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TECHNICAL PAPER

WIND EFFECTS ON FOUNDATIONS OF SILOS AND LIGHT STRUCTURES: SOLUTION BY USE OF STEEL PILES IN DIABASIC SOIL

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KEYWORDS

foundations, piles, wind effect, light structures, load tests, Diabasic soil.

ABSTRACT

Wind solicitations generate horizontal, tensile, and compressive stresses on building foundations. In empty light structures, such as agricultural greenhouses and, in the specific case of silos and elevated structures such as metal water tanks, the consideration of these loads becomes important because the lack of the weight component due to the storage load significantly influences the balance of forces. This study focused on the behavior of metallic steel profiles, aiming at its application as a foundation element for the pile, considering the soil of Diabasic origin common to the Center-South region of Brazil. Load tests in real scale were carried out on three steel profiles, type I, gauge W 250 mm x 32.7 kg m^{-1}, drilled in the ground up to 12m deep by means of a pile driver. One steel profile was submitted to lateral loading, another to vertical compressive loading, and the other to vertical tensile load. Test results determined the bearing load of the pile for each loading type, calculated the soil reaction coefficient for lateral loading, and verified the applicability of load capacity prediction methods to tensile and compressive strengths of piles, commonly used in foundation projects.

INTRODUCTION

High lightweight structures (e.g., metal silos, metal (empty) water tanks, metal sheds, agricultural greenhouses, and others) must be designed to stand on their foundations. Moreover, these buildings are supposed to withstand vertical compressive stress due to loading and own weight, and horizontal tensile and compressive forces caused by wind (Paschoalin Filho & Carvalho, 2010).

Stresses are transmitted to foundations through the horizontal resultant of wind force and through the moment caused at the foundations by this wind resultant force at a certain point of the structure height, generating tensile solicitations (Figure 1). It is noteworthy that several scientific studies have been conducted by technical and academic means in order to understand the structural behavior and foundations of rural constructions when submitted to the loads mentioned, such as Paschoalin Filho & Carvalho (2010); Frank et al., (2015); Frank et al., (2018); Liu et al.(2018); Jansseune et al., (2016).

Due to the great structural efficiency of the cylindrical shape and the high resistance of steel, these structures are light and thin and, therefore, susceptible to losses of local and global stability and pullout resistance. In terms of total service load, the weight of the silo or water tank metal structure may not reach 1% of its stored load. When empty, almost all the vertical component of the load is lost, an important part of the balance of forces when considering the horizontal resultant wind.

The growth of Brazilian agriculture has forced several sectors to adapt production standards to remain competitive, and the use of vertical silos stands out among the alternatives for facilitating feed manufacturing process and eliminating large horizontal deposits. Silos and water tanks of up to 30m in height are commercially available in Brazil (Frank et al., 2015).

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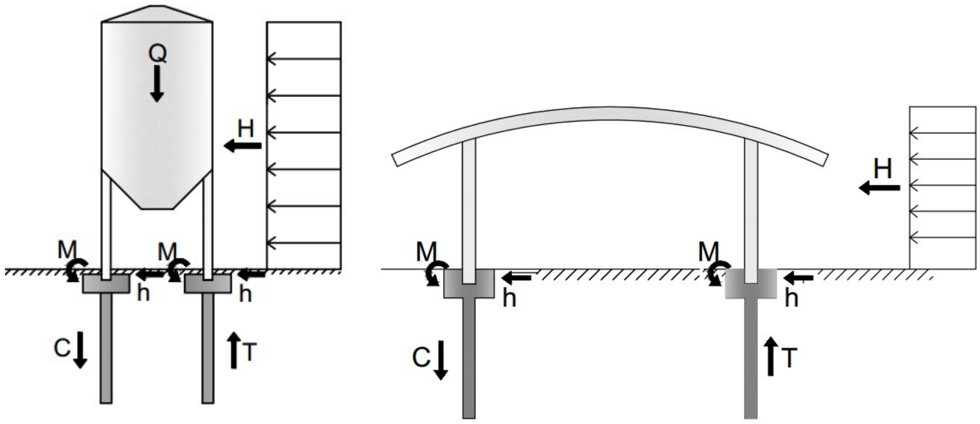


FIGURE 1. Wind stresses acting on the foundations of a structure: H = Total resulting wind stress; M = moment; h = horizontal stress; T = tensile stress; C = compression stress; Q = own weight plus stored load.

The Brazilian Association of Technical Standards (ABNT) establishes the conditions required in the consideration of the forces due to the static and dynamic wind action for building calculations in NBR 6123: 1988 (corrected version 2:2013) - "Wind forces on buildings". Its content presents the isopleths of basic wind velocity for Brazil, observing that winds can reach speeds of 126 km h^{-1} to 180 km h^{-1} in the south region. It also presents building coefficients related to height (a) and width (b) in the following ranges: (a/b) < (1/2); (1/2) ≤ (a/b) ≤ (3/2); (3/2) < (a/b) ≤ 6.

The pile foundations widely used in Brazil were predominantly made of concrete. Steel rolled structural profiles with gauges from 150 mm to 610 mm and resistance limit of 500 MPa are currently available on the market. Foundations composed of embedded steel profiles have become competitive when analyzing the overall foundation costs of certain constructions due to their high resistance, the possibility of using several profile sections, and the use of remaining materials (Cury Filho, 2016).

The soil of Diabasic origin covers extensive areas in southern Brazil, as shown in Figure 2. It is present in the region of Campinas, SP, and is derived from Diabasic alteration products affected by local rework, being classified as a typical Dystrophic Red Latosol, characterized by being very deep, friable, porous, and of a clayey or very clayey texture. This soil type has been studied by Paschoalin Filho & Carvalho (2010), Cury Filho (2016), Carvalho & Albuquerque (2015); Albuquerque (2001), Miranda Junior et. al., (2008), Kassouf et. al., (2016), Cavalcante & Carvalho (2007).

Within this context, this study aims at providing the technical environment with relevant information regarding the behavior of the type of foundation studied, so that technically more appropriate and economically more feasible projects can be elaborated, allowing to reduce the empiricism in the parameters adopted within the conditions presented in this study.

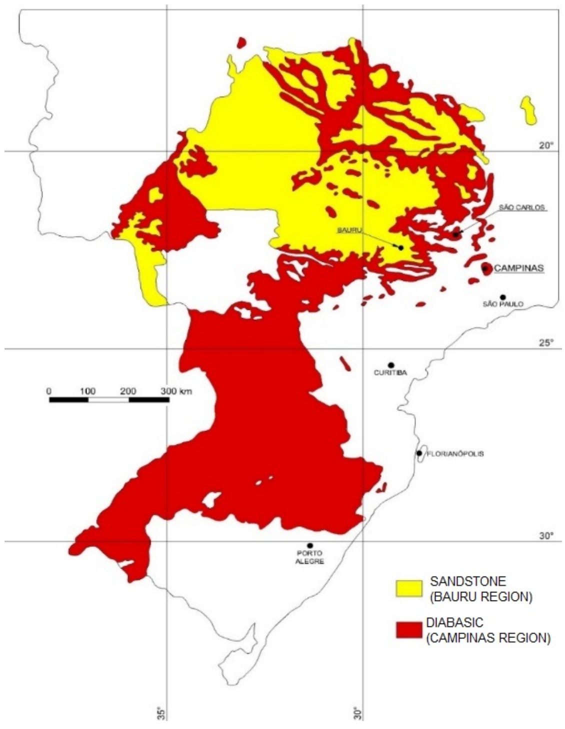


FIGURE 2. Areas with potential for the Campinas-SP profile (Cury Filho, 2016).

MATERIAL AND METHODS

To accomplish this study, three steel profiles with 12m in length were drilled using a piling machine, and load tests were later performed. The load tests used were lateral loading, compression, and traction. Investigations of the geotechnical properties in depth were carried out in the soil under study.

The norm ABNT-NBR 6122/2010 (Project and Execution of Foundations) establishes the need to carry out load tests on piles implanted in areas where there is no previous experience with the type of pile used. In this case, load tests shall be carried out on at least 1% of the piles, under a minimum load test. When there is previous experience with the pile type in a certain soil type, the norm establishes that load tests are necessary from 100 piles on. Carvalho & Albuquerque (2015) present details on the performance of load tests.

As foundation element, three I-shaped structures were used, with 12 m length, w-gauge of 250 mm x 32.7 kg m^{-1}, elasticity modulus (E) of 205 GPa, and area (A) of 42.1 cm^2, as shown in Figure 3. Piles were driven by a 1.9-tonne drop hammer pile driver, free-falling from a height of 0.50 m as recommended in the ABNT-NBR 6122/2010. These profiles are manufactured by the company Gerdau and consist of steel ASTM A 572 - Grade 50, with a flow limit of 345 MPa and resistance limit of 450 MPa.

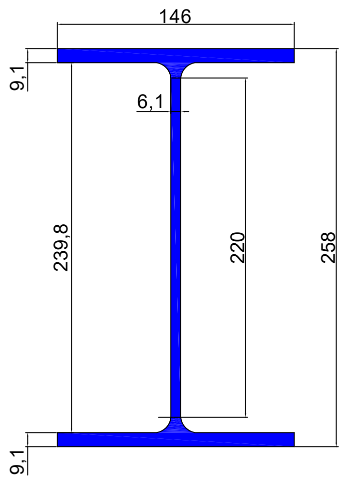


FIGURE 3. Steel profile used - dimensions in mm.

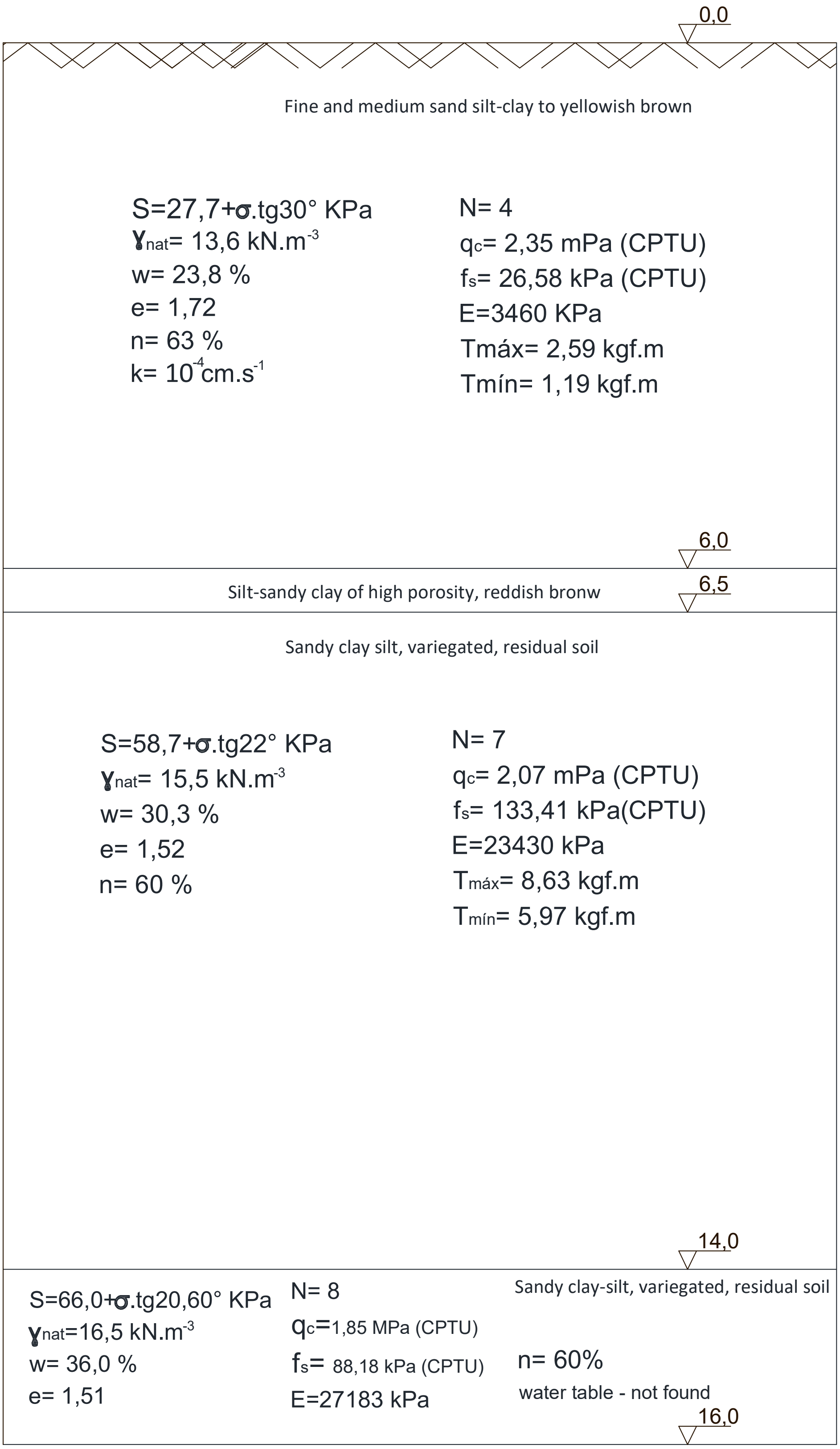
The study was carried out in the experimental field of the School of Agricultural Engineering, State University of Campinas. The area is located in the middle-eastern portion of the Atlantic Plateau of São Paulo state, at the geographical coordinates of 22°53'22" S and 47°04'39" W.

The norm ABNT-NBR 6122/2010 - Foundation Design and Execution - establishes that a preliminary geotechnical investigation campaign must be carried out for any building, consisting at least of cable percussion with standard penetration test (SPT) to determine soil stratigraphy and classification, the position of water level, and to measure the penetration resistance index (N_{SPT}), in accordance with ABNT-NBR 6484/2001 - Soil - Surveys of Simple Recognition with SPT - Test Method.

A well with 16m depth was opened to study the subsoil properties, removing deformed and undeformed samples at each meter. Laboratory testing included granulometry tests, liquidity and plasticity limits, physical indices, and triaxial tests in undeformed samples to determine their shear strength.

Two types of field tests up to 16-m depth were used in the designing of building foundations, using an electrical cone which provides cone tip resistance measurements and lateral cone resistance in contact with soil: 7 simple recognition drilling with SPT according to ABNT-NBR 6484/2001 and 4 "in situ" cone penetration tests (CPT), in accordance with ASTM D5778 - 2012.

The soil of the experimental area belongs to the class of typical Dystrophic Red Latosols. In the semi-detailed soil survey, it fits the Barão Geraldo mapping unit, which also occurs in other places in the state of São Paulo. Figure 4 shows the average results obtained by subsoil layer up to 16 m of the study Experimental Field.



S - Equation of resistance - triaxial shear test; **γ nat** = Natural soil density; **w** = moisture content; **e** = void ratio; **n** = Porosity; **μ** = Coefficient of Poisson; **N** = Mean Nspt; **q_c** = Mean tip resistance; **f_s** = Mean lateral friction; **E** = Modulus of deformation; **T** = Mean torque; **K** =Permeability coefficient

FIGURE 4. Average soil properties up to 16 m depth.

The load tests consisted of static load application on the top of piles through a hydraulic jack. Displacements were measured using strain gauges (analog dial indicators) with an accuracy of 0.01 mm for each load applied, thus load x displacement curves could be obtained. The procedures adopted were those specified in ABNT-NBR 12131/2006 – “Static Load Test” – as a test method.

The hydraulic jack needs to react with an element to apply the load, which in this study was a steel beam anchored in concrete piles, molded in loco, with 0.40 m of diameter and 12 m of depth. In the horizontal load test, the load is applied horizontally on the top, the hydraulic jack reacting with another pile.

In the tensile load test, the transfer beam is supported on the two lateral piles and the test pile is pulled. Kassouf et al., (2016), Albuquerque et al., (2011), and Paschoalin Filho & Carvalho (2010) present details of the performance of load tests with horizontal loading with compression and traction, respectively.

The load capacity of a pile is specific for each type of loading to which it is subjected, therefore values for load capacity must be calculated for horizontal stressing, vertical stressing of compression and vertical stressing of traction (Paschoalin Filho & Carvalho, 2010; Albuquerque et al., 2011, Carvalho & Albuquerque, 2015, Cury Filho, 2016).

To design foundations under horizontal loading, horizontal displacement should be established, from which the allowable stress for the foundation is defined. The theoretical formulation leads to the soil horizontal reaction coefficient (n_h) for the type of soil under study (Kassouf et al., 2016). This coefficient is defined as:

$$n_h = \frac{4,42.(P_H)^{5/3}}{(y_0)^{5/3}.(EI)^{2/3}} \quad (1)$$

In which:

n^h = coefficient of horizontal reaction;

P_H = horizontal stress;

y_0 = horizontal displacement;

E = modulus of elasticity of pile material,

I = moment of inertia of pile section.

Equation (1) shows that n_h depends on horizontal displacement y_0, due to the horizontal stress H. On the other hand, if the value of n_h is known, the lateral displacement value can be calculated by:

$$y_0 = 2,4.\frac{T^3 H}{EI} \quad (2)$$

In which,

$$T = \sqrt[5]{\frac{EI}{n_h}} \quad (3)$$

Figure 5 shows the horizontal load test performed in this study, while Figure 6 illustrates the standard assembly used for the compressive load test.

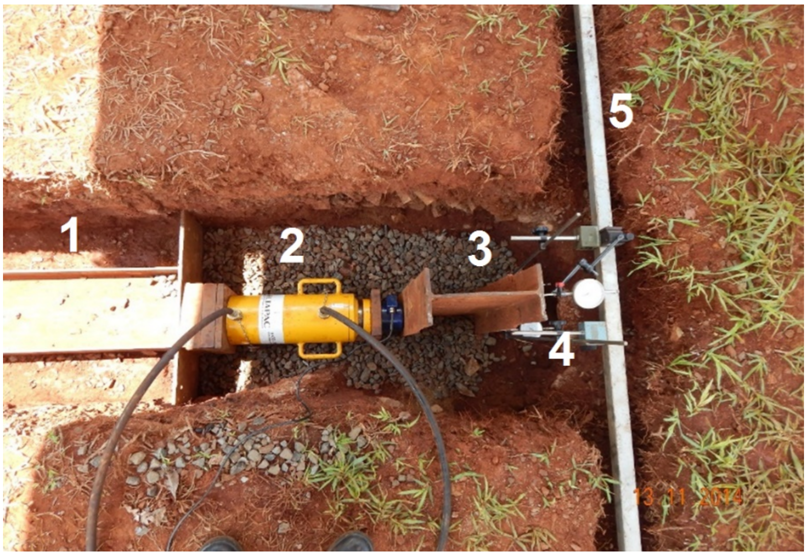


FIGURE 5. Details of the system used in horizontal load tests. View from above. (1) steel profile (supported on the concrete pile to the left); (2) hydraulic jack; (3) steel profile to be tested; (4) strain gauges; (5) reference beam to support the strain gauges.

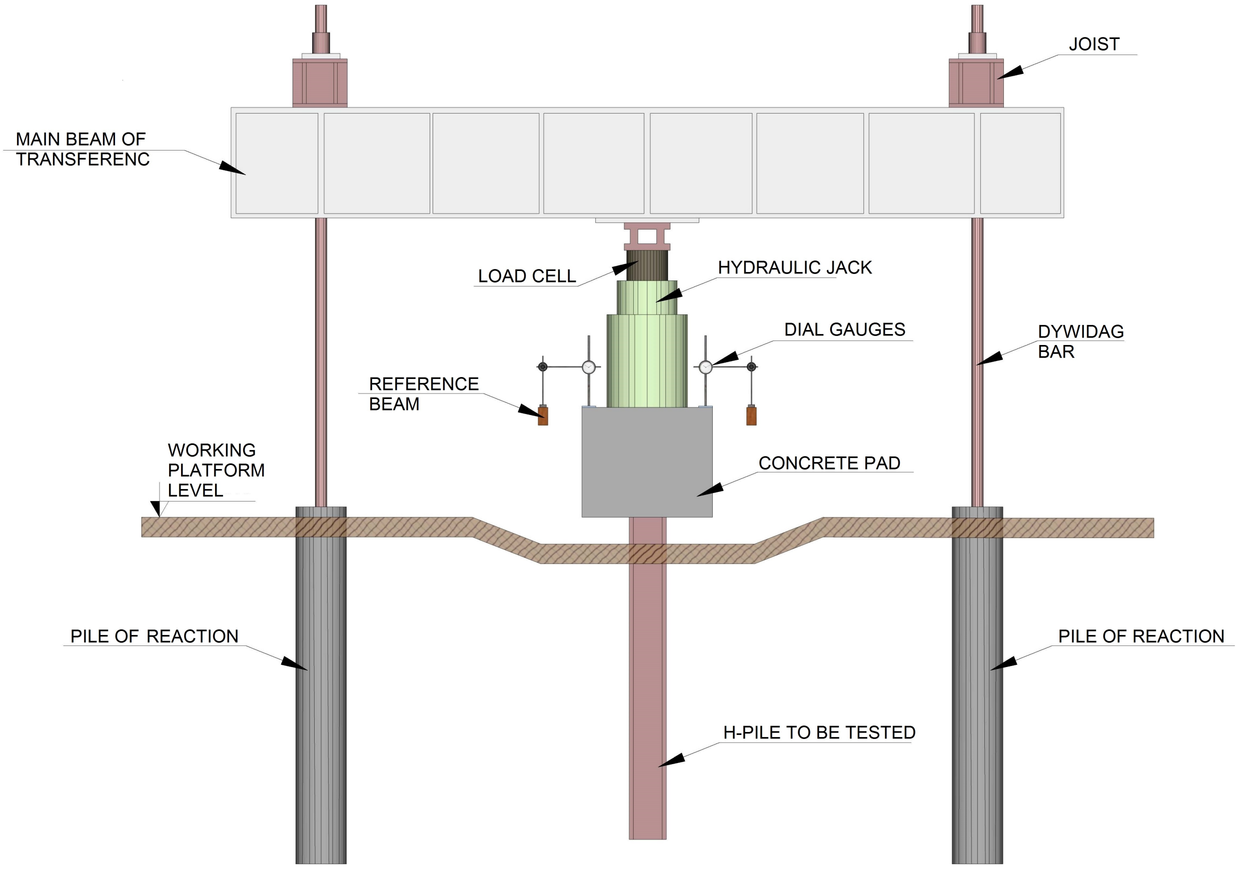


FIGURE 6. Details of the system used in the compressive load tests.

In foundations design practice, since horizontal load tests are usually not available, the value of n_h adopted is based on the experiences of other authors. This value is characteristic of each type of soil, and values which are not determined for the area where the project will be implemented can lead to errors, both for and against safety.

In piles subjected to vertical compression stress, the load applied is supported by the resistance of the tip in contact with the soil (Q_P) and by the lateral friction of the pile and the surrounding soil (Q_L). The theoretical formulations to determine these forces require the values of horizontal thrust coefficient, soil cohesion, and soil friction angle along the depth, which are difficult to obtain and highly variable.

Therefore, the use of calculation methods whose parameters are obtained by means of mathematical correlations with the results of percussion drilling with SPT and CPT essays is common, according to ABNT-NBR 6484 and D5778 - 2012 ASTM (American Society for Testing and Material) respectively. The general formulation used is:

$$P_R = A_P \text{ x } r_P + A_L \text{ x } a_L \quad (4)$$

In which:

P_R = Bearing load of maximum load (kN);

A_P = pile tip area (m^2);

r_P = unitary tip resistance (kN);

A_L = pile lateral area (m^2),

a_L = unitary lateral resistance (kN).

Cury Filho (2016) presents the three calculation methods that stand out the most in the technical environment to determine the pile bearing load: Aoki & Velloso (1975); Décourt (1996), and Alonso (2008); the latter specifically for steel piles. The calculations are based on equation (4), used for determining tip resistance (r_P) and lateral friction (a_L) values of correlations with results of simple recognition drilling with SPT and CPT essays, specifically for each soil type. These methods present parameter values for soils from the places where they were developed. Correlation parameters must be assessed for the type of soil of the construction site.

The common practice for piles subjected to vertical tensile stresses is to use these same methods for the calculation of lateral friction, disregarding tip resistance, which is not present in this type of stress. Theoretical formulations require knowledge of the cohesion and friction angle of the surrounding soil throughout the entire pile length.

RESULTS AND ANALYSES

Figure 7 shows the curve between the horizontal load applied and horizontal displacement obtained for the lateral pile load test. Figure 8 shows the lateral displacement graph (y_0) x lateral reaction coefficient (n_h), constructed from the load test results using equation (1). The projection of the load x displacement curve, using the stiffness concept (Cury Filho, 2016), indicates the bearing load of 900 kN.

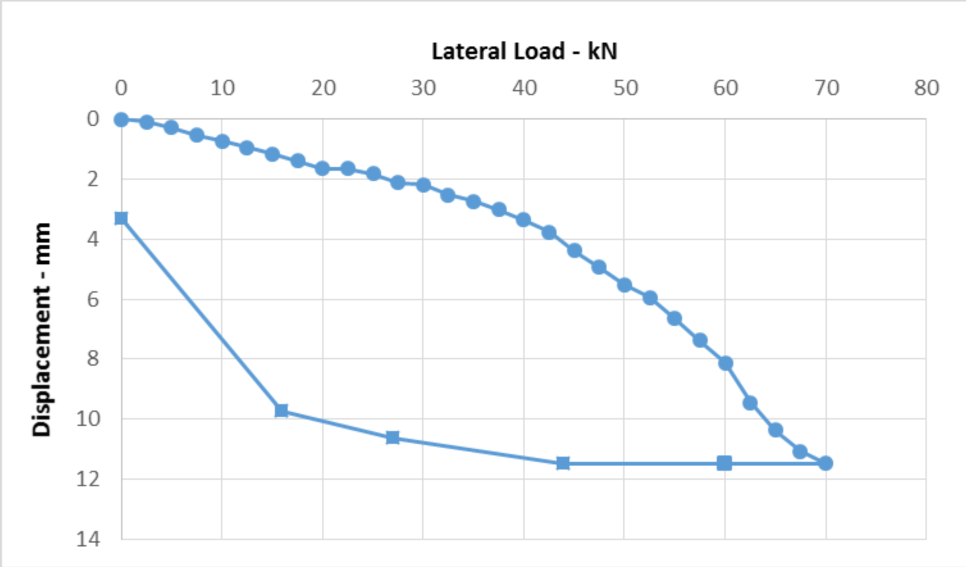


FIGURE 7. Lateral load x displacement curve obtained in the lateral load test – round markers for load and squares for unloading.

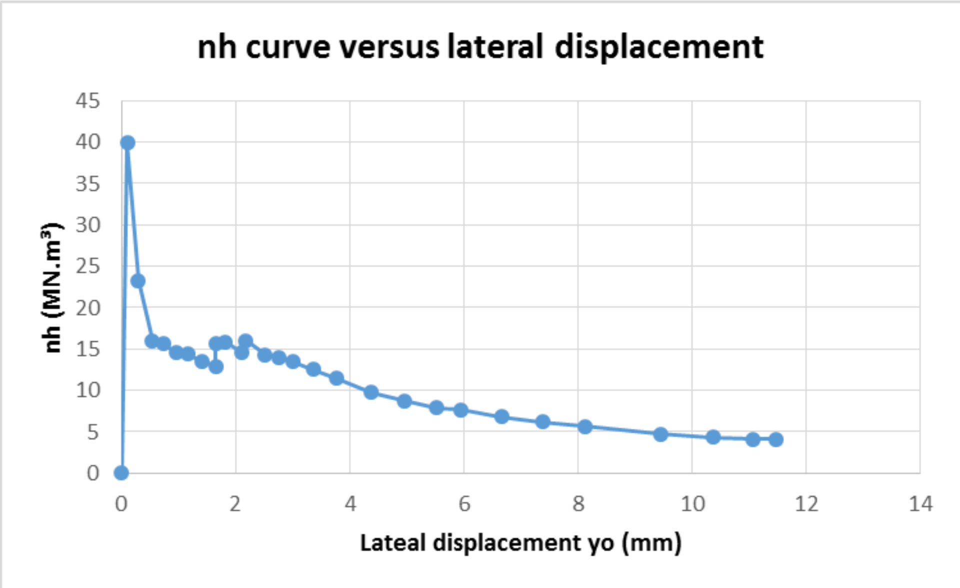


FIGURE 8. Lateral displacement load curve x lateral reaction coefficient (n_h).

The value of n_h varies according to the lateral displacement (y_0). An average value is adopted in a given range of y_0 to define a value to be used in projects, which usually varies between 4 and 10 mm. In this study, the range of 4.4 to 8.1 mm was adopted, which are actual displacements obtained in the load test. The value of the lateral reaction coefficient obtained for the steel pile was 7.7 MN m^{-3}.

Miranda Junior et al., (2008) obtained the value of 11.5 MN m^{-3} using excavated concrete piles for this soil type in the same experimental field where load tests were performed. Kassouf et al., (2016) generically presents the value of 2.6 MN m^{-3} for sandy soils of high porosity, without specifying the type of pile and location. Almeida et al., (2011) obtained the value of 0.65 MN m^{-3} for excavated piles for the sandy soil of the city of São Carlos. Miguel et al., (2001) obtained a value of 6.8 MN m^{-3} for the clayey soil from the Londrina-PR area.

The value obtained in this study for steel pile of 7.7 MN m^{-3} was not known for this type of pile in the soil under study, differing from the value found in the same site for excavated concrete piles (11.5 MN m^{-3}). The variability of the values presented for other types of piles and other sites indicates the importance of determining the value of the lateral reaction coefficient (n_h) for each type of soil under study.

Figure 9 shows the load x lateral displacement curve for the pile subjected to a compressive load test. With the load of 400 k_N, the displacements are observed to become continuous without load increase, characterizing the rupture of the pile x soil connection. This value was also obtained through the analysis of the curve by the rigidity concept (Cury Filho, 2016).

Table 1 shows the findings on bearing loads predicted (PRe) by simple recognition drilling with SPT and CPT essays. The methods of Décourt (1996) [(PRe / PRpc) = 1.13] and Alonso (2008) [PRe / PRpc) = 0.9] are observed to bring results closer to the bearing load (PRpc) obtained in the load test (400 kN).

Figure 10 shows the load x vertical displacement curve for the pile undergoing tensile stress testing. The rupture stress of 450 kN is obtained through the analysis of the curve by the concept of rigidity (Cury Filho, 2016).

Table 2 shows the bearing load results predicted (PRe) through the methods using simple recognition drilling (SPT) and CPT tests. Only the calculated values of resistance by lateral friction were considered since pulled piles have no tip resistance. The results observed to be closer to the bearing load (PRpc) obtained in the load test (500 kN) are those of the Décourt (1996) [(PRe / PRpc) = 0.86] and Alonso (2008) [(PRe / PRpc) = 0.66] methods, both in favor of safety.

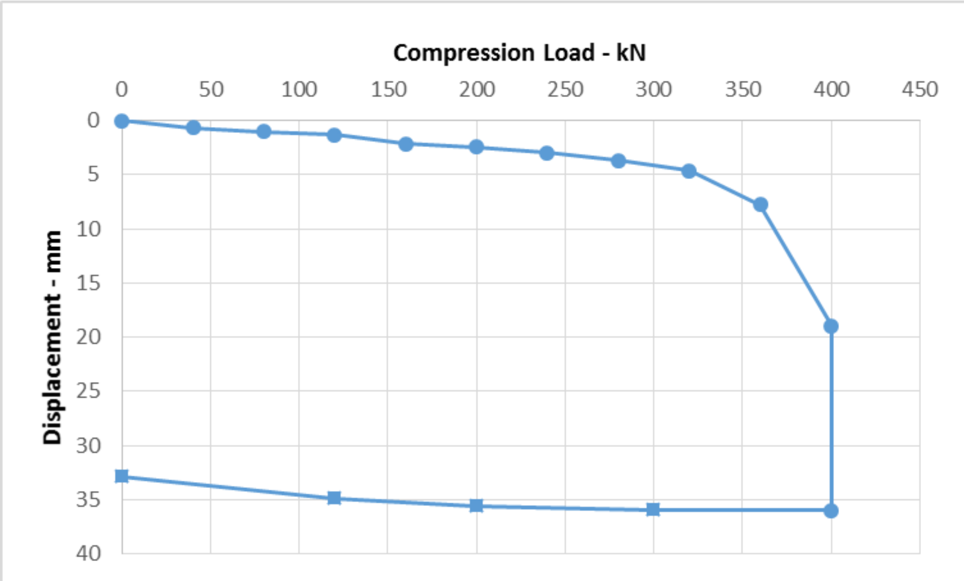


FIGURA 9. Load x vertical displacement curve obtained in the compressive load test – round markers for load and squares for unloading.

TABLE 1. Compression bearing load values obtained by semi-empirical calculation methods using field test data: simple recognition drilling (SPT) and electric cone penetration testing (CPT). Ratio between the estimated load (PRe) and the bearing load obtained in the load test (PRpc).

Profile type	Nailed length (m)	Semi-empirical calculation method	Aoki & Velloso (1975)		Décourt (1996)	Alonso (2008)	Bearing load obtained in the load test
			SPT	CPT	SPT	SPT	PRpc (kN)
W 250x32.7	12	Pre (kN)	223	285	441	350	400
		Pre/PRc	0.57	0.73	1.13	0.9	

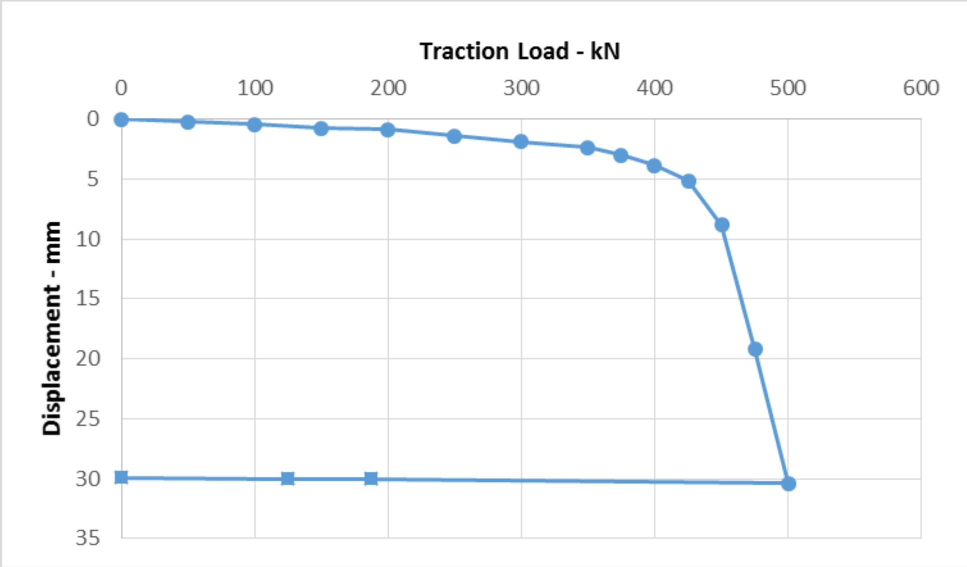


FIGURE 10. Load x vertical displacement curve obtained in the tensile load test - round markers for load and squares for unloading.

Table 2 shows the bearing load results predicted (PRe) by the methods using simple recognition drilling (SPT) and static CPT. Only the calculated values of resistance by lateral friction were considered since pulled piles have no tip resistance. The results observed to be closer to the bearing load (PRpc) obtained in the load test (450 kN) are those of the Décourt (1996) [(PRe / PRpc) = 0.96] and Alonso (2008) [(PRe / PRpc) = 0.73] methods, both in favor of safety.

TABLE 2. Values of the tensile load obtained by semi-empirical calculation methods using field test data: simple recognition drilling (SPT) and electric cone penetration testing (CPT). Ratio between the estimated load (PRe) and the bearing load obtained in the load test (PRpc).

Profile type	Nailed length (m)	Semi-empirical calculation method	Aoki & Velloso (1975)		Décourt and Quaresma (1996)	Alonso (2008)	Bearing load obtained in the load test
			SPT	EPC	SPT	SPT	PRpc (kN)
W 250x32.7	12	Pre (kN)	215	280	430	328	450
		Pre/PRc	0.48	0.62	0.96	0.73	

CONCLUSIONS

The analysis of the load x displacement curves and bearing loads obtained show that the use of steel profiles as foundation elements for piles is technically feasible. Steel piles are available in the market and can be economically more indicated, depending on the construction location and magnitude.

The value of the horizontal reaction coefficient (nh) obtained (7.7 MN / m^3) is unprecedented for this type of soil for the horizontal load, differing from the value known for concrete piles. The variability of this coefficient verified with different types of soils and piles demonstrates the importance of its determination for specific soils.

The bearing load in the horizontal load lest (90 kN) is lower than that in the vertical compressive load test (400 kN). This result highlights the importance of a careful study of the behavior of foundations under horizontal load in the specific situations in which it occurs, and for certain magnitudes.

The load values predicted by the methods of Décourt (1996) [(PRe / PRpc) = 1.13] and Alonso (2008) [(PRe / PRpc) = 0.9] for the pile subjected to compression stress are within a range of plus or minus 20% of the load obtained on the load test. This value is acceptable within the practice of foundation engineering, indicating the feasibility of application of these prediction methods for the type of pile and soil under study.

The load values predicted by the method of Décourt (1996) [(PRe / PRpc) = 0.96] for the pile subjected to tensile load is 4% below the value obtained in the load test, and this value is acceptable within the practice of foundation engineering, indicating the feasibility of applying this prediction method for the type of pile and soil under study. The value predicted by the method of Alonso (2008) [(PRe / PRpc) = 0.73] is 27% below that obtained in the load test, in favor of safety.

The values obtained by Aoki & Velloso (1975) are in favor of safety, but far from the ratio [(PRe / PRpc) = 1.00], indicating the need to correct parameter values for the type of soil and pile under analysis.

The values found, specific for the type of pile and soil under study, demonstrate the importance of conducting field tests to know the subsoil, carrying out load tests for projects, and verifying and calibrating prediction methods for pile behavior.

As results of pile load tests are not always available when carrying out a foundations project, the reliability of the calculation formula to be used is of fundamental importance for good construction performance. The data obtained in this study allowed for an analysis of the precision of the calculation methods analyzed. Using a greater number of load tests on steel piles in this type of soil should lead to an improvement in the parameter values of the three calculation formulas analyzed, so that the ratio (PRe / PRpc) becomes closer and closer to the unit.

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