EXPERIMENTAL AND NUMERICAL ANALYSES OF BORED PILE FOUNDATIONS IN A TROPICAL SOIL

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Abstract
A semi analytical procedure is presented and used herein to compute the settlement and the normal force distribution of axially loaded concrete bored piles. These piles were constructed in the tropical soil of the city of Brasília, which is a typical laterized and collapsible clayey material of the Brazilian Central Plateau. The piles are founded in the experimental research site of the University of Brasília, within its campus. They were constructed under differing construction procedures, which have influenced in their final behavior, in terms of load x settlement curves. The paper demonstrates that with the use of well-established soil parameters for this geotechnical material, with a sound theoretical model & numerical tool, it is possible to simulate reasonably well the in situ behavior of the bored piles.

Key words: Tropical soil, bored pile, deep foundation and numerical analysis

1. Introduction

The Brazilian capital, Brasilia, is a designed city located in the Federal District of Brazil. It was built in the early 60's to house the main Governmental administrative institutions and it has increased its population four times as initially forecasted. This fact has motivated the development, use and research of distinct deep foundation techniques in the several ongoing construction sites of this same city.

Hence, the paper presents experimental results from field loading tests carried out with distinct deep foundations founded in the tropical soil of the University of Brasília research site. Moreover, a numerical analysis was carried out with some of the piles, in order to simulate their in situ behavior with the existing (lab and field) data. Two types of piles were selected for this particular analysis, i.e., a mechanically bored and a "root" type cast-in-place pile.

The numerical analysis was done with a semi analytical procedure, coded in the GEO 4 software, from the FINE Software Company. This software computes the settlement and the distribution of the normal force inside the pile and actual shear resistance at any depth in the pile's shaft. The deformation variant of the solution was selected. The pile-soil interface function is modeled using nonlinear soil springs. Nevertheless, the shear forces are limited to the skin friction of the pile/soil interface. The value of the normal stress in this same interface is a function of the geostatic earth pressure and it can be user modified. Besides, the shear forces strongly depend on the friction behavior of the soil/pile interface, which on the other hand is affected by field construction (displacement, non displacement, etc.) techniques used with the distinct piles.

In this particular case, the known analytical solutions of layered sub soils (see [2,3]) for the shear response of the soil were adopted herein. These solutions are related to the Young modulus and Poisson's ratio of the soil, and the depth of the influence zone around the pile. This zone varies from one to two and half diameters around the pile, being variable during the analysis (it increases with the increase of load on top of the pile).

Thus, the in situ experimental data of the field loading tests were used, together with the lab results from triaxial K0 tests on this same soil type, to numerically assess the behavior of two of the tested piles.

2. Method of analysis

The solution was developed for a layered sub-soil. The pile is discretized into a finite number of cylindrical bar elements, and the soil-pile interface is concentrated in the nodal points. The ultimate shear force in the node is obtained from the formula given below:

$$T_{k,\lim} = 2\pi r_k l_k \tau_{k,\lim} \quad ,$$

where r_k is the radius of the pile in the *k* node,
l_k is the length of the shear influence around the *k* node,
and $\tau_{k,\lim}$ is the ultimate shear strength (skin friction), being proportional to the lateral earth pressure in the soil-pile interface.

The well-established Mohr-Coulomb failure criterion is adopted for the soil. Figure 1 presents an example of this criterion.

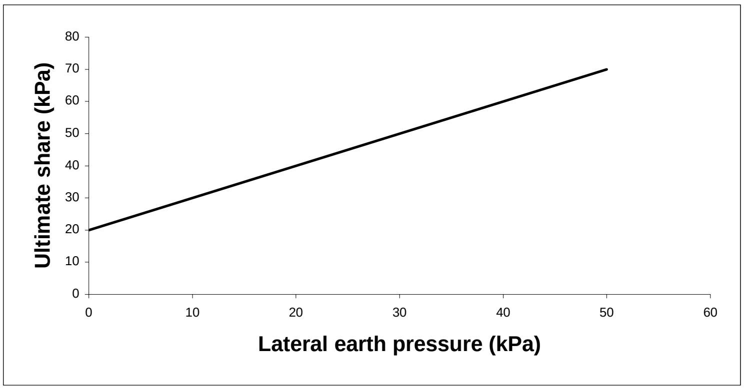

Figure 1: Example of ultimate shear calculation

The influence of the shear zone around the k^{th} pile node is assumed to be represented by a spring [1]. The spring stiffness is calculated from the known analytical formula [2] given below:

$$k_k = 2\pi r_k \sqrt{C_{1k} C_{2k}} \frac{K_1\left(\sqrt{\frac{C_{1k}}{C_{2k}}} r_k\right)}{K_0\left(\sqrt{\frac{C_{1k}}{C_{2k}}} r_k\right)} \quad .$$

where r_k is the current radius of the pile,
C_{1k} , C_{2k} are current Winkler-Pasternak parameters of the soil around the *k* pile node,
and K_0 , K_1 are the modified Bessel functions.

The stiffness of the spring in the base of the pile is given by:

$$k_b = \pi r_b^2 C_{1b} \ ,$$

where r_b is the radius of the pile base, and C_{1b} is Winkler-Pasternak parameter in the pile base region.

Both Winkler-Pasternak parameters depend on the level of load, and, with an increase of this level there is a correspondent increase of the influenced soil region around the pile. The ideas presented above are incorporated in the GEO 4 software product, and are further detailed and explored in [3].

3. Experimental Site and Field Testing

The research site is located in the city of Brasília, the Brazilian capital, which is encompassed by the Federal District of Brazil. Within this district, in the center of this country, it is common the occurrence of extensive areas (more than 80 % of the total area) covered by a weathered laterite of the tertiary-quaternary age.

This "latosol" has been extensively subjected to a leaching process and it presents a variable thickness throughout the District, varying from few centimeters to around 40 meters. It is basically a red residual soil developed in humid, tropical and subtropical regions of good drainage. It is leached of silica and contains concentrations particularly of iron oxides and hydroxides and aluminum hydroxides. It also has a predominance of the clay mineral caulinite and, in localized points of the Federal District, it overlays a saprolitic/residual soil with a strong anisotropic mechanical behavior and high standard penetration resistance, which is originated from a weathered slate, a typical parent rock of the region.

The superficial latosol has a dark reddish coloration, and displays a much lower resistance and a much higher permeability than the bottom saprolitic/residual soil. The studied latosol constitutes into"collapsible" sandy clay with traces of silt, with a high void ratio and coefficient of collapse. Its coefficient of permeability is also high for typical clay, being close to those found for fine to silty sands. This soil is the so-called "porous" clay of Brasília, and is the predominant soil of the experimental research site of the University of Brasília.

In this site several deep foundations were constructed under differing construction techniques, all of them "typical" in the city of Brasília. Herein, solely the mechanically bored and the "root" cast-in-place piles were analysed. For further information on this particular site and the details of the experimental field loading tests in these and other piles, the reader is referred to [4] and [5].

In order to obtain the experimental data it was required the establishment of vertical loading tests on well-instrumented piles founded in this site. This was accomplished with the cooperation of local contractors and the aid of the University of Brasília post-graduate students and staff. All the tests were done in accordance to the recommendations put forward by the Brazilian NBR 12131 standard, and in the majority of the experiments they consisted of slow maintained field loading tests. Besides, the tests were performed in loading intervals of 20 % of the working load (which had an average estimated value of 180 (kN) for all piles), up to failure. The piles were subsequently unloaded in approximate 4 intervals. These load tests adopted a reaction frame and "reaction" piles 4 m apart. Both the top foundation block and the reaction frame were monitored for tilting and vertical displacements, by using 0.01 (mm) precision dial gauges. A 1000 (kN) hydraulic jack was used in conjunction with a 100 (N) precision load cell and the tests were carried out with the soil in its natural moisture content (in the range of 30's %).

The following piles were tested and numerically analyzed:

- One root type (injected, cast-in-place) pile: Also known as "micropile", it was constructed by adopting an injection pressure of 200 kPa during the formation of the mortar shaft, and it is defined herein as R2. This pile was constructed with a specially devised drill rig, which operated hydraulically. The soil was excavated by a continuous and static introduction of a rotating casing with pressurized water. The water "washed out" the generated mud in front of this casing, opening a small annular gap between the casing and the excavated hole. Once drilling was finished, the interior of the casing was cleaned up and the rebars were introduced. Mortar was then poured inside the casing until it was filled. The top of the casing was then connected to an air pressurizing system, and air pressure was applied to the inner fluid mortar. By simultaneously applying air pressure and lifting up the casing, it was possible to form the corrugated pile's shaft (for the piles with injection pressure). This operation was done in sequence, continuously filling up the remaining casing with fluid mortar, thus leading at the end to a pile with an approximate length of 8 m and final average dia. of ≈ 25 cm;

- One mechanically screwed (or bored cast-in-place) pile: Defined as MSP0, it was constructed with concrete being poured just after the soil excavation ("0" means just after excavation). Using a continuous hollow flight auger, which was introduced into the soil by rotation, excavated this pile. The hydraulic mechanical auger was assembled in the back part of a truck specially devised for this type of work. No soil was removed during auger introduction, and, after the final depth was reached, the auger was withdrawn leaving a freshly excavated hole. The designed rebars were then introduced and using the transportable service of a local concrete company promptly poured the concrete. This pile had a length of ≈ 8 m and diameter of ≈ 30 cm.

Figure 2 presents the load-deflection curves obtained for these two pile types.

Figure 2. Vertical load-settlement curves of the studied piles

4. Numerical Analysis and Comparisons

In order to pursue the numerical analyses with the GEO 4 software product, some material characteristics of the (unique) soil layer were adopted herein. However, it shall be pointed out that the "true" soil mechanical and deformation characteristics are variable, since it is a tropical clay subjected to leaching, laterization and weathering process, hence, with variable values along the site. This point is exemplified below by Table 1, modified after [5].

Table 1

Parameter	Unit	Range of Values
Natural unit weight	kNm^{-3}	17-19
Drained friction angle	degrees	26-34
Young's modulus	MPa	1-8
Coefficient of earth pressure in rest		0.44-0.54

Therefore, in order to employ the numerical Pile GEO4 procedure some average values had to be chosen for the soil characteristics. These values are given below:

- drained friction angle 30 degrees;
- cohesion 14 (kPa);
- specific weight 18 (kNm^{-3});
- Young's modulus 8 (MPa);
- coefficient of earth pressure in rest 0.49.

The comparison of results between field and numerical analyses, in terms of the load-settlement curve of the pile MSP0, is given in Figure 3. Figure 4 presents this same comparison, but with the use of a Young modulus of the soil of 16 (Mpa). This latter value is more close to the value proposed by [5] during their backanalyses with this same pile (but by using another software program & theoretical approach).

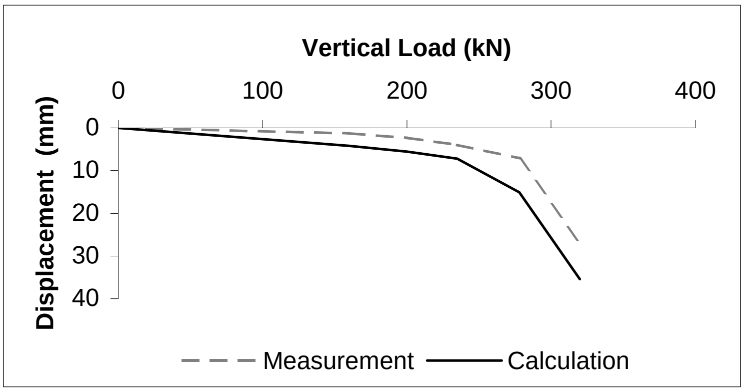

Figure 3. Working diagram of the pile MSP0

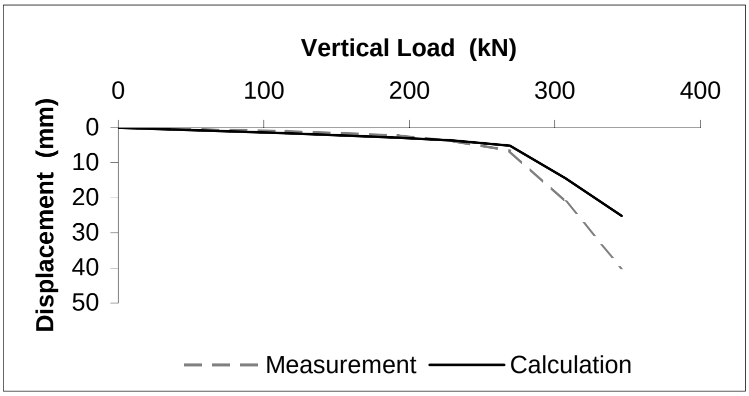

Figure 4. Working diagram of the pile MSP0

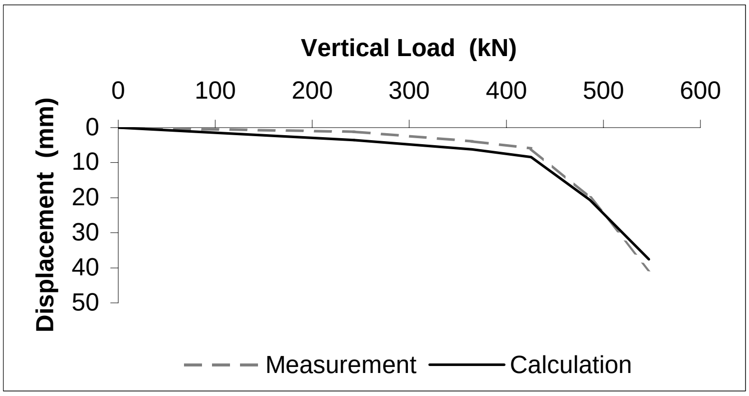

Figure 5. Working diagram of the pile R2

Figure 5 presents the same comparison between experimental and numerical results for pile R2. In this case it was adopted a Young modulus of the soil of 16 (Mpa) and a value of coefficient of earth pressure at rest of 1.0. This latter value is justified by the field construction procedure of this pile, in which the lateral stress is considerably increased during the shaft's formation. A very high value of Young modulus was obtained by [5] in their backanalyses with this same pile, but such a very high value was not necessary herein to obtain a "good" match between numerical and experimental results.

In general terms, it is observed that the numerical procedure (& theoretical model) proposed and adopted herein was able to capture reasonably well the field behavior of the tested piles. This procedure has, therefore, a very high potential for a practical use in the foundation area, in special in the design process of distinct foundation types. The simplicity of the input parameters, and the high accuracy (in geotechnical terms) of the obtained results, corroborates such affirmation.

Conclusions

This paper presented a simple exercise in which a numerical prediction of the field behavior of bored, cast-in-place, piles founded in a tropical collapsible Brazilian clay was carried out. It has briefly presented the general lines of the numerical tool adopted, and it has discussed the results, which were presented in terms of load-deflection curves. The few presented results already demonstrate that the procedure advocated herein has a high potential for usage in practical engineering applications, in special to those related to the design of deep foundations in conventional or "non conventional" (tropical) soils. Nevertheless, more research is still necessary (and is under way) in this area.

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