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The behavior of a foundation transversally loaded at the top over highly porous and collapsible soil

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Abstract
In geotechnical engineering, the use of caisson foundations transversally loaded at the top is common. This type of foundation is frequently used on high-porosity and collapsible soils, which are common in many regions in Brazil. Because of the limited information available in the literature, two loading tests were performed with transversal loading in a caisson built at full scale (0.8 m diameter, 9.0 m depth, 1.6 m base diameter). A load test was performed with the soil in its natural humidity condition, and another load test was performed after the previous soil flooding. Load *vs* horizontal displacement curves and the horizontal direction coefficient of the soil were obtained. The results permitted the verification of the applicability of behavior-predicting theoretical formulae in addition to the proposal of parameters for use on the studied soil. Before executing the load tests, laboratory and in-situ tests were performed to investigate the local subsoil.

Keywords: transversal loading, caisson, porous soil, collapsible soil.

Comportamiento de cimentación cargada transversalmente en su cabeza en suelo altamente poroso y colapsable

Resumen
En la práctica de la ingeniería geotécnica es común el empleo de fundaciones por pilas cargadas transversalmente en la parte superior. Frecuentemente este tipo de fundación es ejecutada en suelos de alta porosidad y colapsables, comunes en varias regiones de Brasil. Debido a la poca información disponible en la literatura, se realizaron dos pruebas de carga con cargamento transversal en una pila (diám. 0,8 m; prof. 9,0m; diám. base 1,60m). Se realizó una prueba de carga estando el suelo en su condición de humedad natural y otra después de la previa inundación. Fueron obtenidas las curvas carga x desplazamiento horizontal y los coeficientes de reacción horizontal. Los resultados permitieron verificar la aplicabilidad de fórmulas teóricas de previsión de comportamiento, así como proponer parámetros a ser utilizados para el suelo. Previo a la realización de las pruebas de carga fueron realizados ensayos de laboratorio y campo para la investigación del subsuelo.

Palabras clave: carga transversal, pila, suelo poroso, suelo colapsable.

1. Introduction

The deep foundation design planner, in addition to the executive-system-related aspects and the type of material employed, is concerned with the loading system, which can be translated due to an axial load, transversal load (horizontal) and bending moments. Regarding the horizontal loading, generally, foundations are subject to forces at the top, for example, in bridges, viaducts, transmission line towers, wind power generation towers, or along a shaft, as for the earth's pressure. In countries with seismic activities, the construction code requires the consideration of the horizontal load in foundation designs, thus minimizing the consequences of a possible earthquake.

In the dimensioning of foundations to resist horizontal loads, the project criteria involve not the capacity of the

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ultimate horizontal loading but the maximum or pre-established displacement that can be reached. Currently, there are many mathematical methods for the prediction of the horizontal displacement of a pile. The common difficulty among these methods concerns the adoption of the geotechnical parameters to be used in the calculations.

The main parameter used is the modulus of the horizontal reaction (n_h), which is defined as the soil resistance along the foundation divided by its deflection at a point. Simplified mathematical models have been created for the analysis because the modeling of the horizontal action problem is tridimensional and extremely complex for routine solutions by the project planners. The most well-known and diffused theory for the evaluation of these actions is the “Theory of the Horizontal Reaction of the Soil”, where the n_h factor represents the proportionality between the reaction and displacement acting on the soil mass. However, this factor is difficult to theoretically estimate. Nevertheless, this factor can be “measured” using load tests and obtaining a reliable value for the horizontal resistance of the soil where the construction will occur.

The soil’s reaction is a function of many factors, such as pile properties, soil stress *vs.* strain, depth of the analyzed point, foundation displacement level, etc. Because of the difficulty of establishing a function including all of these factors, the simplified Winkler’s hypothesis is normally used, where the soil’s reaction is proportional to the pile's displacement.

For the horizontal loading, in the first few meters, the superficial soil has great influence over the load *vs.* horizontal displacement of the foundation’s behavior. To predict the behavior of horizontally loaded foundations, theoretical approaches are available in the literature [1, 2, 3, 4]; however, parameters determined for the local soil are necessary for its application.

Superficial soils with porosities higher than 50% cover great area extensions in Midwest Brazil. Because of their large void volumes, these soils undergo great deformations under loads. In addition, many of these soils are collapsible, i.e., when the soils are under loads and when a significant increase in the moisture content or soil saturation occurs, the structure collapses, which results in unacceptable displacement values for the edifices [5].

Given the lack of available information in the literature concerning horizontally loaded caissons on highly porous collapsible diabase soil, this study was developed to examine the performance of two load tests in a caisson, with soil at its natural and after-flooding.

Based on the horizontal loading tests, the effect of soil flooding on the load *vs.* horizontal displacement curve and the values for the horizontal reaction coefficient for the soil’s conditions at its natural and pre-flooded were verified. The results obtained for the horizontal reaction coefficient were compared with the results for other types of foundations on similar soils.

The acting stresses and displacements on a pile under bending moments and horizontal loadings were determined using the theory of horizontal soil reaction, which is based on the model proposed by Winkler. The soil behavior under horizontal forces is simulated by a set of independent, identical and equally spaced springs. Thus, the soil’s reaction is considered proportional to the displacement of the analyzed point. This supposition simplifies the problem, considering that the relation between the pressure of contact at the base of the foundation and its corresponding consolidation is the same for any support area. Using the model proposed by Winkler, the concept of the modulus of horizontal reaction, K, was introduced by [6]. It is defined as the relation between the soil’s reaction (in units of applied force by the pile’s length) and the corresponding displacement (eq. 1):

$$K = \frac{p}{y} \tag{1}$$

where: K = the modulus of horizontal reaction (FL^{-2}), p = the applied pressure (FL^{-1}) and y = the horizontal displacement (L).

This notation presents the advantage of being independent of the diameter of the foundation. Therefore, the eq. 2 can be rewritten as:

$$K = k_h.D \tag{2}$$

where: k_h = the horizontal reaction coefficient (FL^{-3}) and D = the diameter of the foundation (L).

For pure sands, the elasticity modulus increases (approximately) linearly with depth. Therefore, the soil reaction to the load applied to the pile is assumed to also linearly increase with depth (eq. 3):

$$K = \frac{p}{y} = n_h.z \tag{3}$$

where: n_h = the modulus of the horizontal reaction of the soil (FL^{-3}) and z = the depth (L).

It is necessary to understand the variation of K throughout the foundation for the analysis of its behavior based on the theory of soil reaction. Refinements and sophistications in the reaction modulus function by depth are not justified because the errors in the results of the calculations are very small compared with the ones involved in the estimation of numerical values of the modulus of the soil reaction. [7] completely agree with this assessment because the results are satisfactory and can be obtained for the majority of practical cases as simple forms of variation of the reaction modulus with depth. Additionally, in practical problems, the uncertainty inherent to the soil’s behavior estimate based on conventional tests is generally compatible with the small errors that can be introduced by the depth using a simple form of the soil reaction modulus function.

[8] were the precursors to the presentation of curves obtained for horizontal loads tests on sandy soils. They presented these curves in the form of n_h at the y-axis and the displacement y_0 at the x-axis. To create these curves, the cited authors used eq. (4) by [9] for the displacement for the application of only one horizontal load parallel to the ground surface, i.e.:

$$y_o = \left(\frac{HT^3}{E_p I_p}\right)\Delta_y \quad (4)$$

Where:T is the relative stiffness between the pile and the soil, and for soils with sandy behavior and normally consolidated clays. It is defined by eq. 5:

$$T = \sqrt[5]{\frac{E_p I_p}{n_h}} \quad (5)$$

To calculate n_h, eq. 6 is used:

$$n_h = \frac{4{,}42 H^{5/3}}{y_o^{5/3} \left(E_p I_p\right)^{2/3}} \quad (6)$$

In the present study, the soil characteristics are analyzed using geotechnical laboratory tests and in-situ tests, with the aim of predicting its behavior in terms of deformability, resistance and collapsibility. To determine the horizontal reaction coefficient (n_h), the curves of the horizontal reaction coefficients (n_h) *vs.* the horizontal displacement at the surface (y_o) were obtained based on the performed load tests adopting a range of horizontal displacement values. [8] proposed the curves (n_h) *vs.* (y_o) using values in the 6.35 to 12.70 mm range. Based on these authors' studies but making a small modification in the range, the range between 6.0 mm and 12.0 mm was adopted, which was used by [10, 11, 12, 13]. The curves of the horizontal reaction coefficients *vs.* horizontal displacement were divided into two groups: load tests performed with natural soil moisture content and load tests performed with pre-flooding.

2. Materials and Methods

The aims of this study were achieved based on geotechnical analysis of the soil under investigation, execution of caissons, conduction of load tests in a caisson and analysis of the obtained data.

2.1. Geological and Geotechnical Characteristics

The study was conducted at the experimental site located at the School of Civil Engineering, Architecture and Urban Studies (Faculdade de Engenharia Civil, Arquitetura e Urbanismo) of the University of Campinas (Universidade Estadual de Campinas - Unicamp) in the municipality of Campinas, State of São Paulo, Brazil. The subsoil geotechnical properties were determined by the removal of undisturberd samples up to 8 m in depth and disturbed samples up to 9 m of depth (impenetrable). In-situ tests were performed: the standard penetration test (SPT) and the electric cone penetration test (CPT). The simple characterization tests are presented in Table 1, and the results for the triaxial tests, permeability tests, consolidation tests and the collapse index are presented in Table 2.

Table 1
Mean physical parameters of subsoil.

Layer (m)	LL (%)	PI (%)	γ_{nat} (kN/m^3)	w (%)	e	n (%)	SUCS
0 → 2.0	48	17	14.2	28	1.77	64	MH
2.0 → 8.0	45	10	14.9	27	1.60	61	ML
8.0 → 9.0	52	10	15.2	36	1.67	63	MH

LL- liquid limit; PI – plasticity index; γ_{nat} – natural specific weight; w – moisture content (Feb/2010); e – void ratio; n – porosity; * tests performed without deflocculant.
Source: Adapted from [14]

Table 2.
Resistance parameters, coefficients of permeability, compression indices of edometric test and collapse indices.

Depth (m)	1	2	3	4	5	6	7	8
C (kPa)	7	12	-	5	18	43	43	-
ϕ (º)	22	24	-	23	24	22	21	-
k (cm/s)	1.80	1.50	-	1.50	0.69	-	1.20	-
CI	0.33	0.42	0.26	0.29	0.16	0.15	0.15	0.13
CLI*(%)	6	23	20	27	7	9	11	0.10

C – cohesion; ϕ - Friction angle; k – permeability; CI - Compression index; CLI - Collapsivity index * Stress of 400 kPa
Triaxial test CU (total stress) test
Source: Adapted from [14]

The edometric tests conducted on undisturbed samples with flooding at different stress levels indicate the collapsible characteristics of the soil. Tests performed with tensions of 100 kPa, 200 kPa and 400 kPa. According to [15], indicated that the representative sample at 1 m of depth was observed to be collapsible, with a very elevated index for all the flooding stresses. For the 2 m and 3 m deep layers, it was possible to observe the low collapsibility index for the 100 kPa and 200 kPa stress, which in turn had a high index for the 400 kPa stress. Based on the data obtained for the 100 kPa stress, only the 1 m, 4 m and 8 m depths were observed to be collapsible. However, for the 200 kPa stress, only the 2 m and 3 m depths were not collapsible. Finally, for the flooding stress of 400 kPa, all of the depths were observed to be collapsible, with the exception of the 8 m depth. With the conduction of triaxial tests (CU), numerical values were obtained for the angle of friction and the cohesion intercepts (Table 2) for each depth. [16] verified a significant reduction of these values with the soil saturation.

The results for the SPT and CPT tests performed at 0.50 m from the caisson axis are presented in Table 3.

The grain size analysis indicates that the soil is mostly composed of silt and clay. However, its permeability characteristics with coefficients of the order of 1.5 x 10^{-3} cm/s

Table 3.
Results of the SPT and CPT tests.

Depth (m)	1	2	3	4	5	6	7	8	9
N_{72}	2	4	4	4	4	5	6	8	45
q_C (MPa)	2.56	1.42	1.32	1.86	2.14	2.37	3.00	1.88	1.73
f_S (MPa)	36.6	2.5	2.2	17.9	15.4	22.3	42.0	36.8	63.4
F_R	1.4	0.2	0.2	1.0	0.7	1.0	1.4	2.0	3.7

N_{72} – SPT test penetration resistance index; q_C – CPT test point resistance; f_S –CPT test lateral resistance; F_R- friction ratio (f_S/q_C).
Source: Adapted from [17]

and its characterization through results of the CPT test, when using classification graphs, indicate that its behavior is that of a sandy soil. Therefore, the analysis will be performed based on parameters proposed for the soil of granular behavior.

The information obtained based on the cone penetration test (CPT) and the standard penetration test (SPT) regarding the resistance parameters, soil type and unsaturated condition allow the prediction of a low resistance and most likely collapsible soil.

2.2. Preparation of Caissons

Three caissons were built to perform the load tests: one to undergo the transversal load and two to serve as a reaction to the applied load. All of the caissons had lengths of 9 m, shaft diameters of 0.8 m, base diameters of 1.6 m and base heights of 0.7 m. The caissons were set up along the depth with 15 bars with ϕ=25.0 mm and stirrups with ϕ=10.0 mm, spaced every 15 cm in steel with fyk=500 MPa. The concrete used exhibited fck=20 MPa, and the slump test was equal to 22 mm. The caissons were built using a manual excavation process. The caissons were constructed in a manner in which they would not undergo significant structural strains when subjected to loadings.

2.3. Load Tests

Before the execution of load tests, trenches were excavated between the caissons at a depth of 0.60 m under the caisson top for alignment with the application axis of the horizontal load. The load tests were performed using a hydraulic jack with 500 kN capacity with a pump, applying the load on the test caisson at one side and reacting against two other caissons at the other side, as the model displays in Figs. 1 and 2.

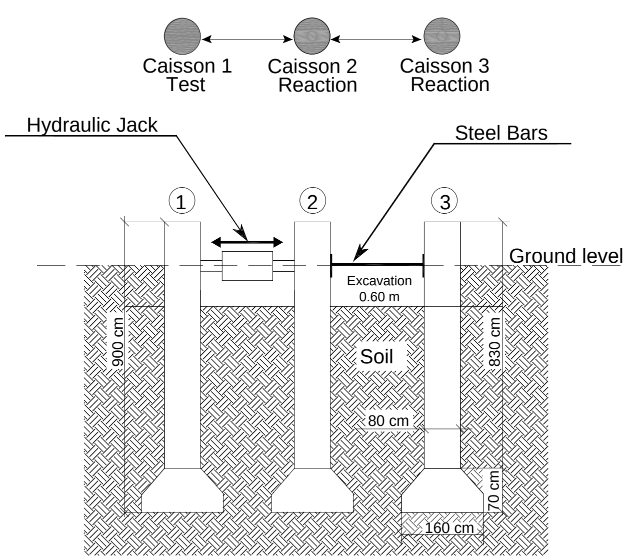

Figure 1. System setting.
Source: The authors.

Figure 2. Assembly detail.
Source: The authors.

To determine the load applied at the top of the caisson, a 500 kN load cell was used, and three deflectometers, with 0.01 mm precision, fixed on a reference beam were used for the measurement of the displacements. In two of the deflectometers, the readings were taken at the same level of the load application (horizontal), and in the third, the reading was taken along the vertical axis of the load.

Two load tests were performed in the same caisson following the guidelines of the standard [18]. The first test was of the slow maintained load type, with the soil in its natural moisture content state. The second, of the quick maintained load type, was performed after the superficial soil flooding with a pit for 48 h. The slow test was conducted with loads applied in equally increasing values, with readings of the displacements taken at pre-determined time intervals until the stabilization of the displacements, when a new load was increased, never more than 20% of the predicted working load. The consolidation was considered stabilized when the value read between the two successive times did not surpass 5% of the total consolidation of the loading stage. To perform the quick test, the load was maintained for 10 min, reading the initial and final stage values. The total load with an increase not higher than 10% of the working load proceeded until reaching twice the predicted working load for the caisson. Unloading was performed soon after the last loading stage in four load levels.

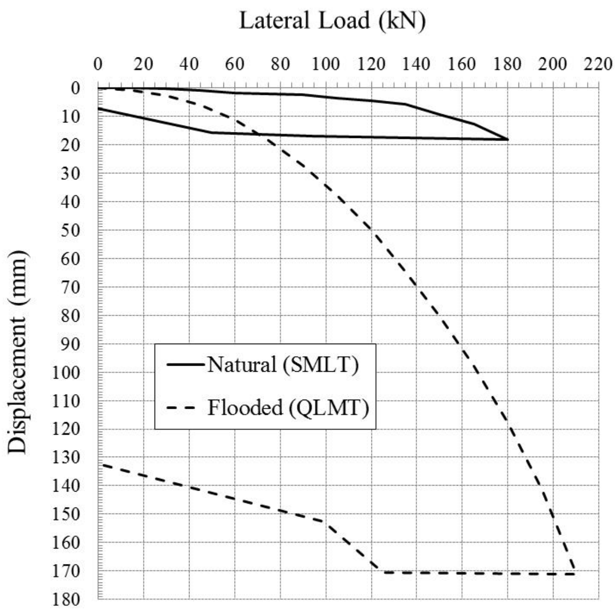

Figure 3. Load *vs.* horizontal displacement curves.
Source: The authors.

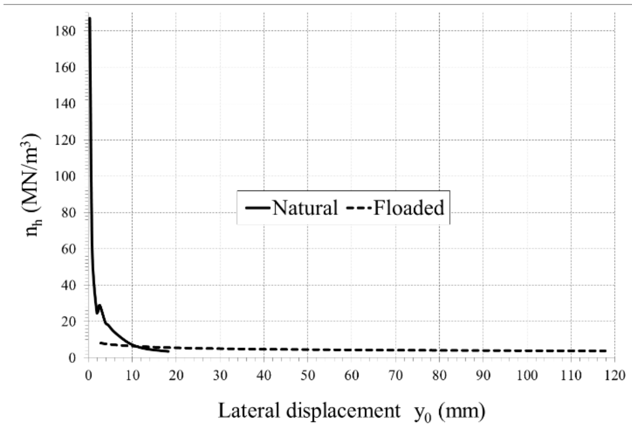

Figure 4. Graph of n_h *vs.* horizontal displacement.
Source: The authors.

3. Results and Analysis

Based on the performance of the load tests, the load *vs.* horizontal displacement curves were obtained. Plots of the horizontal reaction coefficient *vs.* horizontal displacement are presented in Figs. 3 and 4.

By analyzing Fig. 3, the displacement for each applied load level can be verified. For the admissible structure load of the caisson (140 kN), the horizontal displacement at the caisson top was observed to be 9 mm. The observations indicate that the curve obtained for the pre-flooded soil exhibited greater horizontal displacement for the same load applied.

The analyzed soil was lateritic and highly porous and unsaturated; its sand particles were cemented by clay and silt lumps, where the main minerals present were kaolinite and gibbsite. Hence, this soil had matrix potential because of the suction, which was lost when the soil is flooded, leading to a reduction in the resistance. This phenomenon can be observed in the analysis of Fig. 3 and 4, where the loss of stability can be noted in the presence of water, thus reducing its resistance characteristics. Note that the n_h values in the pre-flooded situation practically do not vary, which demonstrates a resistance loss of the soil from the beginning of loading (Fig. 4). Table 4 presents the load and horizontal displacement values in addition to the results for the horizontal reaction coefficients as a function of the subsoil condition.

Table 4. Values of horizontal loads, displacements and horizontal reaction coefficients.

Soil condition	Load to be displaced 6 mm	Load to be displaced 12 mm	Maximum values Load	Maximum values Displacement	n_h (MN/m^3)
Natural	135 kN	165 kN	180 kN	18.17 mm	12
Flooded	47 kN	62 kN	210 kN	171.1 mm	6

Source: The authors.

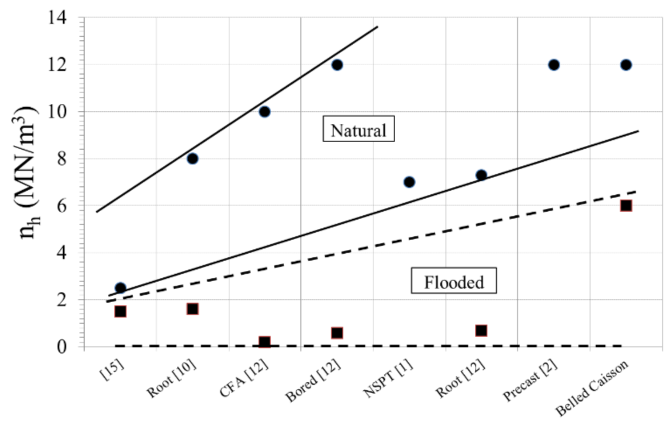

Figure 5. Graph of n_h *vs.* authors load tests.
Source: The authors.

The pre-flooding of the soil caused a pronounced increase in the displacements for the same load applied in the tests with natural soil. The results proved that the pre-flooding caused a reduction of the applied load by 2.5 to 3 fold to reach displacements of 6 and 12 mm. These results demonstrate the intensity of the effect of the variation of the soil moisture on the horizontal displacement characteristics of the pile.

The values for the horizontal reaction coefficients obtained in the literature for different types of deep foundations built on soil with similar behavior to the one from the present study (under natural and pre-flooded conditions) are presented in Fig. 5.

By analyzing Fig. 5, it is verified that in piles built on similar soils (sandy behavior, unsaturated and lateritic), the values for the horizontal reaction coefficient vary between 2 and 12 MN/m^3. With the exception of the precast concrete pile with 0.18 m and the foundation in this paper (belled caisson) with 0.8 m, the other piles exhibited diameters of 0.4 m. The observations indicate that the execution process of the pile did not affect the results. On the same graph (Fig. 3), the pre-flooding effect on the soil can be evaluated, with the reduction of n_h values, in some cases obtaining values lower than 1 MN/m^3. Generally, the values were reduced by at least 50%.

4. Conclusions

Based on the results obtained and the analysis performed, the following can be concluded:

- Because the first few meters of the soil have a great effect on the horizontal loading, their proper geotechnical characterization in terms of porosity, resistance and collapsibility is important.
- The laboratory and field tests indicated a highly porous, collapsible and low resistance soil, allowing the prediction of low n_h values and the great effect of the variation in the soil's moisture content.
- The horizontal reaction coefficient obtained for the soil at its natural moisture content was 12 MN/m^3, a higher value when compared with the literature for soils of high porosity, which suggests values of 2 MN/m^3, thus indicating the importance of its determination for each type of soil and therefore avoiding generalizations.
- The loads for pre-flooded soil to reach certain displacement levels were observed to be on average three times smaller than the ones for the soil at its natural moisture content. For the horizontal reaction coefficient of the soil, the pre-flooded values were approximately 50% lower than the ones for the soil at its natural moisture content.
- For the collapsible soils, the analysis of the possibility of saturation or great humidity variation of the superficial soil during its construction service life was of fundamental importance in the determination of project parameters.

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