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Finding reserves of bearing capacity of bored piles

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Abstract. In recent years, due to population growth plans and accelerated economic development, high-rise buildings have become increasingly common in many cities and megapolises around the world. Due to the development of engineering construction, the type and technology of pile footing, which form the basis of such buildings, as well as the control of both single piles and a group of piles, have been significantly improved. At the same time, today the task of adequate assessment of the pile load capacity and justification of effective methods of revealing the reserves of its increase is actualized, because the manufacturing technology is constantly developing, in addition, often the functional purpose of the building itself, the type and intensity of the loads acting on it change. In view of the above, the purpose of the article is to investigate modern scientific- methodological approaches to search for reserves of bored pile load capacity. In order to carry out the study, the article used numerical methods for analyzing the stress-strain state of piles and means of the software package "Plaxis 3D Faundation". In the course of empirical experiments, it was found that the most acceptable results in the load testing of bored piles are given by the Shen method. Besides, the comparison of the results of static probing and static tests with theoretical calculations allowed to reveal the reserves of the actual pile load capacity, and also to determine on what parameters of its installation and characteristics the difference in load capacity depends more: the soil sciences in the pile base, pile diameter, pile length. Theoretical significance of the obtained results lies in the development of methodology for identifying reserves to increase the load capacity of bored piles. Conclusions have practical value that can be used in the process of laying the foundation of high-rise buildings to optimize the number and geometry of pile placement taking into account the reserve of their bearing capacity.
Key words: bored piles, footing, reliability, soil, depth, load.

1 Introduction

Modern construction in large cities takes place in conditions of dense urban development, and quite often for the construction of new structures and buildings are used areas with difficult engineering and geological conditions, for example, it may be structurally unstable soils, or soils that have subsidence properties and are subsiding even under the action of their

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own weight. This category also includes areas characterized by significant seasonal washout of soil. In addition, high-rise construction in megacities is currently of particular relevance.

All these new circumstances lead to the fact that as a result of increasing building height and the complexity of the soil, their foundations are subjected to significant vertical loads [23]. At the same time the changes which take place in the soils during their loading are very complicated as objects of research and control, and not all aspects of the process of deformation of soil foundations have been studied so far.

The above facts actualize the need to find new types of foundations that would guarantee, on the one hand, the reliable and trouble-free operation of the erected structures, and, on the other hand, would have a minimal impact on the buildings located nearby. Such foundations include pile foundations, which involve the use of various types of piles, including bored piles. Foundations based on bored piles are characterized by high productivity, minimal dynamic impact on the ground, and low noise level [25].

Given all the positive qualities of pile foundations, as well as their widespread use, the issues of finding reserves of bearing capacity of bored piles are of particular importance today. The accumulated experience of testing and observation of such piles indicates that their bearing capacity calculated by formulas and tables approved by state standards is lower than the actual bearing capacity determined by static tests, and sometimes by 2-3 times [21].

In addition, the transition to automated methods of calculation has dramatically changed the priorities towards the need to take into account the non-linearity of deformation of bored and drilled pile foundations. It should also be noted that in the pile field of a high-rise building the distance between rows of piles is about 3 m, so you can observe the mutual influence of the piles one on another due to the overlapping stress zones of neighboring piles. This leads to a change in the physical and mechanical characteristics of the soil and the appearance of plastic zones, which are known to contribute to the redistribution of forces, as confirmed by experimental data [29].

However, taking into account the redistribution of forces of all factors to date is virtually impossible. The interaction of piles with the surrounding soil has a complex spatial and temporal nature and depends on numerous factors.

Therefore, along with the theoretical studies of the interaction of piles with the surrounding soil is no less important study of the impact on the bearing capacity of the pile of technological factors, improving the test methods, clarifying the properties of subsiding soils, subsoil, surrounding buildings, etc., which in general will allow to identify and assess the real reserves of increasing the carrying capacity of bored piles with a high degree of reliability.

Thus, these circumstances predetermine the choice of the topic of this article, and also confirm its theoretical and practical importance.

Literature review. Studies of settlements of multistory buildings erected on pile and slab foundations have been published by Aristov M. [20], Pronozin Y.A., Stepanov M.A., Volosyuk D.V., Shuvaev A.N. [27], Bullock, Zach [3], Wang, Lilin [15], Millen, Maxim D. L. [12], Cong, Shengyi [4], etc.

To determine the bearing capacity of bored piles designers have increasingly begun to use non-traditional methods, namely the method of static soil sounding. Its detailed description is presented in the works of Sokolov N.S. [28], Olgun M., Fidan B., Yenginar Y. [26], Abdelhalim, Reda A. [1], Bayesteh, Hamed; Fakharnia, Mohammadali [2], Yao, Wen-juan [19], Wang, Zhong-Jin [16].

Certain aspects relating to the evaluation of the level of influence of stochastic components adopted in the process of calculating the parameters of reserve bearing capacity of bored piles after strengthening, as well as the effectiveness of a particular method of strengthening in terms of ensuring the reliability of structures in general are in the range of scientific interests of Kupchikova N.V. [23], Konnov A.V. [22], Filippov K.A, Gavrutina

A.V., Mukhin A.A. [32], Huang, Sheng-gen [6], Xing, Haofeng [18], Ling, Zao [8], Li, Zhen-Ya [7], Ma, Hailong [11].

However, despite the wide range of publications and the considerable interest of scientists in the problem under consideration, it should be noted that with the development of new computing technologies, techniques and methods of analyzing big data, a number of new questions in this subject plane arise, which requires additional, more in-depth research.

In particular, the calculation-theoretical apparatus of designing effective large-size pile foundations, taking into account the development of new structural solutions, needs further development. The studies relating to methods for determining the value of the carrying capacity of piles on the properties of the soil foundation, obtained in the test of static pressing load, as well as the value of the carrying capacity of piles taking into account the data of the static sounding are also fragmentary.

Thus, in view of the above, the purpose of the article is to investigate modern scientific and methodological approaches to find reserves of bearing capacity of bored piles.

The research objectives include: 1) study of theoretical approaches to the calculation of the bearing capacity of bored piles; 2) consideration and comparison of techniques that give a more accurate result; 3) conducting an experiment to identify the reserve of increase of bored piles in different soils and at different degrees of their soaking.

Research hypothesis: refinement and use of better methodologies will allow to identify the reserve of bored piles with a high degree of reliability.

2 Materials and Methods

Analysis of normative and scientific sources, technical achievements; standard field methods for studying the operation of piles and foundations under the action of a static load; analytical studies using methods of the theory of elasticity and plasticity; methods for solving soil mechanics problems based on the theory of limit equilibrium, numerical methods for studying value added tax using the Plaxis 3D Faundation software package.

3 Results

To conduct the study, consider a building that is a high-rise structure with one basement, based on a pile foundation. The main system of resistance to lateral and gravitational loads consists of a reinforced concrete core and a reinforced concrete frame of outriggers. The building rests on one monolithic reinforced concrete head 3 meters thick, cast in place, connecting bored piles located at a distance of 1.5 meters from each other. A 1-meter-thick slab extends cantilevered from the pile head as shown in Figure 1. This part of the mat rests directly on the ground. There are several layers of upper and lower bending reinforcement along the entire base of the mat. In a 3 meters' thick part, transverse reinforcement is provided, consisting of rods located at a distance of 60-90 cm from each other.

To search for the bearing capacity reserves of bored piles, a non-linear computer model of the Perform building was developed in accordance with the recommendations of the PEER Tall Buildings Initiative [5, 13]. The mathematical representation of the structure was then subjected to 7 ground motions to simulate different loads on the structural members. The Perform model includes representations of main and extended sliding walls, as well as spacer beams, reinforced concrete and embedded steel connecting beams, basement retaining walls, concrete slabs on the two lower levels, retaining walls on the two lower levels, diaphragm restraints on the remaining levels, and several options for pile plates.

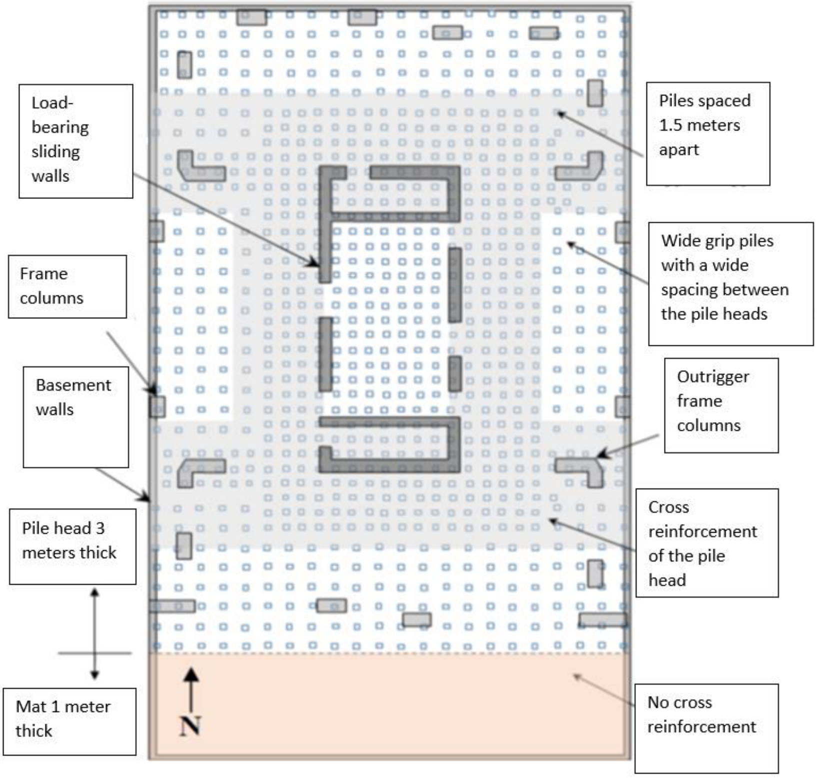

Fig. 1. Foundation plan with pile head.

Today there are a number of criteria used to determine the load-bearing capacity of piles based on the results of load testing:

1. Tangential graphical method: defines failure as the load at the intersection of the initial straight part of the curve and the final straight part of the curve.

2. Terzaghi method: when the pile settlement is equal to 10% of the pile diameter [9].

3. Log load - Log settlement: this method is used for long piles with large diameters by plotting the logarithmic relationship between the value [settlement/diameter] and the load. The maximum load is determined as a function of the pile diameter [10].

4. Chin-Condner extrapolation: according to the Chin method, tests carried out with piles in the field and in the laboratory show that the relationship between load and settlement is hyperbolic. A graph is drawn on one axis of which the pile settlement is plotted, and on the other axis the settlement divided by the corresponding load. After some initial variation, the plotted values lie on a straight line. The inverse slope of this line gives the limit load [17].

$$\delta_1/p = m\delta_1 + c_2$$

where, δ_1 - pile settlement, mm;

p - load, kN;

m - slope of the straight line, dimensionless;

c_2- y-intersection of the straight line for the best fit.

5. Brinch-Hansen method: the square root of each pile settlement value from the load test data divided by the corresponding load value [14].

The ultimate load is then defined as:

$$Qu = \sqrt[1/2]{c_1 \times c_2}$$

where, Qu is the ultimate bearing capacity, kg;

c_1 - slope of the most appropriate straight line, dimensionless.

6. Decort extrapolation: dividing each load by its corresponding design value [24]. This is used to plot the resulting value relative to the applied load. A linear regression over the visible line (often the last points) determines the direction. Decort defined the limit load as the intersection of this line with the load axis.

7. De Beer's method. The essence is to plot the load data in double logarithmic form. The point of intersection of the two straight lines on the logarithmic graph gives the value of the load limit.

8. Sheng's method: a load-deposition curve is plotted with the dependence of the load-deposition on the logarithmic load and a curve with a linear tail is obtained. The starting point of the linear tail is defined as the ultimate load.

In general terms, the ultimate load-carrying capacity for (c) and (φ) soil can be determined by the static formula as follows:

$$Qu = Qb + Qs$$

$$Qu = Ap\left[cN_c + \sigma_{vb}N_q\right] + \sum As\,(c\alpha + K_s\sigma_v tan\delta)$$

where, c is the cohesiveness of the soil, kPa;

φ - angle of internal friction, deg;

Qb - resistance of the end support, kg;

Qs - resistance of surface friction, kg;

Ap - cross-sectional area of the pile, m2;

As - surface area of the pile barrel, m;

N_c, N_q - bearing capacity coefficients, dimensionless coefficients;

σ_{vb} - effective surface rock pressure for the foundation soil, kPa;

K_s - ground pressure coefficient;

σ_v - effective pressure of surface rocks, kPa;

δ - angle of friction at the interface, deg.

Comparing the bearing capacity of the bored pile, which is calculated theoretically with the results of static test, we can analyze what reserve in bearing capacity the pile has. It is also possible to determine on which parameters the difference in bearing capacity depends more: the soil in the pile base, the pile diameter, the pile length.

4 Discussion

In an experimental study, the Schen method was used to select the values of the ultimate bearing capacity of the piles. The calculations showed that the method gave acceptable results for model pile load tests.

Table 1 presents the surface friction and foundation resistance data obtained from the load tests of model bored piles that were tested at the initial degree of saturation in the soaked and unsoaked state of the soil.

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Table 1. Predicted bearing capacity of piles, kg.

Method used	**Degree of saturation - 7 % Collapse potential - 7%**	
	Unsaturated	**Saturated**
Theoretical	45.5	31.6
Tangential graphical method	33	15
Terzaghi method	36	17
Log loads - log precipitation	20	15
Chin-Condner extrapolation	60.97	38.3
Brinch-Hansen method	54.6	33.2
Decort extrapolation	58	26
De Beer method	36.8	20.25
Sheng method	36.8	20.25

Prior to the pile load test, the soil was soaked from the top surface. From the results of the dial gauge measurements of pile and soil settlement, it was found that the settlement of the soil was greater than the settlement of the pile. When the pile was loaded in the soaked condition, there was a significant decrease in bearing capacity, with this trend in behavior similar to that of local shear failure.

Figure 2 shows the shape of the load-pile settlement curve.

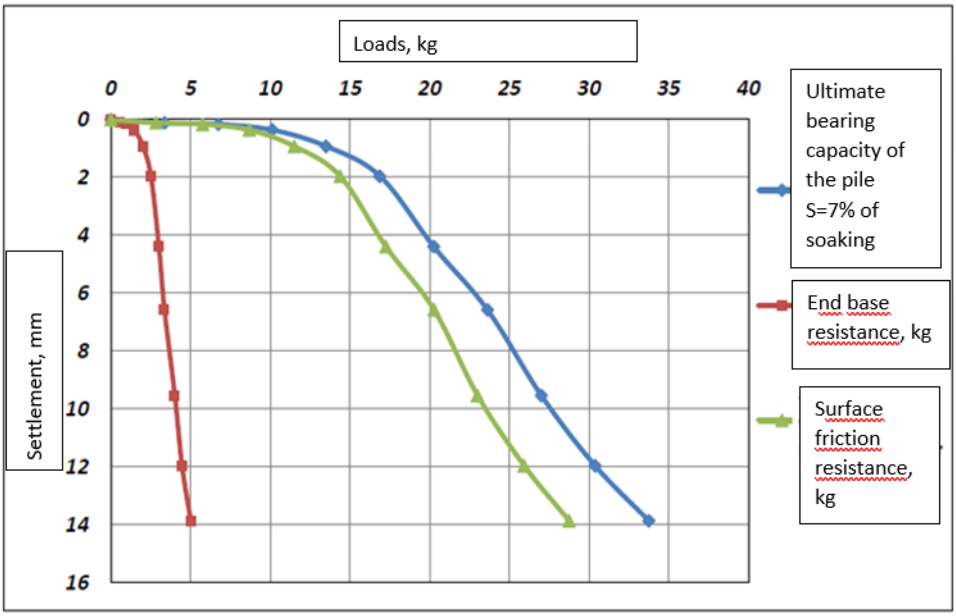

Fig. 2. Load-and-fill curves for a pile with a 7% degree of saturation in the soaked state.

Table 2 shows the performance of the experimental piles of the investigated foundation, on the basis of which the experiment was conducted (length and diameter); the number of tests for each site; the magnitude of the load at which the static test of the pile was terminated; the settling value at that load; the theoretical bearing capacity.

Table 2. Static pile test results and theoretical pile bearing capacity.

No. of the site	Results of static test of piles					Theoretical bearing capacity of piles. kN	Difference between theoretical and actual bearing capacity. %
	No. of tests	Dimensions of tested piles		Load. kN	Settlement. mm		
		Diameter. mm	Length. m				
1	1	620	14	3000	12.9	1807	+66
	2		14	3000	19.9	1788	+68
	3		16	2750	18.2	2018	+36
2	1	820	20	4200	2.06	2755	-13%
	2	820	17	5000	2.15	2720	+84
	3	820	17	4200	3.3	2550	+65
	4	620	22	3600	3.75	1965	+83
	5	620	16	3600	5.92	1532	+135
	6	620	8	3000	6.15	1050	+186
3	1	720	20	4750	6.6	3060	+55
	2	720	20	4750	5.8	2885	-17%
	3	720	18	5000	6.4	2730	83

The building discussed in this article is located on site №2. On sites №1 and №3 there are buildings of the same developer, erected using a similar technology, but on different soils.

On sites №1 and №3 sandy soils prevail and the bearing capacity reserve ranges from 40 to 90%. The most common piles are 620 and 720 mm in diameter and 14...20 m long. The reason for such a reserve, with such pile lengths, is to ignore the entire lateral bearing capacity of the pile through the introduction in the formula of the pile lateral conditions coefficients, which are used for conventional bored piles.

At site №2 there are predominantly dense sands. The calculations carried out showed a fairly large difference between the theoretical values of the carrying capacity of the piles, and the carrying capacity determined by the results of the static test has a much smaller variation, despite the different length of the pile. Thus, it can be assumed that the bearing capacity in dense sands is not as dependent on depth as for other soil conditions.

5 Conclusion

Based on the results of the experimental work, the following conclusions can be made. Of the different methods that were used to estimate the bearing capacity of bored piles, Log load-Log calculation and the graphical tangent method received a lower value than the others. At that time, the Chin-Conder extrapolation method, the Brinch Hansen extrapolation, and the Decort extrapolation gave high estimates of bearing capacity in model pile load tests. Sheng's method gave almost acceptable results in bored pile load tests.

A large decrease in the bearing capacity of the pile was observed when it was subjected to soaking for (24 hours). The percentage reduction in ultimate bearing capacity as a result of soaking was 45%.

In addition, the comparative analysis performed indicates that in 90% of the cases, the bored piles have a reserve of actual bearing capacity compared to the calculated theoretical values. The results of experiments and measurements at the construction sites considered indicate that it is possible to reduce the number of piles, but the installation process must be monitored.

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