Laboratory experimental research of loading friction forces acting on the lateral surface of tapered piles in structurally unstable soils

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Abstract. In modern urban conditions, needs arise for the development of sites, which are geotechnically complex and disadvantageous for construction. The peculiarities of such sites, among other things, include the presence of structurally unstable soils that exhibit subsidence deformations when wet or under dynamic and vibration loads due to a decrease in the strength of structural bonds. In this regard, the development and implementation of rational design solutions are of current interest when designing and constructing foundations in the presence of structurally unstable soils. One such solution is the use of bored piles. When designing piles for structurally unstable soils, the action of loading friction forces should be taken into account; these forces can arise if the subsidence rate of the soil mass around the pile exceeds the subsidence rate of the pile itself. The study of the interaction of a structurally unstable soil mass with piles and the corresponding theoretical justification are necessary to clarify the methods for evaluating loading friction forces. In an experimental study, the effect of reduction of loading friction forces depending on the taper rate of the pile was discovered, and the results of laboratory measurements of loading forces were analyzed using various schemes for modeling subsidence deformations.

1. Introduction

Widely used in the practice of construction, pile foundations are effective in cutting through strata of weak, highly compressive, structurally unstable, non-uniform in terms of mechanical properties, non-compacted fill-up soils. However, cut-through strata of such soils are not only excluded from participation in ensuring the load-bearing capacity of piles in the soil, but in many cases, due to the development of deformations in them, they have a loading effect, thereby reducing the calculated load on the piles.

A feature of structurally unstable soils is the development of subsidence deformations when wet or under dynamic and vibration loads due to a decrease in the strength of structural bonds.

Existing regulatory approaches to taking into account the loading friction forces on the lateral surface of piles are based on assumptions that do not take into account the peculiarities of the formation of a stress-strain state in a dispersed soil medium.

In modern urban conditions, needs arise for the development of sites, which are geotechnically complex and unsuitable for construction. Therefore, finding feasible and cost-effective solutions for the design of foundations is an urgent issue. In accordance with the requirements of current state
regulatory documents [1], when designing piles for structurally unstable soils, the action of loading friction forces should be taken into account, which arise if the subsidence rate of the soil mass around the pile exceeds the subsidence rate of the pile itself. The study of the interaction of a structurally unstable soil mass with piles and the corresponding theoretical justification are necessary to clarify the methods for evaluating loading friction forces.

In an experimental study, the effect of reduction of loading friction forces depending on the taper rate of the pile was discovered, and the results of laboratory measurements of loading forces were analyzed using various schemes for modeling subsidence deformations.

2. Analysis of recent studies and publications

The issues of the development of negative friction forces in pile foundations were studied by domestic and foreign scientists: Dalmatov B.I., Lapshin F.K., Rossikhin Yu.V., Grigorian A.A., Zaretskii Yu.K., Morozov V.N., Broma Beng B., Fellenius B.H., Crawford C.B., Endo M., Bjerrum L., Johannessen I.J., Kerisel J., Lee C.J., Bolton M.D. et al. [2–8].

Among recent publications on the study of tapered piles, the works of Vertynskii O.S. and Yeshchenko O.Yu. should be noted [9–11]. For example, Vertynskii O.S. proposed a design of a cast-in-place tapered pile, the installation of which envisaged thrust of two half-pipes with subsequent filling of the space with concrete. The main goal was to increase the bearing capacity of the pile due to its tapered shape and the prestressed state of the soil mass. However, the work did not address the influence of loading friction forces on the pile.

In their papers, foreign scientists, in particular, Kyu-Ho Paik et al. [12], have studied the behavior of tapered piles in sandy soils compared to that of cylindrical piles, but they did not address the interaction of piles with structurally unstable soils and did not take into account loading friction forces.

The issues of choosing rational forms of piles and researching the peculiarities of their interaction with the soil base, methods of determining the bearing capacity and deformations in relation to driven piles were pursued by Holubkov V.N., Dohadailo A.I., Tuhaienko Yu.F. et al.

In contrast to the mentioned studies, this paper focuses on bored piles, the installation of which is not associated with compaction of the soil mass around the pile.

3. Purpose and objective of the study

In the course of laboratory experimental research, to determine the qualitative and quantitative effect of reducing the influence of loading friction forces on the lateral surface of piles in structurally unstable soils depending on the taper rate of the pile.

4. Main part of the study

In order to determine the effect of the pile taper rate on the value of loading friction forces in the laboratory experiment, one of the key tasks was to model the specific characteristics of the soil forming the mass surrounding the pile without loading the pile until modeling the development of subsidence deformations. The development of subsidence deformations in the soil mass surrounding the pile was implemented in three different variants.

The first variant was based on the method for determining the maximum loading friction forces of soil on pile models proposed by O. Samorodov [13]. According to this method, the subsidence of the soil mass surrounding the pile was carried out by reducing the air pressure in the pneumatic rubber chamber located at the bottom of the tray. The loading force $P_n$ that occurs on the lateral surface of the pile due to soil friction was measured using a dynamometer (Figure 1).

The obtained results [14] show that with a slight (up to 25%) decrease in the lateral surface area of the tapered model pile compared to the cylindrical shape of the shaft, the value of the loading friction forces ($P_n$) decreases by 59%, which indicates the advisability of using tapered bored piles in structurally unstable soils. (Table 1, Figure 2).
Figure 1. Scheme of the first experimental setup for determining the loading friction forces of soil on the lateral surface of piles with different taper rate of the shaft: a) – cylindrical pile; b) – tapered pile; 1 – wooden model pile, 2 – tray, 3 – sand (fine, dry, homogenous $\gamma \approx 15$ kN/m$^3$, $\varphi = 30^\circ$), 4 – dynamometer, 5 – pneumatic rubber chamber, 6 – partition.

Figure 2. Diagram shows that with a slight (up to 25%) decrease in the lateral surface area of the tapered model pile compared to the cylindrical shape of the shaft, the value of the loading friction forces ($P_n$) decreases by 59%.

Table 1. Results of the first laboratory research

| No. | $H$, m | $H_1$, m | $H_2$, m | $D$, m | $d$, m | $\alpha$, degrees | $S$, m$^2$ | $P_n \times 10^2$ kN |
|-----|--------|----------|----------|--------|--------|-------------------|-----------|-------------------|
| a)  | 1.0    | -        | -        | 0.06   | 0.06   | 0                 | 0.16      | 18.3              |
| b)  | 1.0    | 0.85     | 0.15     | 0.06   | 0.03   | 1.011             | 0.12      | 7.5               |

The second variant of modeling the specific characteristics of soil and determining the reduced effect of loading friction forces with changed taper rate of the pile was based on the method of applying vertical loads to the soil mass surrounding the pile without loading the pile itself (Figure 3-5).

Preparation for the experiment and its implementation included several stages:

– the model pile was installed in the design vertical position by free hanging, whereby the lower end of the pile was passed through the entire structure of the tray through special holes in the bottom, with the pile resting on the dynamometer;

– as a model soil, a mixture of sand and polystyrene foam balls in a ratio of 3:1 was selected;

– the mixture was filled up to the entire height of the tray, and the pile was freed from the installation fastening;

– an 8 mm thick metal sheet was laid on the surface of the mass around the pile;

– step load was applied to the mass around the pile;

– using a dynamometer, additional forces were recorded that arose due to the loading friction forces of soil $P_n$ acting on the lateral surface of the pile.
Figure 3. Scheme of experimental setup: 1 – metal support frame, 2 – jack, 3 – ring die for loading the surface of the soil mass, 4 – soil mixture (sand or sand and polystyrene foam balls), 5 – pile: a) cylindrical pile, b) tapered pile, 6 – metal tray, 7 – dynamometer, 8 – tray base.

Figure 4. Laboratory setup.

Figure 5. Dynamometer.
Thus, the subsidence of the soil mass relative to the pile was experimentally modeled, and the value of loading friction forces was measured. Figure 6 presents a comparison of the data obtained for piles interacting with the fill-up mixture of sand with polystyrene foam balls.

The third modeling variant was distinguished by the absence of additives to the sand filler, while the subsidence deformations were modeled based on the loose state of the sand filler. Figure 7 presents a comparison of the obtained data.

**Figure 6.** Comparison of the data obtained for piles interacting with the fill-up mixture of sand with polystyrene foam balls (● – cylindrical pile; ▲ – tapered pile).

**Figure 7.** Comparison of the data obtained for piles interacting with the sand filler (● – cylindrical pile; ▲ – tapered pile).

5. Conclusions

**Figure 8.** Diagram shows that with a slight (up to 25%) decrease in the lateral surface area of the tapered model pile compared to the cylindrical shape of the shaft, the value of the loading friction forces ($P_n$) decreases by 46%.

**Figure 9.** Diagram shows that with a slight (up to 25%) decrease in the lateral surface area of the tapered model pile compared to the cylindrical shape of the shaft, the value of the loading friction forces ($P_n$) decreases by 37%.
The results of the experimental laboratory study showed that with a slight decrease (by 25%) in the lateral surface area of a tapered model pile compared with the cylindrical shape of the shaft, the value of loading friction forces $P_n$ decreased by 59%, 46% and 37%, respectively, in accordance with the selected methods of modeling subsidence deformations (Figures 2, 8, 9). It is advisable to use the studied effect of the pile taper rate on the value of loading forces when cutting through a significant mass of structurally unstable soil.

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