Numerical evaluation of deep foundations in a tropical soil of Brazil

Simulation numérique des fondations profundes dês sols tropicaus au Bresil

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ABSTRACT: This paper focuses on the numerical simulation of deep foundations via existing industrial application software. It presents experimental results from field loading tests carried out with distinct deep foundations founded in the tropical residual soil of the city of Brasília. The commercially available Geo4 software was successfully adopted in the analyses, and it is concluded that this software has a large potential for future applications in the whole South American continent.

1 INTRODUCTION

The Brazilian capital, Brasília, is a pre-designed city located within the "Federal District", in the center of Brazil. It was built in the early 60's to house the main Governmental administrative institutions and its public employees. It has increased (and it is still expanding) four times more than what was initially forecasted, enabling the practical use of distinct techniques for deep foundation execution and design within the several construction sites. Hence, in 1995 the University of Brasília started a major research project in the foundation area, in order to enhance the knowledge on the behavior of the distinct foundation types that are founded in the predominant subsoil of the Federal District. It was decided to carry out horizontal and vertical field loading tests on distinct locally used deep foundation types. These foundations had real (full scale) dimensions and were placed within the University of Brasília campus, at the experimental site of the Geotechnical Post-Graduation Program. The geotechnical profile of this campus is composed by the typical unsaturated and tropical clay of Brasília. Field loading tests on real scale foundations outside the campus have also been carried out. In all cases, the tests counted with the cooperation of local engineering companies.

A large effort was also undertaken to evaluate the design techniques currently adopted to devise the foundations of the Federal District. New techniques, as well as more advanced ones (numerical approaches) have also been evaluated and still are under scrutiny by researchers from the Foundation Group of the University of Brasília. In order to accomplish this goal, several software programs have been acquired and tested against field loading test results from real scale foundations tested to failure (or close to). Some of these foundations were fully instrumented, as those presented herein, enabling the knowledge of the load transfer distribution along depth and throughout loading level (till geotechnical failure). Therefore, the main objective of this paper is to present the summary of some of the findings of the aforementioned research project of the Post-Graduation Program of the University of Brasília, in particular related to a new software program devised to forecast the load-displacement and load transfer curves of vertically loaded piles founded on stratified materials of two distinct sites.

The numerical backanalysis of the behavior of the piles at both studied sites was carried out with the industrial software denominated GEO4 from the commercial company FINE Ltd.

2 GENERAL CHARACTERISTICS AND LOCATION OF THE SITES

Figure 1 presents, in detail, the two studied sites of this paper, respectively denominated as 212N building site and UnB (University of Brasília) experimental research site. Both are located close together within the "North Wing" of the Brasília city. This city, the Brazilian capital, was designed with an "airplane" shape like form and it is located in the Federal District of Brazil, at its Central Plateau. The University Campus is located between the "North Wing" and the Paranoá Lake, as displayed in this figure.

The first site, 212N, is related to a building site where a residential block of apartments (6 floors) are to be built. In this particular site 401 continuous flight auger piles with distinct diameters and lengths have already been constructed. In order to gather more design information, the engineering contractor has agreed to carry out a vertical field loading test in one of the piles, as well as to fully instrument it with strain gauges at distinct depth levels. Details of these experiments are given in Cunha et al. (2002), and briefly presented herein.

The second site, UnB, is related to the experimental research site of the Post-Graduation Program of the University of Brasília. This site has already been extensively studied and presented in literature (Cunha et al. 1999, Cunha et al. 2001). Distinct deep foundations were constructed and vertically and horizontally field loaded in this site, together with the deployment of advanced in situ tests (cone and dilatometer penetration tests, standard penetration tests with torque measurements and others) plus soil suction measurements. Block samples were also retrieved from this site and taken to the laboratory for triaxial, oedometer, direct shear, and standard characterization tests. Details of the laboratory results are presented by Cunha et al. (1999) and others.

Within the Federal District 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. This soil 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.

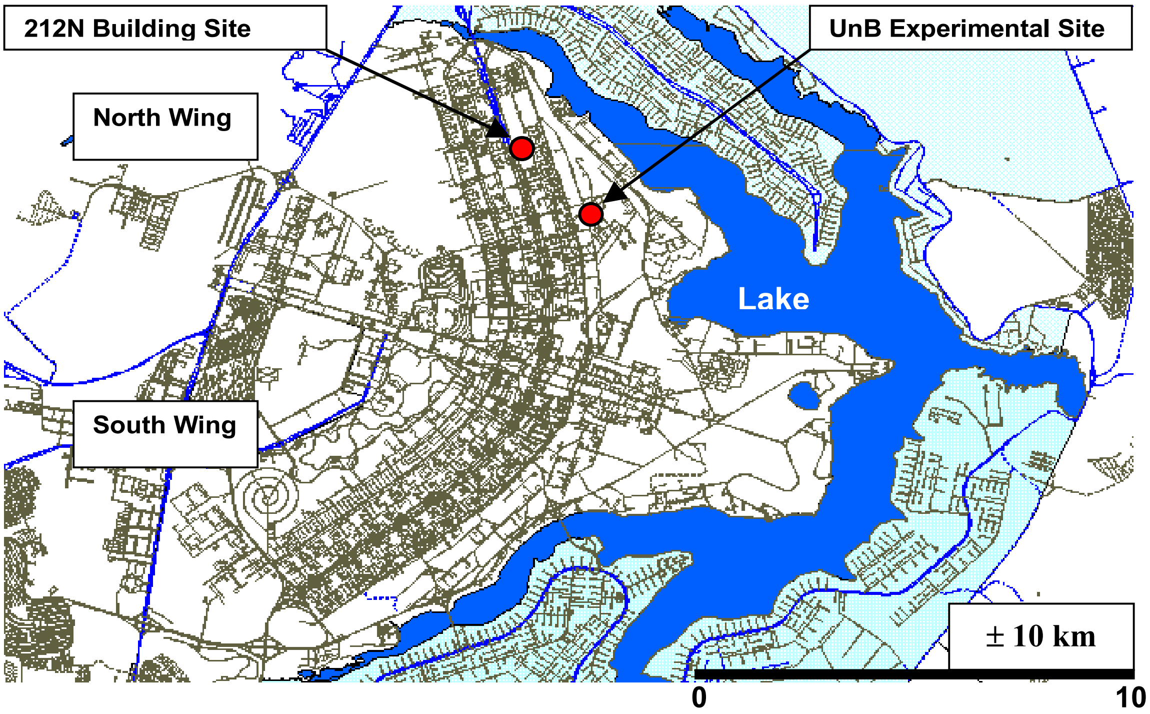

Figure 1. Detailed location of the field testing sites within the city of Brasília

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 (N_{SPT} blow counts), which is originated from a weathered, folded and foliate 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 from slate. Some variability, however, exist between the sites (2 km approximately apart). This variability is reflected on the field N_{SPT} results and it will be also reflected in the input parameters of the numerical backanalysis. This superficial soil is the so-called “porous” clay of Brasília, which major geotechnical parameters have already been presented elsewhere (Cunha et al. 1999 and 2001).

Another aspect to be related herein is that the ground level at 212N site, similar to the pile head level of this same site, is not the same level as the ground level of the UnB research site (level 0). In the 212N engineering site, the soil has been excavated by 4 m for the construction of the subsoil floor level of the building, which, on the other hand, was placed on top of an old embankment fill located in this same area (with thickness of 4 m). Besides, in the UnB research site no water level (NA) was found. These differences will certainly reflect on the input parameters of the numerical backanalyses and also reflect man-made influence on the original behavior of soil deposits.

3 FIELD LOADING TESTS AND INSTRUMENTATION

All the vertical field loading tests were done in accordance to the recommendations put forward by the Brazilian NBR 12131 (1996) standard, and they consisted of slow maintained tests. These tests were performed in loading intervals of approximately 20 % of the working load (which had an average estimated value of 600 and 135 kN, respectively for the piles at the 212N and UnB sites). This loading sequence was increased up to the geotechnical failure of these piles. They were subsequently unloaded in approximate 5 intervals.

The load tests adopted a reaction frame and “reaction” piles some meters apart. Both the top foundation block and the reaction frame were monitored for tilting and vertical displacements, by using (six) 0.01 mm precision dial gauges. A 1000 and a 2000 kN hydraulic jack were used (one for each site) in conjunction with a 100 N precision load cell to take the piles till failure condition. The loading tests at both sites were only carried out with the soil at its natural moisture content conditions, with the characteristics described below:

A) UnB site: The field load test was carried out in July 2000 (dry season). It was tested a mechanically bored, cast-in-place pile, with 0.3 m in diameter and 8 m in length, herein defined as UnB pile. This pile was excavated by using a continuous hollow flight auger, which was introduced into the soil by rotation. The hydraulic mechanical auger was assembled in the back part of a truck specially devised for this type of work. The soil was successively removed during continuous auger introduction and withdrawn, and, after the final depth was reached, the auger was withdrawn leaving a freshly excavated hole. This hole was subsequently filled with concrete poured by using the transportable service of a local concrete company. The pile was loaded till its geotechnical failure, estimated in 270 kN by the Van der Veen (1953) method, being noted a displacement of 9.4 mm at such high load level. The instrumentation followed the procedures put forward by Cintra and Toshiaki (1988), where it is found the step-by-step sequence to work with strain gauges in foundations. The strain gauges of the type KFG-1-120-C11-11, with tolerance resistance of 120Ω, were adopted. They were installed in a full “Wheatstone Bridge” configuration, in order to reduce temperature effects during the load test. They were connected to a 16 mm diameter smooth surface bar, which was positioned centrally to the foundation’s transversal cross section. The strain gauges were placed at distinct positions along the pile, allowing the knowledge of the load transfer mechanism during the load test, at different (head) load levels. Figure 2(a) presents the full load-displacement curve of this test. It was noticed that, at failure stage, less than 5% of the applied load at the pile’s head was transmitted to the base of this pile;

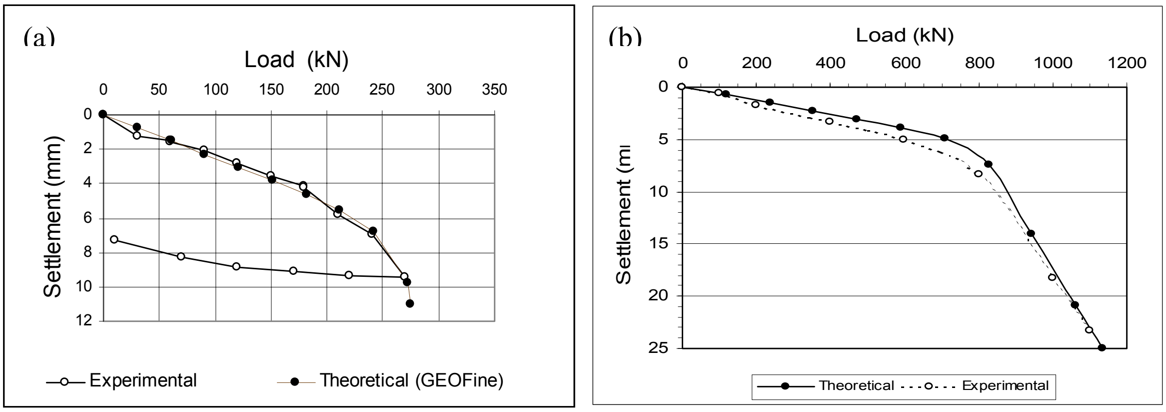

Figure 2 (a). Load-displacement curve obtained for the UnB pile (modified after Mota 2002) and 2 (b). Load-displacement curve obtained for the 212N pile (modified after Cunha et al. 2002).

B) 212N site: The field load test was carried out around July/August 2001 (dry season). It was tested a continuous flight auger (CFA), cast-in-place pile, with 0.4 m in diameter and 18.5 m in length, herein defined as 212N pile. This pile was excavated by using a continuous flight auger equipment (so far the single equipment in the Federal District for this category of pile), which was introduced into the soil by rotation. The hydraulic and computer controlled auger was assembled in the front 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 with simultaneous soil removal and pump of concrete, leaving a finished CFA pile once the auger was totally withdrawn to surface. The pile was loaded till its geotechnical failure, estimated in 1200 kN by the Van der Veen (1953) method, but the reaction system failed when the load was at 1100 kN level. At this level it was noted a displacement of 23 mm, and the load-displacement curve was already in its plastic stage, indicating imminence of failure. The instrumentation also followed the procedures put forward by Cintra and Toshiaki (1988), with the use of strain gauges of the type KFG-1-120-C11-11 with tolerance resistance of 120Ω. They were installed in a ¼ "Wheatstone Bridge" configuration, since the test was carried out at night – hence, with low influence from temperature effects. They were also connected to a 16 mm diameter smooth surface bar, which was positioned centrally to the foundation's transversal cross section. The strain gauges were placed at distinct positions along the pile, allowing the knowledge of the load transfer mechanism during the load test, at different (head) load levels. Figure 2(b) presents the full load-displacement curve of this test. It was noticed that, at failure (1100 kN) stage, 25% of the applied load at the pile's head was transmitted to the base of this pile.

4 GEO4 NUMERICAL SOFTWARE

The numerical backanalysis of the behavior of the piles was carried out with the software denominated GEO4, which simulates the pile behavior, once few input data is given.

In Brazil, in particular, it is one of the first times that this (foundation) module from the whole GEO4 software package is tested with real case civil engineering works. The whole GEO4 software package was kindly donated by FINE Ltd. to the Geotechnical Post-Graduation Program of the University of Brasília with the objective of evaluation and testing, as well as usage in geotechnical research. In regard to this latter aspect, some of the modules of this software are already under scrutiny by M.Sc. and Ph.D. researchers of this same Post-Graduation Program (Mota 2000 and Soares 2001), with successful results so far.

The foundation module is capable of deriving the full load-displacement curve of a vertically loaded pile, as well as the load transfer mechanism of the pile (structural load along pile's depth, for each test load level). The horizontal behavior of the pile can also be simulated in this same module.

Unfortunately this latter characteristic of the software was not tested herein, given field difficulties involved with a lateral load test. This module is based on a semi-analytical solution. This solution is related to the Young modulus and Poisson's ratio of the soil (Winker-Pasternak solution, see Bittnar and Sejnoha 1996, Kuklík and Masopust 2000), as well as the depth of the influence zone. After discretization of the pile on one-dimensional bar elements, the influence zone evolves around each of the nodes. The pile-soil interface is modeled in nodes using nonlinear soil springs. In case of a semi-infinite body surrounded by soil the response is given by the known Mindlin's solution. The shear behavior of pile-soil interface is described using the elastic-plastic material model with the Mohr-Coulomb yield condition. The unknown cinematically admissible displacement follows from the equilibrium condition in the vertical direction. More details of the program and other modules can be found in the GEO4 User´s manual, or alternatively in the FINE Company homepage (www.fine.cz).

5 RESULTS, DISCUSSION AND CONCLUSION

The experimental field loading test results have already been presented in Figures 2(a) and (b). In the case of the load transfer mechanism, measured during the loading test, no results will be provided and discussed herein, given space limitations. This aspect will be further explored in another paper.

The backanalysis consisted of selecting, by trial and error, input geotechnical parameters for the foundation GEO4 module, thus allowing this software to derive, with "reasonable" precision, the load-displacement curve of the pile (in relation to experimental results from both sites). The predicted curve is well compared to the experimental results, as can be seen in Figures 2(a) and (b).

The parameters required to predict the load-displacement numerical curve were also selected with other criteria in mind:

1) To be reasonably representative of the geological nature of the Brasília natural soil deposits – which means to be in the range of known values from other sources, as laboratory or in situ testing results, or backanalyzed parameters from other programs (as those presented by Cunha et al. 2001);

2) To be considered as approximate values, or "estimated guess" of the real values, given all simplifications built in the numerical and experimental analyses;

3) To take into consideration the natural spatial variability of the deposit, in special related to ground level differences between both sites, and given their tropical and residual origin.

Hence, Table 1 presents the assessment of the backanalyzed geotechnical parameters from both testing sites. It shall be mentioned that more research effort still has to be put on this analysis (and they are under way by Mota 2000). Nonetheless, from a practical point of view, they already serve to execute simulation analyses to evaluate the foundation behavior under distinct combinations of diameters and lengths, for the same site – as exemplified by Cunha et al. (2002). They also serve to draw preliminary conclusions from comparative analyses, as done herein.

Table 2. Backanalyzed geotechnical parameters from both sites via GEO4 software.

Sublayer Type	Depth (m)	Geotechnical Parameter ϕ' (deg)	c´ (kPa)	E (MPa)	γ (kN/m^3)	ν
UnB Site:						
Clay I	0-3	27	13	5	16.5	0.3
Clay II	3-8	27	14	13	16.5	0.3
Clay III	8-12	27	52	19	16.5	0.3
Rock	> 12 (Not Deformable)					
212N Site:						
Embankment	0-4	25	0	25	16.5	0.3
Clay A	4-8	27	15	20	16.5	0.3
Clay B	8-15	27	5	40	16.5	0.3
Clay C	15-25	27	5	100	16.5	0.3
Rock	> 25 (Not Deformable)					

ϕ' = Effective Friction Angle; c´ = Effective Cohesion; E = Young Modulus; γ = Apparent Unit Weight; ν = Poisson Coefficien; K = 0.6 (UnB Site) and 0.4 (212N Site); Pile Parameters: E = 20000 MPa, γ = 25 kN/m^3

The difference of results obtained from both sites is somehow related, as explained before, to the spatial variability of the soil deposit, ground level differences, pile construction method differences (mechanical bored pile against continuous flight auger pile), and user considerations (the UnB site backanalysis was carried out by Mota 2000 in a preliminary basis, and accepted herein without any modifications). Nevertheless, both analyses present geotechnical values that are within the range of obtained parameters for the Brasília porous clay deposit, and within the range obtained via numerical backanalyses in this same material. Some observations, however, are required to further clarify this aspect to the reader.

The effective cohesion values obtained for 212N site are much lower than those from UnB site (and lower than the experimental range for this particular soil from direct shear tests). This is given by the fact that a ground water level has been found in the former site, hence considerably reducing the matric suction of the soil material. The cohesion values from the UnB site are, therefore, related to unsaturated soil conditions, found all year round in this particular site.

The Young moduli from 212N site are higher than those from UnB site. Indeed, part of the differences is related to ground level differences from both sites. For instance, Clays I to III from UnB site are mostly related to Clay A (plus a small part of Clay B) from 212N site, if one consider that the only difference between both sites is the topographic level. Under such aspect, the moduli differences are not high, since the highest E values from the 212N site are related to depths well beyond 12/15 m (where the average NSPT blow counts linearly increases above 20) – depths and NSPT resistances that are not found in the UnB site. The differences also indicate that a further refinement of the 212N pile backanalysis would be required.

With herein exercise, it is preliminary concluded that the obtained values from Table 1 are a reasonable representation of the correct magnitude of the values to be used in design in the same sites, when adopting the same pile construction technique and numerical methodology. It is also concluded that a refinement of the values, and more research, would still be necessary to reduce the differences among geotechnical values from soils with the same geological origin but located at distinct sites. Besides, man-made effects have also somehow contributed for the observed differences.

It shall be finally noticed that aforementioned exercise was carried out under the auspices of the University of Brasília with the collaborative work of the Czech Technical University, the FINE Software Company, and local civil engineering contractors. It has validated the high versatility and potential that this particular program has for usage in practical applications, in particular, for the difficult (non classical) case histories considered herein, which consisted of foundations founded on the tropical, unsaturated and collapsible clay of the Brazilian capital Brasília.

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