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Laboratory Investigation on Interaction of the Pile Foundation Strengthening System with the Rebuilt Solid Pile-Slab Foundation

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Abstract

The article presents the results of laboratory studies of pile model foundations in order to determine the effectiveness of the method proposed by the authors for its reconstruction in pile-tile foundation with preliminary pressing and cementation of the soil base. The studies were carried out on small-scale wooden models of foundations in the conditions of a soil paste. The models of foundations were subjected to vertical static loading in a laboratory tray with a diametrical transparent wall. The program of experiments was provided for determination of precipitation of the models: pile foundations without strengthening, with strengthening in the form of reconstruction from the combined foundation and with strengthening in the form of reconstruction into the combined foundation with preliminary stress of the soil base in the span part. Vertical and horizontal movements in the soil mass were also recorded by a contactless method (PIV) in every stage of model loading. On the basis of experimental measurements digital processing of data of sediments and displacements is performed, for drawing plots of sediments, epures and isolines of displacements in the soil base. The main result of the research is confirmation of the high efficiency of the proposed method of strengthening pile foundations due to the maximum use of pre-pressed soil base resources in spans between pile rows. It has been found that compression (pre-stress) significantly reduces soil deformability and allows to include it in operation without additional deformations. The use of pre-compaction reduced the precipitation of the model combined foundation by almost 40%, relative to the combined without compaction. The results of the research open the possibility to develop new methods of strengthening pile foundations from the point of view of effective inclusion in the operation of the soil base in the span part, due to its preliminary tension.

Keywords: Strengthening the Buildings; Soil Deformations; Soil Bed; Pile Foundation; Combined Pile-Slab Foundations (CPSF).

1. Introduction

Rational use of financial and material resources through renewal of residential buildings and urban development makes it possible to save the housing facilities and increase the usable floor area by reconstructing the facilities (40-70%). It is necessary to enumerate the main reasons which cause the need to strengthen the foundations and harden the foundation soils. The following classification is used in this research (Pronozin et al. 2019 [1], Utenov et al. 2017 [2], Khomyakov et al. 2017 [3]):

1.1. Reconstruction of Buildings

Reconstruction of buildings including major repairs, adding storeys, and increased foundation loading.

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Reconstruction and major repairs of buildings and structures are carried out in order to eliminate their physical deterioration and provide their expansion or additional functional use; this is accompanied by strengthening or replacing the structural elements of the building, adding storeys, deepening basements and making basement storeys, interior redevelopment and modification. The result is as follows: foundation loading increases by 30 to 50% (Khomyakov et al. 2017 [3], Mali and Singh 2018 [4], Samorodov 2018 [5], Stepanov et al. 2018 [6]). Thus, pile foundations suffer from overloading and this results in the need to strengthen them by embedding extra piles or strengthening the soil bed.

1.2. Deterioration of Foundations

It is necessary to point out two basic groups of reasons which cause deterioration of foundations.

Firstly, physical and mechanical processes result from interaction of foundations with the environment, namely: wooden members of foundations decay, the binding material is leached, and the masonry is destructed in an aggressive environment; corrosion of the reinforcement, frost destruction, etc.

Secondly, mechanical reasons are caused by various external effects (earthworks in the vicinity of the buildings, dynamic effects of transport and building machinery, etc.). In here, destruction is characterized by masonry disintegration and crumbling of mortar from the joints, cracks in the concrete and reinforced concrete foundations resulting in the loss of strength and rigidity of the foundations. Foundations and lower sections of the walls are destructed as a result of violated water isolation of perimeter walks around the buildings due to fluctuations in the groundwater level (Polishchuk and Tarasov 2017 [7], Stepanov and Rybak 2019 [8], Pronozin et al. 2019 [9])

1.3. Changed Properties of Foundation Soils

During operation of the building to be restored, reconstructed or repaired, it is possible to change the hydrogeological situation within the core area of the soil bed. For example, extra moistening leads to deterioration of the physical and mechanical properties of soils; the strength of the bed decreases and its deformability increases (Shamsi et al. 2019 [10], Lee et al. 2018 [11], Ihsan and Toma Sabbagh 2017 [12], Rabiei and Choobbasti 2015 [13], Pronozin et al. 2018, 2019 [14, 1]).

1.4. Unacceptable General or Local Deformations of the Buildings

Unacceptable general or local deformations of the buildings are usually caused by errors in engineering geological surveys, design and construction of the soil beds and foundations of buildings, their operation, and construction of buildings and structures in the vicinity of the existing ones. In this case, significant non-uniform deformations lead to defects in the superstructures and accidental consequences.

One of the possible effective ways to increase reliability and reduce deformability of the pile-strip foundations is to strengthen them by rebuilding to continuous combined pile-slab or pile-shell foundations by crimping the soil bed. In the span it is achieved by pumping the pressurized mortar mix under the foundation foot (Pronozin et al. 2019 [14], Mali and Singh 2019 [15], Stepanov et al. 2018 [6], Kumar et al. 2017 [16], Mangushev and Nikiforova 2017 [17]).

2. Experimental Laboratory Investigation

The laboratory investigation aimed at the following:

Studying the interaction of the combined pile-slab foundations (CPSF) with a crimped soil bed, i.e. a qualitative assessment of the influence of the foundation system parameters on the deformed soil bed.

A single pile (model No.1), a slab foundation (model No.2), a pile-slab foundation (model No.3) and a pile-slab foundation with the crimped soil bed (model No.4) were considered as foundations.

The experiments included the following:

• Static tests conducted on the foundation models;

• Deformation fields (total, vertical and horizontal) determined in the soil bed given different models of foundations;

• Study of the clayey bed deformability during its loading;

The tests were carried out in an experimental tray which was filled with the clayey paste of a disturbed structure.

A metal half-cylindrical container with a front transparent wall of 1m in diameter and 0.8 m in height was used as the experimental tray (Figure 1). The transparent wall was made of Plexiglas of 10 mm in thickness. A levered rig was used for loading which increased multiply to 4.2. Three independent frames served for measuring, lighting and photographing equipment to be installed.

Figure 1. Configuration of the experimental rig

The model of the pressed-in pile was made of a wooden cylinder of 25 mm in diameter and 250 mm in length sawn longitudinally. The model of the slab foundation was made of a particle board, 300×300×20 (h) mm in dimensions.

The model of the pile-slab foundation (Figure 2b) was like the model of the slab foundation made of the particle board 300×300×20 (h) mm in dimensions and six piles made of wooden cylinders of 25mm in diameter, 250 mm in length and 15cm in pile spacing.

The model of the pile-slab foundation with the crimped soil bed was similar to the model of the pile-slab foundation with the layer of a rubber shell in the contact zone of the slab spans (Figure 2c). The shell presented an expanding rubber chamber with a nipple connected to the compressor. The slab contact surface together with the chamber used for crimping was 80% of the total area of the slab. Air was pumped under the span in the shell for 1-2 min at a pressure of $p_{crimpimg}$ = 0.45 atm (45 kPa). The pressure was monitored using pressure gauges mounted on the compressor.

A specially prepared soil paste with given physical and mechanical characteristics was used in the experiments: density ρ=1.9 g/cm^3, porosity coefficient $e = 0.7$, water content w= 22.7%, plasticity index I_p = 8.7, liquidity index I_L = 0.60, angle of internal friction φ^0=15, specific cohesion c = 24.9 kPa, modulus of deformation $E = 6 - 7\ MPa$.

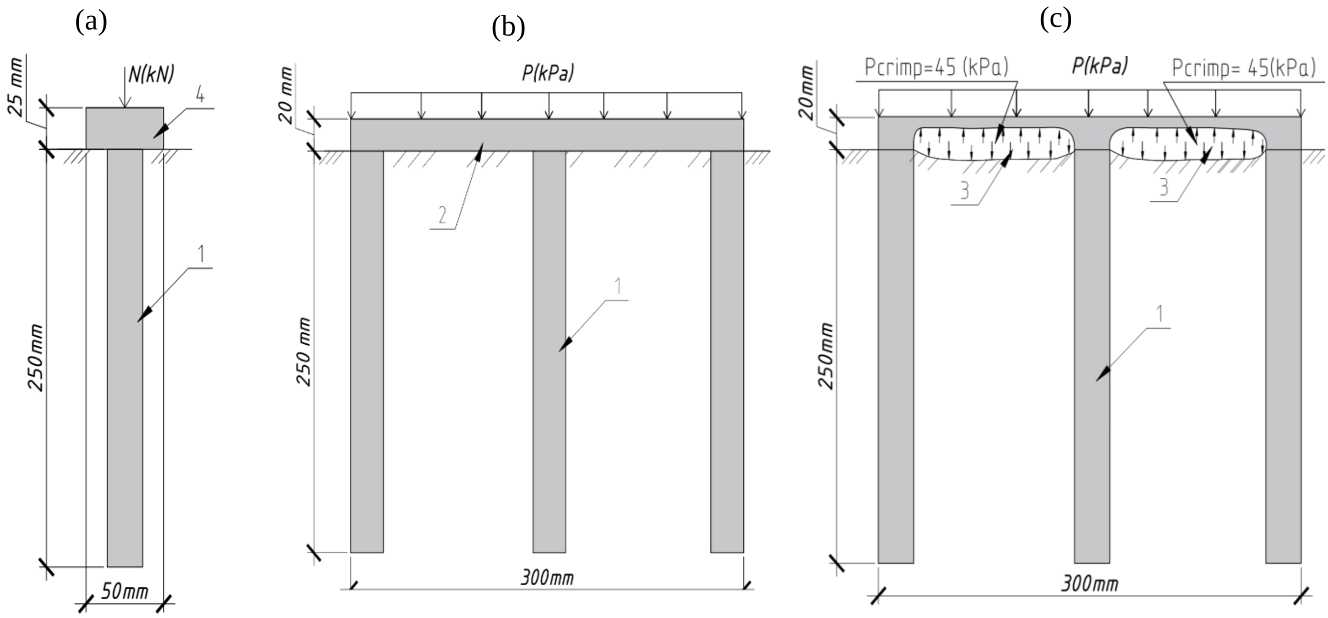

Figure 2. Models of the foundations under study, a) single pile (model No.1), b) slab foundation (model No.2), c) pile-slab foundation (model No.3), d) a pile-slab foundation with the crimped soil bed (model No. 4); 1 - pile Ø 25 mm; 2 - slab 300×300×20; 3 – mortar injection area; 4 - grillage.

When the soil had been compacted, the transparent side wall was demounted in order to install the marks. The marks were installed on a square grid of 0.02×0.02 m in dimensions using a template. The marks were made of a cylindrical polymer tube of 2 mm in external diameter, 1 mm in internal diameter and 5 mm in length.

In the case of static testing, the foundation models were loaded by means of metal loads through the levered rig; the value of loading was regulated by the dead load mass. Each loading stage was maintained until conditional stabilization occurred, when the rate of the settlement did not exceed 0.1 mm in the last 4 hours of observations.

The piles were immersed by means of the levered rig as well. The settlements of the foundation models were recorded using Aistov 6 PAO inclinometers with a scale value of 0.01 mm. To obtain more accurate experimental data, each series of experiments was conducted at least three times to control the repeatability of the results obtained.

3. Results and Discussion

In order to study the deformability of the soil bed under loading by different foundation models, the functions of the settlement versus the average pressure under the foundation foot were obtained (Figure 3).

The functions of the settlement versus loading for slab and pile-slab foundation models up to the third stage of loading were characterized by initial linearity. Nonlinear deformations appeared if pressure values increased.

The settlement of the Ø 25 mm single pile up to 32 kg of loading increased in direct proportion to the external load; then the load increased and one could observe a sharp break in the graph, i.e. 36 kg of loading meant the pile failure.

The settlements of the models No.3 and No.4 were equal prior to crimping, up to the fifth stage, corresponding to $N = 5kN$ ($p_{aver.}$=55 kPa).

After the fifth stage air was forced under the pressure of $p_{crimpin}$= 45 kPa under the footing of the model No. 4 in the expanding rubber chamber to simulate the process of soil bed crimping.

Deformations of the soil bed and its compaction occurred when pressure was forced under the slab span, and the settlement did not increase. This is some kind of the analogue of the pre-stressed structural members, e.g. reinforced concrete structures.

The soil bed having been crimped and the load on the model No.4 having been increased, the rate of its settlement significantly decreased in relation to the similar model No. 3, but without any crimping. In here, when extra loading had been applied corresponding to an average pressure of 88 kPa, the settlement of the model No. 3 was 16.5 mm, model No. 4 - 11 mm, i.e., 1.5 times less.

At the last general stage of loading corresponding to $p_{average}$= 111 kPa, the settlement of the model No.2 was 29.5 mm, model No.3 –23.3 mm, model No.4 –14.7 mm.

Thus, the final settlements of the model No.4 proved to be 37% less than those of the model No.3 due to crimping of the soil bed in the contact layer. It is important to underline that the crimping pressure was 40% of the average pressure ($p_{average}$=111 kPa); this correlated with the difference of the final settlements.

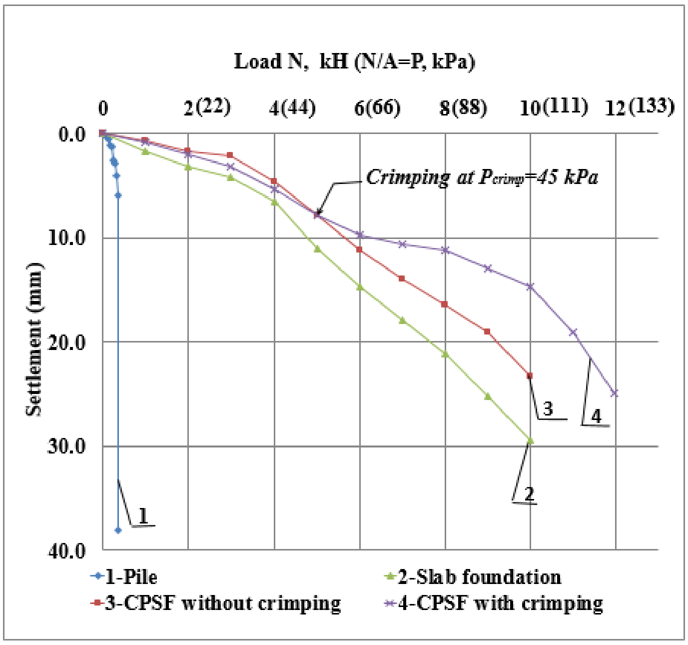

Figure 3. Settlements of foundation models versus vertical pressure values

In order to determine deformations of the soil bed, an axisymmetric OZ coordinate frame was introduced, where Z axis passed through the center of the stamp and was directed vertically down, the axis passed through the center point of the stamp foot and was directed horizontally to the right; accordingly, the contact point of the model and the foundation soil along the axis of its symmetry was the center of coordinates.

Vertical, horizontal and total deformations of the soil were to be determined during the experiment. Soil deformations for pile-slab foundations were evaluated as the difference between the changed geometric position of the marks in the OZ plane and their initial location.

Using this technique, the contour curves of the whole desired deformations were plotted for the foundation models No.3 and No.4 for the stages at $N = 5kN$ ($p_{average}$=55 kPa) and $N = 10\ kN$ ($p_{average}$=111 kPa).

Thus, at $N = 5\ kN$ ($p_{average}$=55kPa) the maximum values of the vertical soil displacements under the contact surface of the foundation model No.3 were 14 mm in the span. The deformations extended to a depth of *1.0B* (where *B* is the width of the foundation), and the maximum values of the vertical soil displacements under the contact surface were 17 mm in the span for the model No.4 after crimping. Deformations extended to a depth of *1.1B.*

When the load increased, the maximum values of the vertical displacements of soil under the contact surface of the foundation model No.3 were 21 mm in the span, at $N = 10\ kN$ ($p_{average}$ = 111 kPa) (Figure 4).

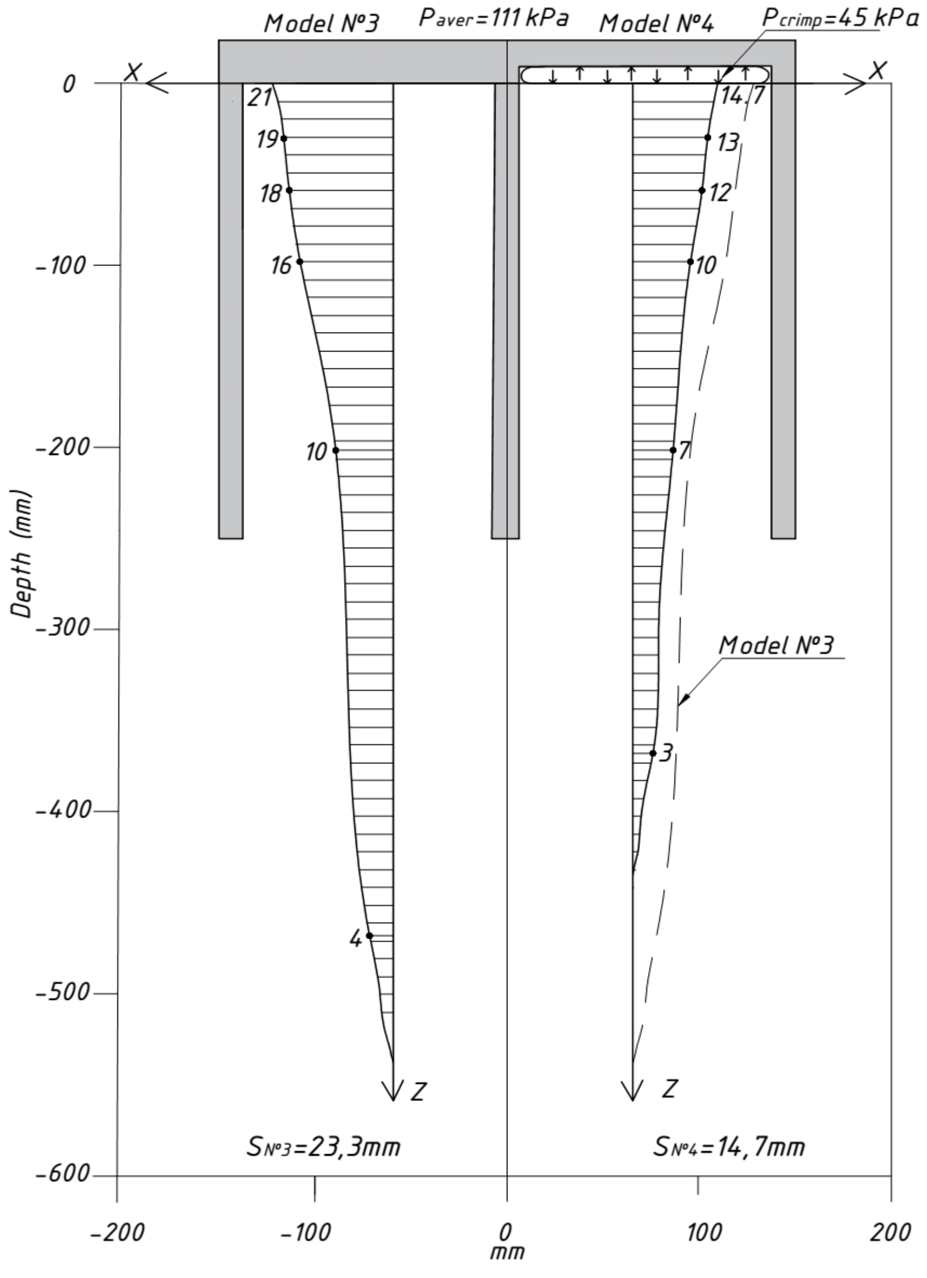

Figure 4. Curve of vertical displacements of soil in the pile space for the foundation model No.3 and foundation model No.4, with N = 10 kN ($p_{average}$ = 111 kPa): a - vertical *w (z)*, b - total Δ *(z, x)*

Deformations extended to a depth of *1.7VB* (*B* is the width of the foundation). The maximum values of the vertical soil displacements in the span were 19 mm for the foundation model No.4 ($p_{average}$=45kPa – crimping, $p_{average}$ = 111 kPa - stage). Deformations extended to a depth of *1.3B*. The depth of the compressible thickness decreased due to compaction of the soil in the upper part of the core and unloading of the piles.

4. Conclusions

The laboratory investigation resulted in the following:

- Crimping of the soil bed performed on small-scale models in the span of the foundation at a rate of 40% of the total final load made it possible to reduce the foundation settlement by 37%.
- After crimping, the settlement was halved as compared to the settlement of the same foundation without crimping of the soil bed.
- The crimped soil bed made it possible to reduce compressible thickness by 23% as compared to similar foundations being loaded without any crimping.
- The crimped soil bed in the span of pile-slab foundations, e.g. in rebuilding the pile-shell ones is an effective engineering solution.

Obviously, the qualitative results obtained on the given models can help determine the patterns of interaction between the existing foundations and soil beds. However, applicability of the proposed method, which proved its effectiveness in new construction, is obvious for buildings under reconstruction and requires further investigation.

5. Acknowledgement

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6. Conflicts of Interest

The authors declare no conflict of interest.

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