Innovative structural and technological developments of pile foundation engineering

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Abstract. The paper considers innovative structural and technological solutions for precast piles, which significantly increase their load-bearing capacity: a transformable pile and a pile with “pockets” (recesses) on the side surface for use in loose soils. In the first case, in the manufacture of precast reinforced concrete piles in the center they set plastic cone-shaped cruciform brake detail with length 0.75 of the pile length, in which after driving the piles destructive non-explosive substance is poured, that increasing in volume in 2-3 times, transforms prismatic pile into a pyramid one. In the second case, when making precast concrete piles, they provide for the arrangement along the side faces of “pockets” (recesses). The liquid hardening compound located in the “pockets” penetrates into the soil of the pile during the driving process and secures it, which significantly increases the lateral friction force of the pile and its load-bearing capacity and reduces the energy of the pile sinking. The considered design and technological solutions allow reducing the energy of pile driving, while increasing their load-bearing capacity.

1. Introduction
Pile technologies in modern foundation engineering are the leading direction for improving their structural and technological solutions. The load-bearing capacity of pile foundations largely depends on the formation of the friction force of the soil on the side surface of the piles. Numerous works of scientists have been devoted to the study of soil friction during the sinking and operation of piles, as well as ways to increase it [1-12].

Currently, special attention is paid to the development and research of innovative structural and technological solutions for driving floating piles, which provide a significant increase in their bearing capacity. The authors conduct research in two areas:
– the transformation of prismatic to pyramidal piles with the use of non-explosive destructive substances;
– development of piles for use in loose soils.

The aim of this work is to develop and study innovative structural and technological solutions for driving floating piles, which provide a significant increase in their load-bearing capacity. To achieve this aim the following tasks were solved:
– development of precast concrete pile structures based on the requirements for them in a specific research area (transformable; for use in loose soils);
choice: expanding substance for transforming piles; fixing compounds for piles used in loose soils;
– development of the technological sequence when applying the developed methods for increasing the load-bearing capacity of piles;
– experimental verification of the effectiveness of the developed methods for increasing the load-bearing capacity of floating piles in laboratory and field conditions.

2. Materials and methods

2.1. Transformable prismatic pile
The transformed pile (Fig. 1) increases its load-bearing capacity by wedging the prismatic (serial) pile into four equal-volume parts and turning it into a pyramid, which has a much greater load-bearing capacity. This is due to the tilt of the four faces of the pile and compaction of the soil around the pile when wedging. In addition, the use of these piles allows achieving energy savings on pile driving, as the prismatic pile is initially driven, and as a result of transformation, it exploits the pyramid pile [13].

![Figure 1. Scheme of a transformable driving pile: 1 – reinforced concrete pile body; 2 – sharpened end of the pile; 3 – plastic tube; 4 – plastic petals that divide the body of the pile into four parts.](image)

However, to obtain a transformable pile in the manufacture of a conventional prismatic reinforced concrete pile, it is necessary to install a plastic cone-shaped cruciform embedded part with a 0.75 length of the pile length, dividing the pile body into four equal parts, in the center of the pile trunk.

Technological sequence of construction of the transformed pile:
– sinking to the design mark of a prismatic reinforced concrete pile with changes in its design made during manufacture;
– submission of a non-explosive destructive substance from above into a plastic cone-shaped cruciform embedded part;
– technological break: during 1.5...2 days, non-explosive destructive substance, increasing in volume by 2...3 times, wedges the body of the pile into four equal parts, thus creating a pyramid pile [14].

A non-explosive destructive substance is a powdery material that solidifies with increasing volume when interacting with water. They prepare a non-explosive destructive substance from crushed quicklime with various additives to improve performance: setting and hardening retarders, lime hydration accelerators, plasticizers and other additives.

2.2. Pile for use in loose soil
The authors solve the problem of increasing the load-bearing capacity of driving piles in loose soils, while the experiments of sinking piles with plaster were performed, given in the works [15-20].
The design of the developed and researched prismatic pile provides for the arrangement along the side faces of “pockets” (recesses) randomness, without affecting the working armature of the pile. The structure of the pile proposed by the authors is shown in Fig. 2.

![Figure 2. Construction of a reinforced concrete pile for use in loose soils.](image)

When studying the load-bearing capacity of piles immersed in a hardening composition, the following assumptions are accepted:
- during operation the pile body and the surrounding soil perceive the load as a single structure;
- the liquid hardening compound located in the “pockets”, during the hammering process, experiences hydrodynamic shocks, as a result of which it penetrates the soil of the pile and fixes it. A silicate-phosphoric formulation using orthophosphoric acid as a hardener and an aluminosilicate formulation using sodium aluminate as a hardener were used as a fixing compound for laboratory studies;
- the depth of penetration of the chemical reagent into the soil depends on the porosity of the soil – \( e \), the number of impacts of the moment – \( n \), that is, in the upper part of the pile, it is much greater than in the lower, and the system “pile – fixed soil” has a slope of the side faces.

**Transformable prismatic pile.**

To determine the effectiveness of the transformed pile, the authors conducted laboratory tests of models of driving piles using a lever mechanism for static immersion of pile models in fine air-dry sand (Fig. 3, a).

![Figure 3. Checking the effectiveness of transformed piles: a) the nature of deformation of the soil adjacent to the pile when it is driven and wedged; b) field tests of wedging four sections of a 1.5 m deep driving pile model using a non explosive destructive substance in fine medium density sand.](image)

Measurements of the resulting deformations of the adjacent soil showed that when driving piles, the adjacent soil sinks together with the pile. In this case, the thickness of the soil layer involved on the surface of the tray reaches 1.0 \( b \) (where \( b \) is the cross-section of the pile), at a depth of 0.5 of the pile length it reaches up to 0.5 \( b \), at the tip of the pile – equal to zero. When wedging models of piles, the
adjacent soil is compacted in the horizontal direction. The thickness of the compacted soil varies within 0.5...1.0 b depending on the angle of inclination of the pile faces and depth. In addition to laboratory tests, field experiments were conducted on models of piles submerged in fine sand of medium density to a depth of 1.5 m. Transformation of models of prismatic piles into pyramidal ones during field tests is shown in Fig. 3, b. The results of studies of prismatic (basic) models and transformable (pyramidal) piles are shown in Fig. 4.

Figure 4. The results of the tests of model piles: a) laboratory data on the dependence of pile upset on load; b) field test data; 1 – for prismatic piles \( (i_2 = 0.00) \); 2, 3, 4 – for piles with the stress of the host soil medium by wedging in the same plane (respectively \( i_3 = 0.02; i_4 = 0.04; i_4 = 0.074 \)).

The results of experimental studies allow concluding that the upset pattern of prismatic pile models and transformed pile models is qualitatively different. Landing a prismatic pile to a certain value is almost directly proportional to the load, after which the pile upset increases sharply, and it loses its bearing capacity.

When the load on the transformed piles increases, there is no sharp increase in upset. This is because, giving the angle of the side faces of the straining piles and the adjacent soil, with subsequent sediment pilings continues to solidify the adjacent soil mass and thus increases the bearing capacity of the pile.

Studies of the efficiency of transformable piles compared to prismatic ones have confirmed an increase in the load-bearing capacity of transformable piles by 40...45 %.

2.2. Piles for use in loose soils
Taking into account the accepted assumptions, models of piles with a size of 20×20×300 mm were tested in a soil tray with fine sand (Fig. 5, a).

Figure 5. Tests of driving piles for use in loose soils: a) the appearance of the installation, devices and models of the pile in a soil tray with fine sand; b) the nature of the distribution of the fixing composition in the depth of models of piles with “pockets” during their driving and after their load testing.
Model of piles with “pockets” with a different location on the lateral surface and the base (without “pockets”) was loaded shock method, as piling with the “pockets” in the collar mounted on the surface of the sand, was added to the fixing composition (volume of structure for each pile – 150 g). When driving the reference (base) models of piles, the number of blows was 80 blows, driving models with “pockets” and in the presence of a fixing liquid composition around the pile, the number of blows was reduced to 30...35. Therefore, the presence of lubricants and greases when driving piles reduces the energy spent on sinking the piles. In our experiments, the energy of driving models using fixing compounds is reduced by more than 50 % compared to the immersion of reference piles.

The holding time of driven pile models before the start of testing is 7...8 days. Static load on the pile model is applied in steps, measuring the amount of their upset. As a result of tests, the bearing capacity of reference (base) piles and piles with “pockets” was established. The results are shown in Fig. 6. The appearance of excavated models of piles with “pockets” is shown in Fig. 5, b.

![Figure 6. Results of laboratory tests of pile models in a ground tray with fine sand (air-dry humidity).](image)

3. Summary
As a result of studies of transformable driving floating piles, the possibility of transforming prismatic driving piles into pyramidal ones with a slope of the side faces using a non-explosive destructive substance was proved. It was found that when driving a model of a prismatic pile, the adjacent thin layer of soil sinks together with the pile, and when the pile is wedged, the soil is compacted horizontally by 0.5 b at a depth of 0.5 of the pile length and 1.0 b at the ground surface, and depends on the angle of inclination of this pile during its transformation. A comparison of the hammering energy of pre-fabricated pyramidal precast concrete piles and prismatic transformable ones suggests that the transformation of piles reduces the energy of their hammering by more than 30 %.

Studies of the developed piles for use in loose soils using chemical fixing compounds allowed establishing that the body of the pile and the fixed soil around it under the influence of load work as a single structure, as when the pile is deposited, the cut plane occurs at the contact “fixed soil – soil”. The thickness of the fixed soil in the upper part of driven piles is considerably greater than in the bottom, while the depth of the pile it gradually decreases, resulting in a prismatic pile is transformed in the pyramid one, where the carrying capacity is much larger than the prismatic. The use of piles with “pockets” on the side surface, through which the chemical composition fixes the loose soil around the pile, allows increasing its load-bearing capacity by 2...3 times. The presence of liquid fixing compounds around the perimeter of the piles reduces the energy of immersion by more than 50% when driving them in comparison with the base piles.
4. References

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