Innovative technologies to increase soil bearing capacity and calculation methods for foundations construction of structures for the production, storage and processing of agricultural products

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Abstract. The article deals with the issues associated with the need to increase the soil bearing capacity during the laying of the pile foundations in agricultural building construction. Technological and design solutions aimed at reduction in consumption of materials and improving the reliability of foundations are offered. The calculation method of the proposed pile foundation structures based on the bearing capacity for cohesive and non-cohesive soils is also analyzed.

1. Introduction

For such light structures as polymer-fenced greenhouses and light structures for intermediate storage of products, the construction of which is carried out in a relatively short period of time, the principle of complete delivery of all structural elements to the installation site must be fulfilled. But at present, especially zero-cycle works are significantly behind in terms of the industrialization and mechanization degree from other stages of construction, which is a limiting factor in the clear organization of construction.

Professional installers in situ have to resort to the services of general contracting organization or their customers for execution of works on laying foundations, which are built, as a rule, on a natural basis with the use of mainly monolithic concrete. Due to difficulties in obtaining cement and other building materials necessary for the construction of foundations, there are delays in the installation and commissioning of food facilities.

Also, the foundations of such types of structures are characterized by high requirements for the accuracy of installation of structures (for isolated supports), which is not feasible when using conventional reinforced concrete structures.

To reduce the material consumption and increase the reliability of foundations, various methods have been used in recent years to increase the bearing capacity of foundations: increasing their density by static and dynamic ramming [1], fixing the bases with various binders, compacting natural bases by adding bulk materials of increased strength to them, transferring loads from the foundation to the base through layers or structural elements with higher strength characteristics than those of the subsoil.
2. Materials and methods

When developing structures and designing foundations, including pile ones, the strength characteristics of the foundation material and those of the subsoil often come into conflict. Because of this, when the ground is overstressed, for example, it is necessary to increase the size of the foundation, so its material remains underloaded, which leads to a significant consumption of structural materials and an increase in funds for the construction of foundations [2].

Manufacturing and subsequent installation of light metal structures of agricultural production buildings on the construction site imposes strict requirements for the accuracy of the foundations. The vertical and horizontal deviation of fasteners on the foundations of all types of greenhouses from the axes should not exceed 0.5...1 cm.

One of the ways to reduce the material consumption and increase the reliability of foundations are various ways to increase the bearing capacity of foundations: increasing their density by static and dynamic ramming, fixing the subsoil with various binders, compacting natural ground by introducing high-strength bulk materials into them, transferring loads from the foundation to the base through interlayers or structural elements with higher strength characteristics than those of the subsoil, etc. [3].

For structures for the production and storage of fruit and vegetable products and during the reconstruction and expansion of production complexes, it is advisable to use foundations that are embedded by static-load pressing [3].

Comparative tests of micro-piles foundations with bases reinforced in various ways show that by injecting the base with clay-cement or compacting it with sand and sand-concrete mixtures, it is possible to achieve a significant 3-4-fold increase in the bearing capacity of the micro-piles. The results of static tests of reinforced concrete micro-piles with a cross-section of 120x140mm and an embedment depth of 0.6-1.8 m give an idea of the work of such foundations when they perceive vertical loads. For example, micro pile with an embedment depth of only 0.6 m in loam with a flow rate of 0.4 has an ultimate loading of 32 kN, and when compacting the base of such pile with a shell of medium-grained sand or sand concrete with sand and embedding to a depth of 1.7-1.8 m with a diameter of up to 400 mm, the ultimate loading on it increases to 117-141 kN or 3.66-4.41 times. A reinforced concrete pile of the same cross-section with a pile point embedded 1.5 m deep in loam with a consistency index of 0.61-0.66 has an ultimate loading of 39 kN, and with a base reinforced with a sand or soil-cement shell, it is capable of bearing capacity of 126-140 kN, i.e. 3.2-3.6 times more.

3. Results

To increase the bearing capacity of micro-pile foundations bases, an effective way is to compact soil by repeatedly dipping the stamp into a well filled with loose materials: soil, sand, small crushed stone gravel mix, concrete, etc.

The technology of foundation production with soil strengthening is proposed. The construction stages are shown in figure1.

The method of increasing the bearing capacity of the foundations by ramming loose rigid materials into the ground mass is widely used in agricultural and industrial construction when installing bored piles and foundations in rammed pits.

Comparative tests of micro-pile foundations with bases reinforced in various ways show that by injecting the base with clay-cement or compacting the base with sand and sand-concrete mixtures, it is possible to achieve a significant 3-4-fold increase in the bearing capacity of micro-piles. Given the fact that the creation of sand compacted zones is more technologically advanced and does not require additional cement consumption, micro-pile foundations with sand shells should be considered the most promising when they perceive vertical loads in greenhouses.

Piles of this design are constructed as follows (figure 1) [3-4]. On a planned construction site, with the help of a round or square hollow stamp 6, embedded in the subsoil by vibration, static-load pressing or ramming down, wells 7 are formed at a given depth with the simultaneous creation of a compacted zone 8.
The study analyzed the shape of the resulting spread and the increase in the bearing capacity of foundations during partial filling of the pit with gravel-sand-crushed stone materials and compaction of the material with rammers of various shapes. In order to identify the degree of increase in the bearing capacity of the embedded piles, both due to resistance along the pile point, and due to an increase in pile skin resistance, experiments were performed with the ramming of bulk materials (sand, loam, hard sand concrete) into the ground mass, filling the well to the full depth. In the process, changes in the total resistance, the resistance at the pile point and pile skin (to be described below), as well as the shape and size of spread from bulk materials depending on the volume and type of the rammed material, the soil mass condition, the geometric shape of the stamp and its immersing depth were revealed.

During the research, experimental tests were carried out in a tray and in full-scale conditions. To determine the shape and size of the spread, the experimental foundations were opened with an exploratory pit to the full depth so that the front wall passed along the middle axis of the foundation. During the extraction process, after stripping the front wall of the pit, the spread was measured in the horizontal and vertical planes after 5-10 cm. The transverse dimensions of the foundation and spread were determined along the middle axis of the plane of the front pit wall and along the part of the foundation protruding into the pit. In each horizontal section of the foundation, the obtained measurement results were summed up and the average value was determined. It should be noted that the size deviations in the mutually perpendicular directions with a square and round cross-section of the stamp did not exceed 5-10 mm. Deviations of the pile from the symmetry axis of the foundation reached 20-25 mm in some experiments.

The shape of the spread revealed as a result of direct measurements, has the form of a body of rotation regardless of the transverse shape of the stamp, in all cases. In the case of a square or round cross-section stamp, the shape of the spread in the horizontal section is close to the circle. When using a rectangular cross-section stamp, the outline of the spread in the horizontal section is an ellipsoid with axes corresponding to the dimensions of the rectangular cross-section of the stamp.

Based on the obtained data, sounding graphs are constructed, with the help of which the specific friction and resistivity along the pile point at any depth of the soil mass is easy to determine, and the bearing capacity of piles is determined from them.

4. Discussion
Comparison of resistances at the stage of ultimate loadings in the compacted base and in the soil of natural composition confirms that the double compaction of the base with medium-grained sand increases the ultimate loading on the pile by 1.37-1.49 times. At the same time, the resistance along the pile point increases by 2.3 times, and decreases by 1.1 times along the pile skin [5]. Testing of piles in the ground compacted with medium-grained sand, with different periods of "rest", shows that
over time, the sand shell decompresses, resulting in a decrease in resistance: along the pile point by 8-
12%, along the pile skin up to 15%.

The calculation method recommended here is developed on the basis of studying the stress-strain
state and other factors of interaction between soil and micro-piles identified in the process, using
fundamental theoretical methods for calculating piles installed with soil displacement.

In the calculation scheme, when designing this type of foundations, the work of the lower pile point
and that of the pile skin are considered separately [6-7]. This consideration is valid, since tests of pile
stamps of various cross-sections pressed to a depth of 1 to 3.5 meters in sandy and clay soils have
shown that the sum of the maximum resistance of the soil under the lower pile point and along the pile
skin determined separately is equal to the maximum load on the entire pile [8]. Thus, the calculation is
based on the condition (1 and 2) [9-10]:

\[ P = P_o + P_b \]  
\[ P_o = P_{ov} + P_{bv} \]  

where

\( P \) - ultimate pile loading, kN;
\( P_o \) - ultimate resistance along the lower pile point, kN;
\( P_b \) - ultimate pile skin resistance, kN;
\( P_{ov} \) - impressing force, kN;
\( P_{bv} \) - resistance along the lower pile point while pressing, kN;
\( P_{bv} \) - pile skin resistance while pressing, kN.

To determine the ultimate resistance along the pile skin of a micro-pile with a base reinforced with
a sand shell, we use the calculation scheme (figure 2).

A micro-pile foundation is considered as a structure consisting of a reinforced concrete shank and a
surrounding soil pile, the installation of which is made with the displacement of the natural ground
beyond its volume [11-12]. The shear and normal stresses of sliding at the contact of the pile and the
shell will be expressed by Coulomb's law in the following form (3) [13]:

\[ f = P_c \cdot \tan \varphi_1 \]  

Figure 2. Scheme for determining pile skin resistances of a micro-pile with a sand shell.

The resistance on a lateral area section with height \( d_z \) is determined by the formula (4) [14-15]:

\[ R = P_c \cdot d_z \]
where $\varphi_1$ - internal friction angle of the shell material, deg.

The normal stress $P_c$ on the micro-pile surface is the total horizontal pressure consisting of the lateral pressure of the shell material $P_1$ and the horizontal pressure of the natural ground [16] (figure 4), resulting from its displacement and compaction and transmitted to the micro-pile shank through the backfill material (5):

$$P_c = P_1 + P$$  \hspace{1cm} (5)

The value of the lateral pressure of the shell material is determined by the formula (6):

$$P_1 = \gamma_1 \cdot z \cdot \xi_1$$  \hspace{1cm} (6)

where

- $\gamma_1$ - bulk density of shell material, kN/m$^3$;
- $\xi_1$ - lateral pressure coefficient of a sand shell.

Comparative tests of micro-piles foundations with bases reinforced in various ways show that by injecting the base with clay-cement or compacting the base with sand and sand-concrete mixtures, it is possible to achieve a significant 3-4-fold increase in the bearing capacity of the micro-piles. The results of static tests of reinforced concrete micro-piles with a cross-section of 120x140mm and an embedment depth of 0.6-1.8 m give an idea of the work of such foundations when they perceive vertical loads. For example, micro piles with an embedment depth of only 0.6 m in loam with a flow rate of 0.4 has an ultimate loading of 32 kN, and when compacting the base of such piles with a shell of medium-grained sand or sand concrete with sand and embedding to a depth of 1.7-1.8 m with a diameter of up to 400 mm, the ultimate loading on it increases to 117-141 kN or 3.66-4.41 times. A reinforced concrete pile of the same cross-section with a pile point embedded 1.5 m deep in loam with a consistency index of 0.61-0.66 has an ultimate loading of 39 kN, and with a base reinforced with a sand or soil-cement shell, it is capable of bearing capacity of 126-140 kN, i.e. 3.2-3.6 times more.

For $P$, we get the dependence (7) [3]:

$$P = P_o \cdot N_1$$  \hspace{1cm} (7)

Taking $N_1 = \frac{2b_0 + \xi(b-h_0)}{2b + \xi_1(b_0-h)}$ we obtain the value of the horizontal pressure of the natural ground resulting from its compaction (8):

$$P = P_o \cdot N_1$$  \hspace{1cm} (8)

where $P_o$ - horizontal pressure on the compacted sand shell contour.

The value of the ultimate loading along the pile point for cohesive soils according to the scheme (figure 3) (9 and 10) [3;15]:

$$P_{u} = \pi \cdot b^2 \cdot \left[ A \cdot c \cdot \frac{E}{4(c \cdot \cos \varphi + \gamma \cdot d \xi)} \cdot \left[ (1 - \mu^2) - 2\gamma \cdot d \xi (2 - \mu) \right] \right]^{1/2} \times \left[ \cos \varphi + c \cdot \tan \varphi - A \cdot c \cdot \cos \varphi + A \gamma \cdot d \xi + Bc \right]$$  \hspace{1cm} (9)

Ultimate loading along the pile point for sandy soils:
\[ P_{\infty} = \pi \cdot b^2 \left[ \frac{E}{4 \gamma \cdot d \zeta (1 + \sin \varphi) \left( 1 - \mu^2 \right) + 2 \gamma \cdot d \zeta (2 + \mu^2)} \right]^{\frac{1}{2}} \cdot \left[ \gamma \cdot d \zeta \cdot \sin \varphi + A \cdot \gamma \cdot d \zeta \right] \] (10)

5. Conclusion

The construction of the foundation according to the above method can significantly increase the soil bearing capacity and reduce the production cost directly of pile shanks by reducing the cross-section and length of a pile.

In fact, under the same ground conditions and with equal bearing capacity, it is possible to reduce the length of the pile by half or more times. Also, this technology allows for the reconstruction of existing structures for various purposes (strengthening of foundations, construction of new foundations in the immediate vicinity of existing buildings) [17-19]. When pressing micro-piles into loose subsoil reinforced with sand shells, two cases of embedding the lower pile point into the shell are possible; the pile point with the compacted core formed under it does not go beyond the boundaries of the sand shell; the lower pile point is located at the interface level of the spherical shell base and the cylindrical side surface of the shell [3], while the height of the compacted core exceeds the radius of the spherical base and the most effective operation of the pile is according to the first option. A significant difficulty at present is the calculation of the bearing capacity and stability of such foundations.

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