Experimental study of the influence of sand base reinforcement on the development of deformations under static and cyclic loading

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Abstract. The results of plate tests conducted in the laboratory of "soil Mechanics" of TSTU are presented. The cases of application of static and cyclic loads on reinforced and unreinforced sand base are considered. In these tests, the density of the sand base, the depth of the reinforcement element, and the initial load stage from which cycling was performed were changed. Three series of experiments were performed in a tank with rigid side walls. As the base, a fine, low-moisture, homogeneous sand was used. In the first series of experiments a stepwise increasing load was transferred to the plate at different densities. In the second series, a cyclic load was transferred to the base, with a value equal to half of the previously found ultimate load. In the third series of experiments, a reinforcing element was placed in the base at various distances from the sole of the foundation model and the load was applied both stepwise increasing static and cyclic. It is shown that the settlement during introduction of cyclic loading is from 20 to 50% of the total value. Reinforcement of the base allows you to reduce the settlement of cycling load. At the same time, there is a significant increase in the bearing capacity of the foundation and a decrease in the values of total deformations.

1. Introduction

At the stage of construction and operation of buildings and structures bases and foundations, these are first subjected to gradual loading, and then, if the technological process uses equipment that repeatedly experiences variable or alternating loads, then cyclic loads are transmitted to the base. The characteristics of cyclic loading - the maximum and minimum values of loads, the coefficient of cycle asymmetry, depend on the production technology and the intensity of equipment used and have a noticeable effect on the strength and deformability of foundation bases.

As experience shows, the loss of bearing capacity and strength of the soil base under the action of cyclic loads occurs due to the accumulation of shifts of individual volumes of soil under the action of normal and tangential stresses [1]. In order to redistribute the stresses to an additional volume of soil, increase the stiffness of the base, and in some cases change the natural frequency of vibrations, soil reinforcement can be used [2-9]. The laboratory of “soil Mechanics” of TSTU has been testing reinforced bases for more than 25 years. Various methods of force action on the base, various schemes and materials of reinforcement were considered, and both cohesive and non-cohesive bases were used [10-12].

In this article presented the results of laboratory experiments to assess the effect of reinforcement on the rate of development of deformations, the bearing capacity of the base at different densities and load introduction rates, were also presented.
The tests were carried out in a metal tank with rigid side walls measuring 70 cm x 55 cm x 53 cm ‘Figure 1’. The soil is fine, uniform sand. The internal friction angle for sand was determined at a density of 1.62 $g/cm^2$ and was $39^\circ$. The sand base was formed by layer-by-layer compaction using a metal rammer until required density is achieved. The thickness of each layer was 5 cm, at the desired depth the necessary reinforcing metal grid was placed. During the tests, the settlement ($S$) was determined over the entire load range by the ICH-10 hour-type indicators mounted on a reference frame. A rigid metal plate with a diameter of 120 mm was used as the foundation model. The load on the plate was applied using a lever system with a gear ratio of 1:10. The loading stages were assumed to be equal to 0.1 of the ultimate load found previously for the unreinforced sand. Each stage was maintained until conditional stabilization of the settlement (20 min) is obtained. The loading was applied either before failure, when settlement increased without increasing the load, or until the conditional maximum settlement of the foundation [5] is occurred.

In the first series were performed experiments on unreinforced sand at different densities (1.66; 1.62; 1.59; 1.53; 1.49) $g/cm^3$. The experimental results are presented as a settlement-pressure relation in ‘Figure 2’. The change in density from 1.53 to 1.62 $g/cm^3$ resulted in an increase in the ultimate load by 1.57 times, and the change in density from 1.62 to 1.66 $g/cm^3$ by 2.42 times. The settlement values obtained by experiments at a pressure of $P = 0.02 \text{MPa}$ were 0.07/0.69/1.2/2.04/3.6 mm at density values of 1.66/1.62/1.59/1.53/1.49 $g/cm^3$. Maximum settlement values were, respectively 4.29/5.04/8.07/11.04/5.67 mm. Pressure under the sole of foundation corresponding to the ultimate load $-0.27/0.11/0.08/0.07/0.03 \text{MPa}$.

Using Schleicher’s formula, the values of the modulus of deformation at each load stage were determined.

$$E = \omega * D * (1 - \nu^2) * \frac{\Delta P}{\Delta S}, \quad (1)$$

where $\omega$ – is the coefficient taken for round foundation which equals 0.8; $D$ - is the diameter of the foundation; $\nu$ – Poisson ratio for sand, taken 0.3; $\Delta$ - the increment of the average pressure on the base of the foundation on the site of the linear relationship between the pressure and the settlement; $\Delta S$ - the increment of the settlement of the foundation by changing pressure at $\Delta P$.

![Figure 1](image1.png)

**Figure 1.** The scheme of experimental set (a), reinforcement diagram (b): 1-metal tank 2-foundation; 3-indicators; 4-lever; 5-counterweight; 6-weights; 7-reinforcing element; 8-knife; 9-reference frame.

The results of experiments performed are as shown in ‘Figure 3’. The maximum increase in the value of the modulus of deformation was observed when the density increased from 1.59 to 1.66 $g/cm^3$.
Figure 2. Dependence of the foundation settlement on the pressure at a density of: a – $\rho = 1.66 \text{ g/cm}^3$, b – $\rho = 1.62 \text{ g/cm}^3$, c – $\rho = 1.59 \text{ g/cm}^3$, d – $\rho = 1.53 \text{ g/cm}^3$, e – $\rho = 1.49 \text{ g/cm}^3$.

Figure 3. Dependence of the modulus of deformation on density.

In the second series of tests ‘Figure 4.5’, cyclic loads were applied to the base at a density of 1.62 $\text{g/cm}^3$ and 1.53 $\text{g/cm}^3$. The value of the cycling load remained constant and was 0.5 of the previously found ultimate load (the pressure corresponding to the cyclic load $p = 0.06 \text{MPa}$). The
load stage from which the application of the cyclic load \( F \) started at a density of 1.62 \( \text{g/cm}^3 \) was \( F = 0.2 \) of the ultimate load \( F_u \) (cycle asymmetry coefficient \( \mu = \frac{F_{\text{max}}}{F} = 6.5 \)); \( F = 0.4 \) \( F_u \) \( (\mu = 3.74) \); \( F = 0.6 \) \( F_u \) \( (\mu = 2.78) \).

Each cycle consisted of a process of five times loading and unloading of the soil with a short-term static load. The loading-unloading cycle was carried out for 10 seconds, then, after stabilization of deformations, the subsequent step loading was carried out until failure. During the cyclic loading period, at a sand density of 1.62 \( \text{g/cm}^3 \), the settlement increased depending on the initial cycling load of \( F = 0.2 \) \( F_u \) \( 0.4 \) \( F_u \) by 1.3 mm (maximum final value, at the failure - 6.4 mm); at \( F = 0.6 \) \( F_u \) by 2.9 mm (maximum final value at failure - 7.95 mm).

![Figure 4](image)

**Figure 4.** Dependence of settlement on pressure at a density of \( \rho = 1.62 \ \text{g/cm}^3 \) and the initial load stage at which the cycle started: a – 0.2 \( F_u \); b – 0.4 \( F_u \); c – 0.6 \( F_u \).

The load stage from which cyclic loading started \( F \) at a density of 1.53 \( \text{g/cm}^3 \) was \( F = 0.3 \) of the ultimate load \( F_u \) (cycle asymmetry coefficient \( \mu = \frac{F_{\text{max}}}{F} = 4.49 \)); \( F = 0.6 \) \( F_u \) \( (\mu = 2.24) \); \( F = 0.7 \) \( F_u \) \( (\mu = 1.79) \).

During the cyclic loading period, at a sand density of 1.53 \( \text{g/cm}^3 \), the settlement increased depending on the initial load at which cyclic loading began: at \( F = 0.3 \) \( F_u \) by 2.1 mm (maximum final value, at the end of the experiment -7.16 mm); \( F = 0.6 \) \( F_u \) by 5.85 mm (maximum final value - 10.89 mm); at \( F = 0.7 \) \( F_u \) by 4.62 mm (maximum final value - 9.67 mm).

It can be seen from the results, that the settlement by introduction of cyclic loading forms 20 to 50% of the total value. The lower the density, the higher the settlement in case of applying cyclic loading.
In the third series of experiments ‘Figure 6-8’, cyclic loads were applied to the base at a density of $1.62 \text{ g/cm}^3$, the load stage from which cyclic loading began ($F$), was 0.2; 0.4; 0.6 of the ultimate load ($F_u$). Preparing the base sand under the foundation and at a depth of $0.2D; 0.3D; 0.4D$ ($D$- plate diameter), a reinforcing element was placed in the form of a metal grid measuring 145 by 125 mm in the from a reinforcing grids with a diameter of 4 mm and a spacing of 35 mm.

During the cyclic loading period, and at the relative depth of the reinforcing element $h_z = 0.2D$, the settlement increased depending on the initial cycling load $F = 0.2F_u$ by 2.87 mm (maximum final value, at the end of the experiment 7.92 mm); at $F = 0.4F_u$ by 4.34 mm (maximum final value - 9.39 mm); at $F = 0.6F_u$ by 4.9 mm (maximum final value - 9.96 mm).

During the cyclic loading period, at the relative depth of the reinforcing element $h_z = 0.3D$, the settlement increased depending on the initial load of cycling $F = 0.2F_u$ by 6.15 mm (maximum final value, at the end of the experiment 11.2 mm); at $F = 0.4F_u$ by 7.24 mm (maximum final value – 12.29 mm); at $F = 0.6F_u$ by 6.25 mm (maximum final value – 11.3 mm).

During the cyclic loading period, at the relative depth of the reinforcing element $h_z = 0.4D$, the settlement increased depending on the initial load of cycling $F = 0.2F_u$ by 7.8 mm (maximum final value, at the end of the experiment 12.92 mm); at $F = 0.4F_u$ by 6.85 mm (maximum final value – 11.9 mm).

Figure 5. Dependence of settlement on pressure at a density of $\rho = 1.53 \text{ g/cm}^2$ and the initial load stage at which the cyclic loading began: a $- 0.3F_u$; b $- 0.6F_u$; c $- 0.7F_u$. 
Figure 6. Dependence of the foundation settlement on the pressure at the initial load stage 0.2 \( F_u \) from which the cycle started, when the reinforcing element is located at a depth of: a \(-\ h = 0.2D\); b \(- h = 0.3D\); c \(- h = 0.4D\).

Figure 7. Dependence of the foundation settlement on the pressure at the initial load stage 0.4 \( F_u \) from which the cycle started, when the reinforcing element is located at a depth of: a \(- h = 0.2D\); b \(- h = 0.3D\); c \(- h = 0.4D\).
Figure 8. Dependence of the foundation settlement on the pressure at the initial load stage $0.6 \bar{P}$, from which the cycle began, when the reinforcing element is placed at a depth of: a $- h_x = 0.2D$; b $h_x = 0.3D$.

At the same time, it can be noted that by reinforcing sand, there is a significant increase in the bearing capacity of the base - from 2.5 to 4 times (when the reinforcement is placed at a depth of $0.2D$, 2.5-4 times; when located at a depth of $0.3D$ – by 3.5-4 times and when located at a depth of $0.4D$, 3.7-3.8 times). The dependence of the coefficient of increasing the bearing capacity of the base on the depth of the grid of the reinforcing element is shown in ‘Figure 9’.

Figure 9. Dependence of the coefficient of increase in the load-bearing capacity ($BCR$) of the base on the depth of the location ($h_x$) of the reinforcing element.

2. Summary

The results showed that the settlement during the cycling loading is from 20 to 50% of the total value. The lower the density, the higher the settlement by applying cyclic loading. The introduction of a reinforcing element in the zone of maximum tangential stresses (at a depth of $h_x = 0.2D$) reduces the cycling settlement.

When reinforcing the soil, there is a significant increase in the bearing capacity of the foundation, the range of increase in the maximum ultimate load is from 2.5 to 4 times, at the same time, there is a decrease in the values of total deformations.

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