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# Bearing capacity of frame-gantry pile foundations

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**Keywords:** experimental flume, clay soil, of wedge-shaped piles, frame-gantry piles, the benchmarks using a special template, the deflectometers for measuring settlement, bases, foundations

**Abstract.** The object of the study is frame-gantry pile foundations embedded in the soil base. To improve the strength of weak soil base, various methods of reinforcement are used, including the foundation constructions in the form of wedge-shaped piles. The paper deals with laboratory studies of the soil base during the installation of small-scale wedge-shaped piles at different angle. The process of soil shearing under the influence of the loads is registered by deformation control benchmarks arranged in the form of a square grid. The interaction between the soil and the frame-gantry foundations appears in a change of the physical and mechanical characteristics in the near pile area. The tests revealed that when piles are installed at the angle of 30° the bearing capacity of the foundation increased. The average density in the fixed active zone of the soil area increased by 12 %, and the average porosity coefficient decreased by 20 %. The deformation modulus changed by 1.8–2.3 times. The angle of internal friction remained virtually unchanged.

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## 1. *Introduction*

The need for infrastructure development due to population growth is forcing the society to build on the soils available in their locality. The main feature of the geological structure of the soil base of many regions of the world, in particular the Tyumen region, is its composition. The upper layers with a thickness of about 3 m are composed of soils with a deformation modulus of 9–20 MPa, and the underlying weak layers are formed by clayey soils of soft-plastic consistency. Weak soils (clay, loam, deformation modulus 2–7 MPa) have a thickness of 8 to 15 meters or more. At a depth of 13–15 m, there are strong underlying layers of soils. Increasing the bearing capacity of soil foundations and the development of effective solutions for the design and study of foundations on such soils becomes relevant. In most cases, weak water-saturated soils cannot be used as the foundation of buildings and structures without their reinforcement using, for example, pyramidal [1], gantry piles [2]. A lot of research is related to vertical wedge-shaped piles with various bulk materials. Such piles are considered in laboratory experiments [3], full-scale experiments [4], however, the authors do not take into account the effect of the pile inclination angle relative to the vertical on the bearing capacity of the soil foundation.

The paper [5] investigates experimentally and numerically the bearing capacity of steel wedge-shaped joints, and does not consider the bearing capacity of the soil foundation. The development of experimental methods for determining the bearing capacity of a piles is given in the works: composite helical micro piles [6], vertical fiberglass micro piles [7, 8], pyramidal-prismatic and prismatic piles for pressing [9].

Experiments with pyramidal-prismatic piles make it possible to reasonably assign length and dimensions cross section of their pyramidal segment.

The article [10] considers experimental studies carried out on conical piles based on the latest achievements. Experiments indicate the advantages of this type of piles compared to their cylindrical counterparts. Conical piles can be advantageous in terms of bearing capacity compared to cylindrical piles [11]. However, this study focuses on the behavior of conical piles buried in sandy soil.

The article [12] theoretically investigates the effect of vertical vibration on the compaction of soil reinforced with a conical pile during the laying process. It is shown that soil compaction has a significant impact on the soil base and the bearing capacity of the pile. It is also important to identify the mechanisms of the compaction effect of the "pile + soil" structure under static loading, but this fact is not considered by the authors of the article.

In the article [13] reviews the developments and applications of geosynthetics in soil stabilization and protection of coastal areas with emphasis on shoreline protection. Geosynthetic materials are widely used in the construction of sand piles reinforced along the contour [14–16] to increase the bearing capacity of the soil base. In [17], on the basis of the mechanical characteristics of a weak soil base reinforced with fiberglass, the mechanism of interaction between geosynthetics, piles and soil under the load from the embankment was analyzed.

All considered piles are vertical and the issue of changing the mechanical characteristics of the soil foundation reinforced with inclined piles remains unexplored.

In theoretical calculations of soil foundations, an increase in the forecast of the bearing capacity of the foundation occurs due to taking into account the plastic deformations of the soil [18], the viscoelastic properties of the soil [19, 20]. The paper [21] presents an experimental characterization of the crack pattern observed in compacted samples at optimum water content with and without fibers. Skirted foundations are popular due to relatively higher bearing capacity and greater stability compared to strip footing [22]. The works [23–25] present some methods for calculating soil bases reinforced in various ways.

In [26], the bearing capacity of a pyramidal pile was studied depending on its volume, length, soil conditions, and the angle (angle of 5–15°) of inclination of the pile faces, which is not enough to increase the bearing in low-rise construction. In designing, the calculated value of piles and foundations settlement does not take into account the nature of the interaction between the foundation and the soil base in the contact zone; the effect of compacted soil on the pile resistance during installation and during loading; uneven distribution of the contact pressure of the base on the pile surfaces.

Foundation structures (pyramidal, gantry piles) can cut through strong layers of soil and rest on a weak soil base, which significantly reduces the efficiency of using such foundations. In the publications reviewed above, there are no experimental studies related to the increase in the bearing capacity of the base by identifying the mechanism of interaction of inclined (at an angle of 30° to the vertical) conical piles with a base of weak soils such as clays and loams. The authors of the article tried to partially fill this scientific gap. A feature of this article, in contrast to the literature sources discussed above, is laboratory experiments with frame-gantry foundations made of wedge-shaped piles located at different angles to the vertical. The difference between the proposed design and the previously known portal foundations is that when the piles are tilted, an angle of 30° is the foundation support area. Due to the wedge shape of the piles, there is full contact of the lateral surface with the ground, compared to conventional prismatic piles. The experimental study aims to analyze the work of frame-gantry strip foundations on the action of vertical loads and their interaction with a weak soil base.

The **object** of the study is frame-gantry pile foundations embedded in the soil base.

The **subject** of the study is the bearing capacity of a weak clay base, together with the proposed foundation design and the assessment of the strength characteristics of the base. In the calculations, it is necessary to indicate the stiffness characteristics of the soil, taking into account the of frame-gantry piles (soil base and pile foundation), therefore, experimental studies aimed at determining the physical and mechanical characteristics in the interaction between soil and the pile foundation always remain an urgent task.

Thus, the interaction of the frame-gantry foundation and the soil foundation must be investigated experimentally for a complete analysis of the deformed state of the soil foundation. However, the control over the settlements of buildings, the determination of the stress-strain state in natural conditions is problematic due to the complexity of testing and measuring stresses and strains at individual points of the foundation. Therefore, the **purpose** of the presented article is to study the stress-strain state of the "soil + + foundation" system in laboratory conditions on small-scale models to identify the nature of the interaction between the soil foundation and the frame-gantry foundation model.

## 2. Methods

The authors carried out tests in the Soil Bases and Foundations laboratory of the Industrial University of Tyumen (city of Tyumen, Russian Federation). The purpose of the experiments was to determine the nature of soil compaction in the core when installing wedge-shaped piles at different angles, to determine the influence of various factors on the operation of the foundations under study and the behavior of the soil base near the pile array.

All experiments of frame-gantry foundations models were done in a specially created experimental setup made in the form of a metal tray with soil. The design of the experimental setup had been made in such a way that when testing model foundations, the conditions of a plane problem were simulated. The main feature of the experimental tray and the test scheme of the foundation model was the use of visual non-contact methods for studying the deformations of the soil mass in depth. The experimental setup was equipped with a large viewing window that allowed recording the main stages of the experiment. The experimental setup and the view of the foundation model are shown in Fig. 1.

The structural model of the frame-gantry foundation was adopted with a scale factor of 1:6. The parameters of geometric scaling were taken from the condition of reducing the influence of edge effects with the existing dimensions of the experimental tray. Models of wedge-shaped piles were made of dense Ash-type wood. The specific shape of the wedge piles was taken from the consideration of the optimal ratio of the pile length and the angle of the working faces convergence according to [27], and amounted to 3°. The structural rigidity of the grillage was provided by two metal studs with a diameter of 12 mm, placed in such a way as to perceive the moment arising from the rotation of the piles.

A clayey soil with a disturbed structure was used during the experiments. It was loam of soft plastic consistency, with a density $\rho$ = 1.95-1.98 g / cm$^3$, humidity $W$ = 25–27 %, porosity coefficient $e$ = 0.7–0.74, angle of internal friction $\varphi$ = 21.1–21.5$^o$, specific adhesion $C$ = 23.5–25.5 kPa, Poisson's coefficient 0.35, die deformation modulus $E$ = 14.5–16.5 MPa and modulus of elasticity $E_u$ = 33–35 MPa. The physical and mechanical properties of the soils were determined immediately before the start of each experiment according to methods of field tests with piles (Russian State Standard GOST 5686-94 “Soils. Field test methods by piles”). The soil was placed in the tray by hand, in layers of 5–10 cm and compacted by manual tamping. Before laying the soil, all dense inclusions larger than 2 mm were removed. The arrangement of the deformation control benchmarks was done before laying the soil. First, a 2–3 cm soil layer was laid out on a wooden sheet moistened with water, then the contact surface was leveled with a wide spatula, then the benchmarks were set using a special template, as shown in Fig. 2, 3, on a square coordinate grid with dimensions of 0.02 × 0.02 m. Each benchmark was made in the form of a rigid cylindrical polymer tube with an outer diameter of 3.0 mm, an inner diameter of 1.0 mm and a length of 6 mm.

**Figure 1. General view of the foundation.**

The models were driven into the soil by percussion method with the help of a rubber construction hammer. Photos were taken through the viewing window every 10 strokes. The installation of piles was being performed until they reached the required level.

The general displacements of the gantry foundation model during settlement were measured by two deflectometers (deflectometer 6PAO, manufacturer – LLC "M-Service", Chelyabinsk city, Russian Federation). The deformation pattern of the model frames and soil was photographed during certain periods of their stepped loading. It is necessary to note that the deformations of the soil had conventionally stabilized by the time of shooting. As a criterion for the conditional stabilization of deformations, the upsetting rate, which is practically equal to zero, is taken.

During the experiments, a rigidly fixed digital camera recorded the current position of the deformation control benchmarks area. The obtained photographs and instrumental data before and after the deformation of the soil were combined. The movements of fixed marks (by distortion of squares) were measured. It was assumed that the deformation of the soil is uniform within any square; there are no relative movements of the marks and surrounding soil particles; friction of the soil against the transparent wall of the tray does not affect the movement of the marks (permissible when studying the qualitative pattern of deformations).

A modernized photogrammetry method was used in the experiment to observe the movements of controlled points along the depth in the cross section of the soil mass. The experiment was carried out in the plane of symmetry of the foundation models under study. The effectiveness of this method for the interaction between the foundation models and the soil base was shown in the works [28, 29].

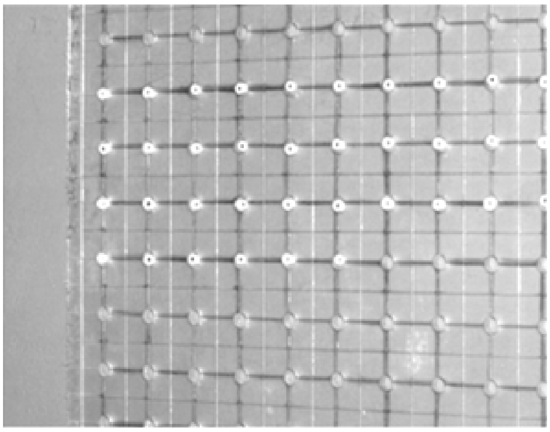

**Figure 2. A template in the form of a square grid with side dimensions of 20×20 mm and holes for installing deformation benchmarks.**

**Figure 3. General view of the laboratory setup window with deformation benchmarks placed in the initial position.**

To process the experimental data, dependences for specific adhesion and modulus of deformation were used from the tables of BCaR (Building Codes and Regulations) 2.02.01-83* (Foundations of buildings and structures):

$$C = 25e^2 - 84.4e + 72.3; \quad E = 57.1e^2 - 127.7e + 77.9,$$

where $e$ is the porosity coefficient of the soil; $C$ is the specific adhesion [kPa]; $E$ is the modulus of deformation [MPa].

Since the process of piles installation will result in the soil deformation this fact will change the porosity coefficient therefore the main quantities become functions of deformation. In this regard, to calculate the settlement of frame-gantry foundations correctly and assess the soil strength under the piles, it is necessary to have data on changes in the specific gravity, deformation modulus, adhesion forces and the angle of internal friction of the soil in the process of driving wedge-shaped piles and static loading of frames.

For a complete analysis of soil deformation in the core under the same conditions, a series of comparative experiments was carried out to test three types of frame-gantry foundation models. The studied foundations consisted of two vertical piles, two piles inclined at an angle of 15° and two piles inclined at an angle of 30°, fixed by a rigid grillage.

In studies of soil deformation during pile driving, it was found that a compaction zone is formed around the driven pile because of soil movement in the space around the pile. During the movement of the pile, soil particles move under its lower end along a certain trajectory down and to the side, forming a compacted dumbbell-shaped zone along the side surface of the pile. In addition, it was determined in all three cases that part of the soil from the area close to the surface, and the soil from subsequent layers the pile had passed through were transferred along with it along the pile axis, i.e. soil compaction occurs in this zone.

It is believed that in the case of driving piles with a variable length section (pyramidal, conical, wedge-shaped, etc.) the soil compaction zone resembles an ellipsoid of rotation. The boundaries of the compacted soil are significantly more than 3 diameters away from the pile edge, and up to 50 % of the load is taken by the upper half of the pile. In all three cases, the well-known conclusion is confirmed that pile installation in the soil results in the improvement of physical and mechanical properties of the near-pile area of the soil base, although the nature of the compaction zone formation and its dimensions will differ slightly in each case.

## *3. Results and Discussion*

Fig. 4–5 show the study results of the soil properties changes in compacted zones after the end of the single pile installation and the framed vertical piles installation. Studies have shown that when driving wedge-shaped piles in clayey soils of soft-plastic consistency, the compaction zones around one pile reach 4d – 4.5d in the horizontal direction (where d is the average cross-section diameter of the pile). In the plane of the tip, the compacted zones extend to a depth of 1.5d – 2.0d. The specific gravity of the soil varies on average from 19.5–19.8 kN/m$^3$ to 23.2–25.0 kN/m$^3$. Fig. 4-5 also show data on changes in the specific gravity of the soil at various distances from the axis and below the plane of the tip of vertical wedge-shaped piles. It can be seen from the given data, that the greatest compaction occurs in the plane of the pile tip and in the upper section, equal to 1/3-1/2 of the pile length.

From the given data it can be understood that the adhesion forces change on average from 0.024–0.025 MPa to 0.037–0.045 MPa, i.e. about 1.4–1.8 times.

Numerous checking of the experiment results has demonstrated that soil compaction in the near-pile area of conical piles does not affect the change of the internal friction angle. As a rule, this measurement is constant. The difference in measurement is only (3–5 %). Experiments have also established that there is a significant increase in the deformation modulus in the compacted zone (Fig. 4–5). As a result of pile driving, there was an increase in the modulus of deformation under the piles at a depth of 1.5d – 2.0d.

In the horizontal direction, the zone of change in the deformation modulus for single piles is 4d – 4.5d. The magnitude of the deformation modulus in the plane of the tip and in the upper section of the piles length (1/3–1/2 of the length) changed from 14.5–16.5 MPa to 29.7–39.1 MPa.

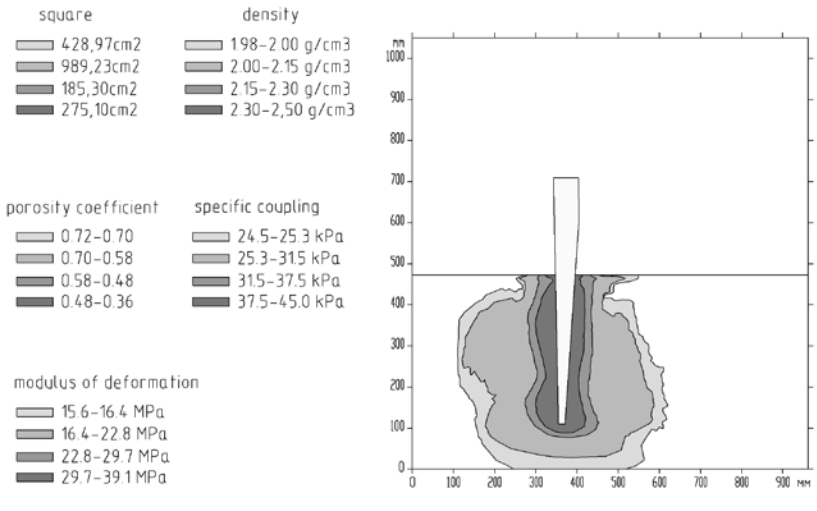

**Figure 4. Contours of changes in the physical and mechanical properties of soils in the compacted zone during the installation of a single vertical pile.**

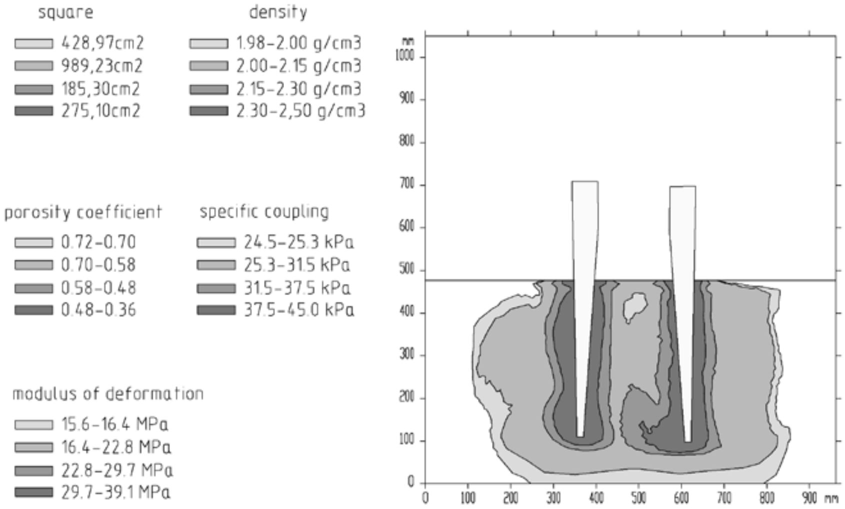

**Figure 5. Contours of changes in the physical and mechanical properties of soils in the compacted zone during the installation of two vertical piles.**

Figure 6-7 shows changes contours in soil properties in the compacted zones after the end of the single pile installation and the framed vertical piles installation inclined at an angle of 15°. Studies have shown that when driving wedge-shaped piles at an angle of 15° from the vertical, in clay soils of a soft-plastic consistency, the compaction zones from the inner face of one pile along the normal to its axis reach 4d – 5d (where d is the average cross-section diameter of the pile). In the plane of the tip, the compacted zones are distributed around the circumference and extend to a depth of up to 3d. The compaction of the soil is combined with the soil heaving on the outer face of the pile. It occurs as the reaction of the soil from the inner face of the pile, and the distribution of the compaction in this case has a different form. When the second inclined pile is installed, the compacted zones of the inner pile faces close together and form a compacted soil mass.The greatest compaction occurs in the area of the pile tips. An area of lower density is marked in the upper part of the piles; it is formed in the result of partial uplift of the soil in the upper part of the pile. The specific gravity of the soil varies on average from 19.7–19.8 kN/m$^3$ to 23.2–25.0 kN/m$^3$.

From the given data, it can be seen that the adhesion forces change on average from 0.023–0.024 MPa to 0.036–0.044 MPa, i.e. about 1.5–1.8 times. The modulus of deformation changes from 14.7–15.5 MPa to 28.5–37.8 MPa that is 1.9–2.4 times.

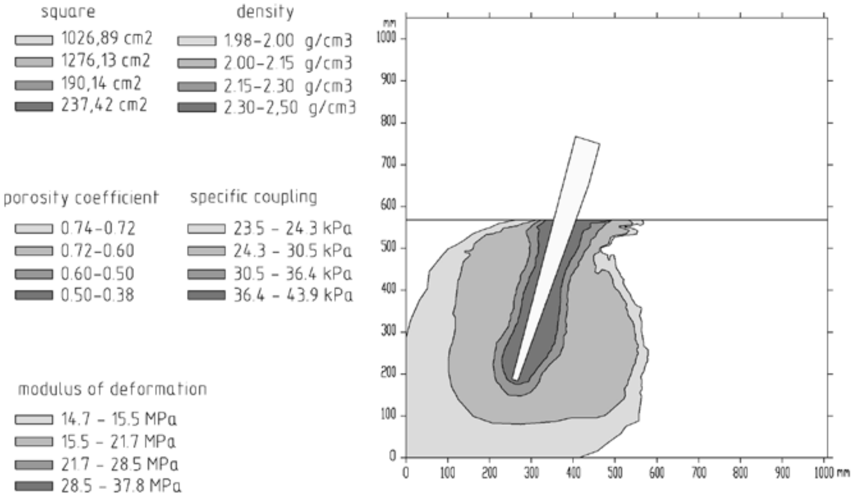

**Figure 6. Contours of changes in the physical and mechanical properties of soils in the compacted zone during the installation of a single pile with a slope of 15°.**

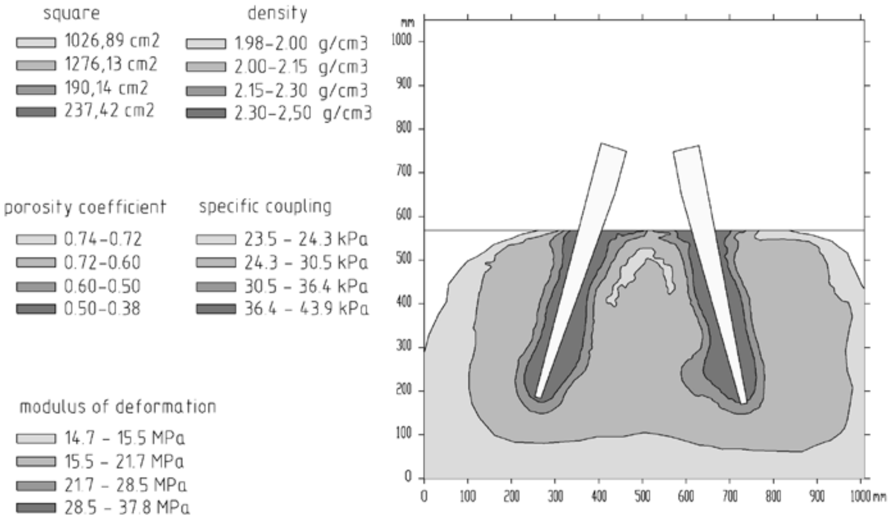

**Figure 7. Contours of changes in the physical and mechanical properties of soils in the compacted zone during the installation of two piles with the slopes of 15°.**

It should be noted that there is no mutual influence between the piles being installed at a distance of 4d. In this case, the change in soil properties in the active pile zones can be taken into account as for one pile.

Fig. 8–9 show contours of changes in soil properties in compacted areas after the installation of a single inclined pile and the framed inclined piles, the angle of piles inclination is 30° from the vertical.

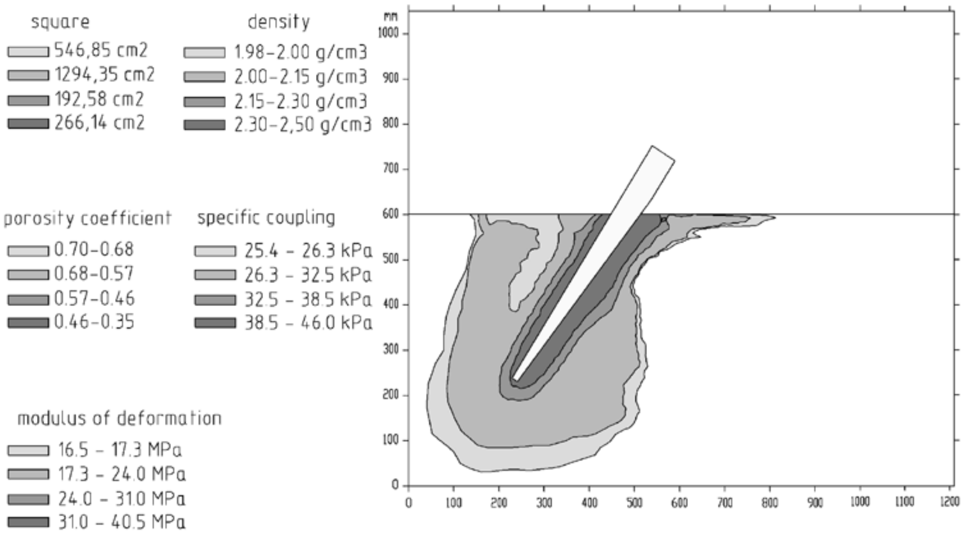

**Figure 8. Contours of changes in the physical and mechanical properties of soils in the compacted zone during the installation of a single pile with a slope of 30°.**

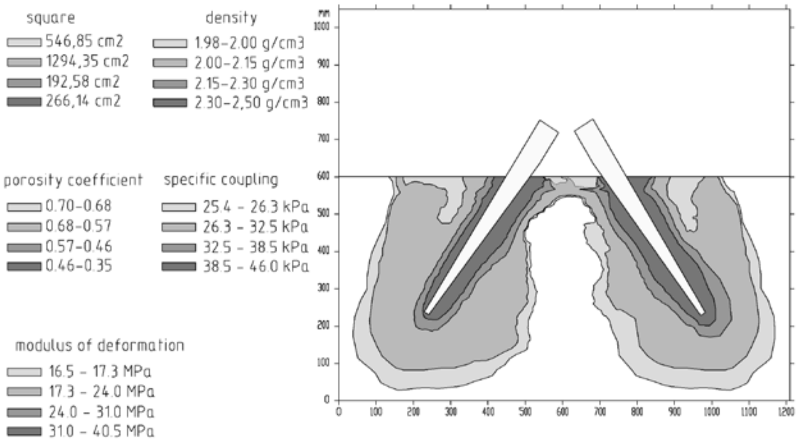

**Figure 9. Contours of changes in the physical and mechanical properties of soils in the compacted zones during the installation of two piles with slopes of 30°.**

Studies have shown that when wedge-shaped piles are driven at an angle of 30° from the vertical, as well as, when piles are driven at an angle of 15° the compaction zones have a nonhomogeneous distribution. From the inner face of one pile, along the normal to its axis, the compaction zones reach 3.5d – 4d (where d is the average cross-section diameter of the pile). In the plane of the tip, the compacted zones are distributed along the pile circumference and spread to a depth of up to 3 d. From the outer face of the pile, soil compaction occurs in the same way as in the case when the pile is driven at an angle of 15°.

The compaction is combined with a big heave, and the distribution of the compaction is nonhomogeneous. There is a zone of lower density in the upper part of the pile, which was not observed during the installation of a vertical pile and a pile with a slope of 15°. When the second inclined pile is being installed, the compacted zones of the inner face of the piles partially close in the upper part of the piles. Thus, when the piles are driven at an angle of 30°, the compacted zones in the near-pile area can be considered as with a single pile. The greatest compaction occurs in the area of the pile tips. An area of lower density is defined in the upper part of the piles. The specific gravity of the soil varies on average from 19.7–19.8 kN/m$^3$ to 23.2–25.0 kN/m$^3$.

From the given data, it can be seen that the adhesion forces change on average from 0.025–0.026 MPa to 0.038–0.046 MPa, i.e. about 1.5-1.7 times. The deformation modulus changed from 16.5–17.3 MPa to 31.0–40.5 MPa, i.e. 1.8–2.3 times.

The tests revealed that the density at the side face of the wedge-shaped pile support of the model changed from an average of 1.98 g/cm$^3$ to 2.5 g/cm$^3$, the porosity coefficient changed from 0.7 to 0.35. Concerning the initial measurements, the average density in the fixed active zone of the soil area increased by 12 %, and the average porosity coefficient decreased by 20 %. As the soil partially moved upwards during the pile installation, the soil from the outer face of the pile was subjected to less compaction. This situation is typical when piles are installed at the angle of 30°.

## *4. Conclusion*

In laboratory conditions on small-scale models we studied the interaction of vertical frame-gantry strip foundations with different angles of inclination of wedge-shaped piles and a clayey base.The new design scheme of the frame-gantry strip foundation at an angle of 30° wedge-shaped piles with respect to the vertical allows the use of the upper layers of soil to distribute vertical static loads on the soil base of a larger area, in contrast to the existing frame-gantry piles. The settlement of the frame-gantry strip foundation, with the slope of the wedge-shaped piles at an angle of 30° relative to the vertical, is formed mainly due to the deformation of the uncompacted soil mass enclosed between the piles, which is 96 % of the entire settlement of the foundation. Experimental studies were carried out with the help of modern approved digital control and measuring systems, calibrated primary converters and calibrated instruments.

The test results also showed:

1. The outline of zones with altered soil characteristics depends on the angle of the piles inclination and the distance between them. The greatest bearing capacity has a foundation with a pile angle

of 30°. This shows that such a foundation design contributes to a better distribution of stresses in the soil mass. Considering the soil base of foundations with vertical and inclined piles at an angle of 15°, it can be noted that the soil shearing in the inter-pile space occurs largely together with piles.

This indicates that the settlement of the foundation takes place mainly due to the deformation of the underlying layer below the ends of the piles. It is noted that in the process of the soil base loading of a frame-gantry foundation with a pile inclination angle of 30°, an increase and closing of the compaction zones occur in the inter-pile space. A significant change in the density of the soil, by 30% from the initial one, occurs directly in the upper part between the piles of the frame during the foundation settlement. The foundation settlement takes place mainly due to the deformations of the non-compacted soil between the piles.

2. When wedge-shaped pile models are installed into loamy soil, the total deformation modulus $\left(E\right)$ and specific cohesion $\left(C\right)$ increase by 1.5–2.4 times, depending on the angle of installation. The angle of internal friction $\left(\varphi\right)$ practically does not change.
3. Bearing capacity at the same settlement of a frame-gantry foundation with wedge-shaped piles inclined to the vertical at an angle of 30°, compared to frame-gantry foundations with piles tilted to the vertical at an angle of 0° and 15°, was higher by 1.3 and 1.2 times, respectively , and when compared with conventional prismatic piles, the specific bearing capacity was 2.2 times higher.

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