Experimental and numerical substantiation the efficiency method of compaction of soil base by creating sealing pressure inside soil massif

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Abstract. This article provides a method of compaction of the soil base by creating a sealing pressure inside the soil massif. Nowadays, in buildings reconstruction, which is accompanied an increase loads on the foundations, in constrained conditions of dense urban development, the question strengthening of bases of foundations is important. The proposed a method of compaction of soil base by creating a sealing pressure inside soil massif is applicable both for new construction and for reconstruction of any objects in dense urban development. It carried out a comparative analysis of results of experimental and theoretical studies of the bearing capacity of piles with different parameters of broadening and compacted zone obtained by the method of compaction of soil base by creating a sealing pressure inside soil massif. Numerical studies to determine the bearing capacity of piles were performed in axisymmetric formulation using Hardening-Soil model. The method of determination of changes bearing capacity of base in depending on the diameters of broadening and compacted zone was carried out on a specially designed stand is presented. The article presents the results of experimental and numerical studies of bearing capacity of bases foundation.

1. Introduction
Nowadays, in buildings reconstruction, which is accompanied an increase loads on the foundations, in constrained conditions of dense urban development, the question strengthening of bases foundation is important. However, many well-known methods of strengthening of bases foundation are often not applicable in dense urban development because of dynamic effects that have a negative impact on existing buildings. Therefore, the actual tendency is to develop methods for strengthening of bases foundation, excluding dynamic effects. There are quite a number of different methods to bases foundation strengthen by piles [1-8]. One of the main defined parameters by strengthening of bases foundation by piles is the bearing capacity of piles. For the numerical solution of tasks by determination bearing capacity of piles with the use elastic-plastic design soil models use of modern specialized software systems (Plaxis, Ansys, Abaqus, etc.) which allow to simulate in enough detail a design situation taking into account various stages of loading of bases foundation, including its preliminary compaction [9-11].

Purpose of paper is to determine the efficiency of a method of compaction of the soil base by creating a sealing pressure inside the soil massif for different parameters of broadening and compacted
zone obtained by numerical and experimental studies. In the paper uses research method: experimental methods for estimation the bearing capacity of pile, numerical methods for calculationing the mixed elastic-plastic FEM task in a physically and geometrically nonlinear formulation to determine the bearing capacity of pile.

2. Methods
Into the development of existing methods of deep compaction of bases soil, the authors propose a method of compaction of soil base by creating a sealing pressure inside soil massif [12]. Experimental studies were conducted in two stages. At the first stage, in the soil mass was created an internal compacting pressure, significantly exceeding the limit critical soil pressure, resulting in the formation of an over-compacted zone, shear zone and a cavity in the soil massif. At the second stage, after filling the formed cavity in soil massif with cement-sand solution, resulting foundation body (pile) was tested for the action of increasing up vertical load to the loss of the bearing capacity of base.

Both stages of research were carried out on a specially designed stand and numerically using the software complex Plaxis 2D. Numerical studies to determine the bearing capacity of piles were performed in axisymmetric formulation using Hardening-Soil model (isotropic hardening). The Hardening-Soil model (isotropic hardening) allows you to design the behavior of different soils types with a complex loading trajectory. In this soil model, there are two main types of hardening: shear hardening and compression hardening. The Hardening-Soil model (isotropic hardening) includes: as the destruction surface the Mohr – Coulomb formulation; to describe the elastic area of stress-deformed state - the hyperbolic Duncan_Chang formulation with variable elastic modules for the primary loading trajectory and trajectories of unloading-re-loading [13-20].

2.1. Baseline data for calculations
During the experiment were used two types of soil as the base: fine sand and clayey soil.

| Name characteristics, designation and dimension | Type of soil base |
|-----------------------------------------------|------------------|
|                                               | Fine sand        | Clayey soil    |
| Unit weight mineral particles soil, \( \gamma_s \), kN/m\(^3\) | 26.6             | 27.0           |
| Unit weight natural moisture content soil, \( \gamma \), kN/m\(^3\) | 17.4±0.1         | 18.7±0.1       |
| Unit weight dry soil, \( \gamma_d \), kN/m\(^3\) | 14.9±0.1         | 15.58±0.1      |
| Porosity, n, %                                | 44               | 42.3           |
| Void ratio, e                                 | 0.785            | 0.733          |
| Moisture content, W, %                        | 17               | 20             |
| Degree of saturation, S,                       | 0.58             | 0.74           |
| Modulus of deformation, \( E_0 \), MPa        | 5±2              | 5±2            |
| Poisson ratio, \( \nu \)                      | 0.3              | 0.35           |
| Cohesive force, c, kPa                        | 0-2              | 18             |
| Angle of shearing resistance, \( \varphi \), degree | 28-30           | 18             |

2.2. Experimental study
Determination of changes bearing capacity of base in depending on the diameters of broadening and compacted zone was carried out on a specially designed stand (figure 1). At this stage, after filling the formed cavity in soil massif with cement-sand solution, the resulting foundation body was tested for increasing vertical load to the loss of bases bearing capacity.

Vertical displacements of the foundation body obtained at the first stage during the studies were measured with the help of indicating gages installed in pairs on its top surface. Installation of indicating gages on the foundation top surface is carried out by means with extension of embedded parts on both sides of foundation. The placement of embedded parts away from the fragment of the
foundation was necessary to prevent the contact of indicating gages with the jack. The possible deviations of indicating gages readings, arising due to angular displacements of foundation in the plane of placement of paired indicating gages, were eliminated by averaging the indicating gages readings.

Fastening of indicating gages of hour type was made on autonomous frame system.

During the experiment was carried out using a step-by-step pressure delivery system. The load was applied in steps equal to 1/15-1/20 of the expected limit load. As a criterion for the loss of bearing capacity of foundations with different parameters of broadening and compacted zone, was taken at unstabilized settlements by constant load on foundation or when the foundation settlements reached the value of 40 mm.

![Figure 1. General view of the stand for the study of bearing capacity of foundation body (pile).](image)

After testing body of the foundation (pile) on the bearing capacity, the opening of the base was performed with the specification of the geometric parameters of broadening and compacted zone.

2.3. Numerical study

The design model for numerical studies is a two-dimensional rectangular massif with a plan size of 500x1000 mm, operating in conditions axial symmetry.

The massif dimensions are based on the following considerations:
- the massif length is taken as radius of pressure chamber, due to the axial symmetry of working conditions of soil mass within it;
- the massif height is taken according to pressure chamber height.

The modeled diameter of broadening in this study is 160 mm, 200 mm, 250 mm. The maximum value of broadening diameter in the numerical study was taken from the maximum value obtained during of experimental studies. The calculation was performed in Plaxis 2D for the conditions of axisymmetric task.

Since on the first stage of numerical studies has been determined [12], that the best convergence of numerical results with experimental data is obtained by using the Hardening-Soil model, therefore, to modeling the bearing capacity of compressioning soil massif of creating a sealing pressure inside the soil massif, only this design soil model was used.

Parameters of Hardening-Soil model were obtained on basis of laboratory tests using approach [19, 20]. For the compacted zone, the characteristics of soil are assumed to be adjusted taking into account its hardening during compaction.
Figure 2. Design scheme for study of bearing capacity of pile. 1 - broadening, 2 - compacted zone.

Figure 3. Horizontal shear deformation in base of pile with broadening, mm.

3. Results

The results of numerical and experimental studies are shown in the figures 4-7

Figure 4. Settlements relationship from load for piles with different diameter of broadening.
Figure 5. Dependence of piles bearing capacity on diameter of broadening.

Figure 6. The settlements dependence from load of piles with a broadening diameter of 250 mm in different types of soil for experimental studies.
4. Discussion
The small size of pile broadening is explained by rapid attenuation of stresses from sealing pressure inside the soil massif, which is due to the small diameter of hole and, accordingly, a small loaded surface. By increasing diameter of the hole, the effect of present method will be much more significant.

The increase in bearing capacity for piles with considered parameters due to formation of broadening and compacted zone for cohesive soils is almost twice greater than for non-cohesive soils. This is due to the fact that stresses from the own weight of soil at the depth of 0.5 m are insignificant and, accordingly, the strength of base is more determined by cohesive force, rather than angle of shearing resistance. With an increase in depth of broadening and accordingly Loading pressure relationship bearing capacity may change in favor of soil, which has a large angle of shearing resistance.

5. Conclusions
1. The proposed a method of compaction of the soil base by creating a sealing pressure inside the soil massif is applicable both for new construction and for reconstruction of any objects in dense urban development. Thus, theoretically it is possible in any soil conditions, in which it is possible to create an compactioning pressure substantially greater than soil strength, that is to create a local over-compacted soil area is in the stage of plastic flow, but excluding heaving (climbing surface) of overlying soil.

2. The effect of application of considered method of compaction of the soil base by creating a sealing pressure inside the soil massif is achieved mainly due to formation of broadening and compacted zone, which can exceed the diameter of the well by 6 or more times. According to calculations, with increasing sealing pressure inside soil massif in range from 0 to 17.65 MPa, angle of shearing resistance in compacted zone increases by 1.8-2 times for clay soils and 1.2-1.4 times for sandy soils, cohesive force in compacted zone increases by 1.2-1.8 times for clay soils and 3.5-4 times for sandy soils.

3. The results of comparison of calculations of pile foundation settlement performed by plane deformed scheme by finite element method according to program Plaxis 2D using the Hardening-Soil model and experimental data showed that their values differ only by 5-10 %.
4. Currently, there is no single method for determining the shaping of piles broadening, which often leads to significant differences between the calculation methods and real results. Therefore, the choice of soil model must be selected separately for each calculation case.

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