An investigation to determine the bearing capacity of driven piles and pressed friction pile using practical method

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Abstract. This article considers the question of the necessity of soil porosity coefficient in determining the bearing capacity of vertically loaded driven and pressed pile (vertical load) by analytical method using the calculated values of soil resistance on the pile’s side surface and under its toe, defined by the tables of standard documents (practical method). Statistical analysis, based on the theory of planning experiments, shows that additional consideration of the soil porosity coefficient allows to increase the accuracy of calculation of pile bearing capacity, which is confirmed by the results of field tests of piles and cone penetration tests of soils. It is shown that, depending on the soil porosity coefficient, the bearing capacity of a vertically loaded pile can vary up to 2 times. To calculate the load-bearing capacity of driven and pressed piles by the analytical method based on the results of engineering and geological surveys taking into account the soil porosity coefficient, the method developed on the basis of Z. Sirojiddinov’s probabilistic-statistical processing of test results by vertical static load testing on a large number of piles in various soil conditions is recommended.

1. Introduction

Analytical method to calculate the bearing capacity of a driven or depressed hanging pile on the ground according to the tables in SP 24.13330.2011 [1], widely used in the practical design and is known as the "practical method", based on the generalization of the test results of a large number of regular and special piles with vertical static load, carried out in different ground conditions, in order to establish the limit values for friction forces between the pile and the surrounding soil, and the ultimate resistance of the soil under pile’s toe. As a result of the analysis and generalization of the experimental datas, tables of calculated soil resistances are obtained that allow to determine the resistance of the pile’s side surface and its toe. Summing up the obtained values according to the formula (1), bearing capacity \( F_d \) is found:

\[
F_d = \gamma_c \left( \gamma_{cr} R A + u \Sigma \gamma_{cf} f_i h_i \right)
\]  

In which \( \gamma_c \) - coefficient of working conditions of the pile in the ground, assumed to be equal to 1; \( \gamma_{cr}, \gamma_{cf} \) - coefficients of soil working conditions respectively under pile’s toe and on its side surface, taking into account the influence of the method of pile immersion on the calculated resistance of the soil, accepted for the purposes of this article for driven and pressed solid and hollow with closed end piles, assumed to be equal to equal to 1; \( R \) - tabular calculated resistance of the soil under pile’s toe, kPa; \( A \) – the area of the pile standing on the ground, \( m^2 \); \( u \) – the perimeter of the cross section of the
pile shaft, m; \( f_i \) - tabular calculated resistance of the i-th layer of the surrounding soil on the lateral surface of the pile; \( h_i \) – the thickness of the i-th soil layer contacting with the lateral surface of the pile, m (figure 1).

In formula (1), the first term represents the resistance of the soil under the toe of the pile, the second – the resistance of the soil on its side surface.

The method to determine the bearing capacity of the pile on the vertical load according to the formula (1) using the tables of the SP [1] has never been criticized, for many years up to the present time it has been applied both in Russia and abroad (with almost no differences), is used as an effective method to assess the bearing capacity of piles. Based on the results of engineering and geological surveys and in combination with the results of cone penetration tests it allows to determine the main parameters of pile foundations and their bearing capacity at an early stage of design.

One of the ways to improve the accuracy of determining the bearing capacity of piles by a practical method is to clarify the calculated resistances of soils on the side surface and under the pile’s toe on the basis of additional experimental data and, in particular, by taking into account their specifications, along with the index of fluidity of clay soils and the grain size of sand, also the porosity coefficient. The necessity for this accounting, noted by many experts, is confirmed by the results of cone penetration tests of soils and subsequent tests of piles by vertical load.

2. The calculated bearing capacity of the pile by the «Recommendation to determine the bearing capacity of driving piles in water-saturated dust-clay and sandy soils» [2]

In 1992, Recommendations were developed to determine the bearing capacity of driving piles in water-saturated dust-clay and sandy soils, in which, at the calculation of the bearing capacity of the pile, by practical method, calculated values \( f_i \) and \( R \) were defined taking into account the coefficient of soil porosity \( e \) [2].

The calculated bearing capacity \( F \) of driven friction piles (square, rectangular, round), in pulverized clay and sandy soils of natural composition, being pressed, is determined by the formula:

\[
F = R^n A / \gamma R + \sum f_i^m h_i / f_i \ ,
\]

in which \( R^n \) – normative resistance of the soil under the toe of the pile, kPa, accepted depending on the depth of immersion of the toe of the pile, flow index \( I_L \) of silty-clay soils, sand grain size and porosity coefficients and others; \( A \) – the cross-sectional area of the pile, m²; \( u \) – perimeter of the pile.
cross-section, m; \( f_i^n \) – normative resistance of the i-th layer of the surrounding soil on the lateral surface of the pile, kPa, accepted depending on the depth of the middle of the considered i-th soil layers, flow index \( I_0 \) of silty-clay soils, sand grain size and porosity coefficients and others; \( h_i \) – the thickness of the i-th soil layer contacting with the lateral surface of the pile, m; \( \gamma_R \) and \( \gamma_f \) – reliability coefficients on the ground under the lower end and on the side surface of the pile, taking into account the confidence probability \( \alpha \).

Determination of bearing capacity of driving piles taking into account the degree of responsibility of the designed buildings and structures makes it possible to use material and labor resources more rationally.

The table values of normative soil resistances on the lateral surface and under the pile’s toe, as well as the corresponding reliability coefficients on the soil, given in the Recommendation [2] are obtained by Ph. D. Z. Sirojidinova’s probabilistic-statistical processing of static load test results with 10219 tests in clay soils and 1274 tests in sandy soils [3] [4] [5] [6] [7].

3. The method of factor analysis
To estimate expediency of calculation of bearing capacity of driven and pressed friction pile by practical method taking into account porosity coefficient of soils enclosing pile array the influence of various factors (factor analysis) on the results of the calculation (determination of the bearing capacity of the pile) is analyzed [8].

Assuming that the influence of a number of factors \( X_1, X_2, X_3, X_4, \ldots, X_k \) on a certain value \( Y \) is studied. To gain this, experiments are carried out on a specific plan, which allows to implement all possible combinations of factors. Moreover, each factor is considered only at two fixed levels. The number of all experiments in this case will be equal to \( n = 2^k \), in which \( k \) – number of studied factors. Setting up experiments on this plan is called a type of complete factor experiment \( 2^k \).

Polynomial for the case of 4 factors:

\[
Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{14} X_1 X_4 + b_{23} X_2 X_3 \\
+ b_{24} X_2 X_4 + b_{34} X_3 X_4 + b_{123} X_1 X_2 X_3 + b_{124} X_1 X_2 X_4 + b_{134} X_1 X_3 X_4 \\
+ b_{234} X_2 X_3 X_4 + b_{1234} X_1 X_2 X_3 X_4
\]

(3)

\[
b_0 = \frac{1}{n} \sum_{j=1}^{n} Y, \\
b_i = \frac{1}{n} \sum_{j=1}^{n} X_j Y
\]

4. Analysis of the influence of various factors on pile bearing capacity by the formula (2)
The following factors affecting the bearing capacity of piles are considered, according to results of studies [9] [10] [11] [12]:

- factor \( X_1 \) – the length of the piles \( L \in [8; 10; 12] \) m;
- factor \( X_2 \) – the diameter of the piles \( D \in [0.4; 0.6; 0.8] \) m;
- factor \( X_3 \) – flow index \( I_L \in [0.4; 0.6; 0.8] \);
- factor \( X_4 \) – porosity coefficient \( \epsilon \in [0.6; 0.8; 1.0] \).

According to tables 2 and 4 [2] values \( R^n \) and \( f_i^n \) are calculated (kPa):

| Table 1. Calculated values \( R^n \) (kPa). |
|------------------------------------------|
| \( L = 8 \text{ m} \) | \( L = 10 \text{ m} \) | \( L = 12 \text{ m} \) | \( L = 8 \text{ m} \) | \( L = 10 \text{ m} \) | \( L = 12 \text{ m} \) | \( L = 8 \text{ m} \) | \( L = 10 \text{ m} \) | \( L = 12 \text{ m} \) |
| \( I_L = 0.4 \) | \( I_L = 0.6 \) | \( I_L = 0.8 \) | \( I_L = 0.4 \) | \( I_L = 0.6 \) | \( I_L = 0.8 \) | \( I_L = 0.4 \) | \( I_L = 0.6 \) | \( I_L = 0.8 \) |
| \( e = 0.6 \) | 3210 | 3440 | 3570 | 2440 | 2605 | 2720 | 1870 | 1970 | 2046.7 |
| \( e = 0.8 \) | 2440 | 2650 | 2720 | 1840 | 1970 | 2046.7 | 1370 | 1470 | 1523.3 |
| \( e = 1 \) | 1790 | 1990 | 2096.7 | 1320 | 1420 | 1496.7 | 970 | 1000 | 1023.3 |
Table 2. Calculated values $f_i^H$ (kPa).

| $L=0,4$ | $L=0,6$ | $L=0,8$ |
|---------|---------|---------|
| $L=8m$  | $L=8m$  | $L=8m$  |
| $L=10m$ | $L=10m$ | $L=10m$ |
| $L=12m$ | $L=12m$ | $L=12m$ |
| $e=0,6$ | 33,4    | 24,2    |
|         | 35,4    | 24,85   |
|         | 36,5    | 25,5    |
| $e=0,8$ | 24,7    | 17,2    |
|         | 25,7    | 17,85   |
|         | 26,7    | 18,5    |
| $e=1$   | 18,2    | 11,7    |
|         | 19,2    | 12,35   |
|         | 20,2    | 13      |

Table 3. The planning matrix and the results of the calculations.

| Номер | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $L(m)$ | $D(m)$ | $I_L$ | $e$ | F (kN) |
|-------|-------|-------|-------|-------|--------|--------|-------|-----|--------|
| 1     | -1    | -1    | -1    | -1    | 8      | 0,4    | 0,4   | 0,6 | 568,754 |
| 2     | 1     | -1    | -1    | -1    | 12     | 0,4    | 0,4   | 0,6 | 810,003 |
| 3     | -1    | 1     | -1    | -1    | 8      | 0,8    | 0,4   | 0,6 | 1327,097 |
| 4     | 1     | 1     | -1    | -1    | 12     | 0,8    | 0,4   | 0,6 | 1830,857 |
| 5     | -1    | -1    | 1     | -1    | 8      | 0,4    | 0,8   | 0,6 | 324,288 |
| 6     | 1     | -1    | 1     | -1    | 12     | 0,4    | 0,8   | 0,6 | 458,282 |
| 7     | -1    | 1     | 1     | -1    | 8      | 0,8    | 0,8   | 0,6 | 759,021 |
| 8     | 1     | 1     | 1     | -1    | 12     | 0,8    | 0,8   | 0,6 | 1037,445 |
| 9     | -1    | -1    | 1     | -1    | 8      | 0,4    | 0,4   | 1   | 313,204 |
| 10    | 1     | -1    | -1    | 1     | 12     | 0,4    | 0,4   | 1   | 458,005 |
| 11    | -1    | 1     | -1    | 1     | 8      | 0,8    | 0,4   | 1   | 732,129 |
| 12    | 1     | 1     | -1    | 1     | 12     | 0,8    | 0,4   | 1   | 1039,845 |
| 13    | -1    | -1    | 1     | 1     | 8      | 0,4    | 0,8   | 1   | 149,615 |
| 14    | 1     | -1    | -1    | 1     | 12     | 0,4    | 0,8   | 1   | 206,932 |
| 15    | -1    | 1     | 1     | 1     | 8      | 0,8    | 0,8   | 1   | 356,521 |
| 16    | 1     | 1     | 1     | 1     | 12     | 0,8    | 0,8   | 1   | 474,302 |

5. Result analysis

By formula (4) and (5) results for $b_i$ are got:

Table 4. Analysis result $b_i$.

| $b_0$  | 677,89 | $b_{23}$ | -80,74 |
|-------|--------|----------|--------|
| $b_1$ | 111,57 | $b_{24}$ | -82,38 |
| $b_2$ | 266,76 | $b_{34}$ | 37,62  |
| $b_3$ | -207,09| $b_{123}$| -13,78 |
| $b_4$ | -211,57| $b_{124}$| -11,47 |
| $b_{12}$ | 39,40 | $b_{134}$ | 3,45 |
| $b_{13}$ | -38,13| $b_{234}$ | 14,93 |
| $b_{14}$ | -33,11| $b_{1234}$ | 0,98 |
and substituting their values in the function (3), we have:

\[
y = 677.89 + 111.57X_1 + 266.76X_2 - 207.09X_3 + 211.57X_4 + 39.4X_1X_2 - 38.13X_1X_3 - 33.11X_1X_4 - 80.74X_2X_3 - 82.38X_2X_4 + 37.62X_3X_4 - 13.78X_1X_2X_3 - 11.47X_1X_2X_4 + 3.45X_1X_3X_4 + 14.93X_2X_3X_4 + 0.98X_1X_2X_3X_4
\]

For illustration purposes, as a result of mathematical analysis, the influence of the considered factors on the bearing capacity of the pile determined by the calculation is shown in the form of diagrams in figure 2.

The diagrams show that, along with these factors, as the geometric dimensions of the pile and the soil flow index, porosity coefficient has a significant impact on the bearing capacity of the pile, determined by the calculation.

![Figure 2](image_url) **Figure 2.** The influence of factors on driven pile bearing capacity

As can be seen from the graphs in figures 3-5, based on the results of the calculations, the bearing capacity of the driven pile under effect of vertical load only with changing the soil porosity coefficient, at constant values of flow index and pile parameters, can vary up to 2 times, what is not considered by the current SP [1].

These figures show only a part of the obtained and analyzed graphs, allow to generally estimate the influence of soil porosity coefficient on driven piles bearing capacity under effect of vertical loading, are determined by analytical method using tables of calculated soil resistances on the pile’s lateral surface of and its toe.
Figure 3. Graphs $F = f(e)$ at $I_L = 0.4$ (a) and $I_L = 0.8$ (b) for $D = 0.4; 0.6; 0.8$ (considering $L = 10\text{m}$)

Figure 4. Graphs $F = f(e)$ at $I_L = 0.4$ (a) and $I_L = 0.8$ (b) for $L = 8; 10; 12\text{m}$ (considering $D = 0.6\text{m}$)
Figure 5. Graphs $F = f(e)$ at $L=8\text{ m}$ (a) and $L=12\text{ m}$ (b) for $I_L=0.4;0.6;0.8\text{ m}$ (considering $D=0.6\text{ m}$)

On figures 6,7 graphs $F/(F_d/1.4) = f(e)$ are given, which show that under effect of vertical load, the ratio of the bearing capacity of driven pile, which is / (isn’t) determined by the porosity coefficient, decreases with increasing $e$.

Figure 6. Graphs $F/(F_d/1.4) = f(e)$ at $I_L=0.4$ (a) and $I_L=0.8$ (b) for $D=0.4;0.6;0.8\text{ m}$ (considering $L=10\text{ m}$)
6. Conclusions

1. Results of analytical calculations and their statistical analysis, conducted on the basis of the theory of planning experiments, showed that, along with factors such as the geometric dimensions of the pile and the flow index of clay soil, the soil porosity coefficient has a significant impact on the bearing capacity of the pile, determined by the analytical method on the tables of calculated values of soil resistances on the side surface and under its toe, which must be considered in the calculations.

2. Determined by the calculation, the bearing capacity of the driven pile under effect of vertical load by taking into account changes in the soil porosity coefficient, at constant values of its flow index and pile parameters, can vary up to 2 times.

3. The degree of influence of the porosity coefficient on the bearing capacity of driven vertically loaded pile, determined by the analytical method on the tables of calculated values of soil resistances on the side surfaces and under it’s toe, increases with the increase of pile diameter and the reduction of porosity coefficient and is practically independent of the length of the piles, and flow index of the soil.

4. It is recommended to use Recommendation [2] for calculation of bearing capacity of driving piles by analytical method according to tables of standard documents developed on the basis of Z. Sirozhiddinov's probabilistic - statistical processing of test results by vertical static load of a large number of piles in various ground conditions.

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