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Behavior of plate load test in sedimentary soil in São Paulo / Brazil

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Abstract. The purpose of this paper was to study formulations, load capacity theories and estimation of displacements for the case of a solution in shallow foundations adopted in the works of a commercial building with 10 floors and 3 underground floors located in the city of São Caetano do Sul/SP, by means of a plate load test analysis. To this end, the local soil was submitted to laboratory testing to characterize and determine the geotechnical parameters that fed the methods proposed and presented in the literature. Tertiary sediments from the High Tietê basin prevail in this location. These sediments are composed of the São Paulo formation, of fluvial origin formed by layers of sandy silts and clayey sands with an N_{SPT} above 30 at the test depth. The test was performed in accordance with Brazilian Standard NBR 6489 following slow loading with a plate diameter of 0.8 m. The maximum stress displayed during the test was in the order of 1,200 kPa and maximum displacement of 28 mm. Semi-empirical and theoretical methods were used to obtain the admissible stress. Probabilistic analyses were produced to provide the index of reliability and ruin probability, so that the safety factor of the foundations could be reduced and the admissible stress of the project design could be increased.

Keywords. Plate load test, Sedimentary soil, Shallow foundation

1. Introduction

The estimated values for the resistance that a particular soil can attain, as well as the deformations it may undergo due to the loading of a structure, are currently calculated using a variety of methods and tools which, no matter how accurate they may be, will always be just estimates. This is because the uncertainties, under which geotechnical engineering operates, on account of the variability of the soil, lead the professional, due to the motives and needs of the market, to estimate resistance parameters based on a single test, the SPT, the one which is most frequently used in Brazil.

So studies are required that effectively strive to characterize and test the soils, with the aim of assessing the performance of methods already well-established in the practice of geotechnical engineering. This performance check is carried out, according to the various treatises [1], [2], [3], [4]; by means of load tests and, specifically in the case of more superficial foundations, plate load tests.

The purpose of this study was to evaluate the soil load support capacity by means of a plate load test with the aim of reducing the area of superficial foundations of a

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building in the town of São Caetano do Sul, São Paulo, Brazil. Initial estimates were performed by obtaining geotechnical parameters through the literature and geotechnical engineering practice, which supplied correlations for determining the admissible stress for the works. Dissatisfied with the value obtained and with the expectation of reducing the safety factor through testing during the project design phase, it was decided to carry out said testing.

2. Plate load test

A plate load test is a reduced-scale footings test, or in other words, a static test with the purpose of reproducing in the field the behavior of the soil-structure system when subjected to the action of compressive loads [1]. It is a question of applying a load to a plate such that the displacement occurring in the soil on account of its deformation can be measured, thereby enabling the production of curves known as stress *vs* settlement curves (Figure 1).

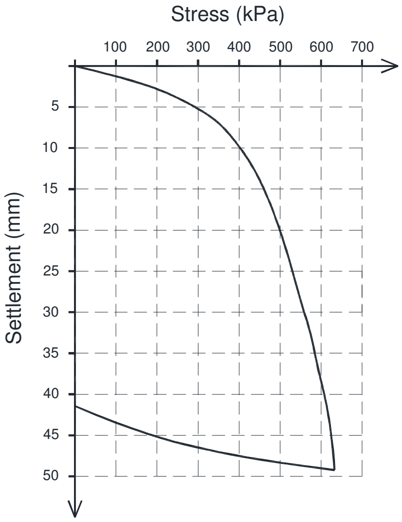

Figure 1. Stress vs settlement curve

The stress *vs* settlement curves are the object of a study to determine load capacity and settlement of superficial foundations, since it is possible through these to obtain data and characteristics of the foundation's deformability and resistance.

According to [5], the authors understand this test to be the most suitable way of determining the stress *vs* settlement characteristics of foundations. The plate test to be the best method for obtaining load-bearing capacity in superficial foundations [2].

[6] reproduced in the laboratory small-diameter plate tests (30 cm) in a box of sand measuring 1.2 m x 2 m x 2 m, in order to check the dissipation of stress applied by the soil on the plate. They concluded that, in addition to being easy to perform, the possibility of picturing the deformations and clearly verifying the soil behavior when subjected to loading at different depths of the test specimen, the laboratory plate load tests were very useful.

The plate test is applicable to soils where the profile is relatively constant in terms of depth, explained by the fact that the pressure bulb moved by the plate is less deep than the bulb generated by the superficial foundation elements. The acquisition of more reliable results based on a plate test should therefore be analyzed, *a priori* the soil beneath the plate, so that it is not disturbed and it retains a defined uniformity at depth [7].

2.1. Test types

Plate load tests may be classified in several ways according to the location, the plate type, load-bearing mode [4] and also the reaction system.

In terms of location: surface, furrows and in holes (greater depths).

As for the plate type (Figure 2):

- conventional plate: rectangular or circular steel plate, perfectly flat and in direct contact with the soil;

- screw plate: consists of a helical plate inserted in the soil by means of rotation.

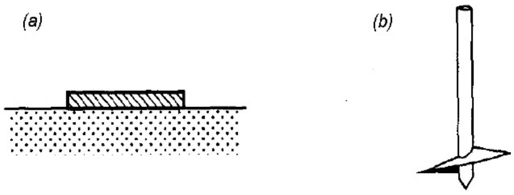

Figure 2. Type of plate: (a) conventional, (b) screw [4]

As for the load-bearing mode [8]:

- Slow Maintained Load Test (SML): equal, incremental loads are applied to the plate. Each increment is applied after the stabilization of the displacement caused by the previous loading. This is the method advocated by the brazilian standard [9] which establishes that the load increment that should take place after the displacement in the current stage should be lower than 5% of the total displacement.

- Quick Maintained Load Test (QML): equal, incremental loads are applied at predetermined time intervals. According to [10], 15 minutes should be sufficient.

- Cyclic Load Test (CLT): the load is applied to one third of the load of the project design, so that it is then discharged up to one half of the load and the cycle is repeated 20 times. The upper load limit is then increased 50%, the procedure being repeated until the point of rupture is reached.

3. Geological and geotechnical characteristics of the location

The location of this research study was Rua Pará, 147, in the São Caetano do Sul downtown, a borough in the region known as ABC Paulista. According to the Pedological Map of the State of São Paulo, in the ABC Paulista region, more precisely in the town of São Caetano do Sul, there is a prevalence of tertiary sediment from the High Tietê basin, composed of two formations: Resende and São Paulo.

The São Paulo Formation, originating in a meandering river system, is composed of layers of sandy clay and clayey sand with good characteristics. The Resende Formation, a lacustrine river system, comprises layers of hard, grey, silty clay and silty sand. The clays are very plastic and have excellent characteristics; however the sands are not very cohesive and are very saturated. The location is composed of an initial layer of sandy clay fill, 2 m thick, followed by a layer of silty clay as much as 20 m deep (impenetrable).

The average soil resistance values along the depth profile and the maximum and minimum values for each meter, originating from the Standard Penetration Test (SPT) percussion drillings, conducted in the location of the study, are exhibited in Figure 3. The variability of the soil resistance along the depth can be observed. Note that the drillings were performed prior to the 8 m dig, which would equate to the bottom of the footings.

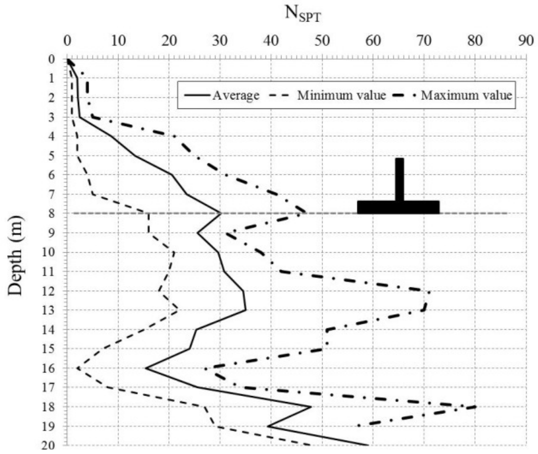

Figure 3. Variation in N_{SPT} values along the depth [11]

An undisturbed sample of soil was removed in order to conduct the soil characterization tests in the location of the study, in accordance with instructions [12]. The sample was molded into the shape of a block measuring 35 cm x 45 cm x 45 cm, at a depth of 8 m, at the bottom of the footings. This depth was attained by digging the entire plot, checked simultaneously by the soil nailing method, so that the subsoil of the building could be built at a future time.

Along with the removal of the non-deformed sample, characterization and triaxial shear tests (CD) were carried out in order to characterize and obtain the geotechnical parameters for the study. The results are shown in table 1.

Table 1. Soil characteristics [11]

Specific weight of soil	20.8 kN/m^3	Plasticity index	28 %
Specific weight of solids	27.6 kN/m^3	Clay	41 %
Moisture content	20.8%	Silt	28 %
Void ratio	0.6	Sand	31 %
Porosity	38 %	Effective cohesion	67 kPa
Degree of saturation	96 %	Effective friction angle	19º
Limit of liquidity	54 %		

4. Load test – assembly, testing and results

The Brazilian standard used for plate tests [9] sets out the conditions which must be satisfied for instances of plate load tests. Accordingly, for the current work, a slow plate load test was carried out.

A reaction system was employed that uses segmented, helical piles with a diameter of 40 cm and length of 12 m. Dywidag ST 85/105 Ø 32 mm type threaded anchor bars were used. According to the manufacturer, the characteristics of this anchor bar include flow and rupture resistance limited to 680 kN and 840 kN, respectively.

The assembly begins with the placement of the metal reaction beam on the two reaction piles in such a way that the assembly of the load test is made possible in accordance with the diagram in Figure 4.

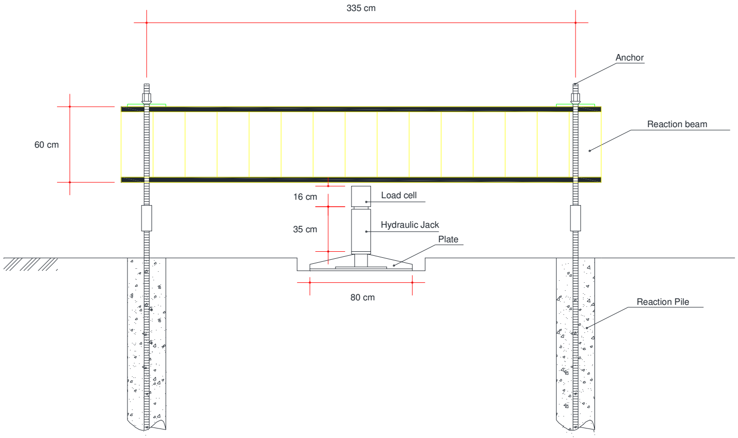

Figure 4. Diagram of load test asssembly

The metal plate for transferring the load to the soil was then positioned, considered to be rigid with an area of 0.5 m², supported on the soil in its natural state, duly levelled, in a pit 10 cm deep. The leveling of the supporting soil was carefully carried out in order to avoid any alteration in the degree of natural humidity and squashing of the soil at the load surface. Around the plate, care was taken to ensure there was no load applied to a strip with a width at least 1.5 times the diameter of the plate, as per recommendations [9].

The transmission device comprised a hydraulic jack so as to ensure that the load was applied vertically in the center of the plate, thereby lessening any jolts or vibrations. In order to take the readings and to control the load application, a load cell was used with a capacity of 1000 kN connected to a panel where the deformation data could be read. Deflectometers, sensitive to 0.01 mm, were placed at four diametrically opposed points of the plate for the reading of the settlements (Figure 5).

Figure 5. Assembled load test.

The load test followed the principles of the standard [9], i.e., in successive stages of no more than 20% of the probable admissible soil rate, a new incremental load only being carried out after the stabilization of the settlements. The results are presented in the form of a graph by way of the stress vs settlement curve (Figure 6). The maximum tension was 1200 kPa and the maximum settlement 28 mm.

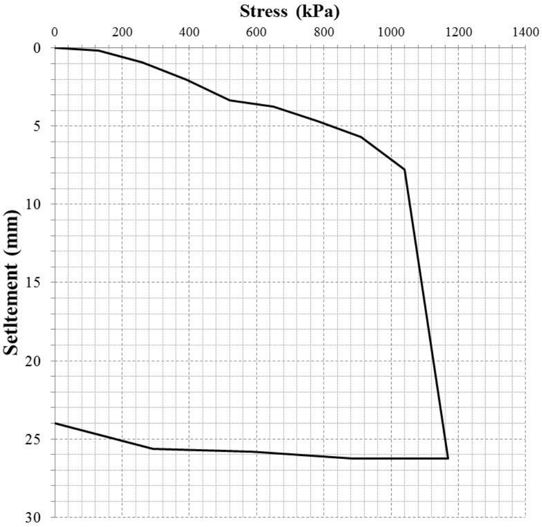

Figure 6. Stress *vs* settlement curve [11]

5. Load capacity

Stress rupture was calculated using theoretical (laboratory tests) and semi-empirical (SPT boring) methods and, based on these, using the safety factors suggested by the literature, the admissible stress values were obtained. Figure 7 shows the results obtained using each method, the variances and a comparison with the load test results obtained.

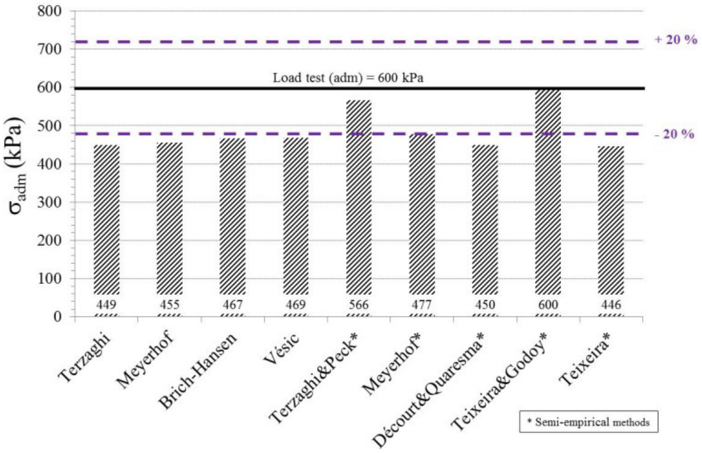

Figure 7. Variation in admissible stress according to the method employed [11]

Looking at figure 7, it can be seen that none of the methods employed exhibited values higher than that obtained via the load test (600 kPa). All the values obtained using theoretical methods had values below an interval considered to be acceptable (± 20%) in relation to the value provided by the load test. Analyzing the semi-empirical methods, it was found that the values provided by Terzaghi & Peck and by Teixeira & Godoy were better as the error fell within a range of ± 20%; the [13] method produced the same values achieved in the test. This method, widely employed to gather initial estimates of admissible stress in geotechnical engineering practice, is the result of research conducted on the tertiary clay in the city of São Paulo. Though a N_{SPT} blow count interval between 5 and 20 is advocated, the method was suitably adapted to the soil in this study with an average N_{SPT} count of 30 blows.

6. Ruin probability

The ruin probability analysis is carried out by analyzing the stress-strain (S) obtaining the dimensions by means of the soil's admissible resistance stress (R), and thus the footings required to bear the weight of the superstructure of the building under construction. Based on these prerogatives, the following measurements are taken: average (μ), standard deviation (σ) and coefficient of variation (υ), both for the stress-strain (S) and the resistance stress (R) in respect of the stress rupture in all the methods employed (Table 2).

Table 2. Statistic values of S and R.

Parameter	Strain	Resistance
Average (μ)	543 kPa	1243 kPa
Standard Deviation (σ)	70 kPa	69 kPa
Coefficient of Variation (υ)	12.9 %	5.6 %

Based on the values presented in Table 2, a value of $\beta = 7.079$ was obtained, resulting in a ruin probability of 1.38 x 10^{12}, with a safety factor (SF) of 2.29. These analyses lead to the adoption of a better soil bearing stress, thus raising the admissible stress to 800 kPa, which gives us a ruin probability in the region of 1:590,000, with a SF = 1.7, which is acceptable for the works in question, enabling a reduction in footings geometry and also costs.

7. Conclusions

- By considering the analysis of load-bearing capacity using theoretical methods, it was possible to find that all the methods employed were seen to be conservative, suggesting the possibility of a reduced safety factor. The results of the semi-empirical methods were variable, also conservative, with the exception of the Teixeira & Godoy method used in local geotechnical practice, giving a result which was the closest to the load test.
- The probabilistic method for superficial foundation reliability was found to be advantageous when compared to traditional, deterministic methods, being more sensitive in terms of the safety factor. In the case of the works in question, it was possible to verify performance through the plate load test. The safety factor could thus be reduced to a value less than that recommended by the brazilian standard, which would reduce foundation costs.
- Although engineering practice is only linked to SPT tests, the load testing in association with the laboratory assays were essential for determining the confidence index, so that a statistical analysis could be conducted with a larger sample size.
- The use of the plate test in the works was fundamental for the evaluation of the admissible stress adopted in the project design and in helping with the decision-making in terms of sizing guidelines.

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