Theoretical computation background for transformation of foundations using pile drains

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Abstract. In the design of foundations for buildings and structures of various purposes, including improved risk, weak water-saturated clay soils with low mechanical characteristics are often found on a construction site. One of the possible ways of using them as a foundation is to seal them in various ways, including using pile drains of sand or rock stone material that are capable of both absorbing the load at the base and accelerating the process of filtration consolidation. This paper describes an analytical solution to the problem of interaction between the pile and the mattress with the surrounding soil of the foundation, taking into account the possibility of expanding the pile shaft. Solutions are obtained for determining the stresses in the shaft of the pile drain and in the soil under the mattress. The solution takes into account the influence of the pre-stressed state of the foundation after compaction on the formation of a stress-strain state during the erection and operation of structures. The solutions are relevant for consolidating pile drains made of rubble or for jet grouting piles, the rigidity of which is comparable to the rigidity of the surrounding soil. The paper describes the technique for determining the characteristics of the strength and deformability of the converted foundation and the results of large-scale tests at the experimental site for the construction of a large energy facility in Russia.

1. Design technique and tools for consolidating of weak bases

In the presence of a high capacity of weak soils in the base, it is not economically expedient to replace it completely with sand or ground bed. In addition, it is quite difficult to provide a quality compaction (ensuring the design quality parameters of the embankment - the density of dry soil or the compaction factor over the entire thickness of the bed) [1]. At present, two methods are used for compaction of weak water-saturated bases: surface compaction using sand draines and embankments, and deep compaction with the use of deep ramming, etc., creating considerable radial stresses in the weak base.

The proposed method is based on the consolidation of cohesive soils under a constantly acting distributed load in the presence of drains, which are rock stone columns. After the construction of the piles, a crushed stone or sand mound is made designed to collect and drain water from the pile drains. It makes it possible to reduce the unevenness of the deformations of the foundation in the process of filtration consolidation.

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In this technique, it is proposed to realize the compaction of a weak foundation of high capacity with the help of a device in it piles of crushed stone.

1. Construction of piles of rock stone is made by batch indenting of an inert material (sand, rock stone, etc.) into the borehole with a large vertical force of the submerged projectile, which results in the occurrence of significant radial stresses and expansion of the walls of the borehole. In this case, excessive pore pressure appears in the water-saturated soil mass around the pile.

2. Water permeability of a pile from rock stone is higher than that of the surrounding weak ground, by several orders of magnitude, which allows them to fulfill the role of drains significantly accelerating the process of filtration consolidation, increasing the rate of the process of water squeezing out of the ground and also shortening the horizontal filtration path (see Fig.1).

3. After manufacturing rock stone piles and finishing the filtration consolidation process, the converted composite (consisting of the consolidating columns and surrounding compacted ground) foundation acts as a single transformed array for which it is possible to determine the specified mechanical characteristics.

The device of ground piles requires equipment for pushing the pilot borehole and pushing loose pile material into it.

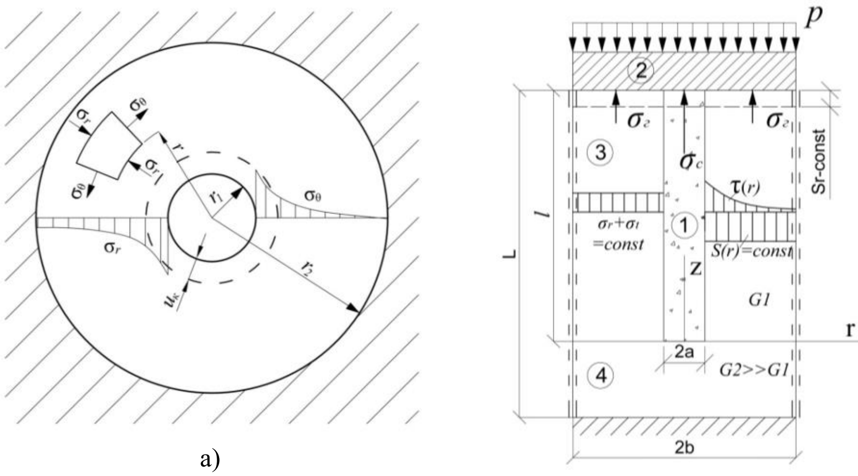
For drilling, any standard equipment used in the construction area may be applied.

The pilot borehole is formed by pressing the working tool to the required depth. Thus, the first compaction takes place. The tool is not removed yet. Then, a bunker is placed on it, which is filled with rock stone. After that, the slide is opened, and the rock stone reaches the lower end of the tool, then the tool is lifted to the specified height, and the rock stone that has reached the bottom of the borehole remains at the same depth and is compacted by pressing the tool (tool immersion) for a certain distance. Thus, the pilot borehole expands significantly to form a rock stone column, and the soil around the column is sealed radially. Compaction of the ground surrounding the column causes activation of the consolidation process due to the appearance of excessive pore pressure.

The simplest pressing tool of a machine can be a pipe of appropriate rigidity (capable of perceiving a vertical load of up to 300 tons) with a closed lower end.

2. Analytical solutions

1. Design of pile drains. For the design of the transformation of a weak foundation with pile drains, we must consider two successive processes - the interaction of the surrounding ground with the expanding pile shaft (in the process of its arrangement) and the interaction of the pile shaft and surrounding soil under load as part of the foundation. In this case, the initial and final radius of the piles are usually pre-determined, that is, the radial movement during the construction of the compaction unit is a predetermined value. The external boundary of the calculated cell is determined by the step of the arrangement of the pile drains, on which the degree of transformation of the weak foundation depends.



a) б)

Fig.1 – a) scheme for expanding the diameter of the pilot borehole during the pile manufacturing process; b) the design scheme of the pile's interaction with the surrounding soil and the foundation slab in the foundation structure according to the compression pile scheme). 1 – pile drain, 2 - foundation slab, 3 - compacted layer, 4 - underlying dense ground

On the basis of a joint examination of geometric, physical and equilibrium equations, the SSS problem of a ground shaft can be reduced to solving a differential equation in displacements [2] of the form:

$$\frac{d^2u}{dr^2}+\frac{1}{r}\cdot\frac{du}{dr}=\frac{u}{r^2} \tag{1}$$

Next, we can write the resulting expressions to find the radial and tangential stresses on the pile-ground contact.

$$\sigma_r=\frac{E_2 A}{(1+\nu_2)\cdot\nu_2^{/}}\left(1+\frac{r_2^2}{r^2}+\left(1-\frac{r_2^2}{r^2}\right)\xi_2\right)+\frac{\sigma_{z2}\cdot\xi_2}{(1+\nu_2)\cdot\nu_2^{/}} \tag{2}$$

$$\sigma_\theta=\frac{E_2\cdot A}{(1+\nu_2)\cdot\nu_2^{/}}\left(\left(1-\frac{r_2^2}{r^2}\right)+\xi_2\left(1+\frac{r_2^2}{r^2}\right)\right)+\frac{\sigma_{z2}\cdot\xi_2}{(1+\nu_2)\cdot\nu_2^{/}} \tag{3}$$

In order to determine the vertical load, which must be transferred through the tamping equipment to the ground, it is necessary to use the limiting equilibrium equation, where the values of vertical and radial stresses will be present as the main stresses. At the same time, the vertical stress should be extreme, so that the layer of the trawl material may exhaust its strength, collapse and take its design position in the already extended well.

The limiting equilibrium equation takes the form:

$$\frac{\sigma_z^*-\sigma_r}{\sigma_z^*+\sigma_r+2c\cdot ctg\,\varphi}=\sin\varphi \tag{4}$$

Then the value of the limiting vertical stress is expressed as follows:

$$\sigma_z^*=\frac{\sigma_r(1+\sin\varphi)+2c\cdot\cos\varphi}{(1-\sin\varphi)} \tag{5}$$

Based of (5), it is possible to express the force N needed to expand the pilot borehole to the required size:

$$N^{*} = \pi \cdot r_1^2 \cdot \sigma_z^{*} \tag{6}$$

2. Interaction of the ground pile of extreme rigidity with the surrounding soil in the composition of the foundation, taking into account the expansion of its diameter in the loading process. Considering the equality of radial displacements on the radius of the pile (r = r1), and also taking into account the equality of deformations [3], we can obtain an expression relating the load to the base slab p and the resulting lateral extensions of the pile under the load u1.

The expression has a complicated form and is represented in a simplified way with the help of special factors, which are presented in [4] the following form:

$$u_1 = p\left(\frac{G}{F} + \frac{J}{K}\right) : \left(\frac{I}{K} + \frac{H}{F}\right) \tag{7},$$

Factors A,B,C,D,E,F,G,H,J,K depend on the geometric and mechanical parameters of the pile and surrounding ground both around it and under its toes.

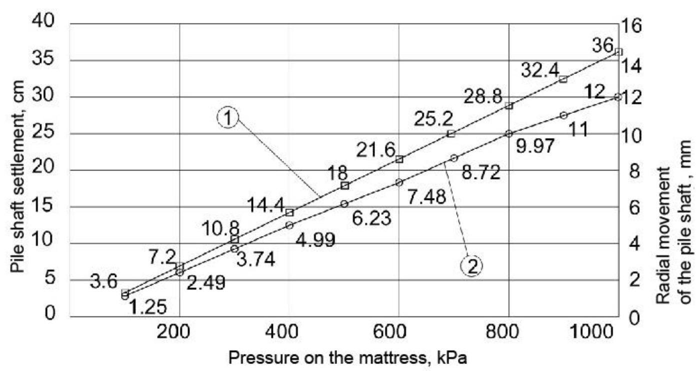


Fig.2 – Dependency graph of the draft of the pile shaft (cm) on the pressure on the mattress slab of the design cell, kPa (1), radial displacement of the pile shaft (mm) on the pressure on the mattress slab, kPa (2)

3. Determination of the given values of the foundation deformation modulus, packed with rock stone pile drains. After the arrangement of pile drains on the site and consolidation of the weak foundation, it is necessary to consider the work of the composite substrate under load. The main issue at this stage is to find the bottom of the foundation of the structure. Since the bearing elements of such a system are the piles themselves and the surrounding soil, it is very difficult to consider them separately. Therefore, dependencies are required to determine the reduced strain modulus [5].

Dependences are obtained for determining the reduced strain modulus in cases where dense soils lie under the sole of the pile drains and the ground is not extruded under the sole, and also for the case when the soils under the sole are deformable and the punching is possible. In the first case, the expression looks like:

$$\overline{m} = \frac{m_c \cdot m_z}{m_z \cdot \lambda + m_c(1-\lambda)} \tag{8},$$

where $\overline{m}$ - relative compressibility coefficient of the calculated cell as a whole;

m_c - relative compressibility coefficient of the pile drain material;

m_2 - coefficient of relative compressibility of the surrounding compacted soil of the foundation.

If a punching of the foundation ground is possible, a more complex relationship the lower end of the pile drain can be obtained, which is more conveniently written in a reduced form:

$$\overline{m} = \frac{D \cdot E}{l} \tag{9}$$

where D,E – values that depend on the geometric and mechanical characteristics, and are described in detail in [4].

Strength characteristics of the transformed foundation are determined by performing a virtual experiment by the finite element method. A triaxial test of the transformed cell is simulated according to Fig. 1b at various hydrostatic pressures in order to obtain the Coulomb limit line and determine the angle of internal friction and the specific adhesion for the cell as a whole. In this case, in the design scheme, each of their constituent parts (pile material, surrounding soil, mound, etc.) is assigned its own parameters.

On the axial-symmetrical design problem in the form of two shafts (the shaft of the ground pile in the shaft of compacted weak ground), the following loads are applied:

- radial, simulating the sample compression;
- vertical, simulating the load on the sample.

The virtual experiment is carried out as close as possible to the triaxial test procedure in accordance with GOST 12248-2010.

Several calculations (at least three) are performed with different compressive stresses to construct stress circles and subsequent laying them on the general graph in order to construct the limit line.

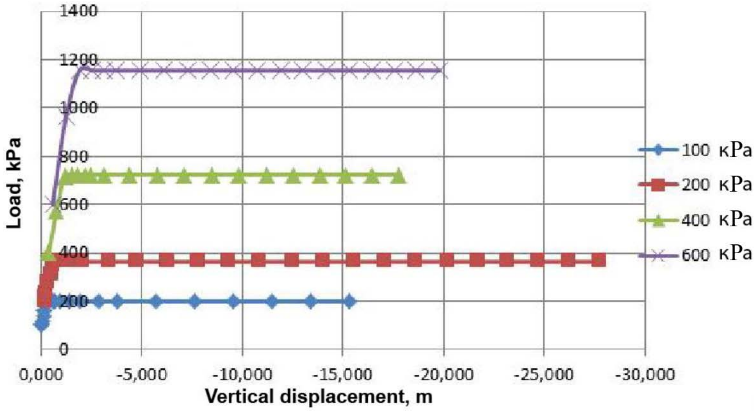


Fig.3 – Dependency graph of vertical displacements (m) on the load (kPa) for different values of the compressive load (100 kPa, 200 kPa, 400 kPa, 600 kPa)

3. Field testing of soil substrates and the pile drain material

For the reliable design of a large nuclear power plant, a pilot site 50x15 m was created, on which three sections of a densified foundation were made with pile steps of 1 m, 1.2 m and 1.5 m with initial diameters of 325 mm, 426 mm and 530 mm, respectively.

After the installation of the consolidating piles and consolidation of the foundation, field tests were carried out with dies of the material of the resulting pile drains.

Table 1. Summary results of field tests of the pile drain material

Depth of experiment h, m	Soil	Value of the strain modulus E, MPa	Average value of the strain modulus E, MPa
7.0	Rock stone of the ground pile	120.5	140.52
7.0		106.92	
7.0		104.3	
7.0		146.7	
7.0		158.15	
7.0		206.57	

In addition, tests of rock stone of pile drains were carried out in laboratory conditions using triaxial compression for specimens of 600 mm height and 300 mm in diameter. According to the results of triaxial tests, the deformation modulus of crushed stone at a density equal to the density of the material in the consolidating column is at least 103.57 MPa.

The tests showed that the rock stone material is sufficiently compacted during the process of piling using the technology in question. Obtaining high deformation characteristics of column material will lead to a significant increase in the overall specified deformation characteristics of the compacted foundation as a whole, since both columns and compacted soil around them will interact [6-8].

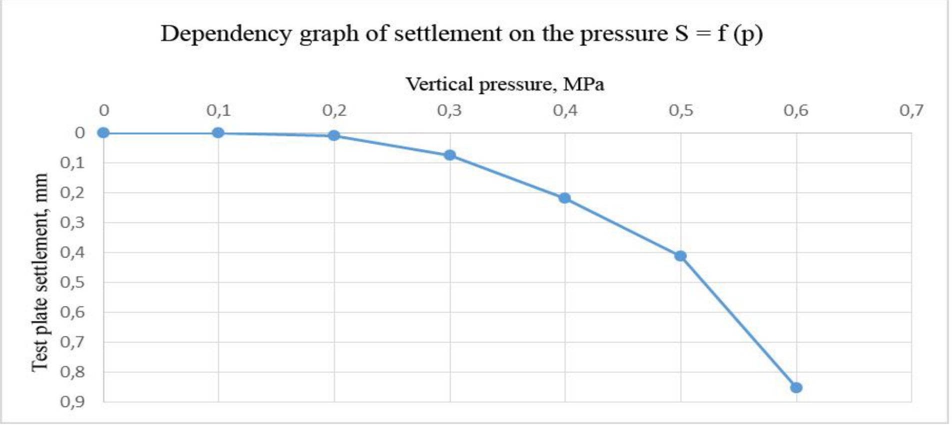


Fig.4 – Curve of plate tests of rock stone material of a pile drain

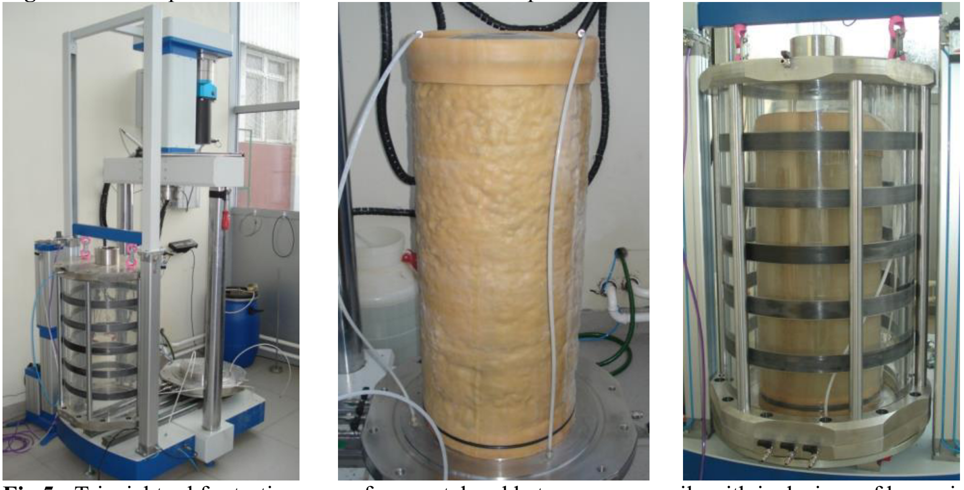


Fig.5 - Triaxial tool for testing macrofragmental and heterogeneous soils with inclusions of large size

4. Nonstandard field tests of the transformed composite foundation

To determine the deformation characteristics of a consolidated foundation as a whole (a composite foundation consisting of a rock stone pile and compacted soil around it), the specialists of the MSUCE Research Institute performed tests of the design cell using flat plates over the area of 7854 cm^2 (1000 mm in diameter) in the well and at the bottom of the pit at a depth of 6.5 m, at the absolute mark of 145.00. A total of three tests were performed. The tests were carried out in accordance with GOST 20276-2012 *Soils. Field methods for determining strength and deformability characteristics.* The resulting strain moduli were 45.07 MPa, 42.88 MPa and 56.64 MPa, which is more than the design value of 40 MPa. The tests confirmed the assumptions about the joint operation of the elements of the composite foundation arranged according to the presented technology, as well as the correctness of the expressions themselves for determining the reduced strain modulus.

Fig.6 – Test plate with a diameter of 1 m

Fig.7 – General view of the test bench with a test plate of a non-standard size

5. Conclusion

1. The technology under consideration for transforming weak foundations is economically viable and effective. Low cost is ensured by the simplicity of the technological cycle, which requires fairly simple machines and mechanisms for its implementation.
2. Analytical solutions are proposed that are sufficient to determine the technological parameters of compaction - pile spacing, final diameter, working stroke of the consolidating equipment, and also to determine the specified deformation characteristics of the transformed foundation.
3. The tests of the design cell of the transformed base and the inter-sealed compacted soil carried out at the test site showed the efficiency of the applied technology and sufficient convergence of the mechanical parameters of the soils to the design ones.
4. Consequently, the developed technique of compaction of the foundation with rock stone pile drains can compete with traditional compaction methods and with more expensive deep foundations.

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