Statistical modelling of impacts on a pile-raft foundation

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Abstract. This paper reviews performance of combined pile-raft foundations (CPRF). The goal of the study is obtaining the ability to design solid, reliable and cost-effective foundations allowing for minimum settlements. The task is to develop methods for calculating CPRF for optimum choice of the foundation raft size, dimensions and number of piles. To achieve these results, an analytical method was used, curves of the ratio of CPRF settlement to raft foundation settlement vs. total load \( N \) on the piles were plotted. The scientific significance of the study is in the method of engineering calculation of CPRF, which is better correlated to the experimental data and allows optimal distribution of loads between the raft and piles, ensuring reliability and operational integrity of buildings, reduction of settlements and the number of piles, which would lead to cost savings and reduced consumption of materials for foundations.

A new coefficient showing the residual stress has been introduced, and a method for its calculation has been proposed. A new equation for determination of the share of total load \( N \) on the piles has been obtained. This equation is more general in comparison with the previously generated equations. It allows excluding the assumption that the stresses arising under the raft completely dissipate at the level of the pile end. Application of the developed methods will increase reliability and reduce settlements and the number of piles, which ultimately will lead to cost savings and reduced consumption of materials for foundations.

1. Introduction

Combined pile-raft foundation (CPRF) is a structure comprising a reinforced-concrete raft foundation and piles. The raft can be either constant or variable in thickness, and the piles can be either constant or variable in length, diameter and spacing [1, 2]. Methods of connection between the piles and the raft can also be different, e.g. rigid or hinged connection or one-sided contact support [3, 4, 5].

The structure is called combined, since the work of its elements is mutually complementary to each other through the foundation soil medium. This is manifested in partial transfer of the building weight at the upper level (under the raft bottom), allowing for increase in friction forces in the upper part of the piles [6], which, in its turn, leads to increase in the maximum load on a pile, while the raft allows
the foundation remaining reliable even after the "failure" of a pile. This agrees with the emergence principle of the systems theory, stating that it is typical of a system to acquire properties of constituent components, as well as new properties.

The grounds stated in the article [7] are based on two basic provisions for comparison of pile foundations (PF) and raft foundations (RF):

- pile foundations are more expensive than raft foundations;
- pile foundations are more rigid.

Combined pile-raft foundation (CPRF) is assumed to be an intermediate option between PF and RF in terms of settlements, rigidity and costs.

Regulatory documents adopted in Russia, containing basic rules for design of bases and foundations [8, 9, 5, 10] do not consider the possibility of using piles in the breakdown zone, i.e. after their "failure". For this reason, the existing documents allow for transfer of no more than 15% of the total weight of the building via the raft to the base [8, 10], which rather corresponds to the classic pile foundation according to the classification [11], which properly accounts for the actual deformability of friction piles and the ability of the raft foundation to take up some load. The EU regulatory document on regulation of geotechnical design [12] classifies combined pile-raft foundations as foundations of Category 3. This means that standard provisions stated in this Eurocode are not applicable to them, and the design procedure should include alternative and specially developed rules and measures.

2. Methodology

The task is to develop methods for calculating CPRF for optimum choice of the foundation raft sizes, dimensions and number of piles, so that settlements would not exceed the ultimate values. The most cost effective and safe number of piles is the number which would provide settlements under the ultimate values. Load and settlement values of PF and RF have been determined for high-rise buildings under load \( N \), with the assumption that the first settlement \( s_{pf} \) is below and the second settlement \( s_{rf} \) is above the ultimate value for the building. Thus, three foundation models are considered – pile (PF), raft (RF) and combined pile-raft (CPRF) – under the same conditions and the same static load \( N \).

The following assumptions were introduced in the work [7]:

1. Bending and torque moments and transverse forces acting on foundation structures are considered negligible.
2. Settlement of piles under load is bilinear, i.e. the value of settlement is directly proportional to the corresponding load before achievement of the design load-bearing capacity; subsequent deformations develop without changes in internal forces of piles.
3. The raft foundation does not resist unless some ultimate load is achieved; all loads from the structure on the base are distributed among the piles. Developing settlement involves overlying soil layers (including the near-pile soil body and the structure as a whole).
4. When the ultimate load-bearing capacity of the piles is achieved, the piles slip along the shaft in relation to soil, and raft foundation resistance appears. It also takes up subsequent additional loads.
5. Deformability of the pile shaft is considered negligible.

Apart from clearly stated assumptions, there is a number of issues that are implicitly omitted: reliability issues (reserve factors), variability in characteristics of construction materials, soils and loads. This is due to the fact that the proposed method [7] does not imply final calculations for such a complex system, but it makes it possible to estimate the required number of piles in the first approximation with the help of a simple engineering calculation.

Analytical calculations performed for three models, taking into account the above assumptions, allowed obtaining an equation of the optimum share of loads from the structure, distributed by piles in CPRF, depending on the total load from the structure, in the work [7]:
\[ \alpha_{cprf} = \frac{s_{pf} - s_u}{s_{rf} - s_{pf}} = \frac{\delta_{pf} - 1}{\delta_{pf} - \delta_{rf}}, \]  

(1)

where \( \alpha_{cprf} \) is the share of total load \( N \) on piles; \( s_u \) is ultimate settlement; \( s_{pf}, s_{rf} \) are total settlements of pile and raft foundations, respectively; \( \delta_{pf}, \delta_{rf} \) are relative settlements of pile and raft foundations.

Equation (1) was obtained after mathematical transformation, during which total settlement of pile and raft foundations \( s_{pf}, s_{rf} \) were divided by the ultimate settlement \( s_u \), and relative settlements of pile and raft foundations were obtained. This conclusion implied an implicit assumption that the vertical stresses due to pressure transmitted along the raft bottom dissipated at the level of the pile bottom end. This assumption can be valid if the length of piles is much larger than the size of the foundation in plan, and the vertical stresses are significantly reduced.

It would be reasonable to assume that there is an opposite extreme assumption that the additional vertical stresses under the raft and at the level of the pile ends are equal. This assumption most closely describes the case when the length of piles is significant in comparison with the characteristic size of the raft foundation. As is the case in [7], taking into account the opposite assumption, we obtain the following:

\[ N_{pf} = \alpha_{cprf} N \]  

(4)

This being the case, \( N_{rf} \) is determined as follows:

\[ N_{rf} = (1 - \alpha_{cprf})N \]  

(5)

If the additional vertical pressure due to the load at the level of the pile bottom ends does not decrease due to pressure transmitted along the raft bottom, then the soil under the piles is loaded with the sum of forces \( N_{pf} \) and \( N_{rf} \). Thus, the pile component of settlement \( s_{cprf,1} \) (due to soil shrinkage below the pile ends) is equal to:

\[ s_{cprf,1} = \frac{N_{pf} + N_{rf}}{k_{pf}} = s_{pf} \]  

(6)

The second component of settlement (due to soil shrinkage under the raft, following the "failure" of piles) is equal to:
The total settlement of CPRF equals to the sum of the following components:

\[ s_{cprf} = s_{pf} + (1 - \alpha_{cprf}) s_{rf} \]  

(8)

If we assume that CPRF settlement equals to the ultimate settlement \( s_u \), then \( \alpha_{cprf} \) can be calculated from equation (8):

\[ \alpha_{cprf} = \frac{s_{rf} + s_{pf} - s_u}{s_{rf}} = 1 - \frac{s_u - s_{pf}}{s_{rf}} = 1 - \frac{1 - \delta_{pf}}{\delta_{rf}}. \]  

(9)

Equation (9) allows determination of the load share taken up by the piles.

3. Results and Conclusion

In the work [2], materials on systematization of the monitoring results with regard to various objects constructed with CPRF are presented. Regularity of changes in the ratio of CPRF settlement to RF settlement \( \frac{s_{cprf}}{s_{rf}} = \frac{\delta_{cprf}}{\delta_{rf}} = \frac{1}{\delta_{rf}} \) (assuming that design CPRF settlement is equal to ultimate settlement, i.e. \( s_{cprf} = s_u \) and \( \delta_{cprf} = \frac{s_{cprf}}{s_u} = 1 \)), depending on \( \alpha_{cprf} \), was determined in the course of the study.

The values \( \alpha_{cprf} \) obtained according to equation (1) in the work [7] were compared to the obtained results, accepting the value \( 0.18 \leq \frac{s_{pf}}{s_{rf}} = \frac{\delta_{pf}}{\delta_{rf}} \leq 0.47 \) from experience (this ratio depends on physical and mechanical characteristics of soil layers composing the base, and their strata as well). This comparison is shown in Figure 1. The results obtained according to equation (9) are presented in Figure 2.

It can be seen in Figures 1 and 2 that two extreme hypotheses provide for distributions close to the limits of actual measurements, which is consistent with the assumption that actual foundation behavior
lies between two abstract assumptions: the vertical stresses from the raft completely dissipate or do not dissipate at all between the levels of the raft bottom and pile bottom ends.

In order to account for a certain actual value of decrease in the vertical stress at the section from the raft bottom to the pile bottom ends, it is suggested to introduce value $\alpha$ representing the ratio of additional vertical stress in the soil body, occurred due to pressure below the raft at the level of the pile bottom ends, to vertical stress which is directly below the raft. In other words, $\alpha$ is the share of undissipated pressure, the value of which is known (for example, its tabulated values are given in Table 5.8 [9], depending on the ratio of the raft sides and the pile length as the depth parameter). In this case, equation (6) takes the following form:

$$s_{cprf,1} = \frac{\alpha_{cprf} N + \alpha(1 - \alpha_{cprf})N}{k_{pf}} = \alpha_{cprf} s_{pf} + \alpha(1 - \alpha_{cprf})s_{pf}.$$  \hspace{1cm} (10)

Considering the residual stress $\alpha$ ($0 < \alpha < 1$), we will obtain $\alpha_{cprf}$ in the following form:

$$\alpha_{cprf} = \frac{\delta_{cf} + \alpha \delta_{pf} - 1}{\delta_{cf} - \delta_{pf}(1 - \alpha)}.$$  \hspace{1cm} (11)

It should be noted that under limit values $\alpha = 0$ and $\alpha = 1$, equation (11) turns into equations (1) and (9), respectively, confirming once again that the mathematical calculations are correct.

Figure 3 shows distribution at the arbitrary value $\alpha = 0.5$ (continuous line), and $\alpha = 0$ and $\alpha = 1$ represented for comparison (dashed lines). Analyzing the results obtained, we can conclude that equation (11) represents a more general expression, which coincides practically with the whole area of distribution drawn on the basis of observations and monitoring [1].

Figure 4 shows the area of possible location of all points if the value $\alpha$ constantly changes from 0 to 1, reflecting, at each $\alpha$, the area of possible location of points in the graph in the same axes.

![Figure 3](image1.png)  \hspace{1cm} ![Figure 4](image2.png)

**Figure 3.** Dependence of the ratio of CPRF settlement to RF settlement vs. $\alpha_{cprf}$ calculated according to equation (11) at the arbitrary value $\alpha = 0.5$.

**Figure 4.** Dependence of the ratio of CPRF settlement to RF settlement vs. $\alpha_{cprf}$ calculated according to equation (11) under possible values of $0 < \alpha < 1$.

It should be noted that although only purely raft and pile foundations correspond to the limit values $\alpha_{cprf} = 0$ and $\alpha_{cprf} = 1$, and there is matching of distribution zones according to the proposed method and those obtained in the result of monitoring, significant deviation in the middle zone of the experimental distribution towards smaller actual settlements of CPRF is observed. This can be
explained by the fact that internal interaction in the pile–raft–soil system is the most pronounced in the middle zone \((0.3 < \alpha_{CPRF} < 0.7)\), and behavior of this system has been studied to a less degree than behavior of separate components (raft or piles).

This fact implies that the proposed method for determining the optimum number of piles is conservative, that is, it can only understake the predicted settlement, which is consistent with the principles of reliability. Nevertheless, this also shows a lack of knowledge on properties of CPRF as a system with effective interaction of its elements.

The method of engineering calculation of CPRF has been proposed, which is better correlated to the experimental data.

The new equation for determination of \(\alpha_{CPRF}\) — the share of total load \(N\) on the piles — has been obtained. Proposed equation (11) is more general in comparison with equations (1) and (9), and excludes the assumption that the stresses arising under the raft completely dissipate at the level of the pile bottom ends.

The new coefficient \(\alpha\) has been introduced, showing the residual stress, and the method for its calculation has been proposed.

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