Justification of instrument parameters for the construction soil strength determination

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Abstract. A portable instrument has been introduced in the construction industry of the Russian Federation for the determination of soil strength grades, which is based on the free weight falling principle. Until the present the theory of such instrument hasn’t yet been completely developed and needs to be improved. In this study on the basis of the theorem on normal stresses on surfaces of a cone to be penetrated into the soil, a logically justified theory of the instrument basic parameter selection has been developed. Stresses on horizontal areas of construction soils are equal to twice the stresses on inclined areas of the cone. At the end of the working section of a rod to be penetrated into the soil there is a round flat punch, which area is A=1 cm². During the punch penetration into the soil by an impact method, a soil compacted cone body appears before the flat punch, which is affected by normal pressure forces and tangential friction forces. For the first time the equation of normal stresses has been obtained on inclined areas of the soil cone. The mathematical model of the instrument doesn’t contain soil parameters, that allows to recommend it for any soil and media. The obtained analytical dependences allow to design similar instruments in order to measure the soil strength using any value of the falling weight mass. In this paper the instrument parameter justification has been made with the impact weight mass \( m_1 = 2.5 \) kg.

Key-words: dynamic instrument, theorem on stresses, static penetration, dynamic penetration, soil classes.

1. Introduction
A number of different instruments have been developed for the determination of the soil strength during the construction of embankments, sites, dams. Portable single-action instruments being reliable in operation are the most relevant for construction purposes. Dynamic density meter with a freely falling weight [1] is one of such instruments. Various theoretical aspects of this instrument are considered in papers [2-5].

Numerous papers of foreign and Russian scientists [6–9] are devoted to the strength determination of soils and materials by means of the impact penetration of a cylindrical rod of a specified length and diameter into tested soils and materials.

This study considers new approaches to the creation of the rational methods of the instrument parameter identification for the soil strength determination.

2. Problem statement
To create methods of the parameter selection of the portable impact action instrument for the construction soil strength measurement.

3. Theory
Initially we consider the theory of the static penetration of a cone-shaped steel body into the soil mass.
Figure 1 shows the design diagram of the steel cone penetration into the soil [4].

![Figure 1. Idealized design diagram of the steel cone penetration into the soil.](image1)

![Figure 2. Idealized design diagram of forces acting on the cone-shaped soil body penetrated into the soil mass: 1 – rod; 2 – soil body.](image2)

The contact problem of the soil cone penetration into the soil is a nonlinear one, as during the penetration the contact area of the cone with the soil is changed. The idealized distribution diagram of the normal stresses $\sigma_1$ acts on the inclined areas of the cone surface. The vertical force $P$ acts on the cone end, the normal pressure force $N$ and the friction force $F$ act on the lateral surfaces. The resultant force of the normal forces $N$ on the inclined areas of the cone can be determined by the formula

$$N = \sigma_1 A = \sigma_1 \pi rl,$$  \hspace{1cm} (1)

where $A$ is the lateral surface of the recessed part of the cone; $r$ is the radius of the base of the recessed part of the cone.

Expressing $r$, $l$ in equation (1) through the cone height we’ll obtain

$$N = \sigma_1 \pi z^2 \frac{\sin \varphi}{\cos^2 \varphi}.$$  \hspace{1cm} (2)

The tangential friction force of the cone lateral surface can be determined by the formula

$$F = fN.$$  \hspace{1cm} (3)

Ignoring the cone mass we’ll write down the equilibrium equation

$$\sum Z = 0; \quad P - N \sin \varphi - F \cos \varphi = 0,$$  \hspace{1cm} (4)

where $\varphi$ is the angle of the steel friction over soil.

Using expressions (1) - (4) we’ll determine the stress on inclined areas

$$\sigma_1 = \frac{P}{\pi z^2 \left( \tan^2 \varphi + f \tan \varphi \right)}. \hspace{1cm} (5)$$

Figure 2 shows the interaction pattern of compacted soil cone 2, which is formed at the end of rod 1 during its penetration into the soil half-space. Taking into consideration that $f = \tan \varphi$, we express the force $P$ through stresses on the soil cone horizontal area

$$P = \sigma_c \pi r^2 = \sigma_c \pi z^2 \tan \varphi.$$  \hspace{1cm} (6)

We’ll determine the horizontal area stresses
\[ \sigma_z = \frac{P}{\pi z^2 \tan \varphi}. \]  

(7)

We’ll find the stress ratio

\[ \frac{\sigma_z}{\sigma_1} = 2. \]  

(8)

Thus, the idealized design diagrams of Figures 1 and 2 have allowed us to prove the following theorem. For the cone penetrated into the soil, stresses on the horizontal area are equal to twice the normal stresses on the cone lateral surfaces. This theorem allows to obtain the theory of the impact instrument for the soil strength measurement.

Figure 3 shows the impact action instrument for the soil strength measurement.

![Figure 3. Dynamic density meter.](image)

Weight \( I \) of mass \( m_1 = 2.5 \) kg can move along the rod, and when falling from the upward position it strikes the shoulder and inserts the working tip with the length \( S_z = 0.1 \) m into the soil in a few impacts. The soil strength is proportional to the number of impacts which are necessary for the working tip penetration into the soil.

Figure 4 shows the instrument design diagram. The weight falls from the height \( H = 0.4 \) m and strikes the rod. The working tip of instrument 2 has the diameter \( d_1 = 10 \) mm, and round flat punch 3 with the diameter \( d = 11.4 \) mm which area \( A = 1.0 \) cm\(^2\) is fixed on its end. Such design allows to eliminate friction forces on the lateral surface of the cylindrical tip with the length \( S_z = 0.1 \) m.
Compacted soil body 4 is formed under the round flat punch. In the result of this during the rod penetration into the soil the interaction of the cone-shaped body with the tested soil takes place. Compacted soil body 4 destroys the soil, moving it apart and releasing space for lowering bodies 2, 3. In one impact bodies 2 and 3 are dropped for the $z_k$ value.

The forces $N$ and $F$ act on the soil cone 4. The soil cone weight can be ignored due to its smallness. The angle $\phi$ in the diagram is considered as the internal friction angle of soil over soil. The sliding friction factor of soil over soil is equal to the tangent of the internal friction angle $f = \tan \phi$. Thus, the design diagram in Figure 4 at specified values $m_1$, $m_2$ and falling height $H$ of weight 1 allows to determine the normal stresses $\sigma_1$ under the end face of punch 3 on the inclined areas of the soil body.

We’ll determine the average normal stress $\sigma_1$ on the inclined areas of the soil cone-shaped body. The normal force $N$ on the lateral surface of the cone is determined by the formula

$$N = \sigma_1 A = \sigma_1 0.5dl. \quad (9)$$

Expressing $l$ through the diameter $d$ of the cone base, we’ll finally write down

$$N = \sigma_1 \frac{\pi d^2}{4 \sin \phi}. \quad (10)$$

The friction force $F$ on the soil cone surface is equal to

$$F = fN. \quad (11)$$

During the rod penetration into the soil the forces $N$ and $F$ perform operation. Two more forces ($m_1 + m_2)g$ exist in the instrument, which also perform operation during the instrument lowering into the soil during the movement for the $z_k$ value of one impact.

The instrument lowering value per one impact is determined by the formula

$$z_k = S_z / C_{imp}. \quad (12)$$

Taking into consideration that for loose and weak soils $C_{imp} = 5$–10. For medium and strong soils $C_{imp} > 10$, that’s why in this case the lowering operation is a small value that may not be taken into account. The operation of resistance forces during the striker movement into the soil can be determined by the integration method
\[
A_{1-2} = \int_{0}^{z_1} N \sin \varphi dz - \int_{0}^{z_2} F \cos \varphi dz. 
\] (13)

In the result of the integration we’ll obtain
\[
A_{1-2} = -\int_{0}^{z_1} \sigma_1 \frac{\pi d^2}{4 \sin \varphi} \sin \varphi dz - \int_{0}^{z_2} \sigma_1 \frac{\pi d^2}{4 \sin \varphi} f \cos \varphi dz = -\sigma_1 \frac{\pi d^2}{2} z_k. 
\] (14)

We’ll determine the weight free falling speed from the height \(H\)
\[
V = \sqrt{2gH}. 
\] (15)

At the moment of weight \(l\) contact with the rod stop the joint movement is started of two masses of the weight \(m_1 g\) and of the rod \(m_2 g\), which is accompanied by an inelastic impact.

The initial joint velocity of two bodies can be determined by the speed conversion formula [4]
\[
U = V \frac{m_1}{m_1 + m_2}. 
\] (16)

The principle of energy during the joint movement of two masses \(m_1\) and \(m_2\) to be penetrated into the soil has the following form
\[
T - T_0 = A_{1-2}, 
\] (17)
where \(T\) is the kinetic energy of the mechanical system of two bodies at the end of the impact; \(T_0\) is the kinetic energy of the system at the start of the penetration process; \(A_{1-2}\) is the operation of forces during the penetration.

After the substitution of known values in equation (17) we’ll obtain
\[
-\frac{(m_1 + m_2)U^2}{2} = -\sigma_1 0.5\pi d^2 z_k. 
\] (18)

Substituting in equations (18) expressions according to equations (12), (16) we’ll obtain
\[
\frac{(m_1 + m_2) \left( \sqrt{2gH} - \frac{m_1}{m_1 + m_2} \right)^2}{2} = \sigma_1 0.5\pi d^2 \frac{S_z}{C_{imp}}. 
\] (19)

From equation (19) we obtain the stress formula on inclined areas
\[
\sigma_1 = \frac{gH \frac{m_1^2}{m_1 + m_2}}{0.5\pi d^2 S_z C_{imp}}. 
\] (20)

The stresses \(\sigma_z\) on horizontal areas are determined by the theorem: \(\sigma_z = 2\sigma_1\).

We’ll determine the dynamic factor of the instrument \(K_d\) as the ratio of the dynamic force on the punch to the striking part weight
\[
K_d = \frac{\sigma_z A}{m_1 g}. 
\] (21)

4. Results discussion
The dynamic impact operating principle is an important advantage of the instrument, which allows with a small size to obtain significant dynamic forces and cover a wide range of the construction soil strength [10].

The table 1 shows the stress values at horizontal areas $\sigma_z$ for different soil types, calculated by formula (20).

**Table 1. Stress study results for different soil classes**

| Soil class | Number of impacts $C_{imp}$ | Stresses on inclined areas $\sigma_1$, MPa | Stresses on horizontal area $\sigma_z$, MPa | Instrument dynamic factor $K_d = \frac{P}{m_1 g}$ |
|------------|-----------------------------|------------------------------------------|-------------------------------------------|---------------------------------------------|
| I          | 1÷4                         | 0.267÷1.068                              | 0.534÷2.136                               | 2.18÷8.72                                  |
| II         | 5÷8                         | 1.335÷2.136                              | 2.670÷4.272                               | 10.89÷17.41                                |
| III        | 9÷16                        | 2.403÷4.272                              | 4.806÷8.544                               | 19.596÷34.84                               |
| IV         | 17÷55                       | 4.539÷9.344                              | 9.078÷18.688                              | 37.02÷76.21                                |
| V          | 36÷70                       | 9.611÷18.688                             | 19.222÷37.376                             | 78.37÷152.42                               |

For the first time the parameter justification problem has been solved of the instrument for the construction soil strength measurement using the normal stress theorem on the cone end and cone inclined surface according to equations (7), (8).

For the reduction of the instrument impact number $C_{imp}$ it is necessary to increase the impact mass $m_1$. Impact units are known with the mass $m_1$ equal to a few tens of kilograms when the instrument movement is measured in one impact. Such instruments represent complex units and they are not considered in this paper.

Obtained equation (20) for the stress $\sigma_1$ on an inclined area is suitable for any similar devices with different masses $m_1$. This equation contains the main instrument parameters and doesn’t contain soil parameters. This means that such instrument is suitable for soils and media of different strengths and different physical nature.

The main parameters of the portable dynamic instrument are: $m_1 = 2.5$ kg; $m_2 = 2.0$ kg; $H = 0.4$ m; $S_z = 0.1$ m; $d = 0.0114$ m. According to the theorem of equation (8) the stress on horizontal areas in one impact is equal to:

$$\sigma_z = 2\sigma_1 = 2 \times 2.66972 = 533944 \text{ Pa.}$$

The dependence equation of normal stresses on the number of the instrument impacts has the following form

$$\sigma_z = 0.534 C_{imp}, \text{ MPa.} \quad (22)$$

5. **Consideration of the results**

1. The theorem has been obtained on stresses on the surfaces of the cone to be penetrated into the soil: the stresses on the cone horizontal area are two times higher than the stresses on the inclined areas.

2. For the first time the parameter equation has been obtained of the instrument for the stress measurement on horizontal soil areas by means of the stress theorem on a cone-shaped compacted body to be penetrated into the soil.

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