Load-settlement characteristics of piles working in a group

Caractéristique charge-affaissement des pieux travaillant en groupe

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ABSTRACT: Load-settlement characteristic (*Q-s*) of an axially loaded pile can be empirically determined from a static pile load test or on the basis of calculations using, e.g. transfer functions or numerical methods (FEM). The transfer functions method usually rely on empirical data, i.e. the function parameters are determined on the basis of numerous pile test results. Thus this method takes into account pile installation technology and is more reliable than FEM, where a proper simulation of the pile installation is yet to be achieved. Load-settlement characteristics are very useful for structural calculations of the pile foundation. However, *Q-s* characteristics refer to a single pile. Moreover, field load tests are usually performed on single piles and hardly ever on pile groups or even just several piles. And yet most foundations are supported by a larger number of piles (group of piles) and it is commonly known that the working conditions of a pile in a group are different than that of a single pile. The described problem is analyzed numerically and empirically using model tests. The results of comparative computations and model tests of CFA and SDP piles working individually and in a group of nine piles are presented and discussed. Some conclusions regarding *Q-s* characteristics of piles working in a group are formulated.

RÉSUMÉ : La caractéristique charge-affaissement (*Q-s*) d'un pieu chargé axialement peut être définie empiriquement à la base des essais de chargement statiques ou des calculs effectués avec la méthode des fonctions de transfert ou la méthode numérique MES. La méthode des fonctions de transfert s'appuie sur les données empiriques puisque ses paramètres sont détérminés à la base des résultats de nombreux essais de chargement de pieux. C'est alors que cette méthode prend en considération, en quelque sorte, la technologie de la réalisation d'un pieu, tout en étant plus fiable que la méthode MES dans laquelle une simulation adéquate de la technologie de la réalisation d'un pieu présente toujours un problème bien important. Les caractéristiques *Q-s* des pieux sont bien utiles dans les calculs statiques des fondations sur pieux. Les essais de chargement sur le terrain sont menés, d'habitude, sur des pieux simples tandis qu'il est rare de les voir dans le cas d'un groupe d'au moins quelques pieux. La plupart des fondations s'appuient, quand même, sur un nombre plus grand de pieux (un groupe de pieux) et il est bien connu que les conditions de travail d'un pieu en groupe diffèrent de celles d'un pieu simple. Dans notre article, le problème ci-dessus avait été analysé d'une façon analytique, numérique et empirique pendant les modèles de test. On avait analysé les résulats des calculs comparatifs et des modèles de test des pieux CFA et SDP, travaillant individuellement et en groupe, celui-ci composé de neuf pieux. On avait formulé des conclusions quant aux recherches et analyses concernant les caractéristiques des pieux travaillant en groupe.

KEYWORDS: pile groups, SDP pile, CFA pile, *Q-s* characteristics, static loading, model tests.

1 INTRODUCTION

A graph presenting load-settlement characteristic (*Q-s*) of an axially loaded pile is usually considered as the sum of shaft and base resistances. This resistance separation is justified, since the mechanism of soil-pile base and soil-pile shaft interactions vary considerably and also causes various shapes of the Q_s-s and Q_b-s curves. The Q_s-s and Q_b-s characteristics of a single pile and a pile in a group are not the same. In the case of a pile group, the interaction between individual piles increases the soil stresses around them and therefore the ultimate soil resistance increases as well. However, the larger settlement (displacement) of the entire structure is also observed. It is mainly caused by greater settlement of the soil underneath the pile bases due to a deeper influenceof additional stress.

Q-s characteristics of piles working in a group depend on several factors: installation technology, number of piles, their spacing, immersion in the bearing soil and mechanical properties of the whole subsoil. *Q-s* characteristics also differ depending on the location of the pile in the group (i.e. on whether the pile is inside the group, on the edge or in a corner).

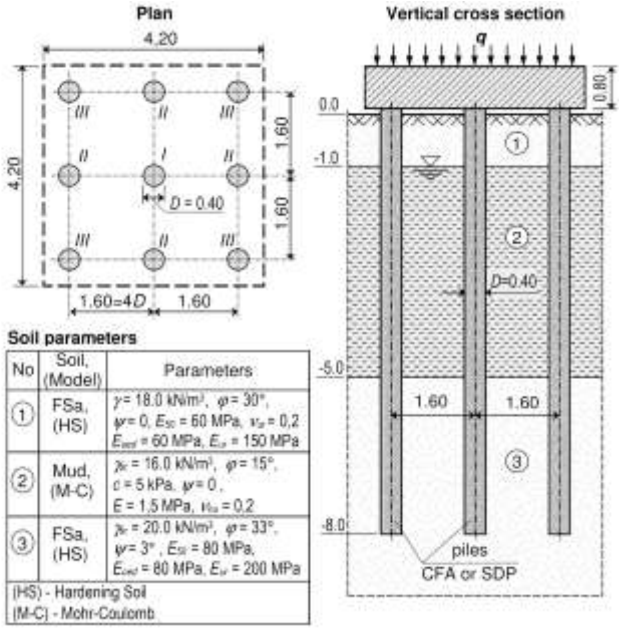
All these factors make the determination of a pile in the group load-settlement characteristics a difficult and complex task. A wide range of research regarding bearing capacity and settlement of pile group can be found in the literature. The works of Whitaker (1957), Vesic (1969), Chow (1986), McVay et al. (1989), Gwizdała and Dyka (2002), Zhang et al. (2010), Wang et al. (2012) might be given as an example. Also in reference to load-settlement characteristics of a single piles many publications can be found (Coyle and Reese 1966, Randolph and Wroth 1978, Fleming 1992, Gwizdała 1996, Liu et al. 2004, Bohn et al. 2016). However, there is very little information regarding *Q-s* characteristics of a single pile working in a group. From a practical point of view the issue is important. Increased and uneven stiffness of piles in a group results in an increased stresses and deformation of the foundation plate, and other elements of the structure. Therefore this issue should be taken into account during the design calculations.

2 NUMERICAL ANALYSIS - FEM

Computational FEM analysis of the pile foundation, composed of the nine piles arranged in a spacing of $4D$ were conducted. Two types of piles were analyzed: bored pile (CFA) and screw displacement pile (SDP). Main geometrical and material data are given in Figure 1. Calculations presented in the article were conducted using Plaxis 3D-Foundation. The task could also be solved in an axi-symmetrical or plane strain system (e.g. in Plaxis 2D). However, the results of such calculations need to be veryfied by 3D FEM or empirical analyses.

In the first stage, calculations were performed on a single pile. Calculation scheme is shown in Figure 2.

During the modeling process, a concrete mix pressure was included in the phase of concreting the pile in the soil. In the case of SDP pile, an extra phase of ground displacement caused by the auger was added. Both of these phenomena were modeled by using a lateral volume strain of the pile cluster in bearing stratum. Values of the volume change were chosen by trial in order to simulate a real scenario when the soil is initially stressed and an increased capacity of SDP pile occurs (compared to the CFA pile). In the case of a CFA pile, the volume increase was of 1%, and for SDP pile of 5%. In addition, soil at pile base level was pre-loaded with a hydro-static pressure of the concrete mix. There are also other ways of modeling installation phases of CFA and SDP piles. One of them was proposed by Krasiński (2014). The calculation results, presented as *Q-s* characteristics with separation of shaft and base resistances are shown in Figure 3.



No	Soil, (Model)	Parameters
1	FSa, (HS)	γ = 18.0 kN/m³, φ = 30°, ψ = 0, E_{50} = 60 MPa, ν_{ur} = 0,2 E_{oed} = 60 MPa, E_{ur} = 150 MPa
2	Mud, (M-C)	γ_{sr} = 16.0 kN/m³, φ = 15°, c = 5 kPa, ψ = 0, E = 1,5 MPa, ν_{ur} = 0,2
3	FSa, (HS)	γ_{sr} = 20.0 kN/m³, φ = 33°, ψ = 3°, E_{50} = 80 MPa, E_{oed} = 80 MPa, E_{ur} = 200 MPa
(HS) - Hardening Soil (M-C) - Mohr-Coulomb		

Figure 1. Material and geometrical data of pile foundation for FEM analyses.

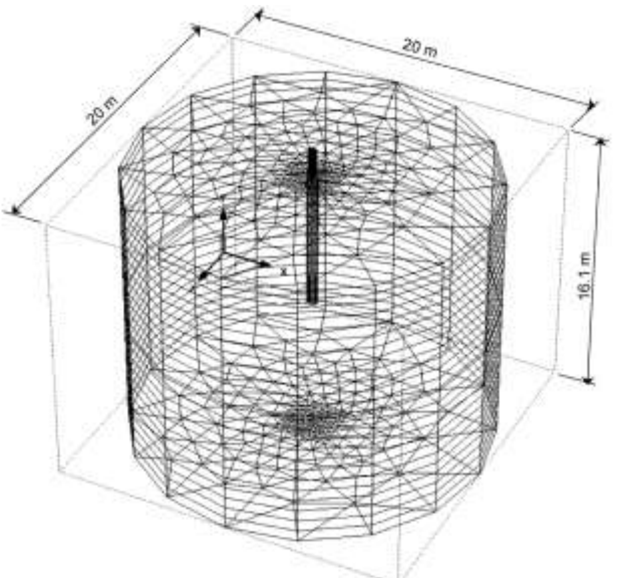


Figure 2. Calculation scheme for single pile FEM computation.

In the second stage, a foundation plate based on nine piles was studied. Calculation scheme is shown in Figure 4. The installation phases were modeled in the same way as for a single pile. External load was applied globally to the upper surface of the foundation plate. The calculation results for chosen piles – in the center of the group (I), on the edge (II) and in a corner (III) are presented in Figures 5, 6 and 7. Similarly as above, for comparative purposes, charts of CFA and SDP piles were put together. Figures 8 and 9 show a *Q-s* characteristics comparison of SDP and CFA piles working in a group and as an individual piles.

3 RESULTS OF PILE MODEL TESTS

Characteristics of interaction between soil and single pile as well as group piles authors also analyzed in a model research. Several series of such a tests (scale of 1:7.5) were conducted in Geotechnical Laboratory at Gdansk University of Technology – Figure 10. More information regarding test arrangement, data and result analysis can be found in the author's earlier publications (Krasiński and Kusio 2014, 2015). This article presents only the results in the form of comparative *Q-s* graphs of CFA and SDP piles working individually and in a group (Figures 11 and 12).

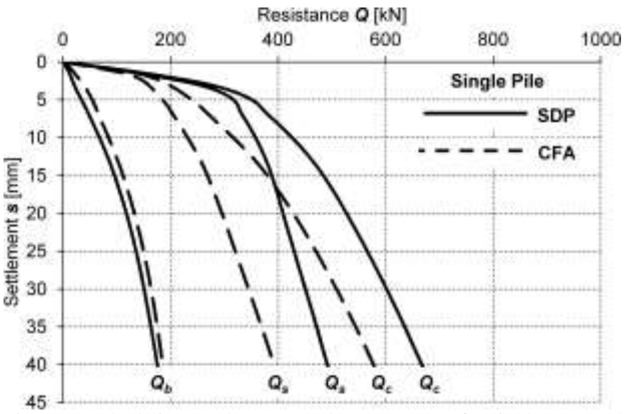


Figure 3. Calculation results presented as *Q-s* curves for single SDP and CFA piles.

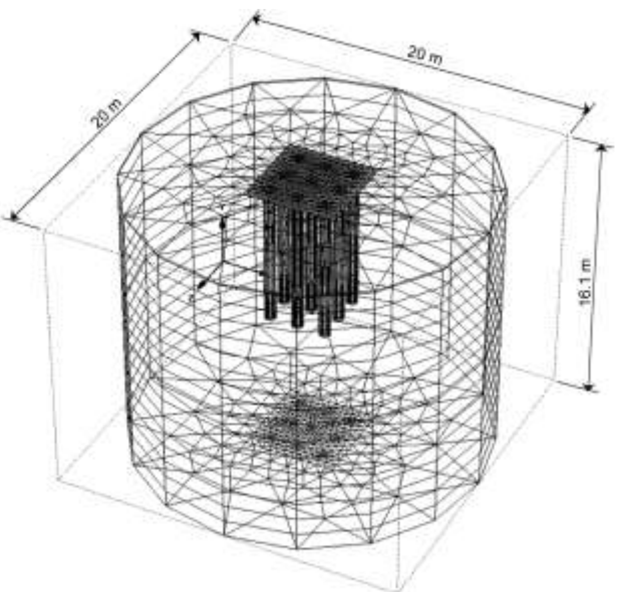


Figure 4. Calculation scheme for piles group FEM computation.

4 CONCLUSIONS

• SDP piles show more stiffer characteristics of interaction with non-cohesive soil than CFA piles. This is mainly due to increased pile shaft resistance of SDP piles. The differences in pile base resistance are low. Similar results were obtained from field tests performed on instrumented SDP piles, published by Krasinski (2013) and Bohn et al. (2016).

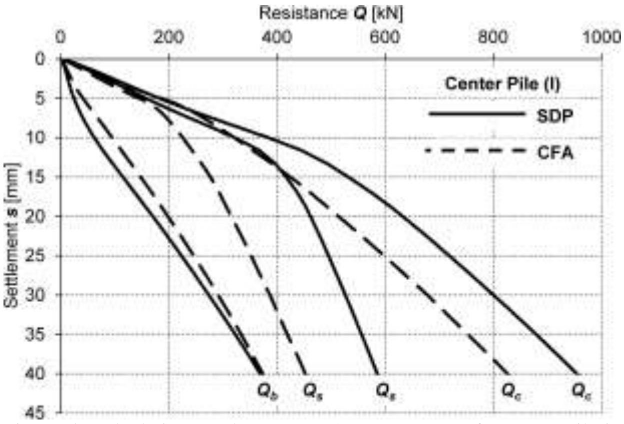


Figure 5. Calculation results presented as *Q-s* curves for center pile in group.

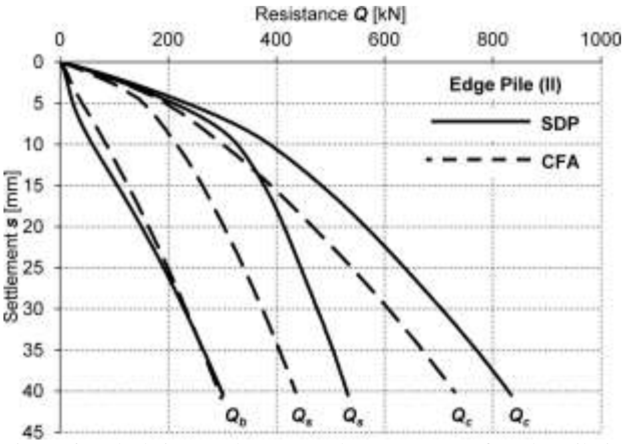


Figure 6. Calculation results presented as *Q-s* curves for edge pile in group.

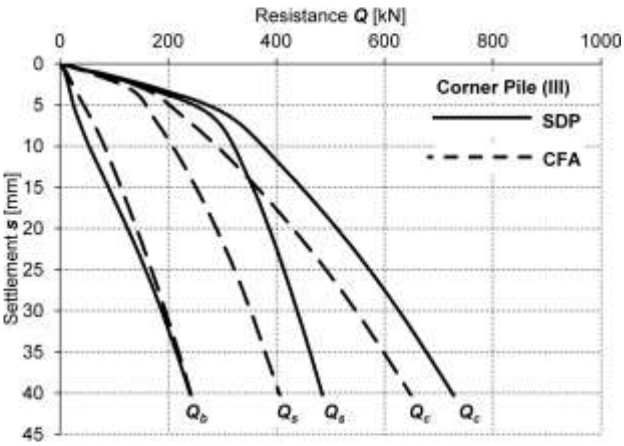


Figure 7. Calculation results presented as *Q-s* curves for corner pile in group.

• In the initial phases of the load, to the settlement of about 5-10 mm, piles working in a group show smaller stiffness than single piles. For larger values of settlements, resistances Q_s and Q_b for piles in a group exceed the corresponding resistance of a single piles, so the ultimate bearing capacity of the pile in a group is greater than that of single pile. The largest increase in the ultimate capacity was shown by the internal pile (central pile), and the lowest by a corner pile. The increase in the bearing capacity of piles working in a group is mainly due to the increase of the base resistance. The increase in the shaft resistance is less significant.

• The settlement of the soil underneath the pile bases has the largest impact on initial stiffness decrease of piles in group in relation to a single pile. This effect highly depends on mechanical parameters of that soil. Ground investigation should therefore be performed to a sufficiently large depth under the pile base. The decrease of the pile group stiffness also depends on the number of piles and their relative spacing.

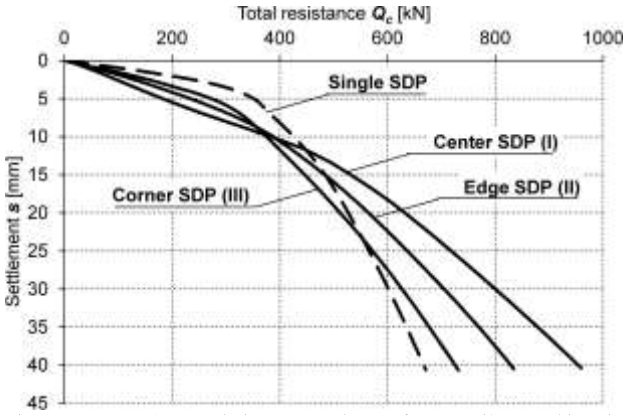


Figure 8. *Q-s* characteristics comparison of SDP piles working in a group and as an individual pile.

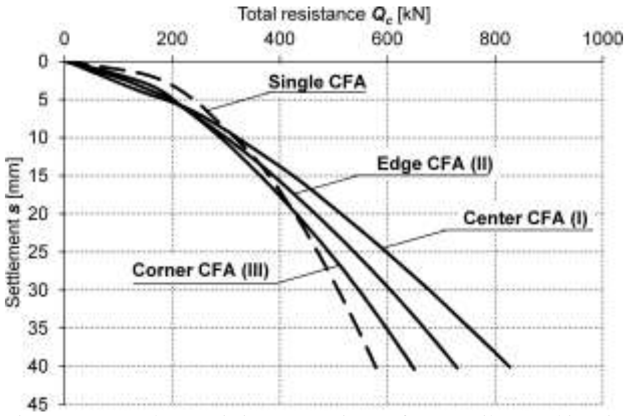


Figure 9. *Q-s* characteristics comparison of CFA piles working in a group and as an individual pile.

• In the group of nine piles, the stiffest *Q-s* characteristics in the initial load phases (settlements around 5-10 mm) are observed in the corner piles and the lowest in the middle piles. However, for the settlement exceeding 10 mm, the situation reverse. The middle piles behavior becomes stiffer than the corner ones. With the increased number of piles in a group, the differences in stiffness of the individual piles may be enhanced.

• The analysis concerned a group of piles in the axial spacing of 4*D*. For larger spacing, the differences in individual pile stiffness for piles working in a group and for single piles will decrease.

• The pile resistance values of Q_s and Q_b obtained from numerical analysis seem to be on the low side compared to those obtained from in situ tests. The main reason for that are the simplifications and the problems of numerical simulation of the pile installation process, which were pointed out in the abstract. Another reason was the inability to calibrate the numerical model with the results of in situ test. Numerical analysis concerned an academic example. Its aim was to identify developments and trends in the behavior of pile working in a group. This objective was fully achieved.

5. CONCLUSIONS BASED ON MODEL TESTS

• Presented selected results of the model tests, mostly confirmed results obtained from numerical analysis. Stiffness diversifications between piles working in a group and in relation to individual piles were observed. Ultimate bearing capacity was also shown to be greater for those pile working in a group, both the CFA and the SDP.

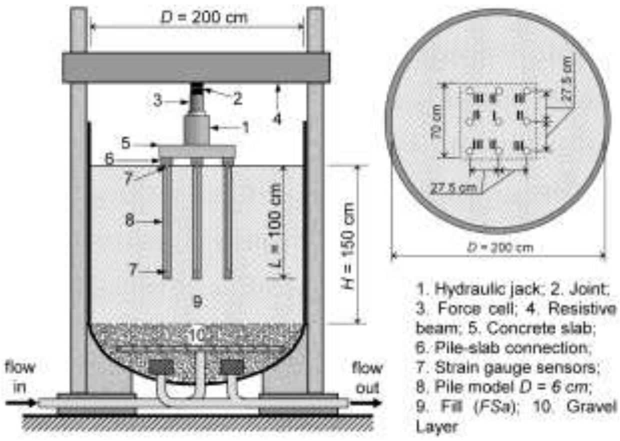


Figure 10. Model test site with pile arrangement plane.

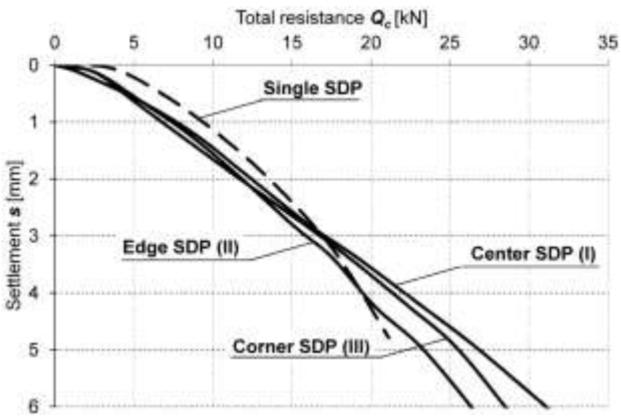


Figure 11. *Q-s* graphs of model scale SDP piles working individually and in a group.

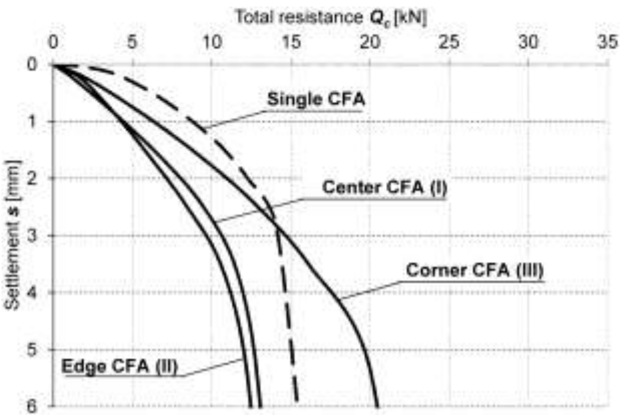


Figure 12. *Q-s* graphs of model scale CFA piles working individually and in a group.

• An increase of stiffness and bearing capacity of SDP piles against CFA piles was more marked in model test than in the case of numerical analysis. It should be noted that the pile model tests were carried out in a fine wet sand ($w = 2.5\%$). Significant influence may have caused so called apparent cohesion of sand.

• Model tests are known to be subjected to a scale effects. In addition, in the analyzed case, a rigid gravel layer was located very close to the basis of model piles, which could lower the value of measured pile settlements.

Presented results of the analyses, in the authors opinion, clearly and accurately highlighted the issue of the behavior of piles in a group. Difference of that behavior in relation to the pile working individually is important and should be, in a more or less approximated manner, taken into account in design calculations of pile foundations.

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