The use of programs complexes “Ansys” and "Plaxis 3D" in assessing the influence of the density of sand base on the modulus of deformation

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Abstract. The article presents a comparison of the values of the soil deformability characteristics obtained at different densities of the sand base based on the results of laboratory tests and the results of computer modeling, using the software systems "ANSYS" and "Plaxis 3D". It was found that for loose sandy soils, at densities of \(1.48 - 1.53 \text{ g/cm}^3\), close to experimental values of the deformation modulus were obtained using a three-dimensional finite-element model of polylinear isotropic hardening "PLAS (Miso)," in the program "ANSYS." For average density bases at \(\rho = 1.55 - 1.66 \text{ g/cm}^3\) minimum differences between experimental and numerical values were obtained using the «Plaxis 3D» complex.

1. Introduction

The widespread method of compression gives underestimated values of the deformation modulus; therefore, stamping tests are widely used in practice to determine the main characteristics of deformability [1, 5]. In this case, a graph of the dependence of settlement on pressure is used, on which a linear section is selected and the deformation modulus is calculated using the Schleicher formula. The secant modulus of deformation is defined as the ratio of pressure to settlement in the selected pressure interval, and the tangential modulus is defined as the ratio of the pressure increment to the slump increment for each pressure interval under the die base. At the same time, the obtained deformation modules reliably characterize the stiffness of only surface layers of soil.

2. Materials and methods

The tests were carried out in a metal tray with rigid side walls measuring 70 cm x 55 cm x 53 cm. Soil - finely dispersed sand, homogeneous. In the experiments, the density of the base was changed (\(\rho = 1.663; 1.620; 1.590; 1.530; 1.487 \text{ g/cm}^3\)). The angle of internal friction for sand in an air-dry state was determined at a density of \(\rho = 1.62 \text{ g/cm}^3\) and amounted to \(39^\circ\). The sand base was formed by layer-by-layer compaction using metal ramming to a given density. The thickness of each layer was 5 cm. During the tests, precipitation \((s)\) was determined in the entire load range by hour-type indicators ICH-10 mounted on the reference frame (figure 1). As a model of the foundation, a rigid metal stamp with a diameter of 120 mm was used. The load on the die was transmitted using a system of levers with a gear ratio of 1:5. Loading stages were taken equal to 0.1 of destructive load. Each stage was held until conditional stabilization of the precipitate (20 min). Loading was carried...
out either until destruction, at which precipitation grew without increasing the load, or until a conditional maximum settlement of the foundation was obtained \( s_{lt} \).

![Figure 1. Laboratory installation.](image)

Numerical simulation of the experiments was performed using the software package "ANSYS" and "Plaxis 3D". The development of displacements was limited in the \( x \) and \( y \) directions, i.e. the displacement could only develop in the vertical direction \( z(x = 0, y = 0) \). Two models were used to model the base:

1) Mohr-Coulomb Model.

The simplest known condition is the strength condition formulated in 1773 by Sh. Coulomb, using the Mohr method which can be presented as:

\[
\frac{(\sigma_1 - \sigma_3)}{(\sigma_1 + \sigma_3 + 2\text{cctg} \varphi)} = \sin \varphi
\]

Using this strength condition, the theory of the ultimate stress state of a loose and cohesive medium base and its application to solving a number of engineering problems has been developed. In the stress invariants \( j_1, j_2, \theta \) the strength condition (1) can be represented as:

\[
f(I_1, J_2, \theta) = -I_1 \sin \varphi + \left(3(1 + \sin \varphi \sin \theta + \sqrt{3}(3 - \sin \varphi \cos \theta) \cos \theta)\right)\sqrt{I_2} - 3c \cos \varphi = 0
\]

\[
f(\xi, \rho, \theta) = -\sqrt{6\xi} \sin \varphi + \left(3(1 + \sin \varphi \sin \theta + \sqrt{3}(3 - \sin \varphi \cos \theta) \cos \theta)\right)\rho - 3\sqrt{2c} \cos \varphi = 0
\]

In the main stress space, the Coulomb-Mohr condition represents an irregular hexagonal pyramid, as shown in figure 2 (a, b).

This condition is widely applied in practice mainly because of its simplicity and acceptable accuracy in solving specific engineering problems [2, 3].
Figure 2. Coulomb-Mohr strength condition: a - in the space of main stresses; b - in the plane of the main stresses [7].

To obtain numerical solutions using a finite element model of the Mohr-Coulomb material, the 10 nodes elements in Plaxis were used in modeling the soil matrix. The modulus of deformation used in the program was calculated using the Schleicher formula based on experimental data, the Poisson's ratio $\nu = 0.3$ the plate model had dimensions $D = 120 \, \text{mm}$, thickness 10 mm, elastic modulus $E = 2.06 \times 10^5 \, \text{MPa}$. The plate was modeled using a linear isotropic model.

2) A three-dimensional finite element model of PLAS (Miso) multilinear isotropic hardening. The Miso material model is used to model linear and nonlinear soil behavior [4]. The nonlinear behavior of the soil is modeled using a multi-line model of isotropic hardening (MISO) material. This model includes the von Mises yield criterion [4]. When estimating the stress-strain state for sand using the PLAS model (Miso) in the ANSYS program, the first point of the stress-strain state curve must be the yield stress. Subsequent points determine the elastic-plastic response of the material.

The equivalent stress equation has the form:

$$\sigma_e = \left[ \frac{3}{2} \{s\}^T [M] \{s\} \right]^{1/2} - \sigma_k = 0 \tag{4}$$

where $\{s\}$ is the deviator stress; $\sigma_e$ – is the current yield stress $\sigma_k$ – is a function that depends on the plasticity of the material. For the case of isotropic hardening, $\sigma_k$ can be determined from the uniaxial strain stress curve [7].

When using PLAS (Miso) according to ANSYS APDL, the finite element (discrete) model consisted of the elements Solid186 (a 20-node hexagonal volumetric element for modeling a soil matrix, which has three degrees of freedom per node - this is the recommended type of elements for 3D models) and Solid187 (the element is defined by 10 nodes having three degrees of freedom at each node and was used to model the stamp). All other source data is the same as in the first model.
3. Results

Tables 1 - 3 and figures 3 - 8 show the experimental values and results obtained by ANSYS APDL, using the viscoplastic PLAS model (Miso) and the Mohr-Coulomb elastic-plastic model for Plaxis 3D.

The values of the modulus of deformation were determined using the Schleicher formula [6].

\[ E = \omega \times D \times (1 - \nu^2) \times \Delta p / \Delta s \quad (5) \]

Where \( \omega \) is the coefficient taken for round plate of 0.8; \( D \) is the diameter of the plate; \( \nu \) is Poisson's coefficient taken 0.3 for sand; \( \Delta p \) – increment of the average pressure on the plate foundation on a plot of the linear relationship between pressure and settlement; \( \Delta s \) – settlement increment of the plate when the pressure changes by \( \Delta p \).

### Table 1. Dependence of sand base modulus of deformation \( E \) on the pressure at a density of 1.487 g/cm\(^3\).

| №  | \( P \) (MPa) | Experimental values | Plaxis 3D | PLAS (Miso) ANSYS |
|----|---------------|---------------------|----------|-------------------|
|    | \( s, mm \)  | \( E, MPa \)         | \( s, mm \) | \( E, MPa \)       |
| 1  | 0.0053        | 0.67                | 0.6960   | 0.225090099       | 2.056989632 | 0.74478 | 0.6261 |
| 2  | 0.0106        | 1.07                | 0.866    | 0.893502196       | 1.03689171  | 1.4393  | 0.6479 |
| 3  | 0.0160        | 1.96                | 0.7137   | 2.0304736         | 0.688391122 | 2.13347 | 0.6557 |
| 4  | 0.0213        | 3.635               | 0.5131   | 3.593894259       | 0.517758138 | 2.82729 | 0.6597 |
| 5  | 0.0266        | 5.67                | 0.4112   | 5.600636916       | 0.41491281  | 3.52076 | 0.6622 |

### Table 2. Dependence of the modulus of deformation on the density of the sand base under ultimate load.

| Density g/cm\(^3\) | 1.663 | 1.620 | 1.590 | 1.530 | 1.487 |
|--------------------|-------|-------|-------|-------|-------|
| \( P, MPa \)       | 0.27  | 0.11  | 0.08  | 0.07  | 0.03  |
| \( E, \) Experimental | 5.4318 | 2.0335 | 0.8665 | 0.5912 | 0.4112 |
| \( E, \) Plaxis 3D  | 4.57  | 2.12  | 0.925 | 0.665 | 0.459 |
| \( E, \) PLAS (Miso) ANSYS | 9.4017 | 3.4138 | 1.5239 | 0.9891 | 0.6622 |

### Table 3. Dependence of the modulus of deformation on the density of the sand base at \( P=0.03 \) MPa.

| Density g/cm\(^3\) | 1.663 | 1.620 | 1.590 | 1.530 | 1.487 |
|--------------------|-------|-------|-------|-------|-------|
| \( P, MPa \)       | 0.03  | 0.03  | 0.03  | 0.03  | 0.03  |
| \( E, \) Experimental | 5.588 | 2.440 | 1.879 | 0.822 | 0.4112 |
| \( E, \) Plaxis 3D  | 7.02  | 2.46  | 1.03  | 0.7   | 0.459 |
| \( E, \) PLAS (Miso) ANSYS | 7.713 | 3.187 | 1.479 | 1.018 | 0.6622 |
Figure 3. $E - P$ Dependence at a density 1.487 g/cm$^3$.

Figure 4. $E - P$ Dependence at a density 1.53 g/cm$^3$.

Figure 5. $E - P$ Dependence at a density 1.59 g/cm$^3$. 
Figure 6. E-P Dependence at a density 1.62 g/cm³.

Figure 7. a) Dependence of the plate settlement on the pressure at a density 1.66 g/cm³.

Figure 7. b) Dependence of the plate settlement on the pressure at a density 1.62 g/cm³.
Figure 8. a) Dependence of the plate settlement on the pressure at a density of: density 1.59 g/cm³.

Figure 8. b) Dependence of the plate settlement on the pressure at a density of: density 1.53 g/cm³.

Figure 8. c) Dependence of the plate settlement on the pressure at a density of: density 1.487 g/cm³.
4. Conclusions

At density values $1.48 - 1.53 \, g/cm^3$, the minimum discrepancies between the experimental and numerical values were obtained using the model of multilinear isotropic hardening "PLAS (Miso)", in the program "ANSYS".

For sands of average density at $1.55 - 1.62 \, g/cm^3$ the minimum discrepancies between the experimental and numerical values were obtained using the Plaxis 3D complex.

A change in density from $1.53 \, g/cm^3$ to $1.62 \, g/cm^3$ according to the results of experiments led to an increase in the breaking load by 1.57 times, and a change in density from $1.62 \, g/cm^3$ to $1.66 \, g/cm^3$ by 2.42 times.

The values of the deformation modulus when changing the density from $1.48 \, g/cm^3$ to $1.66 \, g/cm^3$ according to stamp tests and according to the results of modeling using the "Plaxis 3D" software complex increased almost 10 times.

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