The estimation of efficiency from application the local strengthening of strip foundations by short piles

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Abstract. Currently many multi-populated Russian cities have an acute shortage of usable space in the central part. The superstructure of one or several floors can become a solution, but it entails a danger of overloading the foundations and the occurrence of uneven precipitation. In this connection, the authors proposed a new model for strengthening the foundations of reconstructed buildings: short piles are pressed or stuffed in local areas, the pile heads are tied with a grillage with the existing foundation. The article discusses the practical and theoretical solution of this problem. Two design models were produced on a 1:5 scale: a strip foundation model and a strip foundation model locally strengthening with short piles. The experimental results are obtained. A sand base was also calculated using the finite element method by PC PLAXIS. The calculated and experimental data have sufficient convergence of the results. Based on the calculation and experiment, it was found that the draft of the strengthening foundation is 1.875 times less than the draft of the strip foundation, which proves the effectiveness of this method of strengthening with an increase in the load on the foundation by 1.5-2 times.

1. Introduction

Most multi-populated Russian cities are experiencing an acute shortage of commercial and administrative space in the central regions, since historic buildings of medium height predominate in the development of districts. The solution to this problem is the reconstruction of buildings and the superstructure of floors. In this case, there is a danger of overloading the foundations, therefore, it is advisable to carry out work to increase the bearing capacity of the foundation when building floors and increasing the load on the foundation. The requirement of strengthen the strip foundations are arising for trouble-free operation. For this, soil cement, screwed, crushed, and other types of piles are used, which have a number of certain advantages compared to the artificial improvement of the base.

In article [1], a technique was proposed for reinforcing the foundation slab with piles for a multistorey building under construction: geotechnical calculations taking into account the inclusion of reinforcement piles in work at any stage of foundation loading can reduce pile loads by 20–40%.
In article [2], the authors investigated the stress-strain state of the plate-pile foundation and the development of stresses in the inter-pile soil mass.

The results of experimental studies of the work of pile-slab foundations on models are presented in [3]. Based on the results of the experiments, a methodology for calculating the combined pile-slab foundation was proposed, which made it possible to obtain a share of the bearing capacity of piles and slabs.

In [4], the problems of strengthening the strip foundations of operated residential buildings are considered. A typical solution is the installation of piles with the transfer of load to mud clay-like clay while part of the load continues to be perceived by the foundation of the old foundation.

D. A. Chernyavsky [5] presented the results of numerical studies of the work of brown injection conical piles in clay soils: conical piles are better than cylindrical ones. A review of anisotropic shallow foundations is given in [6].

When calculating a soil base, two types of models are most often used. The first is models that take into account local elastic deformations. This is the Winkler model [7], the two-parameter model of P.L. Pasternak [8] with a variable stiffness coefficient, etc. In the models of the second group, soil is considered as an isotropic homogeneous body, it is a model of elastic homogeneous and inhomogeneous space. Such a model is described in the works of J. Boussineschi [9], which is improved in the works of M.I. Gorbunov-Posadov [10]. Interim solution proposed by P.L. Pasternak [8]. In his model, the elastic foundation is characterized by two coefficients that allow one to take into account the work of the soil in compression and shear.

V.P. Dyba developed an approximate closed-loop solution of the mixed elastoplastic problem of determining the parameters of the stress-strain state of the foundation of a strip foundation of finite rigidity [11]. An analytical solution was obtained on the ultimate stress state of a weightless base with friction and adhesion [12].

The solution of the mixed problem was obtained by V.V. Sokolovsky [13] in a strict setting for perfectly connected soil, with semi-infinite loads. Developing this solution I.V. Fedorov [14] obtained a solution for a weightless half-plane, with semi-infinite loads. M.I. Gorbunov-Posadov [5] obtained a solution to the mixed problem for a rigid strip foundation of finite dimensions, taking into account the formation of the core and curved sliding surfaces.

The stressed state of the base under the strip discontinuous foundation was experimentally investigated by E.A. Sorochan [15], S.I. Evtushenko and T.A. Krachmalnyi [16,17] etc. Refinement of the methodology for calculating intermittent foundations were devoted the research of M. I. Fidarova [18]. In the work of P.G. Kuzmina and V.I. Ferronsky [19] sets out a method for determining the size of the foundation, based on the ultimate deformations of buildings and structures. HER. Linovich and L.E. Linovich [20] proposed a method for determining the size of foundations according to previously calculated design pressure $R$, presented in tabular form.

However, there is no analytical solution describing the joint work of a strip foundation locally reinforced with piles.

2. The experiment of work of a strip foundation, locally reinforced with piles

Employees and students of Civil Engineering Faculty of the Platov South-Russian State Polytechnic University (NPI) was conducted the experiment for work of a strip foundation, locally reinforced with piles, on a sandy soil foundation. The test machine MF-1 was used - a vertical testing machine with a hydraulic drive, a pendulum hydraulic force meter and a central control panel.

The load transfer is regulated through a pump station located under the control panel of the testing machine. The base model is medium-grained, air-dry sand (density 1.80 g/cm$^3$, deformation modulus $E$ - 20.75 MPa, Inner friction angle, $\varphi$ - 43 ° 16', specific adhesion, $C$ - 0 kPa).

The total load that three jacks can create is 1,500 kN (Figure 1).

In an experimental study of the work of a strip foundation, the task is to study the interaction process of a scale model of the foundation on a sandy foundation, with fixing the change in the parameters under study in time for the subsequent construction of a state graph in the entire load
The result of the experiment is a model of the phenomenon under study, which then must be transferred to real objects according to similarity criteria.

![Figure 1. Scheme of loading models of strip foundations: 1 - a jack; 2 - load traverse; 3 - soil foundation, 4 - substructure](image)

The theoretical result of the research is the development of a model of the physicomechanical process of force interaction of the strip foundation reinforced with piles and without reinforcement on a sandy foundation. The result of the work is the development of a new design, verification of its performance. When modeling, the foundation is based on the flexibility of the foundation determined by M.I. Gorbunov-Posadov [21].

For a flat ultimate equilibrium of an elastic-plastic base, as well as for up to an ultimate stress state, modeling conditions according to V.A. Florin [22] should be expressed in the form of the following relations:

\[
\frac{m_b \cdot m_y}{m_\sigma} = 1, \quad \frac{m}{m_\sigma} = 1, \quad \varphi = \text{const},
\]

where \(m_b, m_y, m_\sigma, m_\alpha, m_c\) – simulation coefficients, respectively, of linear dimensions, volumetric forces and adhesion forces, \(\varphi\) – inner friction angle.

Introducing the concept of the simulation number [23] for incoherent soil for \(c = 0\) and \(\varphi = \text{const}\) we obtain:

\[
N = \delta by, \quad N_y = N_\sigma = \text{const},
\]

where \(\sigma\) – medium pressure under the sole of the foundation; \(N_M, N_H\) – simulation number respectively for the model and natural foundation.

To derive the conditions for modeling a spatial problem, we use the equations of the axisymmetric limit equilibrium of V.G. Berezantsev [24].

Due to the great similarity of the shape of the elastic core under circular and square foundations, the solution of the axisymmetric problem is approximately applicable for square foundations [25].

The simulation conditions for the spatial problem [26] will take the following form:

\[
N = \frac{\sigma}{by}, \quad N_M = N_H = \text{const}, \quad \varphi = \text{const};
\]

where \(b\) – is the side of foundation.

According to the results of experiments on a sandy foundation [27], it was found that the limiting values of the simulation numbers are quite close and a conclusion is made that \(N\) is constant. In the experiments of the SRSPU employees [28] it was found that the simulation number is variable and increases with decreasing model sizes.

In the experiments, two designs of the strip foundation continuous to reinforcement and reinforced by piles, the prototype of which is a real strip foundation, were investigated [29]. The occurrence of the “arch effect” phenomenon [30] in combination with the formation of a single compacted zone
uniting closely spaced short piles into a single structure also contributes to the increase in the bearing capacity of the base.

To achieve these goals, six series of experiments were planned and carried out with a total number of experiments equal to 26. In the study of the construction of the foundation without reinforcement, two series of two experiments were carried out. And when studying the work of the construction of the strip foundation after reinforcement (Figure 2), four series of experiments of four experiments each were carried out.

Figure 2. Longitudinal diagram of the strip foundation model: 1 - 6-PAO grade deflection meter; 2 - ball bearings; 3 - indicator of the sentry type ICh-10 (measurement of console movement); 4 - load traverses; 5 - model of the baseplate; 6 - sand base; 7 - tray walls

Figure 3 shows the preparation of the model (driving piles of strengthening), figure 4 shows the model of the reinforced foundation and the general view of the MF-1 testing machine.

Figure 3. Prepared base after driving piles of strengthening.  
Figure 4. General view of the strengthening foundation model in the tray of the testing machine MF-1.

3. FEM Analyses of work of a strip foundation, locally reinforced with piles
To analyze the adopted design decisions, this task was also calculated using the FEM, the PLAXIS program was used. The design scheme is fully consistent with the experiment (Figure 5, figure 6). In this calculation results of stresses were received: vertical shear stresses, total normal stresses (figure 7, for strip foundation, effective normal stresses (figure 8) for pile foundation. Also, were received results of total displacement: figure 9, figure 10 for strip foundation and figure 11, figure 12 for pile foundation.
Figure 5. The design scheme of strip foundation.

Figure 6. The design scheme of pile strengthening foundation.

Figure 7. Total normal stresses for strip foundation.

Figure 8. Effective normal stresses for pile strengthening foundation.

Figure 9. Total displacement for strip foundation, view from above.

Figure 10. Total displacement for strip foundation, incision.
4. Conclusion

According to the results of experiments and calculations, it was revealed that when applying reinforcement with short piles in local areas, the bearing capacity of the foundation significantly increases, and its settlement decreases. So, the draft of the strip foundation at the maximum experimental load was 15 mm, while the draft of the pile (reinforced) foundation was 8 mm. Thus, the settlement of pile foundations is 1.875 times less than strip foundations, which makes it possible to increase the load on the foundation by almost two times, taking into account the strengthening of the foundation. This option is suitable for superstructure floors (increase the useful area of the building), to strengthen the foundations of buildings and structures that are in an inoperable technical condition due to the work of foundations.

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