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RESULTS OF EXPERIMENTAL STUDIES OF PILES ON HORIZONTAL LOADS *

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Statement of the problem. The results of laboratory tests of a horizontally loaded pile reinforced with a steel grid located in the ground and a free-standing pile without a grid are considered and compared.
Results. A comparative assessment of the load-bearing capacity of the pile for a horizontal load is made during a laboratory experiment. To compare the results of various tests in the laboratory, expe-riments were performed in a tray with sand at the same diameter and length of the pile. The experiments were carried out on models at the center for collective use named after Prof. Yu. M. Borisov (Voronezh).
Conclusions. The data of laboratory experiments have shown that the use of piles reinforced with steel mesh can significantly increase the load-bearing capacity of pile foundations and reduce horizontal movements compared to free-standing piles at the same load.

Keywords: pile, horizontal displacement, pile foundation, steel mesh, load-bearing capacity, horizontal load.

Introduction. Considerable horizontal loads are experienced by the foundations of bridge piers, windmills, telecommunications towers, viaducts, aqueducts and other structures. The sources of large horizontal loads are winds, earthquakes, sea waves, floods and tsunamis, etc. Considerable horizontal loads are experienced by the structures of railway and road bridges affected by the processes of braking and starting the movement of trains and road transport. Therefore the assessment of displacements and the load-bearing capacity of piles for horizontal loads is currently of prime importance.

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In the studies by a number of researchers [1, 3—10, 13—16, 19], a universal method for calculating pile foundations for the combined action of horizontal loads in a multilayer foundation is shown.

The researchers set forth models for calculating the horizontal load of a single-pile foundation in the form of a pyramidal-prismatic combined pile as well as a calculation scheme for a pyramidal pile for a horizontal load in a multilayer Winkler foundation. It is particularly noted that studies of the so-called new non-standard pile designs, mostly single piles used as a foundation for columns, are currently of importance [2, 5]. The fact that the greatest effect is achieved while employing driven pyramidal piles is emphasized, data of statistical studies of a driven pyramidal pile on a horizontal load are shown [1, 7]. In spite of a great deal of experimental data obtained by various authors and the variety of existing methods for calculating pile foundations for horizontal loads, the effect of horizontal loads on the overall stability of construction objects under construction is yet to remain an urgent problem due to researchers being divided on the issue as well as flawed calculation methods [3, 8, 11, 12, 17, 18, 20—23].

The operating conditions of structures might cause an increase in horizontal movements, loss of the load-bearing capacity of the foundation under the action of horizontal loads on pile foundations, there is thus a need to strengthen such foundations.

The authors set a goal to improve the efficiency of horizontally loaded piles by increasing the rigidity of the "foundation — base". To this end, it is suggested that the soil around the pile with a steel mesh located at a certain depth from the soil surface is reinforced. The horizontal load from the pile is transferred to the mesh by means of a hoop around the pile and welded to the mesh. The positive effect of the solution is a considerable reduction in the horizontal and angular displacements of the pile and a significant increase in its load-bearing capacity.

1. Preparing the experiment. The experiments were conducted at the Center for Collective Use Named after Prof. Yu. M. Borisov (Central Collective Use Center of the VSTU), Voronezh. First, a single pile without a grid was tested three times for investigaring the resistance to horizontal loading under the same loading conditions. The experiments were then conducted with a pile reinforced with a steel mesh located in the ground at different depths. The depth at which the steel mesh was placed was changed 3 times: initially it was 5 cm, in the subsequent test it became 10 cm, and in the final experiment it was 15 cm.

The tests were performed in a large flume of the Central Collective Use Center of the VSTU with overall dimensions of 2.4 × 2.4 × 3.0 m. The horizontal load was transferred to the pile by means of a DG-50 jack complete with an NRG-7035 pumping station and an exemplary pressure gauge. The jack was fixed with a perpendicular stop to the wall, the load on the head of the tested pile was transmitted through a wooden rod. The horizontal load on the pile was measured by the dynamometer of the N.G. Tokar DOS-0.5 system ocated between the jack and the wooden rod through the course of the experiment.

In order to measure the vertical and angular displacements of the pile using Maksimov deflectometers, a 100 cm long pin was attached to its head. The horizontal displacements of the pile were measured with a dial indicator with a division value of 0.01 mm. Prior to loading the pile, zero readings were set on the deflection meters and the dial indicator. At each stage of pile loading, data were recorded from all devices. The deflection meters and the dial indicator were fixed on horizontal beams on a fixed basis. The scheme of the experimental setup as an assembly is shown in Fig. 1.

The experiments were performed in a tray with the following characteristics of sand: modulus of deformation E = 20330 kPa, specific gravity γ = 17 kN/m^3, internal friction angle φ = 36°, specific cohesion C = 14 kPa, Poisson's ratio υ = 0.3, moisture content W = 3.3 %. To perform the test, soil with a volume of 50 × 50 × 75 cm was taken out of the tray. The soil area and the pile model are shown in Fig. 2.

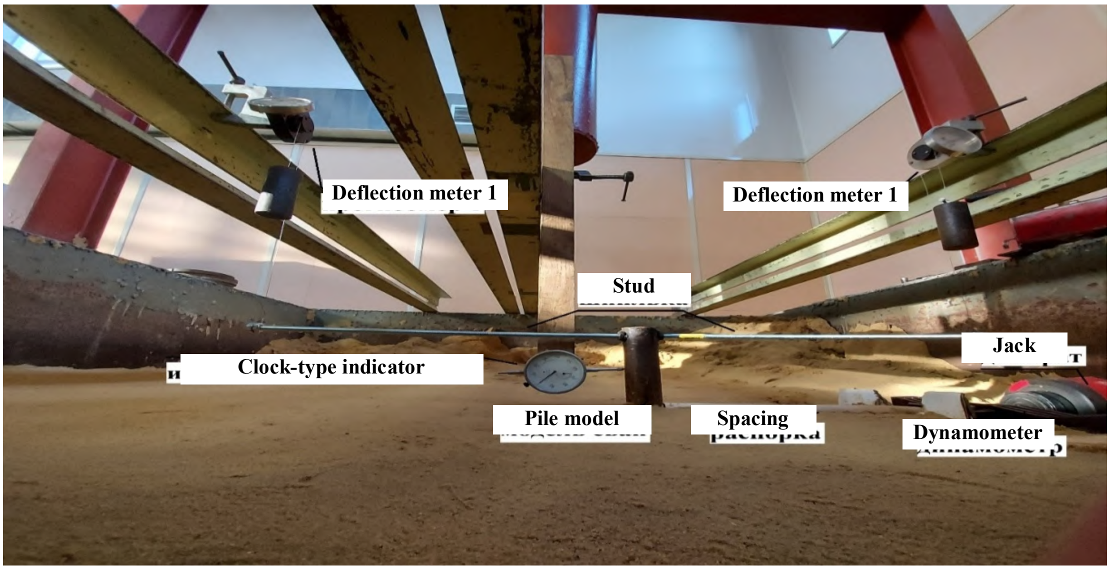

Fig. 1. Scheme of the assembled experimental setup

For the tests a cylindrical model of the pile was produced with sandpaper glued on the side surface simulating the roughness of concrete in full-scale piles. The pile model was produced of a steel pipe with the diameter of 5 cm and the length of 75.6 cm reinforced with a steel welded wire mesh with the cross section of 1.6 mm and the rod spacing of 20 mm. The mesh size is

26 × 26 cm, the pipe wall thickness is 2.8 mm. At the same time, the bending stiffness of the pile corresponds to $EI = 23.19$ kNm^2. The depth of the pile in the ground was assumed to be 60 cm.

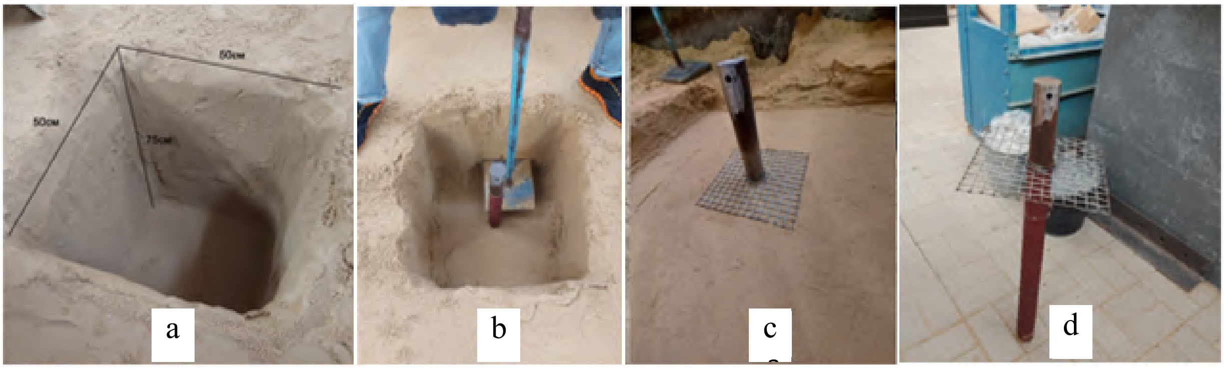

Fig. 2. Image of the soil area and pile model:
a) the area of the soil mass under the pile foundations; b) layer-by-layer compaction of the base around the pile;
c) setting up a mesh in the base of the pile; d) general view of pile with a mesh

The stages of preparation of the foundation for the pile included that of the pile in the ground and the location of the grid, a certain procedure for compacting the soil around the pile. The tamping process was the same in all the soil layers: the soil was laid in the layers of 15 cm followed by tamping and control of density and moisture in each layer.

2. Method of testing the piles. The tested pile was loaded with a stepped load. At each loading stage, horizontal displacements were maintained until conditional stabilization was reached — 0.01 mm for 6 minutes of observation. Through the course of testing the pile, the load increased in stages by 0.2 kN until there was a critical increase in the deformations of the upper part of the pile. As a criterion for the loss of the load-bearing capacity of the pile, a “violation” of the displacement schedule was taken, i.e., a sharp increase in displacements in the absence of that in a load.

3. Results of the pile testing for a horizontal load. Through the course of the experiment, there were cracks in the base approximately in the middle of loading; at the end of loading, an area of soil uplift was formed in front of the pile. The length of the uplift area in front of the pile was 30 cm, which approximately equals 6 pile diameters. The rise of the soil in the uplift zone was approximately 6 mm. Behind the pile, a gap was formed with the width of approximately 2 cm, which corresponds to approximately 0.4 of the pile diameter. The dimensions of the uplift area are shown in Fig. 3.

Through the course of a series of the experiments, the results of tray tests were obtained and analyzed. At the first stage, a single pile without a mesh was tested 3 times, and then a pile with a steel mesh was tested three times at different depths.

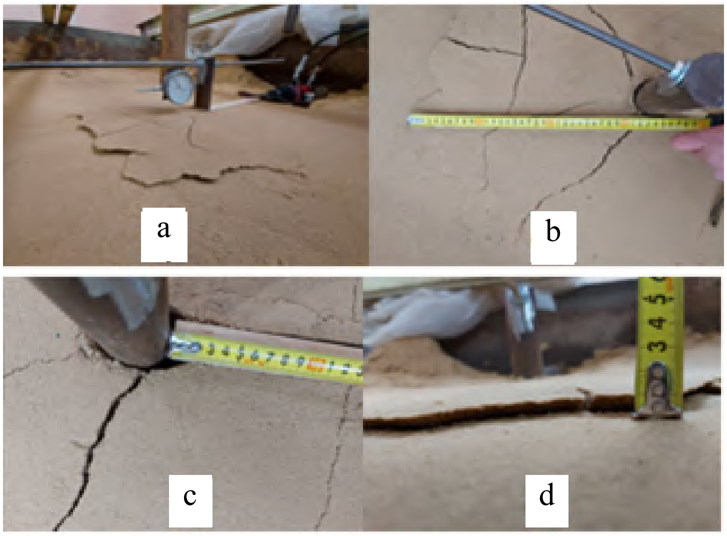

Fig. 3. Dimensions of the uplift area:
a) general view of the bulge area; b) the length of the uplift area in front of the pile;
c) dimensions of the gap behind the pile; d) lifting of soil in the uplift zone

Table shows the maximum values of the quantities measured during the experiments.

Table

Results of horizontal load tests of a single pile and piles with mesh installed at different depths

Parameter	Single pile	Pile with a steel mesh deepened by		
		5 cm	10 cm	15 cm
Maximum horizontal experimental load under which the pile movements *H* were stabilized, кN	2.6	3.4	4	3.6
Horizontal movement of the pile head corresponding to the maximum load on a pile in the experiment *U*, mm	22.8	20.6	22.6	21.8
Vertical movement of the pile head corresponding to the maximum load on a pile in the experiment *S*, mm	–1.65	–3.17	–2.93	–3.42
Pile head angle corresponding to the maximum load on a pile in the experiment Θ, radians	4.35E-02	4.68E-02	5.12E-02	5.06E-02

Fig. 4 shows the test results in the form of pile loading graphs in the "load-displacement" axes. The dependence of the horizontal displacements of the pile on the load is also presented. The black graph shows the constraint for the pile without a mesh, and the 3 colored graphs show the constraint with the mesh present. The best result is obtained when the mesh is de-epened by 10 cm. The meshes deepened by 5 and 15 cm yield the worst results.

Fig. 5 shows the graphs of vertical displacements of the pile head in the ground under a horizontally applied load. Fig. 6 shows the values of the angles of rotation of the pile head under loading.

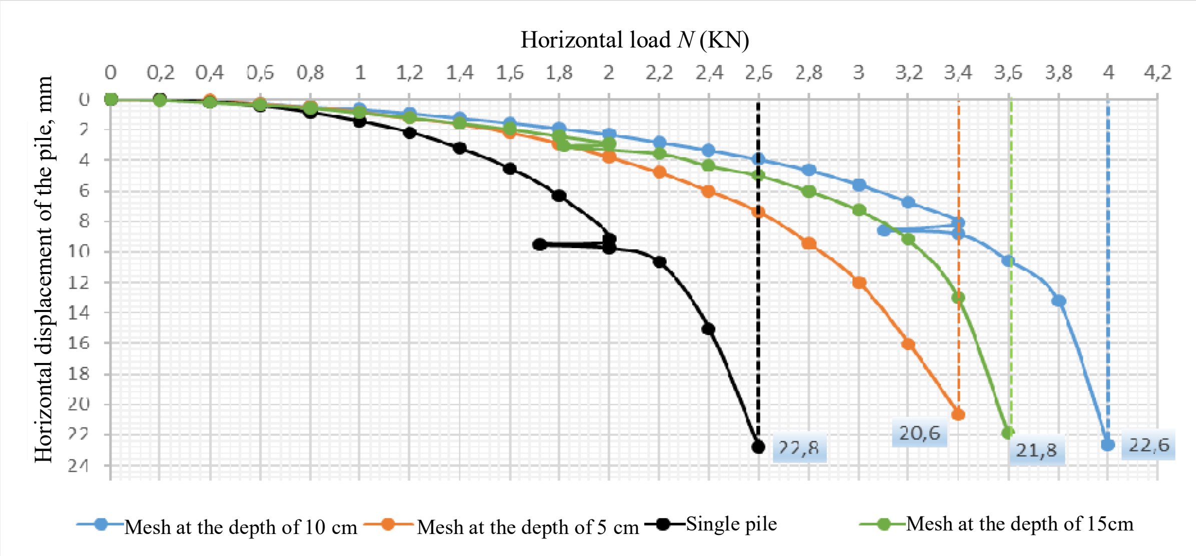

Fig. 4. Dependence of the horizontal displacements of the pile head on the horizontal load

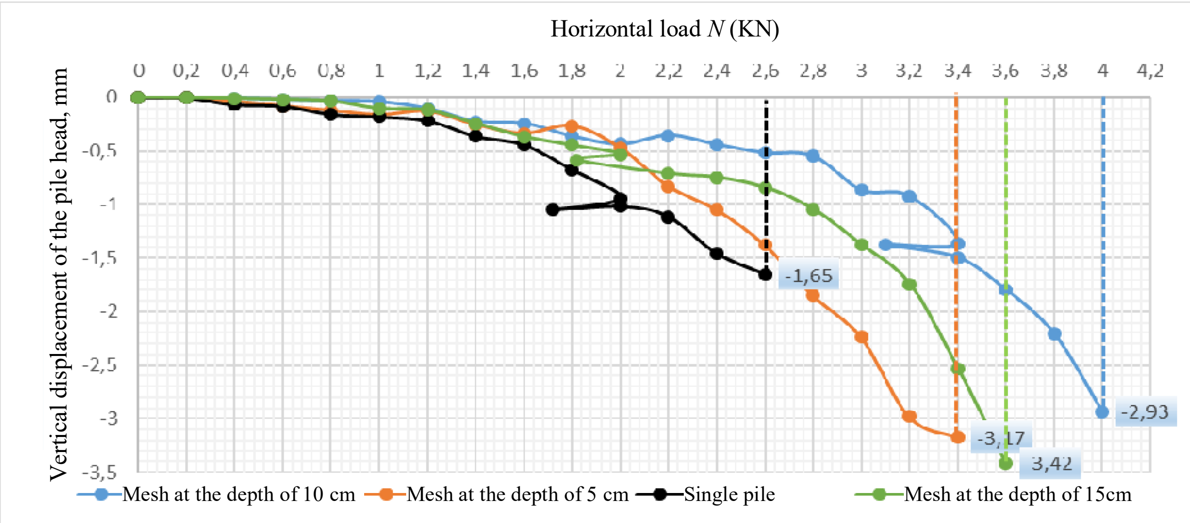

Fig. 5. Dependence of the vertical displacements of the pile head on the horizontal load

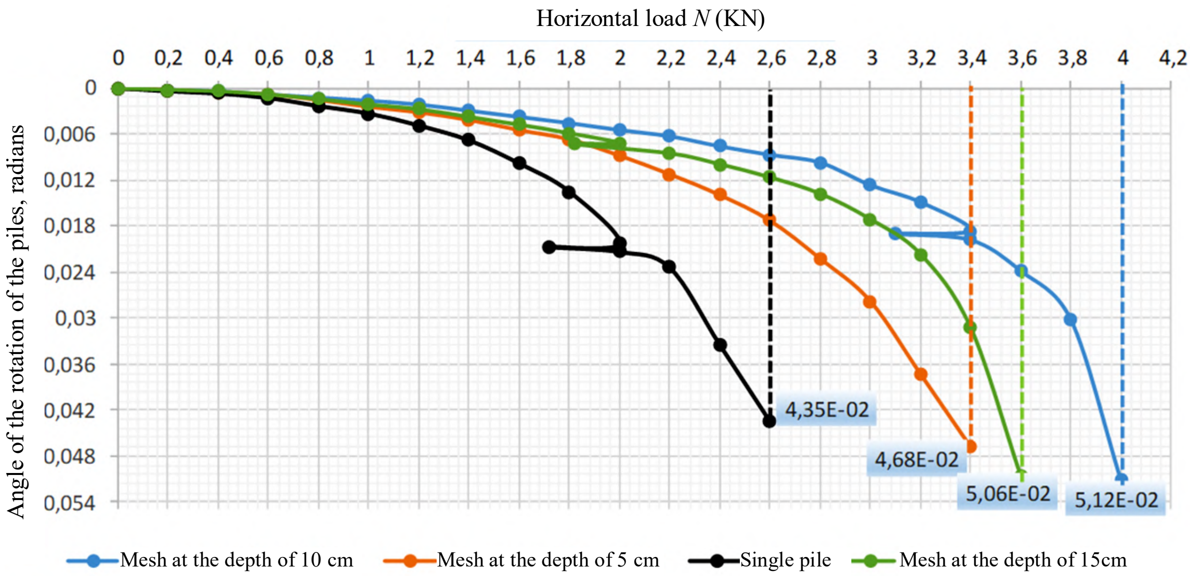

Fig. 6. Dependence of the angle of rotation of the pile head on the horizontal load

Conclusions. The article looks at the major results obtained through the course of the laboratory flume experimental tests of a single pile and a pile with a steel mesh for horizontal loads. According to the test results, it was found that:

1. Under equal loads, the steel mesh installed at the base of the pile enables one to reduce its horizontal displacement U by 1.2 times when the mesh is deepened from the ground $h = d$, by 2.9 times at $h = 2d$ and by 1.3 times at $h = 3d$ where d is the diameter of the pile cross section;

2. The presence of a steel mesh in the ground helps to reduce the angle of rotation of the pile head Θ. Thus with equal loads the angle Θ decreases by 1.8 times at the mesh depth $h = d$, by 2.5 times at $h = 2d$, and by 2.0 times at $h = 3d$;

3. The most optimal depth of the grid according to the results of the experiments was $h = 2d$;

4. In all the experiments with and without a grid, the maximum permissible horizontal displacement of piles $U = 0.05$d corresponds to approximately the same value of the angle of rotation of the pile head $\Theta = 0.006$ radians.

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