Determination of modeling conditions for the strip foundation reinforcement construction by the method of bringing the foundation plate with fixed formwork in the chute experimental studies

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Abstract. The article discusses the conditions for creating a model for conducting experimental studies in a chute of a patented reinforcement design of existing strip foundations. It is proposed to simulate and investigate the effectiveness of the new construction of the strip foundation reinforcing, allowing to take into account the rheological processes in the soil base when carrying out the measures for structural reinforcement, using a shaped sheet in the conjunction with monolithic elements. Based on the rules of modeling and similarity theory, it is proposed to determine the optimal conditions for experimental modeling of a solution to strengthen the existing monolithic reinforced concrete strip foundations by working together with a monolithic reinforced concrete slab, divided by a shaped sheet in height into two parts (upper and lower) with the injection wells for the hardening mortar intrusion directly under the fixed formwork from a shaped sheet.

Introduction
One of the common technical solutions for reinforcing strip foundations is the installation of a monolithic reinforced concrete slab in the inner space of the foundation faces’ contour [1, 2, 3], which significantly increases their bearing capacity, since increasing the foundation area dramatically decreases the average pressure under its base. However, in order for the foundation slab to come into operation, it is necessary that the load from the building is transferred to the slab itself through the interface nodes with the existing construction of strip foundations, and this is possible only after a considerable time and with additional precipitation, which we want to avoid.

The proposed method of reinforcing strip foundations, [4] issued by the patent [5], involves strengthening them by working together with a monolithic reinforced concrete slab, divided by a shaped sheet in height into two parts (upper and lower) with the injection wells for the hardening mortar intrusion directly under the fixed formwork from a shaped sheet. This design of the foundation plate makes it possible to start working with the soil in the building basement immediately upon strengthening, avoiding the additional precipitation by forcing into the space between the upper and lower parts of the hardening composition. It is assumed that the load from the building is transferred to the slab through the nodes of its interface with the existing construction of strip foundations. The pressure acting on one side of the basement soil through the slab bottom compresses it, and on the other
hand, presses on the top of the foundation slab and raises it, including the entire foundation reinforcement structure.

It is clear that in design practice there are a fairly large number of successfully applied constructive methods for strengthening foundations [6, 7]. However, the involvement in the work of the base soils existing strip foundations is associated with technologically complex and expensive reinforcement methods, the effectiveness of which is very difficult to control. That is why in the practice of designing buildings and structures that have defects in the supporting structures, indicating insufficient bearing capacity of the strip foundations’ structures or the foundation soils, as well as during reconstruction associated with an increase in average pressure under the foundation base due to a superstructure or the installation of massive technological equipment, often, the designers make the constructive decisions that are much easier to control in the production process.

Pronozin Y.A. proposed similar constructive solutions [8] for the construction of foundations with a shell under the supporting walls of the building, however, in these structures, the shells were made on an artificially made soil base of a certain curvature with preliminary compaction during new construction, and not during reinforcement.

The proposed patent solution [5] is that in concrete shirts arranged along the inner edge of the bearing walls, formwork is formed from a shaped sheet with injectors, having previously arranged the concrete base of a given section reinforced in the lower zone. Then, a reinforcing mesh is arranged on top of the shaped sheet in the upper zone of the upstream foundation slab, after which concreting of the upper slab of a given section height is performed. After the concrete has hardened through the injectors, the hardening composition is delivered to a value commensurate with the design value of the average pressure in the space between the shaped sheet and the base plate’s bottom.

Analysis of the soil base stress-strain state experimental studies’ experience on the foundation models
The most reliable way to confirm the effectiveness and efficiency of the proposed technical solution for strengthening the foundations is the experimental research. Carrying it out on a full-scale object is expensive and time-consuming, therefore it is planned to conduct the research on the model. This will make it possible to reproduce a real picture of the reinforced foundations interaction with a soil base on the model and obtain the data on the stress-strain state (SSS), showing a real picture of the processes occurring in the soil base.

Carrying out the experimental studies of the proposed technical solutions is planned on the foundations and bases laboratory basis of the department “Industrial civil engineering, geotechnics and foundation engineering” SRSPU(NPI), named after M.I. Platov in the chute of the testing machine MF-1 designed by Yu.N. Murzenko (Figure 1), which is the central link in the automated system of scientific research (ASSR) of the bases and foundations on the models [9].

The power frame of the machine consists of vertical columns and a beam - traverse, to which the hydraulic jacks are jointly suspended with a movable trolley. Depending on the test setup, one, two or three jacks may be included in the work, which can be fixed on any part of the guide. The jacks are located with the plunger down and equipped with return springs. The load transfer is regulated through the control panel of the machine, which has a measuring scale with three measurement limits: up to 100, 200 and 500 kN and a division price of 200, 500 and 1000 N, respectively. The chute of the MF-1 machine is reinforced concrete, has internal dimensions of 3.0x3.0x2, 2 (depth) m and is filled with medium-grained air-dry sand of the Oryol quarry of the Volgograd region, which simulates a sandy base with the following physical and mechanical properties: loose density $\gamma=1,565$ g/cm$^3$; compacted density $\gamma=1,89$ g/cm$^3$; the internal friction angle $\varphi = 43^\circ16'$; the deformation modulus $E=20,75$ MPa.

A prerequisite for conducting the experimental research in the chute is to create the optimal foundation model and recreate the soil conditions.

The conditions for modeling the joint work of bases and foundations are devoted to the work of V.A. Florina, P.D. Evdokimova, Yu.N. Murzenko et al.

V.A. Florin [10] obtained the modeling conditions for the plane problem of the elasticity theory,
using the similarity theory, a system of equilibrium equations and limit equilibrium.

Similar conditions were obtained by Yu.N. Murzenko [11]. Comparing the results of experimental studies and analyzing the conditions of similarity, Murzenko Yu.N. also established that in the extreme conditions of the soil mass, to obtain the most reliable results, it is necessary to use the non-linear modeling conditions that take into account the influence of the models’ scale on the change in the shape of the compaction zones, the elastic core and sliding surfaces. For a sandy base, such modeling conditions were obtained and tested by Yu.N. Murzenko and his students in [12-14].

The conditions for modeling the construction work of reinforcing the strip foundation by the method of summing the foundation plate with the fixed formwork

Due to the fact that the simulated strip foundation is extended in the plan, we use the condition of V.A. Florin for the plane limit equilibrium of the elastoplastic base, as well as the pre-limit stress state:

\[
\frac{k_b k_f}{k_\sigma} = 1, \frac{k_\gamma}{k_\sigma} = 1, \varphi = \text{const},
\]

where \(k_b, k_f, k_\sigma, k_\gamma, k_c\) - are the coefficients or scale factors of modeling, respectively, of the linear dimensions, stresses, volumetric forces and adhesion forces.

When introducing the concept of simulation number \(N\) for incoherent soil at \(c = 0, \varphi = \text{const}\), we get:

\[
N = \frac{\sigma}{b \gamma}, N_M = N_H = \text{const},
\]

where \(\sigma\) - is the medium pressure under the foundation base;

\(N_M, N_H\) - are the simulation numbers respectively for the model and natural foundation.

We will take a strip foundation consisting of a reinforced concrete strip 1.0 m wide with a wall of concrete blocks 500 mm thick resting on it as a full-scale prototype.

The strip foundation model, based on the modeling conditions and the dimensions of the chute in the plan, we will accept the following design (Fig. 1):

- tape width \(b_m = 300\) mm, tape length \(l_m = 2400\) mm, tape thickness \(h_m = 60\) mm;
- model material - plywood of the FSF and FSB brand.

In this case, the scale factor of modeling for the geometric dimensions: \(k_b = 0.3\).

Using the methodology [11], we determine the modeling conditions, which include the parameters of the soil base and the structure itself, necessary for their joint work.

In order to comply with the similarity conditions, we set the same flexibility parameters for the model and the natural foundation.

According to the theory of calculating the beams and plates on an elastic base, we use the well-known formula of M.I. Gorbunov-Posadov [15] for the beams’ flexibility indicator:

\[
t = \frac{(1 - \mu^2) \pi E_o b L^3}{(1 - \mu_0^2) 4 EI},
\]

where \(\mu, \mu_0\) - define the Poisson’s ratios of the foundation material and soil base, respectively; \(EI\) – is the foundation rigidity; \(E_o\) – is the soil base deformation module; \(b\) – is the base sole width; \(L\) – is the foundation length; \(I\) – is the cross-sectional moment of inertia.

Marking the flexibility of the model as \(t_m\), and the flexibility of the natural foundation as \(t_n\), then we obtain the following condition: \(t_n = t_m\), or

\[
\frac{(1 - \mu_n^2) \pi E_o b_n L_n^3}{(1 - \mu_0^2) 4 E_n I_n} = \frac{(1 - \mu_m^2) \pi E_o b_m L_m^3}{(1 - \mu_0^2) 4 E_m I_m}.
\]
After conversion, the condition will receive the following form:

\[
\frac{(1-\mu_n^2)b_n L_n^3}{E_n I_n} = \frac{(1-\mu_m^2)b_m L_m^3}{E_m I_m}
\]  \hspace{1cm} (2)

If the linear scale factor is taken as

\[
k = \frac{b_m}{b_n},
\]  \hspace{1cm} (3)

then the geometric parameters of the natural foundation can be determined according to the following condition:
\[ I_m = \frac{k_b^4 E_n (1-\mu_m^2)}{E_m (1-\mu_n^2)}, \]

\[ I_n = \frac{b_n^3 h_n^3}{12}, \]

(4)

Plywood model deformation module \( E_m = 6000 \) MPa, the Poisson’s ratio of material \( \mu_m = 0.065 \).

With the value of the reinforced concrete deformation initial modulus \( E_n=265\,000 \) MPa and \( \mu_n = 0.2 \), as well as with the coefficient of linear dimensions \( k_b=0.2 \), the condition for determining the dimensions of the natural foundation cross-section has the form:

\[ I_n = \frac{6000(1-0.2^2)}{0.3^4 \cdot 26500(1-0.065^2)} I_m = 26.95 \times I_m. \]

(5)

The natural foundation cross-section inertia moment:

\[ I_n = \frac{b_n h_n^3}{12}. \]

(6)

The foundation model section inertia moment:

\[ I_m = \frac{b_m h_m^3}{12}. \]

(7)

So, for the foundation model section inertia moment \( b_m \times h_m \) (0.3 m x 0.06 m) the cross-sectional dimensions of the natural foundation \( b_n \times h_n \), given the expression 5 can be determined from the expressions 6 and 7.

The sectional foundation height is:

\[ h_n = \sqrt[3]{\frac{26.95 \times b_m h_m^3}{b_n}} = \sqrt[3]{\frac{26.95 \times 0.3 \times 0.06^3}{1.5}} = 0.11 \text{m}. \]

(8)

Therefore, the accepted model of the strip foundation with a width of 300 mm and a section height of 60 mm corresponds to a full-scale tape with a width of 1000 mm and a section height of 110 mm.

Taking into account the size module between the apartment building walls’ axes, equal to 6.0 m, the thicknesses of the walls from the FBS blocks with 500 mm, as well as the reinforcement coating thickness 250 mm on both sides of the walls, the reinforcement plate width will be \( L_p = 6.0 - 2 \times 0.25 - 2 \times 0.25 = 5.0 \) m. Therefore, with the dimensions of the cross-section of a full-scale foundation reinforcement plate \( l_p \times h_p \) to determine the foundation reinforcement plate model size, we use the formula of M.I. Gorbunov-Posadov [15] for the plates’ flexibility indicator:

\[ t = \frac{3\pi b^4 E_0 (1-\mu_0^2)}{h^4 E (1-\mu^2)}, \]

where \( b, h \) – define the length, width and height of the foundation plate;

\( E_0, \mu_0 \) - show the deformation modulus and lateral expansion coefficient of soil;

\( E, \mu \) - denote the deformation modulus and lateral expansion coefficient of the plate material.

The expression (9) in the range of small loads is quite accurate; in the elastoplastic stage of the base, this formula becomes approximate.

Marking

\[ C_p = \frac{E_0}{1-\mu_0^2}, \quad u C_p = \frac{E}{1-\mu^2}, \]

(10)

we rewrite (10) in the form
$$t = \frac{3\pi b^3 C_p}{h_p^3 C_p}.$$  \hspace{1cm} (11)

Let us consider the similarity criterion based on the equality of flexibility indicators $t$ for the model and the natural foundation.

Provided that $k_t = 1$ and $k_{CP} = 1$

$$\frac{k_b^3}{k_{hp} k_{CP}} = 1.$$  \hspace{1cm} (12)

The cylindrical deformation modulus of the model, determined experimentally, was

$$C_p = \frac{6000}{1 - 0.065^2} = 6025 \text{ MPa}. $$  \hspace{1cm} (13)

With the values for reinforced concrete $E_p = 3 \cdot 10^4 \text{ MPa} \quad \mu_p = 0.2$,

$$k_{CP} = \frac{C_{PN}}{C_p} = \frac{3 \cdot 10^4}{(1 - 0.2^2) 0.6025 \cdot 10^4} = 5.2.$$  \hspace{1cm} (14)

Thus, at the accepted values $C_{PM} \quad C_{PN}$

$$\frac{k_b^3}{k_{hp}^3} = 5.2.$$  \hspace{1cm} (15)

Provided, that $k_b = 0.3$

$$k_{hp} = \sqrt[3]{\frac{0.3^3}{5.2}} = 0.17.$$  \hspace{1cm} (16)

Thus, with the linear dimensions’ coefficient is $k_b = 0.3$, the desired value is $k_{hp} = 0.17$.

According to the accepted conditions, the full-scale reinforcement plate with a length of 5.0 m and a thickness of 0.2 m corresponds to the model of a reinforcement plate with a length of 1.5 m and a thickness of 0.03 m.

**Summary**

In order to obtain the reliable results when conducting the experimental studies comparable with the real system “soil foundation - strip foundation” operation, it is necessary to perform a model that meets the basic modeling conditions. This is a prerequisite for conducting the experimental studies of foundation models on a soil foundation. Thus, the obtained data on the foundation model construction behavior and the stress-strain state of the soil selected as the base will reduce the research costs.

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