TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
ENVIRONMENT ENGINEERING | ŚRODOWISKO

1-Ś/2013

GRZEGORZ KACPRZAK, PAVEL KRAVCHENKO, WAWRZYNIEC SMOLAK*

COMPARISON OF CPRF MODELING STUDIES RESULTS TO THEORETICAL ONES IN SOIL WITH A LOW BEARING CAPACITY

PORÓWNANIE WYNIKÓW BADAŃ MODELOWYCH FUNDAMENTU PŁYTOWO-PALOWEGO POSADOWIONEGO NA PODŁOŻU SŁABONOŚNYM Z WYNIKAMI TEORETYCZNYMI

S t r e s z c z e n i e

W artykule przedstawiono porównanie wyników badań modelowych fundamentu płytowo-palowego posadowionego na podłożu słabonośnym z wynikami teoretycznymi otrzymanymi przy wykorzystaniu procedury obliczeniowej Poulos'a. Przedstawiono zastosowany model laboratoryjny z interpretacją wyników w postaci zależności obciążenie-osiadanie oraz procentowego udziału pali w przenoszeniu obciążenia.

Słowa kluczowe: badania modelowe fundamentu płytowo-palowego, teoretyczne określenie udziału pali w przenoszeniu obciążenia

A b s t r a c t

The paper summarizes the results of modeling studies of combined pile-raft foundation (CPRF) built on soil with a low bearing capacity to theoretical results obtained by using the design procedure by Poulos. Laboratory model used for investigation as well as interpretation of results in form of load-displacement relationship and percentage of load carried by piles were characterized.

Keywords: modeling studies of piled raft foundation, theoretical determination of pile contribution in load transfer

* Ph.D. Grzegorz Kacprzak, Instytut Dróg i Mostów, Wydział Inżynierii Lądowej, Politechnika Warszawska.

** M.Sc. Eng. Pavel Kravchenko, M.Sc. Eng. Wawrzyniec Smolak, Wydział Mostów i Tuneli, Petersburski Państwowy Uniwersytet Komunikacyjny.

Symbols

V – total vertical applied load
V_A – applied load at which pile capacity is mobilized
V_{pu} – ultimate capacity of piles (single pile or block failure mode, whichever is less)
V_{ru} – ultimate capacity of raft
K_{pr} – axial stiffness of piled raft system
K_r – axial stiffness of raft
K_p – axial stiffness of pile group
β_P – proportion of load carried by piles

1. Introduction

The subject of Combined Pile-Raft Foundation (CPRF) was previously discussed by Zeevaert [20], Davis and Poulos [3], Hooper [9, 10], Burland et al. [4], Sommer et al. [16], Price i Wardle [15], Franke [6], Bartolomey et al. [1], Gandhi and Maharaj [7], Borel and Combarieu [2], Kurillo et al. [12], Tejchman et al. [17], Ulickiy et al. [19], Fioravante and Jamiolkovski [5], Mirsayapov and Artemev [13] and others authors. Despite this studies and theoretical analyses it is difficult to define the part of the load carried by the elements of CPRF. In Russia and Poland there is no proper branch guidance that encourages engineers engaged in the designing process of CPRF enabling them to take into account the transfer of the load to the raft and to the piles simultaneously.

Due to the three-dimensional nature of the problem, a detailed analysis of CPRF is very complex and compels to conduct numerical simulations or laboratory tests. Hence, trying to point out the existing cooperation between elements of CPRF, the authors of this article present some laboratory results of CPRF model built on loose silty sand typical to the soil condition in the region of Petersburg, Russia. Further, the theoretical results obtained by using the design procedure by Poulos were compared to laboratory ones using the load-displacement relationship as well as the percentage of load carried by piles.

2. Practical design procedure for CPRF [14]

Poulos and Davis developed a simplified hand calculation method for constructing the overall load-settlement curve until the failure of CPRF was reached. The elastic solution is used for determination of the initial stiffness of the piled raft and of the raft itself. In consequence a three-linear load-settlement relationship is obtained reflecting the work of the main elements of piled-raft foundation. It should be underlined that only perfectly rigid or perfectly flexible rafts can be considered.

Randolph developed the convenient approximate equations for the stiffness of a piled raft system and the load sharing between the piles and the raft. The method is restricted to linear behaviour of the piled raft system i.e. the initial portion of the load-settlement curve. Other approaches with similar concept were presented by Franke et al. and van Impe and de Clerq. In the latter case, the piled raft is represented by a series of pile-raft segments having a circular cap. The various interactions are modeled using elastic theory, and the piled behaviour is given by a modification of the analysis by Randolph and Wroth. Although the resulting equations need to be solved using a computer, the calculation process is simple and does not require specialised software. The approach is limited to perfectly flexibe or perfectly rigid raft.

A method which combines and extends the approaches by Poulos and Davis and Randolph is described below. It includes the following aspects:

a) estimation of the load sharing between the raft and the piles, using the approximate solution of Randolph
b) hyperbolic load-deflection relationship for the piles and for the raft, thus providing a more realistic overall load-settlement response for the piled raft system than the three-linear approach by Poulos and Davis.

Figure 1 shows diagrammatically the load-settlement relationship for the piled raft. Point A represents the state at which the pile capacity is fully mobilised when the total vertical load V_A is applied. Over this point, both the piles and the raft share the load. The settlement (S) can be expressed as follows:

$$S = \frac{V}{K_{pr}} \tag{1}$$

Beyond point A, additional load must be carried by the raft, and the settlement is given by:

$$S = \frac{V_A}{K_{pr}} + \frac{V - V_A}{K_r} \tag{2}$$

The load V_A can be estimated from:

$$V_A = \frac{V_{pu}}{\beta_p} \tag{3}$$

One can use the approximate expression described by Randolph for K_{pr} in equation (1) and β_p in equation (3), namely:

$$K_r = XK_p \tag{4}$$

$$X \approx \frac{1 - 0,6(K_r / K_p)}{1 - 0,64(K_r / K_p)} \tag{5}$$

$$\beta_p = \frac{1}{1+\alpha} \tag{6}$$

$$\alpha \approx \frac{0,2}{1 - 0.8(K_r / K_p)}\left(\frac{K_r}{K_p}\right) \tag{7}$$

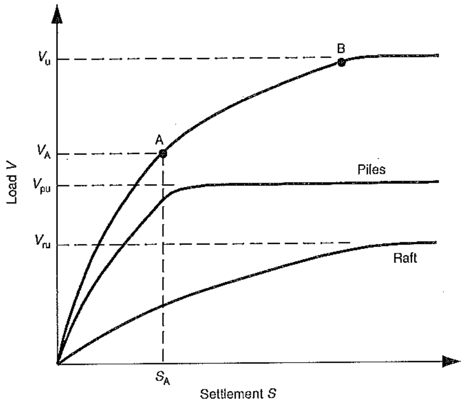

Fig. 1. Load-settlement relationship for CPRF acc. [13]

It is assumed that the pile and raft load-settlement relationship are hyperbolic, then the secant stiffness of the piles (K_p) and the raft (K_r) can be expressed as follows:

$$K_p = K_{pi}(1 - R_{fp}V_p / V_{pu}) \tag{8}$$

$$K_r = K_{ri}(1 - R_{fr}V_r / V_{ru}) \tag{9}$$

where K_{ri} and K_p denote initial axial stiffness of raft and initial axial stiffness of pile group respectively.
The load carried by the piles is given by:

$$V_p = \beta_p V \leq V_{pu} \tag{10}$$

and the load carried by the raft is:

$$V_r = V - V_p \tag{11}$$

Substituting equations (3)–(11) in equations (1) and (2), the following expressions are obtained for the load-settlement relationship of the piled raft system.

For $V \leq V_A$:

$$S = \frac{V}{XK_{pi}\left(1 - \frac{R_{fp}\beta_p V}{V_{pu}}\right)} \tag{12}$$

For $V > V_A$:

$$S = S_A + \frac{V - V_A}{K_{ri}\left(1 - R_{fr}\frac{\left(V - V_{pu}\right)}{V_{ru}}\right)} \tag{13}$$

where:

$$S_A = \frac{V_A}{XK_{pi}\left(1 - R_{fp}\right)} \tag{14}$$

with V_A is given by equation (3)

Equations (12)–(14) provide a method for estimating the average load-settlement relationship for the CPRF. Because K_r and K_p will vary with the applied load level, the parameters X and βp will also generally change.

3. Modeling studies of CPRF

The CPRF model consisted of four piles (aluminum tubes of 16 mm diameter with wall thickness of 1.5 mm and 300 mm long) connected to the acrylic glass square-shaped plate (50 mm high and 150 mm width). The model is shown in Fig. 2.

Plate (8) provided guides (2), into which piles (1) were instaled. At the top of each pile, aluminum tubes (3) of 6 mm diameter was installed. Steel arm (4), connected directly to frame (5) and plate (8) by spring (6), was set on element (3).

The load was transferred directly on the plate by the pin coupled to the displacement measuring gauge. When the pile was switched on to transfer the load, arm (4) moved causing the spring enlargement measured by gauge (7).

The application of load was carried out gradually; each load step was considered completed when certain stabilization of settlement was achieved. The criterion of settlement stabilisation was adopted at the level of 0.01 mm in 15 minutes.

Fig. 2. Model of CPRF used in presented studies

4. Determination of stiffness of CPRF elements

3.1. Stiffness of pile group

3.1.1. Stiffness of measurement spring

Prior to testing, the equipment was subjected to the procedure of calibration in order to link the displacement of arm (4) which is equal to enlargement of spring (6) in response to applied load i.e. to define the linear stiffness of spring (6), k_1 = 19 kG/mm.

3.1.2. Stiffness of single pile

Secondly, the non-linear stiffness of the pile k_2 (Fig. 3, dotted lines) was described. In the same soil conditions and using the same laboratory equipment three series of load of single pile tests were performed.

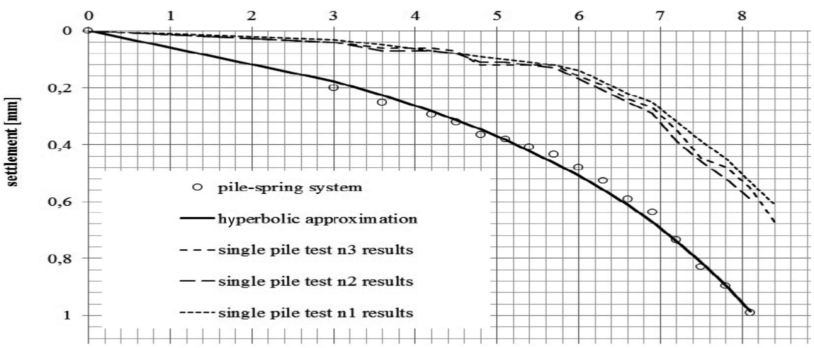

Fig. 3. Load-settlement relationship of single pile (top) and pile-spring system (bottom)

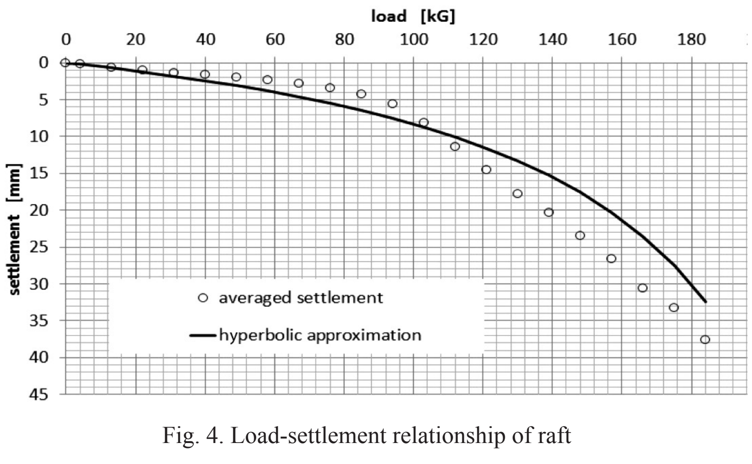

Fig. 4. Load-settlement relationship of raft

The aluminum tube was pressed into the soil to the same depth as for experiments with CPRF model. Then the load was gradually increased and directly transferred to the pile. The increase of load caused the settlement of the pile. Again, the application of load was carried out step-by-step; each load step was considered completed when the settlement of pile was not greater than 0.01 mm in 15 minutes.

3.1.3. Stiffness of serial pile-measurement spring connection system

For the system consisting of serial connection of two springs with different stiffness (pile and measurement spring), the forces acting on each spring, without taking into account the weight of springs, are identical. The total elongation of this system is the sum of extensions of both springs. Hence, we have formulas:

$$F = k_1 x_1, \quad F = k_2 x_2, \quad x = x_1 + x_2, \tag{15}$$

which enable us to calculate finally that the total stiffness of the system k is:

$$\frac{1}{k} = \frac{1}{k_1} + \frac{1}{k_2} \tag{16}$$

3.1.4. Impact factors of pile working in a pile group (Tejchman [17])

Finally, knowing the total stiffness of the system composed of measurement spring and single pile and using the factor of impact of pile acting in a group, one can define the stiffness of pile group. To make easier, the calculation of impact factor of a pile group consisted of 4 piles in square-shaped form installed at the distances equal to 3 fold diameter between them was assumed as 1.0 according to studies made on pile groups in sand by Tejchman [17].

Now, the secant stiffness of pile group in hyperbolic form (8) can be calculated using the following formulas

$$K_{pi} = K_{i1} \cdot 4/1 \tag{17}$$

$$R_{fp} = R_{fp1} \tag{18}$$

$$V_{pu} = V_{pu1} \cdot 4 \tag{19}$$

3.2. Stiffness of raft

By analogy with the definition of stiffness of a single pile, the stiffness of the plate was determined. Three series of tests were done. The square-shaped raft 150 mm width was founded on the flat surface of the ground and then gradually loaded. Again, application of load was carried out step-by-step; each load step was considered completed when a settlement of raft was not greater than 0.01 mm in 15 minutes.

5. Comparison of theoretical results from design procedure by Poulos [14] with those obtained from model studies

The aim of this study was to verify the theoretical model procedure given by Poulos [14] whereby piles participate in load carrying up to its bearing capacity and later additional load must be carried by the raft only (see Chapter 2).

Using the design procedure of CPRF presented by Poulos [14] and recalled in chapter 2, settlement of piled-raft foundation in the function of applied load can be obtained and compared with the results from laboratory tests (Fig. 5 left). Analogously, the portion of load carried by the piles can be estimated (Fig. 5 right). Interpretation of both presented figures enables to conclude that the theoretical procedure underestimated the contribution of the pile in load transfer which results in lower stiffness of foundation system (CPRF).

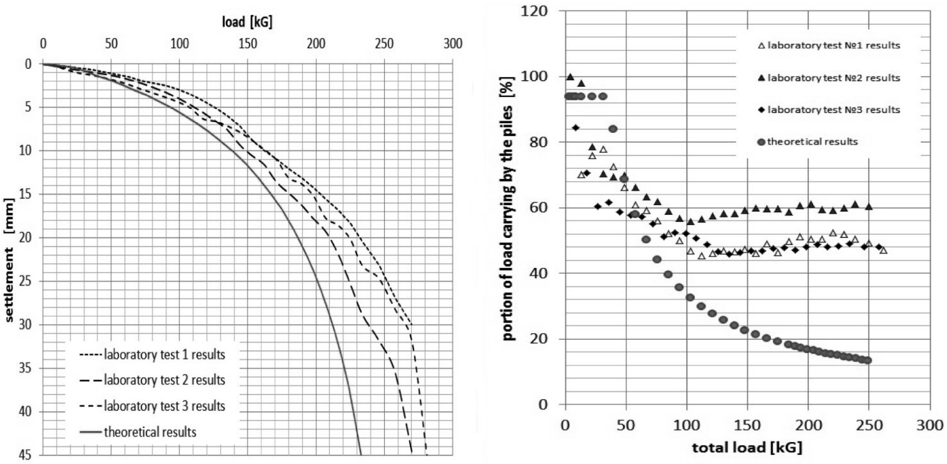

Fig. 5. Comparison of theoretical results to those obtained in laboratory tests. Left: load – settlement relationship. Right: portion of load carried by the piles

Entering the correction factor for the piles by simple enlarging the ultimate capacity of pile groupe V_{pu} by multiplying by 1.75 results in better fitting the theoretical load-settlement curve to the laboratory results (Fig 6. left). Unfortunately, increased capacity of piles doesn't fit very well to the observation made during laboratory tests: piles take more load then raft at the beginning of loading (up to 40% of total load) and then raft dominates according to theoretical procedure.

From the engineering point of view, the observation of laboratory model tests provide very important information about load distribution on the elements of CPRF foundation. We have noted that piles hold more load then that calculated using Poulos procedure. The same was observed by Hanisch [8] who showed using the FEM analysis that the piles in pile-raft foundation work better showing a steady increasing trend beyond the settlement of pile head corresponding to 3% of pile diameter.

Finally, summarizing the research done, it can be noted that the CPRF design procedure by Poulos enables to safely estimate the load-settlement relationship of CPRF (lower stiffness of foundation system) as well as the load carried by the piles resulting in a larger number of piles. The authors showed that modification of Poulos method by this factor by simple enlarging the ultimate capacity of pile groupe V_{pu} multiplying by 1.75 enables to optimize the total number of piles in Combined Pile Raft Foundation.

Because the research concerned sandy soils, further studies should be focused on CPRF behavior in cohesive soils taking into account secondary consolidation.

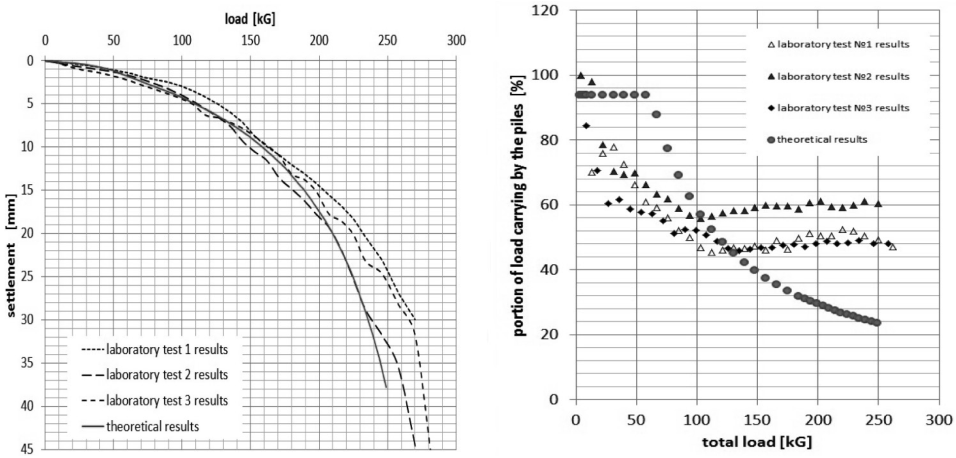

Fig. 6. Comparison of theoretical results with correction factor to those obtained in laboratory tests. Left: load – settlement relationship. Right: portion of load carried by the piles

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