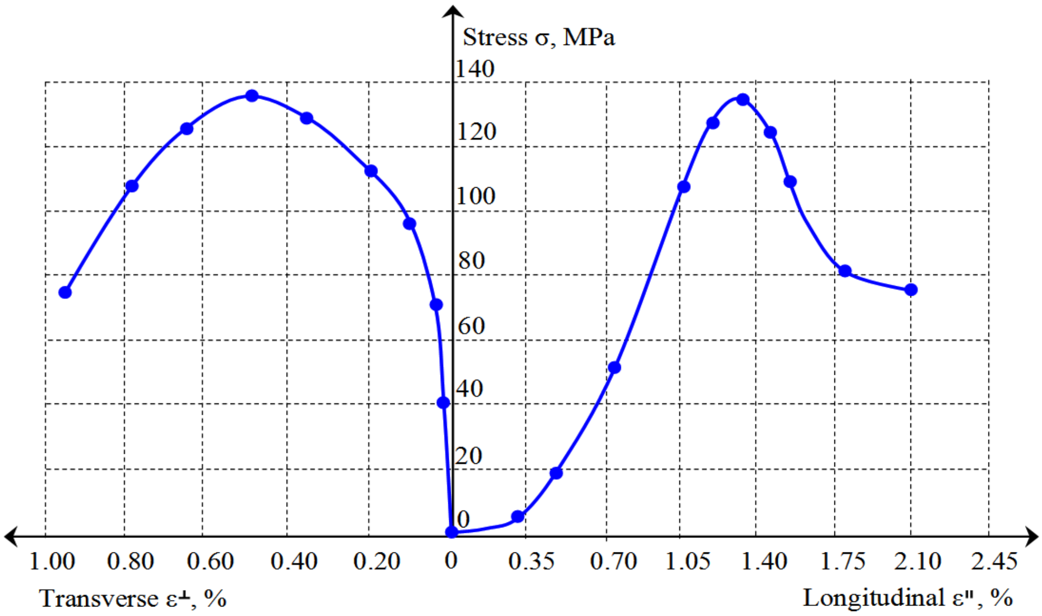



Figure 4 – Dependences of “stress – relative deformations” of sample No. 3

Table 5 – Temporary resistance to uniaxial compression ($R_c$) for samples of different sizes

| Sample number | Rock type | Specimen size, mm | $R_c$, MPa |
|---|---|---|---|
| 1 | Magnetite-amphibole shale of fine-grained structure | 30×30×30 | 205 |
| | | 50×50×50 | 182 |
| | | 75×75×75 | 130 |
| | | 100×100×100 | 122 |
| 5 | Pegmatite of medium crystalline structure with quartz and feldspa | 30×30×30 | 166 |
| | | 50×50×50 | 155 |
| | | 75×75×75 | 115 |
| | | 100×100×100 | 111 |

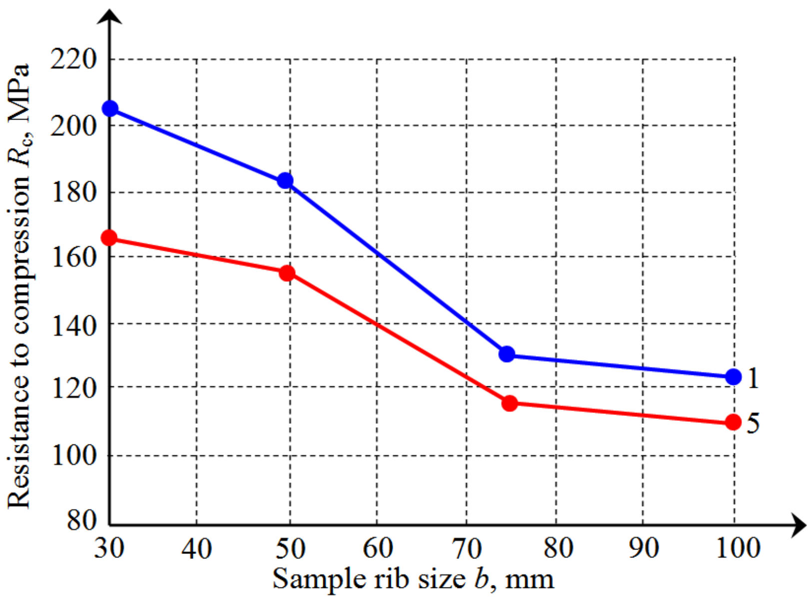



Figure 5 – Strength of specimens of different sizes for samples No. 1 and No. 5

The test results indicate the presence of a scale effect of strength in the rocks of uranium deposits with a characteristic inversely proportional relationship.

Within this discussion, we note that the rock massif contains various disturbances (breaks, cracks, laminations, etc.). In order a section of the massif loses its stability, the destruction of intact material and firm rock bridges must occur. Therefore, to calculate and predict the stability of mine workings, it is necessary to know and take into account the strength of the entire structural ensemble of the rock massif. In practice, this is very difficult to do due to the impossibility of directly testing the strength of a huge part of the rock massif. To solve this problem, research in geomechanics is being developed in several directions.

The first direction is characteristic of classical geomechanics. It consists of testing a statistically sufficient number of rock specimens of the same lithotype and different sizes using standard methods. Subsequently, the average strength indicators, coefficients of their variation and, if possible, the scale strength factor are determined.

The second direction is the creation and implementation of experimental methods for determining the strength parameters of rocks in the conditions of their natural occurrence. The reliability of these methods, first of all, depends on a statistically significant number of measurements, as well as on the significance and sufficient severity of the relationship between the informative parameter of the method and the strength characteristics of the massif.

The third direction consists in the determination of scale coefficients by modeling methods. The basis of this method was formulated by Dutch scientists B.H.G. Brady and E.T. Brown [5]. This method attempts to quantitatively determine the scale factor in rock massif by synthesizing the behavior of the ensemble with the known behavior of the components that can be sufficiently accurately determined on a small scale. Such a numerical model is called a synthetic rock mass (SRM).

There are other areas, but these three are the main ones and are constantly developing. For example, in our work carried out for the Kryvyi Rih basin and the Nosachevske deposit of apatite-ilmenite ores, the correlation of uniaxial compressive strength values in specimens of different diameters was weak. Considering this gap, similar studies were carried out on concrete specimens of different sizes and with different grain sizes (firm rock aggregate). Compatible nonlinear regression analysis of firm rock and concrete showed better agreement between the results of the multifractal scaling model and the influence of the specimen size effect.

An example of some results obtained by scientists of the Kryvyi Rih National University for rocks of the Kryvyi Rih iron ore basin with a significantly larger volume of testing is shown in Fig. 6. The pattern practically repeats the established trend for the rocks of the uranium deposits. This allows us to assert the identity of the scale effect of strength in the rocks of the Ukrainian crystalline shield.

The presented results indicate that in order to minimize the scale effect of strength, it is advisable to test rocks on samples with the largest possible size. But in this case, problems arise with the selection of rock material, its preparation for testing and the testing process itself due to technical limitations of the equipment.

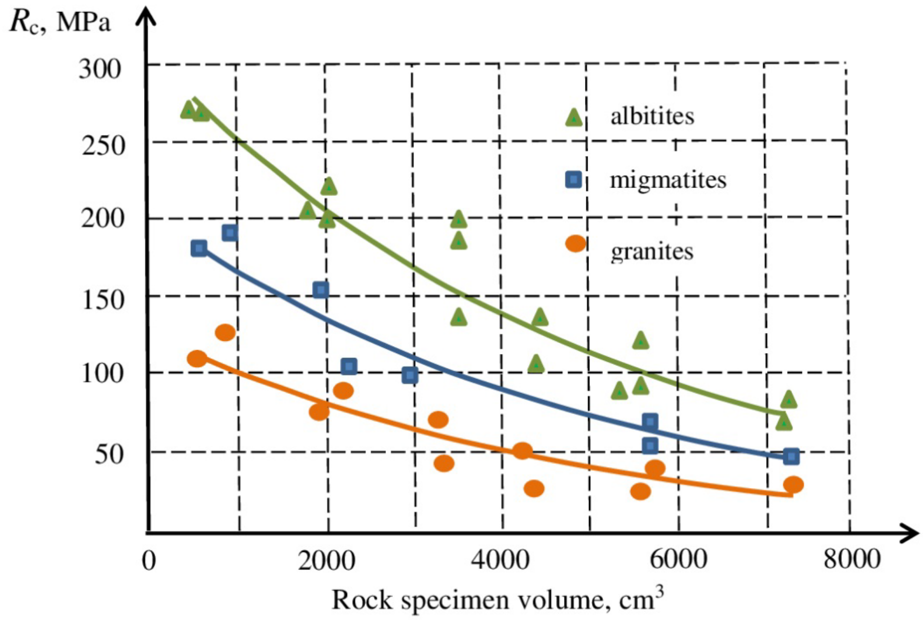



Figure 6 – Results of tests of the strength of specimens of different sizes of rocks of the Kryvyi Rih basin

In general, there is no consensus among experts about the optimal dimensions of an object for determining the true values of strength parameters. For example, M. Rocha [11], based on tests of support laminations on the surface of rock massifs, suggested that the strength of the rock massif would be several times greater than the average distance between laminations. At the same time, R.A. Schultz [12] suggested that a massif can be considered a continuum when the scale of the problem exceeds the size of the block or the distance between the cracks by 5–10 times. In turn, E. Hoek and E.T. Brown [10] simply state that in order to apply their empirical strength criterion, the underground mine must be "large" and the block size comparatively "small". This will lead to a strong movement of the rock mass. Some researchers [13, 14] suggest that the scale factor can be explained by interpreting the geological strength index (GSI) on an appropriate scale.

In our department, we traditionally distinguish several types of scale effects of strength and stress in a rock massif. One type is related to the volume of rock involved in defining the characteristic. The other arises from the scale dependence of rock parameters used in interpreting strength and stress properties. The latter type is a direct consequence of the discontinuous structure of rock massifs found at all scales. Since rock engineering structures are always constructed at different scales (from micro to macro), this understanding of rock behavior is very significant.

It is known that the deformation properties of rocks are characterized by moduli of elasticity, shear and volumetric compression. In this case, the elastic modulus is of two types: static $E_S$ and dynamic $E_D$. For rocks, there are relationships between them and the general deformation modulus $E_G$: $E_S > E_D > E_G$. The difference between the static modulus of elasticity and the modulus of total deformation depends on the type of rock and its structure. For rocks this ratio is approximately 2.

Note that fracturing has a significant impact not only on the strength, but also on the deformation of rocks. In terms of physics, this is explained by the fact that the surface of cracks is usually bumpy due to the presence of macro- and microscopic protrusions and depressions. Therefore, the actual contact area of two rock blocks can be tens of thousands of times less than the geometric contact area. Therefore, when compressive stresses normal to the crack plane occur, a concentration of stresses occurs on the protrusions and adjacent zones, exceeding the strength of the material. As a result of deformation or brittle fracture of the protrusions, the two surfaces come closer together. At the same time, the area of actual contact between the surfaces and the resistance to deformation increases.

Another characteristic that affects the deformation properties of rocks is their lamination. When laminated rock specimens are compressed, the deformation modulus in the direction parallel to the layers is usually higher than at perpendicular direction. This can be explained as follows. In the first case, the stiffer laminations of rock resist compression. In the second, compressibility is determined mainly by the deformation of the most pliable laminations sandwiched between rigid slabs.

As follows from the Table 3, the strength of rocks of uranium deposits under compression conditions is much higher than under tension. That is why most structures are designed so that the rock massif deforms in a field of compressive stresses. Mining workings are also structures, but their specificity is that they are located in a field of complex stress-strain state. Moreover, the ratio and influence of stress components are such that their horizontal components can play the main role.While calculating stability of an underground structure, these processes require prevailing consideration of the tensile resistance of the rock. A special approach to methods and means of maintaining mine workings in a safe condition is also required for calculations.

One of the explanations of this complexity is the dilatancy of rocks during deformation and destruction under conditions of unequal compression. This is especially evident in the area affected by mining operations, when the mine working is under the influence of temporary support pressure. During this period, the greatest increase in deformations occurs, which cannot be explained by rock creep, since the period is short-lived. This is also due to the increase in the volume of rocks with strength beyond the limits. Note that the latter is possible only under the simultaneous influence of several anomalous factors. For example, in zones of tectonic stress and bearing pressure.

## 4. Conclusions

The standard laboratory studies established that the rocks of the uranium deposits of Ukraine belong to the II and, partially, to the I and the III categories of strength by the scale of prof. Protodyakonov. That is, they are basically very hard. However, the structural and textural features of these rocks lead to the occurence of a large-scale strength effect in them. This effect, even in small volumes (a few cubic decimeters), reduces the strength of specimens by approximately 30–40% compared to standard sizes. In addition, the complex structure of uranium deposits, the steep angle of dip of the rocks, their lamination, as well as the significant size of the workings further reduce the strength of the massif. In fact, while calculating stability of the mine workings and choosing the parameters for their support, the strength of rocks in a massif should be determined as 0.5 $R_c$, where $R_c$ is the temporary resistance to uniaxial compression of a standard specimen. When using nomograms or other templates, it is necessary to reduce the strength category by one step in relation to the laboratory data. In our case, this corresponds to the third category.

The study of the behavior of rock specimens within and beyond their strength limits established that they have almost no plastic properties. It is shown that the ratio of the modulus of decrease to the static elastic modulus for all studied types of rocks of uranium deposits is greater than unity ($M / E > 1$). This clearly indicates the tendency of rocks to accumulate potential energy and cause brittle destruction of the massif beyond its strength limit. The results indicate that at great depths the main problems in mine workings associated with rock deformation processes will manifest themselves in the form of rock bumps, collapses or other dynamic phenomena. However, this does not exclude the possibility of deformation or destruction of the supports under the action of static loads. Such processes can arise as a result of collapses of massive rock blocks, the weight of which is critical in relation to the bearing capacity of the support.

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## ДОСЛІДЖЕННЯ МІЦНОСТІ ТА ОСОБЛИВОСТЕЙ ДЕФОРМАЦІЇ ГІРСЬКИХ ПОРІД УРАНОВИХ РОДОВИЩ

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**Анотація**. Предмет досліджень – фізико-механічні властивості гірських порід уранових родовищ України. Мета роботи – дослідження характеристик міцності і особливостей деформування порід уранових родовищ за межею їх міцності для забезпечення стійкості виробок на великих глибинах. Методи досліджень - експериментальні з використанням стаціонарного лабораторного обладнання і спеціальної реєструючої апаратури. Дослідження виконані до і за межею міцності. Зразки гірських порід виготовлені з матеріалу, відібраного в шахті уранового родовища. Комплекс досліджень включав визначення загальнофізичних властивостей порід (густини, питомої ваги, пористості, вологості і коефіцієнту зчеплення); основних параметрів міцності (опору стиску і розтягу в залежності від вологості і шаруватості, кута внутрішнього тертя, модуля пружності, коефіцієнта Пуассона, модуля спаду і залишкової міцності) та деформаційних характеристик. Виконано розрахунки масштабного коефіцієнта міцності. Проаналізовано результати. Показано, що породи уранових родовищ України за шкалою Протод'яконова відносяться до міцних і дуже міцних. Однак, структурно-текстурні особливості призводять до появи в породах масштабного ефекту міцності. Складна структура уранових родовищ, крутий кут падіння порід, їх шаруватість, а також суттєві розміри виробок додатково зменшують міцність масиву. Показано, що в розрахунках стійкості виробок і виборі параметрів їх кріплення міцність порід в масиві треба зменшувати вдвічі від значення, яке отримано стандартними лабораторними випробуваннями. Характеристики породних зразків до і за межею їх міцності вказують на майже відсутність в них пластичних властивостей. Відношення модуля спаду до статичного модуля пружності для всіх досліджених типів порід уранових родовищ має значення більше одиниці. Це однозначно вказує на схильність порід до накопичення потенційної енергії і крихкого руйнування масиву за межею міцності. Тобто на великих глибинах основні проблеми у гірничих виробках, що пов'язані з процесами деформування порід, будуть проявлятися у вигляді гірських ударів, обвалень або інших динамічних явищ. Це не виключає можливості деформування або руйнування кріплення дією статичних навантажень.

**Ключові слова**: уранове родовище, гірська порода, лабораторне дослідження, позамежне напруження, фізичні властивості, міцність, пружність, масштабний фактор.