Behavior of Bored Piles in Two Soil Layers, Sand Overlaying Compressible Clay (Case Study)

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Abstract. Piles foundations have the function of transferring loads from the superstructure through weak compressible strata onto stiffer or more compact soils or onto rock. This is soil profile is considered the ideal profile for pile foundations. While for soil profile including strong soil strata overlaying compressible soils, the estimation of piles behavior will be more difficult. Forty six residential buildings consisted of twelve stories were constructed at the north of Nile delta in Egypt. Bored piles with lengths equal to or more than 27.0 m were chosen to support the raft foundations of these buildings. Soil investigations concluded that the soil consists of dense sand overlaying compressible clay that extended down to 40.0 m, while the ground water was found near ground surface. Soil properties were determined through drilling four boreholes at the site with 60.0 m depth and disturbed and undisturbed samples were collected. Six cone penetration tests (CPTU) with 25.0 m depth were achieved to estimate soil properties and also to estimate bearing capacity of the piles. Five preliminary pile load tests were carried out on different types of piles. Four rotary drilling bored piles and one contentious flight auger were tested having lengths ranged between 27.0 m and 37.0 m, while its diameter ranged between 0.60 m and 0.7 m. The static load tests continued to load equal to 200 t which is equal to 250% the allowable pile load. Some tests completed within 48 h and some within 7 days to check the time-load-effect. In the light of these measurements, comparisons have been achieved between the bearing capacities of piles estimated by the results of CPTU and those measured by field tests. Moreover, the ultimate bearing capacities of piles estimated by Egyptian and Canadian Codes have been compared with those measured by field tests. Good agreement was noticed between the bearing capacity of piles estimated by methods depended directly on CPTU. While the indirect methods depended on soil parameters derived from CPTU produced lower values than the measured. It was also noticed that the estimated bearing capacities of piles based on soil properties derived from lab tests did not soundly match with the measured values.

1 Introduction

Pile foundations are considered more expensive relatively to shallow foundations, so it should be only selected when shallow foundations cannot satisfy an acceptable factor of safety against bearing failure in the foundation soils or acceptable settlements during

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the life of the structure. These two independent design criteria can be arise due several reasons among them are nature and magnitude of structural loads, settlement-sensitive structures and type of soil. Hence, the main goal of piles is to achieve the design criteria by transferring structural loads to the deep, stable and strong soil strata. Sometime the case can be more complex when the stronger soil layers with relatively small thickness exist above weak soil that extended to great depths. In this case, the methodology of using pile foundations includes some uncertainties and the behavior of piles cannot be certainly expected. The uncertainties of pile behavior arise from non-homogeneity of soil and alteration of soil properties after piles installation. Moreover, most of the rules or approaches for estimating the bearing capacity of piles took in consideration the general case that weak soil is overlaying strong soil. As pile behavior depends mainly on soil properties and method of pile instillation, great efforts have been achieved to determine soil properties throughout lab and field tests. Cone penetration test (CPTU) has been widely used for several decades because it is the most effective in-situ test method for obtaining practically continuous soil properties reliably. Data from the CPT can be used directly in foundation design or in the estimation of soil parameters. Un-drained shear strength (s_u) and angle of shear resistance (Φ) are the most important quantities for geotechnical design in clay and sand respectively. It is knowledge that north of Nile delta in Egypt contains soft clays. Soft clay exists sometimes near ground surface overlying stiff clay or sand and sometimes it exists at relatively deep depths underlying sand. At Port-Said area, dense sand with thickness 8.0 m to 10.0 m is existed overlying compressible clay which extended down to about 40 m while the ground water was found near ground surface. On this soil profile, forty six residential buildings consisted of twelve stories were constructed at Port-Said area, north of Nile delta in Egypt. Soil stratification at the site failed to support shallow foundations with acceptable and allowable settlements. So, bored piles with lengths ranged between 27.0 m and 34.0 m were chosen to support the raft foundations of these buildings. Several preliminary pile load tests were carried out up to load equal to 200 t. Some tests completed within 48 h and some within 7 days to check the time-load-effect. Six CPTU with depth 25.0 m and four boreholes with depth 60.0 m were carried out at the site.

This paper shows comparison between the bearing capacities of piles estimated by the results of CPTU and those measured by field tests. Moreover, the ultimate bearing capacities of piles estimated by several methods included Egyptian and Canadian Codes have been compared with the measured values. The differences between the behaviors of bored pile and CFA pile were also discussed.

2 Cone Penetration Tests, CPTU

The cone penetration test has been recognized as one of the most widely used in situ tests. Cone penetration testing has gained rapid popularity in the past twenty years. The cone penetration test consists of advancing a cylindrical rod with a conical tip into the soil and measuring the forces required to push this rod. The friction cone penetrometer measures two forces during penetration. These forces are: the tip resistance (q_c), which is the soil resistance to advance the cone tip and the sleeve friction (f_s), which is the sleeve friction developed between the soil and the sleeve of the cone penetrometer. The friction ratio (R_f) is defined as the ratio between the sleeve friction and tip resistance and is expressed in percent. The penetrometer is capable of registering pore water pressure (u_2) induced during advancement of the penetrometer tip using an electronic pressure transducer. These measurements are measured by electrical methods, at a minimum of every 50 mm of penetration. The resistance parameters are used to classify soil strata and to estimate strength and deformation characteristics of soils.

Six CPTU were carried out at the site down to depths 25.0 m below ground surface. The standard CPTU (according to ASTM D 5778 with cross-section area of 10 cm^2) was performed by pushing the cone into the ground at a rate of 20 mm/s. Data of the tip resistance q_c, sleeve friction f_s, and pore water pressure u_2, are collected every 12 mm penetration using electric data acquisition equipment and a portable computer. Figures 1 and 2 shows the measured and derived parameters respectively for CPTU # 3 for example.

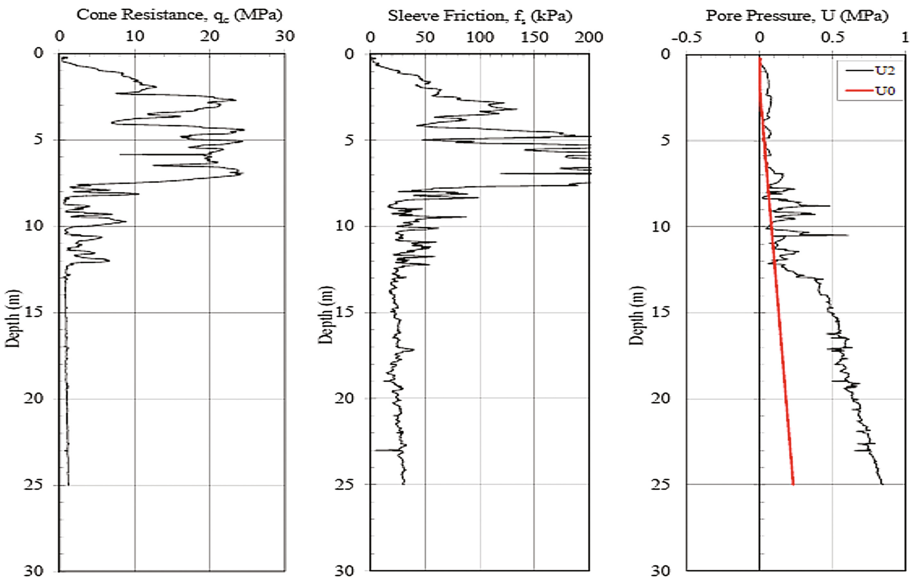

Fig. 1. Measured parameters for CPTU # 3

2.1 Soil Classification and Soil Parameters

There are several methods for soil classification, each method took in consideration certain parameters.

Methods of Robertson et al. (1986) and Jefferies and Davies (1993) are considered the famous ones that depends on the three measured parameters, q_c, f_s and u_2 besides total σ_v, effective σ'_v overburden pressures and in situ pore water pressure u_o. Accordingly, soil in the site could be classified as follows:

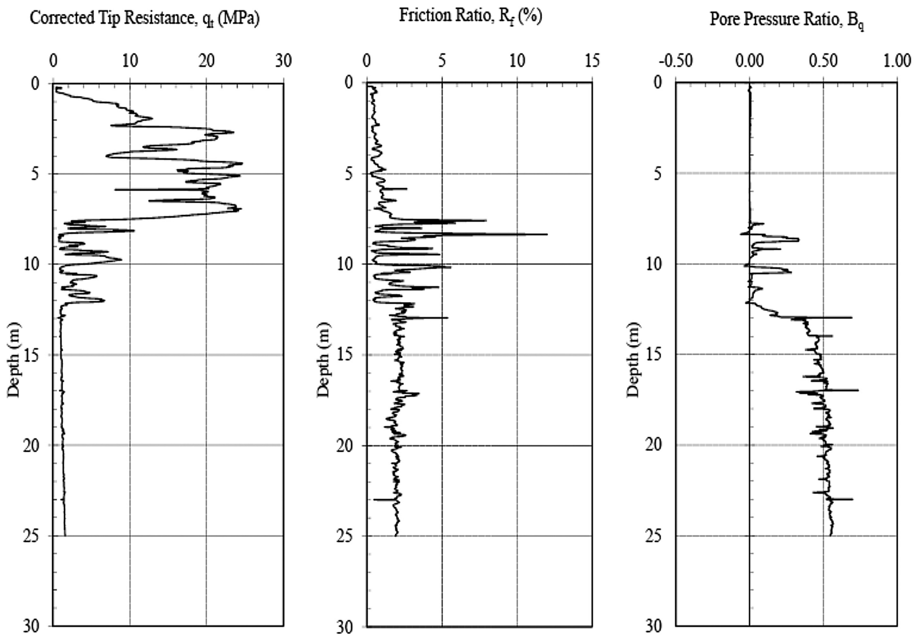

Fig. 2. Derived parameters for CPTU # 3

From 0 to 2.0 m top soil layers of intercalated silty clay and sand mixtures followed by sand layers down to 8.0 m. From 8.0 m down to 12.0 m intercalated silty sand, sandy silt and clayey silt mixtures followed by firm (soft to medium) silty clay down to 25.0 m, as shown in Fig. 3.

The undrained shear strength (s_u = c_u) of the soil is commonly used for stability and bearing capacity analyses. The classical approach to evaluating s_u from CPT readings is via the corrected cone resistance:

$$S_u = (q_t - \sigma_v)/N_k \tag{1}$$

where q_t = corrected cone resistance, σ_v = total overburden stress N_k = cone factor. Knowledge of the cone factor N_k is essential for reliable estimation of s_u, and numerous attempts have been made by researchers to develop accurate N_k values by empirical approaches (Lunne and Kleven 1981; Aas et al. 1986; Lunne et al. 1986; Stark and Juhrend 1989). In general, most of the researchers agreed that N_k values ranged between 15 and 20.

The friction angle Φ of sand could be also estimated through different methods (Meyerhof 1976; Robertson and Campanella 1983; Kulhawy and Mayne 1990). The results of (s_u and Φ) are shown in Fig. 3.

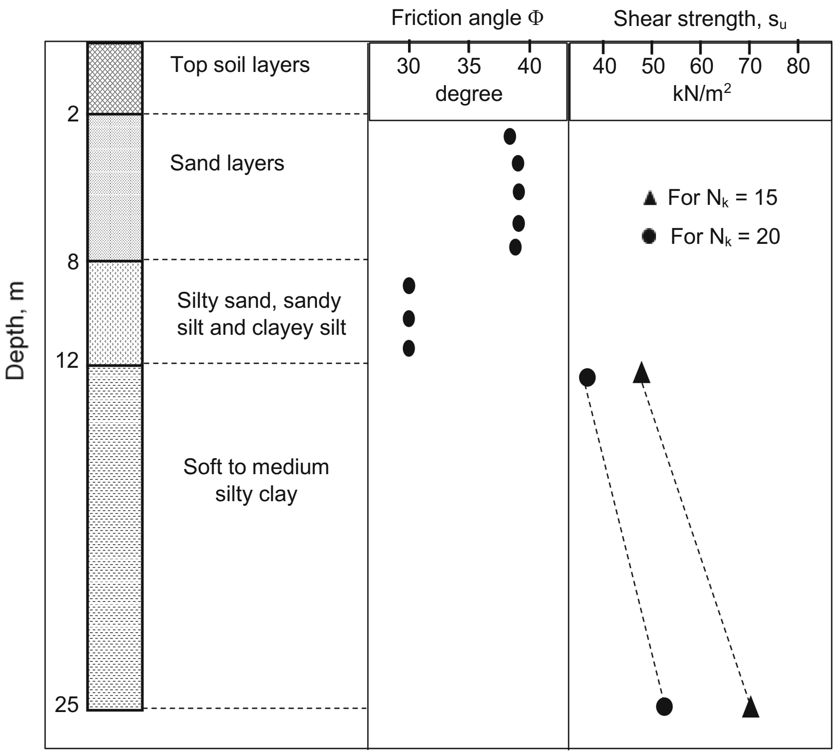

Fig. 3. Shows the derived soil classification and soil parameters from CPTU

3 Estimation of Pile Bearing Capacity

Two methods were used to estimate pile bearing capacity, static formula and cone penetration test. Static formula used soil parameters estimated from laboratory or derived from CPT data. Two approaches for application of cone data to pile design have been evolved, direct and indirect methods. Direct methods more or less equal the cone resistance with the pile end resistance. Some methods use the cone sleeve friction in determining the pile shaft capacity. Indirect methods employ soil parameters estimated from cone data as based for estimating pile bearing capacity. Although the site under study with its complicated profile is located in Egypt, the Egyptian code for foundations did not give direct approach depending on CPT to estimate pile bearing capacity for similar soils. Hence, the Canadian code was used for this estimation. Tables 1 and 2 show the estimated values of pile bearing capacities for different methods.

Table 1. Pile bearing capacity estimated by different methods (rotary drilling bored piles with diameter = 0.60 m and length = 27 m)

The method	Ultimate bearing capacity (t)			Measured (t)
	End bearing	Friction	Total	
*Egyptian Code, 2001	18	78	96	Load test = 200 Ultimate load ≈ 223 t to 244 t
*Canadian Code, 2006	14	134	157	
*de Ruiter and Beringen (1979)	14	138	152	
**Egyptian Code, 2001	11	63	74	
**Canadian Code, 2006	9	105	114	
***Canadian Code, 2006	15	215	230	
***Schmertmann (1978)	42	227	269	
***Bustamente (1982)	15	215	230	
***Tumay and Fakhroo (1981)	42	163	205	
***Eslami and Fellenius (1997)	16	238	254	

Notes: * Depends on soil properties derived from CPT
** Depend on soil properties derived from laboratory tests
*** Depend on q_c and f_c

Table 2. Pile bearing capacity estimated by different methods (CFA pile with diameter = 0.70 m and length = 27 m)

The method	Ultimate bearing capacity (t)			Measured (t)
	End bearing	Friction	Total	
*Egyptian Code, 2001	24	91	115	Load test = 200 Ultimate load ≈ 335
*Canadian Code, 2006	19	156	175	
*de Ruiter and Beringen (1979)	19	161	180	
**Egyptian Code, 2001	15	73	88	
**Canadian Code, 2006	12	122	134	
***Canadian Code, 2006	20	250	270	
***Schmertmann (1978)	57	265	322	
***Bustamente (1982)	20	250	270	
***Tumay and Fakhroo (1981)	57	190	247	
***Eslami and Fellenius (1997)	22	278	300	

Notes: * Depends on soil properties derived from CPT
** Depend on soil properties derived from laboratory tests
*** Depend on q_c and f_c

4 Pile Load Tests

Six preliminary pile load tests were carried out before starting the project to verify the calculated ultimate and allowable bearing capacities of piles. Two bored piles with length 34 m were excluded because they did not match with depth of CPTU. Three bored piles had diameter 0.60 m and length of 27.0 m while one CFA pile had diameter 0.70 m and depth of 27.0. The piles were loaded up to 200 t which equal to 250% allowable load and the tests completed within different durations ranged between 48 h and 7 days to check the time-load-effect, Fig. 4 shows load-settlement curves. Two different methods were used for estimating the ultimate loads, Modified Chin Method and Brinck Hansen Method as recommended by Egyptian code. The expected ultimate loads for the piles were reported in Tables 1 and 2.

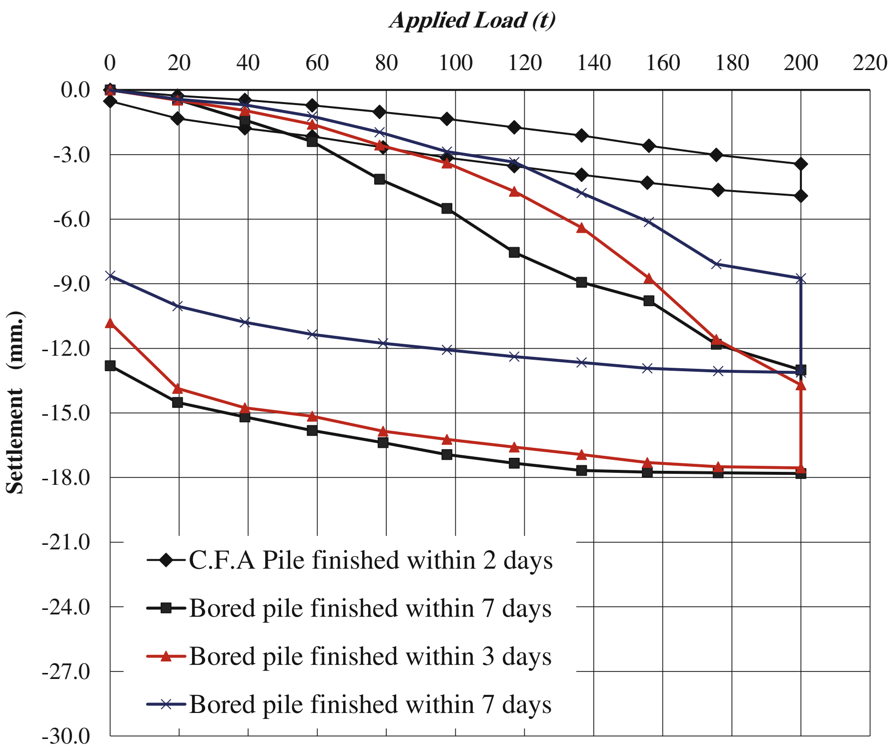

Fig. 4. Shows load-settlement curves for piles with length of 27.0 m

5 Discussion of Tests Results

5.1 Soil Parameters

Soil parameters (Φ and c_u) are considered the best important parameters for estimating the bearing capacity of foundations. The accuracy the determination of soil parameters is the accuracy of foundations bearing capacity. These parameters are usually determined from different lab tests that depend mainly on the accuracy of extracted undisturbed samples. Although well-controlled undisturbed samples were achieved during drilling works in our case study, the disturbed behavior dominated which could be noticed on the shape of $e - \log \sigma'$ curves for consolidation test. The values of c_u for silty clay layer were highly affected by the samples disturbance. It can be noticed that values of (Φ and c_u) determined from lab tests are obviously lower than those derived from CPT, see Fig. 5.

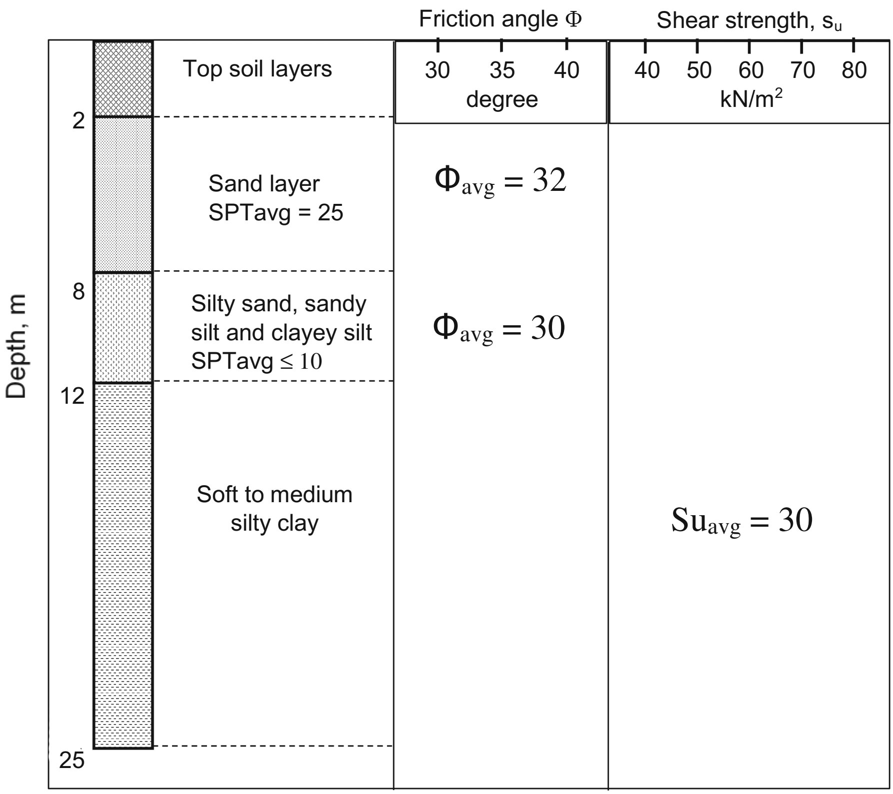

Fig. 5. Shows soil parameters determined from lab tests

5.2 The Ratio c_u/σ'_v

Due the difficulties of determining of c_u in lab especially for soft clay, several empirical relationships have been proposed between c_u and the effective overburden pressure σ'_v (Bowles 1984; Jamiolkowski et al. 1985; Bazaraa et al. 1986). Most of the correlations agreed that the ratio c_u/σ'_v range between 0.22 and 0.30 for most soft clays. These correlations depended on estimating undrained shear strength by different lab tests. For our case study, this ratio ranged between 0.2 and 0.25. According to the data of CPTU, the ratio c_u/σ'_v ranged between 0.3 and 0.4 with an average value 0.37. This improvement of c_u could be attributed to two factors, the first is to the limited disturbance of soil during cone tests and the second is to the existence of dense sand overlaying soft clay.

5.3 Pile Bearing Capacity

Although the ultimate bearing capacities estimated by methods depending on soil parameters derived from CPT are obviously lower than those measured from pile load tests, but they are still better than those estimated by methods depending on soil properties derived from laboratory tests, see Tables 1 and 2. On the other hand, the methods that depended directly on q_c and f_c produced good agreement with the measured ultimate bearing capacities. The Egyptian code gave the lowest values although its approach is similar to that in the Canadian code. The reason is that Egyptian code put some precautions for bored pile installation led to decrease the values of soil parameters Φ and c_u. It could be also noticed that CFA pile produced relatively higher ultimate bearing capacity than those of bored piles as shown in Table 2 and Fig. 4.

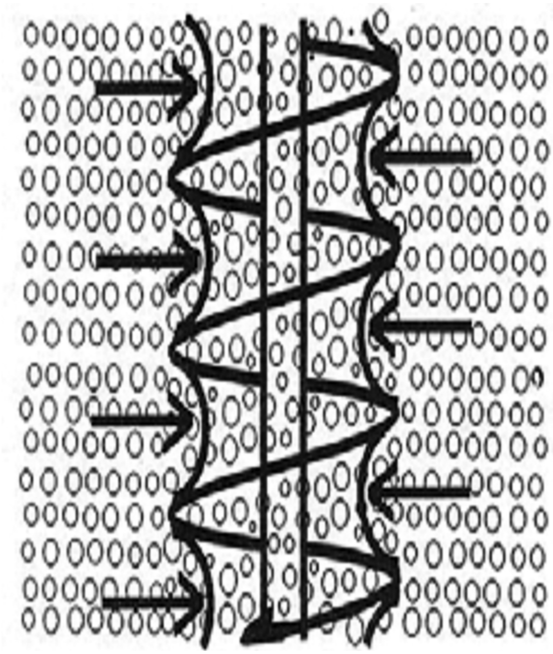

Fig. 6. Effect of over-excavation with CFA piles (after Fleming 1995)

5.4 CFA Methods in Sand Overlying Firm Clay

The key component of the CFA pile system, contributing to the speed and economy of these piles, is that the pile is drilled in one continuous operation using a continuous flight auger, thus reducing the time required to drill the hole. While advancing the auger to the required depth, it is essential that the auger flights be filled with soil so that the stability of the hole is maintained. If the auger turns too rapidly (over-rotation), with respect to the rate of penetration into the ground, then the continuous auger conveys soil to the surface. This action can result in a reduction of the horizontal stress necessary to maintain stability of the hole, lateral movement of soil towards the hole, ground subsidence at the surface and reduced confinement of nearby installed piles, see Fig. 6 (Brown 2005).

Brown et al. (2007) reported that the installation of CFA piles can be problematic in the very soft soils. In these soils, the installation of CFA piles can present problems concerning ground stability due to soft-ground conditions, which can produce necks or structural defects in the pile. Also if hard soil is overlain by soft soil, the installation of CFA piles is typically difficult. The problem occurs when the hard stratum is encountered and the rate of penetration is slowed with respect to rotation because of the difficult of drilling. Accordingly, decompression of the ground inside the hole, loosening of the in-situ soil around the hole and ground subsidence adjacent to the pile are expected, see Fig. 7.

In our case study the situation is conversely, CFA have balanced auger rotation and penetration rates in the upper dense sand. As soon as the auger reaches the underlying

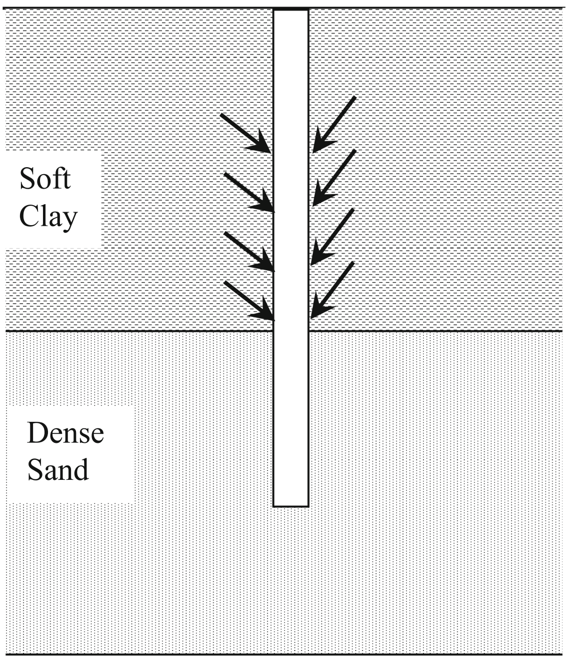

Fig. 7. Difficult conditions for CFA piles (hard soil overlain by Soft clay)

compressible clay its penetration rate will increase with respect to the rotation (over-penetration). This over-penetration is considered the best situation for CFA and the defects that can be occur in soft soils overlying hard soil are limited.

Whatever, it can attribute the better behavior and the higher ultimate bearing capacity of CFA pile than those of bored piles to the contentious drilling of CFA and placing the concrete by pumping under pressure.

5.5 Time-Load-Effect

The assessment of creep resistance of pile is particularly relevant in the design of raft foundations supported on piles in poor ground when there is no underlying bearing stratum. King et al. (2000) studied the creep failure of CFA pile in soft clay through 12 pile load tests. All the piles were instrumented and loaded up to failure and the durations of loading for some tests continued for over 300 h. They found that the creep

Table 3. Results of field pile load tests

Test # 1			Test # 2		Test # 3		Test # 4	
Load (t)	Time (h)	Set. (mm)	Time (h)	Set. (mm)	Time (h)	Set. (mm)	Time (h)	Set. (mm)
19.5	1	0.27	1	0.44	1	0.47	1	0.43
39	1	0.46	1	1.40	1	0.95	1	0.69
58.5	1	0.71	1	2.39	1	1.59	1	1.22
78	3	1.02	3	4.14	3	2.56	3	1.96
97.5	3	1.34	3	5.50	3	3.39	3	2.68
117	3	1.73	3	7.54	3	4.71	3	3.35
136.5	3	2.11	3	8.93	3	6.39	3	4.78
156	3	2.59	3	9.79	3	8.74	3	6.13
175.5	3	3.01	3	11.81	3	11.58	3	8.08
200	0	3.44	0	13.0	0	13.68	0	8.75
200	12	4.91	144	17.81	48	17.55	144	13.12
175.5	0.25	4.63	0.25	17.78	0.25	17.5	0.25	13.06
156	0.25	4.31	0.25	17.75	0.25	17.3	0.25	12.93
136.5	0.25	3.94	0.25	17.67	0.25	16.93	0.25	12.65
117	0.25	3.53	0.25	17.33	0.25	16.56	0.25	12.38
97.5	0.25	3.14	0.25	16.93	0.25	16.23	0.25	12.07
78	0.25	2.67	0.25	16.38	0.25	15.84	0.25	11.76
58.5	0.25	2.16	0.25	15.81	0.25	15.15	0.25	11.35
39	0.25	1.78	0.25	15.18	0.25	14.76	0.25	10.79
19.5	0.25	1.32	0.25	14.51	0.25	13.86	0.25	10.04
0	0	0.99	0	13.18	0	11.49	0	8.80
0	12	0.52	3	12.81	4	10.81	4	8.63

Test # 1: CFA and completed within 2 days between 13 and 15 Nov. 2013
Test # 2: Rotary drilling and completed within 7 days between 3 and 10 Nov. 2013
Test # 3: Rotary drilling and completed within 3 days between 10 and 13 Nov. 2013
Test # 4: Rotary drilling and completed within 7 days between 3 and 10 Nov. 2013

loads were ranged between 70% and 50% of peak loads depending mainly on pile diameter, i.e. the high ratio belong to the small diameters.

In our case study, Table 3 shows that the test load of 200 t was left about 144 h for two tests and 48 h for one test. Creep behavior, i.e. increasing settlement at constant or peak load, could be obviously noticed for each pile test but unfortunately the creep load was not measured. The creep behavior is considered a phenomenon related generally to the peak or failure load. So, creep behavior could not be noticed for loads much less than the failure which could explain the unnoticeable creep behavior for CFA.

6 Conclusions

This paper presented the behavior of bored piles in sand overlaying compressible clay. Several approaches were used to estimate the ultimate bearing capacity of piles depending on soil parameters and on CPTU. Soil parameters were estimated from lab tests or derived from CPTU data. The important points can be concluded as follows.

1. The soil profiles in which strong soil stratum overlying compressible clay are not the ideal profile for pile foundations whether displacement, bored or CFA piles. Hence the analysis of pile behavior in these soil profiles should be distinguished.
2. The behavior of pile depends mainly on the accuracy of determining soil parameters that are estimating from laboratory tests or field tests. Still there are difficulties for extracting undisturbed samples from soft clays especially at deeper depths so that the values of shear strength can be very low relatively to that in filed.
3. Cone penetration testing (CPT) is a fast and reliable field means of conducting site investigations for exploring soils and soft ground with limit disturbance. The values of soil parameters that have been derived from the data of CPT, were obviously higher than those estimated from lab tests. So that the estimated bearing capacities of piles depending on lab soil parameters were obviously less than those depending on soil parameters derived from CPT.
4. The ratio of c_u/σ'_v derived from CPT was ranged between 0.3 and 0.4 with an average value 0.37. These values are considered higher than that customary for soft clays. This improvement of shear strength could be attributed to the limited disturbance of soil during cone tests. The unique soil profile, dense sand overlaying compressible clay, may also participate in this improving.
5. The direct approaches for estimating ultimate bearing capacities of piles from CPT produced good agreement with the measured ultimate bearing capacities.
6. Egyptian code approach produced the lowest and illogical values of ultimate bearing capacities because of the precautions for bored pile installation that led to decrease the values of soil parameters Φ and c_u.
7. The precautions for CFA piles in soft clays should be discussed with the soil profile. It was found that the behavior of CFA piles in sand overlying compressible clay was better than those of bored piles.
8. In soil profile when there is no underlying bearing stratum, the creep resistance of pile should be assessed.

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