Backanalyses of field loading tests on deep foundations in a tropical clay

Analyse régressive des essais de chargement au chantier en fondation profunde sûr des argiles tropicales

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ABSTRACT: This paper presents the back-analyses of field loading tests carried out with distinct deep foundations founded in a tropical, collapsible clay existing in the University of Brasília research site, in Brasília, Brazil. These foundations were constructed under differing construction procedures, as follows: Seven mechanically bored, one manually augered, and three "Strauss" type, cast-in-place concrete piles; One precast driven concrete pile and three "Root" type cast-in-place piles. The vertical failure load of each of the piles, and the Young modulus of the soil around them, was computed and cross compared using the field load-displacement curves. These curves were derived from vertical loading tests in which the soil was tested under natural moisture content conditions. The paper concludes on items that are of practical interest for those who design deep foundations in tropical "non-classical" soils.

RÉSUMÉ: Ce papier présente le dos analyse de champ qui charge des épreuves porté dehors avec fondations profondes distinctes fondées dans une argile tropique, pliante qui existe dans l'Université de Brasília emplacement de la recherche, dans Brasilia, Brésil. Ces fondations ont été exécutées sous étant différent procédures de la construction, comme suit: Sept ont percé mécaniquement, un manuellement augered, et trois " Strauss " écrivent à la machine, dépouillez-vous des tas concrets dans - place; Un precast le tas du béton commandé et trois " type de la Racine " se sont dépouillés des tas dans - place. La charge de l'échec verticale de chacun des tas, et le Jeune modulus du sol autour d'eux, a été calculé et la croix a comparé utiliser les courbes du déplacement de la charge du champ. Ces courbes ont été dérivées d'épreuves du chargement verticales dans que le sol a été testé sous conditions de la tente de l'escroquerie de l'humidité naturelles. Le papier conclut sur articles qui sont d'intérêt pratique pour ceux qui conçoivent des fondations profondes dans les sols non - classiques " tropiques ".

1 INTRODUCTION

The Brazilian capital, Brasilia, is a designed city located in the Federal District in the Central Region of Brazil. It was built in the early 60's to house the main Governmental administrative institutions. It has increased its population four times as compared to the one initially forecasted. This fact has motivated the practice of distinct techniques for both deep and shallow foundation designs in the several construction sites.

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 which were 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. A large effort was also undertaken to characterize this experimental site, by using in situ testing techniques such as the Dilatometer, Pressuremeter and Penetration tests. A laboratory program aiming to characterize the genesis and mechanical behavior of the soil has also been conducted. Laboratory testing included soil characterization, consolidation, potential of collapse, K0 and CK0D triaxial tests.

Therefore, the objective of this paper is to present a summary of some of the findings of the aforementioned research project, in which the effect of the construction method (or foundation type) on the (failure) load capacity of each foundation type, and on the Young modulus of the soil was evaluated. It shall be pointed out that this project was undertaken in association with local engineering contractors, and by employing several MSc and DSc students of this same Program. Since then, a plentitude of information has been acquired and published in terms of theses (Perez 1997, Jardim 1998) and papers (Cunha & Perez 1998, Cunha et al. 1999, etc.), enabling a better knowledge in this technical field.

2 GENERAL SITE CHARACTERISTICS

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.

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. 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 a "collapsible" sandy clay with traces of silt, with a high void ratio and coefficient of collapse. Its coefficient of permeability is also high for a typical clay, 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.

These parameters were obtained by a comprehensive laboratory testing program carried out with undisturbed block samples taken from an inspection well dug at the research site. The given range represents the natural variability of this deposit, where distinct rates of leaching and weathering took place along the depth.

Table 1. Geotechnical parameters of Brasília porous clay

Parameter	Unit	Range of Values
Sand percentage	%	12-27
Silt percentage	%	8-36
Clay percentage	%	80-37
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
Drained cohesion	KPa	10-34
Drained friction angle*	degrees	26-34
Young's modulus**	MPa	1-8
Coefficient of collapse	%	0-12
Coefficient of earth pressure rest***	--	0.44-0.54
Coefficient of permeability	Cm/s	10^{-6}-10^{-3}

*From triaxial CK0D tests: soil at both natural and saturated conditions;
**From triaxial CK0D tests: soil at natural moisture content, and 50% of failure deviator stress;
***From triaxial K0 tests: soil at natural moisture content conditions.

3 FIELD LOADING TESTS

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 tests were done in accordance to the recommendations put forward by the Brazilian NBR 12131 standard, and they consisted of (slow and quick) maintained tests.

The loading 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. The tests were carried out with the soil in its natural moisture content, with the piles listed below.

Four mechanically screwed (or bored cast-in-place) piles: Defined as MSP0, MSP3, MSP7 and MSP15. They were constructed with concrete at different days after the soil excavation (0, 3, 7 and 15 days, according to above nomenclature, where "0" means just after excavation). A fifth pile denominated MSP0(A) was also constructed and field loaded. It was casted just after excavation, but it was composed by a concrete mixed with an special expander additive. All the mechanically screwed (bored – MSP) piles were 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. 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, in the MSP0 and MSP0(A) piles, the concrete was promptly poured by using the transportable service of a local concrete company. The MSP piles had a length of ≈ 8 m and diameter of ≈ 30 cm, and were loaded by slow maintained tests.

One manually augered (or bored cast-in-place) pile: Defined as MAP0, and casted in place just after soil excavation in a similar way as previously described for the MSP0 pile. In the former case, however, the excavation was done with a shell type auger that was manually introduced (hand augered) in the field by adopting successive 1 m steel rods. The MAP0 pile had a final approximate length of 8 m and diameter of 28 cm. Same loading as before.

Three Strauss (Brazilian denomination) type piles: Defined as SWCND, SCD and SCND, they were also bored cast-in-place piles. The Strauss pile is a locally used deep foundation which has the execution process close to, but not similar to, the one used for "Franki" piles. They were constructed by adopting a cylindrical metallic shell with a bottom valve bailer that was handled in the field by means of a hoist mounted on a tripod. This shell was continuously advanced as the bailer removed the soil softened by a bottom punching with auxiliary water. The hole was encased for two of the piles (SCD and SCND), and not encased for the third one (SWCND). The casing was punched into the hole as soon as the shell excavation stage finished. This operation, however, was done in steps, since the shell had to be lifted up to surface several times to be internally cleaned of its "entrapped" soil. At the end of the excavation, at the desired depths, the bottom of the hole was cleaned out, the designed rebars were introduced and fresh concrete was poured. For one of the piles (SCD) the concrete was compacted afterwards by using a 2.5 kN hammer falling onto it, whereas for the other piles (SCND, SWCND) the concrete was simply poured. All the piles had a final approximate length of 8 m and diameter of 30 cm. Same field loading as before.

One precast driven centrifuged (displacement) concrete pile: Defined by PD, it was dynamically inserted into the soil by using a 32 kN (free fall) drop hammer falling from a height of 30 cm. A wood cushion was used to soften the impact on the top of the pile, and it was mounted together with the hammer on the leaders of a standard crawler crane. The precast (hollow) pile had a final length of 8.4 m with an external and internal diameter of, respectively, 33 cm and 25 cm. Same loading as before.

Four Root type (injected, cast-in-place) piles: Also known as "micropiles", they were constructed by adopting distinct injection pressures (0, 200, 300 and 500 kPa) during the formation of the mortar shaft. They are defined herein as R0 for the pile without injection pressure (mortar just poured from surface), R2 for an injection mortar pressure of 200 kPa, R3 for an equivalent pressure of 300 kPa and R5 for a pressure of 500 kPa. These piles were executed 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 piles with an approximate length of 8 m and final average dia. of ≈ 25 cm. They were loaded by quick maintained tests.

Figure 1 presents some of the load-deflection curves obtained with the field tests.

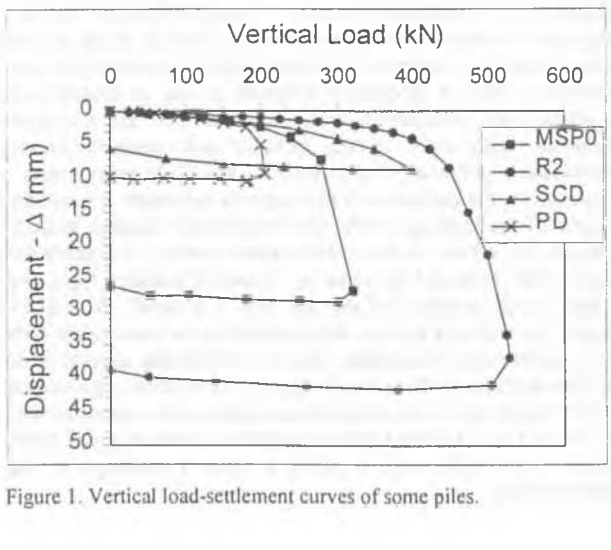

Figure 1. Vertical load-settlement curves of some piles.

4 RESULTS AND DISCUSSION

The vertical failure load for each of the piles was determined with the load-settlement curves obtained in the field and by using recognized assessment methods, as those of Brinch-Hansen (1963) and Mazurkiewicz (1972). The failure load was defined as the average value between the predictions of Brinch-Hansen (1963) and Mazurkiewicz (1972), since, according to Perez (1997), these methods yielded failure loads which were closer to the "physical failure" values (asymptote of the load-deflection curve) from each of the foundations. The only exception is for the Strauss piles, in which the NBR 6122 standard method was adopted because this standard presents a procedure to define the failure load for continuously increasing testing curves, in which the maximum load is not clearly depicted. This feature was noticed for the Strauss piles.

Figure 2 presents a plot of the vertical failure load of all piles. In regard to this figure some observations can be given:

The mechanically bored pile with the expander additive (MSP0(A)) had a failure load 8.0 % higher than the equivalent load of the pile without the additive (MSP0).

The failure load of the mechanically bored piles (MSP) decreased with the time span between excavation and casting (from MSP3 onwards). The failure load has unexpectedly increased 8.5 % from MSP0 to 3, perhaps due to unnoticed differences in nominal ("as built") length/diameter of these piles.

The failure load of the root piles has marginally increased with the increase of injection pressure (comparing R0 to R3 and R5). This load has considerably increased (as far as 55 %) from R0 to R2, which is indicative of an "optimal" injection pressure of 200 kPa (in terms of bearing capacity) for this type of pile and soil characteristics. A possible explanation is derived from the simultaneous (and distinct) effects of collapse and increase of lateral stress on the failure load of the soil. It is postulated that such combined factors (stress/collapse) unequally affect the capacity and the rigidity of the soil when increasing the injection pressure inside the borehole. As commented above, it seems that a "threshold" pressure of around 200 kPa exists, beyond which a major structural soil breakage starts to take place. These combined effects led to an increase in the failure load of the piles, predominantly due to the gradual increase of the level of lateral stress with the increase of injection pressure. Besides, with the increase of injection pressure there was a marginal increase in the final ("as built") pile diameter (hence, final point bearing resistance). It appears, however, that beyond the "threshold" pressure, the influence of the collapse of the soil on the failure load surpasses the influence of any of the other factors (as the increase in lateral stress and pile diameter). This happened because, as hypothesized herein, the structure of the soil surrounding the hole was completely destroyed. With this destruction the soil/pile interface partially lost its lateral friction. It has already been experimentally shown that the generalized collapse of the soil is extremely non beneficial, since it reduces the soil/pile interface friction. The pile capacity stayed constant from R3 to R5, probably given the generalized collapse of the soil surrounding the borehole at such high pressure stages.

The pile with the compacted concrete SCD had the highest failure load for the Strauss type piles. It seems then that was the "concrete driven" effect, not the use of casing during excavation, that caused a beneficial response on the bearing capacity of this type of pile.

The dynamic insertion of the precast driven pile in this type of soil considerably affected its natural structure, given its fragile nature. It was noted, for all piles tested herein, that the driven pile was the one with the lowest failure load.

The vertical Young Modulus of the soil surrounding each of the piles was determined with a unique point of the load-settlement field curve, i.e., the point in which the load was half the value of the aforementioned failure load. By using this (working) load and its associated settlement it was possible to numerically backanalyze the Young modulus by adopting a program denominated DEFPIG (Deformation Analysis of Pile Groups, Poulos 1990). This software determines the deformations and load distribution within a group of piles and isolated piles subjected to general loading. It was specifically written for piles designed under the "conventional approach", by considering a group of identical elastic piles having axial and lateral stiffness that are constant with depth. It also allows for the eventual slippage between the piles and the surrounding soil. The stress distributions are computed from the theory of elasticity, more specifically from Mindlin's solutions for an isotropic, homogeneous, linear elastic medium. It can also take into account, although in a simplified manner, the soil non-homogeneity along the length of the pile (i.e., variation of the soil modulus with depth). It has already been successfully used before (for instance, in Cunha et al. 2000), and has perfectly served for the present exercise.

Figure 3 presents a plot of the Young modulus of the soil around each of the piles.

In regard to this figure the some observations can be given:

The mechanically bored pile with the expander additive (MSP0(A)) had a Young modulus of the soil around its shaft much higher than the equivalent modulus of the pile without additive (MSP)). This means that this latter pile has settled much more than the former one, at similar loading conditions.

The augered pile (MAP0) had a Young modulus of the soil around its shaft much lower than the equivalent modulus of the mechanically bored pile (MSP0). This means that the augered pile has settled much more than this latter one, at similar loading conditions.

Similar trends as before (for failure load) are observed for the mechanically bored piles, i.e., the Young modulus of the soil

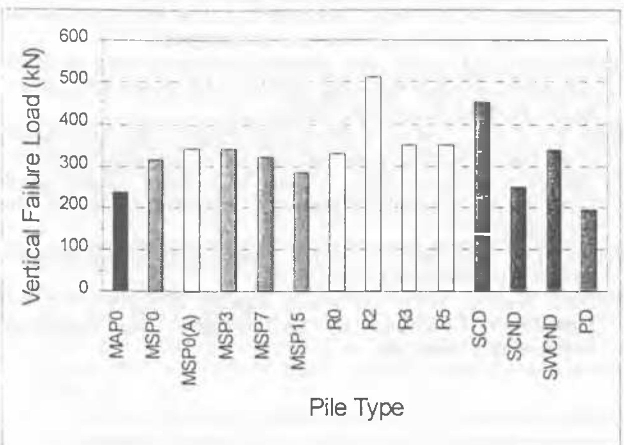

Figure 2. Vertical failure load for all piles.

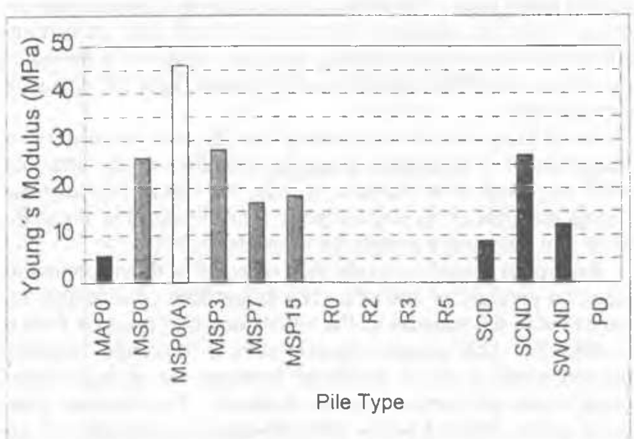

Figure 3. Backanalyzed Young modulus of the soil around the piles.

around the piles decreased with the increase of the time span between excavation and casting (from MSP3 onwards). Hence the piles settled more with the increase of time span between excavation and casting. Similarly as for the failure load, the Young Modulus has unexpectedly increased from MSP0 to 3. The same aforementioned reason is given herein to explain such behavior.

Some of the piles (as the root and the precast driven piles) could not be backanalyzed by the program, since the obtained moduli were unrealistically high. This was related to the nature of these piles, rather than to the program itself. These piles had very low settlements (around ±1 mm, at working loads), which were of the same magnitude of their (estimated) structural elastic compression. This particular feature has hampered the backanalysis, since it was done on the basis of an assumed structural Young modulus for each of the piles. Hence, small differences in the assessment of the elastic compression of the piles (by the program) yielded large estimations on the value of the Young modulus of the soil;

The pile with the compacted concrete SCD had the lowest Young modulus for the soil around its shaft (hence the highest settlement at working load) in comparison to the others Strauss type piles. This feature is exactly the opposite of what has been found in terms of failure load, and may be indicative of the fact that, for this type of tropical collapsible soil, the concrete "compaction effect" is beneficial solely in terms of failure load. This effect was clearly detrimental in terms of the Young modulus, as can also be noticed with the comparison of piles SCND (with casing) and SWCND (without casing). The Strauss pile without casing (SWCND) was executed by punching down a heavy weight onto the soil, rather than by using a casing with an internal metallic shell (as in the case of SCND). It can be seen in Figure 3 that the SCND pile presented a much higher Young modulus of the soil around its shaft (hence lower settlement at equivalent load) than the SWCND pile.

5 CONCLUSIONS

This paper emphasized the backanalyses of several field loading test results with deep foundations located at the experimental research site of the University of Brasilia. Typical foundations adopted within the Federal District were vertically loaded, yielding loading displacement curves and estimated parameters that were cross-compared and discussed. This led to some major conclusions, presented below.

Manually augered piles yield much lower failure load and Young modulus (hence settling more) than the respective mechanically bored ones, possibly due to a higher stress relief that occurs during the soil excavation, besides of the soil collapse given the introduction of water during its excavation process.

The use of an expander additive mixed in the fresh concrete increases both the failure load and the Young modulus of the soil around bored piles. This effect is caused by the lateral stress increase given the expansion of the pile's shaft after its casting. Although the expander additive was used only for a mechanically bored pile, the conclusions are broaden here for manually augered ones.

Bored piles should be preferably cast-in-place between 0 to a maximum of 3 days after the soil excavation, since, after the third day, there is a decrease of both the failure load and the Young modulus of the soil around it. This is caused by the stress relief that takes place around the excavated hole.

Root piles should be preferably executed with an (optimum) injection pressure of 200 kPa. The failure load considerably increases with the increase of the mortar injection pressure from 0 to 200 kPa. This pressure appears to be a "threshold" pressure beyond which a major structural breakage, or collapse, takes place in the soil surrounding the borehole. For injection pressures above 200 and below 300 kPa there is a tendency of decrease of the failure load of the pile. This load stabilizes for injection pressures beyond 300 kPa.

Strauss piles should be executed with the casing and by compacting the fresh concrete after it is poured into the hole, if the main interest is the gain of failure load. However, if the main variable of interest is the settlement, then the Strauss pile should be executed without compaction of the concrete. It was noticed that a large increase in both the failure load and the settlement of the pile was obtained with this compaction procedure.

Whenever possible, precast driven piles should be avoided in this type of soil.

This paper presented the initial results of an ongoing research line on deep foundations and in situ testing of the Geotechnical Post-Graduation Program of the University of Brasilia. Given the reduced number of foundations and the limited spatial size of the studied area within the geographical context of the Federal District, it is evident that more studies are still necessary. Nevertheless, these preliminary results can already be seen of practical and academic interest for those who want to design deep foundations in similar "non classical" tropical soil types.

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7 REFERENCES

Brinch Hansen, J. 1963. Hyperbolic stress strain response: Cohesive soils. *Journal Soil Mechanics and Foundation Division*. ASCE, 89: 241-242.

Cunha, R.P. & Perez, E.N.P. 1998. Backanalyses of Elastic Parameters from Piles Executed in a Tropical Porous Clay. *3rd International Geotechnical Seminar Deep Foundations on Bored and Auger Piles*, Ghent, 377-383.

Cunha, R.P., Jardim, N.A. & Pereira, J.H.F. 1999. 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, 113-122.

Cunha, R.P., Small, J.C. & Poulos, H.G. 2000. "Class C" analysis of a piled raft case history in Gothenburg, Sweden. *Year 2000 Geotechnics – Geotechnical Engineering Conference*, Bangkok, 1: 271-280

Jardim, N. 1998. *Evaluation of the vertical and horizontal bearing capacity of deep foundations with the use of the Marchetti dilatometer*. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Brasília . (In Portuguese).

Mazurkiewicz, B.K. 1972. *Test loading of piles according to Polish regulations*. Royal Society and Academy of Eng. Sciences. Comm. on Pile Research. Stockholm, Report no. 35.

Perez, E.N.P. 1997. *The use of the elasticity theory in the determination of the Young's modulus of the soil adjacent to vertically loaded piles founded in the porous clay of Brasilia*. M.Sc. Thesis, Department of Civil and Environmental Engineering, University of Brasília .(In Portuguese).

Poulos, H.G. 1990. *DEFPIG User's Guide*. Centre for Geotechnical Research. University of Sydney. 55 p.

Van der Veen, C. 1953. The bearing capacity of a pile. *Proc. 3rd International Conference on Soil Mechanics and Foundation Engineering*. Switzerland.