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Applied problems of penetration of sedimentary rocks

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A number of topical applied problems on studying the physical and mechanical characteristics of sedimentary rocks using the already sufficiently tested high-speed penetration method are considered, such as: the influence of tip sizes on the value of the static probing index of sands; the influence of the surface quality of conical tips on the results of penetration and probing; improvement of the tip for penetrating rocks with anisotropic properties. New practical possibilities of using the equations of the relationship between the physical properties of rocks and their mechanical parameters, in particular, the specific resistance to penetration or the penetration index, to generalize the results of experiments are shown.

Keywords: sedimentary rock, penetration, penetration tip, penetration index, specific penetration resistance, relationship, rock skeleton density, anisotropy.

Прикладні задачі пенетрації осадових гірських порід

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Розглянуто ряд актуальних прикладних задач з дослідження фізико-механічних характеристик осадових гірських порід із застосуванням вже достаньо апробованого швидкісного методу пенетрації, зокрема: вплив розмірів наконечників на величину показника статичного зондування пісків; вплив якості поверхні конічних наконечників на результати пенетрації та зондування; удосконалення наконечника для пенетрації порід з анізотропними властивостями. Показано нові практичні можливості використання рівнянь взаємозв’язку між фізичними властивостями гірських порід і їх механічними параметрами, зокрема питомим опором пенетрації чи показником пенетрації, для узагальнення результатів експериментів. Зокрема. доведено. що застосовуючи метод пенетрації та маючи значення щільності-вологості, в будь-якому елементі масиву осадових гірських порід можливо визначити необхідну характеристику. Шляхом кореляційного аналізу однозначно встановлено повну незалежність величини показника зондування від розмірів гладких конічних наконечників для піску кварцевого, крупного, малого ступеню водонасичення в широкому діапазоні зміни його щільності. Експериментально встановлено, що опір ґрунту занурення ідеально шорсткуватих наконечників одного діаметра практично не залежить від кута розкриття конуса. Наведено наочні приклади, що показують високу ефективність і достовірність використання рівняння взаємозв'язку між фізичними і механічними параметрами гірських порід при вирішенні різних емпіричних завдань досліджень. Розроблено та запатентовано «Наконечник для пенетрації ґрунтів з анізотропними властивостями» та «Спосіб визначення коефіцієнта анізотропії ґрунту методом пенетрації», які дають можливість підвищити достовірність оцінювання напружено-деформованого стану масивів масивів гірських при використанні в їх моделі фізичних співвідношень ортотропного чи трансверсально-ізотропного середовища.

Ключові слова: осадова гірська порода, пенетрація, наконечник для пенетрації, показник пенетрації, питомий опір пенетрації, щільність скелету гірської породи, взаємозв'язок, анізотропія.

Introduction

The penetration method, together with probing, composite testing, and rotary sectioning, is traditionally referred to as the so-called high-speed methods for studying the physical and mechanical properties of sedimentary rocks (soils).

It is based on the slow immersion of a conical tip into the rock to a depth *h*, which should not exceed the height of the cone h_k. When conducting penetration tests in the laboratory, the load is usually transferred in stages, while recording the depth of the tip immersion. The duration of exposure of each individual load stage is taken to be the same (usually 1-2 minutes) [1].

The generalized parameters of these penetration studies were obtained by V.F. Razorenov on the basis of solutions to the axisymmetric problem of the theory of limiting equilibrium [2]. In particular, for cohesive sedimentary rocks (clay, loam, sandy loam), this indicator is the ratio of the penetration force *P* to the square of the cone immersion depth, which is called the specific penetration resistance *R*, MPa.

Practice has shown that the main advantage of penetration studies of homogeneous sedimentary rocks is the so-called invariance condition of the results obtained, i.e., complete independence from the applied force and the corresponding depth of the cone immersion, and, taking into account the constants of the tips used, independence from the angle of their opening. Consequently, in this case, the results of the study do not depend on the means of recording the penetration resistance and the design of the penetrometers themselves [3].

Review of the research sources and publications

The method of penetration testing of rocks, in particular, is recommended for:

– 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.). The effect of the impact is determined by the ratio of the values of the specific resistivity of penetration R/R_0 (or penetration indices U/U_0) obtained before and after the impact [4];

– control of the results of mechanical tests of rocks performed by traditional methods [5];

– identifying the relationship between physical condition indicators and strength characteristics of sedimentary rocks [6, 7].

In the current practice of penetration testing of sedimentary rocks, several quite popular areas can be identified. First of all, the equipment for penetration and static rock probing and the methods of processing and interpreting the results of these studies continue to be improved [8, 9].

Another modern trend in the penetration studies of sedimentary rocks, to the development of which the specialists of National University "Yuri Kondratyuk Poltava Polytechnic" (NU "Poltava Polytechnic") made a significant contribution, is the comprehensive substantiation of the equations of the relationship between the physical and mechanical properties of soils for certain types of rocks that have constant, so-called, indicative characteristics (e.g. plasticity number, mineralogical composition, structural features, etc. etc.) based on the results of generalization of numerical experimental data [10-12].

Thus, the general relationship equation of the form (1) has already been well tested for solving applied problems of determining the physical and mechanical characteristics of both cohesive and non-cohesive sedimentary rocks.

The general relationship equation in this case is as follows

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

where *R* – specific penetration resistance, MPa;

$R_0 = 1$ MPa;

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

$$M_{kpf} = 1 - \frac{1/e_0}{1/e}; \quad (2)$$

$1/e_0$ and $1/e$ – 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;

ρ_w – water density (1 g/cm^3);

ρ_d – density of dry soil (or soil skeleton).

Thus, having equations of the form (1) for specific types of sedimentary rocks, defined as a certain engineering and geological element, it is possible to determine the corresponding values of: specific resistance to penetration, R; modulus of deformation, E; angle of internal friction, φ; specific adhesion, *c*, based on their known values of the porosity coefficient (*e*) and moisture content (*W*).

And using similar expressions obtained from equation (1) [10, 11], it is possible to determine the mechanical properties of the rock based on the known values of the specific resistance to penetration, *R*, and the moisture content, *W*: *E*; φ; *c*.

It should also be noted that the methodology for assessing the physical and mechanical properties of sedimentary rocks using the relationship equation (1) has been repeatedly tested in the study of compaction zones in various piles and foundations [10].

A number of publications [13-15] are devoted to the interpretation of the results of penetration tests of sedimentary rocks on the sea shelf.

Recently, the use of penetration studies to evaluate the anisotropic properties of sedimentary rocks has also gained some popularity [16, 17]. Thus, the definition of the coefficient of anisotropy of the mechanical characteristics of the rock as the ratio of the values of the specific resistance to penetration at a certain angle to the plane of isotropy to the same parameter, but at a zero angle, has been tested.

Definition of unsolved aspects of the problem

However, the application of the equation of the form (1) is possible to solve a number of other relevant phenomenological problems of studying the physical and mechanical properties of sedimentary rocks.

Problem statement

Therefore, the purpose of the work was to expand the scope of applied problems for studying the physical and mechanical parameters of sedimentary rocks using a sufficiently tested high-speed penetration method. Some of them will be considered below.

Basic material and results

Influence of tip sizes on the value of the sands probing index.

When developing a general methodology for static probing of sands, this issue is of some interest.

The experimental studies were carried out in the laboratory at the laboratory probing unit LZU-1 designed by National University "Poltava Polytechnic".

The sand studied was quartz, coarse, homogeneous, air-dry with a SO_2 content of 98.7%.

In the tray, the sand was given six values of its skeleton density ρ_d = 1.50, 1.52, 1.55, 1.60, 1.64, 1.67 t/m^3.

The density of sand was achieved for the loose state by pouring through a funnel, and for the dense state by surface and deep vibration with loading.

The probing was carried out with smooth conical tips with an angle between the base and the vertical of α = 15°.

The tips of five different sizes were used with cone base diameters α = 2.9, 3.5, 3.9, 4.5, and 5.0 cm.

In all cases, the ratio of the cone diameter to the rod diameter $dc/dsh \geq 1.8$ was maintained. The tip immersion rate in the rock did not exceed 0.25 m/min.

For each experiment, the probing index V was determined [11].

Each value of this indicator corresponded to a certain value of rock density, $1/\rho_d$.

To summarize the test results, they were presented in the coordinates "inverse of the dry soil density, $1/\rho_d$ - logarithm of the probing index, lgV".

This graph is shown in Fig. 1.

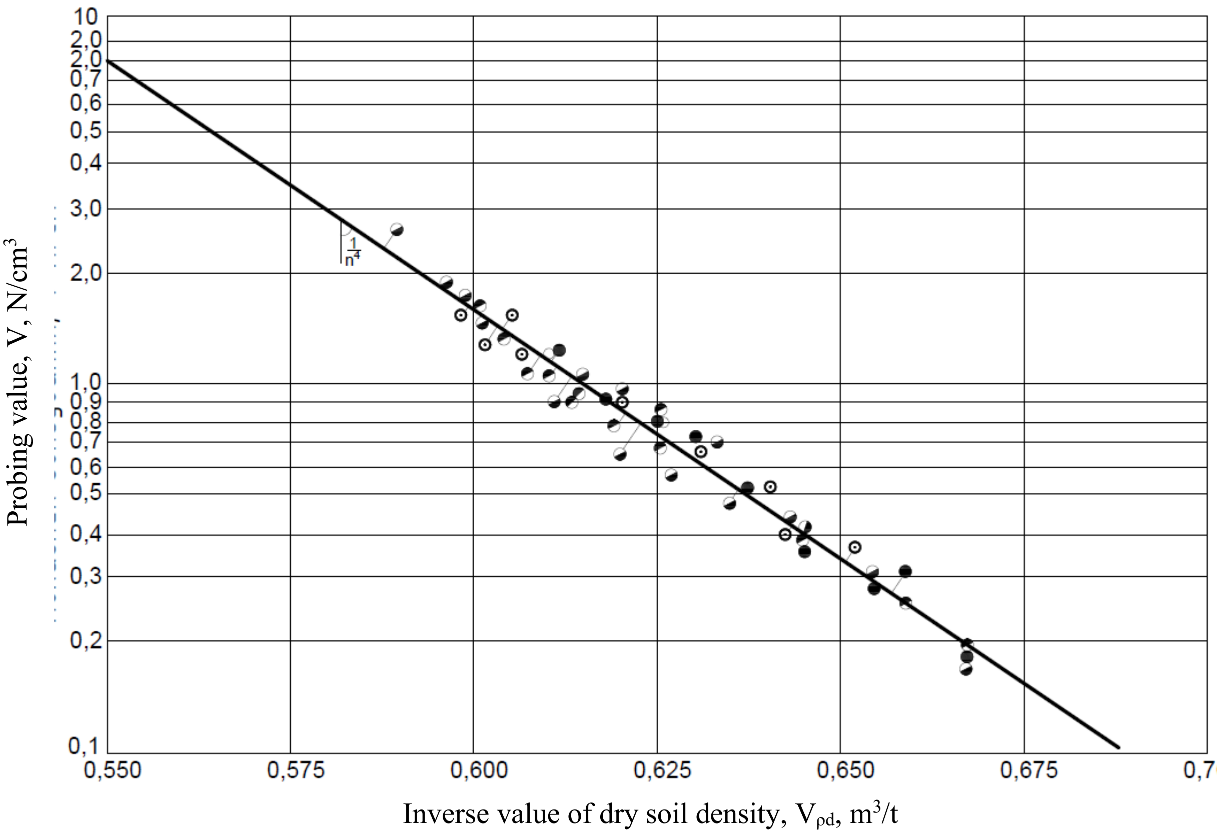

Figure 1 – Results of sand probing with tips of different sizes

Interpreting it in accordance with equation (1), we obtain the linear equation (3)

$$\frac{1}{\rho_d} = 0.886 - 0.0716 \lg \frac{V}{0.1}, \quad (3)$$

with the correlation coefficient r = 0,99.

Thus, as a result of the correlation analysis, the complete independence of the value of the probing index, V, from the size of smooth conical tips for quartz sand, coarse sand, and sand with a low degree of water saturation in a wide range of changes in its density was unequivocally established.

Influence of tapered tip surface quality on penetration and probing results.

Studies by many experts point to the influence of the surface quality of the conical tip on the results of penetration and probing.

It is customary to use a polished metal cone for these tasks [11].

However, the surface of the cone is disturbed during operation, especially in the field. Meyerhoff introduced the concept of a rough cone when the friction along its lateral surface is equal to the tangent of the angle of internal friction of the test sedimentary rock. He proposed a concrete wedge and a copper cone treated with sand for testing.

A new design of a so-called perfectly rough cone was proposed at National University "Poltava Polytechnic".

The scheme of this stepped conical tip is shown in Fig. 2.

It includes a cone and a shank and is characterized by the fact that, in order to create friction conditions on the ground, the cone is made with cylindrical steps.

The tip consists of a cone - 1 and a shank - 2.

The cone is made with cylindrical steps having a ratio of $\delta/h_c = tg\alpha$, and the ratio of the step height to the cone height is taken to be 0.05 - 0.1.

When the tip is buried in the soil under the cylindrical steps, areas of compacted soil are formed, which move with the tip and form a soil jacket in the form of a cone with a base at an angle to the vertical, α.

The proposed tip clearly meets the conditions of a rough cone and creates conditions for friction between soil and soil.

Penetration and probing tests were conducted in sandy and clay soils to identify the expected phenomenon.

The methodology of these studies was based on a set of experimental data on penetration and probing of soils of various types and conditions, and then generalization of the results obtained in accordance with the conditions adopted for equation (1).

Fig. 3, a shows the experimental data on the penetration of coarse, homogeneous, quartz, air-dry sand by a smooth and stepped conical tip with the same geometric parameters:

α = const;

hc = const;

dc = const.

The test was performed using a laboratory penetrometer LP-1.

The porosity coefficient of the sand varied from 0.90 to 0.72 and, accordingly, the angle of internal friction from 32° to 36°.

Line 1 establishes the relationship between the inverse of the dry soil density, $1/\rho_d$, and the logarithm of the penetration index, *U*, obtained with a smooth metal cone.

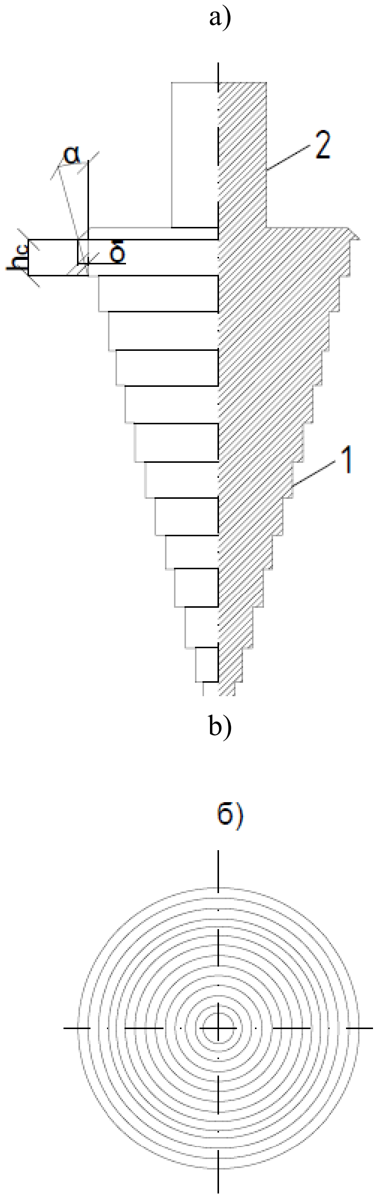

Figure 2 – Stepped conical tip for penetration and probing:
a - section; b - plan; 1 - conical part; 2 - shank, hc - height of steps; δ - ledge; α - angle between the vertical and the cone face

Line 2 establishes a similar relationship, but with a stepped tip.

There is a large difference between the values of the penetration rates - they are 3 times higher for stepped tips.

Fig. 3, b shows similar data for a loam of a disturbed structure.

The angle of internal friction of the soil varied between 14 and 16°.

All things being equal, the specific penetration resistance obtained with a rough tip is 1.3 times greater than for a smooth one.

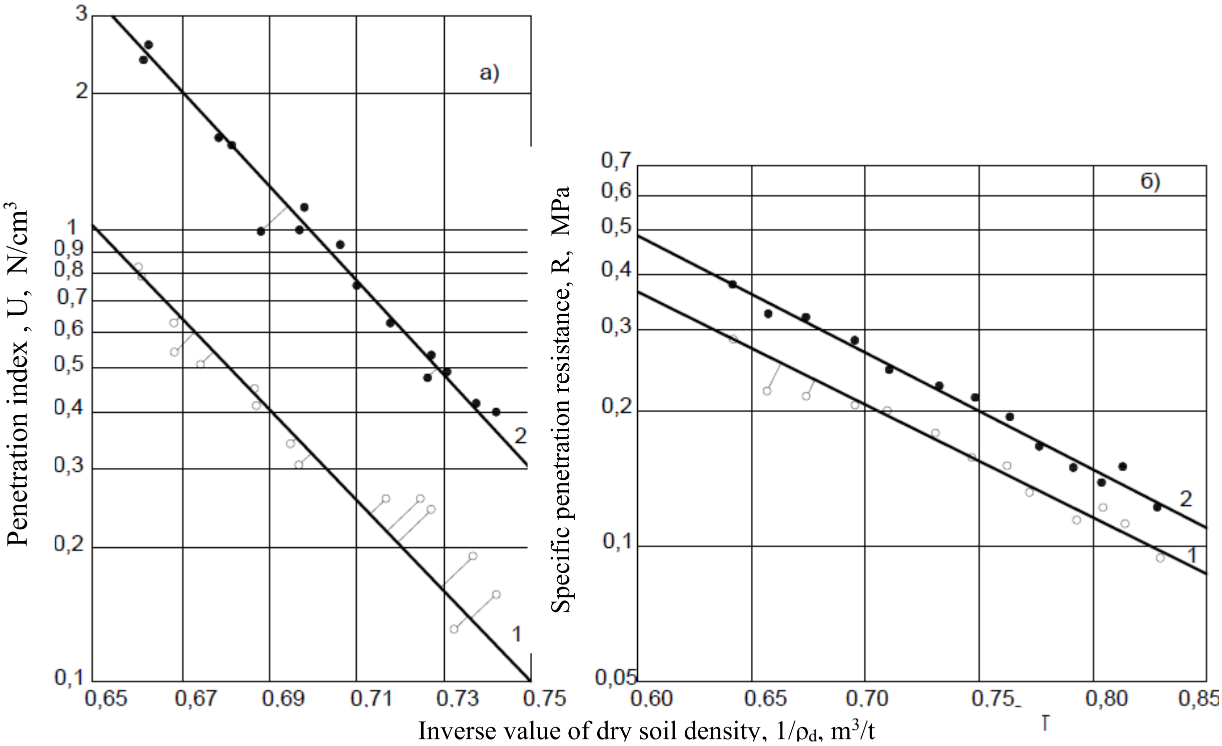

Figure 3 – Results of penetration tests of soils with smooth and stepped conical tips:
a - sands; tips: 1 – smooth, 2 - stepped;
b – loam; tips: 1 – smooth; 2 – stepped

The results confirm the notion that a soil shell is formed around the stepped tip, which moves along with the tip. This causes friction between the soil and the tip.

This value determines the value of the penetration index for sands and the specific penetration resistance for loams. If we assume the coefficient of friction of the metal on the soil $f = 0.10 - 0.12$, then the results can be confirmed by calculation.

Thus, the greater the angle of internal friction of the soil, the greater the error when using a conventional smooth metal tip in penetration tests. It is noticeable when testing sands and may be negligible when penetrating water-saturated clay soils.

Fig. 4 shows the results of probing coarse, homogeneous, air-dry, quartz sands in laboratory conditions using the LZU-1 installation with tips with different angles, α, between the base and the vertical of the cone.

Conical tips with the same cone base diameter d_c = *const* were used.

Fig. 4, a shows the data for smooth tips, and Fig. 4, b – for stepped tips.

For each value of the angle α, the probing was performed at seven values of the dry soil density, ρ_d, of both smooth and rough tips.

As a characteristic of sand probing, the value V_A was taken, which is calculated by the following formula

$$V_A = \frac{P - P_o}{H \times A}, \qquad (4)$$

where A – cone base area.

The obtained data confirm the well-known statements [11] about the formation of an elastic core under flat and conical dies.

According to these ideas, the shape of the elastic core is close to conical, and its angle α ≈ 22.5°.

If the smooth tip has a 2α < 22.5°, the core is not formed, and friction occurs on the metal.

If 2α > 22.5°, then elements of this core appear, and the larger α, the more elements of the elastic core are formed.

A flat die has a complete elastic core.

The graphs in Fig. 4, a show that with the formation of elastic core elements, the intensity of the increase in the probing index decreases, i.e., the effect of friction on the soil is manifested.

Fig. 4, b shows the graphs obtained using stepped tips.

According to these data, the soil resistance to penetration of perfectly rough tips of the same diameter is practically independent of the cone opening angle.

There is a slight tendency to increase the probing resistance with an increase in the angle α, which confirms Meyerhoff's conclusions.

These examples show the high efficiency and reliability of using the relationship equation (1) in solving various phenomenological research problems.

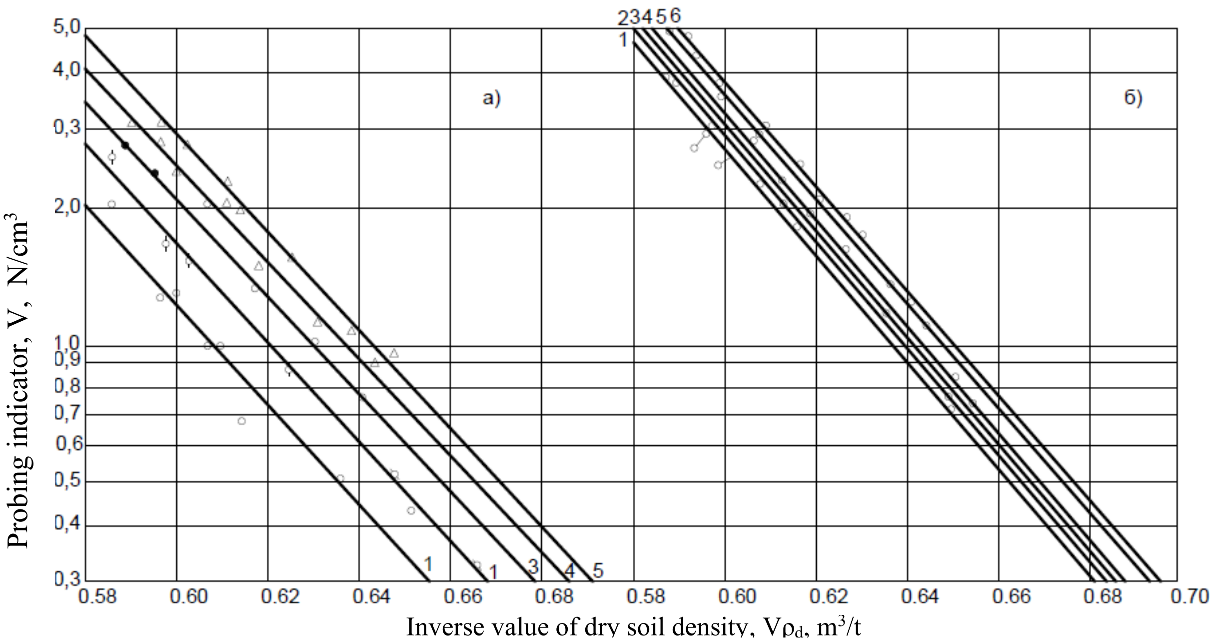

Figure 4 – The probing results of sands with smooth and stepped conical tips:
a - smooth with angle α: 1-10°; 2-15°; 3-22.5°; 4-30°; 5-45°;
b - stepped with angle α: 1-10°; 2-15°; 3-22,5°; 4-30°; 5-45°

Improving the tip for penetrating soils with anisotropic properties.

At National University "Poltava Polytechnic", a "Penetration tip for soils with anisotropic properties" was created (Patents for: invention No. 17737 and industrial design No. 1473) (Fig. 5).

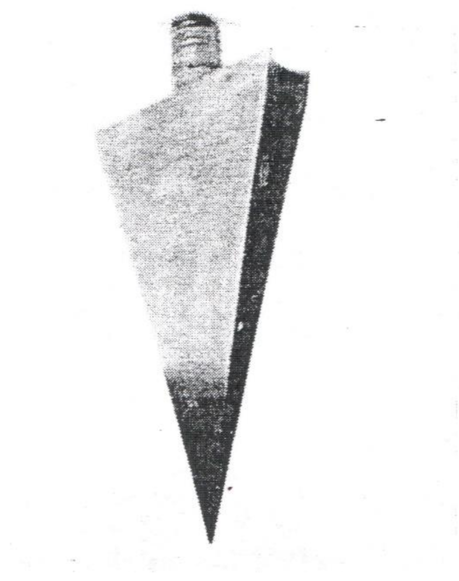

Figure 5 – Tip for penetrating soils with anisotropic properties

Due to the small angle between the working faces and the concavity of the side faces (which eliminates the interaction of the rock with the side surfaces), the tip introduces minor measurement errors in anisotropic sedimentary rocks.

The interaction of the soil occurs only along the surfaces of the working faces, i.e. at an angle that differs slightly from the direction of the central axis: for example, if the angle between the working faces is 8, the angle by which the working surface of the faces is deviated from the central axis is 4°.

The side faces do not interact with the rock (they are still lubricated with grease).

To improve the accuracy of n_α, we developed a "Method for determining the soil anisotropy coefficient by the penetration method" (Patent for Invention No. 49904).

It involves stripping at least two adjacent areas to the shape of planes located at different angles α to the horizon and penetrating each of them in a direction perpendicular to its tip according to Patent No. 17737.

Penetration in each direction is carried out with at least four tips with different angles between the working faces, for example, β = 20, 15, 10, and 5, with the determination of R for each direction of penetration and each angle β, calculation of the values of the coefficient $n_{R\alpha}$ for the corresponding angles β, approximation of the data of the dependence $n_{R\alpha} = f(\beta)$, in particular, by a power function, and extrapolation to the value of $n_{R\alpha}$ corresponding to $\beta = 0°$.

Thus, in cases where the values of soil anisotropy coefficients differ significantly from $n_\alpha = 1.0$, the accuracy of estimating the stress-strain state of rock masses can be increased by using physical relations of orthotropic or transverse-isotropic media in their model.

Conclusions

Thus, by expanding the subject matter of applied problems for studying the physical and mechanical parameters of sedimentary rocks using the tested high-speed penetration method, the following was established.

1. The equations of the relationship between the physical and mechanical properties of soils are established for individual varieties that have constant indicative characteristics (plasticity number, mineralogical composition, structural features, etc.) based on the results of generalizing numerical experimental data. Using the penetration method and having the density-moisture values, it is possible to determine the required characteristic in any element of the soil massif.

2. The possibility of using the equations of the relationship between the physical and mechanical characteristics of soils to generalize the results of experiments in solving research problems is proved.

3. The "Penetration tip for soils with anisotropic properties" and the "Method for determining the soil anisotropy coefficient by the penetration method" were developed and patented, which make it possible to increase the reliability of the assessment of the stress-strain state of rock masses when using physical relations of orthotropic or transversal-isotropic media in their model.

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