III European Conference on Computational Mechanics
Solids, Structures and Coupled Problems in Engineering
C.A. Mota Soares et.al. (eds.)
Lisbon, Portugal, 5–8 June 2006

Numerical evaluation of bored piles in tropical soils by means of the geo-technical engineering "GEO4" Fine Software

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Keywords: Back-analysis, Bored Pile, Drilled Shaft, Geo4 (Pile), Mohr-Coulomb failure criterion.

Abstract:
This paper presents backanalysis of field loading tests in bored pile and drilled shaft performed on the tropical soil at the experimental research site of the University of Brasilia. The numerical simulation was carried out using the commercial software GEO4 from FINE Inc. This software computes the load-displacement curve on the pile head and the distribution of normal and shear forces along the shaft. The shear behavior of the pile-soil interface is described according to a modified Mohr-Coulomb's theory. This paper also focuses on the determination of parameters of strength (angle friction and cohesion) and settlement (Young modulus) for deep foundation. The use of GEO4 for foundation design is explained in details herein. Cohesion was verified to be of important effect when calculating the shaft strength. Moreover, few research topics nowadays deal with the determination of this parameter for bored piles. The assessment of geotechnical parameters is a vital component of geotechnical design and some formulations are also presented for this evaluation.

1 INTRODUCTION

Foundation and *in situ* testing are two demanding research topics at the Brazilian capital, Brasilia. This city was pre-designed and built in the early 60's to house the main Governmental administrative institutions and its public employees. Brasilia has increased and is still expanding more than initially forecasted, thus enhancing the need of engineering solutions for the local deep foundation problems. These problems are associated with some particular characteristics of the predominant subsoil of the Federal District, i.e. the Brasilia "porous" clay.

This paper presents experimental results of field loading tests carried out on deep foundations performed on the tropical soil of our experimental field at the University of Brasilia (UnB). Two types of foundations were selected for this particular analysis, namely, a mechanically bored pile and a drilled shaft. Moreover, a numerical analysis is carried out in order to simulate to response obtained on site.

The numerical analysis was done by means of a semi analytical procedure, coded in GEO4 software from FINE Inc. Ltd. This software computes the settlement and distribution of normal forces on the pile and also the actual shear resistance at any depth along the shaft. The values of shear force are limited to that of pile-soil interface skin resistance. The values of normal stress on this interface are a function of the user inputted geostatic earth pressure. Besides that, the shear forces strongly depend on the friction behavior of the soil-pile interface, which on the other hand is affected by field construction techniques (displacement, non displacement, etc).

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

In summary, the laboratory data is used together with *in situ* tests results to numerically assess the response of two piles performed on our research site at the University of Brasilia.

2 METHOD OF ANALYSIS

The methodology was developed for layered subsoil. The pile is discretized into finite number of cylindrical bar elements and the soil-pile interface is concentrated at nodal points. For each pile element we determine the limit value of shear force transmitted by the pile skin. To proceed, we first calculate the geostatic stress at a given depth using the following equation:

$$\sigma_z = \sum \gamma_i h_i \tag{1}$$

where h_i is the thickness and γ_i is the soil bulk modulus on the ith layer.

The ultimate shear force in the kth node $T_{k,\lim}$ is obtained from Equations (2) and (3):

$$\tau_{k,\lim} = c' + K \cdot (\sigma_z \tan \phi') \tag{2}$$

$$T_{k,\lim} = 2\pi\, r_k l_k \tau_{k,\lim} \tag{3}$$

where $\tau_{k,\lim}$ is the ultimate shear strength (skin friction) proportional to the lateral earth pressure on the soil-pile interface; σ_z is the normal stress on the ith layer; c' is the effective cohesion; K is the coefficient of earth pressure; ϕ' is the internal friction angle; r_k is the pile radius at the kth node and l_k is the shear influence length around the kth node.

The shear zone influence around the k[th] node is assumed as a spring [1]. The spring stiffness is calculated from the known analytical formula given in Equation (4) (see [2]).

$$k_k = 2\pi r_k \sqrt{C_{1k} C_{2k}} \frac{K_1\left(\sqrt{\dfrac{C_{1k}}{C_{2k}}} r_k\right)}{K_0\left(\sqrt{\dfrac{C_{1k}}{C_{2k}}} r_k\right)} \tag{4}$$

where r_k is the pile current radius; C_{1k} and C_{2k} are current Winkler-Pasternak parameters around the k[th] node; and K_0 and K_1 are modified Bessel functions.

The spring stiffness at the base of the pile is given by Equation (5):

$$k_b = \pi r_b^2 C_{1b} \tag{5}$$

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

Both Winkler-Pasternak parameters depend on the load level. An increase of that load level corresponds to an increase of the influenced region around the pile. The soil strength is expressed in terms of its deformation and resistant values. The ideas presented above are incorporated into GEO4 and are further detailed and explored in [3].

During a standard analysis of a vertically loaded pile immersed in a layered soil, the following steps are performed:

a) The pile is subdivided into several elements. The number of elements is based on the ratio length to diameter (ℓ/d) of the pile, for which the program derives the solution of the soil shear stiffness surrounding the pile. The length of each element must be at least 2.5 times smaller than the pile diameter. The program nevertheless automatically assumes a minimum ten elements to avoid spurious results. The soil shear stiffness is however still based on a ℓ/d ratio of 2.5;

b) Each element is supported by a spring at the bottom end. The spring stiffness is derived using the parameters C_1, C_2 and modified Bessel's functions (Winkler-Pasternak model). C_1 and C_2 are functions of the Young modulus and Poisson's ratio of the soil. The depth of influence zone that affects the values of C_1 and C_2 is variable and changes with pile deformation (settlement). For zero settlement, the depth of influence zone is set equal to one time the pile diameter, whereas at the onset of geotechnical pile failure, it is set to 2.5 times the pile diameter. The reliability of C_1 and C_2 depends on a good assessment of soil deformation parameters;

c) For each pile element, the program determines the maximum value of shear force transmitted to the shaft via skin friction. This is done by using a modification of Mohr Coulomb failure criterion, as shown on Equation (2). The lateral stress is equal to the geostatic stress times the coefficient of lateral earth pressure K, a user input value dependent on the pile construction methodology;

d) Using both spring stiffness and limit force values (by means of maximum shear force), the program starts to incrementally load the pile head. Forces developed on individual springs of all elements are computed at each increment. These forces are then compared with the maximum shear force (T_{lim}) estimated on the previous step for each element. If the spring force exceeds T_{lim}, then the spring stiffness is reduced so that the force acting on the spring equals T_{lim}. The exceeding force for this particular load increment is redistributed into the remaining springs. Each load increment is iterated until the force developed in every spring is less than T_{lim}. The gradual softening of individual springs leads to a final nonlinear load-displacement curve for the loaded pile if geotechnical failure starts to take place during the simulation, i.e. if pile, soil and loading conditions are such that soil plasticizes. Evidently, at high load levels all springs can no more bear load increase and the pile starts to penetrate into the soil. At that level, support is solely given by the base (heel) spring. It is worthy to mention that there is no restriction with respect to the force magnitude on the base spring as assumed by GEO4. This does not hold true for actual pile foundations cases though;

e) Eventually the program gives the load-displacement curve. By default, that curve is derived for the maximum allowable displacement of 25 mm. The user, however, may change this default value. Apart from that curve, the program also presents the distribution of normal shear forces along the pile at each loading level. The program enables you to visualize the relationship between skin friction and displacement at any pile element as well.

3 GENERAL SITE CHARACTERISTICS

The Federal District has a total area of 5814 km^2 and is limited in the north by the 15°30' parallel and in the south by the 16°03' parallel. In Figure 1, the dot on the small Brazilian map represents the Federal District. The zoomed area in same figure shows Brasilia and the small star corresponds to UnB, where the studied site is located.

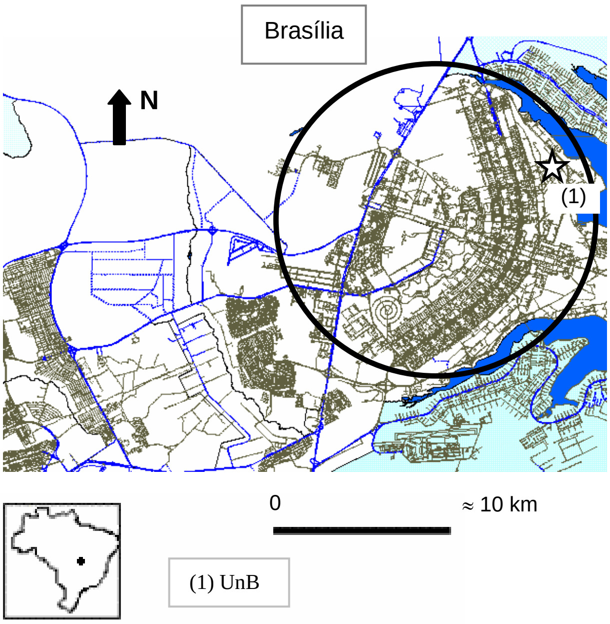

Figure 1. Localization of the area of study.

The site has been extensively studied: (a) pile foundations have been constructed and vertically and horizontally loaded; (b) advanced *in situ* tests, such as cone and dilatometer penetration tests, standard penetration tests with torque measurements have been performed; (c) soil suction has been measured; and (d) conventional triaxial, oedometer, direct shear and standard characterization tests have been carried out. Some of those data can be found elsewhere [4, 5]. Table 1 presents a summary of geotechnical parameters of our site.

More than 80 % of the Federal District is covered by a weathered laterite from tertiary-quaternary age. This soil, called "latosol", has been subjected to an intense leaching process and presents variable thickness, ranging from a few centimeters to around 40 meters. The leaching process basically removes the silica and leaves the oxides and hydroxides of iron and aluminum hydroxides in the soil [6, 7].

Parameter	Unit	Range
Sand percentage	%	12-27
Silt percentage	%	8-36
Clay percentage	%	80-37
Dry unit weight	kN/m^3	10-17
Natural unit weight	kN/m^3	17-19
Moisture content	%	20-34
Degree of saturation	%	50-86
Void ratio	--	1.0-2.0
Liquid limit	%	25-78
Plastic limit	%	20-34
Plasticity index	%	5-44
Drained cohesion[a]	kPa	10-34
Drained Friction angle[a]	degrees	26-34
Young's Modulus[b]	MPa	1-8
Coefficient of Collapse	%	0-12
Coeff. Earth Press (K_0)	--	0.44-0.54
Coeff.Permeability	m/s	10^{-8}-10^{-5}

Table 1 General Geotechnical parameters from UnB.

a- Triaxial CK0D tests-Inundated Soil and at natural moisture content; b- Triaxial CK0D tests: Soil at natural humidity-50% failure deviator stress; c- Triaxial K_0 tests: Soil at natural moisture content.

The superficial latosol has dark reddish coloration and displays much lower strength and higher permeability than the bottom saprolitic-residual soil from slate, as it can observed in many areas of D.F. Figure 2 shows the DMT lift off (p_0) and 1.1 mm membrane expansion (p_1) from the second DMT logging. The DMT logging was performed down to 12 m, close to the top of the saprolitic slate. It followed the standard procedure with tests at 0.2 m interval approximately. Figure 2 also presents average values of N_{SPT} (Standard Penetration Test) for our site.

4 INSTRUMENTATION AND FIELD LOAD TESTS

The slow maintained field loading tests were done in accordance with recommendations put forward by the Brazilian NBR 12131 [8]. Those tests were performed using loading intervals of 40 and 150 kN for the bored pile and the drilled shaft were, respectively.

Both top of foundation block and reaction frame were monitored for tilting and vertical displacements, using six 0.01 mm precision dial gauges. A 1000 and 2000 kN hydraulic jack were used together with a 100 N precision load cell to load the piles till failure condition. The loading tests were carried out with the soil under natural moisture content conditions.

The field load test was performed on a mechanically bored, cast-in-place pile, with 0.3 m in diameter and 8 m in length. This pile was excavated using a continuous hollow flight auger, which was introduced into the soil by rotation. The hydraulic mechanical auger was assembled on the back part of a truck especially devised for this type of work. The soil was removed during continuous auger introduction and withdrawn. After reaching the required depth, the auger was withdrawn leaving a freshly excavated hole, which was subsequently filled with concrete. The drilled shaft has 0.7 m shaft diameter, 1.65 m bell diameter and 8 m length. Figure 3 (a, b) shows the results from the load tests performed on these foundations.

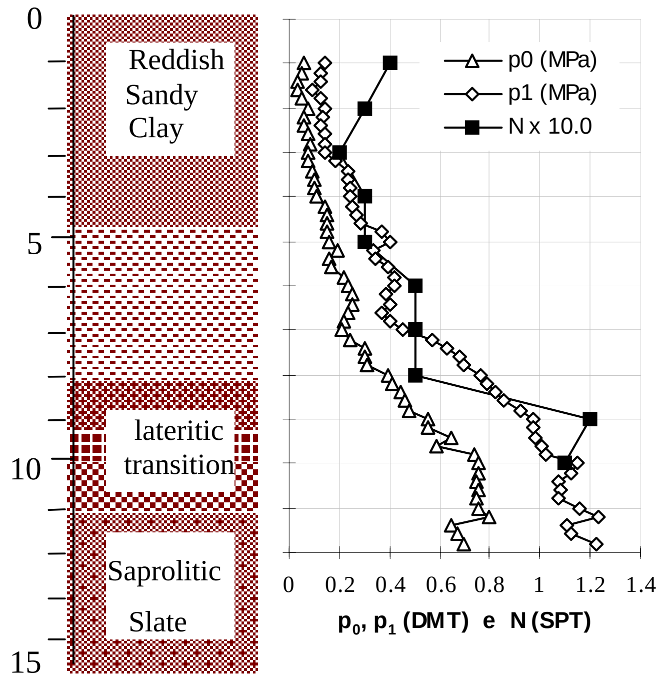

Figure 2. DMT and SPT results for the site [3].

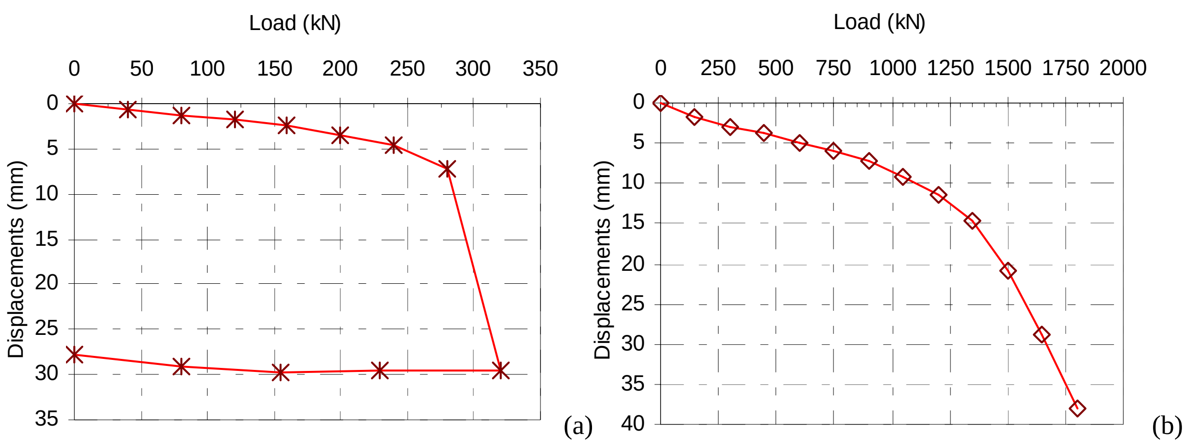

Figure 3. Results of load tests in (a) Bored Pile and (b) Drilled Shaft at UnB site.

5 NUMERICAL SOFTWARE

The numerical backanalysis of the pile behavior was carried out using the commercial software GEO4 from FINE Inc. Ltd., headquarters in Prague, Czech Republic. Although simple to use, this software has a high potential for application in practical civil engineering projects, not only for pile foundation design but also for retaining walls, shallow foundations, embankments, pavements, diaphragm walls, slope stability. There are personalized modules for each aforementioned technical area.

The whole GEO4 software package was donated to the Geotechnical Post-Graduation Program at the University of Brasilia to be evaluated and tested, as well as to be used in our geotechnical researches. The module *Pile* can derive the full load-displacement curve of a vertically loaded pile, as well as its load transfer mechanism (structural load along pile depth for each test load level). The horizontal behavior of the pile can also be simulated on this module. Unfortunately this latter characteristic was not tested herein due to difficulties involved with lateral load tests.

The module *Pile* can be used to determine the vertical bearing capacity of a pile from the load-displacement curve. A database of parameters, such as internal friction angle, cohesion, bulk weight and Young modulus, for various types of soil and rock is also available in this module. As a result, the program gives the load-displacement curve till a pre-specified limit deflection or failure. The pile vertical bearing capacity is related to this limit deflection.

6 RESULTS AND DISCUSSION

A comparison between backanalyzed geotechnical parameters and experimental data in terms of load transfer curves and numerical predictions of average skin friction and pressure at the bottom of the pile will be presented and discussed as follows.

6.1 Geotechnical Parameters

The backanalysis consisted of selecting by trial and error input geotechnical parameters for the GEO4 module *Pile*. The software derived the load-displacement curves of the pile that later were compared with those obtained from experiment (Figures 4 and 5).

In order to obtain those curves some criteria were put in mind:

a) Be reasonably representative of the geological nature of soil deposits herein studied, i.e. be in the range of known values gathered from other sources, such as laboratory, *in situ* testing, or backanalyzed parameters obtained from other programs [11];

b) Be considered as approximate values, or “estimated guess” of real values, due to simplifications built in the numerical and experimental analyses;

c) Take the deposit natural spatial variability into consideration, in special with respect to ground level differences and geology between the sites;

d) Take the deposit natural special variability into consideration, given its tropical and residual origin. This latter aspect has already been exemplified for our site, via dilatometer test results [12].

Table 2 presents the backanalyzed geotechnical parameters for the three testing sites. Although more research is required, those parameters can already be used to carry out simulation of piles performed on similar deposits to those herein studied. It is worthy to mention that a parametric and simulation analysis was already presented in [13].

It is important to mention that similar load-displacement curves can be obtained by slight different combinations of geotechnical parameters input. Indeed, it has been demonstrated using the software PLAXIS that, before pursuing the back-analysis, the magnitude order of parameter, such as cohesion and friction angle, must be known *a priori* [16]. This order of magnitude can be obtained from several sources, namely, *in situ* and laboratory tests, or regional experience. In our case, the friction angle has low seasonal variation and, from our experience, it ranges from 27º to 30º. Cohesion, on the other hand, has great variability, in particular due to changes of matric suction. In this paper, it is obtained according to the formulation presented in [15]. The value of K was set around that of K_0. The Young modulus was left to vary above the one shown in Table 1. This latter assumption is based on a backanalysis carried out in [18].

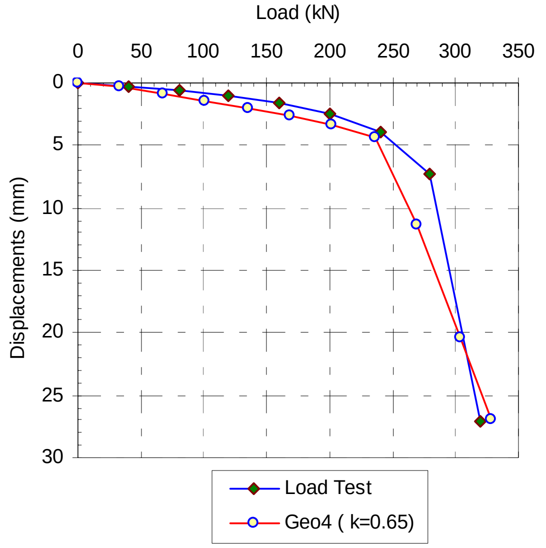

Figure 4. Load-displacement curve for the bored pile.

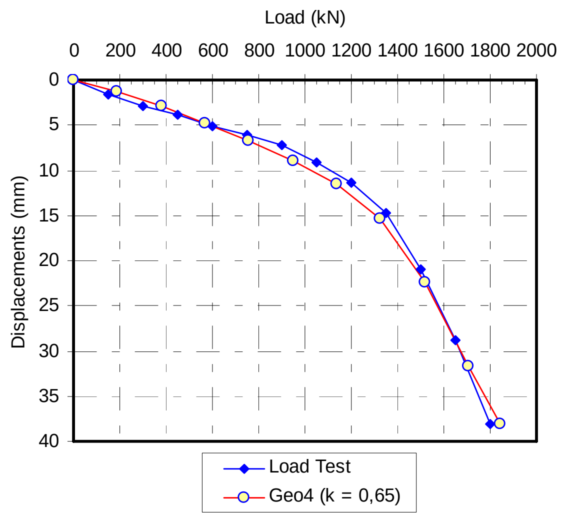

Figure 5. Load-displacement curve for the drilled shaft.

Depth (m)	ϕ (º)	c' (kPa)	γ_t (kN/m³)	ν	E (MPa)	Observations
0 a 2	36.6	4	13.5	0.29	23	$\gamma_{concrete}$ = 24 kN/m³ E_p = 16 GPa ρ = 27 mm $E = 18.6 + 1.7q_c^*$ (q_c^*→ MPa →E MPa) k = 0.65
2 a 6	29.8	10	14.4	0.33	20	
6 a 8	31.4	9	15.0	0.32	22	
8 a 9 (Base)	33.1	7	18.0	0.31	23	
9 a 12	33.2	7	17.8	0.31	24	
12 a15	37.1	3	18.5	0.28	35	

Table 2 Backanalyzed geotechnical parameters from UnB via GEO4.

ϕ→ [14]; c'→ [15]; γ_t→ [16]; ν→ [17]
q_{c*} is a average value of point resistance in CPT Test for each layer
E is a empirical formulation derived by local experience.

Site investigation and field load testing are fundamental to safely design deep foundations, and, whenever possible, they should be included in the budgetary analysis of any foundation work. As presented in [13], once the field load-displacement curve of a pile can be forecasted, we believe that GEO4 is also able to simulate other piles in the same site but under distinct geometric conditions. Of course, more research is required to fully prove that.

Pile construction method is another issue driving differences on backanalysis parameters, for instance, for the same geology, distinct values of Young moduli and coefficients of earth pressure are obtained. Actually, the latter is believed to be the most affected by construction method. Different boring techniques certainly influence the surrounding excavated soil; however, such influence is difficult to be distinguished from that caused by geology variability. Although construction technique influence is readily recognized, its quantification was not possible in this work due to lack of more data.

7 CONCLUSION

This paper emphasized the application of a numerical methodology to derive backanalyzed geotechnical parameters, useful for design of projects in the civil engineering foundation field. After being calibrated, this methodology can be further used in parametric analysis of other different pile geometries performed on the site of study, therefore, optimizing the foundation design.

The mathematical model was based on a well-established solution coded on the software GEO4. Simulations of instrumented field loaded, large scale, bored foundations have validated the versatility and potential of this program for practical use. This also holds when analyzing non classical case histories as those ones herein considered, i.e. foundations performed on tropical and stratified soils of the Federal District, Brazil.

From the previous discussion, the following conclusions are addressed:

1. For the same pile construction technique and numerical methodology, the values presented on Table 2 are reasonable description of average magnitude values to be used in practical applications and parametric analyses for sites under similar conditions. However, a more refined analysis might be desirable to lessen differences;
2. The software has proven to well represent the response of vertically piles performed on tropical stratified deposits of the Federal District. Some dispersion on the results may be accounted for distinct geological, topographical and pile construction conditions;
3. An initial calibration of the software using large-scale field load testing results is suggested before using the software on a real design. This pre-backanalysis will account for the geology and pile construction method used on site;

It is finally pointed out that, due to reduced number of foundations and limited spatial size of the area of study, it is evident that more investigation is necessary. Nevertheless, the methodology for data interpretation, the gained experience and the presented results can be seen of practical interest for those involved with foundation design in Brasilia and elsewhere in Brazil.

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