https://doi.org/10.31713/m1212

IMPROVEMENT OF THE INVESTIGATION OF PHYSICAL AND MECHANICAL CHARACTERISTICS OF SEDIMENTARY ROCKS BY EXPRESS METHODS

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Abstract

Field and laboratory express methods for studying physical and mechanical parameters of sedimentary rocks (penetration, static sounding, rotational displacement), as well as traditional methods of evaluating their mechanical properties, are considered. The peculiarities of detecting these characteristics for cohesive and non-cohesive sedimentary rocks are clearly divided. Theoretical prerequisites have been confirmed by experimental studies. It is proved that the objective credibility criterion of the reliability of the penetration and sounding characteristics is their invariance, embedded in the limit equilibrium equation. The method of determining the strength of sands based on the results of penetration and sounding has been developed. For cohesive rocks, a method of combined testing by penetration and rotational shear is proposed for this. The results of experimental studies are presented, which confirm the sufficient convergence of the values of strength parameters obtained by standard and express methods. The generalization of experimental data is proposed according to the calculation schemes of the relationship of the properties of sedimentary rocks.

Keywords: sedimentary rock, penetration, sounding, rotational displacement, invariance, equations of limit equilibrium, strength, relationship.

Introduction

To correctly determine the physical and mechanical properties of sedimentary rocks, complexes of their laboratory and field tests were conducted [1].

However, these complexes are usually quite time-consuming and long. Therefore, a promising direction for studying the characteristics of sedimentary rocks is the introduction of so-called express methods [2-6]: in the laboratory, this is penetration and rotary cutting, and in field conditions - sounding.

Thus, penetration is widely used for the classification of cohesive rocks (clay, loam, sandy loam) [7-10], penetration and sounding - for evaluating the strength of non-cohesive rocks (sands) [11-13], combined penetration and rotary section tests - for a similar problem of determining the strength of cohesive rocks [13-16].

Express methods have also been tested for a number of mining and geotechnical problems, for example, penetration - to estimate the parameters of the anisotropy of the environment [17,18], as well as the study of mechanical properties of rocks under special conditions, in particular, static sounding - to determine the strength of marine sediments [19-21], etc.

1. Interpretation of the investigation results of the physical and mechanical rock properties by express methods

Processing of experimental data was carried out according to the calculation schemes of the relationship of the properties of rocks, the theoretical base of which was developed under the guidance of V. Razorenov [3].

Ultimate force on a conical tip with an angle between the generatrix and the vertical α=15° with axisymmetric loading is determined by the three-term formula

$$F = U_o \gamma_1 h_c^3 + V_o \gamma_1 h_c^2 + N_o c_1 h_c^2; \text{ kN} \quad (1)$$

where U_0, V_0, N_0 - coefficients of the equation depending on the angle of internal friction of the sedimentary rock φ_1^0; γ_1- specific weight of the breed, kN/m^3; specific adhesion, kPa; h_c - height of the conical part of the tip, m; H - depth of the base of the cone from the earth's surface, m.

If the depth of immersion of the conic tip, h, is less than its height, h_c, the process of rock penetration occurs. With H=0 and the expression (1) takes the form

$$F = U_o \gamma_1 h^3 + N_o c_1 h^2; \text{ kN.} \quad (2)$$

The specific resistance of penetration, R, which is the ratio of the penetration force, F, to the square of the depth of immersion of the tip into the rock, is taken as a parameter of penetration tests [3]

$$R = \frac{F}{h^2} = U_o \gamma_1 h + N_o c_1; \text{ kPa.} \quad (3)$$

Let us consider three possible cases of using the equation (3).

Case 1: When $\varphi \neq 0$, C=0 it is characteristic of air-dry and completely water-saturated sands

$$R = U_o \gamma h; \text{ kPa.} \quad (4)$$

The penetration index was proposed as a characteristic of the penetration tests of these sands

$$U = \frac{R}{h} = \frac{F}{h^3} = U_o \gamma; \text{ kN/m}^3. \quad (5)$$

Graphs of invariance of shallow, quartz sand with a low degree of water saturation are shown in Fig. 1*a*.

The penetration index is defined as the tangent of the angle of inclination of the averaged straight line to the ordinate axis.

Case 2: when $\varphi \leq 24°$ and $C \neq 0$ characteristic of clay soils. With small sizes of conical tips (up to 100 mm), the first term of equation (3) does not exceed 5% of the total value of specific penetration resistance. It can be neglected.

Then

$$R = \frac{F}{h^2} = N_0 c \text{, kPa.} \tag{6}$$

Graphs of the invariance of the specific penetration resistance are shown in Fig. 1*b*.

Case 3: When $\varphi > 24°$, $C \neq 0$; characteristic of sands and loams. If $R_0 = N_0 C_1$ is accepted, then expression (3) taking into account (5) can be written as

$$R = R_o + Uh \text{, kPa.} \tag{7}$$

The graph according to equation (7) is presented in Fig. 1*c*.

Shown in Fig. 1 of the penetration graphs indicate the invariance of the penetration index, *U*, or the specific penetration resistance, *R*, i.e., the correspondence to the averaged straight line of the equation describing one of the cases of penetration.

If the condition of invariance is violated, that is, the test points deviate from the averaged straight line, this indicates factors that are not taken into account by the calculation scheme and their nature should be explained.

This can be the effect of the ring walls, the heterogeneity of the rock in terms of penetration depth, malfunction of the penetrometer, etc.

Plotting the invariance, *U*, or, *R*, is usually done during the tests themselves. This allows timely detection of deviations from the accepted calculation scheme that were not foreseen by the experiment.

Rotational section is a method of studying the mechanical parameters of soils by determining the resistance of the soil to the rotation of wing tips formed by two intersecting planes.

When testing soils from the earth's surface, when the winged tip is immersed in the soil only to its height, the self-weight of the soil can be neglected and the ultimate resistance of the rotary section can be taken as equal to the specific adhesion of the soil, *C*.

The ultimate resistance of the rotary section is defined as the ratio of the maximum moment of the rotary section, M_{max}, to the static moment of the cut surface,

$$\tau = \frac{M_{max}}{K_\tau} \tag{8}$$

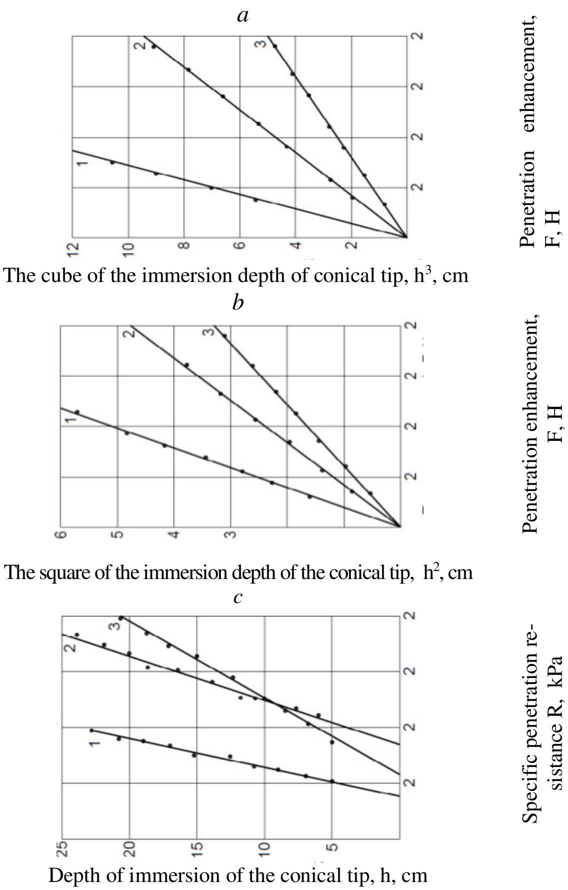

Fig. 1. Penetration graphs: *a* - sands: u_1 = 0,29 mN/m^3; u_2 = 0,84 mN/m^3; u_3 = 1.6 mN/m^3; *b* - loam: R_1 = 7,8 кПа; R_2 = 16,8 kPa; R_3 = 24 kPa; *c* - loams: R_{01} = 16 kPa; R_{o2} = 22 kPa; R_{03} = 35 kPa

When the wing tip is immersed in the soil only to its height, the cut is made along the cylindrical and lower circular surfaces, then is determined by the formula

$$K_\tau = \frac{AD^2}{2}\left[\frac{D}{6} + h\right], \tag{9}$$

where *D* and *h* - diameter and height of the wing tip.

When penetrating clayey soils in case 2, the specific penetration resistance is proportional to the specific adhesion. Solving equation (6), we get

$$C = \frac{1}{N_o}R = K_\varphi R. \tag{10}$$

As a derivative of the carrying capacity coefficient, N_0, limit equilibrium equation (1) coefficient $K_\varphi = f(\varphi°)$ and is equal to

$$K_\varphi = \frac{C}{R}. \tag{11}$$

Sounding is a method of studying the properties of rocks by determining the reactive resistance of the rock to the conical tip when it is immersed to a depth exceeding the height of the cone h_c.

In the equation (1) $H \neq 0$.

Consider a type of static sounding of rocks, when the ratio of the diameter of the cone to the diameter of the rods $(d_c/d_m) \geq 1{,}6$.

In this case, in addition to the complete or partial removal of friction on the side surface of the rods, the rock protrudes into the cavity between the rod and the well wall. In this case, in addition to the complete or partial removal of friction on the side surface of the rods, the rock protrudes into the cavity between the rod and the well wall.

For cohesive rocks at the value of the angle of internal friction $\varphi < 20°$ the first two terms of the expression (1) do not exceed 5% of the total value, So,

$$F = N_o c_1 h^2. \tag{12}$$

As an objective characteristic of the results of static sounding of cohesive rocks, the specific resistance of sounding is used *Q*

$$Q = \frac{F}{h_c^2} = N_o C. \tag{13}$$

The invariance of the specific resistance of sounding in a layer of homogeneous rock is manifested in the fact that the sounding force in it remains constant.

On the sounding graph, this is expressed by a straight line parallel to the ordinate axis (Fig. 2*a*).

Comparing equations (6) and (13), we can write that

$$Q = R = N_o C \quad . \tag{14}$$

The values of the specific resistances of sounding and penetration of cohesive rocks are equal to each other due to the free protrusion of the rock from under the cone during penetration - to the surface, during sounding - into the borehole cavity.

The effect established by the results of numerous comparative tests allows the results of penetration tests to be widely used also in the analysis of data of static sounding of rocks with an extended conical tip.

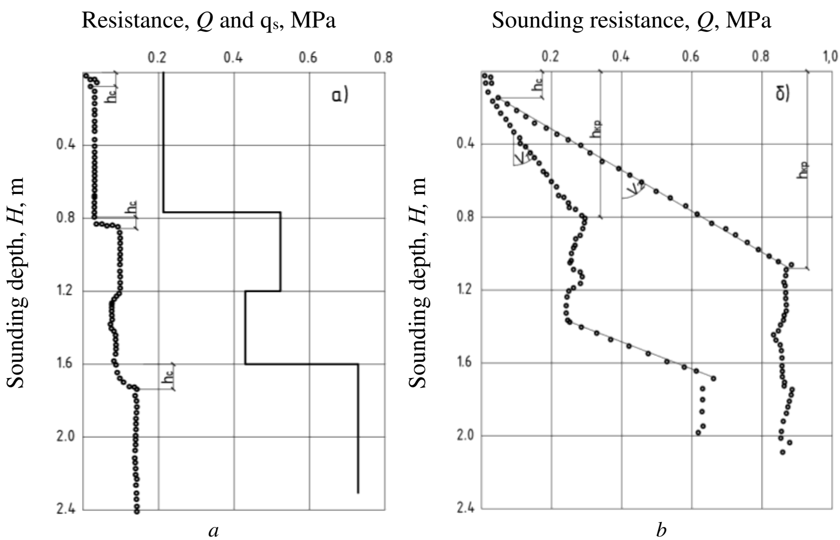

Fig. 2. Graphs of sounding: *a* - loam of rigid plasticity:
1 - $Q=f(H)$; 2 - $Q_s f(H)$; b - shallov, loose sands $V_3 = 0{,}34\frac{MPa}{m}$; medium density

$$V_2 = 0{,}488\frac{MPa}{m}\ ;\ V_{23} = 1{,}3\frac{MPa}{m}$$

Sometimes it is convenient to use the resistance value of the cone rock, q_s

$$q_s = \frac{F}{A} = 4.433Q \quad , \tag{15}$$

where A is the area of the base of the conical tip.

For non-cohesive rocks at $C = 0$ (air-dry and water-saturated sands), the sounding process is described by the first two terms of equation (1), with the first term representing a constant value.

It is proposed to use the sensing index as the sensing characteristics of such rocks V

$$V = \frac{Q_1 - Q_2}{H_2 - H_1} = V_o \gamma \quad . \tag{16}$$

In a layer of homogeneous rock, the invariance of the sounding index is manifested in the fact that the specific sounding resistance Q increases linearly with the depth of sounding with the angular coefficient V - the sounding index (Fig. 2*b*).

The established regularity in a layer of homogeneous sand will manifest itself up to a depth called critical. Below this depth, when the rock is homogeneous, the specific resistance to sounding does not change.

The value h_{cr} depends on the density of the sand and the size of the conical tip. The greater the density of the sand and the greater the diameter of the base of the cone, the more h_{cr} is. Similar regularities were observed [11,12] during the immersion of piles and their models.

The following studies established a connection between the characteristics of high-speed research methods and the physical and mechanical properties of rocks.

2. Express determination methods of physical and mechanical rock properties

General expression for determining the force on a conical tip with an angle between the generatrix and the vertical α=15° during penetration and sounding are given in (1). The physical characteristics in (1) are represented by the specific gravity of the rock γ. Strength characteristics are in the form of specific adhesion C and bearing capacity coefficients U_0, V_0 and N_0, which depend only on the angle of internal friction φ. The bearing capacity coefficients of equation (1) can be determined on the basis of the solutions of the axisymmetric problem of the theory of limit equilibrium, performed, including for conical stamps with an angle α=15°, by V. Berezantsev [3]. In Fig. 3 shows the dependence of the coefficients U_0, V_0 and N_o on the angle of internal rock friction φ.

For the convenience of using these dependencies, they are presented in the form of correlation equations with the corresponding statistical indicators

$$\varphi^{\circ} = 25{,}03 + 6{,}1 \ln U_o\,; \tag{17}$$

variance 0,15; coefficient of variation $v = 0{,}014$

$$\varphi^{\circ} = 15.0 + 7.03 \ln V_o\,; \tag{18}$$

variance 0,17; coefficient of variation $v = 0{,}03$

$$\varphi^{\circ} = 7.75 + 9.8\, lnN_o\,; \tag{19}$$

variance 0,18; coefficient of variation $v = 0{,}02$

$$\lg t\,g\varphi = -1.29 \lg k_{\varphi} - 1.276\,; \tag{20}$$

variance 0,12; coefficient of variation $v = 0{,}014$.

Fig. 3. Graphs of dependence of bearing capacity coefficients U_0,V_0,N_0 on the angle of internal friction φ°

To determine the strength characteristics of sandy loams and sands, when their angle of internal friction is more than 24°, a penetration test method with a tip height h_c=25 cm. Such studies can be carried out only in field conditions using mechanized penetration units, which allow the tips to be immersed in the array at a speed of no more than 0,5 m/min. The sequence of operations for determining rock strength characteristics is as follows.

1. At a given depth in a trench or pit, the surface of the array is cleaned and penetration tests are performed with height tips. h_c=25 cm and the angle α=15° in a quantity sufficient for statistical generalization (at least 6).

2. In parallel with the penetration tests, the density-moisture of the test rock is determined.

3. The results of each penetration test are presented in the form of a linear relationship (7) with the use of computer programs, with the help of which the values are set R_0 and U_0 with determination of their dispersion and coefficient of variation. According to statistical indicators, the obtained results are rejected.

4. Using equation (17), the angle of internal friction is determined by the value of U_0, φ.

5. Specific adhesion is defined as a ratio

$$C = \frac{R_o}{N_o}. \tag{21}$$

where N_0 is set according to equation (19) according to the already known value of the angle of internal friction.

In the Table 1 shows the data for the determination of the angle of internal friction φ and the specific adhesion *C* of quartz, fine sand, of medium density, saturated with water at the site in the city of Kremenchuk on the right bank of the Dnieper according to the data of penetration tests.

Table 1

Calculated data for determining the angle of internal friction and ideal sand adhesion of the site by the penetration method

Conditions of the experiment	Number of trials	Coefficient of water saturation	Specific gravity of the soil, γ		Penetration rate	
			γ, kN/m^3	Coefficient of variation, *v*	*U*, H/cm	Coefficient of variation, *v*
The water level is below the surface of the rock	47	0,92	20,1	0,13	7,2	0,18
The water level is above the rock surface	54	1,00	10,5	0,11	3,15	0,17

Conditions of the experiment	Indicator U_o	Angle, φ°	N_o	Parameter		Specific cohesion, *C*, kPa
				R_o, kPa	coefficient of variation, *v*	
The water level is below the surface of the rock	3,44	33	18.5	25	0.16	1.4
The water level is above the rock level	3,01	32	16	13	0.15	0.8

Table data 1, as well as the results of research conducted at other research sites, show that:

1. The considered method of processing the results of sand penetration tests allows determining the strength characteristics based on the results of one immersion of the conical tip at 6-8 degrees of load.

2. The high sensitivity of the penetration method draws attention. With its help, the adhesion value of 0,8-1,4 kPa with the coefficient of variation was established *v*=0,15, which is practically impossible to achieve by the single-plane displacement method.

3. With an increase in specific adhesion and a decrease in the angle of internal friction within the limits that characterize cohesive soils, the capabilities of the proposed method certainly decrease. It is

already difficult to set the value of the penetration index U when the general characteristics R are scattered $\varphi \approx 22$.

As the penetration tests of sands have shown, they can have a certain amount of cohesion. Let's consider the regularities that occur in the sand during sounding. Calculation schemes of sand penetration and sounding are shown in Fig. 4.

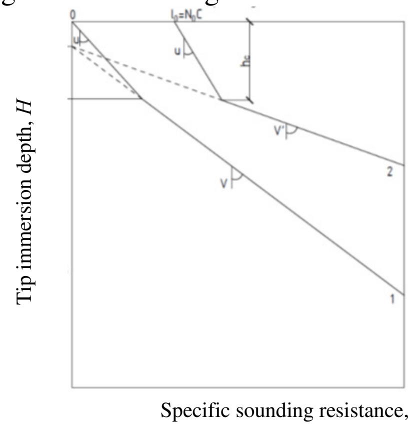

Fig.4. Schemes of sounding graphs of sands to the critical depth:
1 – at C=0; and *2* – at C≠0

When C=0, the sounding indicator

$$V = \frac{Uh_c}{h_v}. \tag{22}$$

In the presence of cohesion, the graph of the penetration index shifts parallel to the right from the origin of the coordinates

$$V' = \frac{R_o + Uh_c}{h_v}. \tag{23}$$

Dividing both parts of (23) by expression (22), we get

$$\frac{V'}{V} = \frac{R_o}{U} \times \frac{1}{h_c} + 1. \tag{24}$$

It follows from this that the systematic error in the sounding index is a linear function of the soil specific adhesion C.

As the angle of internal friction increases, the systematic error in the sounding index, V', due to adhesion will noticeably decrease.

The value of the absolute error can be calculated using the formula

$$\Delta V = V' - V = \frac{R_o}{h_v}. \qquad (25)$$

Therefore, for cohesive sands, the sounding index, V', is defined as the tangent of the angle of inclination of the sounding graph to the ordinate axis below the depth of penetration, is a function of the angle of internal friction, φ, and the specific adhesion, C.

This provision makes it possible to solve the problem of determining the characteristics of the strength of sandy soils based on the data of static sounding with conical tips of two different sizes. Then, accordingly, $V_1 < V'_2$ and the differece between them will be

$$V'_1 - V'_2 = \frac{R_o}{\frac{U}{V}}\left[\frac{1}{h_{c2}} - \frac{1}{h_{c1}}\right]; \qquad (26)$$

or

$$\frac{R_o}{\frac{U}{V}} = \frac{V'_1 - V'_2}{\frac{1}{h_{c2}} - \frac{1}{h_{c1}}}. \qquad (27)$$

On the basis of (25), the equality can be established

$$\Delta V_1 \times h_{o1} = \Delta V_2 \times h_{o2}; \qquad (28)$$

then

$$\left.\begin{aligned} \Delta V_1 = V'_1 - V = -\frac{V'_2 - V'_1}{\frac{h_{c1}}{h_{c2}} - 1} \\ \Delta V_2 = V'_1 - V = -\frac{V'_2 - V'_1}{1 - \frac{h_{c2}}{h_{c1}}} \end{aligned}\right\}. \qquad (29)$$

It can be seen from expression (29) that the corrected value of the sounding indicator is equal to the measured value $V'_1(V'_2)$ minus the systematic error

$$V = V'_1 - \Delta V_1 = V'_2 - \Delta V_2. \qquad (30)$$

With a known value of soil specific gravity γ, the generalized sounding indicator V_o is

$$V_o = \frac{V}{\gamma}. \tag{31}$$

With a known value of soil specific gravity γ, the generalized sounding indicator V_0 is and $U_0;N_0$.

The specific cohesion can be determined as a result of the transformation of the formula (3.25)

$$C = \frac{U_0}{V_0 N_0} \Delta V_1 \times h_{c1} \tag{32}$$

The considered method of determining the strength of sands based on the data of static sounding with an extended conical tip with an angle between the vertical and horizontal α=15° is widely used in engineering and geological surveys.

In the Table 2 shows some data of such definitions.

Attention is drawn to the close convergence of the strength values established for the site in Kremenchuk, based on the results of penetration and sounding tests of fine watered sand.

The method of combined tests of cohesive soils by penetration and rotary section allows determining the angle of internal friction φ and the specific adhesion C of clay rocks in the field and in the shortest possible time in a quantity sufficient for statistical processing.

For combined tests in the field, mechanized static sounding installations, additionally equipped with devices for rotary cutting, are used.

Preferably, separate tips are used for penetration in the form of a cone with an angle between the vertical and vertical α=15° and for a rotational section in the form of two planes intersecting at an angle of 90°.

During the study on each horizon, the points of penetration and rotational section are arranged in a staggered order with a distance between adjacent points of at least $6D_c$, where D_c - diameter of the base of the cone.

The equation of the relationship between the physical and mechanical properties of sedimentary rocks is established for their individual varieties, which have constant indicative parameters (for example, plasticity number, mineralogical composition, structural features, etc.), by means of statistical processing of a sufficient sample of random values [3, 13-15].

Applying the penetration method and having the density-moisture value, it is possible to determine the required characteristic in any element of the array.

Table 2

Calculated data for determining the angle of internal friction and specific adhesion of sands based on static sounding data

Ground	Type of sand	Number of experiments	Tip height h_c, cm	Experimental value of the sounding indicator, U		Indicator U, kN/cm$_3$
				U, kN/cm^3	coefficient of variation , v	
Kherson region	medium-sized, wet	34	9,0 15,0	1,78 1,37	0,10	0,98
Kremen-chuk	shallow watery sand	129	25,0 9,0	0,35 0,72	0,16	0,11
Myko-laiiv re-gion	large wet	40	9,0 11,0 13,3 15,0 18,4 21,9 9,0 11,0 13,3 15,0	1,20 1,06 1,01 0,92 0,91 0,87 0,31 0,27 0,26 0,23	0,09	0,65
	large wa-tered				0,075	0,165

Soil specific gravity		Generalized sounding indica-tor, V_o	Angle of inter-nal friction, φ	Bearing ca-pacity factor, U_o	Specific ad-hesion C, kPa
γ, kN/m^3	coefficient of variation, v				
16,7	0,08	58,6	41,6	0,0046	0,33
10,5	0,15	10,5	32,2	0,019	1,00
17,0	0,06	38	39,4	0,0062	0,3
10,0	0,06	16,5	35	0,0126	0,4

Conclusions

The description of sounding and penetration of sedimentary rocks by the traditional three-step formula of the limit state of the massif made it possible to establish the objective parameters of penetration and sounding. The features of detecting these characteristics are clearly divided for cohesive and noncohesive rocks. Theoretical postulates have been confirmed by experimental studies.

An objective criterion for the reliability of the penetration and sounding parameters is their invariance, embedded in the limit equilibrium equation. Features of the invariance of penetration and sounding characteristics for cohesive and noncohesive rocks have been recorded. Violation of the invariance of the penetration and sounding parameters indicates the presence of factors that were not taken into account when planning the experiment. Invariance control is a way to detect them.

To determine the bearing capacity coefficients in the three-term equation of the limit state of rocks during penetration and sounding, the solution of V. Berezantsev for axisymmetric deformation was taken as a basis. Techniques have been developed for assessing the strength of sands, including those with cohesion, based on the results of penetration and sounding, and in cohesive rocks, combined penetration and rotary shear tests should be used for this. Sufficient convergence of the values of strength parameters obtained by normative and express methods was confirmed.

References

1. **Briaud J.-L.** *(2013).* Geotechnical Engineering: Unsaturated and Saturated. Soils. Wiley.

2. **Baluch M.M., Vivatrat V. & Ladd C.C.** (1980). Cone penetration in soil profiling. Journal of Geotechnical and Geoenvironmental Engineering, vol. 106.

3. **Razorenov V.F.** (1980). Penetratsyonnye yspytanyya hruntov. M.: Stroyyzdat. [in Russian].

4. **Terzaghi K., Peck R.B. & Mesri G.** (1996) Soil Mechanics in Eng. Practice. John Wiley and Sons, Hoboken, NJ, USA.

5. **Robertson P.K. & Cabal K.L**. (2012). Guide to cone penetration testing for geotechnical engineering. *Book Gregg Drilling & Testing Inc.*

6. **Mechi J.** (2013). Geotechnical Engineering Examples and Solutions Using the Cavity Expanding Theory. Budapest: Hungarian Geotechnical Society.

7. **Schmertmann J.H.** (1978). Guidelines for Cone Penetration Test: Performance and Design, Federal Highway Administration, Washington, DC, USA.

8. **Belviso R., Ciampoli S., Cotecchia V. & Federico A.** (1985). Use of the Cone Penetrometer to Determine Consistency Limits. *Ground Eng.*, 18, No. 5, 21–23.

9. **Robertson P.K.** (1990). Soil classification using the cone penetration test. Canadian Geotechnical Journal, vol. 27, No. 1, 151–158.

10**. Powell J.J.M., Shields C.H. & Wallace C.F.** (2015). Liquid Limit testing – only use the Cone Penetrometer! Proc. of the XVI ECSMGE Geotechnical Eng. for Infrastructure and Development. Edinburg, 3305–3310. https://doi:10.1680/ecsmge.60678

11. **Plantema I.G.** (1957). Influence of density on soundings results in dry, moist and saturated sands. Proc. of the IV Intern. Conf. on Soil Mechanics and Foundation Eng., vol. 1. London.

12. **Kerisel J**. (1957). Mesures in situ pour determiner la portance d'une foundation interpritation de usultats du penetromettre. Cahiers du Centre scietque et technique du bätiment, No. 30. [in French].

13. **Zotsenko M.L. & Vynnykov Yu.L.** (2019) Fundamentu sho sporudguutsy bez vuymanny gruntu. Poltava: PoltNTU imeni Yuri Kondratuka. [in Ukrainian].

14. **Zotsenko N. & Vynnykov Y.** (1999). Rapid Investigation Methods of Soil Properties and Interpretation of their Results for Bridge Foundations Design. IABSE New Delhi Colloquium reports on "Foundations for Major Bridges: Design and Construction". New Delhi, 19–24.

15. **Zotsenko M., Vynnykov Y. & Yakovlev A.** (2010). Modern practice of determination of strength characteristics of cohesive soils by penetration methods. Proc. of XIVth Danube - European Conf. on Geotechnical Eng. Bratislava: Slovak University of Technology, 245-253.

16. **Uhlig M. & Herle I.** (2015). Advanced analysis of cone penetration tests. Proc. of the XVI ECSMGE Geotechnical Eng. for Infrastructure and Development. Edinburg, 3073–3078. https://doi:10.1680/ecsmge.60678

17. **Ma H., Zhou M., Hu Y. & Hossain M.S.** (2017). Effects of cone tip roughness, in-situ stress anisotropy and strength inhomogeneity on CPT data interpretation in layered marine clays: numerical study. Eng. Geology, vol. 227, 12-22.

18. **Vynnykov Yu.L. & Aniskin A.** (2019). Practical problems of anisotropic soil mechanics: Monograph. Varazdin: University North, Croatia.

19. **Rajasekaran G. & Rao S.N.** (2004). Falling cone method to measure the strength of marine clays. Ocean Eng., vol. 31, No. 14-15, 1915-1927.

20. **Xiuli F. & Weiquan S.** (2006). Marine Engineering Geological Monograph. China Ocean University Press, Qingdao, China.

21. **Wu B., Wang G.,** Li J.**, Wang Y. & Liu B.** (2018). Determination of the Engineering Properties of Submarine Soil Layers in the Bohai Sea Using the Piezocone Penetration Test. Advances in Civil Eng. https://doi.org/10.1155/2018/9651045.