Experimental studies of a weak clay base reinforced with sand piles

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Abstract. The study was aimed at assessing the deformability of a weak water-saturated clay base reinforced with a group of sand piles in the form of a continuous pile field, when they are jointly deformed under load. Existing studies consider the interaction of free-standing soil piles with the surrounding soil, methods for their calculation, without taking into account the joint operation of a group of piles in a deformable soil massif. The main research results were obtained in the form of new experimental data on the operation of a group of sand piles during their joint deformation with weak water-saturated clay soil massif under a stamp. The significance of the results obtained for the construction industry lies in the fact that the experimental data presented can be used in further theoretical studies to develop a calculation model that allows taking into account the peculiarities of the interaction of sand piles in a pile field with each other and with the surrounding soil massif and are of practical value.

1. Introduction
One of the effective methods for improving the construction properties of substrates composed of weak, water-saturated clay soils is the use of reinforcing elements in the form of sand piles. With the advent of modern materials, it became possible to further improve the characteristics of sand piles by external cylindrical reinforcement with geosynthetic grids or geosynthetic non-woven material, which can significantly reduce their transverse deformations and, as a result, reduce their vertical deformations. At the same time, the process of siltation of the body of sand piles occurs more slowly.

Currently, various authors have carried out a number of scientific experimental and theoretical studies on the deformability and bearing capacity of sand piles reinforced along the contour with geosynthetic materials. The studies of Z.G. Ter-Martirosyan, A.Z. Ter-Martirosyan [1] examined the main methods for improving the properties of weak clay soils with their surface and deep compaction. The solutions of the axisymmetric problem of consolidation of a weak clay base reinforced by sand piles, taking into account changes in pore pressure and the degree of consolidation, are presented. The stress-strain state of the reinforced soil cylinder in the cell volume is estimated based on the Lyame problem.

The work by Z.G. Ter-Martirosyan, A.Z. Ter-Martirosyan, V.A. Sidorov [2] provides solutions to the problem of the interaction of a soil pile and a foundation slab with a surrounding soil cylinder, based on an incompressible base according to the "pile-rack" scheme. The authors obtained closed
solutions for determining stresses in the body of piles and soil under a stamp. As a pile material, a sand-gravel mixture is considered.

In his work, Yu.A. Novikov [3,4] on the basis of complex experimental studies in laboratory and field conditions, revealed an effective ratio of the diameter of the sand pile to its length, revealed the peculiarities of the stress-strain state of the weak clay base of the strip foundations, reinforced with reinforced sand piles along the contour. The work also developed a method for calculating the base reinforced by sand piles from weak water-saturated clay soil. Based on the results of laboratory studies, the author made the following conclusions:

- reinforcement of sand piles along the contour with geosynthetic material leads to a decrease in transverse deformations of piles and, accordingly, vertical deformations are reduced;
- soil piles, in the form of a cylinder in a reinforced shell, part of the loads are transferred to a base located below the border of reinforcement;
- deformability of the soil base when reinforced with reinforced sand piles decreases by 1.8 to 2.8 times.
- effective ratio of the diameter of the reinforced piles to the length was 1/4.

A further decrease in the ratio of the diameter of the pile to the length of the length leads to a slight decrease in deformations of the settlement of the base, but the material consumption and labor costs for the manufacture of the pile increase significantly.

The works by A.B. Ponomarev, R.A. Usmanov, R.I. Shenkman [5-7] consider the technology of improving a weak soil foundation using soil piles of crushed stone in a geosynthetic shell. To study the reinforced base, laboratory and semi-natural experiments, numerical modeling were carried out. In the process of semi-natural tests, several options for transferring loads to a reinforced base and reinforcement technologies were considered. Loads through a hard stamp were transferred directly to piles (tests of soil piles), transfer of loads through sand and gravel pads (tests of a reinforced massif). Single piles and a group of piles of three elements were used as reinforcement. The authors note that when loading a reinforced massif from soil piles, it is not possible to achieve a significant draft reduction. The reason for this may be the use of small stamp sizes, as well as the effect associated with the fact that before the pile is included in the work, some precipitation must occur. Values of these deposits can reach up to 50 mm. The authors also note that today, although there are developed methods for determining the draft of reinforced piles, there is a need to study the draft of a group of soil piles reinforcing weak water-saturated bases.

The results of studies in the field of application of sand piles, the technology of their construction and operation under loads, the deformation of weak water-saturated soils under static and cyclic loads, data on the study of the effectiveness of soil reinforcement with geosynthetic materials are also given in [8,9]. The results of numerical studies of the foundation of a slab foundation made of weak clay soil reinforced with sand piles showed [10] that the vertical deformation of the stamp and the bending of piles mainly depend on the diameter of the piles, their length and pitch. Good reinforcement performance is achieved when the ratio of the length of piles to the thickness of a weak soil layer is 0.75.

In the aforementioned works, the cell is mainly considered, consisting of a single reinforced sand pile during joint deformation with the surrounding soil within the cell. However, under continuous slab foundations in different zones, different conditions of the stress-strain state are realized, and the conditions of pile deformation depending on the location will differ significantly, which, of course, must be taken into account when determining the draft and bearing capacity of the base as a whole. To date, the work of a group of soil piles used to improve a weak water-saturated clay base has not been studied enough, and there is a need to develop methods for calculating the draft of such bases, based on new experimental data.

2. Experimental studies of the deformability of a massif reinforced with sand piles

In order to study the stress-strain state of a weak clay base under a hard stamp, a series of laboratory studies were conducted on small-scale soil models in the laboratory of the Department of OFDS and
IG of KazGASU. In modeling, the method of geometric similarity was used when constancy was observed with respect to all similar sizes. The stand tray had internal dimensions of 500x500x500 mm. Loam of disturbed structure was used as soil; the physicomechanical characteristics are given in Table 1. To achieve the specified moisture content in the soil, the calculated amount of water was added to the soil, the finished soil paste was stacked in layers in a tray. Each layer was sealed with a load equal to the weight of the overlying layers. To control humidity and density, 2 samples were taken in each layer. The average values of the angle of internal friction and specific adhesion according to the test results of samples taken in layers were $\varphi = 11^\circ$, $c = 12$ kPa.

Table 1. Physico-mechanical characteristics of the soil

| Indicator                  | UOM          | Value       |
|----------------------------|--------------|-------------|
| Specific gravity           | kN/m$^3$     | 18.5-18.9   |
| Preset humidity            | %            | 38          |
| Plasticity number          | %            | 16          |
| Liquidity index            | unit fr.     | 0.93-0.96   |
| Porosity coefficient       | unit fr.     | 0.94-0.98   |
| Water saturation coefficient| unit fr.     | 0.96-0.98   |

Three series of samples were made: 1 series (2 samples) —natural base (samples without reinforcement); 2 series (3 samples) - soil reinforcement with sand piles with a diameter of 25 mm and a length of 200 mm reinforced with geosynthetic material along the contour; 3 series (2 samples) - soil reinforcement with sand piles with a diameter of 25 mm and a length of 300 mm reinforced with a geosynthetic contour. In samples of series 2, the load is transferred to the reinforced massif (through the sand layer), and in samples of series 3, the load is transferred directly to the piles. The pitch of the piles in the plan is adopted 60 mm. For the setup of piles, a pipe with a pointed punch inside was immersed into the massif. After reaching a predetermined depth, the punch was removed, geosynthetic tissue was lowered into the pipe. Further, sand with a rolling punch was loaded in a layer into the pipe cavity. Coarse sand with moisture content $W = 3\%$ and density $\rho = 1.9$ g/cm$^3$ was used as material for piles. Density was controlled by the flow of sand to fill the piles. The load on the massif was transferred through a hard metal stamp with a diameter of 160 mm, the pressure under the stamp was increased in steps of 1/10 of the expected ultimate load on the base. Each stage was maintained until the soil deformation was conditionally stabilized. The criterion for conditional stabilization of deformations was the stamp settlement rate, not exceeding 0.1 mm in the last two hours. The value of the maximum draft of the stamp adopted 100mm. Test diagrams are shown in Figure 1.

![Figure 1. Diagram of soil models.](image)

The test results in the form of "draft-pressure" graphs for three series of experiments are presented in Figure 2. The graphs are plotted based on the averaged values of several experiments in each series.
3. Analysis of experimental data

Based on the study of the graphs of the stamp settlement, depending on the pressure of the graphs, the following conclusions can be drawn:

1. when the value of the predefined maximum permissible settlement of the stamp value of 10 cm, the maximum pressure was:
   - to the base without amplification - 73 kPa;
   - on the base with reinforcement by sand piles 200 mm long - 145 kPa;
   - on the base with reinforcement by sand piles 300 mm long - 156 kPa;

2. setup of sand piles in a weak water-saturated clay soil massif has led to an increase in the ultimate load by 2.0 to 2.1 times.

3. in samples of the 3rd series, sand piles are made 300 mm long with their arrangement through a layer of sandy soil directly under the sole of the stamp. However, in comparison with samples of the 2nd series, where sand piles were made 200 mm long only within the limits of a weak soil layer, the maximum load on the base increased by only 7.5%, which indicates the inefficiency of pairing sand piles directly with the stamp.

The test results of samples of the 1st series on the example of one experiment are presented in Figure 3.

As can be seen from the diagram (a), by the end of the tests, a loss of stability of the stamp is observed, accompanied by a small uplift on the surface of about 15 mm indicating that the pressure on the base has reached its limit value. By the end of the experiment, a deformation compaction core is formed under the stamp, as evidenced by control measurements of humidity and density at various points in the massif (diagrams b and c). On the surface of soft soil, a depression of up to 58 mm is observed. Migration of water occurs in the direction from the deformation core down and to the sides. A significant change in the density of the massif and humidity extends to a depth of 1.5 diameters of the stamp.

The test results of samples of the 2nd and 3rd series with the reinforcement of the weak base with sand piles are presented in Figure 4 and 5.
Figure 3. Test results of the 1st series of samples (authors' diagrams)

For samples of the 2nd series, a compacted soil zone is formed almost within the entire length of sand piles. At the same time, due to lateral soil pressure, the distances between the piles slightly increased, however, the piles practically retained their verticality. As can be seen in the diagrams in Figure 4, a deepening of up to 5.6 cm is observed on the soil surface. Therefore, the vertical deformations of medium piles in a weak soil massif are much larger, approximately equal to the diameter of the piles after expansion. This indicates that the load on the piles within the stamp is not transmitted uniformly, the average piles are loaded more.

Figure 4. Test results of the 2nd series of samples (authors' diagrams).

Compared with the soil mass without reinforcement, the depth of soil density and moisture changes is much greater, almost equal to the thickness of the sample. The movement of water occurs mainly from the central zone to the side zones of the tray, in the horizontal direction. In the lateral parts of the tray, approximately at the level of the bottom of the piles there are zones with a maximum increase in sample moisture.

In sand piles, a significant change in humidity also occurred upwards. Humidity in sand piles after the experiment was about 10% - 17% - 12% in the upper, middle and lower zones, respectively, with an initial sand moisture of 3%. The indicated change in humidity indicates that a significant amount of moisture is filtered into the body of sand piles, as drainage elements.
For samples of the 3rd series, deformation of the piles in the horizontal direction with bending is observed, which indicates excessive flexibility of the piles due to the large ratio of the diameter of the piles to the length. As measurements of soil density after the experiment showed, the compacted soil zone for this series was formed only within the upper zone of sand piles. Therefore, lateral expansion of the soil within the compacted zone led to bending of the piles in the horizontal direction to the sides, while the lower zones of the piles retained their verticality. However, due to the transfer of the load from the stamp directly to the piles, a significant slippage in the massif was observed. For medium piles, the magnitude of slippage deformations is significantly larger than for extreme piles. Bending of piles led to a significant decrease in their bearing capacity, therefore, the deformation of the stamp for the 3rd series is slightly different from the deformations of the samples of the 2nd series.

4. Conclusion

The ultimate load during the reinforcement of a weak water-saturated clay soil massif with sand piles in a geotextile shell increased by 2.1 times. This confirms the effectiveness of the use of these piles and is in good agreement with the field and numerical experimental data of other researchers [4-9]. When studying the deformations of piles, it can be distinguished that the average piles under the stamp are loaded more, which is accompanied by an increase in their settlement compared to the extreme piles. The extreme piles cannot be fully included in the work, since they experience both vertical and horizontal deformations; bending of the piles in the direction from the stamp occurs under the stamp within the formed compaction core. In this case, the upper and lower zones of the piles retain their verticality, although there is some lateral displacement of the piles themselves. It should also be noted that when transferring the load from the stamp directly to the piles, a substantial increase in the bearing capacity of the base does not occur. This leads to the slippage of the piles in the massif and an increase in the draft of the stamp as a whole. In the case when the pressure from the stamp on sand piles is transmitted through a layer of soil with good deformation and strength characteristics, an additional lateral compression of the body of sand piles occurs, which increases their bearing capacity and reduces the draft of the stamp. Despite the fact that reinforced sand piles quite effectively improve the deformation characteristics of the base from weak water-saturated soil, precipitation reaches quite large values. As other researchers point out, this is most likely due to the fact that certain deformations occur before the incorporation of soil piles.

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