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Predicted and measured behavior of a tall building in a lateritic clay

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ABSTRACT: For design purposes, SPT-Ts and in situ determinations of G_0, were carried out. The efficiency of the Brazilian SPT is, on average, 72%. Settlement rather than capacity governed the design. Later, with the building already under construction, other tests were performed, exclusively for research purposes. A load test was carried out on a square footing foundation, up to the conventional failure load, Q_{uc} (the load corresponding to a settlement of 10% of the equivalent width of the foundation, B_{eq}). Based on these test results, predictions of capacity and deformations of the foundations were made. And, what is unusual in any foundation experimental field, a 25 storey building was constructed, the settlements of its columns being measured. However, these settlement measurements started only when about 2/3 of the nominal column loads had already been applied. Computer programs were developed, for allowing correct assessments of column loads and settlements, since the very beginning of the loadings. The measured settlements, up to the end of construction were very small, less than 10.0 mm, no matter the stresses applied to the footings being very high, typically 1.2 MPa, confirming the high stiffness (load/settlement) of this lateritic clay.

1 INTRODUCTION

The Carmel Building was constructed by Grotta Company, owned by the second author. The foundation design was made by the first author. For design purposes SPT-Ts were carried out. The SPT-T is the traditional SPT complemented by torque measurements, T, Décourt & Quaresma Filho (1994).

The equivalent (N_{eq}) is defined: $N_{eq} = T$ (kgf.m)/ 1.2. Considering that the boring results suggested that the clay layers were lateritic, Cross Hole and SDMT tests have also been carried out. The correlation $G_0 \times N_{SPT}$, established by Barros and Pinto (1997) was used for identifying this type of soil. Décourt (1994) demonstrated that lateritic clays present stiffness much higher (tipically 2 or more times) than other clays, with similar N_{SPT} values.

2 THE FOUNDATION DESIGN

In the area where the building was constructed, the bearing layer was a hard sandy silty clay, red and yellow.

The values of N_{SPT} and N_{eq} were 26 ± 15%, the lower bond value corresponding to the average of the N_{eq} values and the upper bond value, the average of the traditional penetration resistance, N_{SPT}.

Cross Hole and SDMT tests confirmed that these clays were lateritic. The design was based exclusively on settlement predictions, using the method proposed by the first author, Décourt (1999).

$$\log q/q_{uc} = C\,(1 + \log s/B_{eq})$$

where s= settlement and B_{eq} is the square root of the footing area. The two fundamental parameters in the above formula, the stress corresponding to the conventional bearing capacity, q_{uc} and the Coefficient of Intrinsic Compressibility, C, were much better for this lateritic clay than those for common soils.

For most of soils found in São Paulo city, whose grains are made of quartz, C values are 0.4 ± 10%, and q_{uc} is obtained using correlations with N_{SPT}, proposed in Décourt (1995). For partially saturated soils, other than sands, q_{uc} in kgf/cm² units is approximately, equal to the Brazilian N_{SPT} (average efficiency of 72%). Using the official SI units: q_{uc} (MPa) = N_{SPT} /10. For sands, q_{uc} is approximately 20% higher and for saturated clays, approximately 20% lower.

The average value of N_{SPT} considered was 26 and a majorating factor β_l, for lateritic clays, equal to 1.5 was adopted. Therefore, q_{uc} (MPa) = $(0.8\times1.5\times26)/10 = 3.12$ MPa (lateritic saturated clay).

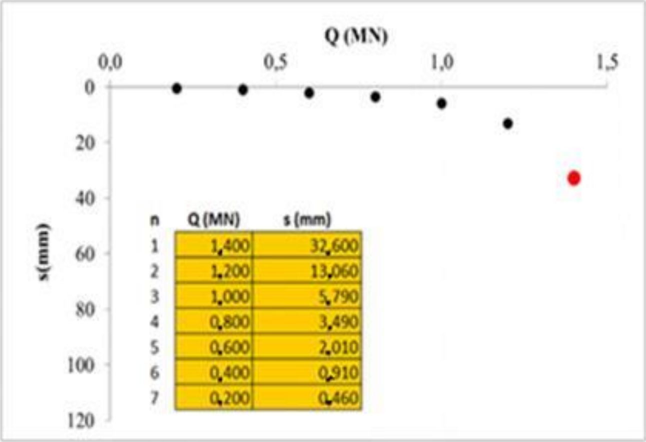
The C value considered was the most adequate for São Paulo clays, 0.42. The maximum tension applied to the soil by the footings was 1.2MPa. The expected settlements were about 20.0mm.

3 LOADING TESTS

With the construction of the building under way, the first two authors decided to implement at this site a foundation experimental field.

In a region behind the building, here named Site I, a load test was carried out on a square block foundation with 78.0 cm in width. The average N_{SPT} value (efficiency of 72%) was 21, corresponding to $N_{60} \cong 25$.

The results of this loading test are presented in figures 1, 2 and 3.



n	Q (MN)	s (mm)
1	1,400	32,600
2	1,200	13,060
3	1,000	5,790
4	0,800	3,490
5	0,600	2,010
6	0,400	0,910
7	0,200	0,460

Figure 1 - Load test data

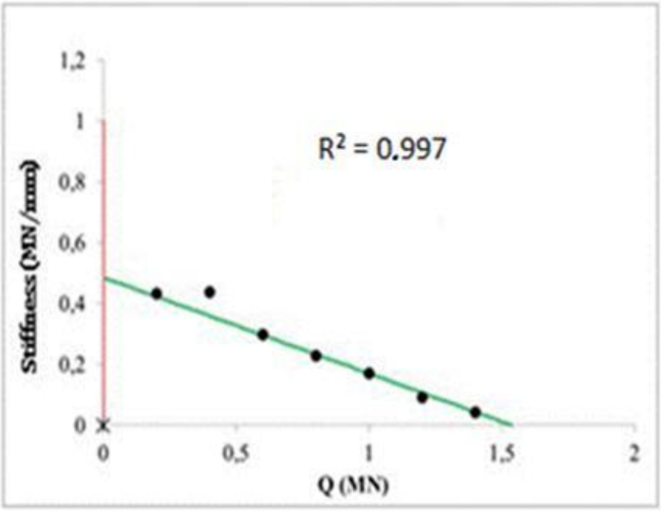


Figure 2 – The stiffness plot, Décourt (1999)

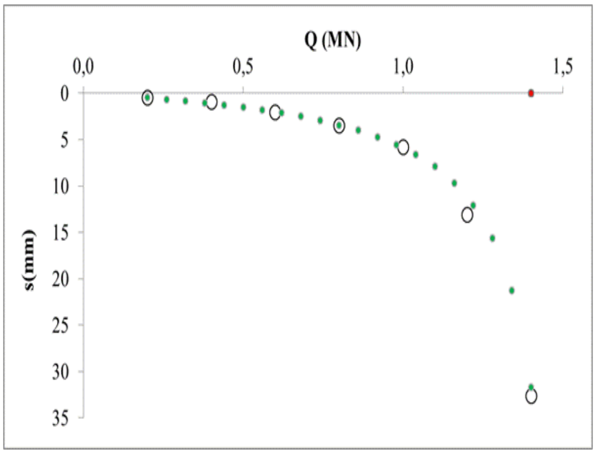


Figure 3 – Measured values and the regression curve that best fits the data

The results and the interpretation made using the stiffness plot, developed by the first author, Décourt (1999) are presented. The relation load x stiffness was a straight line; see Fgure 2.

The conventional bearing capacity, Quc, according to this method was 1.46MN and the corresponding stress, q_{uc}, was 2.40MPa. In Figure 4 relationships between $q/q_{uc} \times s/B_{eq}$ for common soil are presented, for different values of C. Observe that lateritic clays may follow, sometimes, a different pattern, as for example the cases of Carmel Building and Décourt (2003).

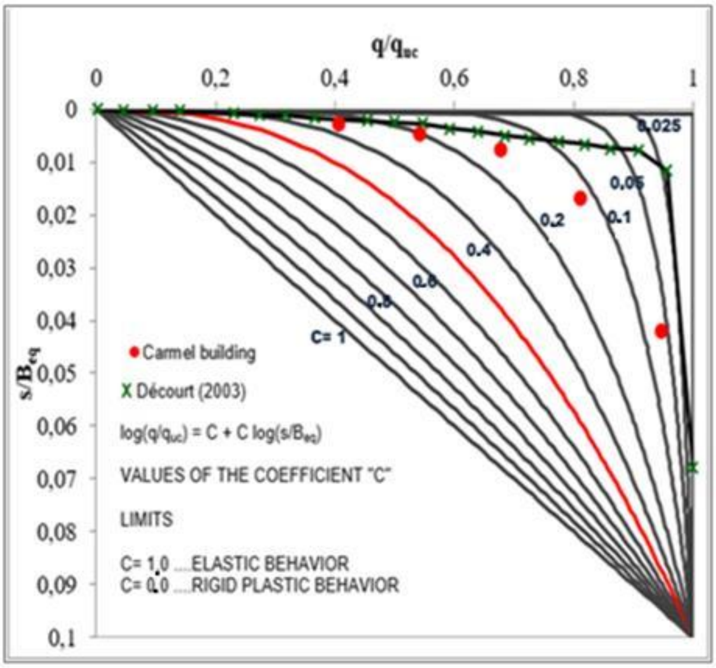


Figure 4 – Values of q/q_{uc} x s/B_{eq} as a function of C

4 SETTLEMENT MEASUREMENTS

4.1 *Measured values*

Column settlement measurements have been made by a team of the Technological Research Institute of São Paulo (IPT) under the guidance of the fourth author. Unfortunately, these measurements started only when about 60% of column loads had already been applied. However, the knowledge of the magnitude of these settlements, since the very beginning of the loadings, was considered fundamental.

4.2 *Correction method*

The second author developed a program in order to estimate the loads applied to the building columns, at any stage of the construction, taking into account the permanent static loads of the following elements, namely: structure, masonry (with built-in installation), subfloor, internal parget, external parget, floor and wall tiles.

As settlements were measured by IPT (Technological Research Institute), the loads applied by the above elements (according to the stage of execution at that moment) were estimated and distributed on the columns previously built. Accordingly, only live loads were considered. In order to obtain the settlement missing informations, a computer program was developed by the first author. The stiffness plot, Décourt (1999), was used. The program corrects the measured settlements of the columns. Using both programs, it was possible to simulate a loading test for each of these columns

4.3 *Checking the validity of the proposed correction method using load test data*

For checking the reliability of the proposed method for correcting the measured settlements, the loading test carried out on the square block was used.

For the load of 0.6MN, the measured settlement, in the load test, was 2.01mm. This value was subtracted from all other measured settlements. In figure 5 the plot stiffness x load is presented.

The coefficient of correlation, R^2 was very poor, 0.922 as compared with the one corresponding to the original load test, 0.997. The method for settlement correction was applied and a settlement of 2.06mm for the load of 0.6MN was obtained, a value that differs from the measured one (2.01mm) by only 2.48%, confirming its reliability.

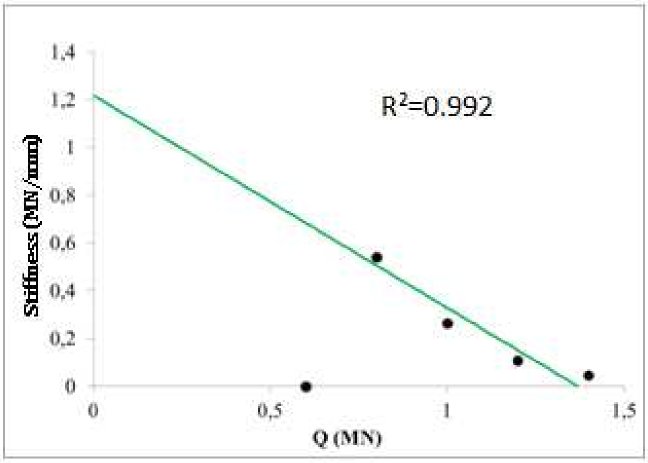
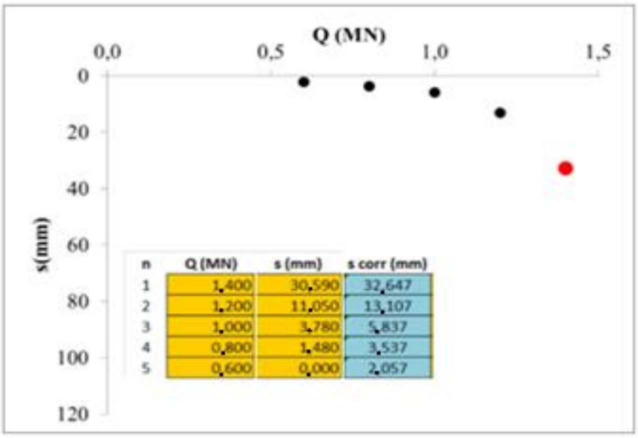


Figure 5 – Stiffness plot for the simulated curve



n	Q (MN)	s (mm)	s corr (mm)
1	1,400	30,590	32,647
2	1,200	11,050	13,107
3	1,000	3,780	5,837
4	0,800	1,480	3,537
5	0,600	0,000	2,057

Figure 6 – Corrected load settlements curve

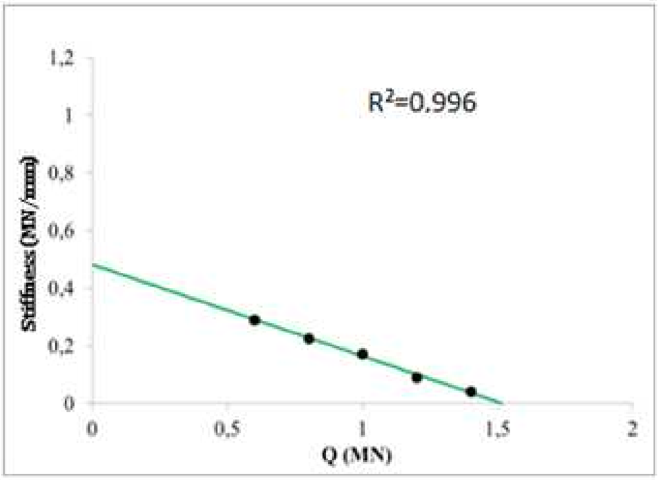


Figure 7 - Stiffness plot for the reconstituted curve

In the stiffness plot, with this value included, the coefficient of correlation was again very high, 0.996, a value practically identical to that corresponding to the original loading test, 0.997.

5 CORRECTED SETTLEMENT VALUES

In figures 8, 9 and 10 the corrected load-settlement curves are presented, for 3 columns.

These curves allowed not only the knowledge of the full range of settlement values, but also represent the best fit to the measured ones.

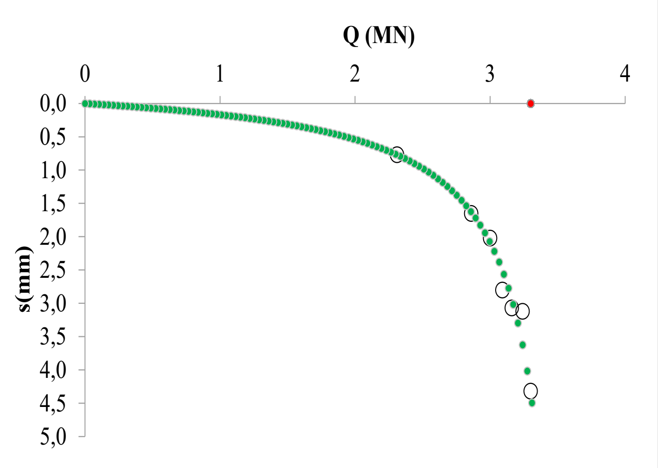


Figure 8 – Corrected load-settlement curve for P6A

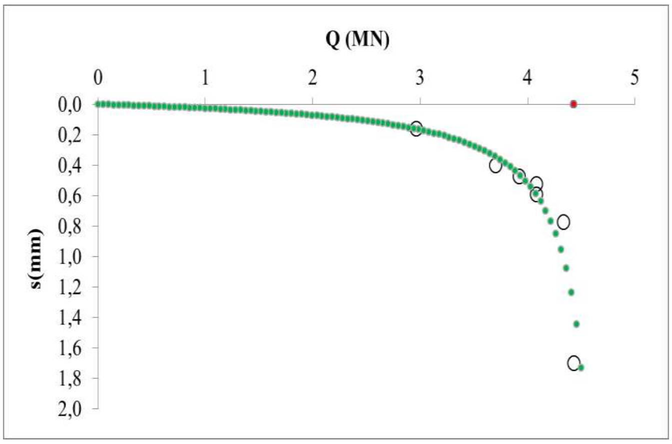


Figure 9 – Corrected load-settlement curve for P23A

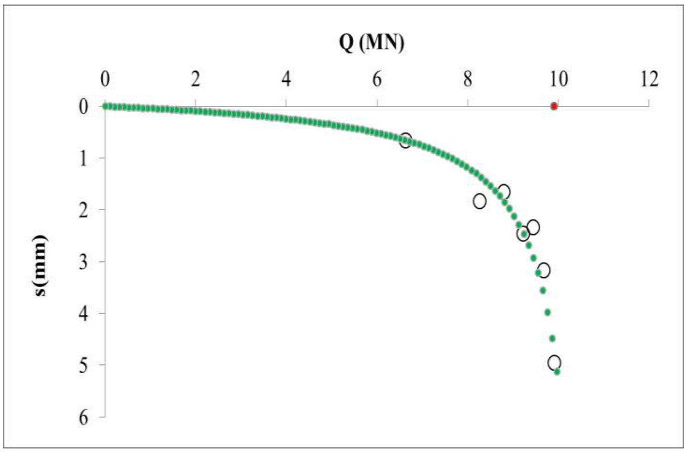


Figure 10 – Corrected load-settlement curve for P13B/P15B

In Table 2, for each column whose settlements were measured, estimates of q_{uc}, are presented, Décourt (1999). Knowing q_{uc}, the corresponding values of N_{SPT} could be derived, assuming valid for lateritic clays, Décourt (1995) proposals. Two soil conditions were considered, non saturated soil (type II) and saturated soil (type III).

Table 2. Soil parameters derived from settlement measurements

Column	s_c (mm)	q_{uc} (MPa)	C	N_{SPT^*}
6A	4.320	2.470	0.210	25/31
21A	3.098	2.142	0.205	21/27
23A	1.701	2.277	0.177	23/28
12A/14A	1.225	2.520	0.229	25/31
13A/15A	1.837	xx	xx	xx
Average		2.352	0.205	23.50/29
3B	7.740	2.420	0.290	23/29
8B	7.901	1.950	0.223	19.5/24.5
20B	6.923	2.530	0.256	25/31
12B/14B	5.988	2.400	0.284	24/30
13B/15B	4.942	2.050	0.208	20.5/25.5
Average		2.270	0.252	22.5/28

* Lower values corresponding to non saturated soils (type II) and higher values corresponding to saturated soils, type III, Décourt (1995).

xx Results considered non reliable.

The range of values, for both, blocks A and B were more or less the same 23/29. The average values of C, however, varied substantially, from 0.205 for block A, to 0.252 for block B. The difference in C values is the main responsible for the differences in the measured settlements, much higher for block B, than for block A.

It is also interesting to observe that this range of values, 23/29, falls within the range of average values given by the borings 22/30, the lower value being average of N_{eq} and the higher value average of N_{SPT}.

6 CONCLUSIONS

The initial investigations, SPT-T, Cross-Hole and SDMT allowed correct assessment of capacity and confirmed the lateritic characteristics of the clay layers. But these tests gave no information on the compressibility of these layers which is fundamental for correct settlement predictions.

The load test on a square block, 0.78m in width, confirmed the predicted capacity of shallow footings on this clay. But, what is of paramount importance, is that the average Coefficient of Intrinsic Compressibility, C, was half the value considered in design. Besides, C values were not constant, as it usually happens for most of the soils, but decrease as the applied stresses increase. Such behavior is characteristic of some soils with cemented particles and have already been detected by Décourt (2003). The analysis of the settlement measurements, simulating load tests, suggested that characteristic N_{SPT} values and q_{uc} were about the same for both blocks A and B, but C values were higher for block B as compared to block A (0.252 and 0.205). The measured settlements for block B at the end of construction were, on average, less than half the values predicted in design and those for block A, on average, less than 50% of those corresponding to block B.

Notwithstanding the applied stresses being more than twice those currently considered in design, the settlements were less than half the expected values, demonstrating the outstanding importance of recognizing lateritic clays.

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