Mecánica Computacional Vol. XXI, pp. 1045–1062
S. R. Idelsohn, V. E. Sonzogni and A. Cardona (Eds.)
Santa Fe–Paraná, Argentina, October 2002

EVALUATION OF DEEP FOUNDATIONS IN TROPICAL RESIDUAL SOIL BY A SEMI ANALYTICAL MATHEMATICAL PROCEDURE CODED IN INDUSTRIAL SOFTWARE

R. P. Cunha[*], P. Kuklík[†] and J. Laurin[††]

[*]Geotechnical Post Graduation Program
Department of Civil and Environmental Engineering, University of Brasília
Brasilia, DF, 70910-900, Brasil
e-mail: rpcunha@unb.br, web page: http://www.unb.br/ft/enc/geotecnia

[†]Czech Technical University in Prague
Faculty of Civil Engineering, Department of Structural Mechanics
Thákurova 7, 166 29 Prague 6, Czech Republic
e-mail: kuklikpa@fsv.cvut.cz

[††]FINE Professional Civil Engineering Software Company Ltd.
Na Vlèovce 4, 160 00 Prague 6, Czech Republic
e-mail: hotline@fine.cz, web page: http://www.fine.cz

Key words: Numerical Analysis, Industrial Software, Civil Engineering Application & Design.

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 (and collapsible) soil of the city of Brasília, Brazil. The experimental curves of pile load versus displacement, and load transfer along the pile's shaft are presented, discussed, and numerically simulated by a semi-analytical procedure. This procedure is coded in the industrial software denominated GEO4, from the FINE Professional Civil Engineering Software Company. This software computes the load-displacement curve of the pile's head, plus the distribution of normal and shear forces along the pile's shaft. Although simple to use, the software has a large potential for usage in design. It is concluded that this commercially available industrial software has successfully aided the analysis, demonstrating its large potential for future application 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 soil materials.

In summary, the paper presents experimental results from a field loading test carried out with one deep foundation founded in the tropical residual (and collapsible) soil of the University of Brasília research site. It also presents the experimental results of a fully instrumented pile from an engineering site within the Brazilian Federal District. The experimental curves of pile load versus displacement, and load transfer along the pile’s shaft (this latter curve only for the pile located in the engineering site), are presented, discussed and compared to numerical predictions from a semi-analytical procedure. This procedure is coded in the industrial software denominated GEO4, from the FINE Professional Civil Engineering Software Company (details in www.fine.cz). This software simulates the pile behavior, once few (geotechnical and structural) input data is given. In Brazil, in particular, it is one of the first times that this technology is employed and tested within a rational research basis.

2 GENERAL CHARACTERISTICS OF THE STUDIED SITES

2.1 Location of the sites

The experimental research site of the Geotechnical Post-Graduation Program of the University of Brasília is located within the city of Brasília. 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, as displayed in Figure 1. This figure also shows the research site (star) that is located in the vast area of the University Campus, between the "North Wing" and the Paranoá Lake.

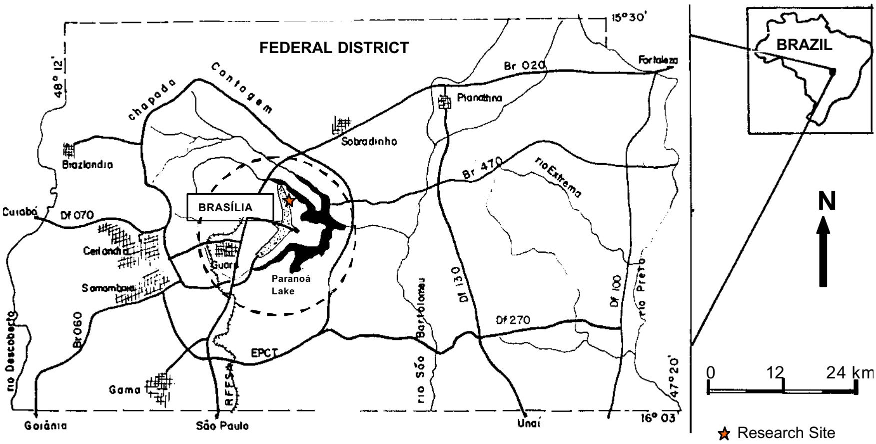

Figure 1. Location Map of the Federal District and the Brazilian Capital Brasília.

Figure 2 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.

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)[1], 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[2], Cunha et al. 2001[3]). 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) and soil suction measurements. Block samples have already been retrieved from this site and taken to the laboratory for triaxial, oedometer, direct shear, and standard characterization tests. Details of the laboratory results will also be briefly presented herein.

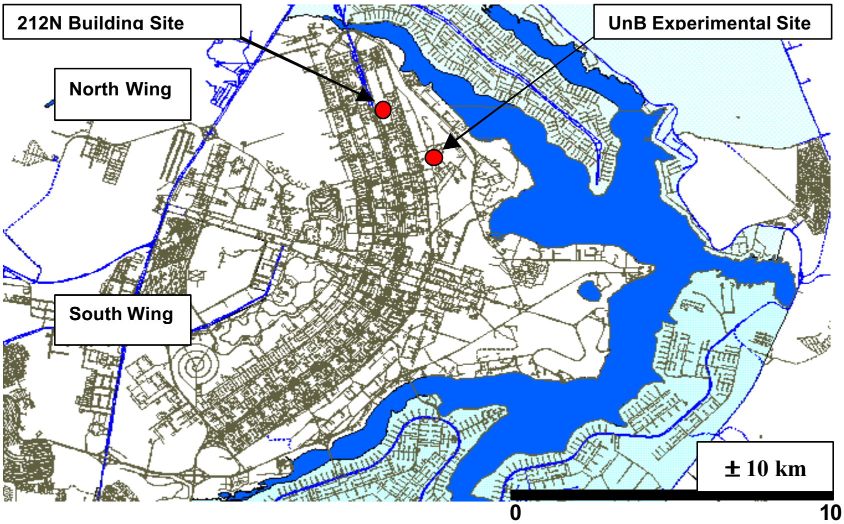

Figure 2. Detailed Location of the Field Testing Sites.

2.2 Geological and geotechnical characteristics of the sites

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. 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 (US Bureau of Mines 1996[4]). 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 (Cunha and Camapum de Carvalho 1997[5]).

The surficial 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, as we can observe in both Figures 3 and 4 by the N_{SPT} readings (respectively for UnB and 212 N sites). Figure 3 also displays the Marchetti dilatometer P0 and P1 pressure readings.

These figures also serve to show the variability of the geotechnical profile from one site to the other (2 km approximately apart). As demonstred by these figures, this variability is reflected on the field N_{SPT} results. It will be also reflected in the input geotechnical parameters of the numerical backanalysis – to be discussed later herein.

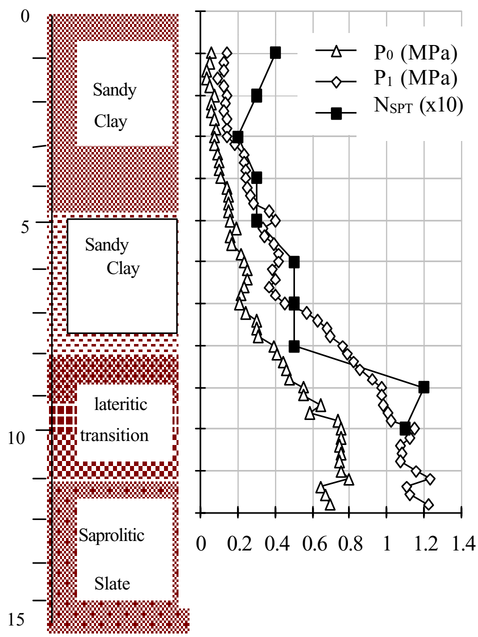

Figure 3. Geotechnical Profile of the UnB Research Site

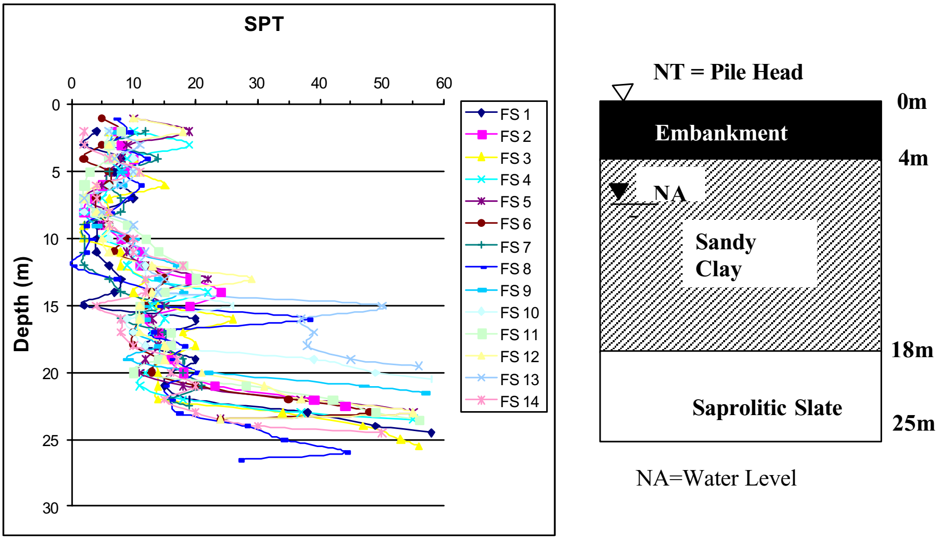

Figure 4. Geotechnical Profile of the 212N Building Site

Hence, the studied latosol at both sites constitute 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 clays, being close to those found for fine to silty sands. This soil is the so-called “porous” clay of Brasília, which major geotechnical parameters are displayed in Table 1, presented next.

These parameters were obtained by a comprehensive laboratory testing program carried out with undisturbed block samples taken from an inspection well dug at the UnB research site. The given range represents the natural variability of this deposit, where distinct rates of leaching and weathering took place along the depth. It is herein assumed that the soil of the other site, 212N, geologically from the same origin, has similar range of geotechnical parameters as those presented in Table 1. Some variability, however, exists.

The ground level at 212N, similar to the pile head level of this same site (denominated as NT in Figure 4), is not the same level as the ground level of the UnB research site (level 0 in Figure 3). 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 NA was found. These differences will certainly reflect on the input geotechnical parameters of the numerical backanalyses.

Table 1. Approximate Geotechnical Parameters of the Brasília Porous Clay (Cunha et al. 1999[2])

Parameter	Unit	Range of Values
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 pressure at rest[c]	--	0.44-0.54
Coefficient of permeability	cm/s	10^{-6}-10^{-3}
Vertical coefficient of consolidation	m^2/s	10^{-8}-10^{-5}

OBSERVATIONS:

a- Range from triaxial CK0D tests with the soil at both natural moisture and saturated conditions;

b- Range from triaxial CK0D tests: soil at natural moisture content, and 50% of failure deviator stress;

c- Range from triaxial K0 tests with the soil at natural moisture content conditions.

3 FIELD LOADING TESTS AND INSTRUMENTATION

It was required the establishment of vertical loading tests on well instrumented piles in order to fully obtain the necessary data for the present paper. All the field loading tests were done in accordance to the recommendations put forward by the Brazilian NBR 12131 (1996)[6] standard, and they consisted of slow maintained tests.

The loading 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, as schematically displayed in Figure 5. 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.

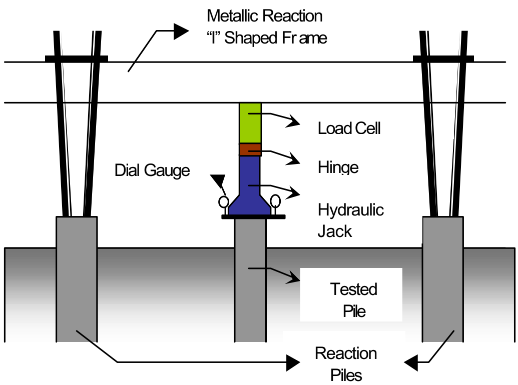

Figure 5. Schematic Drawing of the Vertical Field Load Testing System

The loading tests at both sites were only carried out with the soil at its natural moisture content conditions, with the characteristics described below:

- 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)[7] 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)[8], 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 6 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;

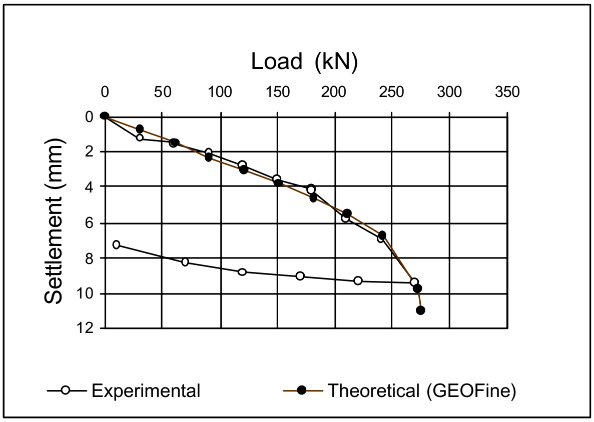

Figure 6. Load-Displacement Curve Obtained for the UnB Pile (Modified after Mota 2002[9])

- 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 unique 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)[7] 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)[8], 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 7 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.

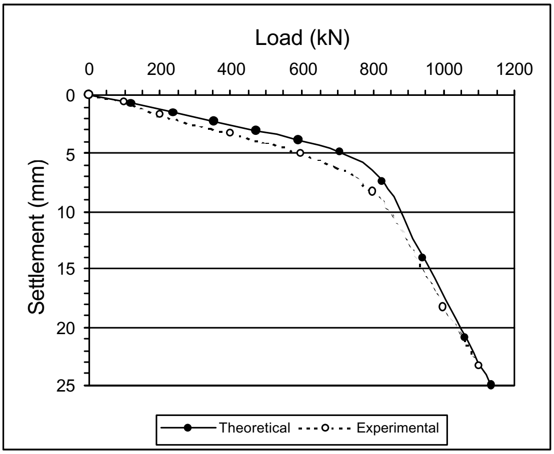

Figure 7. Load-Displacement Curve Obtained for the 212N Pile (modified after Cunha et al. 2002[1])

4 NUMERICAL INDUSTRIAL SOFTWARE

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 Professional Civil Engineering Software Company Ltd., with headquarters in Prague/Czech Republc.

Although simple to use, this software has a high potential for usage in practical civil engineering applications – not only in the pile foundation area, but also in many others as retaining walls, shallow foundations, embankments, pavements, diaphragm walls, slope stability and so on (given distinct personalized modules for each of aforementioned technical areas). It is worthy to mention that the GEO4 software is solely oriented to the geotechnical area, but the user may find, from this same company, other softwares oriented to the structural (civil engineering) area.

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 has been donated 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[9], Soares 2002[10], Magalhães 2002[11]), 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 Bittar and Sejnoha, 1996[12]), 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 each theoretical aspect of this module are given next.

4.1 Vertical bearing capacity

This module of the program also serves to determine the vertical bearing capacity of a pile – simply by derivation of the limit of the load-displacement curve. The main advantage of the program is the accessibility of soil and rock parameters, respectively. The program requires the knowledge of the angle of internal friction, cohesion, bulk weight and the Young modulus of the soil & rock. As a result, the module provides the load-displacement curve till a pre-specified limit deflection (or failure according to some standards). The pile's vertical bearing capacity is related to this limit deflection.

4.2 Theoretical grounds

The pile is modeled using standard beam elements, while the behavior of surrounding soil, in terms of load distribution, is described by a known fundamental solution of a layered soil structure. In case of a semi-infinite body the solution is known as Mindlin's solution. The solution is improved by incorporating the structural strength of soil in a similar way as used for modeling settlement of spread footings. The influence of underground water is incorporated using the Archimedes law. The shear behavior of pile-soil interface is described using the elastic-plastic material model with the Mohr-Coulomb yield condition. The normal stress is found from the geostatic stress and the stress of soil (concrete mixture) at rest. The unknown cinematically admissible displacement follows from the equilibrium condition in the vertical direction. The material nonlinearity is reflected by using the variable secant modules for the soil "springs".

4.3 Solution procedure

The following steps are followed during a standard analysis of a vertically loaded pile immersed in a layered elasto-plastic soil material:

1) The pile structure is modeled as a member composed of several elements. The number of elements is then determined from the length to pile diameter ratio, for which the program derives the solution of the shear stiffness of the soil surrounding the pile. The element length should be about 2.5 times larger then the pile diameter. Nevertheless, the program automatically assumes at least ten elements to avoid spurious results. The shear stiffness of the soil is, however, still based on the l/d ratio of 2.5;

2) Each element is supported at its bottom end by a spring. The spring stiffness is derived by employing parameters of elastic subsoil C1, C2 and modified Bessel's functions (Winkler-Pasternak model). Values of C1 and C2 are determined from the Young modulus and Poisson´s coefficient of the soil. The depth of the influence zone, which affects the values of C1 and C2, is variable and changes with pile deformation (settlement). For zero deformation it is set equal to one time the pile diameter, whereas at the onset of geotechnical pile failure the influence zone is set to 2.5 times the pile diameter. It shall be mentioned that the reliability of the values C1 and C2 depends on a good assessment of the soil deformation parameters;

3) For each pile element the program determines the maximum value of shear force transmitted to the shaft via skin friction. This is done with the use of the traditional Mohr Coulomb failure criteria, plus the lateral stress at each pile element. This stress is found via geostatic stress distribution multiplied by a coefficient of lateral earth pressure K (user input – since is dependable on the pile's construction methodology);

4) With the knowledge of both spring stiffness and limit force value (via maximum shear force) the program starts to incrementally load the pile, with the given force(s) applied at the pile's head. Forces developed in individual springs of all elements are computed at each increment. These forces are then compared with the maximum shear force (Tlim) estimated in the previous step, for each of the pile elements. If the spring force exceeds Tlim, then the stiffness of this spring is reduced in such a way that, for a given deformation, the spring force equals Tlim. The exceeding force for this particular load increment is then redistributed into the remaining springs. Each load increment is iterated until the force developed in every spring is less than Tlim. The gradual softening of the individual springs leads to a final nonlinear load-displacement curve for the loaded pile, if geotechnical failure starts to take place during this numerical simulation (i.e. if the pile, soil and loading conditions are such that allow soil plastification during the simulation). Evidently, at a certain (high) load level all springs will lose capability of increasing its force, and the pile will start to penetrate into the soil with support solely given by the base (heel) spring. It is also worthy to mention that in mathematical terms there is no restriction on the magnitude of force to be developed in the base spring (as assumed by GEO4), although this will not hold true for real (physical) cases of deep foundations;

5) The program then provides the load-displacement curve of a vertically loaded pile. By default,

it is derived for the maximum allowable displacement of 25 mm. The user, however, can change this default value. Apart from this curve, the program presents the distribution of normal shear forces along the pile, at each loading level. The program also enables the visualization of the relationship between skin friction and displacement at any pile element.

More details of the program and other modules can be found in the GEO4 User´s manual, or alternatively (for some aspects) in the FINE Company homepage.

5 RESULTS AND DISCUSSION

The experimental field loading test results have already been presented in both Figures 6 and 7. In the case of the load transfer mechanism, measured during the loading test, only the result from the 212N site will be presented, as the result from the UnB site is still under assessment by another researcher (Mota 2002[9]). Hence, Figure 8 presents the load transfer results (in tf) for the 212N site.

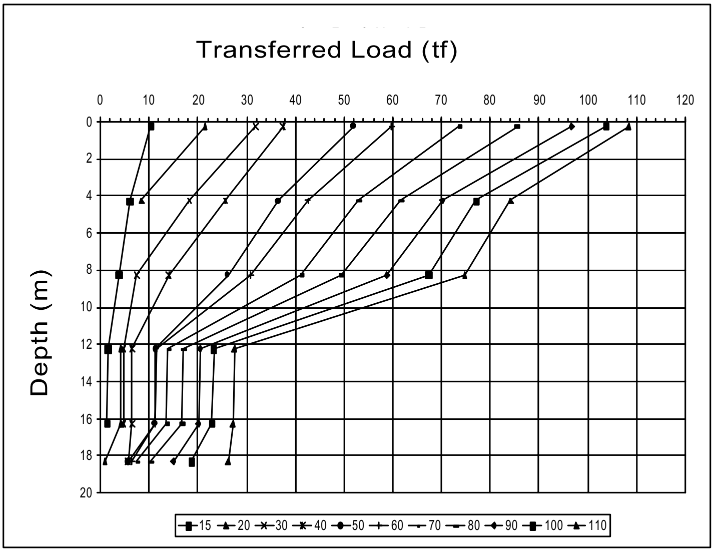

Figure 8. Load Transfer Curve Obtained for the 212N Pile (modified after Cunha et al. 2002[1])

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 6 and 7.

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[3]);

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 (zero) ground le vel differences between both sites (as discussed before);

4) To take into consideration the natural variability of the deposit, given its tropical and residual origin. This latter aspect has already been exemplified, via dilatometer test results, for the UnB site (see Mota et al. 2000[13]).

Hence, Table 2 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 2002[9]). Nonetheless, from a practical point of view, they already serve to execute simulation analyses (evaluating the foundation behavior under distinct combinations of diameters and lengths, for the same site) – as exemplified by Cunha et al. (2002)[1].

Table 2. Backanalyzed Geotechnical Parameters from Both Sites via GEO4 Software

Sublayer Type	Depth	Geotechnical Parameter				
	(m)	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)					

OBSERVATIONS:
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);
Structural 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 2002[9], 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 (see Table 1 and Cunha et al. 2001[3]). 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 range expressed in Table 1). 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 UnB 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 N_{SPT} blow counts linearly increases above 20) – depths and N_{SPT} 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.

The necessity of a further refinement is also evident when comparing the load transfer curves of this same site. For instance, Figure 9 presents the numerical results obtained with the parameters of Table 2 for the load transfer curves of 212N pile. It is observed, based on the results of this figure and the experimental values, that, for the failure condition (1100 kN), 37% of the applied load at the pile's head was transmitted to the base of this pile (numerical prediction). This value is higher than the value that has been experimentally measured at this same loading stage (as presented before, equal to 25%). Besides, for the working condition (550 kN), the software has estimated that 6% of the applied load at the pile's head would be transmitted to the base of this pile. This value, in this case, is lower than the value that was experimentally measured at this same loading stage (as presented by Cunha et al. 2002[1], equal to 12%). Nevertheless, the comparison, at failure condition, of the average unit skin friction between numerical (32 kPa) and experimental (38 kPa) values was reasonably good. For comparison purposes, the average experimental unit skin friction of the UnB pile, also at failure condition, was 36 kPa.

Therefore, it can be concluded that the obtained values from Table 2 are a reasonable representation of the correct magnitude of the values to be used in design (practical applications / parametric analyses) 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. In summary, in terms of a research point of view, the results could be accepted as initial, first guesses, of the real values. In practical terms, however, they would suffice for the design and further parametric simulations.

It shall be finally pointed out, for comparison purposes, that the backanalysis exercise which was done for both piles, at the sites presented herein, took less than one day´s work (8 hours) using a standard Pentium III computer. This time also includes the parametric analyses (as presented in Cunha et al. 2002[1]) accomplished for 212N pile.

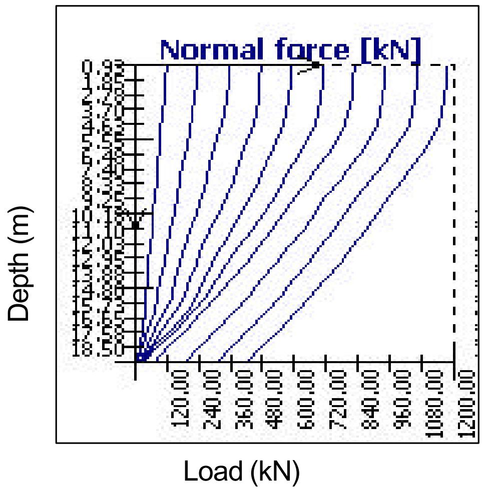

Figure 9. Numerical Load Transfer Curve Obtained for the 212N Pile (modified after Cunha et al. 2002[1])

6 CONCLUSIONS

This paper emphasized the use of a numerical methodology to derive backanalyzed geotechnical parameters that are useful for design applications in the civil engineering foundation area. The mathematical procedure is based on a well-established semi-analytical solution coded on an industrial software program, which can be readily available in practice.

The utilization of this software to successfully simulate two field loaded to failure, and fully instrumented, large scale bored foundations, has validated the high versatility and potential that this particular program has for usage in practical applications. This also holds, 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 city of Brasília.

The aforementioned numerical exercise and experimental research was carried out under the auspices of the Foundation Group (M.Sc., Ph.D., Professors and Technicians) of the Geotechnical Post-Graduation Program of the University of Brasília. This enterprise was conducted with the collaborative work of the Czech Technical University in Prague, the FINE Professional Civil Engineering Software Company, and local civil engineering contractors.

It shall be finally pointed out that, given the reduced number of foundations and the limited spatial size of the studied area, it is evident that more studies are still necessary. Nevertheless, the preliminary results presented herein can already be seen of practical interest for those involved with foundation design in Brazil and somewhere else in South America.

7 ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the engineering contractors Embre, Sonda, WRJ and Consórcio Base for all field support, and to the Governmental sponsorship organizations CAPES and CNPq for the numerous scholarships provided to the Geotechnical Post-Graduation Program. This paper was also possible due to the hard work of some of the Professors and Students of this particular Program, in special Prof. J.H.F. Pereira, Prof. J.H. Camapum de Carvalho, and students Neusa Mota, Moura Soares, Yuri Mestnik, Renato Guimarães and Edimarques Magalhães.

8 REFERENCES

[1] Cunha, R.P., Soares, J.M., Pereira, J.H.F. and Silva, C.M. Numerical analyses of a field loading test in deep foundation founded in tropical soil of the Federal District of Brazil. To be published in *Argentinean National Congress of Soil Mechanics – Geotecnia 2002*, Trelew, Argentina, (2002). (In Portuguese).

[2] Cunha, R.P., Jardim, N.A. and Pereira, J.H.F. In situ characterization of a tropical porous clay via dilatometer tests. *Geo-Congress 99 on Behavorial Characteristics of Residual Soils*, ASCE Geotechnical Special Publication 92, Charlotte, USA, 113-122, (1999).

[3] Cunha, R.P., Pereira, J.H.F., Soares, J.M., Mota, N.M.B. and Poulos, H.G. Backanalyses of field loading tests on deep foundations in a tropical clay. *XV International Conference on Soil Mechanics and Geotechnical Engineering – XV ICSMGE*, Istanbul, Turkey, Vol. 2,.869-872, (2001).

[4] US Bureau of Mines. *Dictionary of mining, mineral, and related terms.* Second Edition, U.S. Department of the interior, (1996).

[5] Cunha, RP and Camapum de Carvalho, J. Analysis of the behavior of a drilled pier foundation in a weathered, foliated and folded slate. *XIV International Conference on soil Mechanics and Geotechnical Engineering – XV ICSMGE*, Hamburg, 785-786, (1997).

[6] NBR 12131. *Piles - static loading test*. Brazilian Association of Technical Norms, (1996). (In Portuguese).

[7] Van Der Veen, C. The Bearing Capacity of a Pile. *III International Conference on soil Mechanics and Foundation Engineering – III ICSMFE*, Zurich, Switzerland, Vol. 2, (1953).

[8] Cintra, J.C.A. and Toshiaki, T. *Instrumentation of model piles with "strain gauges".*

Publication 049/88. University of São Paulo – São Carlos, Geotechnical Department, (1988). (In Portuguese).

[9] Mota, N.M.B. *Evaluation of design methodologies and the behavior of deep foundations founded in collapsible soils via in situ tests.* On Going Ph.D. Thesis. Geotechnical Post-Graduation Program, Civil and Environmental Engineering Department, University of Brasília, (2002).

[10] Soares, J.M. *Evaluation of soil-structure interaction and design.* On Going Ph.D. Thesis. Geotechnical Post-Graduation Program, Civil and Environmental Engineering Department, University of Brasília, (2002).

[11] Magalhães, E.P. *Experimental and numerical study of the behavior of anchored diaphragm walls composed of closed spaced bored piles and located in the Federal District*. On Going M.Sc. Thesis. Geotechnical Post-Graduation Program, Civil and Environmental Engineering Department, University of Brasília, (2002).

[12] Bittar, Z and Sejnoha, J. *Numerical methods in structural mechanics*. ASCE Press, Thomas Telford, New York, 422 p., (1996).

[13] Mota, N.M.B., Cunha, R.P. and Cortopassi, R.S. Influence of the stratigraphy and penetration system on the results of dilatometer tests carried out in the porous Brasília clay. *IV International Symposium on Structures, Geotechnics and Construction Materials*, Santa Clara, Cuba, 80-87, (2000). (In Portuguese).