Experimental and theoretical studies of the interaction of slotted foundations with the basis

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Abstract. The article presents the results of experimental and numerical modelling of slotted foundations. Model and large-scale experimental studies were conducted. The influence of the number, thickness, and depth of sinking of the slotted foundation walls on the distribution of stresses and deformations in the basis is established. The results of numerical studies show the distribution of stress and strain components at the base of slotted foundations, taking into account the elastic-plastic properties of the soil. For the estimation of slotted foundations based on the maximum permissible precipitation using solutions of nonlinear soil mechanics, the factors affecting the precipitation are identified and the corresponding approximate dependencies are obtained. The use of non-linear calculation methods makes it possible to design slotted foundations based on the ultimate deformations. These studies are confirmed by the results of experiments of various authors. Designs of slotted foundations are implemented in the construction of buildings and structures, which reduce the cost of the zero cycle, reduce the material consumption in comparison with standard solutions. The article is of interest to specialists in the field of soil mechanics, geotechnics, and foundation engineering.

1. Introduction

One of the promising directions in the field of foundation construction is the use of effective structures of slotted foundations. The classic experimental and theoretical investigations [1-20] are devoted to the study of the interaction of slotted foundations and barrettes with the basis.

The slotted foundation consists of several rows of vertical plates arranged parallel to each other, which are supported through the distribution element of the aboveground structures. Vertical plates are made by concreting or installing precast elements in previously cut slots in the soil mass. In the plan, the slits are installed as continuous under the entire wall, and in the form of separate elements, located intermittently [1-6].

In the construction of slotted foundations are eliminated technological operations: preparation of a trench, preparation of substrate, installation of formwork, the execution of the backfill soil [1-7]. Vertical wall reinforcement is not required, except when such foundations are used in buildings with basements.

Slotted foundations have a number of advantages over other types of foundations:

- low material consumption per unit of load-bearing capacity on the ground, significant bending stiffness per 1 m³ of reinforced concrete;
- loads transmitted to the slotted foundation are perceived by friction on the side surface and the work of the tip (lower part);
• characterized by increased specific load capacity as a result of the inclusion of a larger volume of soil in contact with the side surface;
• work well with vertical, horizontal and torque loads;
• slotted foundations can be made as tape, or under free-standing supports, have a different shape in the plan;
• possibility of manufacturing slotted foundations using the method of ramming with the formation of a compacted zone in the base.

2. Experimental investigations

2.1. Model experimental studies

To study the interaction of slotted foundations with the base, model experiments were conducted in a soil tray with a size of 2.5×2.0×0.25 m with a front transparent wall having a scale grid of 50×50 mm for the convenience of laying layers and photofixing experiments [1, 2].

The pressure on the base was reported through the lever system in steps of 0.02 MPa. Deformations of the bases were recorded after their stabilization using an IC-50 hour-type indicator. In experiments, the gradual process of forming a zone of deformations at the base of slotted foundations was photographed. The main dimensions and indicators of slotted foundations are shown in figure 2. As a ground base, fine, loose sand was used. Experimental models of slotted foundations are shown in figure 1. On vertical wall mounted base plate – grillage.

Figure 1. The modelling of the slotted foundation

Figure 2. The double-slot foundation settlement dependence under the load:
1 – h=10 cm, 2 – h=15 cm, 3 – h=20 cm

Figure 3. The foundation settlement dependence under the number of slots:
1 – single-slotted, 2 – double-slotted, 3 – three slotted
As a result of experimental studies, the influence of the wall length $h$, wall thickness $\delta$, number of walls on the load-bearing capacity and precipitation $S$ of one-, two-and three-slot foundations was established (figure 2, 3).

During the experiments, layer-by-layer movements of soil at the base of foundations and soil deformations in the core were recorded.

In a two- and three-slot foundation, vertical walls and soil enclosed between the foundation walls can be considered as a foundation on a natural basis of depth $h$, which works by transferring pressure along the sole and friction of the soil along the side surface of the foundation.

2.2. Full-scale experimental study

For the use of slotted foundations, the issue of reliable assessment of their bearing capacity in various ground conditions is of great importance [8-20]. Large-scale tests of the foundations were carried out in a soil tray with a size of $1.9 \times 2.0 \times 1.7$ m. medium-sized sand, loose with $\gamma=19.0$ kN/m$^3$, $e=0.720$; $W=0.04$, was used as the basis. The experiments used single-and double-slotted foundations with a wall thickness of $\delta = 4$ and 8 cm, the depth of immersion of reinforced concrete walls was $h=25$, 50, 75 cm (figure 4, 5, 6).

**Figure 4.** Dependence of the single-slot (a) and double-slot (b) foundation settlements on the load at $\delta = 4$ cm: 1 – $h=25$ cm; 2 – $h=50$ cm; 3 – $h=75$ cm

**Figure 5.** The dependence of foundation settlements on the depth of the wall immersion $h$ at $\delta = 4$ cm
Layer-by-layer deformations in the base were measured using deep marks that were sunk below the tip plane and connected by a steel string with a diameter of 0.3 mm with an hour-type indicator with a division price of 0.01 mm. Model settlements were measured with Maximov PM-3 deflection meters with an accuracy of 0.1 mm. For determining the stresses in the base and along the side surface of the models, general pressure pseudoses were used (figure 7) [12, 13].

Testimony massdot was shot with an automatic electronic tester strains HADES-4. Figure 4a shows the dependence of the single- and double-slot foundation settlements on the load at different depths of wall immersion. Figure 4b shows the dependence of the slotted foundation settlements on $h$. From the data shown, it can be seen that an increase in the depth of the slotted foundation leads to a smooth decrease in precipitation. Thus, when $h$ changes from 25 cm to 75 cm, the single-slot foundation settlements decreases by 2.1 times ($P=90$ kN), and the double-slot foundation settlements decreases by 4.8 times ($P=90$ kN). The foundation and soil located between the walls of a two-slot foundation work as a single array.

Analysis of layer-by-layer displacements at the base of slotted foundation models showed that the largest displacements were obtained by marks located below the plane passing through the tip of the foundation models. Vertical movements decreased with increasing depth and tended to zero at the lower boundary of the compressible thickness.

The concentration of vertical stresses $\sigma_z$ is observed in the area adjacent to the plane of the tip of the slotted foundations, and reaches maximum values of 0.15-0.18 MPa. From a depth of (2,0-2,1)$h$ below the plane of the tip, the attenuation of vertical stresses is recorded.

To assess the load-bearing capacity, a series of field experimental studies of slotted foundations was conducted on a test site composed of refractory clay (IGE-1) with the following physical and mechanical characteristics: $\gamma=20.0$ kN/m$^3$; $\varphi=18^\circ$; $c=0.028$ MPa; $E=13.0$ MPa. The clay is underlain by fine, loose sand (IGE-2) with $\gamma=21.0$ kN/m$^3$; $\varphi=24^\circ$; $E=12.0$ MPa.
Experiments were conducted with single- and double-slit foundations with a wall depth of $h=0.75$ m; 1.50 m; 2.25 m, wall thickness $\delta=13$ cm, foundation length $l=2.4$ m, the width of the sole of the grillage is assumed to be $b=40$ cm, 60 cm, the height of the grillage is $h_p=40$ cm.

The figure 8 shows the dependence of settlements on load for slotted foundations with different depths of immersion. The active zone is located at a depth $(1.0-1.2)h$ below the plane of the sole of the walls. As a result of research, it was found that the grillage does not start working immediately, but after compressing the soil under the sole when the foundation precipitation is $S=2-3$ mm and takes up to 25-30% of the load transferred to the slotted foundation. The results of field experiments show that the calculated vertical load on the slotted foundation is $250-400$ kN/m. An increase in the load-bearing capacity of slotted foundations by 20-40% is possible by plunging the prefabricated wall into a cut slot of smaller dimensions or ramming narrow slots with an inventory punch followed by filling with concrete.

Experimental and theoretical studies performed for most types of soils and types of foundations show that the relationship between the load applied to the slotted foundation and its precipitation is nonlinear. Therefore, further improvement of the slotted foundation design methodology should be based on solutions of nonlinear soil mechanics.

2.3. Numerical study

The finite element method was used to estimate the deformed and stressed state of the slotted foundations, taking into account their joint operation. The numerical study was performed by changing the number and depth of immersion of walls, strength ($\phi$, $C$) and deformation ($E$, $\nu$) characteristics of the soil to change the stress-strain state of the bases of slotted foundations by the finite element method in the framework of a mixed problem of the theory of elasticity and plasticity, in which the elastic-plastic model of Mohr-Coulomb is implemented (figure 9-14) [16-20].

To solve this problem, geotechnical complex Plaxis was used, it implements the finite element method numerically. Simultaneous consideration of the strength and deformation properties of the soil in the calculations of the stress-strain state of the base of the sleeper foundation is carried out in the solution of the plane problem of the finite element method. The soil in the pre-limit state is a continuous linearly deformed medium that passes with subsequent loading into the limit (plastic) state in accordance with the Mohr-Coulomb yield criterion (strength). The calculation was performed using a step-by-step load application procedure. The boundary conditions assume the restriction of horizontal movements along the edges of the area and the absence of horizontal and vertical movements along the lower border [8].

When selecting the size of the region, the condition of attenuation to the minimum values of the value of deformations and stresses in the base was assumed.
Figure 9. The single-slot foundation settlement dependence under the load

Figure 10. The double-slotted foundation settlement dependence under the load

Figure 11. Vertical displacements $U_z$ in the basis of the double-slotted foundations

Figure 12. Horizontal displacements $U_x$

Figure 13. Vertical stresses $U_z$ displacements

Figure 14. Plastic deformation zones
3. Conclusions
A numerical study of the influence of the number and depth of immersion of walls \( h \), strength \( \phi; c \) and deformation \( E; v \) characteristics of the soil on the change in the stress-strain state of the bases of slotted foundations by the finite element method in the framework of a mixed problem of the theory of elasticity and plasticity, in which the model of elastic-plastic medium is implemented. Factors \( \phi; c; E; v; P \) were identified for calculating slotted foundations based on maximum permissible precipitation using solutions of nonlinear soil mechanics; h) that affect the precipitation and the corresponding approximate dependences are obtained.

A multi-factor power dependence is used as a mathematical model that relates the settlements value to the initial parameters \( \phi; c; E; v; P; h \):

\[
S = S_0 \cdot k
\]

where \( S_0 \) is the reduced slotted foundation settlement with soil deformation characteristics: \( E=20 \) MPa, \( v=0.3 \) Poisson's ratio.

\[
S_0 = \frac{p^{2.090}}{1.714 \cdot h^{0.965} \cdot \phi^{1.120} \cdot c^{0.298}} \quad \text{(single-slotted foundation)}
\]

\[
S_0 = \frac{p^{1.818}}{1.327 \cdot h^{0.696} \cdot \phi^{1.098} \cdot c^{0.183}} \quad \text{(double-slotted foundation)}
\]

The use of non-linear calculation methods makes it possible to design sleeper foundations based on the ultimate deformations.

Making cracks by ramming allows you to create a compacted zone around the vertical walls and significantly increase the bearing capacity of the foundation.

The use of slotted foundations in comparison with standard solutions can reduce the material consumption by 1.2-1.5 times, labor costs and deadlines by 1.5-2.0 times, and reduce the volume of earthworks by 5-10 times.

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