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Approbation of the express penetration method for assessing the strength of sedimentary cohesive rocks

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The advantages of express methods of penetration and probing for evaluating the mechanical parameters of cohesive sedimentary rocks over traditional methods of testing them in single-plane displacement devices, odometers, and stabilometers are analyzed, such as: complete independence from the applied force and cone immersion depth; simplicity and reliability of the equipment; high reliability of results, etc. The methodology and results of 185 sets of penetration-shear tests of various clay rocks, from sandy loams to clays, are presented. Their results were used to determine the strength indicators of cohesive rocks (angle of internal friction and specific adhesion). Through statistical processing of experimental data, it was confirmed that for the water-saturated state of clay rocks there is an almost functional relationship between the penetration index and the porosity coefficient.

Keywords: well, sedimentary cohesive rock, strength, express method of penetration, specific penetration resistance, uniplanar displacement, internal friction angle, specific adhesion, the equation of interrelation.

Апробація експрес-методу пенетрації для оцінювання міцності осадових зв’язних гірських порід

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Проаналізовано переваги експрес-методів пенетрації та зондування для оцінювання механічних параметрів зв’язних осадових порід перед традиційними способами їх випробувань у приладах одноплощинного зрушення, одометрах і стабілометрах, як-то: повну незалежність від прикладеного зусилля та глибини занурення конуса; простоту й надійність обладнання; високу достовірність результатів і т. ін. Виділено галузі їх раціонального використання, у т. ч.: лабораторні та польові методи визначення параметрів міцності й стисливості різновидів осадових, а особливо зв’язних, гірських порід; обґрунтування рівнянь взаємозв'язку між фізичними і механічними властивостями різновидів порід, які мають постійні індикаційні характеристики за узагальненням дослідних даних та ін. Відзначено, що результати пенетраційних випробувань відповідно до рішень вісесиметричної задачі теорії граничної рівноваги оцінюють за питомим опором пенетрації. Подано методику і підсумки 185 комплексів пенетраційно-зрушувальних випробувань різних глинистих порід, від супісків до глин. Їх результати використано для визначення показників міцності зв’язних порід (кута внутрішнього тертя й питомого зчеплення). Шляхом статистичної обробки дослідних даних підтверджено, що для водонасиченого стану глинистих порід існує майже функціональний зв’язок між показником пенетрації і коефіцієнтом пористості. Встановлено, що питомі опори зрушенню глинистих порід за умови однакового фізичного стану лінійно взаємопов’язані з відповідніми середніми величинами питомого опору пенетрації при коефіцієнті кореляції близько 0,80. Проведення вишукувань за рекомендованою методикою суттєво зменшує обсяг нормативних випробувань на одноплощинне зрушення, а також дає можливість одержати достатньо достовірні результати з меншою трудомісткістю та тривалістю робіт.

Ключові слова: свердловина, осадова зв’язна гірська порода, міцність, експрес-метод пенетрації, питомий опір пенетрації, одноплощинне зрушення, кут внутрішнього тертя, питоме зчеплення, рівняння взаємозв’язку.

Introduction

The level of technical reliability and cost-effectiveness of innovative design and technological solutions for underground components of modern mining facilities, in particular, various types of oil and gas wells [1, 2], etc., significantly depends on the correct determination of the physical and mechanical characteristics of sedimentary rocks of natural massifs.

Typically, cylindrical samples of sedimentary rocks of natural structure, pre-selected during field surveys, are tested in the laboratory in a relatively simple compression device (odometer) to assess their deformation properties, and then to determine the strength parameters in a uniaxial shear device.

However, the most realistic stress-strain state (SSS) of the rock in the massif corresponds to the study of its cylindrical (sometimes cubic) samples in much more complex three-axis compression devices (stabilometers). The results of such tests can be used to determine both compressibility and strength characteristics [3-5].

Various types of stamp tests are used in field studies. However, these well-tested and reliable methods are quite labor-intensive, and for large volumes of the same type of tests, they are also time-consuming.

Therefore, in rock mechanics, the so-called express methods of studying the physical and mechanical properties of sedimentary rocks, such as penetration and probing, have become quite widespread.

This method of penetration is based on the slow immersion of a conical tip (indenter, cone) into the rock to a depth h, which does not exceed the height of the cone itself h_k. During penetration tests in the laboratory, the load is usually transferred in stages, while simultaneously recording the depth of the indenter. The duration of the load steps is kept constant (most often 1-2 minutes).

The generalized parameters of penetration tests were obtained on the basis of known solutions to the axisymmetric problem of the theory of limiting equilibrium. In particular, for cohesive sedimentary rocks (sandy loam, loam, clay), the ratio of the penetration force P to the square of the tip immersion depth - the specific penetration resistance R, MPa - is taken as such an indicator.

Practice has proven the main advantage of penetration tests of homogeneous sedimentary rocks, the so-called invariance condition of their results, i.e., complete independence from the applied force and the corresponding depth of the indenter immersion, and, taking into account the constants of the cones used, also independence from the angle of their opening. Thus, the results of the research do not depend on the means of recording the penetration resistance and the design of the penetrometers.

In addition, the penetration method is distinguished by: simplicity and reliability of the equipment; high reliability of test results; effective control over their probability; the ability to set up numerous experiments both in the field and in the laboratory; the ability to determine the mechanical parameters (mainly strength) of any natural and artificial materials, from gelled systems to rocks [6-8].

Thus, further development of high-speed penetration and sensing methods is relevant to reduce the labour intensity and duration of work to determine the mechanical properties, primarily strength parameters, of sedimentary rocks for the subsequent correct design of underground components of modern mining facilities.

Review of the research sources and publications

The express method of penetration in rock mechanics has been gaining some popularity gradually.

In particular, it is advisable to highlight the following most important stages of its development, in the authors' opinion.

1. Use of penetration testing to assess the condition of clayey rocks by consistency (or flowability).
2. Comprehensive substantiation of theoretical schemes of interaction of conical dies (indenters) with non-cohesive (sand) and cohesive (clay) rock.
3. Substantiation of the interaction between conical indenters and sedimentary rock from the standpoint of the theory of limit equilibrium, which was already approved at that time.
4. Introduction of research on sedimentary rocks by means of their ball tests.
5. Proposals for the use of resistivity and penetration index, as well as their use to establish the relationship between the physical and mechanical properties of cohesive (clay) rocks.
6. Further spreading of penetration tests for quantitative assessment of mechanical properties of sedimentary rocks, mainly their strength parameters and to a lesser extent - their deformability properties.

The most commonly used method for testing sedimentary rocks is with a tapered tip with a taper angle of $\alpha = 30°$.

In the modern practice of penetration testing of sedimentary rocks, it makes sense to highlight a number of popular areas. First of all, the equipment for penetration and static rock sounding, as well as the methods of processing and interpreting the results of these studies, continue to be improved [9, 10].

In recent years, the theoretical foundations of the penetration method have been improved by mathematical modelling using the solution of an axisymmetric problem by the finite element method in a physically and geometrically nonlinear formulation of the stress-strain state of a continuous medium around conical indenters (tips) when they are immersed in a certain volume of sedimentary rocks [11-14].

Mining practice has shown that various variations of the method of penetration testing of sedimentary rocks have been successfully tested for:

– classification of sedimentary rocks [15];

– quantitative assessment of changes in the state and mechanical properties of various sedimentary rocks under any type of external impact on them (compaction, moistening, drying, freezing, thawing, etc.) [16], as well as under dynamic (e.g., seismic) impact [17]. The quantitative effect of the impact on rock properties is usually assessed as the ratio of the values of the specific resistivity R/R_0 for cohesive rocks (or the penetration indices U/U_0 for non-cohesive rocks) obtained before and after the impact;

– control of the results of mechanical tests of rocks performed by traditional methods [18];

– laboratory and field methods for determining strength parameters [19-21] and sometimes deformability (compressibility) [22] of dispersed sedimentary rocks;

– identification of a certain relationship between the physical state indicators and strength characteristics of genetically homogeneous sedimentary rocks [23];

– substantiation of generalising equations of the relationship between the physical and mechanical properties of individual rock types that have constant, so-called, indicative characteristics (e.g., ductility number, mineralogical composition, structural features, etc.) based on the results of generalising numerical experimental data [24];

– interpretation of the results of penetration tests of sedimentary rocks in certain characteristic regions, in particular, on the sea shelf [25-27];

– evaluation of anisotropic mechanical properties of sedimentary rocks, in particular, determination of the anisotropy coefficient of mechanical characteristics of the rock as a ratio of the values of the specific resistance to penetration at a certain angle to the isotropy plane to the same parameter, but at zero angle [28];

– comprehensive geophysical, geomorphological and geotechnical studies to identify risk zones in landslide massifs composed of clayey rocks (such data are useful for understanding the mechanisms of landslide triggering, its depth, shape and condition of the material in the landslide body) [29];

– to assess the degree of heterogeneity of artificial massifs of sedimentary rocks [30];

– to assess the hydraulic conductivity of marine and deltaic sediments based on piezocone testing [31].

Definition of unsolved aspects of the problem

However, despite the noted advantages of rapid penetration and sensing methods for assessing the mechanical parameters of cohesive sedimentary rocks over traditional methods of testing them in single-plane displacement devices, odometers and stabilisers, these high-speed methods have not yet been widely tested and are almost not reflected in regulatory sources.

Problem statement

Therefore, the aim of the work is to test the penetration method for rapid but reliable determination of the strength of sedimentary cohesive rocks.

The objective of the study is to establish possible quantitative relationships in sedimentary cohesive (clay) rocks in a water-saturated state between the penetration index and the porosity coefficient, as well as between the specific shear resistance and the corresponding average values of the specific penetration resistance.

The object of the study is the interaction of conical indenters (stamps) and sedimentary cohesive rocks.

The subject of the study is the strength parameters of sedimentary cohesive rocks determined using the rapid penetration method.

Basic material and results

Theoretical justification of research methodology.

First of all, it should be noted that the presence in the theoretical expression of the resistance of a cohesive (clay) rock to shear of two conditional, but generally accepted, parameters of its strength, namely the angle of internal friction φ and the specific cohesion c, somewhat complicates the practical application of the penetration method.

The methodology for calculating the angle of internal friction φ of clay rocks of disturbed and natural structures is based on the known condition of proportionality between the specific cohesion c and the specific resistance to penetration R, which is based on the basic theory of the limiting equilibrium of the medium from the immersion of a conical tip

$$c = K_\varphi \cdot R\,, \tag{1}$$

where K_φ – is the proportionality function, which depends on the taper angle α and the dimensionless coefficient M_φ, which in turn is a function of the internal friction angle φ, or

$$K_\varphi = 1/(D_0 \cdot \pi \cdot tg^2\alpha/2)\,, \tag{2}$$

Theoretically, the coefficients M_φ and K_φ were calculated for a certain range of values of the rock internal friction angle $\varphi = 0 \div 20°$ and a tip with a taper angle $\alpha = 30°$, in particular for:

$\varphi = 0°,\ M_\varphi = 16{,}0\ and\ K_\varphi = 0{,}87;$

$\varphi = 10°,\ M_\varphi = 21{,}5\ and\ K_\varphi = 0{,}646;$

$\varphi = 20°,\ M_\varphi = 37{,}0\ and\ K_\varphi = 0{,}376.$

At the same time, however, the genesis of the sedimentary rock itself and the peculiarities of experimental methods for determining the angle φ were not taken into account.

Subsequently, the Geotechnical School of National University "Yuri Kondratyuk Poltava Polytechnic" determined the values based on the data of combined tests of lake-glacial clay (with the plasticity number $I_p = 20{,}4\%$ and the moisture content at the yield point $W_L = 41{,}7\%$).

The experiments were conducted using a well-tested laboratory penetrometer LP-1 with a rotational shear attachment and a combined tip with a taper angle of $\alpha = 30°$, which had mutually perpendicular wings.

This made it possible to obtain the specific penetration resistance in each experiment, and, after rotational displacement, the maximum torque $M_{\max}$.

Then, using the tip constant K_τ, the specific resistance to rotational displacement τ was determined, and identifying τ and c, the coefficient $K_\varphi = c / R$ and the value of the internal friction angle φ were determined.

The results of numerous field experiments of this clay were summarised in the graph $c = f(R)$, from which the value of K_φ as the tangent of the angle of inclination of the line drawn from the origin to the axis of the coordinates was derived. For a certain number of experiments, the average values of R, c, and K_φ were determined under conditions of similarity of rock moisture and density.

It turned out that the values of K_φ give angles φ very close to those theoretically obtained for the values of the internal friction angle of the rock $\varphi = 0 \div 20°$ and a tip with a taper angle $\alpha = 30°$.

Methodology of penetration-shear tests of clay rocks

At 60 sites in the Poltava region, 185 sets of penetration and shear tests were performed on various quaternary clay rocks, from sandy loam to light clay (with a plasticity index of I_P = 1-18 %).

Their results became the research basis for identifying the relationship between the specific resistances to shear τ and penetration R of these rocks.

The algorithm of laboratory tests, in particular, included the following blocks.

1. Cutting out samples from the cores taken from the boreholes using cutting rings 33-35 mm high and 70-71 mm in diameter, and determining the parameters of the initial physical state of the rock (moisture content, porosity coefficient e, etc.).
2. Preliminary compaction of the samples with their soaking.
3. Penetration tests of samples on both sides with 4-7 degrees of loading for each geological element (rock layer) and determination of the average value of its specific resistance to penetration $\overline{R}$.

By the way, the property of invariance of the resistivity of penetration with respect to a certain initial value of the cone immersion was also confirmed, which depends on a number of factors related, in particular, to the quality of preparation of the sample surface for penetration, the state of the cohesive rock under the tip, etc. The influence of these factors can be excluded if the first one or two degrees of loading on the tip are not taken into account.

Fig. 1 shows the test of a clay rock sample using the laboratory penetrometer LP-1, which was improved (by including a clock-type indicator in the process of fixing the indenter's immersion value in the rock) at Poltava Polytechnic.

4. Testing of these samples for rapid uniaxial shear according to the consolidated-drained scheme, determination of the specific shear resistance τ and the corresponding strength indicators φ_{II}, c_{II}. It should be noted that in the experiments, the actual height of the specimens allowed the shear plane to be created below the penetration mark.
5. Determination of the final values of moisture content and density of clay rock samples.
6. Determination of the coefficient $K_\varphi = c_{II} / \overline{R}$ for each geological element.
7. Comparison of the values of K_φ from penetration-shear experiments and φ_{II} from the results of consolidated-drained shear, i.e: $K_\varphi = f(\varphi)$.

Figure 1 – Testing a clay rock sample with an advanced laboratory penetrometer

The range of variability of the strength properties of clay rocks was as follows: $\overline{R} =$ 60-600 kPa; $c_{II} =$ 8-65 kPa; $\varphi_{II} =$ 9-36°; $K_\varphi =$ 0,061-0,329.

The penetration and one-plane shear indices of water-saturated and pre-compacted clay samples of the same physical condition obtained from the comprehensive penetration and shear tests allowed us to make the following generalisations of the results.

Results of penetration-shear tests of clay rocks

The processing of the results of shear and penetration showed that it should be carried out in a differentiated manner, separating a group of experiments related to sandy loam and a group of experiments that included loams and clays.

It turned out that the most effective relationship between the penetration and uniaxial displacement indicators exists between the average specific resistance to penetration $\overline{R}$ and the specific resistance to displacement τ under conditions of constant vertical pressure $\sigma = const$.

Both parameters characterise the strength of the rock and, after statistical processing, make it possible to establish the relationship between R and τ.

Thus, it is advisable to develop one of the possible methods of using the penetration index $\overline{R}$ for practical calculations of rock strength parameters φ and c.

In Fig. 2 shows the test points and the corresponding approximated graph of the dependence of $K_\varphi = f(\varphi)$.

Fig. 3 shows the experimental points and the corresponding graph of the dependence between $\overline{R}$ and τ at a vertical pressure of $\sigma=const=100\ kPa$ for sandy loam (50 complexes were statistically processed).

Fig. 4 shows similar dependences between $\overline{R}$ and τ at a pressure of $\sigma=const=100\ kPa$ for loams and clays (more than 130 complexes were statistically processed).

In all cases, the correlation coefficients of these empirical dependencies were about 0.80, which for rocks indicates a close connection.

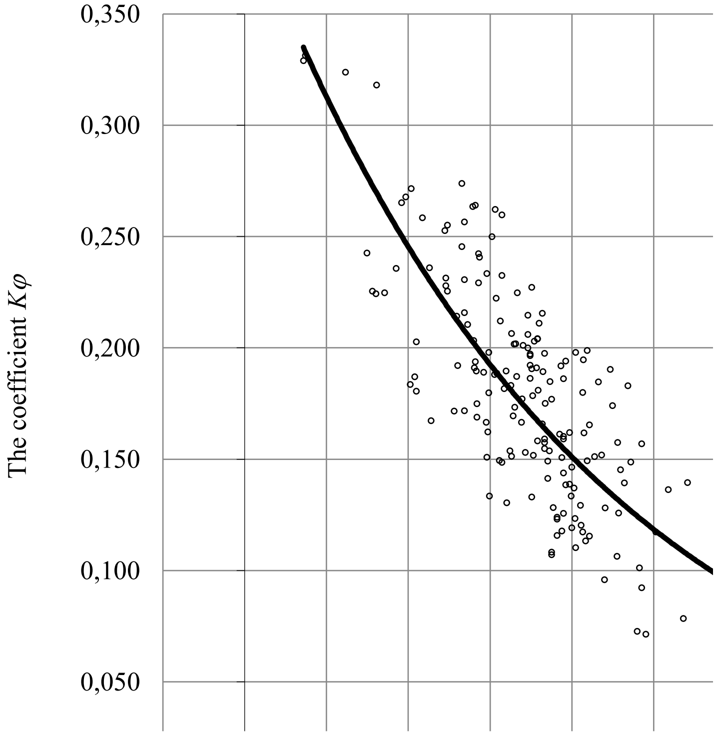

Figure 2 – Dependence of the coefficient K_φ on the angle of internal friction φ

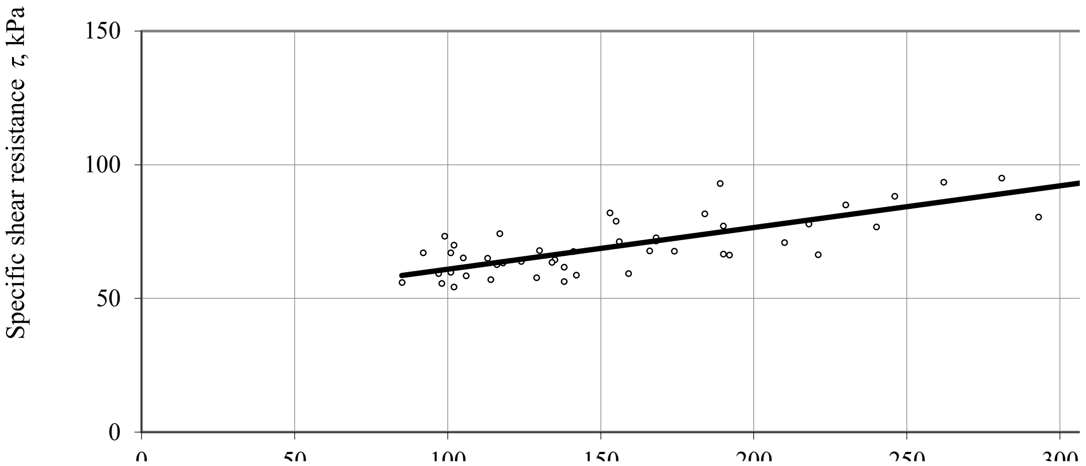

Figure 3 – Dependence between the specific resistance to penetration $\bar{R}$ and the specific shear resistance τ at a pressure of $\sigma=const=100\ kPa$ for sandy loams

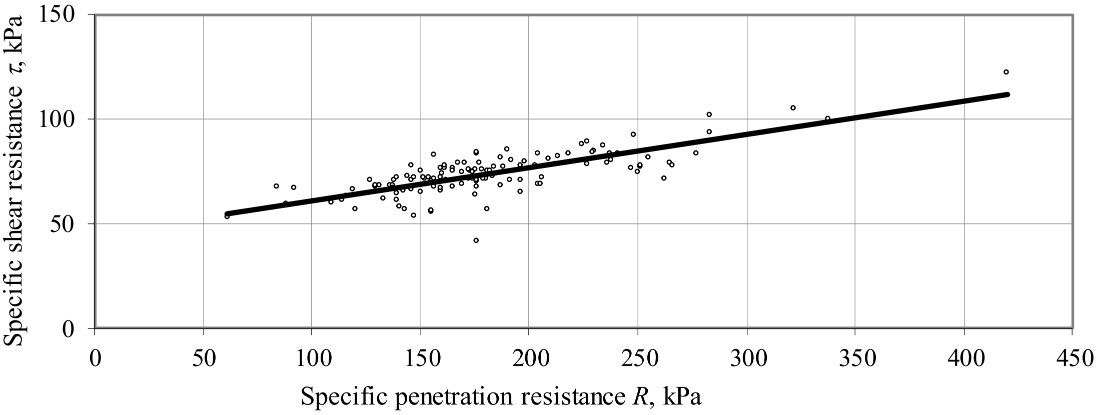

Figure 4 – Dependence between the specific resistance to penetration $\overline{R}$ and the specific shear resistance τ at a pressure of *σ=const=100 kPa* for loams and clays

The equation of the relationship between the penetration indicators and the strength of sedimentary cohesive rocks

Based on the results of determining the relationship between the specific resistances of penetration $\bar{R}$ and one-plane displacement τ under the condition *σ=const*, we have

$$\sigma = 100\,kPa,\ \tau = 0,2156\cdot\overline{R}+36,86; \tag{3}$$

$$\sigma = 200\,kPa,\ \tau = 0,5378\cdot\overline{R}+15,03. \tag{4}$$

Then

$$tg\varphi_{II} = \frac{0,5378\cdot\overline{R}+15,03-(0,2156\cdot\overline{R}+36,86)}{200-100} =$$

$$= 0,003\cdot\overline{R}-0,1883$$

and the specific adhesion (from the expression $c_{II} = \tau - \sigma\cdot tg\varphi_{II}$) is

$$c_{II} = (0,5378\cdot\overline{R}+15,03)-200\cdot(0,003\cdot\overline{R}-0,18) =$$

$$= -0,1062\cdot\overline{R}+32,68$$

Let's look at an example of such a calculation.

The average value of the specific resistance to penetration $\overline{R}$ =152,2 kPa was obtained on the clay rock samples of the site after their compaction and water saturation.

It was determined after 12 tests of 6 samples on both sides of the ring to the cone immersion depth *h*>10 mm.

Based on the results of one-plane shear of the same samples, 12 values of the specific shear resistance τ were obtained, and after their statistical processing, the values of the internal friction angle $\varphi_{II}=16°$ and the specific adhesion $c_{II}=36,4$ kPa were calculated.

According to the above dependences $\tau = f(\overline{R})$, we have $\tau_{100} = 66,67\,kPa$ and $\tau_{200} = 96,89\,kPa$, respectively, at a vertical pressure of $\sigma = 100\,kPa$ and $\sigma = 200\,kPa$.

Then $tg\varphi_{II} = (96,89-66,67)/(200-100) = 0,302$; the angle of internal friction is equal to φ_{II} =16,8°; and the specific adhesion $c_{II} = -0,1062\cdot 152,2+52,69 = -16,16+52,69 = 36,5 kPa$. Thus, the results of the established relationship between the parameters *R* and τ made it possible to determine the strength of the experimental heavy dusty loam (with a plasticity number $I_p = 14,5\%$), which practically coincided with the data of its tests for uniaxial shear.

The validity of these generalisations can be easily checked by looking at the porosity coefficient *e*, the flowability (consistency) index I_L and the water saturation coefficient S_r for clayey rocks.

As an example, for semi-hard clays, Table 1 shows the calculated values of K_φ and $\overline{R}$.

The final equation for the dependence of $\tau = f(\overline{R})$, which does not depend on the porosity coefficient *e*, is as follows

$$\tau = (11,75+0,206\cdot\sigma)+(0,166+0,00047\cdot\sigma)\cdot\overline{R} \tag{5}$$

Thus, it is possible to determine the strength parameters of clay rock (internal friction angle φ_{II} and specific adhesion c_{II}) from the average value of the specific penetration resistance $\overline{R}$ of compacted samples after their water saturation (usually reduced to the water saturation coefficient $S_r \geq 0,80$).

Of course, similar calculations and tables can be drawn up for other clay consistency values, as well as for loams or sandy loams.

It makes sense to establish the final equations of the relation $\tau = f(\overline{R})$ for a sufficiently wide range of variability of the clay rock yield factor, for example, $0 \leq I_L \leq 0,75$, in the form

$$\tau = A + B\cdot\sigma + (C + D\cdot\sigma)\cdot\overline{R} \tag{6}$$

where *A, B, C, D* – are the empirical coefficients of the equation.

Table 1 - Estimated values of the coefficient K_{φ}, depending on the rock strength parameters φ_{II} and $\bar{R}$

	Clay porosity coefficient *e*					
	0,55	0,65	0,75	0,85	0,95	1,05
$K_{\varphi} = f(\varphi)$	0,196	0,204	0,211	0,219	0,235	0,250
$\bar{R} = c_{II} / K_{\varphi}$	413	333	255,1	214,2	174,6	143,9
Specific shear resistance τ, kPa, at vertical pressure σ, kPa						
σ=100 kPa	119,0	104,0	88,4	79,5	69,7	60,9
σ=200 kPa	157,7	140,8	122,9	112,0	98,3	85,8
σ=300 kPa	190,2	177,2	157,2	144,8	127,0	110,8

Conclusions

1. It has been experimentally confirmed that for the water-saturated state of a cohesive (clay) rock, there is a practically functional relationship between the penetration index and the porosity coefficient. The specific shear resistances of clayey rocks, under the condition of the same physical state, are linearly interrelated with the corresponding average values of the specific resistance to penetration.

2. From the interrelation equations of the type (8), it is easy to determine the specific resistance to penetration obtained in the experiment from the average value of the specific resistance to shear of clay rocks at least at two values of vertical pressure, and then - the strength of the cohesive rock and (and, if necessary, taking into account the reliability factors, their calculated values).

3. The use of the expressions $K_{\varphi} = f(\varphi)$ and $K_{\varphi} = c / \bar{R}$ gives grounds for the use of simplified tests of cohesive rock for uniaxial shear, which consist in the penetration of pre-compacted water-saturated samples with the determination of the specific resistance to penetration, the performance of uniaxial shear at the minimum possible pressure and the establishment of the corresponding value of the specific cohesion.

4. Conducting surveys according to the recommended methodology significantly reduces the volume of regulatory tests for single-plane displacement, and also makes it possible to obtain sufficiently reliable results with less labour intensity and duration of work. Further testing of the penetration method for determining the strength of cohesive rocks opens up prospects for a wider reflection of this express method in regulatory sources.

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