Vertical-load design of a large-size bored pile

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Abstract. The results of experimental and theoretical studies of vertically loaded large-size (from 50 and more meters long) bored pile work features are presented. The results of testing the vertically loaded large-size bored piles with a diameter of 2m, a length of 55m and 65m in clay soils by the submerged jack method are analyzed. According to the test results, the features of the soil resistance formation under the pile tip and on the side surface are identified. On this basis, the need to design such piles according to the second soil limit state, taking into account the compressibility of the pile shaft is justified. The kinematic scheme of inclusion the soil base and the pile shaft into work under vertical loading is given. On this basis, a technique for calculating the settlement of a single pile and a method for determining the allowable load on the pile are developed. This load does not allow pile settlement to exceed the allowable settlement of the designed building. An example of a bored pile calculation by the developed method is given.

1. Introduction
Bored piles have been used in construction for over 100 years. During this period, geotechnical engineers have done a lot of experimental research, and developed a number of methods for designing these piles. Following generally accepted, experimentally proved and well-studied physical conceptions of bored pile work in the ground under vertical load, pile resistance due to the soil resistance on the pile side surface and under its tip is formed \[1, 2\], etc. In this case, the limit state of the pile base appears first on the side surface under certain settlement (usually small one, within 1-2 cm), which is called contact ("shear") settlement, then after increasing the load up to a certain value, the limit state of the base under the pile tip is reached, which is characterized by continuous pile settlement without load increase. This load is taken as the ultimate one.

2. Experimental technique
Most methods for calculating the pile load-bearing capacity are based on the physical conception of pile work and on the use of a two-part formula presented in the normative document on the design of pile foundations. In this case, the design ground resistance to friction on the pile side surface and under its tip is determined by various methods, including empirical formulas \[3\] cone penetration data \[4, 5\], physical characteristics \[6\] and the theory of ultimate equilibrium \[7\]. At the same time, it is taken as a rule that the ground limit state occurs when the settlement is less than the allowed by the Codes, on the basis of which the calculation of piles is carried out taking into account the first limit state, i.e. by the bearing capacity of the foundation soil. The settlement at which the pile base limit
state occurs may significantly differ depending on the soil conditions, the pile shaft shape and its geometric dimensions. In accordance with A.A. Grigoryan’s design scheme [8] the pile load-bearing capacity is formed due to the shifts in the area of the pile tip along fixed inclined surfaces. The methods of pile calculation on the maximum allowable deformations should also be noted [9]. The paper [10] presents a method for calculating bored pile settlement, but the compression of the pile shaft is not taken into account.

This approach is well approved for piles up to piles up to 20-25m in length. However, at present, large-size bored piles with a diameter of 1.0 – 2.0 m and a length of 50 m or more-up to 100 m are used more often [11]. Such piles are applied in the construction of high-rise buildings, industrial high towers, masts and bridges, which is characterized by large (up to 3000-5000ts per pile) loads, as well as difficult ground conditions, for example, when strong bearing layers of soil lie at a great depth.

The work of long bored piles under load is significantly different from the standard relatively short piles (up to 20-25m long). The existing calculation methods for such piles are not applicable. The peculiarity of long piles is that when the vertical load is applied, the pile shaft is compressed and the deformation of the pile shaft can reach 4-5 cm, which is necessary to consider when calculating piles. In addition, static testing of such piles according to the standard method is technically impossible, which does not allow obtaining a “load – settlement” graph directly from the static test data in order to assess the settlement and load-bearing capacity. Testing of such piles is carried out by a special technique of a submerged jack (Osterberg method) [12]. The parameters of soil resistance on the side surface of the pile and under its tip are determined on the obtained results.

The results of such tests do not allow obtaining the “load-settlement” relationship for the pile as a whole, but the parameters of the soil resistance on the pile side surface and under its tip can be used to analyze the stress-strain state of the pile-soil base system at different stages of vertical loading.

In this regard, there is a need for studying the behavior of large-size piles under the influence of vertical load and developing a calculation method taking into account these features.

3. Results of experimental studies

Let us consider the results of long pile testing with the use of the submerged jack method (Osterberg method), presented in [11]. The diagram of the pile test using this method is shown in figure 1. Two bored piles with a diameter of 2m and a length of 55 and 65m were tested at the experimental site. The soil conditions of the experimental site were as follows:

- solid clays, \( \varphi = 19^\circ \), \( C = 0.2 \) MPa, \( E = 30 \) MPa, from the surface to a depth of 14 m,
- morainic solid clays, \( \varphi = 26^\circ \), \( C = 0.38 \) MPa, \( E = 100 \) MPa, below to a depth of 19 m
- vendian solid clays, \( \varphi = 26^\circ \), \( C = 0.85 \) MPa, \( E = 200 \) MPa down to a depth of 75 m.

![Figure 1. Structural scheme of piles testing by submersible jack method.](image-url)
The experimental results are presented in the schemes of figure 2.

![Figure 2. Specific soil resistance: (a) on the pile side surface depending on its displacement; (b) under the pile tip depending on its settlement.](image)

The results of the pile tests allow us to analyze separately the regularities of the friction force formation on the pile side surface and the soil resistance under its tip in the entire range of vertical load. So, from the graphs in figure 2 (a), it follows that the increase in the friction resistance on the side surface of the pile is completed with displacements of 10-15 mm, i.e., with such settlement, the soil friction resistance is fully realized. This confirms the data obtained for short piles [13], for which the "shear" settlement equals 5-15 mm.

Figure 2 (b) shows graphs of the “pile tip settlement - soil resistance” under pile tip dependence. As it can be seen, the soil resistance increases linearly over the entire range of settlements up to the one of 120-140 mm with no signs of the limit state.

On that basis, it becomes possible to formulate the concept of pile head settlement formation regularity under vertical load.

The pile head settlement includes the following stages:
- compression of the pile shaft, it can reach 4-5 cm for long piles;
- settlement of the pile tip, measured more than 10-12 cm without limit state of the base under the pile foot;
- settlement caused by deformation of the near-pile soil, which can be possibly measured up to 2-3 cm.

Thus, the total pile head settlement can be reach up to 20 cm or more with no limit state of the base under the pile tip, which is much more than the allowable settlement (10-15 cm) for most buildings and constructions.

This implies that in such piles design, the priority must be given to the calculation of the pile settlement.

4. Calculation method

Let us consider the formation mechanism of the stress-strain state of the pile – soil foundation system. The kinematic diagram of the interaction of a long vertically loaded pile with soil by increasing load is shown in figure 3.

The task consists in determining the final pile head settlement in a compressible soil base assuming that the pile is considered as an elastically deformable body.

At the initial pile loading up to a certain load \( N_{01} \), axial stresses arise in the pile shaft, then they disappear at the depth \( z \). The pile shaft gets compressed. As a result, the pile side surface is included into work at this site.

The load \( N_{01} \) is taken only by the pile side surface up to the depth \( z \), at which the limit state (full realization of friction) is reached on the pile side surface in the upper section (at \( z = 0 \)) (figure 3, position 1). Therewith, before the pile slipping into the soil, elastically compression of the near-pile soil massiv occurs the value of which \( S_m \) gets maximum at the contact with the pile side surface and disappears at some distance from the pile.

As the load increases to a certain value of \( N_{02} \), more and more deep soil layers are put into operation, and, therefore the axial stress moves down the length of the pile, and when these stresses reach the pile tip, the shear stress diagram (friction on the pile side surface) will have the form as shown in figure 3 (position 2). At this load, the friction on the pile side surface reaches its limit values.
at the site where the pile shaft compression reaches the value of contact settlement, but below the friction decreases to zero towards the pile tip. Herewith, the soil resistance under the pile tip is equal to zero, i.e. the pile foot is not included into work.

With a further load increase to a certain value of \( N_{03} \), the contact settlement arises along the entire pile length, and the soil base is put into action under the pile tip (figure 3, position 3). In this state, the pile head settlement is determined as the sum of the settlements due to the compression of the pile shaft \( S_p \), the pile tip settlement due to the soil consolidation under the pile tip \( S_l \), and settlement based on the surrounding soil deformation \( S_g \).

The \( S_p \) is defined as

\[
S_p = \frac{1}{2} \frac{N_f l}{EA} + \left( \frac{N_{03} - N_f}{EA} \right) = \frac{l(2N_{03} - N_f)}{2EA},
\]  

where 
- \( l \) is the length of the pile in the soil;  
- \( E \) is the pile concrete modulus of elasticity;  
- \( A \) is the pile cross-section area;  
- \( N_f \) is the total pile resistance due to the soil friction on the pile side surface.  
- The \( N_f \) value is defined by the formula:

\[
N_f = \pi d \sum f_i l_i,
\]

where \( f_i \) - is the design friction resistance of the i-th soil layer on the pile side surface;  
- \( l_i \) is the thickness of the i-th soil layer;  
- \( d \) is the pile cross-section diameter.  

The \( f_i \) value can be defined by different methods, including:

- Static penetration tests;  
- The limit equilibrium theory analysis (Coulomb’s theory);  
- Static tests results get by the submersible jack method;  
- Tabular data obtained from experimental study results.

The pile tip settlement caused by soil consolidation at this load is equal to the contact settlement \( S_c \), as this state is aligned with the full friction realization on the pile side surface along the full length. According to some experimental studies \([13, 14]\) the contact settlement of bored piles is equal to 10-15 mm. With a further load increase, the settlement of the pile head \( S_c \) remains constant and no longer increases.

Thus, at this loading stage, the pile head settlement is defined as

\[
S = \frac{l(2N_{03} - N_f)}{2EA} + S_g,
\]

Further load increase to a certain value of \( N_{04} \) (figure 3, position 4) leads to pile head settlement due to the pile shaft compression and the soil consolidation under the pile foot caused by the soil reaction under the pile tip.

In any case, with any vertical load \( N_0 \), the pile head settlement due to shaft compression \( S_p \) is calculated by formula (1) where \( N_{03} \) is replaced by \( N_0 \).

The settlement of the pile foot \( S_l \) due to the soil consolidation under it upon condition of the linear settlement-load dependence can be calculated according to the theory of elastic half-space (Schleicher’s formula)

\[
S_l = \frac{(1-\mu^2)\omega d P}{E_0 A},
\]

where \( P \) is the load transmitted to the pile foot and calculated by formula

\[
P = N_o - N_c\]

\( d \) is the diameter of the pile cross-section; \( E_0 \) is the elasticity modulus under the pile foot; \( \mu \) is Poisson’s ratio; \( \omega \) is the shape coefficient taken equal to one for a circular cross-section.

Settlement \( S_l \) implies contact settlement \( S_c \).
The soil modulus under the pile tip should be calculated with taking into account overconsolidation, as it is of great importance at great depths.

Then the total pile head settlement will be written as

\[ S = \frac{(2N_0-N_f)}{2EA} + \frac{d(N_0-N_f)(1-\mu^2)}{E_0A} + S_g, \tag{6} \]

Solving equation (6) with respect to \( N_0 \) and substituting \( S_{\text{perm}} \) for \( S \) (where \( S_{\text{perm}} \) is allowable settlement), and substituting \( N_g \) instead \( N_0 \) we obtain the allowable pile load \( N_g \), at which the settlement will not exceed the allowable value

\[ N_g = \frac{2S_{\text{perm}}+2S_g+N_f(1B+2D)}{2(1B+D)}, \tag{7} \]

where \( B = \frac{1}{E_0A}; \quad C = \frac{1}{E_0A}; \quad D = d(1-\mu^2)C, \tag{8} \)

The pile settlement caused by the near-pile soil settlement can be calculated by Z.G. Ter-Martirosyan’s method [15].

In the case of pile penetration into a multi-layer subsoil of different depth, it is necessary to determine the optimal pile length, which depends on the lithological section and the peculiarities of the soil occurrence with different characteristics.

In such soils, when pile length changes, the ratio of settlement values also changes due to the resistance on the pile side surface and under its tip. If the layer is strong and solid at a certain depth, the pile length is taken on the base of the pile foot penetration into this layer.

If there is no such layer in the lithological section, the optimal pile length should be determined by making calculations according to formula (7) for piles of different lengths with an interval of 1 m, following by the determination of ratio \( N_0/V \) and checking of the condition below

\[ N_0/V = \text{max}, \tag{9} \]

where, \( V \) is a volume of pile concrete.

Example of Calculation.

It is necessary to define allowable load on a reinforced concrete bored pile with a diameter of \( d = 2 \) m, a length of \( l = 65 \) m, buried in clay soils of equal depth.

- The soil resistance to friction on the pile side surface along the full length is taken from the experimental data shown in the graph of figure 3 \( f = 35 \text{ t/m}^2 \).
- The deformation modulus under the pile foot is taken as \( E_0 = 20,000 \text{ t/m}^2 \).
- The modulus of concrete elasticity is \( E = 3\times10^6 \text{ t/m}^2 \);
- Poisson's ratio is \( \mu = 0.4; \)
- The cross-sectional pile area is \( A = 3.14 \text{ m}^2 \);
- The allowable settlement is \( S_{\text{perm}} = 15 \text{ cm} \);
- The near-pile soil settlement is approximately assumed as \( S_g = 3 \text{ cm}. \)

According to the results calculated using formula (7), the allowable load is 16370 t. Herewith, the pile resistance due the friction on the pile side surface is 14270 t, and due to the resistance under the pile foot is 2,100 t. This fact implies that the realized resistance under the pile tip is 668 t/\text{m}^2 that practically corresponds to the pile testing results (see the graphs in figure 2 (b)).

Let us determine the settlement values separately due to the pile shaft compression and the load taken by the pile side surface and the pile tip.

The measured settlement caused by the pile shaft compression is 6.3 cm, the one caused by the soil resistance along the pile side surface and the soil compression under the pile tip is 5.7 cm, which totally equals 12 cm and meets the requirement of not exceeding the allowable settlement \( S_{\text{perm}} = 0.15 \text{ m} \), taking into account the fact that the settlement of the near-pile soil is \( S_g = 0.03 \text{ m}. \)
5. Conclusion
1. On the testing results of two bored piles with a diameter of 2 m and 55 and 65 m in length in clay soils by the submersible jack method, the regularities of soil resistance formation on the pile side surface and under the pile tip are established. The soil resistance to the friction on the pile side surface reaches the maximum at a pile settlement of 10-15 mm. It is not increased with further loading. The soil resistance under the pile tip increases with its foot settlement of 120-150 mm with no signs of the pile base limiting state. It means that with the allowable of the building and construction settlements, the limit state of the pile base will not be reached, and therefore, it is necessary to design such piles soils on the base of the second limit state.

2. Using the experiment results, the method for determining a single long bored pile settlement with account of the pile shaft compression is developed. The method for calculating the pile load, with which the pile settlement will not exceed the allowable settlement of the designed building or construction, is also developed.

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