Experimental Study of the Group Effect on the Bearing Capacity of Bored Piles in Sandy Soil

J. Melchior Filho, V.H.F. Bonan, A.S. Moura

Abstract. A foundation design must meet at least the following basic requirements: a) acceptable deformations under the working conditions; b) adequate safety against soil failure; and c) adequate safety against failure of structural elements. For the pile design, depending upon the spacing adopted among them, a pile may affect the other's behavior. This occurs both in terms of bearing capacity and settlement. Researches on the group effect of bored piles in typical soils of Fortaleza (Northeast Brazil) is scarce, which justifies and motivates studies on the subject. The aim of the research reported here was to evaluate the group effect of bored piles in sandy soil, typical condition of the city of Fortaleza. An experimental campaign with 26 piles was performed on a site inside the campus of the Federal University of Ceará (Experimental Field of Geotechnics and Foundations of the Federal University of Ceará). The results of tests on single piles and groups were compared with estimations based on methods presented in the literature. The tested piles were observed to behave only by side friction, and group effect was noticed for all spacings investigated.

Keywords: bearing capacity, bored pile, group effect, pile group.

1. Introduction

The execution process of bored piles can cause changes in geostatic stresses due to decompression of ground during excavation. In cohesive soils and above the water table, decompression is expected since no casing is used. On the other hand, in non-cohesive soils, metallic casing is placed with the advance of excavation, which may reduce soil expansion and, consequently, stress relief. Between these two extremes, there is the possibility of execution with the use of stabilizing fluid.

During the execution of bored piles, a portion of loose soil remains at the pile toe, which cannot be removed by the drilling tool (piling auger). This effect will cause a reduction in the pile bearing capacity (Scallet, 2011). Pérez (2014) studied the behavior of these piles via slow-type static load tests. Three diameters of instrumented bored piles were evaluated. The author shows that the load transfer occurred to a large extent by side resistance, and a larger displacement would be necessary to mobilize the base resistance because of the loose soil at the pile toe.

The load-displacement response of piles is different if executed alone or in groups. When executed in groups, interactions occur among several piles during the load transfer to the soil mass. This interaction creates a stress superposition, which affects the load-displacement response of the pile group. In order to quantify this group effect, several authors use mainly the spacing among piles of the same group or neighboring caps and the soil characteristics (Vesic 1969).

The geotechnical literature provides several methods for the estimation of bearing capacity and displacement of single piles. However, pile groups are often adopted in foundation design. When piles are executed close to each other, the load-displacement response of the group can change according to the spacing between piles, when compared to a single pile.

According to NBR 6122 (ABNT, 2010) the group effect on piles is the interaction of various elements that constitute a foundation when transferring loads to the ground. This interaction involves a superposition of stresses, usually causing different displacement of isolated elements, which changes the individual behavior of each pile of the group. The Canadian Foundation Engineering Manual, CGE (1992), recommends that the group effect can be disregarded if the space between two piles is larger than 8 diameters (D).

The soil-structure analysis of a pile group represents a complex problem because the group effect can be influenced by: the pile installation method; the type of load transfer (floating pile or end bearing pile); the nature of the foundation soil mass; the three-dimensional geometry of the group; the presence of the pile cap; the pile cap relative stiffness. (Chan, 2006).

According to Poulos (1993), there are several uncertainties in the applicability of the different methods for pre-

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dicting the behavior of pile groups, regarding bearing capacity and displacement, mainly due to the scarcity of documented cases, particularly for bored piles.

The efficiency of a pile group can usually vary with the influence of soil excavation, the type of soil and its compactness, and the spacing between the piles. Silva & Cintra (1996) performed 6 static load tests, two of them on single piles with cap, and the others on pile groups with cap. The pile groups were: one 2-pile group (1 x 2); two 3-pile groups, one in line pile group (1 x 3) and the other in triangular shape pile group (3Δ); and one 4-pile group arranged in square shape (2 x 2). The authors also analyzed the influence of the cap on the bearing capacity of the pile groups. The efficiencies found with and without contribution of the cap, respectively, are: 1.15 and 0.90 (1 x 2); 1.17 and 0.92 (1 x 3); 1.20 and 1.09 (3Δ); 1.07 and 0.97 (2 x 2). All the piles were manually drilled type piles with 0.25 m diameter (D), 6 m length, and 3D pile spacing.

Sales (2000) found efficiency of 100 % for piled footings with 4 bored piles with 0.15 m diameter, 5 m in length and 5D pile spacing (s). On the other hand, Garcia (2015) found efficiencies of 79.1 % (2 piles), 69 % (3 piles) and 76.1 % (4 piles). Garcia (2015) carried out static load tests on piled rafts composed of mechanically excavated piles of 0.25 m in diameter and 5 m in length. The piled rafts comprised two, three and four piles, spaced 5D.

For piles embedded in loose sandy soils, the literature reports that the efficiency would be maximum for a spacing of 2D due to the effect of compaction caused by the vibration of the process (Kézdi, 1957; Stuart *et al.*, 1960). The efficiency returns to about 100 % for a pile spacing of 6D. Meyerhof (1976) suggests adopting efficiency of 2/3 for a pile spacing (s) from 2 to 4D for groups of bored piles in sand.

Vesic (1969) conducted a study in which a series of experiments in a reduced scale model was performed in the field with groups of 4 and 9 instrumented piles in sand. The author compared the bearing capacity of pile groups with the bearing capacity of single piles. The piles had 10 cm in diameter and 150 cm in length, and were driven into the ground using a pile driver, with spacing between axes from 2 to 6 diameters. The groups were tested in two scenarios: in medium dense homogeneous deposit (Dr = 65 %); the second one is composed of two layers, a top layer of loose sand (Dr = 20 %) and a bottom layer of dense sand (Dr = 80 %)

Few studies are observed in the literature related to the group effect of bored piles in sandy soils, and still less in tropical soils typical of those that occur in Fortaleza. Within this context, this work aims to contribute to better understanding of the group effect on bored piles in sandy soils. The objective of this research is to evaluate, experimentally, through static load tests performed on groups of excavated piles, the group effect on sandy soil profiles in terms of the bearing capacity of the piles.

2. Materials and Methods

2.1. Experimental site

The present study was carried out in the Experimental Field of Geotechnics and Foundations of the Federal University of Ceará (-3.752297 S, -38.572821 W), located according to Fig. 1.

2.2. Characterization tests

The sieve analysis was performed on soil samples obtained at depths of 1.0 to 2.0 m, because it is the length of the piles. The particle-size distribution of the soil samples obtained are shown in Fig 2.

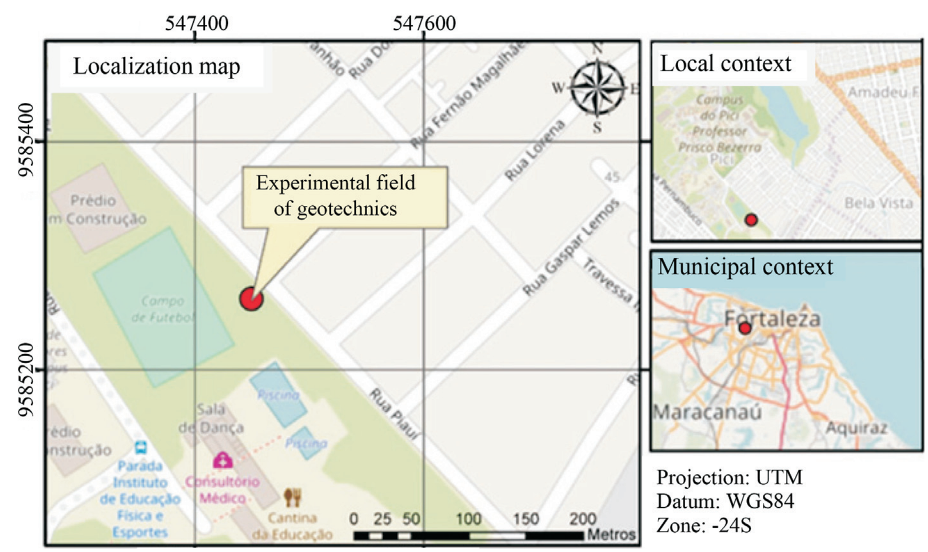

Figure 1 - Location of the experimental site.

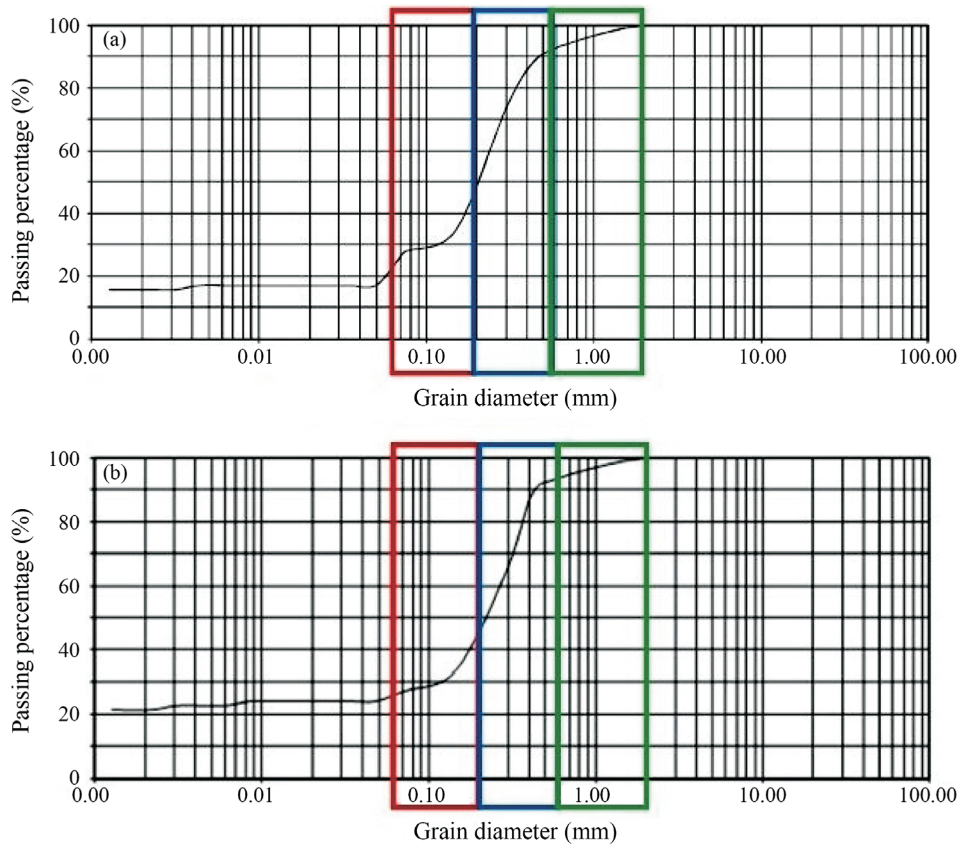

Figure 2 - Granulometric curve of the soil layer in depths of (a) 1.0 m and (b) 1.5 m.

According to the particle-size distribution, the soil is predominantly sandy, and its composition is approximately 78 % sand in the most superficial portion and 73 % sand in the soil present between the depths of 1.5 to 2.0 m, which was classified according to NBR 6502 (ABNT, 1995). In the curves, the portions of fine sand, medium sand and coarse sand are highlighted, respectively, by red, blue and green lines. The values of specific gravity of grains in depths of 1.0 and 2.0 m varied between 2.62 and 2.64, respectively.

2.3. Standard penetration test

The soil sampling carried out together with the Standard Penetration Test indicated a predominantly sandy-silt soil profile up to 7.45 m depth. The water level was found at the depth of 7.36 m. The N_{SPT} values varied from 12 to 18 blows/30 cm at 4.45 m depth and, from there, decreased to 4 blows/30 cm at 7 m depth.

Using the method proposed by Odebrecht (2003), the efficiency of percussion drilling was estimated at 72 %. The value of 72 % is nearly coincident with the standard adopted in Brazil. To evaluate whether the semi-empirical methods used in this research, which do not specify reference efficiency could lead to more consistent Q_{ult} predictions, the N_{SPT} values used in this research were also corrected to the reference efficiency of 60 % (Table 1), which is the standard adopted in the United States (Odebrecht, 2003; Skempton, 1986).

2.4. Execution of isolated and group piles

The pile work load was defined according to the Brazilian Standard for Design and Construction of Foundations NBR 6122 (ABNT, 2010). Groups of 2 and 4 piles were constructed varying the spacing between the piles, in addition to two other isolated piles. Table 2 presents some geometric information of the pile groups.

Table 1 - Corrected values of N_{SPT} for 60 % efficiency.

Depth (m)	N_{SPT}	Corrected values of N_{SPT}		
		Odebrecht (1st case)	Odebrecht (2nd case)	Average values
0.4	15	20	18	19
1.0	12	16	14	15
2.0	15	20	18	19
3.0	18	24	22	23
4.0	18	24	22	23
5.0	6	8	7	8
6.0	3	4	4	4
7.0	4	5	5	5

The construction of the piles happened within two consecutive days, being constructed 13 piles per day. The groups of 4 piles had two piles constructed per day, in diagonal arrangement and the groups of 2 piles had one pile constructed per day. The excavation was performed with a shell-type driller. At the beginning of the procedure, a certain amount of water was added to the hole to facilitate the excavation. The following procedure was used for pile grouting: placement of the steel cage; concrete mixing into a 400 L concrete mixer, then measuring the slump of the mixture through the Slump test and releasing for launch. The concrete was poured with buckets of 18 L in order to estimate the volume released. Finally, the concrete was densified manually using a metal rod. The slump adopted was between 22 and 24 cm, and the characteristic compressive strength (f_{ck}) was 20 MPa.

The piles caps were executed later with no contact with the ground and, therefore, there was no contribution of the caps for group capacity. For caps with 2 and 4 piles, the spacing between piles was adopted as 2D, 2.5D, 3D and 4D, in which D is the pile diameter. In addition, two caps for single piles were executed, which gives 26 piles distributed in 10 caps. To avoid the group effect between nearby caps, a minimum distance of 8D between caps was adopted, as suggested by the literature (CGE, 1992). In order to evaluate the load distribution on the pile, two separate piles were executed, one of them with Styrofoam at the toe, thus the toe bearing capacity is assumed to be null.

Regarding the application of the methods for designing larger piles than those in this study, Nasr (2014) stated that the factors that must be considered in the usage of small-scale models are the soil particle size, construction techniques and boundary conditions. According to Franke & Muth (1985), scale error is not relevant for a ratio of the pile diameter to the mean grain size (D_{50}) greater than 30. Since in this study the pile diameter is 10 cm, and D_{50} is approximately 0.3 mm, such condition is fulfilled. Regarding the remaining factors, the tests presented in this research are supposed to represent the behavior of full-scale bored piles installed in a similar type of soil as the models. Therefore, the small-scale tests performed are considered as representative of full-scale foundations.

As previously reported, a similar study was performed by Vesic (1969) in which a series of experiments in a reduced scale model was performed in field with groups of 4 and 9 instrumented piles. The piles had 10 cm in diameter and 150 cm in length but were driven into the ground using a pile driver, with spacing between axes from 2 to 6 diameters. The groups were installed in sand profiles of different relative density.

2.5. Static load tests

The Static Load Tests (SLT) were performed with the load applied in quick stages based on the recommendations of the Brazilian Standard NBR 12131 (ABNT, 2006). Ho-

Table 2 - Summary of geometric information of piles and caps.

Group	Number of piles	s/D	Pile caps			Piles					
			Length (cm)	Width (cm)	Height (cm)	Total length (cm)	Reductions			Pile length (cm)	Pile diameter (cm)
							Cap height (cm)	Lean conc. (cm)	Excavation (cm)		
1	1	-	30	30	20	180	20	5	5	150	10
2	1	-	30	30	20	180	20	5	5	150	10
3	2	2	50	30	20	180	20	5	5	150	10
4	2	2.5	55	30	25	185	25	5	5	150	10
5	2	3	60	30	30	190	30	5	5	150	10
6	2	4	70	30	35	195	35	5	5	150	10
7	4	2	60	60	30	190	30	5	5	150	10
8	4	2.5	65	65	35	195	35	5	5	150	10
9	4	3	70	70	40	200	40	5	5	150	10
10	4	4	80	80	50	210	50	5	5	150	10

wever, during the tests, 7 to 9 loading stages and 3 unloading stages were performed. The number of load stages was defined aiming to adjust the duration of the tests to the time available for the research. For this reason, only 3 stages were adopted for the unloading stages. In addition, situations occurred in which, before reaching the maximum expected load stage, failure happened, which led to the end of the loading stage.

The displacements were monitored with 4 dial gages, in 0, 1, 2, 5 and 10 min. The arrangement of the dial gages in diametrically opposite positions allows for the evaluation whether, throughout the tests, the applied load remains centered over the cap. In cases where displacement stabilization was observed before 10 min, the next stage was performed. The limiting factor for the execution of these tests was the reaction system.

The reaction system was composed of a loaded truck and a metallic I-beam, whose axis was positioned over the pile cap (transversely). The load tests assembly is shown in Fig. 3.

Initially, slow load tests (SLT) were performed on 2 isolated piles. The first test was performed by subjecting the pile to the predicted compressive capacity taking into account both shaft and toe bearing capacities. The second load test was performed on an identical pile to the previous one, including, however, a Styrofoam disc at the pile toe in order to eliminate the toe bearing contribution to the pile bearing capacity.

Subsequently the load tests were performed in groups of 2 and 4 piles varying the spacing between piles (2D, 2.5D, 3D and 4D).

2.6. Bearing capacity predictions

The semi-empirical methods of Aoki & Velloso (1975), Décourt & Quaresma (1978) with contributions by Décourt (1996), and Teixeira (1996) were used to estimate the bearing capacity of the isolated piles.

In order to predict the bearing capacity of the groups of piles, methods commonly found in the literature were used to estimate the efficiency (Feld's Rule (Feld, 1943) and a rule of uncertain origin - both found in Poulos & Davis (1980), Converse-Labarre (Bolin, 1941), Los Angeles Group Action equation - in Das (1998), and Sayed & Bakeer, 1992).

3. Analysis and Discussion of Results

3.1. Results and analysis of load tests

Figure 4 shows the results of the slow load tests performed on the isolated pile, with and without the toe bearing capacity. Both tests were performed with the application of 8 loading stages and 3 unloading stages. Figure 4 shows practically coincident curves, which implies that in the piles' bearing capacity there is no contribution from the toe.

It is worth mentioning that the maximum displacement of the pile without Styrofoam at its toe was 7.12 mm and its residual displacement was 6.83 mm. And for the pile with Styrofoam at its toe the maximum displacement was 9.59 mm and the residual displacement was also 9.59 mm.

Figure 5 shows the load-displacement responses obtained from the tests performed on the groups with 2 piles and Fig. 6 shows the results of the tests performed on the groups of 4 piles.

The pile group with 4D spacing exhibited failure at the 4th loading stage, corresponding to 68.7 kN. Subsequently, an integrity problem in one of the piles of the group was confirmed by means of excavation around the pile, which prevented the test to be continued.

3.2. Bearing capacity predictions

Table 3 shows the estimated bearing capacity, Q_{ult}, of the isolated piles, as well as the portion due to the shaft friction, Q_l, and to the toe resistance, Q_p, respectively, considering the two groups of N_{SPT} values considered.

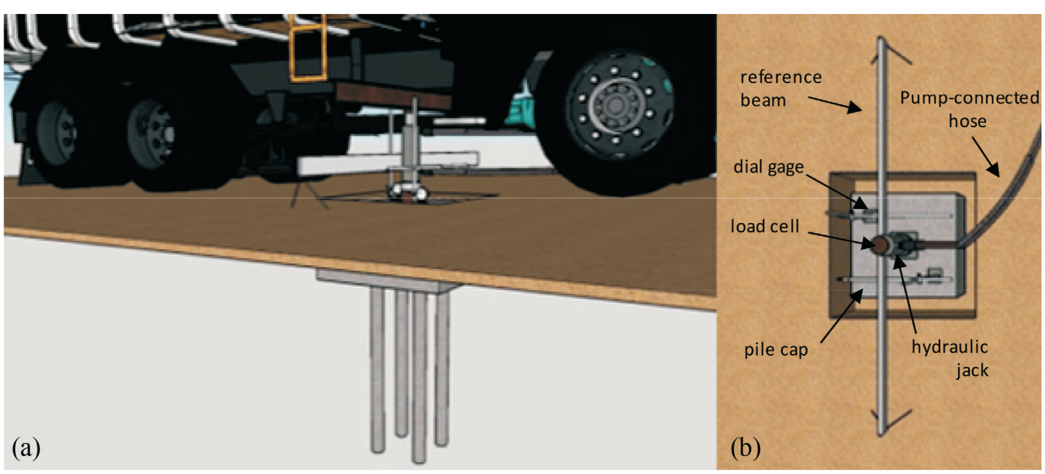

Figure 3 - Illustration of SLT performed: (a) perspective; (b) top view.

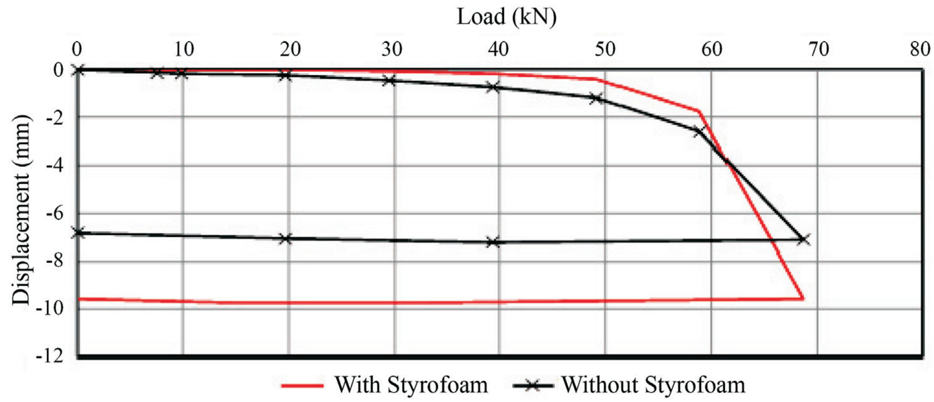

Figure 4 - Load-displacement curves of the isolated piles with and without toe bearing contribution.

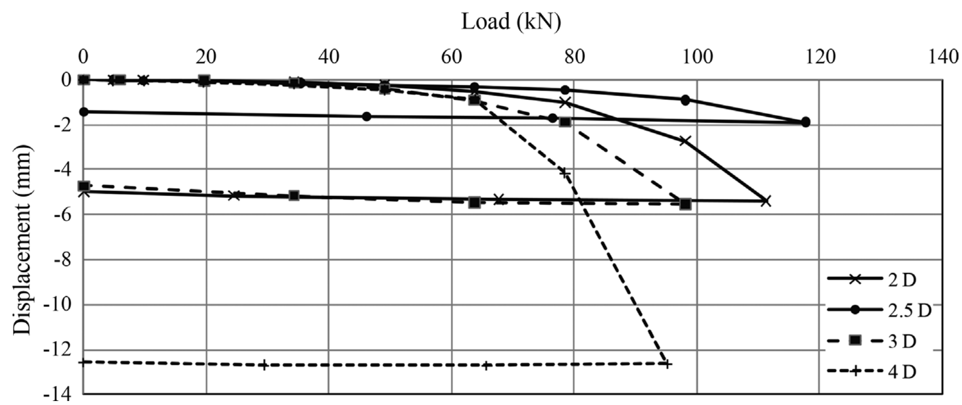

Figure 5 - Load-displacement curves of the groups with 2 piles.

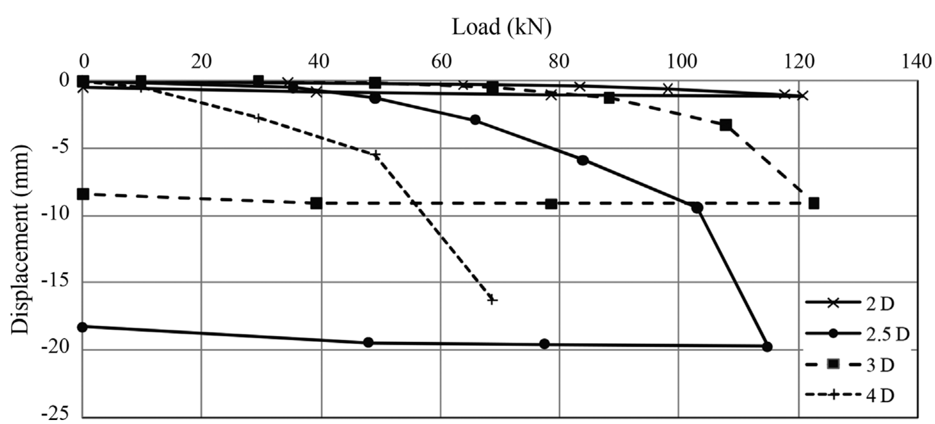

Figure 6 - Load-displacement curves of the groups with 4 piles.

The method of Teixeira (1996) presents the highest estimated values of Q_{ult}, followed by Aoki & Velloso (1975) and Décourt & Quaresma (1996) methods. By comparing the estimates made from corrected and uncorrected values of N_{SPT}, the correction of the efficiency to 60 % increased, in all methods used, the Q_{ult} estimates by about 25 % above those made using N_{SPT} values without efficiency correction.

Table 4 shows a comparison of the estimated Q_{ult} of the isolated pile, obtained from corrected and uncorrected N_{SPT} values as a function of the efficiency, with the reference value, 68.6 kN, which was obtained through the results of the SLT. The mentioned table presents the values of Factor of Safety (FS) obtained for each method when the values presented in Figure 7 are divided by 2 and taken as the pile work load. The Q_{ult} predictions using semi-empirical methods are lower than the reference value, with values up to 4.4 times lower, even when the corrected N_{SPT} values are used. The closest estimate was obtained with the

Table 3 - Summary of Q_{ult}, Q_l, and Q_p estimated of isolated piles.

Method	N_{SPT}	Q_{ult} (kN)	Q_l (kN)	Q_p (kN)
Aoki & Velloso (1975)	Field	37.3	15.7	21.6
	Corrected e = 60 %	47.1	19.8	27.4
Décourt & Quaresma (1996)	Field	33.1	17.2	15.9
	Corrected e = 60 %	40.9	20.8	20.0
Teixeira (1996)	Field	50.5	26.0	24.5
	Corrected e = 60 %	63.6	32.8	30.8

Table 4 - Comparison of the estimated Q_{ult} of the isolated pile, obtained from corrected and uncorrected N_{SPT} values and values of Factor of Safety (FS) obtained for each method.

Method	N_{SPT}	Q_{ult}	FS
Aoki & Velloso (1975)	Field	37.3	3.7
	Corrected e = 60 %	47.1	2.9
Décourt & Quaresma (1996)	Field	33.1	4.1
	Corrected e = 60 %	40.9	3.4
Teixeira (1996)	Field	50.5	2.7
	Corrected e = 60 %	63.6	2.2
Slow load test		68.6	-

method of Teixeira (1996) and using the corrected N_{SPT} values. However, even in this case, the estimated value was 2.6 times lower than the reference value.

Tables 5 presents estimated values of efficiency for groups of 2 and 4 piles, respectively. And Table 6 presents the predicted bearing capacity for the groups of piles as a function of spacing (s/D), which were determined by multiplying the number of piles in the group by the estimated efficiency and by the ultimate capacity of a single pile (68.6 kN), obtained via load test on the isolated pile.

For almost all methods, except for the Feld's Rule that provides a constant value, the efficiency of the group increased with the pile spacing increase. The highest values were obtained for the rule of uncertain origin (Poulos & Davis, 1980). The values of efficiency below unit obtained in the current study are in agreement with the indications for bored piles in sand by Meyerhof (1976), it suggests that an efficiency of 2/3 for pile spacing from 2 to 4 diameters.

3.3. Bearing capacity determination

The bearing capacity of the isolated piles and the groups of piles were determined from the results of each slow load tests.

Figures 7 and 8 show the graphs for the determination of the ultimate load (Q_{ult}) using the Van der Veen (1953) method and the Décourt (1996) method, which is based on the stiffness of the foundation.

The load value corresponding to the failure obtained visually in the load-displacement curve for the single pile, was compared with values obtained by Van der Veen (1953) and Décourt (1996). Figures 7 and 8 present similar values obtained by Van der Veen (1953) and Décourt (1996). Van der Veen (1953) estimated the ultimate load at 68.6 kN and by Décourt (1996) the estimated value was slightly higher, 74.2 kN. So the value adopted for the ultimate load (Q_{ult}) from the SLT's is 68.6 kN. The adoption of this value is due to the fact that Van der Veen's (1953) method provides the physical ultimate load, in the same way as the semi-empirical methods used in the present research, and the results are compared below.

Table 7 shows the Q_{ult} values obtained by the Van der Veen (1953) method for single pile and pile groups. The efficiency (η) of the pile groups is also shown in Table 7, obtained by dividing Q_{ult} of the group by the number of piles in the group, times Q_{ult} of the single pile (68.6 kN). According to these results, the group efficiency was lower than one. For groups with larger spacing, the efficiency reduced or remained almost constant. Finally, groups with s/D greater than or equal to 3 showed that the efficiency remained lower than one, and it indicates that there was group effect at all spacings investigated.

Table 5 - Efficiencies of the groups with 2 and 4 piles.

Methods			Efficiencies				
			Feld's Rule	Rule of uncertain origin	Converse-Labarre	Los Angeles	Sayed & Bakeer (1992)
Groups with 2 piles	s/D	2	0.94	0.94	0.84	0.92	0.76
		2.5	0.94	0.95	0.87	0.94	0.79
		3	0.94	0.96	0.89	0.95	0.80
		4	0.94	0.97	0.92	0.96	0.83
Groups with 4 piles	s/D	2	0.81	0.83	0.68	0.78	0.61
		2.5	0.81	0.86	0.75	0.83	0.67
		3	0.81	0.89	0.79	0.86	0.71
		4	0.81	0.92	0.84	0.89	0.76

Table 6 - Estimates of capacity for the groups with 2 and 4 piles corrected with efficiency.

Methods			Bearing capacity (kN)				
			Feld's Rule	Rule of uncertain origin	Converse-Labarre	Los Angeles	Sayed & Bakeer (1992)
Groups with 2 piles	s/D	2	128.6	128.6	115.4	126.3	103.8
		2.5	128.6	130.3	119.7	128.5	107.8
		3	128.6	131.5	122.6	129.9	110.4
		4	128.6	132.9	126.3	131.7	113.7
Groups with 4 piles	s/D	2	223.0	228.0	187.0	215.3	168.3
		2.5	223.0	237.3	204.5	227.1	184.1
		3	223.0	243.4	216.2	235.0	194.5
		4	223.0	251.2	230.7	244.8	207.7

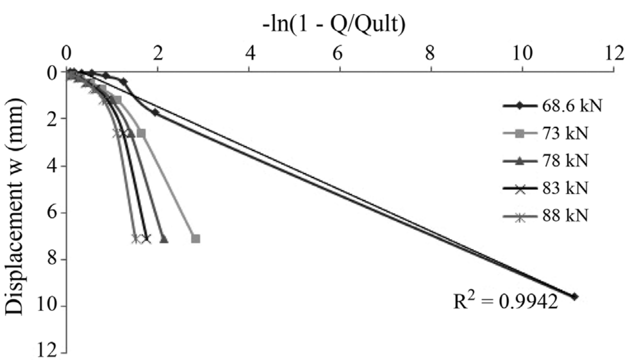

Figure 7 - Determination of Q_{ult} for the isolated pile using the Van der Veen (1953) method.

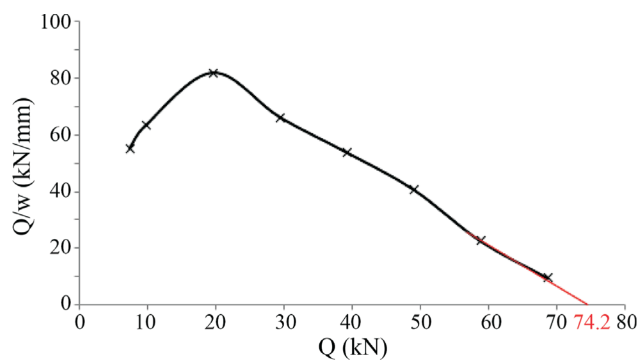

Figure 8 - Determination of Q_{ult} for the single pile using the Décourt (1996) method.

Afterwards, a comparison between the estimated ultimate load of the groups of 2 and 4 piles was carried out, for all the spacings investigated, and the respective reference values, obtained experimentally from the load tests.

For the 2-pile group and s/D = 2, the method that presented the closest estimate to the reference value was Converse-Labarre method, being 2.4 % higher. The other methods presented values ranging from 7.9 % lower to 21.8 % higher than the reference value. In the same way, for the 2-pile group and s/D = 2.5, it is noted that the closest estimate to the reference value was Converse-Labarre, being 0.5 % lower. The other values obtained presented variations from 10.4 % lower to 14.1 % higher in relation to the reference value.

Table 7 - Q_{ult} values estimated for the single pile and pile groups.

Number of Piles	s/D	Q_{ult} (kN)	η
Isolated	-	68.6	-
2	2	114.0	0.82
2	2.5	121.7	0.88
2	3	99.0	0.71
2	4	95.5	0.69

On the other hand, for the 2-pile group and s/D = 3, the method that provided the closest estimate to the reference value was Sayed & Bakeer (1992) method, however with a value higher than the one obtained in SLT. Again it is observed that, for the 2-pile group and s/D = 4, the prediction closest to the reference value was given by the Sayed & Bakeer (1992) method, however, with a value higher than the one obtained in SLT. And all the other estimates were higher than the reference value.

For the 4-pile group and s/D = 2 and 2.5, the predictions closest to the reference value were the ones proposed by the Sayed & Bakeer (1992) method, however, with a value higher than the reference value. The predictions made with the other methods were higher than the reference value, obtained through the SLT. Comparing the values of Q_{ult} with the reference value for the 4-pile group and s/D = 3, the estimates provided by all methods were higher than the reference value, with the Sayed & Bakeer (1992) method showing the most concordant result with the reference value.

Figures 9 and 10 compare the bearing capacity obtained by the SLTs for the groups with 2 and 4 piles. In these same figures are also indicated the Q_{ult} that the groups would have if there was no group effect (without GE), and

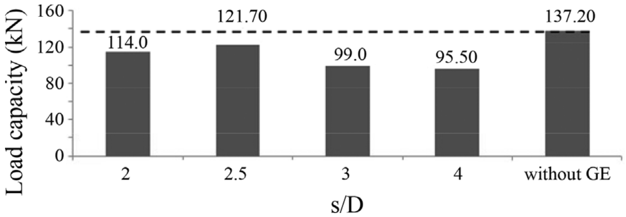

Figure 9 - Comparison of the Q_{ult} values obtained by SLT for the groups of 2 piles with s/D = 2, 2.5, 3 and 4.

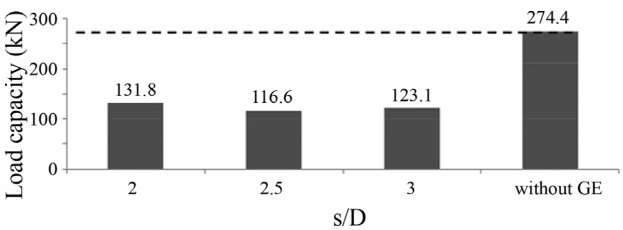

Figure 10 - Comparison of Q_{ult} values obtained via SLT for the 4-pile groups with s/D = 2, 2.5 and 3.

which were determined by the Q_{ult} product of the isolated pile obtained experimentally by the number of piles in each group.

According to Figs. 9 and 10, the group effect can be noticed in all the groups and all the spacings, because the bearing capacity of the groups was lower than the product of single pile Q_{ult} by the number of piles in the group. For the 4-pile group, this effect was more intense, reaching a value 2.4 times lower than when compared to the hypothesis of disregarding the group effect. It is worth mentioning that, if disregarding the group effect, the designer can lead the structure to failure, since the FS normally adopted is 2. Finally, a graph of the efficiency *vs.* the spacing is presented in Fig. 11.

Figure 11 shows that the group efficiency was, in all cases, less than 1.0. For the groups of 2 piles, an average value of $\eta = 0.78$ is observed and, for groups of 4 piles, the average efficiency was 0.44. Values of η lower than 1.0 are in agreement with the literature for bored piles in sand (Meyerhof, 1976 and O'Neil, 1983).

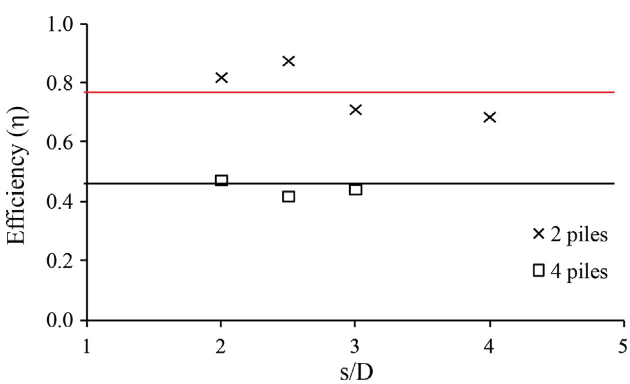

Figure 11 - Efficiency *vs.* spacing for groups with 2 and 4 piles.

For 2-pile groups, the larger the pile spacing the lower the group efficiency is. This trend was not observed in tests with pile spacing between 2D and 2.5D. Similarly, for 4-pile groups, no reduction of η is observed with the increase of pile spacing.

4. Conclusion

The accomplishment of this research allowed us to conclude that:

- Comparing the results of the SLTs performed in isolated piles, with and without Styrofoam disc at the toe, it was observed that the excavated piles bore all the applied load only by its lateral friction;
- The estimates of bearing capacity of isolated piles calculated by the semi-empirical methods proposed by Aoki & Velloso (1975), Décourt & Quaresma (1978) and Teixeira (1996) were in disagreement with the experimentally obtained values. Among the methods used, Teixeira's method (1996) provided the closest estimates to the values obtained from the load tests performed;
- For isolated piles, the use of N_{SPT} values corrected for 60 % efficiency led to closer Q_{ult} predictions than experimentally obtained values;
- Regarding the pile groups, the methods of Converse-Labarre and Sayed & Bakeer (1992) initially presented convergent estimates (2 piles and s/D equal to 2 and 2.5). On the other hand, for the other configurations, the estimated values were higher than those measured in the static load tests performed. The methods of Feld's rule, uncertain origin rule and Los Angeles equation presented estimates higher than the values obtained in the load tests performed in all situations;
- In all groups of piles (with 2 and 4 piles and s/D equal to 2, 2.5, 3 and 4) the group effect was verified;
- Lower efficiency values (η) were obtained in the 4-pile groups than in the 2-pile groups, indicating that for the investigated spacings, the group effect was more intense in the groups with the highest number of piles. This was due to the larger volume of soil contained between the piles of these groups. In this research, the group effect was even more intense because the piles worked exclusively by lateral friction.

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