The Factor of "Synergy" in the Design and Construction of Foundations of Driven Piles

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Abstract. The existing methods for assessing the bearing capacity of pile foundation from driven piles, are based on calculation schemes that do not fully take into account the factors that affect its joint work with the foundation soil. One of them is the factor of "synergetics" - self-organization of pile-soil system as a change in the physical and mechanical characteristics of the compacted zone the soil massif in the process layout of the pile foundation. It is assumed that around the pile driven into the base is formed the symmetric zone of compacted soil. When piling group these zones are deforming in the process of their interaction in the event that the boundaries of the zones are superimposing on each other. The general geometric shape of the compacted soil zone under the base of the pile foundation is also distorted that leads to erroneous conception of the soils bearing capacity. The energy costs of piling indicate availability or lack of interaction of the compacted zones. Experimental tests of the flat profiled driven piles allowed to formulate the basic law of the interaction of compacted soil zones around the piles taking into account the total energy costs of the piles driving. Authors propose a new characteristic – the soil compaction parameter which allows to taking into account intensity of interaction of the compacted soils zones around the piles when designing of pile foundations.

Use of the soil compaction parameter at assessing of pile bearing capacity will increase the efficiency of a pile foundation construction and to avoid a probable non-driving of piles.

1. Introduction

At the build of pile foundation from the driven piles in soil, surrounding a pile, there is increasing deformation. Around a single pile of the compacted soil zone around the pile symmetrical relative to the vertical axis of the pile is formed.

Process of forming of the compacted soil zone around the piles is accompanied by a certain amount of work spent for sink a pile. It is confirmed by the data obtained by V.N. Golubkov \cite{2} at sink of single prismatic piles in soils of different initial density.

By results of these researches he came to a conclusion that pile driving in more firm soil is characterized by high consumption of the energy spent by the mechanism of pile driving and at the same time greater bearing capacity in comparison with sank of a pile in less firm soil.

Similar results were received at sink of driven piles in plan of pile foundation at distance between their axes accepted according to the recommendations of paragraph 8.13 \cite{3}.
Full sink of piles to a design level, even with the same soil density in the plan of the pile foundation, was observed very rarely. Mainly the pile fields abound with the lots of non-driving piles to a design level, with the broken heads, so-called «popov».

At sink the piles that are a part of the pile foundation, the first pile is drove to a design level without any problems. Already bigger amount of energy in comparison with the energy spent for drive of the previous piles is spent for sink of the next pile. Moreover, if to take the total amount of the energy spent for sink of the first pile, equal to one, then on sink of the next pile driven at a distance equal 3d from the first pile the total amount of energy much more and can reach 2 units.

Assuming that soil massif density in plan of one foundation is the same, there is a question – what prevents to drive all piles to a design level with identical expenses of energy?

For obtaining the answer to this question it is necessary to analyze the entire technological chain from the development of design documentation and finishing with the construction of pile foundation.

Having received the results of engineering-geological surveys, the design institute performs calculations of the piles bearing capacity by the soil base, and then, having calculated external load from the building on the foundation structure, the number of piles on the pile field is calculated. Having distributed pile on loadings with determination of quantity and to distance between their axes, the designer determines locations and the number of under testing single piles on the pile field. The quantity and requirements for dynamic and static tests have to be performed in accordance with GOST 5686 [1]. Works on tests are included into the design and estimate documentation. Therefore they have to be organized and pay by the contractor who receives the order after the auction.

After receiving results of dynamic and static tests of single piles, the designer is obliged to correct the pile field if bearing capacity of piles does not satisfy to results of the design solution.

Thus, the construction of the foundation pile field actually is based on results of calculations and testing of a single pile. At the same time, as S.N. Levachev notes, "the mutual influence of piles through the soil medium is not take into account" [7]. This state of affairs raises the question is a need to research of a state the soil surrounding a pile and a piles group, both in the construction process of pile foundations and their exploitation.

Partially the answer to this question was for the first time obtained through a new technique with use of the developed laboratory equipment and deformation sensors [8]. With their use it is possible to receive information on changes in the density of the soil at the points of the soil massif at impact on it to external loading and pile driving in structure of the pile foundation.

Use of the new method allowed to study laws of formation the compacted soil zones around the piles in the process of construction the pile foundations from flat profiled piles having inclined side faces [9].

Results of researches showed, that when sink of the flat profiled piles (having the form of a flat wedge) in structure of the pile foundation, compacted zones of soil with high density is formed, for which a certain amount of energy is consumed [4], dependent, in particular, from a geometrical shape of the piles.

As a result of experimental tests of the pile foundations from the driven flat profiled (wedge-shaped) piles with foundation soil laws of interaction of compacted soil zones around the piles as the main factor of "synergetics"-self-organization of the pile-soil system for the first time are open.

Results of researches [4, 5, 6] showed that at sink to a design level the first pile which is a part of the pile foundation, relative to its central axis forms a volume compacted soil zone around the piles of symmetrical shape. The next pile which is part of the pile foundation, drove at a distance more than six diameters from the first pile forms the same volume compacted soil zone. And, the total energy costs for sink of the first and second piles were appeared equal – therefore, the compacted zones of the soil do not intersect and do not interact with each other.

Conversely, when the distance between axes of the piles was reached less than three diameters according with paragraph 8.13 [3], the first pile when at sink to a design level, formed a symmetrical, concerning its central axis, compacted soil zone. The next pile, from the structure of the pile foundation, at sink to the design level, formed the deformed volumetric zone of soil around the piles.
At the same time, the total energy reached one and a half the magnitude in comparison with the total energy spent for sink of the first pile.

As a result of experimental researches [4, 5] were studied:

a) laws of forming and geometrical characteristics of the compacted soil zones around the piles at flat profiled (wedge-shaped) piles;

b) laws of mutual influence of the compacted soil zones around the piles at flat profiled piles when forming of volume compacted zone of soil massif in the abstract foundation;

c) laws of the mutual influence of compacted soil zones around the piles with determination of the energy spent for sink of the piles that are a part of the pile foundation;

d) at the same time it is found that that there is no mutual influence of piles with each other, and there is a mutual influence of compacted soil around piles formed by sink of adjacent piles in the abstract foundation structure.

The laws of mutual influence of compacted soil zones around the pile, revealed at model and field researches allow to draw the main conclusion – in mechanics of soils the new law on mutual influence of the compacted soil zones around the piles when forming the abstract foundation from the driven and indentation piles is open.

The intensity of interaction of the compacted soil zones forming in the process of pile driving in the structure of the pile foundation, can be considered by proposed author of the soil compaction parameter (\(K_k\)) determined from a simple relations:

\[ K_k = \frac{\sum E_{\text{od}}}{n_i \times \sum E_{i}} \]  

(1)

where \(K_k\) - soil compaction parameter in the pile foundation;

\(\sum E_{i}\) - total energy, kJ, spent for sink of all piles that are a part of the pile foundation to a design level;

\(n_i\) - number of piles in the foundation;

\(\sum E_{\text{od}}\) - total energy, kJ, spent for sink of the first pile as a single to the design level and determined by the formula:

\[ E_{\text{od}} = G \times H \times n \]  

(2)

\(G\) - weight of a impacting part of a pile-driving hammer, kN;

\(H\) - height of jumping up of a impacting part of a diesel hammer, m;

\(n\) - number of impacts hammer diesel.

The physical meaning of soil compaction parameter reflects the general law of interaction of the compacted soil zones around the piles foundation and is determined as the ratio of the total energy going for sink of all the piles that are a part of the foundation by the total energy going for sink of number single piles, equal with it.

The analysis of experimental researches results showed that the soil compaction parameter can be used for refine of bearing capacity of the pile foundation.

Bearing capacity of a single pile drove into foundation structure of the first and rest piles, being are part of the pile foundation, are determine by dynamic or static tests according to requirements of chapter 7.3 [3].

At the same time, a soil compaction parameter of the pile foundation will be determined by a formula:

\[ K_k = \frac{F_{DK}}{F_{OD} \times n} \]  

(3)

where \(K_k\) – the soil compaction parameter of pile foundation, dimensionless value;

\(F_{DK}\) – the bearing capacity of pile foundation determined by actual tests, kN;

\(F_{OD}\) – the bearing capacity of the single pile (driven with the first into structure of the foundation), determined by actual tests, kN;

\(n\) - number of piles in the foundation.
At soil compaction parameter equal $K_k \leq 1$, bearing capacity of the pile foundation will be maximal. In this case the piles included in the foundation will work as the single, compacted soil zones around the piles at sink of piles will not intersect (interact). The effectiveness of such a foundation is maximal.

The condition of the maximum bearing capacity of a piling is equality to its sum of bearing capacities of single piles:

$$\frac{F_{DK}}{K_k} \leq F_{OD} \times n$$

(4)

where $F_{DK}$, $K_k$, $F_{OD}$, $n$ - the same values, as in a formula (3).

At soil compaction parameter values of equal $K_k \geq 1$, bearing capacity of the pile foundation will reduce because the compacted soil zones around the piles will be intersect (interact). At the same time, the total energy costs will increase by sink of each subsequent pile after the first. Besides, at interaction of compacted soil zones around the piles formed at sink of the first and subsequent pile as showed results of our researches [5], the reasons of a non-drive of piles in the construction of pile foundations were revealed and as their result – formation of so-called "popov".

The number of piles in the foundation is determined according by the proposed method from a ratio:

$$n = \frac{F_{DK}}{K_k \times F_{OD}}$$

(5)

$F_{DK}$, $K_k$, $F_{OD}$, $n$ - the same values, as in a formula (3).

Bearing capacity of the pile which is part of the pile foundation will be determined:

$$F_{OD} = \frac{F_{DK}}{K_k \times n}$$

(6)

$F_{DK}$, $K_k$, $F_{OD}$, $n$ - the same values, as in a formula (3).

Bearing capacity of foundation soils a single pile in the structure of pile foundation and out of it according with paragraph 7.1.11 [2] is determine by calculation of a formula:

$$N \leq \frac{F_{DP}}{\gamma_k}$$

(7)

where $N$ – the design load transferred to a pile (the limit force arising in it from the design loads affecting on the foundation at their most unfavorable combination), determined by a formula (8).

$F_{OD}$ – the foundation soil bearing capacity of a single pile called further by bearing capacity of a pile and determined according with paragraph 7.1.11 [3].

Reliability coefficient, $\gamma_k$, is accepted:

1.2 - if bearing capacity of a pile is determined by calculation for results of actual tests by a static load;

1.25 - if bearing capacity of a pile is determined by calculation for results of static soil probing, by results of dynamic tests of the piles, made taking into account elastic deformations of soil and also by results of actual tested of soil a standard pile or probe pile;

1.4 - if bearing capacity of a pile is determined by calculation, including by results of dynamic tests of the piles performed without taking into account the elastic deformation of soil;

1.4 (1.25) - for the foundations of bridge supports at a low piling, floating piles and standing piles, at a high piling - only at the standing piles taking up a compression load regardless of piles number in the foundation.

At a high piling or a low piling which bottom leans on highly compressible soil and floating piles, and the standing piles taking up the pulling out loading, $\gamma_k$, is accepted depending on number of piles in the foundation:

- with 21 piles and more .................. 1.4(1.25);
- from 11 to 20 piles ......................... 1.55(1.4);
- from 6 to 10 piles .......................... 1.65(1.5);
from 1 to 5 piles………………… 1.75(1.6);

for the foundations from a single pile under a column at load of a driven pile of square cross section more than 600 kN and a filling pile - more than 2500 kN value of the coefficient \( \gamma_k \) should be accepted equal 1.4 if bearing capacity of a pile is determined by tests results of a static load, and 1.6 if bearing capacity of a pile is determined by other methods;

\( \gamma_k = 1 \) - for solid pile fields of rigid constructions with the maximum draft of 30 cm and more (at number of piles more than 100) if bearing capacity of a pile is determined by results of static tests.

The design load on a pile \( N \), kN, is determined by a formula 7.3 [3], considering the pile foundation as the frame structure taking up vertical and horizontal loads and bending moments.

For the foundations with vertical piles the design load on a pile is allowed to be determined by a formula:

\[
N \leq \frac{N_{DK}}{n} \pm \frac{M_x}{y_i} \pm \frac{M_y}{x_i}
\]  

(8)

where \( N_{DK} \) - design force of pressing on the foundation, kN;

\( M_x \) and \( M_y \) - design moments of bending, kN * m, rather principal central axes \( x \) and \( y \) of the piles plan in the plane of the bottom of the piling;

\( n \) - number of piles in the foundation;

\( x_i, y_i \) - distances from principal axes to an axis of each pile, m;

\( x, y \) - distances from the principal axes to an axis of each pile for which the design load is calculated, m.

2. Conclusion

The analysis of experimental results researches and the above material on design and the construction of the foundations from driven flat profiled piles, taking into account a factor of "synergetics", as the pile-soil system, allows up to draw the following conclusions:

1) At the construct of the pile foundation around the first pile is forming the compacted soil zone, having the symmetrical shape relative its central axis;

2) At the construct of the foundation around each subsequent pile the compacted soil zone the deformed shape relative its central axis is forming, in case of its interaction with previous, formed at the first pile. At the same time the general geometric shape of the compacted soil zone the pile foundation is shifted towards pile driving. As a result the designer cannot determine the dimensions and shape of the conditional foundation according with paragraph 7.4.2 [2];

3) The requirement of paragraph 8.11 [2] loses meaning because of inability to place resultant permanent loads in a gravity center of the piles plan in the foundation;

4) On a design stage and determination of soil compaction parameter on a site of construction there was an opportunity to solve a problem of placement a driven piles of any design on plan of the piles foundation;

5) At soil compaction parameter values of equal \( K \leq 1 \) driven piles which are a part of the pile foundation can be loaded by the external loading close to bearing capacity of piles on foundation soil.

Soil compaction parameter makes the opportunity to compare on bearing capacity the pile foundations from any designs of driven piles.

The received results set the following tasks:

1) Development of a method on models of forming the compacted soil zone at driving of a single prismatic pile and piling of the abstract foundation;

2) Detection of a form of the compacted soil zone around the pile;

3) Finding of boundaries of the compacted soil zone around the pile under the base of a single pile under the set specified physical and mechanical conditions of a soil massif;

4) Determination the soil compaction parameter of the conditional foundation the compacted zone under the base of a single pile and a piles group under the set specified physical and mechanical conditions of a soil massif.
3. References

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