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RESEARCH OF STRENGTH CHARACTERISTICS OF COARSE CLASTIC MATERIAL OF A HIGH EARTHEN DAM

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Abstract. Currently, in the construction of earth dams and other structures associated with large volumes of coarse-grained materials, multi-fraction rock mass is used instead of sorted stone. Therefore, in construction practice there is increasingly a need to determine the granulometric composition of various coarse ground. Correct determination of the design characteristics of the gravel-pebble mixture and rock mass is extremely important, since this affects the choice of an economical design solution, effective technology for its construction, and trouble-free operation of the constructed structure. The issue of determining the strength characteristics of coarse soil used as a dam material in hydraulic engineering is still relevant in the practice of domestic and world engineering surveys.

The presence of large inclusions in the soil does not allow the use of standard instruments and requires the development of special instruments and special techniques. The article discusses a plane shear device, provides a methodology for conducting laboratory studies of the strength characteristics of coarse-grained soil and processing its results.

Analysis of laboratory research results shows that a decrease in strength occurs with an increase in stress. This should be taken into account when constructing the thrust prism of the dam, which is the main element of the upper cofferdam, i.e. the thrust prism should be erected in accordance with the requirements of its charged state and uniformity of the material should be achieved when laying soil in different zones of the dam body, this will ensure uniformity of strength properties. A change in the strength properties of coarse soil depending on the grain composition of the stone at the same degree of compaction is possible only by increasing the coefficient of engagement.

Keywords: coarse soil, model mixture, soil strength characteristics, plane shear device, stress state, vertical and horizontal deformations.

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ГРУНТТЫ БИІК БӨГЕТТІҢ ІРІСЫНЫҚТЫ МАТЕРИАЛЫНЫҢ БЕРІКТІК СИПАТТАМАЛАРЫН ЗЕРТТЕУ

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Аннотация. Қазіргі уақытта үлкен көлемдегі ірі түйіршікті материалдармен байланысты жер бөгеттері мен басқа құрылыстарды салуда сұрыпталған тастың орнына көп фракциялы тау жыныстары қолданылады. Сондықтан

құрылыс тәжірибесінде әртүрлі ірі топырақтың гранулометриялық құрамын анықтау қажеттілігі барған сайын арта түсуде. Қиыршық тас қоспасы мен тау массасының жобалық сипаттамаларын дұрыс анықтау өте маңызды, өйткені бұл үнемді жобалық шешімді таңдауға, оны құрудың тиімді технологиясына және салынған құрылымның ақаусыз жұмысына әсер етеді. Гидротехникада бөгет материалы ретінде пайдаланылатын ірі топырақтың беріктік сипаттамаларын анықтау мәселесі отандық және әлемдік инженерлік зерттеулер тәжірибесінде әлі де өзекті болып табылады.

Топырақта үлкен қосындылардың болуы стандартты аспаптарды қолдануға мүмкіндік бермейді және арнайы құралдар мен арнайы техниканы әзірлеуді талап етеді. Мақалада жазық ығысу құрылғысы қарастырылады, ірі түйіршікті топырақтың беріктік сипаттамаларына зертханалық зерттеулер жүргізу және оның нәтижелерін өңдеу әдістемесі қарастырылған.

Зертханалық зерттеулердің нәтижелерін талдау күштің төмендеуі, стресстің жоғарылауымен бірге жүретінін көрсетеді. Бұны бөгеттің тірек призмасын тұрғызу кезінде ескеру керек, ол жоғарғы бөгеттің негізгі элементі болып табылады, яғни итеру призмасы оның зарядталған күйінің талаптарына сәйкес орнатылуы керек және бөгет корпусының әртүрлі аймақтарында топырақты төсеу кезінде материалдың біркелкілігіне қол жеткізу керек, бұл беріктік қасиеттерінің біркелкілігін қамтамасыз етеді. Бірдей тығыздалу дәрежесінде тастың түйіршіктік құрамына байланысты ірі топырақтың беріктік қасиеттерінің өзгеруі тек қосылу коэффициентін арттыру арқылы мүмкін болады.

Түйін сөздер: ірісынықты топырақ, үлгі қоспасы, топырақтың беріктік сипаттамалары, жазық ығысу құрылғысы, кернеу күйі, тік және көлденең деформациялар.

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ИССЛЕДОВАНИЕ ПРОЧНОСТНЫХ ХАРАКТЕРИСТИК КРУПНООБЛОМОЧНОГО МАТЕРИАЛА ВЫСОКОЙ ГРУНТОВОЙ ПЛОТИНЫ

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Аннотация. В настоящее время при строительстве грунтовых плотин и других сооружений, связанных с большими объемами крупнообломочных материалов, вместо сортированного камня используют многофракционную горную массу. Поэтому в строительной практике все чаще возникает необходимость определения гранулометрического состава различного крупнообломочного грунта. Правильное определение расчетных характеристик гравийно-галечниковой смеси и горной массы имеют исключительно важное значение, так как это влияет на выбор экономичного решения конструкции, эффективной технологии ее возведения, безаварийной эксплуатации построенного сооружения. Вопрос определения прочностных характеристик крупнообломочного грунта, используемого в качестве материала плотины в гидротехническом строительстве, по-прежнему актуально в практике отечественных и мировых инженерных изысканий.

Наличие крупных включений в грунте не позволяет применять стандартные приборы и требует разработки специальных приборов и особых методик. В статье рассмотрен прибор плоского сдвига, приведена методика проведения лабораторных исследований прочностных характеристик крупнообломочного грунта и обработка его результатов.

Анализ результатов лабораторных исследований показывает, что снижение прочности происходит с увеличением напряжения. Это следует учитывать при возведении упорной призмы плотины, которая является основным элементом верховой перемычки. То есть упорную призму следует возводить согласно требованиям ее наряженного состояния и добиваться однородности материала при укладке грунта в разные зоны тела плотины, этим будет обеспечиваться однородность прочностных свойств. Изменение прочностных свойств крупнообломочного грунта в зависимости от зернового состава камня при одинаковой степени уплотнения возможно только за счет увеличения коэффициента зацепления.

Ключевые слова: крупнообломочный грунт, модельная смесь, прочностные характеристики грунта, прибор плоского сдвига, напряженное состояние, вертикальные и горизонтальные деформации.

Introduction. Currently, the rational use of stone materials obtained by explosive mining of rocks is of particular relevance (Ibragimov, et al, 2023; Petrov, et al, 1994; Zhantasov, et al, 2017). Increasingly, instead of sorted stone, rock mass is used, which is a mixture of a multi-fraction composition. Therefore, in construction practice there is increasingly a need to determine the granulometric composition of various coarse soils. Moreover, if the size of individual fractions reaches 500, 1000 mm or more, then assessing the grain composition using the traditional weight method becomes very labor-intensive. At the same time, the construction of soil structures for large energy facilities, as well as the preparation of foundations for powerful units of thermal power plants, are associated with large volumes of coarse clastic materials. Correct determination of the design characteristics of the gravel-pebble mixture and rock mass is extremely important, since this affects the choice of an economical design solution, effective technology for its construction, and trouble-free operation of the constructed structure (Baibolov, 2022).

A large number of theoretical works and experimental studies are devoted to the study of the strength characteristics of coarse soils. Research conducted under the direction of Shabayev S.N. made it possible to establish that an increase in the particle size of a single-fraction medium leads to an increase not only in the angle of internal friction, but also in specific adhesion (Shabaev, 2020; Shabaev, et al, 2020). He also proposed an improved version of the KU-54 type wedge installation, through which it is possible to adequately evaluate the shear resistance of pre-compacted coarse-grained media using the oblique cut method and identify the strength characteristics of the material, namely the angle of internal friction and adhesion. On a shear installation of a different type, a research group led by Sagybekova A.O. (Alimseitov, et al, 2018) determined that residual strength is a more accurate characteristic of soil resistance. It was concluded that the compaction of coarse soils depends on the grain size, the amount and composition of the filler, the shape of large fragments and the nature of their surface, and the strength of the fragments. They also noted that the compaction of coarse soils also depends on the initial packing density of structural elements. Sainov M.P., studying the works of researchers of the last century (Sainov, 2016), noted that the power function well describes the increase in the value of the shear modulus of coarse soils depending on the soil compression stress. He also determined that gravel-pebble soil is less deformable and has higher strength than rock mass under the same conditions. Research results of Kozionov V.A. (Kozionov, et al, 2007) confirmed the reinforcing effect of large inclusions on the strength properties of coarse soils. A connection has been established between the parameters of strength, structure and physical state of the soil. It is noted that with an increase in the size of inclusions and their number, the strength characteristics of the soil increase, and an increase in humidity leads to their decrease. A group of researchers led by Kolos A.F. (Kolos, 2017) revealed that increasing the roundness of grains leads to a significant decrease in the adhesion between grains in crushed stone ballast, but has almost no effect on the angle of internal friction. Among the modern publications devoted to solving this problem abroad, the following authors can be noted: Ghorashi S., Khodaparast M., Khodajooyan Q. (Ghorashi, et al, 2023), Fard M. (Fard, 2020), Wu E., Zhu J., Guo W., Zhang Z. (Wu, et al, 2020) and others.

Research materials and methods. In construction practice, two devices are used to study the strength characteristics of coarse soils in laboratory conditions: a plane shear device and a stabilometer (Artykbaev, et al, 2024).

In plane shear devices, the measured parameters in tests are normal σ and shear stresses τ in the shear plane, from which the shear coefficient C_S is calculated.

In a stabilometer, unlike a plane shear device, two main stresses are measured: maximum σ_1 and minimum σ_3 ($\sigma_1 = \sigma_3$). In this case, the shear coefficient can be calculated only after preliminary calculations of normal and shear stresses along the destruction sites according to the formulas:

$$\sigma = \frac{2\sigma_1\sigma_3}{\sigma_1+\sigma_3} \quad (1)$$

$$\tau = \frac{\sigma_1-\sigma_3}{\sigma_1+\sigma_2} \cdot \sqrt{\sigma_1\sigma_3} \quad (2)$$

$$C_s = \frac{\sigma_1-\sigma_3}{2\sqrt{\sigma_1 \cdot \sigma_3}} \quad (3)$$

Taking this into account, the results of experiments both in plane shear devices and in stabilometers can be interpreted in the same way in the form of the dependence $C_s = f(\sigma)$, i.e. according to the Coulomb-Mohr theory. Numerous studies carried out by various organizations on these devices show almost the same results. Only the experimental methodology and interpretation of the results are somewhat different.

It should be noted that using a plane shear device it is possible to examine coarse-grained soils that are close in grain composition to natural ones. At the same time, working with this device is characterized by a simple research methodology. Also, when testing rock mass (broken stone), from an economic point of view, the use of this device is more profitable than the use of a stabilometer.

The flat shift device with dimensions 700x700x700mm consists of the following main elements: lower and upper carriages; hydraulic jacks for creating vertical and horizontal loads and deflectometers for measuring vertical and horizontal deformations. The movable lower carriage is a metal container on rolling supports. The fixed upper carriage is a frame placed on the rollers along the lower carriage. The soil sample is placed in a container formed between the upper and lower carriages. The vertical load on the sample is transmitted through the dies. The load on the die is created by a hydraulic jack DG-100 and controlled by a pressure gauge. The horizontal load is created by a horizontal jack, its magnitude is also controlled by a pressure gauge. The carriage movements are recorded by deflectometers.

One of the important stages of preparation for conducting experiments is calibrating the hydraulic system of the device, which includes the pump, pressure line and jack. Calibration is carried out using two standard dynamometers with measurement limits of 50-100 tons. In this case, the dynamometer is installed between the support beam and the jack (for vertical and horizontal loads) (GOST 12248.1, 2020). Pressure is created through a pumping station. Increasing the pressure, take readings on the pressure gauge and dynamometer. The obtained data is superimposed for each jack on a graph reflecting the pressure loss in the system with increasing load.

The significant size of fractions of coarse soils (100, 200, 500 mm and more) requires labor-intensive and expensive experiments on unique large-sized installations. For this reason, in the practice of experimental research, much attention has to be paid to the issues of modeling the composition, size and other parameters of coarse soils. Based on the condition that the ratio of the diameter of the device to the size of the maximum fraction should not be less than five (Artykbaev, et al, 2024; GOST 30416-2020, 2020), i.e. $d_{dvc} \geq 5d_{max}$, then for our flat shear device with dimensions 700x700x700 mm, grain compositions are accepted with a maximum diameter d_{max}=140 mm.

If natural soil has fraction sizes exceeding the capabilities of the device, then experiments are carried out with model mixtures. In this case, the model mixture is composed of natural soil material with a fraction reduction in *n* times, i.e., the grain composition curves of the natural and model soil must be parallel, and the grain composition of the model soil is limited to the maximum fraction d_{max}=140 mm, i.e., the modeling scale is selected so as not to exceed the maximum fraction size. Full-scale and model soil compositions are shown in Figure 1. Moreover, on the recommendation of specialists from the National Research University MSCU, the model mixture was compiled with a maximum fraction of 120 mm.

The sequence of work when testing the strength characteristics of coarse soil using a plane shear device is as follows:

1) the sizes of the diameters of model soil fractions is calculated by multiplying the diameters of natural soil fractions by a scale factor and the soil for experiments is prepared;

2) prepared soil of model or natural composition is placed in layers in the carriages of the device. In this case, the thickness of the soil laying layer is $h=1.2 \cdot d_{max}$; in our case, the thickness of the soil layer was 14 cm. Each layer is compacted using a manual tamper. The soil being laid is weighed and the average density of the soil in the device is calculated. The range of soil density in our case was 1.98÷2.03t/m^3;

3) after placing the soil in the device, its assembly is completed: a die, vertical and horizontal jacks, a thrust beam, thrust and support nuts, and deflectometers are installed. The initial value of the vertical position of the die is recorded;

4) the vertical load is created by a vertical jack in increments of 0.05-0.1 MPa to a given value and is controlled by a pressure gauge. When a given load is reached, the values of vertical deformation are recorded based on the die settlement at each load level;

5) after reaching the vertical load of a given value, a horizontal load is applied in increments of no more than 0.05 MPa. Moreover, when a horizontal load is applied, the vertical load must remain unchanged;

6) the shear moment is recorded by the growth of horizontal deformations noted by deflectors at a constant shear (horizontal) force;

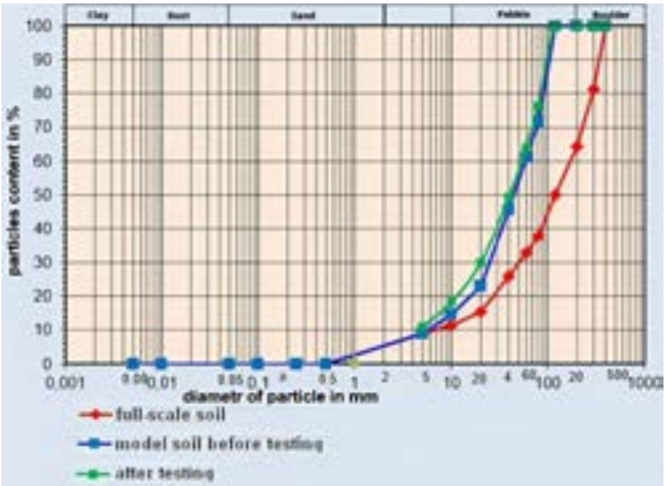

Figure 1. Graph of the grain composition of natural soil and model mixture before and after the experiment

7) after the end of the experiment, the pressure in the jacks is released: first vertical, then horizontal. Then the device is disassembled, the soil is sieved into fractions through sieves and each fraction is weighed. Next, a grain composition curve is constructed after the experiment, as shown in Figure 1. Analysis of the grain composition after the experiment provides information about the crushability of each fraction of the soil composition;

It should be noted that in connection with the transition of the assessment of strength characteristics to a confidence probability, standard and calculated values of the material should be established by statically processing the results of experimental data in an amount of at least six for each vertical load. In our case, there are 4 variants of vertical load, the number of experiments was 24 accordingly.

Results and discussion. Shear tests are performed for 4 variants of vertical loads: 2; 4; 8; 12 kgf/cm^2. Based on experimental research data, graphs are constructed $\tau=f(\Delta l)$; $\tau=f(\sigma)$, where τ - horizontal stresses, shifts; Δl - magnitude of horizontal deformations, mm; σ - vertical pressure values, kg/cm^2.

Determination of the shear coefficient $tg\varphi$ and engagement C are calculated using the least squares method using the formulas:

$$\mathrm{tg}\phi = \frac{n\sum_{i=1}^{n}\sigma_i\tau_i - \sum_{i=1}^{n}\sigma_i\sum_{i=1}^{n}\tau_i}{n\sum_{i=1}^{n}\sigma_i^2 - (\sum_{i=1}^{n}\sigma_i)^2} \quad (4)$$

$$C = \frac{\sum_{i=1}^{n}\sigma_i^2\sum_{i=1}^{n}\tau_i^2 - \sum_{i=1}^{n}\sigma_i\sum_{i=1}^{n}\tau_i\sigma_i}{n\sum_{i=1}^{n}\sigma_i^2 - (\sum_{i=1}^{n}\sigma_i)^2} \quad (5)$$

where n - number of experiments; C- engagement.

The determination of the principal stresses σ_1 and σ_3 is carried out by constructing the Mohr circle. Assuming that there is no coupling, (4) takes the form

$$\tau = \sigma \cdot \text{tg}\phi \qquad (6)$$

The point of intersection of the circle with the abscissa axis will give the desired value of the main stresses σ_1 and σ_3, and the angle of inclination of the tangent to the abscissa axis will be the angle of internal friction φ for a given vertical stress.

The shear coefficients $tg\varphi$ and engagement coefficients C are calculated using the least squares method. If there is adhesion or engagement for the stone material (rock mass), the shear angle is determined by the formula:

$$\text{tg}\Psi = \text{tg}\phi + \frac{C}{\sigma} \qquad (7)$$

where ψ - shear angle; ϕ - angle of internal friction; C - engagement; σ - vertical stress.

The calculated strength values are obtained by dividing the standard values by the soil safety factor, the physical meaning of which is that the actual values of the strength characteristics will not exceed the maximum strength of the soil with the corresponding confidence probability.

The soil safety factor is calculated from a set of paired measurements of vertical stresses and shear loads from σ_{min} to σ_{max} and depends on the variation of these values, i.e., the coefficient of variation "V":

$$\Delta = n\sum_{i=1}^{n}(\sigma_i)^2 - (\sum_{i=1}^{n}\sigma_i)^2 \qquad (8)$$

$$\text{tg}\phi = \frac{1}{\Delta}(n\sum_{i=1}^{n}\tau_i\sigma_i - \sum_{i=1}^{n}\tau_i\sum_{i=1}^{n}\sigma_i \qquad (9)$$

$$c = \frac{1}{\Delta}(\sum_{i=1}^{n}\tau\sum_{i=1}^{n}\sigma^2 - \sum_{i=1}^{n}\sigma_i\sum_{i=1}^{n}\tau_i\sigma_i) \qquad (10)$$

We obtained the calculated strength values by dividing the standard values by the safety factor for the soil and have presented in Table 1. This means that the actual values of the strength characteristics will not exceed the limit values of soil strength with the corresponding confidence probability.

Table 1 - Strength characteristics of rock mass depending on vertical pressure

Vertical stress σ, kgf/cm^2	2	4	8	12
Shift coefficients $tg\phi$	1,149	0,958	0,862	0,831
Angle of internal friction $\phi°$	48,9	43,8	40,8	39,7

Analysis of the data in Table 1 shows that a decrease in strength occurs with an increase in stress. This should be taken into account when constructing the thrust prism of the dam, which is the main element of the upper cofferdam, i.e., the thrust prism should be erected in accordance with the requirements of its charged state and uniformity of the material should be achieved when laying soil in different zones of the dam body, which will ensure uniformity of strength properties.

The results of the studies are shown below on the dependence graphs $\tau=f(\Delta l)$ for 4 variants of vertical load (Figures 2-5) and the dependence graph $\tau=f(\sigma)$ presented in Figure 6.

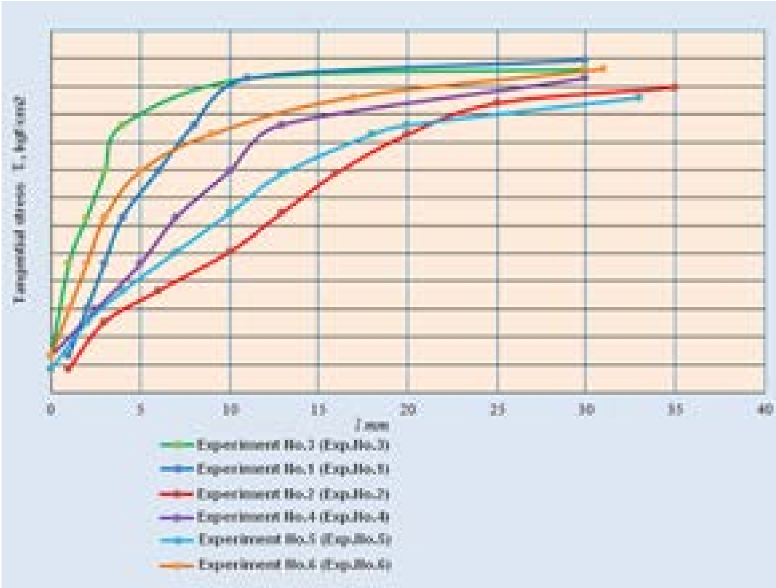

Figure 2. Dependence graph $\tau=f(\Delta l)$ at a load of 2 kgf/cm^2

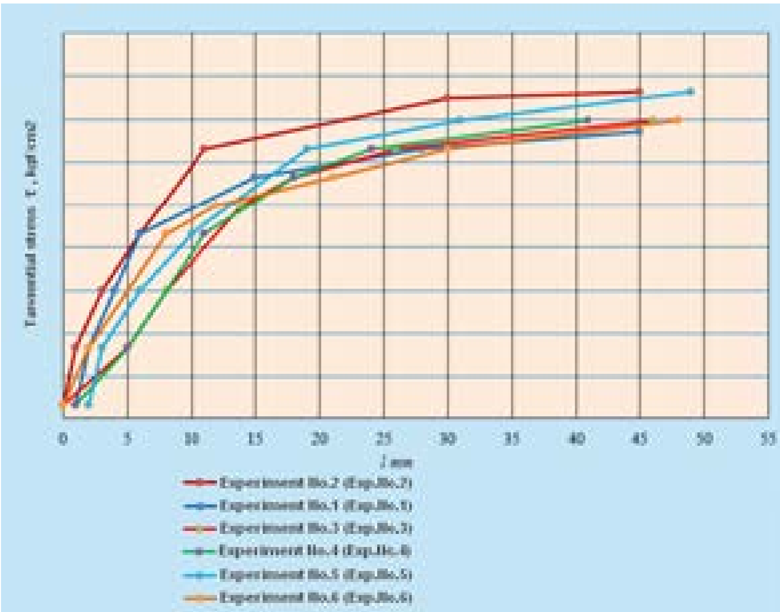

Figure 3. Dependence graph $\tau=f(\Delta l)$ at a load of 4 kgf/cm^2

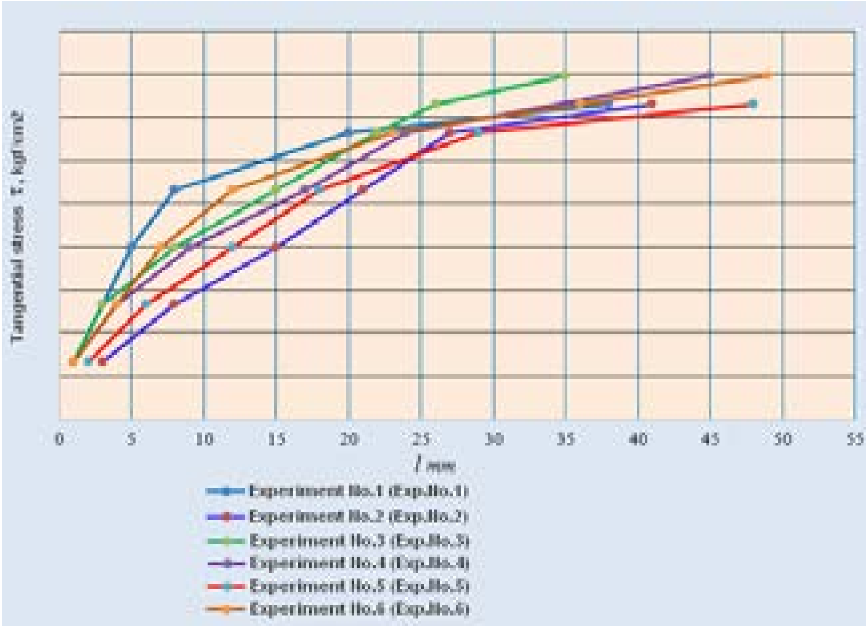

Figure 4. Dependence graph *τ=f(Δl)* at a load of 8 kgf/cm²

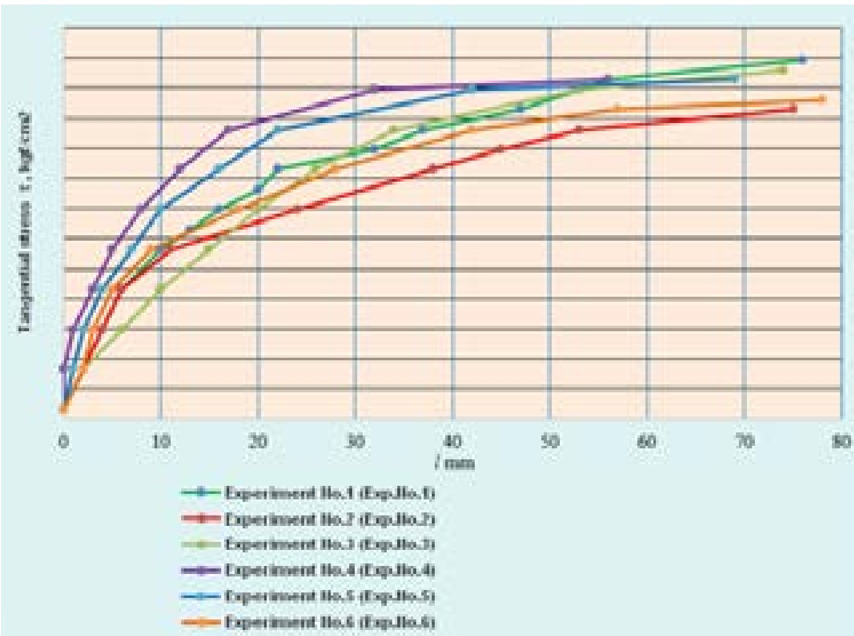

Figure 5. Dependence graph *τ=f(Δl)* at a load of 12 kgf/cm²

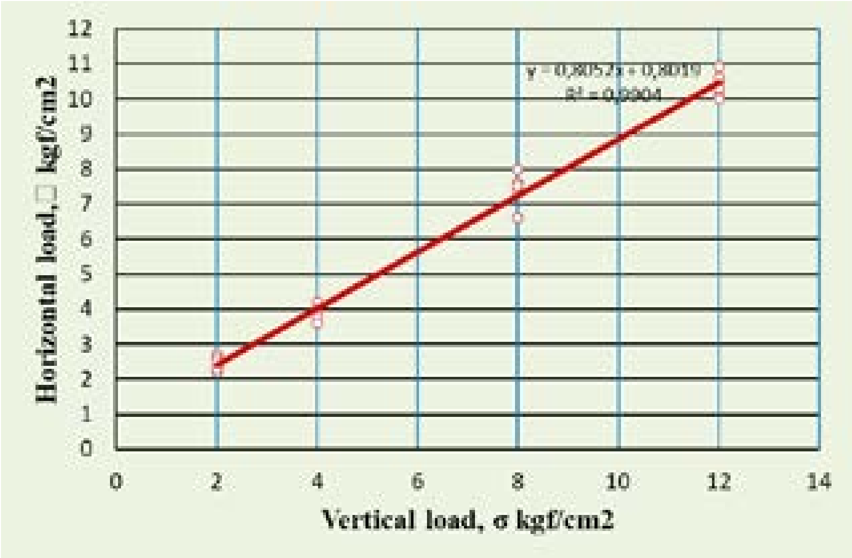

Figure 6. Dependency graph *τ=f(σ)*

Conclusions. The experimental studies of the strength characteristics of the rock mass under single-plane shear conditions allow us to draw the following conclusions:

- strength indicators determined from the results of tests under vertical loads from 2.0 to 12.0 kg/cm^2, compressive σ and shear τ stresses at the moment of sample failure are accepted according to the Coulomb-Mohr condition. The number of experiments and processing of the results were carried out in accordance with the requirements of regulatory documents (SN RK 3.04-03-2023, 2023; GOST 20522-2012, 2014).

- based on the results obtained, calculated characteristics were established for the actual particle size distribution with a confidence probability α = 0.95, which are characterized by a shear angle ϕ = 48.9 to 39.7° depending on the value of the vertical load from 2.0 to 12.0 kg /cm^2.

- a change in the strength properties of coarse soil depending on the grain composition of the stone at the same degree of compaction is possible only by increasing the *C* coefficient of engagement.

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CONTENT

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