INFLUENCE OF INSTALATION OF PILES WITH PARTIAL AND FULL DISPLACEMENT OF THE SOIL ON THE SUBSOIL STRENGTH

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Abstract

Many advantages of displacement piles result in their very common use of present. In case of displacement pile, of particular importance are the phenomena occurring in direct vicinity of the pile shaft, where partial or total pushing the soil out aside is observed. Changes of vertical and horizontal stresses, pore water pressure generation, changes in soil structure, its moisture content and density taking place during installation of displacement piles create almost new soil conditions at the contact of pile shaft and subsoil. The paper presents the results of CPT tests carried out in the subsoil around CFA piles particularly in layered soils (non-cohesive/cohesive ones). Special attention is paid to a selection of proper parameters of drilling machine and concreting technology to form the pile. It is planned to continue the investigations based on theoretical description in the frame of soil mechanics.

Streszczenie

Stosowanie wierconych pali przemieszczeniowych jest obecnie bardzo częste. Wiele zalet tych pali będzie predysponowało je do powszechnego stosowania. Szczególne znaczenie mają zjawiska zachodzące w bezpośrednim sąsiedztwie pobocznicy pala gdy mamy do czynienia z częściowym lub całkowitym rozpychaniem gruntu na boki. Zmiany stanu naprężenia pionowego, poziomego, generacja ciśnienia wody w porach gruntu, zmiana struktury gruntu, wilgotności i zagęszczenia stwarza zupełnie nowe warunki oddziaływania w strefie pobocznica pala – zmienne podłoże gruntowe. W artykule przedstawiono wyniki badań sondą statyczną CPT w sąsiedztwie pali CFA, ze szczególnym uwzględnieniem gruntów uwarstwionych: grunty spoiste/grunty niespoiste. Zwrócono uwagę na dobór parametrów maszyny i technologii betonowania w zależności od rodzaju gruntu. Dalsze badania będą zmierzały do wyjaśnienia zmian w podłożu gruntowym w odniesieniu do zasad opisujących zmiany w ujęciu teorii mechaniki gruntów.

Keywords: **Displacement piles, CPT tests, layered soils, soil density, technologies of pile installation, remolded soil.**

1. INTRODUCTION

Pile foundation are normally used in unfavourable soil conditions, characterized by strongly layered subsoil with soils of different strength and deformability forcing the transfer of foundation vertical and horizontal loads into lower soil layers of high strength. Each pile installation is related to the disturbance of natural soil structure. Degree of this disturbance should be considered in a technological and ecological sense (see also [5]). Modern techniques of pile installation prefer the technologies with minimal drillings, which are compensated by partial or full displacement of the soil around the pile. Simultaneously, it causes local improvement of the soil which in turn increases the level of loads to be transferred and rigidity of the pile supports reflected in load-settlement characteristics. The visible gains cause that currently one can observe intensive growth of the number of displacement piles applied. In last decade this type of piles covered 60% of total number of piles installed in the Europe [4]. Additionally, increasing popularity of displacement piles caused the development of new displacement technologies [8].

On the global deep foundation market, pile foundations occupy 50%. For comparison, all soil improvement technologies cover merely 10% of this market, [1].

To the most intensively developed displacement technologies belong the piles formed by continuous flight auger (CFA) as well as full displacement drilled piles such as Omega, Atlas, FDP piles. The range of its applicability differs depending on the specifics of soil conditions in given area. e.g. in Belgium displacement drilled piles constitute 70% of all deep foundations [1].

Wide range of application of displacement piles requires detailed analysis of their work within the subsoil. Particular attention should be paid to the zone directly adjacent to pile shaft, within which largest soil displacements accompanied by changes in soil structure are observed.

In this analysis one can distinguish following, important soil parameters and geotechnical conditions:

- original soil type and its granular composition expressed by coefficient of uniformity and content of fine fraction,
- density of non-cohesive soils and its susceptibility to compaction or loosening in case of dense soils,
- original state of cohesive soils, possible soil structure changes in the direct vicinity of pile shaft, moisture content changes during pile installation and concreting, pore water generation influencing soil strength parameters in shear zone along the pile shaft,
- stress state in natural subsoil and its susceptibility to further consolidation,
- alternate layering of the subsoil (cohesive – non-cohesive soils with different strength and drilling resistances during penetration of the auger),
- permeability of the subsoil around the pile,
- coefficients of permeability, particularly in horizontal direction.

Complex changes in soil structure, in state of the soil, moisture content as well as in stress state after installation of displacement piles can be analyzed based on the results of in situ tests using for example various penetrometers (CPT, CPTU, DMT).

Some of the aspects of mentioned phenomena and problems occurring during formation of displacement piles will be discussed in details below for the case of CFA piles.

2. DIRECTION OF CFA PILES DEVELOPMENT

In recent years CFA pile are most successive type of piles. They cover approximately 20% of global piling market and in some countries this number reaches 50% of all foundations made on piles [6]. In a new generation of CFA piles, a pile with 1200 mm diameter and 30 m length can be formed. Assuming proper selection of the grout and construction of the reinforcement, the later can be placed along whole CFA pile length (if it is required by design conditions). Recently, the investigations are carried out into new reinforcement systems, which could be based on reinforced steel additionally improved by fibres [6].

Bored displacement piles are often classified as classical bored piles. In practice, one can observe essential differences between these piles resulting from specifics of their installation. Similarly to driven piles, bored displacement piles cause pushing the soil apart, which changes their density. Simultaneously, they can achieve significant bearing capacities. As a consequence of horizontal soil displacement along the pile shaft during its installation the soil remains in the subsoil and it is extracted onto soil surface. Pushing the soil out is caused by special shape of the auger. Majority of bored displacement piles is formed with short tip auger since such geometry assures quick rate of soil displacement [1]. Recently, more and more popularity gain Omega and FDP (Full Displacement Piles), [5].

In case when the reinforcement is inserted into the pile from the soil surface into fresh concrete, the technologies of displacement piles require preparation of special concrete mix designs. In this case the factors which influence the placement of the reinforcement cage into the pile as well as possible changes of the characteristics of soil parameters should be carefully considered.

3. EXEMPLARY IN SITU INVESTIGATIONS OF DISPLACEMENT PILES

Phenomena occurring in the subsoil, in the vicinity of displacement pile shaft cause significant changes in soil structure, thus they are a subject of intensive investigations in many countries. Papers regarding this problems were presented during the cyclic Deep Foundation on Bored and Auger Piles conferences held in Ghent, BAP I, BAP II, BAP III, BAP IV.

The results of these investigations made with the use of cone penetrometer can be partially referred to the results achieved by the Author presented below.

3.1. Investigations on CFA piles [7]

In Waddinxween, the Netherlands a series of investigations regarding the application of piles of various technologies (pre-cast, Vibro, Vibrex, and CFA piles) was carried out. Total of 55 piles were made. The goal of these investigations was to analyse the changes in soil strength occurring in the subsoil during installation of the piles. The analysis was based on the results of CPT tests carried out prior to and after the installation of the pile.

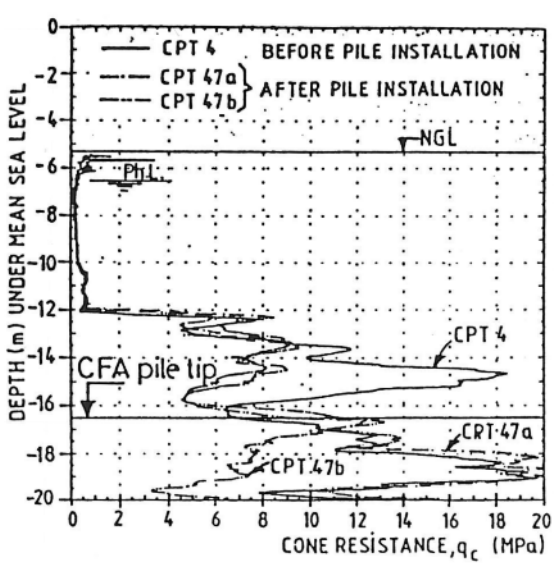

Figure 1.
Results of CPT tests: CPT4 – prior to pile installation; CPT47a, CPT47b – after pile installation [7]

Fig. 1 presents the distribution of cone resistance q_c before and after the installation of CFA pile. The pile was L=11.0 m long with the 0.35 m diameter. First CPT test was carried out along the pile axis and subsequent two ones on the opposite pile sides, in the 0.5 m distances from the pile shaft. The pile was embedded 16.5 m into the sandy soil layer, above which, at the depth of 10.0 to 12.0 m there were lenses of peat and weak clays. It can be seen that in the upper part of the pile, up to the depth of 6.5 m, cone resistance q_c does not change. It regards a zone where peat and weak clays were found, for which resistance q_c does not exceed the value of 1.0 MPa. Along the zone of pile embedded in sands, where q_c was estimated in the range from 5 MPa to 19 MPa, one can observe essential decrease of penetration resistance and loosening of the soil. Below the pile base, up to the 4 m depth, both little rise in resistance as well as its decrease were observed, see CPT 47a and 47b, respectively.

3.2 Investigations of CFA piles [3]

In order to compare the values of cone resistances q_c of the soil prior to and after the pile installation two penetration tests were carried out in Le Havre, France. Similarly to the Dutch tests, first test was carried out along the pile axis, whereas the second one in a distance of 0.5 m from the pile shaft. The pile with the length of 8.0 m was installed in coarse sand layer, at the depth of 10.5 m below the ground surface. Corresponding distributions of the cone resistances in the soil prior to and after the pile installation were shown in Fig. 2.

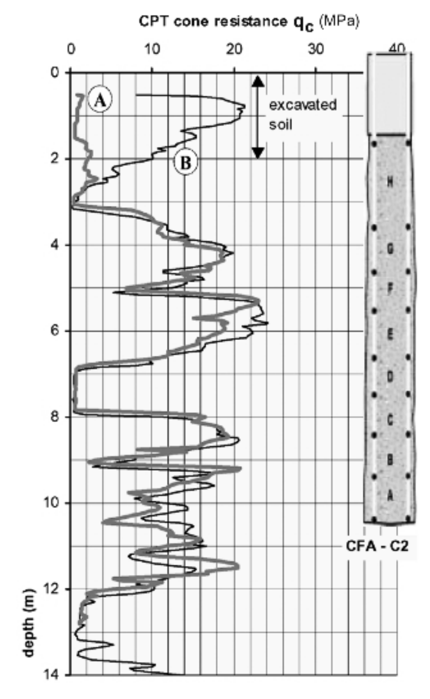

Figure 2.
Results of CPT tests: B – prior to pile installation; A – after pile installation [3]

The analysis of the results indicates that the installation of the pile did not significantly change the soil

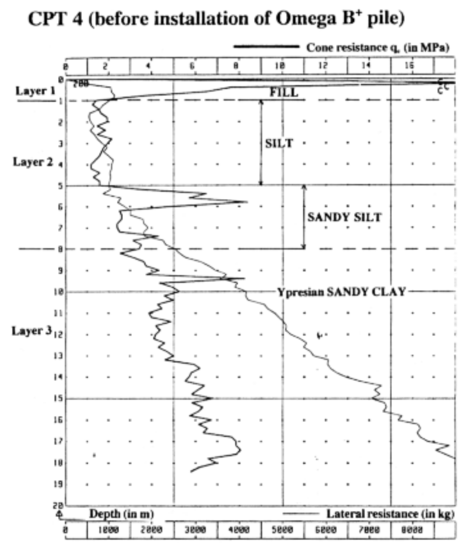

Figure 3.
q_c resistances of a subsoil prior to installation of Omega pile measured along its axis [2]

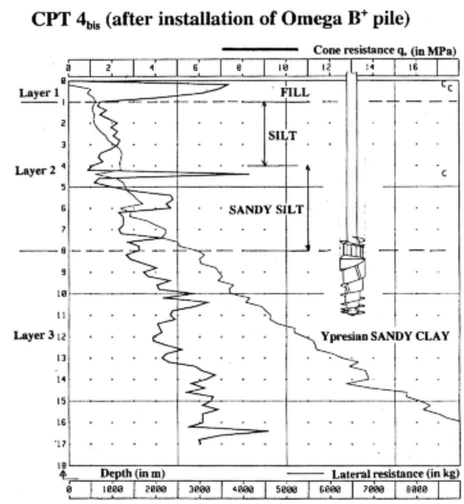

Figure 4.
q_c resistances of a subsoil after the installation of Omega pile [2]

conditions. However, some decrease of q_c value in upper part of the pile where fine sands dominate, can be observed. The same can be also seen at the depth of the pile base which suggests loosening of the soil at this level. In the zone of silty clay, for resistances below 1 MPa, changes in the soil are practically invisible.

3.3 Investigations on Omega piles [3]

Series of CPT tests carried out in Belgium allowed the analysis of the soil strength changes for Omega B* piles (with additional repeated embedding of the auger into the concrete). In Fig. 3 the distribution of q_c values prior to installation of Omega B* pile along its axis, is presented. The penetration was made to the 19.0 m depth. and 11.0 m long Omega B* pile was made by the auger with 360 mm diameter. The distribution of cone resistance after the pile installation was shown in Fig. 4.

Installation of Omega B* pile caused small changes in q_c resistance along the whole pile length. However, at the depth of pile base as well as below it, where sandy clays were found, the increase of soil strength can be observed. (q_c around 5 MPa). Comparison of Figures 3 and 4 shows clear trend of changes in soil strength due to installation of Omega B* pile.

4. INVESTIGATIONS OF CFA PILES MADE BY THE AUTHORS

4.1 Investigations of CFA piles in layered soils

Layering of the subsoil always creates additional difficulties and possibilities of uncontrolled changes in the soil strength in the vicinity of the pile and under its base. Below, additional example of the influence of CFA piles installation on the changes in the soil conditions are presented.

The CFA piles of the diameter of 750 mm were 15.0 m long. Spacing of the piles, the place of its installation and soil conditions are presented in Figures 5-8. Within the whole area of foundation similar soil conditions were found. With regard to natural soil profile, below the soil surface the fill was recognized and below medium dense sands, clayey sands and sandy clays of low plasticity. The piles were embedded in the layer of clayey sands of very low plasticity. Control CPTU tests have been performed at two investigation stands. First stand is represented by CPTU1, CPTU2, CPTU3 tests, Figures 5 and 6b and the second one by CPTU 4, CPTU 5, CPTU 6 tests shown in Figures 7 and 8. Two of the tests were made beyond the pile impact and they were treated as reference tests, (CPTU1 and CPTU 6, respectively), two additional were carried out inside the group of four piles (CPTU2, and CPTU 4), and the last two

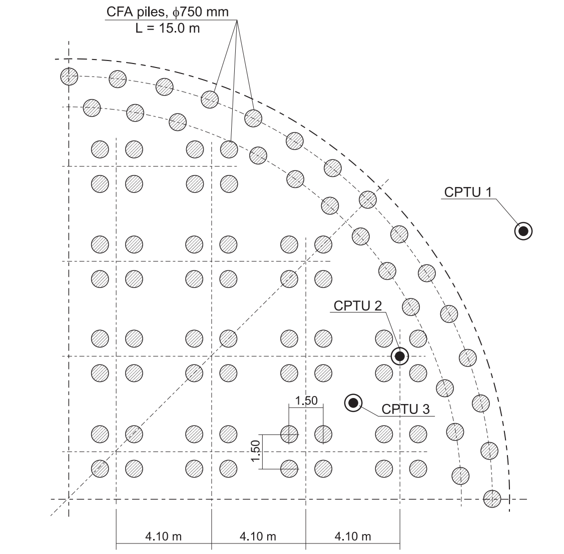

Figure 5.
Piling lay-out and location of CPTU tests No. 1, 2, 3

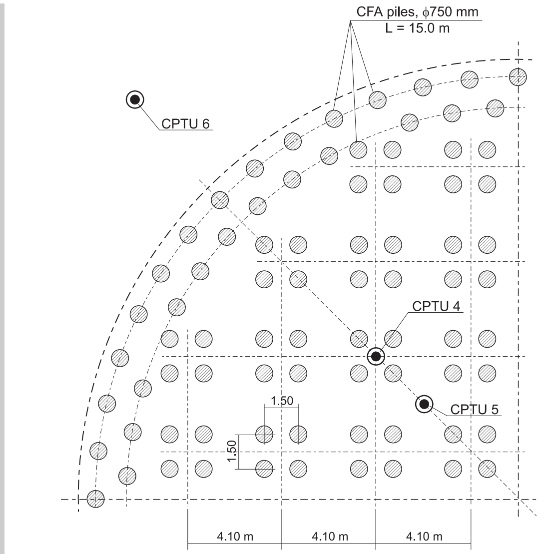

Figure 7.
Piling lay-out and location of CPTU tests No. 4, 5, 6

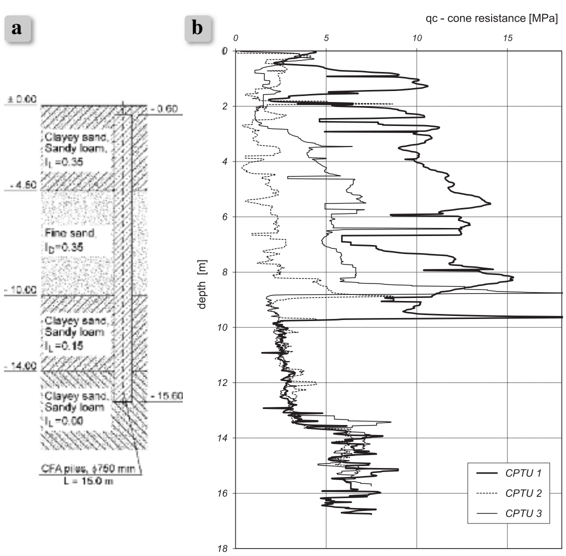

Figure 6.
a) General soil profile. b) Results of CPTU tests No. 1, 2, 3

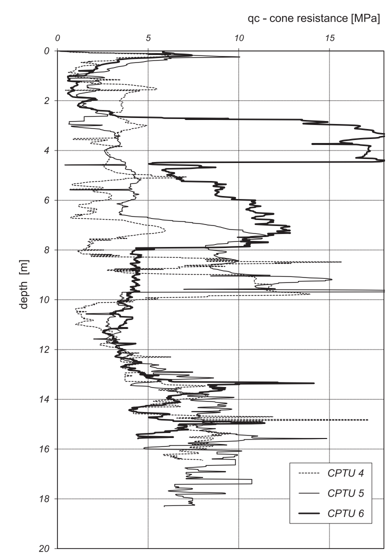

Figure 8.
Results of CPTU tests No. 4, 5, 6

ones between the pile groups. It should be noted that during the installation of CFA piles the lifting up of the sand by the auger plates and storing on the ground surface was observed. It caused significant loosening of sandy soil layer. Independently of very small relative spacing of the piles (r=1.5/0.75=2), the influence of boring resistance on the soil loosening should be noted. The layering of the subsoil, Figures 6a, 6b and 8 supported by the increase in boring resistance as well as decrease of boring rate after reaching the clayey layer caused lifting of soil by the auger and resulted in its loosening. Additionally, essential influence of the capacity and functionality of drilling machine as well as layering of the soil on the soil conditions after the pile installation can be observed.

It should be also noted that despite difficulties in overcoming the boring resistance in sandy clay, visible changes in strength of this soil expressed by the cone resistance were not observed.

4.2 Investigations of CFA piles on Warszawa-Okęcie International Airport site

The tests were made on the site of Warszawa-Okęcie International Airport by Geokomp sp. z o.o. company from Cracow. The goal of the tests was to compare the state of the soil near the piles prior and after their installation.

First part of the investigations regarded the tests made along the axis of CFA pile prior to its installation and the second part was performed 28 days after. The penetrations were carried out up to the depth of 16.60 m.

Analysed pile of 0.80 m diameter was 13.0 m long and was embedded into the subsoil at the depth of 15.5 m. The pile was made of B20 concrete with liquid consistency equivalent to K 5. Main reinforcement in the form of reinforcement cages was made of A-IIIN steel, Bst500S, whereas spiral reinforcement was made of A-I steel, St3S-b. Tested pile No. 129 was installed in 24 minutes time, out of which 17 minutes were required for drilling and additional 7 minutes for pile concerting. Amount of additional concrete was 21%. Spacing of the neighbouring piles and sequences of their installation are presented in Fig. 9 and Table 1. For tested pile static load test was made. The results of the test in the form of load-settlement curve are shown in Fig. 10. The shape of the curve confirms good interaction of the pile with surrounding subsoil. The pile was installed in layered subsoil composed of sandy clays and clayey sands as well as coarse and medium sands. Geotechnical profile and soil parameters are presented in Figures 11-13. Fig. 11 shows the results of CPT tests made respectively:

a) prior to pile installation,

b) after 28 days of pile installation in the distance of 0.5 m from the pile shaft,

c) after 28 days of pile installation in the distance of 1.5 m from the pile shaft.

Table 1.
Schedule of installation of neighbouring pile to the pile No. 129

Item	Pile No.	Date of installation	Start of installation [hour]	Start of concreting [hour]	Drilling Δt_1 [min]	End of concreting [hour]	Concreting time, Δt_o [min]	Execution time, Δt_2 [min]
1.	140	10.04.2006r.	09.49	10.52	3	11.00	8	11
2.	138	10.04.2006r.	11.33	11.48	15	12.14	26	41
3.	132	10.04.2006r.	12.52	13.44	52	13.56	12	64
4.	136	10.04.2006r.	14.20	14.36	16	14.57	21	37
5.	139	11.04.2006r.	08.21	08.56	35	09.15	19	54
6.	137	11.04.2006r.	09.47	10.02	15	10.10	8	23
7.	135	11.04.2006r.	10.56	11.12	16	11.20	8	24
8.	134	11.04.2006r.	11.45	12.03	18	12.24	21	39
9.	128	11.04.2006r.	12.57	13.14	17	13.56	42	59
10.	131	11.04.2006r.	16.51	17.09	18	17.25	16	34
11.	141	12.04.2006r.	11.25	11.46	21	11.53	7	28
12.	142	12.04.2006r.	12.19	12.31	12	13.03	32	44
13.	143	12.04.2006r.	13.24	13.58	34	14.08	10	44
14.	144	12.04.2006r.	14.40	14.52	12	15.29	37	49
15.	133	19.04.2006r.	07.21	07.48	27	08.25	37	64
16.	130	19.04.2006r.	10.37	10.55	18	11.09	14	32
17.	127	19.04.2006r.	11.38	11.51	13	11.59	8	21
18.	129	20.04.2006r.	12.04	12.21	17	12.38	7	24

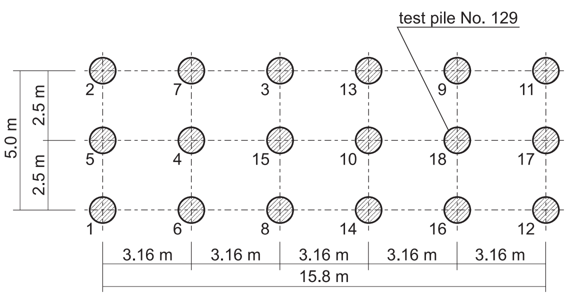

Fig. 9.
Sequences of piles installation and location of tested pile No. 129

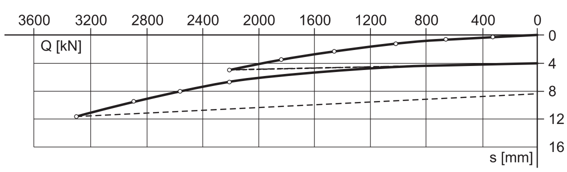

Fig. 10.
Load-settlement curve of test pile No.129 (CFA pile, D=0.8 m, L=13.0 m)

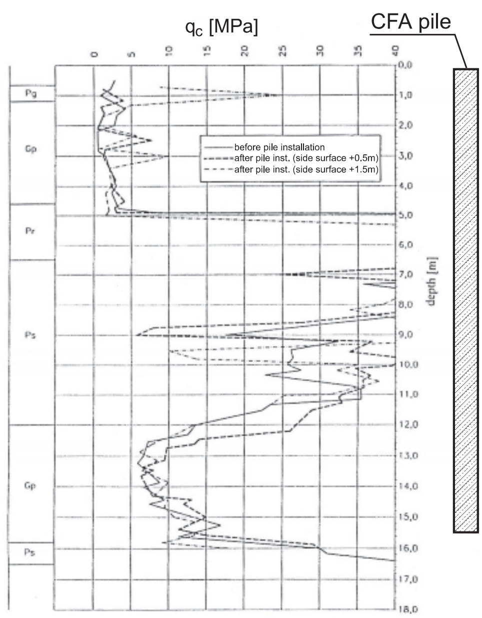

Fig. 11. qc resistances of a subsoil prior to and after installation of test pile No. 129

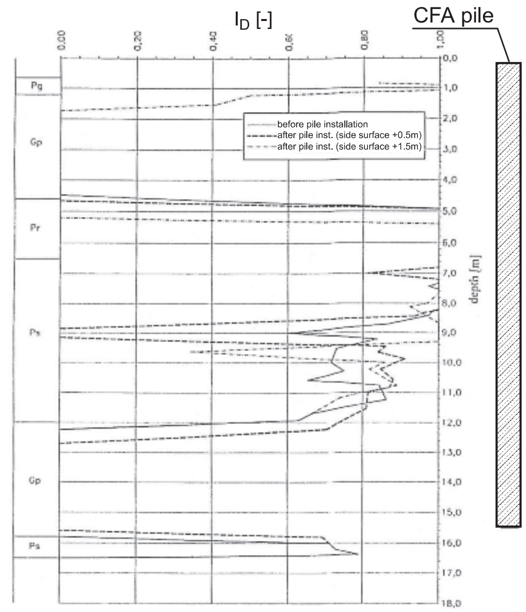

Fig. 12.
Changes in density index prior to and after installation of pile No. 129

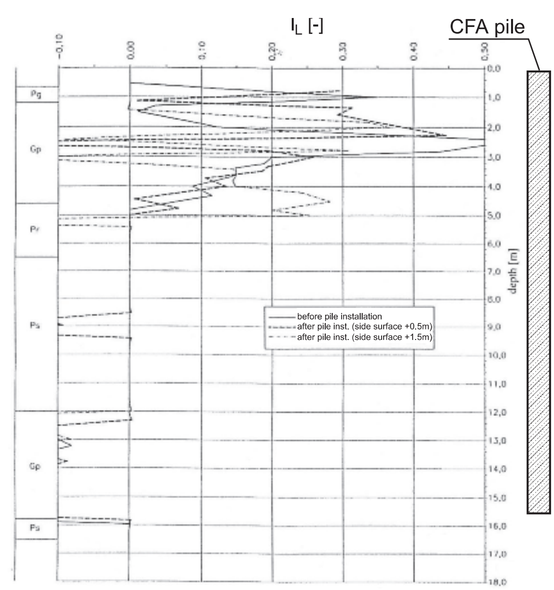

Fig. 13.
Changes in liquidity index prior to and after installation of pile No. 129

Additionally, in Figures 12 and 13 the soil state expressed by the density liquidity indices are shown using Baldy's correlations (Baldy, 1986) as well as formulas proposed by Geoteko company from Warsaw. For the region of Warsaw the values of ID and IL were determined including preconsolidation effects as well as values of q_c and effective vertical stress.

CPT test were made 27 days after installation of the tested pile (17.05.2006). In general, when analysing the results shown in Fig. 11, small influence of the CFA pile on the surrounding soil can be observed. It confirms proper selection of the parameters of drilling machine as well as other technological parameters. No changes of soil strength in radial direction are noticed. Changes in cone resistance can be negligible from the engineering point of view. For larger depths, exceeding 12 m, where vertical stress component may play role, small increase of q_c in sandy clay was observed. In general, non-cohesive soils represented by medium sands in our case, are more sensitive to the installation of CFA piles. In these soils, zones of their loosening as well as compaction were observed, Figures 11 and 12. Resistances of the penetrometer show rather local soil loosening in small sector along pile length. It should be noted that natural soil layering in the form of alternate dense non-cohesive soils/strong cohesive soils does not cause loosening of the sandy layer, compare Figures 6 and 8.

5. SUMMARY

CFA piles are used in civil engineering for many years. Evaluation of factual bearing capacity of the pile and particularly determination of reliable load-settlement characteristics is still serious challenge for engineers. In the paper some parameters and factors influencing the changes of the soil state, pile-subsoil interaction, transmission of the loads by the pile into the subsoil as well as natural soil conditions were presented. Particular attention was paid to the following aspects:

- type and state of natural soil,
- influence of initial soil density on its loosening during the installation of the pile,
- almost negligible changes in the state of cohesive soils,
- small improvement of cohesive soils at larger depths due to increase of stress components caused by proper installation of displacement piles,
- arrangement of soil layers, particularly when stronger soils follow the weaker ones what generates alternate resistances during the drilling process,
- proper selection of the capacity of drilling machine for given geotechnical conditions, especially torque and pushing force values (lack of such analysis is rather a standard),
- no changes in soil state are observed in weak cohesive soils for resistances lower than 1.0 MPa,
- little attention paid to the quality and control of pile installation e.g. with respect to the measurement of pressure during concreting as well as selection of grout for given soil type.

Despite many years of experience in application of CFA piles there are still some problems requiring further research. Little knowledge is gained with respect to fully displacement piles. Often displacement piles are used intuitively and the phenomena occurring within the subsoil and at the contact with the pile on both macro and micro scale are still poorly recognized.

Recent experience shows that displacement piles have a lot of advantages and wide opportunities in its application, however real behaviour related to transmission of the loads can be observed only in terms of in situ tests.

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