Experimental and Numerical Research of Stress-Strain State of Homogeneous Soil Massif at Interaction with Single Barrette

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Abstract. Deep foundations are used for the design of high-rise buildings due to a large pressure transfer on the soil base. The foundations of buildings sometimes use barrettes which are able to perceive significant vertical and horizontal loads due to improved lateral surface. Barrettes have increased load bearing capacity as compared with large diameter piles. In modern practice the interaction between barrettes and soil is investigated by analytical and numerical methods and has no sufficient experimental confirmation. The review of experimental methods for the research of the intense stress-strain state of the uniform soil massif at interaction with elements of a deep foundation is provided in this article. Experimental research are planned with the use of laboratory stand for the purpose of qualitative data obtaining on the interaction barrettes with an assessment of a settlement model adequacy and also at the research of the intense stress-strain state by numerical methods.

1. Introduction
A large number of experimental and theoretical works are dedicated to the issue of pile interaction with the surrounding soil and the nature of their on-load operation. The main results were accumulated when conducting experimental and field work, which were then summarized as theoretical instructions.

The research, made by V.V. Znamenskiy, N.M. Doroshkevich, N.Z. Gothman, Ye.E. Devaltovskiy, Whitaker, J. Hanisch and others, demonstrated the difference in transmission of load to the soil between a single pile and a cluster of piles. In case of spacing between the piles in the cluster of more than 5…6d the influence of the state of stress of the soil massif bulk around the pile on adjacent ones and juxtaposition of ground mutual displacement zones do not take place, meaning that they are operating as single ones. In its turn, if decreasing the spacing between the pile axes in the cluster to 3…4d the friction forces on the lateral surface get lower, and the interpile soil blocking phenomenon takes place (a pile and the ground coat operate as a whole unit), and the load between the piles is distributed unevenly [1].

In modern practice the research data are used for barrettes and utilized for designing barrette foundations calculated as drill platforms or drill piles according to the provisions of SP 24.13330.2011 "Pile foundations". However, distinctive features of barrettes compared to the piles (their geometrical form, cross-section size) [2-6] are not taken into account.
When examining the interaction of barrettes with the soil masif, in general numerical and analytical approaches as well as natural experiments are used. Nevertheless, laboratory experiments with the least timing and resources spent allow obtaining the data on the change in displacement fields of the ground coat in the physical model when interacting with it of single barrettes and a group of barrettes, and assessing the faithfulness of results obtained using the numerical approach.

2. Experimental equipment
The research of influence of a single barrette from press loads action on the change in the strain-stress state of the ground coat was made using the automated test rig ("ASIS" ATR) consisting of the laboratory test stand (flat shoot) and the "ASIS" measuring system produced by the GEOTEK Scientific and Production Enterprise, Penza.

The laboratory research was performed in laboratory 2 "Bases and Foundations on soft grounds" of the Gersevanov Research Institute of Bases and Underground Structures (NIIOSP) for the purpose of studying the strain-stress state of the homogeneous ground coat when interacting with a single barrette in the framework of the Master's Thesis.

The general view of the equipment and measuring system is presented on Figure 1.

![Figure 1. General view of the laboratory stand and equipment (left), Experimental test arrangement (right): 1 – laboratory stand, 2 – computer, 3 – control and signal recording unit. h - element height; t - element thickness.](image)

In terms of design the stand is made as a shoot having the following internal sizes: length – 722 mm; width – 156 mm; height – 536 mm. The stand is made as a flat shoot with transparent front and back walls made from the glass (duplex) of 12-mm thickness.

In order to eliminate bending of the transparent walls two steel grids are installed having back-up washers in the junction points. The external load (flat die) is created using a pneumatic loader. The vertical displacement of the foundation model is measured by a displacement sensor, and the load - by means of a strain-gage sensor. The deformation (settlement) of the ground surface is measured by displacement sensors (VD) to be fixed on the cross-beam [7].

The results and data obtaining of the experimental test (sand ground displacement field) is processed using the Particle Image Velocimetry (PIV) digital processing method.

The experimental examination using the digital image processing method is performed in the flat deformation conditions. The photos of particles are recorded on the digital camera computer media,
and the subsequent processing of images allows calculating the displacement of particles between a pair of processed photos, for example, for an increment of load applied to the barrette cap. After measuring the particle displacement, a two-component displacement field is built with further calculation of deformations.

3. Procedure of experiments

The experiments were performed using the physical modeling method for barrettes in situ having the depth of 10 m and width 0.6 m, which taking into account the scale factor 1:50 corresponds to the depth and width of barrettes in the model equal to 20 and 1.2 cm.

The sand in the air-dried state is used as a physical model of the ground coat. The sand is characterized as mean size sand under the classification of GOST 25100-2011 [8-10]. The barrettes, made from 12-mm thick plywood pasted over with the average sized grain abrasive paper from both sides for the purpose of creating more realistic friction against the side surface typical for the barrettes in situ, are taken as the elements of the physical model.

The load, applied to the barrette cap, is taken on the basis of the preliminary performed calculation of the carrying capacity of barrettes in situ on the ground according to the provisions of SP 24.13330.2011 “Pile foundations” [11-13]. The influence of end walls on the carrying capacity of the barrette was not taken into account when making the calculation.

Based on the calculation results the carrying capacity of the barrette in situ in the first group of limit states made 1,787 kN/lin m. Taking into account the scale factor of the physical model, we have the carrying capacity of the barrette for the model conditions as equal 0.71 kN. Taking into account the shoot width of 155 mm, the load applied to one barrette is determined as N = 0.71 / 0.155 = 4.6 kN/m.

The load is served step by step and corresponds to the value 1/10 from the maximum value of the load. After serving the load to every of the barrettes, the barrette is conditioned until full stabilization of settlement in the physical model elements. The test process is automated using the "ASIS" software allowing to record vertical displacements of the mold during loading of the elements.

Before the beginning and after serving the load to the barrette foundation elements by every of the steps, the photofixation is performed for further processing of the results and obtaining sand ground displacement fields using the Particle Image Velocimetry (PIV) digital photo processing method.

4. Analysis of strain-stress state of the soil massif based on the results of conducted experiments and numerical modelling

According to the test procedure stated above there were 3 shoot experiments performed for examining the strain-stress state of the homogeneous ground coat in interaction with the single barrette.

In the course of load transfer by every of the steps to the cap of the "experimental" barrette the sensors of vertical deformations (VD) of the automated measuring system "ASIS" recorded vertical displacements of the mold.

Based on the results of digital processing of photos using the Particle Image Velocimetry (PIV) method two-component fields of displacement of particles between a pair of processed photos were obtained, which correspond to the experiment stages before applying the press load after applying every of the steps.

In order to verify the faithfulness of the change in the fields of displacements of the ground coat under the action of the press load on the barrette, obtained based on the results of digital processing of photos in the course of the laboratory research, the comparison was made with the results of numerical modelling performed using the finite-element software system Plaxis 2D.

When modelling the analytical model of the shoot experiment the maximum load, applied to the surface of the physical model element in the form of the barrette, was modelled on the basis of the results of performed tests and corresponds to the value, where the unlimited evolution of the settlement under the barrette toe takes place, i.e. in case of the carrying capacity both on the side surface and under the barrette toe is exhausted.
Maximum load on the barrette cap transferred through the mold having the size of 0.05 x 0.1 m is:
\[ N = 150 \text{ kPa} \times 0.05 \text{ m} \times 0.1 \text{ m} = 0.75 \text{ kN}. \]
With regard to the shoot width of 155 mm, we obtain the strip load equal to 4.84 kN/m corresponding to the pressure transmitted to barrette surface equal to 150 kPa.

The comparison of isofields of vertical displacements of the ground coat based on the laboratory test results, performed for the physical model of the "experimental" barrette under the action of the vertical load, corresponding to the stage of loading with the critical load and numerical modelling is presented on Figure 2.

![Figure 2. Isofields of vertical displacements of the ground coat at the stage of critical load application defined on the basis of the laboratory experiment results. Left – laboratory experiment, right – numerical calculation using Plaxis 2D](image)

Based on the calculations, performed using the numerical method, the estimated values of settlement of the "experimental" barrette under the action of every of the steps of load, applied to the element surface were obtained with further comparison of the results obtained in the course of the tests.

The calculations were made on the basis of using the elastic-plastic Mohr-Coulomb model of the ground requiring the input of the following estimated parameters: \( G \) – shear modulus, \( \nu \) – Poisson's ratio, \( \varphi \) – internal friction angle, \( c \) – cohesion, \( \psi \) – dilatancy angle. For modeling the interaction of the barrette with the surrounding ground the interface elements (contact between the construction and surrounding ground) were used. Whereat, the following estimated values of strength characteristics on the "construction-soil" contact are taken: specific cohesion \( \gamma_k^c \), angle of ground friction against the construction material \( \delta = \gamma_k \gamma_k \varphi \), where \( \varphi \) - ground internal friction angle, \( \gamma_k \) – operation condition factor taken from the table 9.1 SP 22.13330.2011 [14-15]. The results of performed numerical experiments on ground coat deformation are presented on Figure 3.

When studying isofields of vertical displacements of the ground in the flat shoot at the stage of load application, when the ground surrounding the barrette starts operating nonlinearly, the distance from the central axis of the "experimental" barrette to the zone where the deformations have minimum values made up 0.026 m, which taking into account the scale factor corresponds to the distance in situ of 1.3 m and 2.2d. At the same time the results of numerical modelling demonstrated the active zone of ground deformation at the distance of 0.0225 m, which taking into account the scale factor corresponds to the distance in situ of 1.1 m and 1.9d. The divergence of influence zones of the single barrette, obtained on the basis of the results of laboratory experiments and numerical calculations,
made 14% which indicates the qualitative convergence of the experimental and numerical examination methods.

![Figure 3](image_url)

**Figure 3.** Ground coat vertical displacement and load dependence diagram

5. Conclusions
The following conclusions can be made on the basis of the results of laboratory and numerical examinations:

- The comparison of isofields of vertical displacements of the homogeneous ground coat obtained in the laboratory tests, performed for the physical model of the element in the form of the barrette under the action of the vertical load stages, and data of the numerical modeling of the shoot experiment, indicate the qualitative convergence of the results of test and estimated data.
- The values of vertical displacements of the ground coat obtained on the basis of the laboratory tests do not correspond to the values obtained in the course of numerical modeling performed using interface elements and corresponding values, given in Table 1.
- The preliminary zone of influence of the single barrette both based on the results of shoot experiments and numerical modeling demonstrated the qualitative convergence of obtained results and is equal to, for the first ones, 1.9d, for the second ones, 2.2d which corresponds to the divergence of 14% between the obtained values.

**References**

[1] Ter-Martirosyan Z G, Sidorov V V and Strunin P V 2013 The calculation of the stress-strain state of a single compressible barrette and piles in the interaction with the soil *Civil Engineering* 9 pp 18–21

[2] Ter-Martirosyan Z G and Sidorov V V 2010 The computation of settlements of deep Foundation, given its stiffness *Civil Engineering* 5 pp 36–8

[3] Ter-Martirosyan Z G, Sidorov V V and Strunin P V 2014 Theoretical bases of calculation of deep foundations - piles and barrettes *Bulletin of Perm national research polytechnical university. Building and architecture* 2 pp 190–206

[4] Ter-Martirosyan Z G, Sidorov V V and Ter-Martirosyan K Z 2013 Creep and long-term bearing capacity of long piles submerged into the soil massif of clay *Scientific and Engineering Journal for Construction and Architecture* 1 pp 109–15

[5] Ter-Martirosyan Z G, Ter-Martirosyan A Z, Sidorov V V and Buslov A S 2014 The initial
critical pressure under the circular Foundation and under the toe of bored piles of circular cross section *Natural and technical Sciences* **11-12** pp 369–73

[6] Lei G 2001 *Behaviour of excavated rectangular piles (barrettes) in granitic saprolites* (Hong Kong: Department of Civil Engineering Hong Kong University of Science and Technology. Clear Water Bay)

[7] Boldyrev G G, Melnikov A V and Novichkov G A 2014 Interpretation of the results of field and laboratory tests to determine strength and deformation characteristics of soils. Part I. Interpretation of results of field testing to determine strength characteristics of soils *Engineering surveys* **5-6** pp 68–77

[8] Mangushev R A 2016 Analytical and field evaluation of the bearing capacity of deep piles and barrettes in soft soil at St. Petersburg *Architecture and Engineering* vol 1 **1** pp 54–9

[9] Shulyatev O A, Shulyatev P O, Dzagov A M and Bokov I A 2013 Correction of soil design parameters for the calculation of the foundation based on the results of barrettes static load test *Proc of the 18th Int conf on soil mechanics and geotechnical engineering*

[10] Ter-Martirosyan A Z, Ter-Martirosyan Z G and Sidorov V V 2016 Interaction of compaction piles with surrounding soil with due regard for pile diameter expansion *Soil Mechanics and Foundation Engineering* vol 53 is 3 pp 166–73

[11] Ter-Martirosyan Z G, Ter-Martirosyan A Z, Sidorov V V and Aniskin N A 2016 The definition of necessary axial force for extension of initial borehole for soft soil compaction process design *MATEC Web of Conferences* vol 86 p 03014

[12] Telichenko V I, Ter-Martirosyan A Z and Sidorov V V 2016 The Rate if the Pile Settlement in Clay Soil with Regard to its Visco-elastic and Elastic-plastic Properties *Procedia Engineering*

[13] Ter-Martirosyan Z G, Ter-Martirosyan A Z and Sidorov V V 2013 Creep and long-term bearing capacity of a long pile in clay *Proc of the 18th Int conf on soil mechanics and geotechnical engineering* pp 2881–4

[14] Vasenin V A 2010 Numerical simulation tests of bored piles and barretta for the construction of high-rise buildings in Saint-Petersburg *Geotechnics* **5** pp 38–47

[15] Ter-Martirosyan A Z, Ter-Martirosyan Z G and Sidorov V V 2016 The interaction of ground piles finite stiffness of the surrounding soil in the composition of the Foundation, taking into account expansion of pile diameter *Soil Mechanics and Foundation Engineering* **3** pp 10–5