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# Correlation equation between physical and mechanical properties of sedimentary rocks

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The results of parallel experimental studies of the physical and mechanical properties of sedimentary rocks of natural structure, including their penetration tests, are presented. The possibility of establishing empirical equations of the relationship between the physical (soil skeleton density and moisture content) and mechanical (specific resistance to penetration, angle of internal friction, specific adhesion, deformation modulus) characteristics of cohesive (on the example of light dusty loams of loess origin) and non-cohesive (on the example of fine sands, quartz) sedimentary rocks of natural structure is tested. It is noted that such equations are correct only for genetically identical types of sedimentary rocks

**Keywords:** sedimentary rock, penetration, humidity, specific penetration resistance, strength, deformation modulus, relationship

# Кореляційні рівняння між фізичними та механічними властивостями осадових гірських порід

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The current situation in the field of strength properties evaluation of sedimentary rocks using the express methods, such as penetration test, is analyzed. It is noted that a condition for setting up the relationship between the indicators of the physical state of sedimentary rock (natural moisture content, porosity coefficient) and indicators of mechanical properties (specific resistance to penetration, angle of internal friction, specific adhesion, deformation modulus) is the accumulation of test results to determine the listed characteristics of soils with a relatively constant plasticity number and genetically homogeneous. The results of parallel experimental studies of the physical and mechanical properties of sedimentary rocks of natural structure, including their penetration tests, are presented. The possibility of determining empirical equations of the relationship between physical (soil skeleton density and moisture content) and mechanical (specific resistance to penetration, angle of internal friction, specific adhesion, deformation modulus) characteristics of cohesive (light loams soils of loess origin) and non-cohesive (fine sands of quartz) sedimentary rocks of natural structure has been tested. The values of statistical indicators (coefficient of correlation, variation, and dispersion) of these equations substantiate a rather close relationship between mechanical and physical parameters. The possibility of studying the anisotropic properties of cohesive rocks of natural structure using penetration tests and determining empirical equations of the relationship between their physical and mechanical characteristics is also proved. A practical recommendation is given on the expediency of using correlation equations between the physical and mechanical properties of sedimentary rocks of natural structure to reduce the volume of laboratory tests in determining their mechanical parameters

**Keywords:** sedimentary rock, penetration, humidity, specific penetration resistance, strength, deformation modulus, relationship

**Introduction**

The current experience of mining mechanics and geotechnics shows that determining the mechanical characteristics of sedimentary rocks (soils) both in their natural and in their compacted state in sufficient quantities for appropriate calculations, modeling, and design involves significant expenditures of material resources and time [1-3].

Therefore, for example, for preliminary calculations of the foundations of buildings and structures allow determining the values of the parameters of deformability and strength of soils by their physical parameters (for sands, by the particle size distribution and porosity coefficient *e*, and for clay rocks, by the index of soil fluidity $I_L$ and porosity coefficient).

The practice of compiling tables of approximate values of the deformation modulus *E*, the angle of internal friction *φ*, and the specific cohesion *c* for sedimentary rocks in a given region has been tested, in particular, for sands depending on the granulometric composition and soil porosity coefficient, and for clay soils depending on their classification indexes, $I_L$ and *e*. An increase in the porosity coefficient e of a rock, ceteris paribus, necessarily causes a decrease in its strength and an increase in its compressibility. Accordingly, an increase in the moisture content *W* or the fluidity index $I_L$ of a clay soil leads to the same result.

It was also found that correlation or even functional dependencies can be obtained between the indicators of mechanical properties and physical state of soils under certain conditions. Thus, it makes sense to use such dependencies to reduce the number of laboratory studies of the mechanical properties of sedimentary rocks.

**Review of the research sources and publications**

M. Maslov established the dependence of the decrease in the angle of internal friction and specific cohesion on the decrease in density and increase in soil moisture with its incomplete consolidation. And M. Goldstein et al. for compacted loess loams obtained the dependence of the increasing of specific cohesion at a constant angle of internal friction with an increase in soil density [4].

Of great practical importance is the generalization of 31 empirical equations that relate the unconfined compressive strength and angle of internal friction of sedimentary rocks (sandstone, shale, limestone, and dolomite) to their physical properties (such as velocity, modulus, and porosity) [5]. In particular, it makes sense to use these equations to estimate the strength of a rock based on parameters that can be measured using geophysical logs.

Numerous studies have been devoted to establishing the relationship between the physical and mechanical properties of sedimentary rocks. For example, in 1948, M. Gersevanov showed that there is a linear relationship between the porosity coefficient e and the logarithm of the ultimate shear resistance *lgτ*. A similar conclusion was made for compression dependencies [6, 7].

The practice has also confirmed the prospects of the direction of evaluating the strength properties of sedimentary rocks using the express-methods: penetration test and rotary shear test. In particular, the main advantage of penetration tests of homogeneous sedimentary rocks is the condition of invariance of the data obtained, i.e., complete independence from the acting force and the corresponding depth of the cone penetrate, and, taking into account the tip constants, independence from the angle of their tip, etc. The method of penetration studies was recommended to identify the relationship between the indicators of physical state and mechanical characteristics of sedimentary rocks [7-11].

This direction was most fully developed by specialists of the scientific school founded by V. Razorenov, namely: Y. Velykodnyi, G. Zhornik, V. Zabara, M. Zotsenko, I. Skryl, V. Khilobok, V. Shytov, A. Yakovlev, and others [7, 8, 12-15]. In particular, for cohesive sedimentary rocks of a disturbed structure under conditions of their complete water saturation, the following dependence was established on the basis of penetration tests

$$W_i = W_0 - {}^1\!/_{r_0} \cdot \lg \frac{R_i}{R_0}, \qquad (1)$$

where $W_i$ i $W_0$ – are the values of the total soil moisture content corresponding to two values of the soil porosity coefficient $e_i$ and $e_0$;

$R_i$ – specific resistance to penetration of a water-saturated soil with a porosity coefficient $e_i$;

$R_0$=1 – for the accepted dimension $R_i$ (kPa, MPa) (based on this premise, the value of $e_0$ is set);

${}^1\!/_{r_0}$ – is the angular coefficient of the linear dependence represented in the coordinates "$W – lgR$".

Under the conditions of the three-phase state of clay rocks, the degree of their water saturation should be taken into account when establishing the relationship between physical and mechanical parameters. Then the basic equation of the calculation scheme is as follows

$$W_i \cdot L_0 = W - {}^1\!/_{r_0} \cdot \lg \frac{R_i}{R_0}, \qquad (2)$$

where $L_0$ – is the water saturation function equal to

$$L_0 = 1 + \left( \frac{1}{S_r} - 1 \right) \cdot \frac{{}^1\!/_{r_0}}{{}^1\!/_{r}}, \qquad (3)$$

where ${}^1\!/_{r}$ – angular coefficient of linear dependence for the case $S_r < 1$ (while $W_i = const$).

**Definition of unsolved aspects of the problem**

However, despite the undoubted advantages of using correlation equations between the physical and mechanical properties of sedimentary rocks to reduce the amount of research on their mechanical parameters, under the conditions of the natural state of these rocks, there is an additional difficulty in establishing the relationship between their physical and mechanical properties due to the peculiarities of their structure.

The calculation scheme of the relationship is based on the same prerequisites as for soils of disturbed structure. Therefore, further testing of this approach is required for both cohesive and non-cohesive sedimentary rocks of natural structure.

**Problem statement**

Therefore, the purpose of this work was to determine empirical equations of the relationship between the physical and mechanical properties of cohesive and non-cohesive sedimentary rocks of natural structure through experimental studies, including penetration tests.

As a criterion for the reliability of such equations, it is advisable to accept the value of the correlation coefficient r not less than 0.80 (in this case, the relationship between the factors of the equations is considered close).

**Basic material and results**

The experimental basis for obtaining empirical relationship equations was parallel laboratory determinations of physical (humidity, plasticity number, dry soil density, porosity coefficient) and mechanical (specific penetration resistance, angle of internal friction, specific cohesion, deformation modulus) characteristics of cohesive (sandy loam, loam, clay) and non-cohesive (sand of various sizes) sedimentary rocks of natural structure.

The methodology of such studies is described in detail in a number of sources [7, 11, 14].

For practical problems of identifying the relationship between the physical and mechanical properties of the three-phase state of sedimentary rock of undisturbed (natural) structure, it is necessary to determine its three indicative features - the free term and two angular coefficients of conditional linear equations.

The general relationship equation in this case is as follows

$$\lg\frac{R}{R_0} = W_R\frac{1}{e_0} + \frac{\rho_w}{\rho_s}\cdot\frac{1-M_{kpf}}{1/e_0} - W\frac{M_{kpf}}{1/e_0} - \frac{\rho_w}{\rho_d}\cdot\frac{M_{kpf}}{1/e_0}, \qquad (4)$$

where $R$ – specific penetration resistance, MPa;

$R_0$ =1 MPa;

$W_R$ – moisture content of water-saturated rock at $R_0$ =1 MPa;

$$M_{kpf} = 1 - \frac{1/e_0}{1/e};$$

$1/e_0$ та $1/e$ – are the angular coefficients of the linear equations, respectively, for the case of complete water saturation of the rock and under the condition of constant moisture;

$\rho_w$ – water density (1 g/cm$^3$);

$\rho_d$ – density of dry soil (or soil skeleton).

Experimental studies have shown that in establishing the relationship between the properties of clay rocks, the plasticity number ($I_p$), the mineralogical composition of the clay component, as well as the particle size distribution and mineralogy of the coarse rock component, influence the indicative indicators of equation (4).

A condition for establishing the relationship between the indicators of the physical state of sedimentary rock (natural moisture content $W$, porosity coefficient $e$) and indicators of mechanical properties (specific resistance to penetration $R$, angle of internal friction $\varphi$, specific cohesion $c$, deformation modulus $E$, etc.) is the accumulation of test results to determine the listed characteristics of soils with a relatively constant plasticity number and genetically homogeneous.

The coefficients of the relationship equations for each set of experimental data are determined by the least squares method with the estimation of the necessary statistical indicators, such as correlation and variation coefficients, as well as errors of direct determinations. Thus, for each type of sedimentary rock, it is possible to establish a number of dependencies of the following form:

$$\lg\frac{R}{R_0} = A_R - B_R\cdot e - C_R\cdot W; \qquad (5)$$

$$\lg\frac{E}{E_0} = A_E - B_E\cdot e - C_E\cdot W; \qquad (6)$$

$$\lg\frac{c}{c_0} = A_c - B_c\cdot e - C_c\cdot W; \qquad (7)$$

$$\lg\frac{tg\varphi}{tg\varphi_0} = A_\varphi - B_\varphi\cdot e - C_\varphi\cdot W, \qquad (8)$$

where $R_0$, $E_0$, $c_0$, $tg\varphi_0$ – values equal to the unit of the selected dimension;

coefficients $A$, $B$, $C$ are functions of soil indicators, i.e. $1/e_0$, $1/e$, $W_R$.

Having equations (5-8) for a certain type of sedimentary rock, the following dependencies were established for it:

$$\lg\frac{E}{E_0} = A_E - \frac{B_E}{B_R}A_R - W\left(C_E - \frac{B_E}{B_R}C_R\right) - \frac{B_E}{B_R}\lg\frac{R}{R_o}; \qquad (9)$$

$$\lg\frac{c}{c_0} = A_c - \frac{B_c}{B_R}A_R - W\left(C_c - \frac{B_c}{B_R}C_R\right) - \frac{B_c}{B_R}\lg\frac{R}{R_o}; \qquad (10)$$

$$\lg\frac{tg\varphi}{tg\varphi_0} = A_\varphi - \frac{B_\varphi}{B_R}A_R - \\ -W\left(C_\varphi - \frac{B_\varphi}{B_R}C_R\right) - \frac{B_\varphi}{B_R}\lg\frac{R}{R_o} . \quad (11)$$

For example, the equations of the relationship between the physical and mechanical properties of cohesive sedimentary rocks, in particular, loess loam, light dusty (with plasticity number $I_p = 0.11$ and rock particle density 2.71 g/cm$^3$), established at one of the experimental sites in Poltava, are proposed:

$$\lg\frac{R}{R_0} = 1.44 - 1.34e - 6.7\cdot W; \quad (12)$$

at the correlation coefficient *r=0.949*;

$$\lg\frac{E}{E_0} = 3.0 - 1.84e - 2.8\cdot W; \quad (13)$$

at the correlation coefficient *r=0.954*;

$$\lg\frac{C}{C_0} = 0.53 - 1.1e - 7.0\cdot W; \quad (14)$$

at the correlation coefficient *r=0.890*;

$$\lg\frac{tg\varphi}{tg\varphi_0} = 0.4 - 0.31e - 3.17\cdot W; \quad (15)$$

at the correlation coefficient *r=0.910*;

$$\lg\frac{E}{E_0} = 1.02 + 6.32\cdot W + 1.37\cdot\lg\frac{R}{R_0}; \quad (16)$$

$$\lg\frac{C}{C_0} = -0.65 - 1.5\cdot W + 0.82\cdot\lg\frac{R}{R_0}; \quad (17)$$

$$\lg\frac{tg\varphi}{tg\varphi_0} = 0.07 - 1.63\cdot W + 0.23\cdot\lg\frac{R}{R_0}; \quad (18)$$

Studies have shown that for non-cohesive sedimentary rocks, i.e., sandy soils, it is also possible to establish dependencies of type (4). In accordance with the accepted gradation, sandy soils are divided into air-dry, moist, and water-saturated soils according to the degree of pore filling.

For air-dry sands, with an increase in moisture content from zero, their mechanical properties increase up to a certain moisture content, which depends on their particle size distribution.

This humidity range is $W = 0 - 0.07$. Larger values correspond to fine and dusty sands.

At higher moisture content, dependence (4) does not appear.

However, when the sand becomes wet and then water-saturated, an increase in moisture content leads to a slight decrease in the strength characteristics of the sand. However, the intensity of this decrease is much less than that of clay soils.

Below are the obtained equations of the relationship between the physical and mechanical properties of fine quartz sands of the experimental site in Kremenchuk, Poltava region.

$$\lg\frac{R}{R_0} = 0.01 - 1.03e - 1.36\cdot W; \quad (19)$$

at the correlation coefficient *r=0.967*;

$$\lg\frac{E}{E_0} = 1.65 - 0.68e - 0.35\cdot W; \quad (20)$$

at the correlation coefficient *r=0.914*;

$$\lg\frac{C}{C_0} = 1.58 + 5.5e - 3.2\cdot W; \quad (21)$$

at the correlation coefficient *r=0.890*;

$$\lg\frac{tg\varphi}{tg\varphi_0} = 0.321 - 0.58e - 0.467\cdot W; \quad (22)$$

at the correlation coefficient *r=0.910*;

$$\lg\frac{E}{E_0} = 1.64 + 0.55W + 0.66\cdot\lg\frac{R}{R_0}; \quad (23)$$

$$\lg\frac{C}{C_0} = -1.53 - 4.06W + 5.34\cdot\lg\frac{R}{R_0}; \quad (24)$$

$$\lg\frac{tg\varphi}{tg\varphi_0} = 0.315 - 0.3W + 0.56\cdot\lg\frac{R}{R_0}; \quad (25)$$

It should be noted that the values of the correlation coefficients of all the above empirical equations of the relationship between physical and mechanical properties of both cohesive and non-cohesive sedimentary rocks of natural structure exceed 0.80, i.e., the relationship between the factors of the equations is close.

In our opinion, the equations of the relationship of the form (4) between the physical and mechanical characteristics of loess loam, light dusty (plasticity number $I_p$ = 0.09 - experimental site in Kobeliaky, Poltava region) both in the natural structure and within the compacted zone around the pile in three directions ($0^0$, $45^0$, $90^0$) relative to the horizontal plane are also worthy of attention. They are summarized in Table 1.

In particular, two well-known types of penetrometers (PD-2 and MV-2) and two cones with different angles at the top ($30^0$ and *17°40'*) were used to study the anisotropic properties of sedimentary rocks. The corresponding methodology of penetration studies, sampling and subsequent laboratory tests is described in monographs [14, 15].

The obtained values of statistical indicators (correlation ($r > 0.80$) and variation ($v < 0.20$) and dispersion ($D < 0.03$) coefficients) for the empirical equations of the form (4), which are also presented in Table 1, indicate a rather close relationship between the mechanical (penetration resistance $R$) and physical (dry density $\rho_d$ and soil moisture $w$) characteristics in all three experimental directions relative to the horizontal plane for both penetrometers and angles at the top of the cone.

**Table 1 - Equation of the relationship between the physical characteristics of light dusty loam and the results of penetration tests in different directions relative to the horizontal plane**

| Penetrometer | Angle at the top of the cone | Direction relative horizontal plane | Empirical equations for determining: | | Meaning of statistical indicators | | |
|---|---|---|---|---|---|---|---|
| | | | $lg\ R$ = | $\rho_d$ = | $r$ | $v$ | $D$ |
| PD-2 | 30° | 0° | 2.59 - 4.94 W-2.88 (1/$\rho_d$) | 2.88 / (2.59 - 4.94 W - lg R) | 0.96 | 0.09 | 0.003 |
| | | 45° | 2.12 - 4.12 W -2.42 (1/$\rho_d$) | 2.42 / (2.12 - 4.12 W - lg R) | 0.92 | 0.12 | 0.006 |
| | | 90° | 1.54 - 2.67 W -1.89 (1/$\rho_d$) | 1.89/ (1.54 - 2.67 W - lg R) | 0.92 | 0.12 | 0.005 |
| MV-2 | 30° | 0° | 1.98 - 3.93 W - 1.99 (1/$\rho_d$) | 1.99 / (1.98 - 3.93 W - lg R) | 0.87 | 0.16 | 0.02 |
| | | 45° | 1.85 - 1.66 W - 2.47 (1/$\rho_d$) | 2.47 / (1.85 - 1.66 W - lg R) | 0.84 | 0.20 | 0.03 |
| | | 90° | 1.69 - 0.30 W - 2.62 (1/$\rho_d$) | 2.62 / (1.69 - 0.30 W - lg R) | 0.85 | 0.16 | 0.02 |
| | 17° 40′ | 0° | 1.23 - 2.11 W - 1.80 (1/$\rho_d$) | 1.80 / (1.23 - 2.11 W - lg R) | 0.85 | 0.14 | 0.004 |
| | | 45° | 1.50 - 2.33 W - 2.15 (1/$\rho_d$) | 2.15 / (1.50 - 2.33 W - lg R) | 0.86 | 0.17 | 0.005 |
| | | 90° | 1.89 - 1.24 W - 2.98 (1/$\rho_d$) | 2.98 / (1.89 - 1.24 W - lg R) | 0.86 | 0.16 | 0.006 |

**Conclusions**

Thus, through parallel experimental studies of the physical and mechanical properties of sedimentary rocks of natural structure, including their penetration tests, the following was established.

1. The possibility of establishing empirical equations of the relationship between the physical (soil dry density and moisture content) and mechanical (specific resistance to penetration, angle of internal friction, specific cohesion, deformation modulus) characteristics of cohesive (for example using the light dusty loams of loess origin) and non-cohesive (for example using the fine sands, quartz) sedimentary rocks of natural structure was tested. The values of the statistical parameters of the equations indicate a fairly close relationship between mechanical and physical parameters. Such equations are correct for genetically identical types of sedimentary rocks.

2. The possibility of studying the anisotropic properties of cohesive rocks of natural structure using penetration tests and establishing empirical equations of the relationship between their physical and mechanical characteristics has been proved.

3. In practice, the use of correlation equations between the physical and mechanical properties of sedimentary rocks is advisable to reduce the volume of laboratory tests in determining their mechanical parameters..

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