Piles installed in soft clays: assessment of bearing capacity predictions using static load tests

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ABSTRACT
This paper describes a case study in a soil profile which is very common in the Brazilian coast, with layers of soft clays interspersed with fine sand strata. The analysis involves four concrete driven piles and two Franki piles. The piles were submitted to static load tests and three piles reach soil failure. In the research, the ultimate loads were predicted on the basis of three semi-empirical methods: Aoki and Velloso (1975), Décourt-Quaresma (1978) and Bustamante e Gianeselli (1982). CPT and SPT tests were carried out near the piles location. For the tests that didn't reach failure the predicted results were compared to load-settlement curves extrapolations. Comparatives graphs were obtained and the deviations between predicted and measured resistances were quantified. The limitations of conventional methods based on SPT and CPT results are assessed for soft soils foundation design.

RÉSUMÉ
Cet article décrit une étude de cas dans un profil de sol qui est très commun dans la côte brésilienne, avec des couches des argiles molles entrecoupées de couches de sable fin. L'analyse implique des pieux de différents types et diamètres, avec quatre pieux battus en béton et deux pieux Franki. Les pieux ont été soumis à des tests de charge statique avec trois pieux atteignent la rupture du sol. Poor cette recherche, la charge ultime, étaient prévus sur la base de trois méthodes semi-empirique: Aoki et Velloso (1975), Decourt-Quaresma (1978) et Bustamante e Gianeselli (1982). Les essais in situ CPT et le SPT ont été effectuée près de l'emplacement des pieux. Les résultats prédits ont été comparés aux courbes charge-déplacement des extrapolations. Graphiques comparatifs ont été obtenus et les écarts entre les résistances prédites et mesurées ont été quantifiés. Les limitation des méthodes basées sur les essais SPT et CPT sont évaluées pour les projets des fondations en sols mous.

1 INTRODUCTION

Normally, in geotechnical engineering, the prediction of soil properties is based on field tests to have a limited number of laboratory tests performed on samples taken from specific locations. Typically, soil parameters are obtained through conservative estimates based on the results of these tests, without considering the variability of properties and other uncertainties involved in interpreting the results.

The installation of structures on soft clay of the Brazilian coast is becoming more common, although there is limited information on the behavior of foundations in this soil profile. It is known that this behavior can best be studied using, in addition to field testing, static load tests performed on piles. This paper aims to contribute with new information, comparing results of static load tests on piles of an industrial facility in a specific site of interest. The load capacity of the piles was calculated by established methods based on SPT and CPT, and load tests that were not taken until the failure were extrapolated to obtain the ultimate load.

2 SITE DESCRIPTION

2.1 Stratigraphic Profile

The available data for this study are from a construction area with important economic value, located on the coast of Rio de Janeiro state. The soil consists of clay layers separated by sand layers of different thicknesses, a stratigraphy very common on the Brazilian coast. The water level is near the surface.

Compressible clays are of particular interest in this site. The clay layers are often found in the following depths: clay 1 (2.0 to 6.0 m) and clay 2 (9.0 to 18.0 m), as shown in Figure 1. In this study, two main layers of sand were also considered, at depths from 6.0 to 9.0 m (sand 1) and below 18.0 m (sand 2).

A statistical analysis was performed on the data in order to achieve a better understanding of the properties of soil layers in the area (Reinert et al, 2010). It was concluded that the two clay layers show high variability of CPT and SPT resistance parameters. Because of being a soft clay layer, the resistance parameters values are generally quite small and small fluctuations in their original values can represent large percentual changes. For sand layers, it is interesting to note that the coefficients of variation (COVs) of the CPT parameters (qc and fs) are much smaller than in the clay layers parameters. This aspect is different in the SPT parameter (N_{SPT}), in which the coefficients of variation are not very different to clay and sand layers, but higher than the COV of qc and fs.

2.2 Piles

The piles made for foundations tests are located on the site according to Figure 2. Six piles were studied in this research, with characteristics described in Table 1. It also can be seen in Figure 2 the location of CPT tests performed around the piles.

Table 1. Characteristics of tested piles.

Pile	Type	Diameter	Length	Nearest Tests
PI-1	Concrete driven	50 cm	32,20 m	SPT-154, CPT-155
PI-2	Concrete driven	50 cm	21,40 m	SPT-154, CPT-155
PI-3	Concrete driven	70 cm	35,60 m	SPT-153, CPT-152
PI-4	Concrete driven	70 cm	26,50 m	SPT-151, CPT-152
PI-5	Franki	52 cm	16,00 m	SPT-156, CPT-152
PI-6	Franki	52 cm	27,50 m	SPT-156, CPT-152

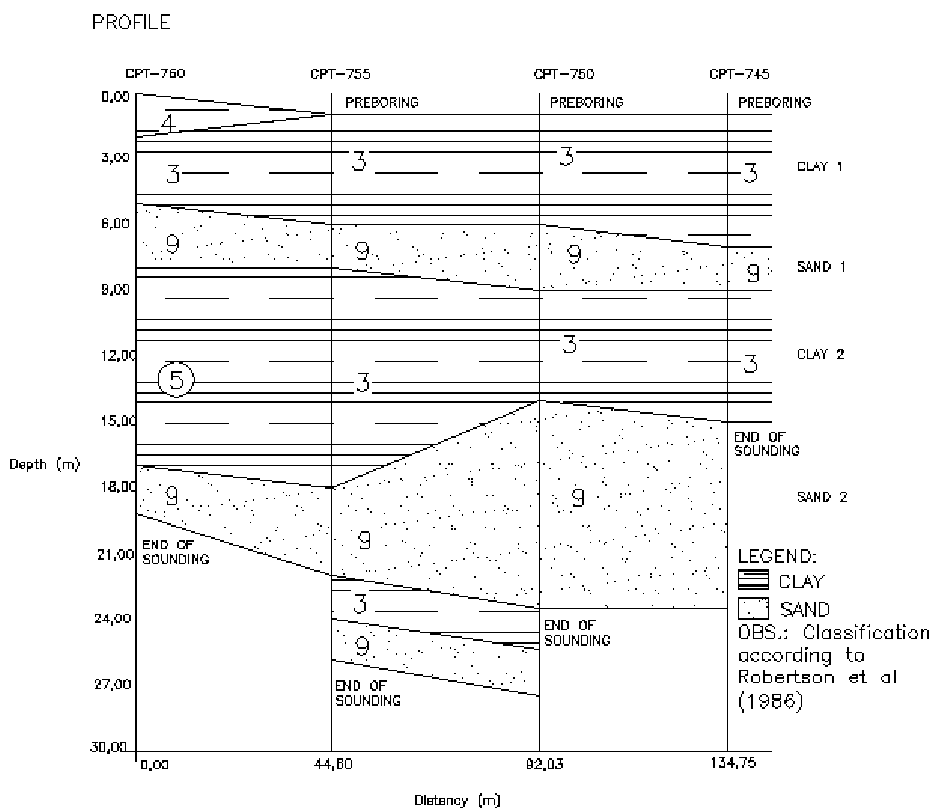

Figure 1. Site profile.

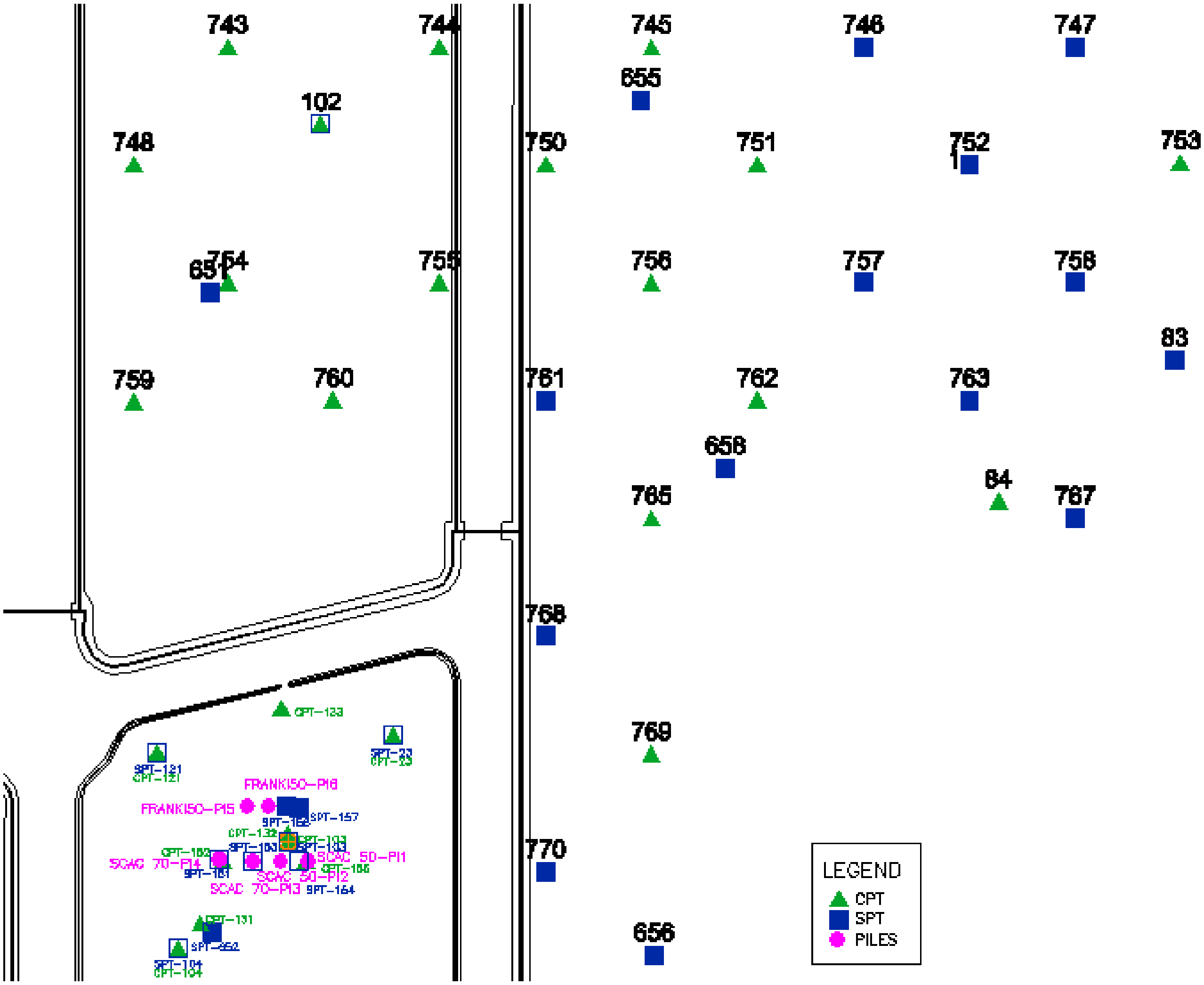

Figure 2. Piles and tests location.

The piles were executed or driven between 25/Oct/2006 and 12/Nov/2006. All of them were tested under compression static vertical load, in order to evaluate the load versus displacement behavior and to estimate the ultimate load capacity.

The tests were conducted using the methodology of rapid cyclic loading, provided by NBR 12131 (ABNT, 2006), in which the loading is done in equal successive stages. The load was maintained at each stage for 5 min. independently of stabilizing displacements, as a customer's request.

Analyzing the load versus displacement curve obtained in static loading tests, it could be noted that the piles PI-2, PI-4 and PI-6 had similar behavior. In the initial loading steps, the strain was basically elastic, having a significant increase in the last applied loads.

The pile PI-1 showed a considerable shift from the first cycle of loading/unloading, reaching the failure. On the other hand, pile PI-3 had a significant shift, with a residual settlement smaller than 5 cm, being a test whose importance should be reduced.

3 LOAD TESTS

3.1 Extrapolation Methods

According to NBR 6122 (ABNT, 2010), the result of a load test may not indicate a clear failure load. When this fact occurs, the Brazilian standard allows the load-settlement curve extrapolating for failure load evaluating by criteria established in Soil Mechanics Fundamentals.

The methods used in this study are based on mathematical shapes by adjusting the load settlement curve to a known curve, that might be hyperbolic (Chin-Kondner, 1970) or an exponential curve (Van der Veen, 1953). These methods, besides defining the failure load, allow the extrapolation of the load settlement curve as a proposed mathematical form.

The method proposed by Van der Veen (1953) is a mathematical representation of the exponential curve load-settlement. In this study, it was used the modification proposed by Aoki (1976), given by equation 1.

$$Q = Q_{ult}.(1 - e^{-(a\rho+b)}) \qquad [1]$$

Where:
Q – Load applied on the pile top;
Qult – Failure load;
ρ – Settlement corresponding to the charge Q;
a and b – curve shape coefficients.

In this method, the load is defined by attempts, through a mathematical equation adjusted as a function to the load-settlement curve. According to Velloso and Lopes (2010), the extrapolation of load-settlement curves by the method of Van der Veen may be considered a suitable procedure if the settlement reached at the maximum test load is at least 1% of the pile diameter. The applicability of the method is restricted to tests that have reached at least 2/3 of the failure load.

According to the method proposed by Chin (1970) for piles, using the work of Kondner, each load value is divided by the amount of each settlement. The resulting value should be plotted as a function of settlement. After an initial variation, the plotted values assume a straight line. The inverse slope of the straight section is the failure load of Chin-Kondner.

Fellenius (2009) warns about the indiscriminate use of Chin-Kondner extrapolation. According to the author, it is much easier to reach a false Chin value if the method is applied too early in the load test.

3.2 Load Capacity Prediction Methods

The Brazilian standard NBR 6122 (2010) defines the allowable load of a single pile as the pile applied force that causes only settlements compatible with the building and simultaneously provides satisfactory safety against both soil and foundation element failure. As the soil is usually the weakest material, the foundation load capacity is controlled by the geotechnical characteristics of the pile surrounding mass.

To estimate the load capacity of the piles, three semi-empirical methods were chosen in this study, based on correlations between pile capacity parts (tip and shaft resistance) and results SPT and CPT tests.

Aoki-Velloso method (1975) was used with CPT and SPT data. The expressions of the pile load capacity are presented in equations 2 and 3, relating the tip resistance and skin friction of the pile with the results of CPT and SPT respectively.

$$Q_{ult} = A_p.\frac{q_c}{F_1} + U.\sum\frac{\alpha.q_c}{F_2}.\Delta l \qquad [2]$$

$$Q_{ult} = A_p.\frac{k.N_{SPT}}{F_1} + U.\sum\frac{\alpha.k.N_m}{F_2}.\Delta l \qquad [3]$$

Where:
Ap – Area of the pile toe;
qc – Cone tip resistance;
U – Pile Perimeter;
α – Coefficient (proposed by Begemann, in 1965) to correlate the cone lateral friction with the toe resistance;
k – Conversion factor from the cone tip resistance to N_{SPT};
Δl – layer depth;
Nm – average N_{SPT} of the layer;
N_{SPT} – N_{SPT} of the pile toe.

The coefficients F_1 and F_2 are correction factors of toe resistance and skin friction which take into account behavior differences between the pile and the static cone. The coefficients k and α are dependent on soil type.

The Décout-Quaresma (1978) method is based exclusively on SPT field test data. In its second version, Décourt and Quaresma (1982) refined the method in order to estimate the lateral load. The final expression proposed by the authors is presented in equation 4.

$$Q_{ult} = \alpha.k.N_p.A_p + U.\beta.\sum 10\left(\frac{.N_m}{3} + 1\right).\Delta l \qquad [4]$$

Where:
Ap – Area of the pile tip;
Np – Average N_{SPT} at the pile toe, 1 m above and 1 m below;
U – Pile Perimeter;
Nm – Average N_{SPT} at the lateral layer;
Δl – Layer depth.

In Nm and Np determination, the N_{SPT} values lower than 3 should be considered equal to 3. The N_{SPT} values greater than 50 should be considered equal to 50. The coefficients α and β are function of the pile type and the soil type. According to Lobo (2005), in 1996, Quaresma et al proposed new values for these coefficients that were used in this work. The coefficient k relates the toe resistance with the value Np as a function of soil type.

The method Bustamante and Gianeselli (1982) was created at the Laboratoire Central dês Ponts et Chaussées in France and is based on CPT tests. The equation 5 is the general expression to determinate the ultimate load.

$$Q_{rup} = k_c.q_{ca}.A_p + \sum\frac{q_{ci}}{\alpha}.A_{si} \qquad [5]$$

Where:
kc – Conversion factor from qc to pile toe resistance;
qca – Cone toe resistance;
Ap – Area of the pile tip;
qci – Average toe resistance for the layer i;
Asi – Lateral area of the pile for the layer i.

The coefficient α depends on the pile type and toe resistance. To calculate the cone toe resistance (qca), the values of qc in the range of (+1.5. d) above and (-1.5. d) below the pile should be used.

4 RESULTS

4.1 Load Tests Extrapolation

The load tests were extrapolated in the case of piles that were not tested until failure (PI-2, PI-3 and PI-5). The PI-1 PI-4 and PI-6 piles were tested to failure. Therefore, to extrapolate these tests were used only loads up to 2/3 of the failure, according to the Van der Veen method.

The error (equation 6) of each method of extrapolation was calculated for the such piles. Table 2 shows the extrapolations results and error values of each method.

$$E = \frac{Failure.load - Method.load}{Failure.load} \quad [6]$$

It can be noted that the Van der Veen method modified by Aoki is the method with the smallest error compared to the failure load measured in static load tests.

In the graphic shown in Figure 3, it can be seen the best closeness of the points of the Van der Veen method modified by Aoki to the zero-error line than Chin-Kondner method.

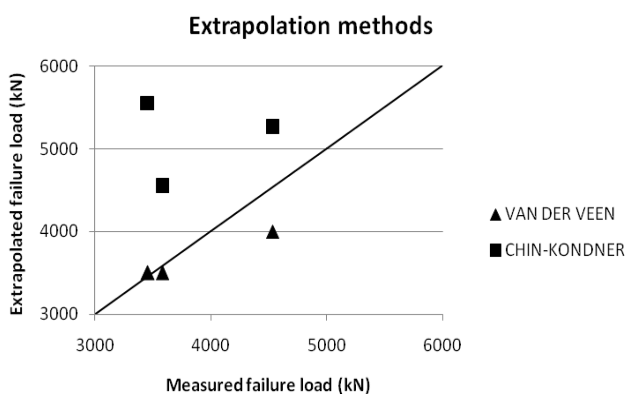

Figure 3. Extrapolated failure load *versus* measured failure load.

Table 2. Results and errors of extrapolations.

Pile	Failure Load	VAN DER VEEN	Error	CHIN-KONDNER	Error	Pile Error
PI-1	3583	3500,00	2,32%	4545,46	26,86%	14,59%
PI-2	-	2250,00	-	2040,82	-	-
PI-3	-	8000,00	-	12500,00	-	-
PI-4	4532	4000,00	11,74%	5263,16	16,13%	13,94%
PI-5	-	2950,00	-	3333,33	-	-
PI-6	3456	3500,00	1,27%	5555,56	60,75%	31,01%
Method Error			5,11%		34,58%	

4.2 Estimated Load Capacity

The load capacity was estimated by using traditional methods based on SPT tests (Aoki-Velloso and Décourt-Quaresma) and CPT tests (Aoki-Velloso and LCPC). The stratigraphic profile adopted to the pile load capacity prediction was determined using the nearest field tests to the piles.

The error of each prediction method was calculated for the piles that reached failure. Table 3 shows the results of load capacities and the estimated error of each prediction method.

It should be noted that the LCPC method showed the lowest error in comparison with the others. The SPT based methods had similar errors, although they were still high.

The error was also calculated in relation to the extrapolated load-displacement curves. It was used the Van der Veen extrapolation method modified by Aoki, because it showed the smallest error in relation to the measured failure loads. This error was inferred because, in most cases, static load test are not loaded until failure and the extrapolation methods are used in large scale. Therefore, it was necessary to calculate the error of methods in relation to the extrapolation method of load tests. These results are presented in Table 4.

Again, the error of LCPC method showed the smallest error, keeping very close to the error based on the measured failure load. It also indicated an error decrease when compared with the extrapolation results, but the value of the errors was still high, above 40%.

The graphic shown in figure 4 shows a better closeness of the LCPC method points to the zero error line compared to the other methods. It can also be noted that the values of the estimated load capacity are mostly above the measured value, which could affect the actual safety factor.

Table 3. Results and errors of prediction methods.

	(kN)	Prediction methods based on SPT				Prediction methods based on CPT			
Pile	Failure load	AOKI-VELLOSO	Error	DÉCOURT-QUARESMA	Error	AOKI-VELLOSO	Error	LCPC	Error
PI-1	3583	4595,44	28,26%	4137,45	15,47%	3063,63	14,50%	3613,078	0,84%
PI-2a	-	3820,07	-	3229,08	-	1539,61	-	2263,152	-
PI-3	-	10462,21	-	8485,58	-	8488,94	-	6542,43	-
PI-4	4532	8771,84	93,55%	7082,59	56,28%	5993,30	32,24%	5420,525	19,61%
PI-7a	-	2818,68	-	3692,78	-	2012,65	-	2023,10	-
PI-8a	3456	4848,48	40,29%	6800,77	96,78%	9595,73	177,65%	5254,83	52,05%
Erro por método		54,03%		56,18%		74,80%		24,16%	

Table 4. Results and errors of prediction methods, compared to the extrapolated results.

	(kN)	Prediction methods based on SPT				Prediction methods based on CPT			
Pile	Van Der Veen	AOKI-VELLOSO	Error	DÉCOURT-QUARESMA	Error	AOKI-VELLOSO	Error	LCPC	Error
PI-1	3500,00	4595,44	31,30%	4137,45	18,21%	3063,63	12,47%	3613,078	3,23%
PI-2a	2250,00	3820,07	69,78%	3229,08	43,51%	1539,61	31,57%	2263,152	0,58%
PI-3	8000,00	10462,21	30,78%	8485,58	6,07%	8488,94	6,11%	6542,43	18,22%
PI-4	4000,00	8771,84	119,30%	7082,59	77,06%	5993,30	49,83%	5420,525	35,51%
PI-7a	2950,00	2818,68	-4,45%	3692,78	25,18%	2012,65	31,77%	2023,10	31,42%
PI-8a	3500,00	4848,48	38,53%	6800,77	94,31%	9595,73	174,16%	5254,83	50,14%
Method error		47,54%		44,06%		50,99%		23,18%	

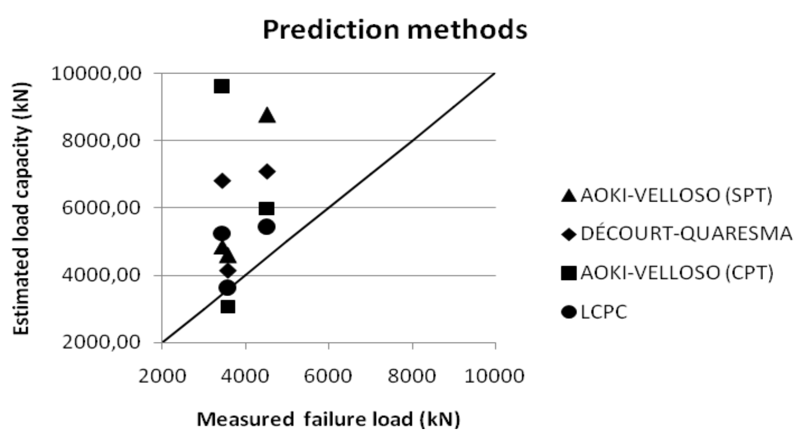

Figure 4. Estimated load capacity x measured failure load.

5 CONCLUSION

This paper aims to contribute with new information about pile behaviour on soft soils. Results of static load tests in an actual industrial plant piles were analyzed using methods widely applied in geotechnical practice.

This investigation is based on the results of static load tests performed on concrete driven and Franki piles. The load capacity of piles was estimated by using traditional methods based on SPT data (Aoki-Velloso and Décourt-Lent) and CPT data (Aoki-Velloso and LCPC). Load tests that were not taken until failure were extrapolated in order to assess the ultimate load.

In the extrapolation of the load tests that reached failure, it could be noted that the Van der Veen method modified by Aoki presented the smallest error in relation to the measured strength.

Referring to the calculation of load capacity of piles, it was observed that the LCPC method presented the lowest error. The SPT based methods had similar errors, although they were still high.

When compared with the extrapolated results, the LCPC method again showed the smallest error, keeping very close to the error based on the measured failure loads. It also indicated a decrease in the error when comparing the load capacity results with the extrapolation, but the value of the errors was still high, above 40%.

It is known that the SPT test can provide limited information on soft soils characteristics. Consequently, the pile capacity methods based on this field test did not present good results. The CPT can give better information about soft soils than SPT. But most of the CPT based pile capacity methodologies use average parameters values and the variability of soil behaviour along the pile length is not considered.

The high prediction errors presented in this work show the importance of carrying out pile load tests for design purpose. In order to estimate pile load capacities improved methodologies should be developed, especially when soft soils are present. Statistical approaches can be useful to improve predictions and provide a better understanding of the influence of subsoil variability in pile load capacity.

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