Innovative Pile Technologies in Modern Foundation Construction

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Abstract. The article considers innovative pile technologies that can significantly increase the load-bearing capacity of reinforced concrete piles by increasing the friction forces on the side surface of hanging piles. The authors developed designs of modular reinforced concrete piles for the perception of various combinations of external influences, and also studied the influence of the granulometric composition of the soil adjacent to the pile body on its load-bearing capacity. The study included dynamic tests of t-shaped and square piles, theoretical studies of the interaction of t-shaped piles with clay soil by mathematical modeling, and the selection of the composition and distribution of coarse-grained filler around the pile developed by the authors with "pockets" (cavities) during its driving. The developed innovative solutions allow increasing the angle of internal friction of the soil adjacent to the reinforced concrete pile, while increasing the load-bearing capacity.

1. Introduction

In modern foundation construction, active research is being conducted in the direction of increasing the load-bearing capacity of pile foundations in various types of soils. One of the promising directions is to develop ways to increase the friction forces on the side surface of driven hanging piles, which can be achieved by increasing the area of their side surface [1-8] or by increasing the friction forces along it, for example, by changing the granulometric composition of the soil adjacent to the pile [9-15].

The authors consider the development of modular piles with an increased side surface area and the issues of increasing the load-bearing capacity of driven hanging piles by changing the granulometric composition of the soil adjacent to the pile during its driving.

The purpose of this work is to develop and study innovative pile technologies that significantly increase the load-bearing capacity of driven hanging piles.

The following tasks were solved:

– to develop designs of modular reinforced concrete piles with an increased side surface, allowing them to create composite structures for various combinations of external influences on the Foundation;
– to develop structures of precast reinforced concrete driving piles that allow changing the granulometric composition of the soil adjacent to the pile during its driving with the help of a loose filler;
– select the composition of the granular filler to change the granulometric composition of the soil around the pile and its effect on the friction force on the side surface of the pile;
– develop a technological sequence of work using the developed pile structures;
– perform experimental verification in laboratory and field conditions of the effectiveness of the developed methods for increasing the load-bearing capacity of driven piles, developed structures.

2. Influence of the cross-section shape on the load-bearing capacity of the pile

The following cross-sections of piles are considered: triangular, cross-shaped, t-shaped, ring, three-petal and, as a basic option, square. To select a rational cross-section of piles, a program was developed that used the dependencies of modern standards and tabular values of specific friction forces and ground drag [16]. The calculations are carried out for sandy, clay and silty-clay soils.

The dependences of the specific consumption of reinforced concrete piles of various cross-sections (the ratio of the pile volume to 1 ton of load-bearing capacity) on the depth of immersion in the above-mentioned soils are studied. In addition, the ratio of friction forces on the side surface to the resistance of the soil under the tip of piles of various cross-sections was studied. Figure 1 shows the results obtained for piles with a cross-section of 30×30 cm, with different cross-sections in clay soils with $I_l = 0.5$.

![Figure 1](image_url)

**Figure 1.** Dependence of a) the specific flow rate of reinforced concrete piles with a cross section of 30×30 cm on the depth of immersion in clay soils with $I_l = 0.5$ and b) the ratio of friction forces to resistance under the tip of piles in clay soils with $I_l = 0.5$; 1 – t-section; 2 – square section; 3 – triangular section; 4 – three-petal section.

Based on the data presented in Fig. 1, it is established that the maximum material consumption is provided by square-section piles. The specific consumption of reinforced concrete with a developed side surface compared to a square one is 25% lower at a depth of 6 m, and 40% lower at 12 m. Based on the manufacturability of piles in concrete goods factories, the t-section is recognized as the most efficient cross section for the modular piles.

Modular t-section piles with a developed side surface were tested in full-scale conditions in clay soils at construction sites in Belgorod, Russia. Static tests were performed on piles with a depth of 6.0, 8.0 and 18.0 m. The results of testing of t-type and standard piles with a depth of 8.0 and 6.0 m are shown in Fig. 2.
Given that the t-section pile consumes 1.8 times less concrete and steel than a square one, and bearing capacity of it in relation to the square one is only 30% less, the specific bearing capacity of t-section piles is 1.2 times higher than that of the square ones.

In addition, t-shaped and square piles with a depth of 18.0 m were subjected to dynamic tests in difficult engineering and geological conditions. The results of dynamic tests after a six-day rest of these piles are shown in Table 1.

**Table 1.** Results of dynamic testing of piles with a depth of 18.0 m after a six-day rest.

| Number of strokes | t-section 1 | Failure, mm t-section 2 | square |
|-------------------|------------|-------------------------|--------|
| 3                 | 2          | 2                       | 3      |
| 5                 | 3          | 6                       | 4      |
| Σ 3+5             | 5          | 8                       | 7      |

The load-bearing capacity of piles determined by the dynamic method and their volume of reinforced concrete are shown in Table 2.

**Table 2.** Load-bearing capacity of the compared types of piles and their specific load-bearing capacity (per 1 m$^3$ of reinforced concrete).

| Type of pile | Load-bearing capacity, m | Pile volume, m$^3$ | Specific load capacity, t/m$^3$ |
|--------------|--------------------------|-------------------|-------------------------------|
| T-section    | 129.9                    | 0.9               | 143.33                        |
| Square       | 105.9                    | 0.9               | 116.66                        |
|              | 132                      | 1.62              | 81.48                         |

The results obtained, presented in Table 2, showed that the t-section piles are 35% larger in terms of specific load-bearing capacity than typical square-section piles.

To confirm the experimental data, theoretical studies of the interaction of t-piles with clay soil were verified using the method of mathematical modeling, while the clay soil is considered as a solid array [17-20]. To solve this problem, a phenomenological approach is adopted: the components of the stress-strain state, characterized by stress and strain tensors, satisfy the geometric Cauchy equations and the Saint-Venant conditional compatibility. Taking into account that the operation of foundations involves low pressure in the ground and the absence or insignificance of the size of the destruction zones, the Hooke model is used.
To approximate a continuous function with a discrete model, we used the finite element method (FEM). When modeling, the depth of immersion of piles was assumed to be 5.5 m, and the modulus of clay deformation was 17 MPa.

The computational grid for modeling the stress-strain state of a pile in clay is shown in Fig. 3.

![Figure 3. Calculation scheme for modeling the stress-strain state of a pile in clay.](image)

A comparison of the obtained data on the total draft of the t-section pile from the load is shown in Fig. 4.

![Figure 4. Dependence of the total draft of a composite pile of a t-section on the load: 1 – based on the results of field tests, 2 – based on mathematical modeling, 3 – based on calculated data.](image)

The results obtained showed that the dependences of the t-section pile sediment on the load obtained by three methods have a satisfactory convergence in the range of 8...12 %.

Based on the research results, "Technical specifications for modular T-shaped driven piles" were developed, approved and registered, considering the following options for the layout of foundation systems based on modular t-section piles, depending on the nature of the current load (Fig. 5).

![Figure 5. Options for layout of the pile foundation on the basis of modular piles t-section.](image)
3. Influence of the granulometric composition of the soil adjacent to the pile on its bearing capacity

The developed method for increasing the load-bearing capacity of driven hanging piles by changing the granulometric composition of the soil adjacent to the pile during its driving provides for the use of a combined pile with "pockets" (cavities) on the side surface. On the surface of the soil above the pile a tray-funnel is set and filled with coarse-grained filler, which is in driving piles with pockets, fills them and sinks together with the pile. When the hammer hits the pile, the granular filler is forced out of the "pockets" into the nearby soil and mixes with it changing its granulometric composition. The composition of the filler should be selected in such a way that the friction of the mixture of the adjacent soil with the filler significantly increases the load-bearing capacity of the pile [21].

To study the effect of changes in the granulometric composition of the soil around the pile on the friction force, we conducted a series of experiments with dusty air-dry sand with an internal friction angle of $\phi = 33^\circ$ (at $e = 0.6$), and the weighted average particle diameter $D_w = 0.41$ of the natural composition. As coarse-grained additives to sand, crushed stone of four fractions was used: 5.0, 2.5, 1.25 and 0.65 mm. The internal friction angles of the prepared samples from a mixture of pulverized sand and additives to it from crushed stone were determined using a standard single-cut method using a shear device of the PSG-3M Hydroproject design. The content of the additives to the sand varied from 0 to 90 %. The results of studying the effect of coarse-grained additives to sand on its internal friction angle are shown in Fig. 6.

![Figure 6. Results of studying and influence of the granulometric composition of powdery sand ($D_w$) on the angle of internal friction ($\phi$, deg): 1 – the dependence of the internal friction angle of the dropout from large particles; 2 – the effect of 30% additives of various fractions to the dusty sand on the internal friction angle; 3 – the effect of adding a 2.5 mm fraction to the dusty sand from 15% to 90% on the internal friction angle.](image)

The results obtained allowed us to determine the effect of the size of granular additives and their quantity on the angle of internal friction of sand with a natural dusty composition. Bigger size of the fraction of sand additives (Fig. 6, item 2) increases its internal friction angle by 19 %. Increase in the content of coarse-grained additives to sand (Fig. 6, item 3) allows to increase the angle of internal friction to 26 %.

Therefore, when using the method developed by the authors to increase the load-bearing capacity of hammered hanging piles with "pockets" by increasing the thorn on the side surface, it is recommended to use coarse-grained material with a particle size significantly larger than the soil particles in which the pile is immersed as a filler in the funnel-collar.

To confirm this, a series of experiments was conducted in a ground tray with powdery sand with the above characteristics using the method [21]. Models of basic piles (prismatic without pockets) and models of piles with "pockets" with filler in a funnel tray on a surface with a particle size of 1.25 mm were tested.
The results of testing these piles with static load according to the method are shown in Fig. 7.

![Graph of the dependence of the precipitation of pile models on static load](image)

**Figure 7.** Graph of the dependence of the precipitation of pile models on static load a) basic (prismatic) pile models b) pile models with "pockets" and filler.

According to the data obtained, the average load-bearing capacity of three models of basic (prismatic) piles was 358.8 N. The average load-bearing capacity of models of piles with "pockets" and with a filler size of 1.25 mm reached 454.3 N. Thus, the developed method allows increasing the load-bearing capacity of driven piles by 25...27 % compared to prismatic ones.

Immersion of models of piles with "pockets" at the transparent wall of the tray allowed us to establish the distribution of coarse-grained filler (painted black) around the models of the pile, when it is driven into the dusty sand. (Fig. 8).

![Image of coarse-grained filler distribution](image)

**Figure 8.** The nature of the distribution of coarse-grained filler around the pile model with "pockets" when it is driven into the dusty sand in the tray.

Based on the processing of the data obtained (5 models of piles clogged at the transparent wall), it was found that the angle of the contact plane of the filler with the dusty sand surrounding the pile is 9...11°. If we assume that the maximum value of the pile equilibrium when its load-bearing capacity is exhausted will occur along the contact plane "filler-surrounding soil", then its load-bearing capacity should be defined as pyramidal.

4. Conclusion

The conducted research allows us to conclude that the comparison of the specific load-bearing capacity of driven piles of different cross-sections (t/m²), showed that the most rational cross-section option is a t-shaped one. Developed, approved and registered "Technical specifications for modular T-shaped driven piles" allow manufacturing, transporting, and submerging this type of piles for industrial and civil construction. Variants of the layout of foundation systems based on modular piles of t-section depending on the nature of the current load on them are proposed.

It is experimentally established that an increase in the size of additives to powdered sand and an increase in the number of coarse-grained additives can increase the angle of internal friction of sand up
to 26%. The use of hammered hanging piles with "pockets" cavities on the side surface in combination with funnels and coarse-grained filler allows increasing the load-bearing capacity of piles by 25...27% compared to prismatic ones. It is established that in the process of driving piles with "pockets", the distribution of coarse-grained filler around the piles, when they are driven, has a pyramidal shape (with depth, the distribution of filler decreases), therefore, the clogged pile can be considered as a pyramidal one.

5. References
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