Improvement of a dispersed non-cohesive soil deformation model

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Abstract. The development of new territories, as a rule, is complicated due to a preliminary preparation of soil foundations to improve their deformation properties. Modern preference is basically given to mechanical ways, namely to compaction of soil foundations. The development of new and elaboration of the existing models of soil deformation are promising directions in improvement and development of new technologies for mechanical compaction of soil foundations. Theoretical researches were performed to estimate the description adequacy of deformation in a dispersed non-cohesive soil with practical results by the existing models. A sandy soil was used as a sample of disperse non-cohesive soil for which a deformation characteristic was defined in laboratory conditions. The comparative analysis of theoretical and experimental data allowed us to estimate approximation adequacy of results for laboratory studies of a sandy soil deformation for the examined models. The maximum value of a relative error of laboratory data approximation for this model did not exceed 0.145. According to results of conducted studies, a model of a dispersed non-cohesive soil deformation is proposed. Coefficients $k_8, k_9, k_{10}$ of the given relationship are to be calculated according to the results of compression tests of simulated dispersed non-cohesive soil in the operating pressure range.

Key words: dispersed non-cohesive soil, deformation model, soil foundation.

1. Introduction
The development of new territories is characterized by a variety of modern technologies applied in a construction of buildings for industrial, residential and civil purposes. Thus, it is proposed to enhance a foundation carrying capacity due to an essential increase of soil density at the face, pit's walls and mouth or wells, considering deformation properties of soil foundations [1]. Up to date process equipment, for example, pneumatic punches [2] and rolling out mechanisms are proposed for the compaction of soil foundations [3]. The use of «thermal diode» technology is proposed to provide stability of permafrost soils in Far North conditions [4]. Utilization of artificial thermal insulating materials, not aggravating soil foundation carrying capacities is suggested to reduce heat losses to the environment, first of all in a soil, and to decrease risk of loss in stability of tanks for liquid hydrocarbons storage on soil foundations [5]. Using of a geocell is a promising direction of increasing the bearing properties of cohesive and non-cohesive soils [6-8]. At the same time, obsolete technologies with a low efficiency and high resource intensity are often used for the preparation of soil foundations and bases. Obviously, it is caused both by a variety of soils composing the foundations of constructed facilities and stochastic nature of soils bedding. As a rule, this is related primarily to insufficient accuracy and lack of models, which adequately describe the processes occurring in soils
under the action of external forces and effects. This results in a widespread use of field-based research techniques of mechanical soil properties, practice of preparation of test foundations and bases, which leads to the increase in terms of work realization and inefficient use of material resources. A study of the behavior of non-cohesive soils under load is of practical interest [9-11]. The use of modern advances in computer engineering, tools of remote, contactless recording, including high-speed processes, enables deeper understanding of the processes proceeding in a soil under the action of external forces. Thus, high-speed video shooting allowed us to refine the dynamics of a conic model in a sandy soil in the process of its impact compaction [12]. In the course of theoretical studies, the relationships describing the dynamics of a conic model in a dispersed non-cohesive soil have been obtained [13]. The technique of calculation and selection of specialized equipment to record the dynamics of studied models in a soil has been developed at a preliminary stage of the experimental studies focused on validation of previously obtained theoretical results [14]. The model's motion footage in a soil obtained by high-speed video shooting and subsequent digital processing have confirmed correctness of theoretical data on the dynamics of a conic model in a sandy soil. Thus, the experience of theoretical and experimental studies allows us to conclude that the development of models based on data of laboratory researches and adequately describing the soil deformation under loading will enable us to reduce material and time expenditure at the stage of calculation and design of foundations and bases. In the long term, such models can serve as a basis of developed automated software systems carrying out calculation and selection of sound technologies and proper production equipment for specific soil conditions.

2. Problem Statement
The solution of problem for a model selection, describing a dispersed non-cohesive soil deformation is in a comparative analysis of available theoretical models and data of laboratory studies on deformation characteristics of the dispersed non-cohesive soil.

3. Theory
Numerous studies of a die impact on a soil in field and laboratory conditions established non-linear dependences between the applied stresses and the deformations caused in a soil. Professor N.Ya. Harkhuta for example, was engaged in the research of a die impact on a soil in field conditions and forecasting of the soil deformation caused [15]. Professor V.N. Tarasov [16] and professor A.A. Bartolomey [17] were involved in theoretical studies of a soil deformation under loading and problems of a soil deformation simulation. Professor G.G. Boldyrev was engaged in laboratory methods of research of soil mechanical properties [18]. Professor S.R. Meschyan proposes three options of approximating functions to describe a nonlinear dependence of relative deformation $\varepsilon$ versus stress $\sigma$, arising from the loading applied to the soil [19]:

$$\varepsilon = k_1 (1 - \exp(-k_2 \sigma))$$  \hspace{1cm} (1)
$$\varepsilon = k_3 \sigma^{k_4}$$  \hspace{1cm} (2)
$$\varepsilon = k_5 \sigma + k_6 \sigma^{k_7}$$  \hspace{1cm} (3)

where $\varepsilon$ is a relative soil deformation; $k_1 \ldots k_7$ are coefficients defined experimentally; $\sigma$ is a stress causing a soil deformation.

Coefficient $k_2$ of equation (1) is calculated by the solution of numerical methods of the following equation:

$$\varepsilon_2 = k_1 \cdot \frac{1 - \exp(-k_2 \sigma_2)}{1 - \exp(-k_2 \sigma_1)}$$  \hspace{1cm} (4)

where $\varepsilon_1$ and $\varepsilon_2$ are the relative deformation of a soil from stresses of $\sigma_1$ and $\sigma_2$ respectively, causing the soil deformation.

Thus, the value of coefficient $k_1$ of equation (1) is defined by relationship:
Coefficient $k_4$ of equation (2) is defined by relationship:

$$k_4 = \ln\left(\frac{e_2 \cdot e_1}{\ln(\sigma_2 / \sigma_1)}\right)$$  \hspace{1cm} (6)

In its turn, the value of coefficient $k_3$ of equation (2) is determined by relationship:

$$k_3 = \frac{e_1}{\sigma_1}$$  \hspace{1cm} (7)

Coefficient $k_7$ of equation (3) is defined by the solution of numerical methods of the following equation:

$$e_3 = \frac{\sigma_3}{\sigma_1} e_1 + \frac{e_3 \sigma_1 - e_1 \sigma_2}{\sigma_1 \sigma_2^k - \sigma_1 \sigma_1^k} \left(\sigma_3^k - \frac{\sigma_3}{\sigma_1} \sigma_1^k\right)$$  \hspace{1cm} (8)

where $e_1$, $e_2$ and $e_3$ are the relative soil deformation from stresses $\sigma_1$, $\sigma_2$ and $\sigma_3$ respectively, causing the soil deformation.

Coefficient $k_6$ of equation (3) is determined by relationship:

$$k_6 = \frac{e_2 \sigma_1 - e_1 \sigma_2}{\sigma_1 \sigma_2^k - \sigma_1 \sigma_1^k}$$  \hspace{1cm} (9)

And the value of coefficient $k_5$ of equation (3) is defined by relationship:

$$k_5 = \frac{e_1 - k_6 \sigma_1^k}{\sigma_1}$$  \hspace{1cm} (10)

The analysis of correctness for models 1 – 3, proposed for the description of deformation properties in silty-clayed soils of different consistency has established that the obtained calculated values of relative deformation $\varepsilon$ significantly exceed experimental data results. In the course of additional theoretical studies, the equation connecting relative deformation $\varepsilon$ of a soil with stress $\sigma$ has been proposed [20]:

$$\varepsilon = k_8 (1 - \exp(-k_9 \sigma))^{k_{10}}$$  \hspace{1cm} (11)

Coefficient $k_9$ of equation (11) can be defined by numerical methods solving the following equation:

$$e_3 = e_1 \left(1 - \exp(-k_9 \sigma_3)\right) \left(\ln(e_2 / e_1) \ln\left(\frac{1 - \exp(-k_9 \sigma_1)}{1 - \exp(-k_9 \sigma_3)}\right)\right)$$  \hspace{1cm} (12)

where $e_1$, $e_2$ and $e_3$ are the relative soil deformation from stresses $\sigma_1$, $\sigma_2$ and $\sigma_3$ respectively causing the soil deformation.

Coefficient $k_{10}$ of equation (11), in turn, is defined by relationship:

$$k_{10} = \ln\left(\frac{e_2}{e_1}\right) \cdot \ln\left(\frac{1 - \exp(-k_9 \sigma_1)}{1 - \exp(-k_9 \sigma_2)}\right)$$  \hspace{1cm} (13)

The value of coefficient $k_8$ of equation (11) is determined by relationship:

$$k_8 = e_1 (1 - \exp(-k_9 \sigma_1))^{k_{10}}$$  \hspace{1cm} (14)
The possibility to calculate numerical values of coefficients $k_1$...$k_{10}$ by means of equations 4 – 10 and 12 – 14 will allow us to estimate the correctness of use for proposed models 1 – 3 and 11 for data approximation of compression researches obtained experimentally or in laboratory conditions.

4. Results of laboratory studies

A sandy soil of average size has been selected as a sample of non-cohesive dispersed soil to carry out laboratory studies to explore deformation characteristics (figure 1, A). The selection of average size sandy soil, as well as the program of its compression tests is determined by the practical importance of obtained results. In preparation of tank foundation RVSPK-50000 m$^3$ for storage of oil and oil products according to regulations in force, the construction of foundation from a sandy soil of average size is provided [21]. Characteristics of the product stored and dimensions of the tank define the maximum value of compressing stress $\sigma$ under the tank bottom.

![Figure 1. A sample of average size sandy soil (A) and laboratory equipment for a soil test in compression conditions (B)](image)

The studies performed previously have established the range ($w = 3 \ldots 15 \%$) of optimum values of humidity in the average size sandy soil when its deformation value is maximum under the action of external force [5]. Adopting a hypothesis of practically instantaneous proceeding of consolidation in a dispersed non-cohesive soil with a small extent of water saturation ($S_r < 0.5$) due to large values of a filtration coefficient ($c_f = 10 \ldots 24$ m/day) and small values of optimum humidity ($w < 15 \%$), we make an assumption of a possibility to use data on a compression of a dispersed incoherent soil sample in laboratory conditions to simulate its dynamic compaction.

At the initial stage of laboratory studies a particle size distribution of a sandy soil has been defined by a sieve method, see table 1.

| Indicator          | Soil fractions, mm |
|--------------------|--------------------|
| Mass of soil fraction, g | 0.00 0.00 1.02 5.39 16.69 46.60 |
| Content of fraction, %  | 0.0 0.0 1.5 7.7 23.9 66.9 |
| Name                | Sandy soil of average size |

The sample of a sandy soil has been investigated on a soil test installation in compression conditions to define deformation characteristics (figure 1, B).

The program of compression tests and obtained laboratory data on deformation characteristics of the studied sample of sandy soil are given in table 2.
Table 2. Results of soil test by a compression method.

| Indicator                      | Loading stage |
|--------------------------------|---------------|
|                                | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
| Pressure on a soil sample, MPa | 0.000 | 0.024 | 0.050 | 0.075 | 0.100 | 0.124 | 0.149 | 0.174 | 0.179 |
| Absolute deformation of a sample, mm | 0.000 | 0.309 | 0.785 | 1.204 | 1.498 | 1.728 | 1.906 | 2.063 | 2.115 |
| Relative deformation of a sample | 0.000 | 0.012 | 0.031 | 0.048 | 0.060 | 0.069 | 0.076 | 0.083 | 0.085 |

5. Discussion of Results

The obtained data of laboratory researches for the average size sandy soil sample allowed us to calculate $k_1 \ldots k_{10}$ coefficients of analyzed models 1 - 3 and 11 for the case of compression by means of relationships 4 - 10 and 12 - 14, see table 3.

Table 3. Coefficient of equations 1-3 and 11.

| Coefficient | $k_1$ | $k_2$ | $k_3$ | $k_4$ | $k_5$ | $k_6$ | $k_7$ | $k_8$ | $k_9$ | $k_{10}$ |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|
| Value       | 0.1164 | 7.2401 | 0.2334 | 0.5901 | 0.6521 | -3.4944 | 2.7254 | 0.1050 | 10.7242 | 1.3646 |

Thus, equations 1 – 3 and 11, respectively, will look like:

$$\varepsilon = 0.1164 \cdot \left(1 - e^{-7.2401 \sigma}\right)$$

(15)

$$\varepsilon = 0.2334 \cdot \sigma^{0.5901}$$

(16)

$$\varepsilon = 0.6521 \cdot \sigma - 3.4944 \cdot \sigma^{2.7254}$$

(17)

$$\varepsilon = 0.1050 \cdot \left(1 - e^{-10.7242 \sigma}\right)^{3.646}$$

(18)

Data of theoretical calculations and laboratory studies are shown in a graphic form to carry out a comparative analysis (figure 2).
The graphic data show that a maximum divergence value of theoretical and laboratory data is observed at the initial loading section – in the range of 0.000 … 0.075 MPa. Simulation accuracy of a dispersed incoherent soil compaction can be estimated by the value of a relative error of approximation (figure 3).

![Graph showing relative approximation error](image)

Figure 3. A relative approximation error of results for compression tests of average size sandy soil by equations 15 – 18.

The diagrams presented in figure 3 demonstrate that the maximum value of a relative approximation error for equation 15 is 0.525, for equation 16 is 1.111 and for equation 17 is 0.276. Equation 18 for which the maximum value of a relative approximation error is 0.145 has the largest compliance degree. It is 3.62 times less, than a similar value for equation 15, it is 7.66 times less, than for equation 16, and it is 1.90 times less, than for equation 17. The relative error of approximation for considered equations 15 – 18 does not exceed 0.022 in the range of 0.100 … 0.179 MPa. Estimating the correctness of approximation for the dispersed non-cohesive soil deformation in case of average size sandy soil by various equations it should be noted that according to the construction practice taking into account a stochastic nature of soils’ bedding, 15 … 20 % divergence of theoretical and experimental data is admitted as satisfactory.

6. Conclusions
In the course of performed researches we have obtained theoretical relationships allowing us to calculate a relative deformation of average size sandy soil under loading in the range of 0.000 … 0.179 MPa. The comparative analysis of a relative vertical deformation of the soil from the applied loading for the equations obtained, in turn, has clarified the model of a dispersed non-cohesive soil deformation. For an average size sandy soil, the value of a relative approximation error for results of compression tests calculated by means of the proposed equation has not exceeded 0.145. We propose to use equation \( \varepsilon = k_8 (1 - \exp(-k_9 \sigma))^k_{10} \) as a functional relationship most adequately describing the effect of a compressive stress on a relative soil deformation. Coefficients \( k_8 \ldots k_{10} \) of the proposed relationship are to be calculated according to the results of compression tests of a simulated dispersed non-cohesive soil in a working range of pressures.
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