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Control and prediction of the pile foundations behavior through settlement measures

Contrôle et Prévision du comportement des piliers de fondation au moyen de la mesure des tassements

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ABSTRACT

This paper shows experimental results of settlement measurements of a residential building during construction. The foundation is composed by deep continuous auger pile. The foundation strata is basically constituted by soft/loose soils. Important aspects are pointed out regarding soil-structure interaction and its influence on mechanical response of the building. A brief description of the surveying methodology is presented. The evaluation of the loading in the foundation was done by a three dimensional numerical model. Two different mechanical approaches were considered: fixed foundation (no movements) and one dimensional movements foundation, where the foundation is considered to displace in vertical direction only. The soil-structure interaction was assessed by comparison the measured settlements against the loads obtained through two approaches considered. These results allowed the evaluation of factors that play important role on the load re-distribution due to soil-structure interactions, mainly the increase of structure rigidity.

RÉSUMÉ

Cet article présente les mesures expérimentales de tassement d'um bâtiment résidentiel durant la phase constructive. Les fondations du batiment sont des pieux continus en hélice. Le massif de fondation est constitué de sols moux ou tendres. Des aspects importants de l'interaction sol-structure sont la matière de la discussion ainsi que son influence dans le comportement du bâtiment. On présente brièvement une description de la metodologie adoptée pour le suivi des tassements. La determination des charges des fondations se realise au moyen d'un modèle tri-dimensionnel du bâtiment. Deux modèles de fondations sont considérés : un fixe indéformable et l'autre mobile dans le sens vertical. La comparaison des tassements registrés après application des charges obtenues dans les deux cas ont permis l'appréciation de l'interaction sol-structure. Les résultats obtenus ont permis aussi la determination de facteurs qui quantifient la redistribution des charges et la dispersion des tassements dus à l'interaction sol-structure.

1 INTRODUCTION

Basically, buildings are composed by three main parts: superstructure, foundation and subsoil. These three parts constitute themselves the soil-structure system.

In geotechnical engineering it is usual monitoring displacements in buildings foundation caused by load generation in construction and also live loads. These displacements can be vertical, horizontal or rotational. The vertical displacements, called settlements, are more frequently observed in buildings. The occurrence of settlements is not a disturbing fact, but when the buildings foundation suffers settlement with different magnitudes, special attention is needed. This fact is justified by the significant amount of aesthetical and structural problems observed in the building, caused by the differential settlements on foundation structure. Differential settlements may be understood as difference between two foundations unity of the building. When the values of these displacements rise above a certain limits, a modification in the structural stress state of building and therefore, a redistribution of the foundations loads occurs. Then, the differential settlement may be one of the causes of damage of building structure, as the walls cracks and, eventually, the structural collapse (Velloso and Lopes, 2002). In this way, the construction efficiency depends on the capacity to absorb and to redistribute the stress increment generated by the differentials settlements. This is called soil-structure interaction. It is defined by the displacements compatibility of ground and building structure, that, in spite of its relevance, it is commonly by-passed in most projects. During the evolution of the building settlements, the soil-structure interaction generates regularization of foundation displacements. It will be depending, fundamentally, on the stiffness soil-structure combination. This regularization reduces the building structure distortion and, therefore, may prevent from damage to appear.

Results in the literature show that the effect of soil-structure interaction in buildings induces load increments in the pillars with low loads, at most. Consequently, in these pillars, the measured settlements will be larger than those predicted by the conventional methods, when the foundations are considered rigid. In the most loaded pillars, the inverse behavior takes place; i.e., the decrease of load and also in the calculated settlement. The effect of soil-structure interaction depends, specially, on the structure stiffness. As the stiffness of the structure is very influenced by the height of the construction and by the wall elements, the constructive sequence plays an important role in the soil-structure behavior. (Gusmão and Gusmão Filho, 1994; Lucena et al. 2004; Gusmão, 1994; Gusmão Filho, 2002). The lack of consideration of the differential settlement effects in the hyper-static structures calculation makes the foundations work in conditions different that one which was predicted on the project (Chamecki, 1961).

On the other hand, to evaluate the influence of the subsoil, comparisons can be made between predicted and observed settlement along with a comprehensive numerical analysis of the structure. However, the validity of the soil-structure interaction model should be associated to the difference between coefficient of variance of predicted and observed settlements (Gusmão Filho, 2002).

In any case, monitoring movements of the foundation is essential.

The Brazilian foundation practice considers the foundation monitoring only in special and emergence cases where cracks and fissures appear.

Danziger at al (2000) point out that recent failures have called for the importance of monitoring. In fact, foundation monitoring can give chance to early interventions that will certainly be cheaper than later interventions.

It is mister to point out that foundation, which is the most important element in a building construction, are almost always not monitored nor controlled for attesting its quality, despite the fact it is suggested by the norm NBR 6122/96 (ABNT, 1996). Controls are restricted, in most cases, to the data analysis of the foundation work (Danziger et al., 2000).

Settlement control is of crucial importance in order to enhance design of the foundation and the structure, as well.

However, it does not matter how accurate is the settlement analysis, if the actual value which can be supported by the structure, is not known (Skempton e MacDonald, 1956).

In accordance to exposed, this paper presents experimental results of monitoring foundation of a residential building and therefore to assess the soil-structure interaction behavior.

2 STUDY CASE

This work presents the results obtained from monitoring settlement of a residential building during construction in the Region North of the State of Rio de Janeiro, Brazil.

The object of this analysis is a twelve-storey building plus a garages floor. Figure 1 shows the three dimension numerical model used for evaluation the foundation loads. The building structure consists of conventional reinforced concrete and brick ceramic masonry in walls. The building foundation had been defined as continuous flight auger, with 22 meters average in depth and 50 and 60cm of diameter. These are directly beneath the pillars located in body of the building. To the pillars in periphery, shallow footing with 1.5m deep was used.

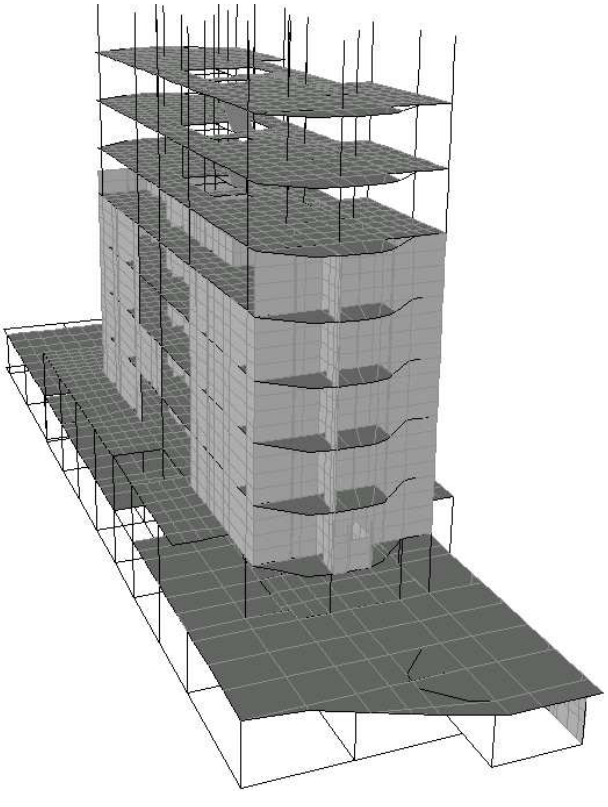

Figure 1 – 3D model considered for the evaluation of the loads.

The local subsoil is mainly constituted by material of alluvial deposits, with occurrence of thick layers of soft/loose soils. Figure 2 presents the geologic profile determinated from SPT recorded files. It can be noticed that the points of the piles are placed in resistant material layer. However, there exist soft material layers along the pile shaft.

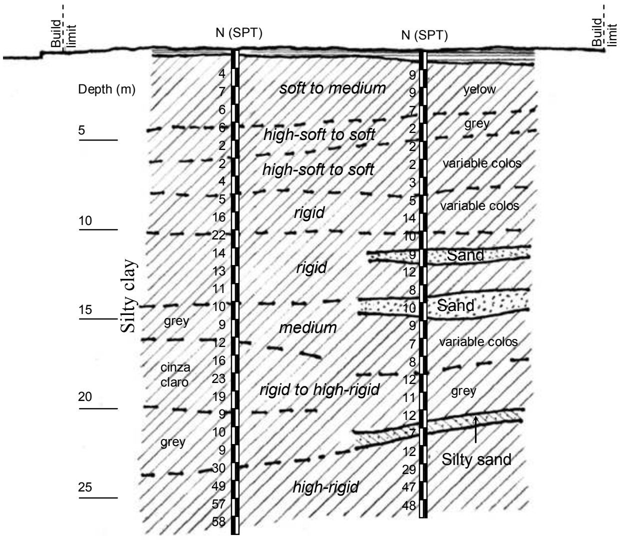

Figure 2 – Geologic profile of local subsoil

3 DISPLACEMENT MESUMENT METHODOLOGY

The settlement monitoring was made through the measurement of the vertical displacements of the pillar in stilts area, in relation to deep datum. The benchmark datum was placed in region that is believed to be free from the influence of the construction or any other cause that can mess up the measurements.

The measurement of the displacements was made through Terzaghi water level, with 0,04mm standard error and 0,06mm of accuracy, designed and enhanced to both supply the needs and to overcome specific difficulties of the study case. Details of the equipment and procedures of measurement are presented by Maia et al. (2004).

The installation of the bolts in the pillars and the first measurement took place after construction of the pillars in stilts area and before the first floor concreting. The subsequent readings had been made immediately before the concreting of each floor. This made possible the definition of the evolution of settlement during the construction, providing conditions of evaluating the foundations efficiency. Maia et al. (2004) presents details of the bolts setting.

4 RESULTS AND DISCUSSIONS

By means of 3D numerical structural modeling of the building, the estimation of loads transmitted for the foundation was possible. For the foundation two hypotheses had been considered: fixed supports and supports with degree of freedom in the vertical direction. Figure 3 presents the load versus stress curves for the foundations pillars over a group of two piles with equal diameter 60cm and considering the first hypothesis of foundation.

For the second hypothesis, the measured vertical displacements of the foundations had been imposed to the structural model as prescribed values. Figure 4 presents the load versus stresses curves considering the second hypothesis of foundation.

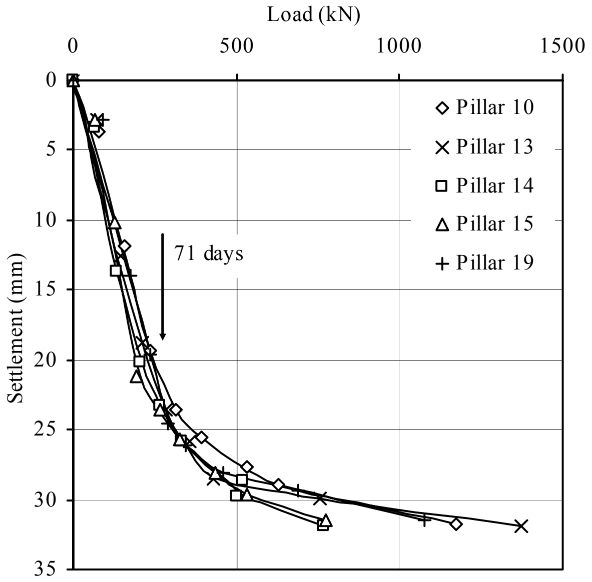

Figure 3 – Load versus stress curves for fixed foundations hypotheses

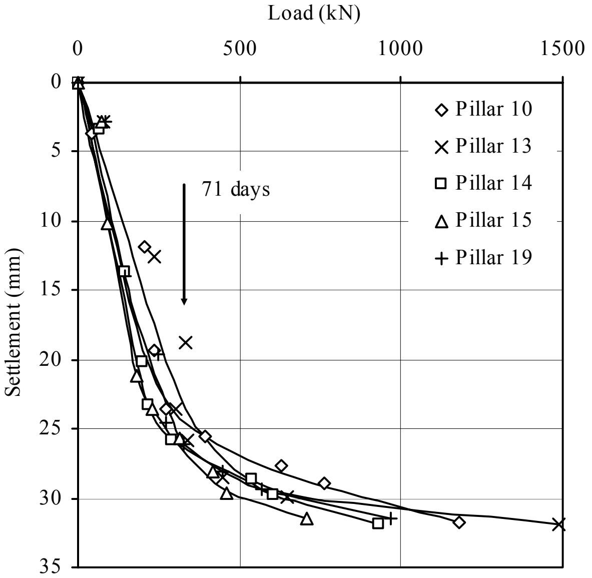

Figure 4 – Load versus stress curves for foundations hypotheses with degree of freedom in the vertical direction

From Figures 3 and 4 it can be verified that a clear modification of the foundation load occurs when the foundation displacements are considered. In this in case the soil-structure interaction provoked the increase or the reduction of foundation loads, depending basically on the position of the pillar in the structure: periphery or central, respectively.

Figures 5 to 7 present the evolution of load redistribution in function of the settlement dispersion. The redistribution of loads F_Q is defined by the following expression:

$$F_Q = \frac{Q_{ssi} - Q_i}{Q_i} \quad \text{for} \quad Q_i \geq Q_{ssi} \tag{1}$$

or

$$F_Q = \frac{Q_{ssi} - Q_i}{Q_{ssi}} \quad \text{for} \quad Q_i < Q_{ssi} \tag{2}$$

where Q_i is the load of pillar i that was estimated for the structure with fixed supports and Q_{ssi} is the estimated load of pillar i considering the soil-structure interaction. In this way F_Q assumes negative or positive values when the pillar loses or gains load due the soil-structure interaction, respectively, and it takes always the values between -1 and 1.

The dispersion of settlement D_w is defined by the following expression:

$$D_w = \frac{w_i - \overline{w}}{\overline{w}} \tag{3}$$

Where w_i is the settlement of pillar i and w is the average settlement over the whole area. Generally D_w assumes values between -1 and 1.

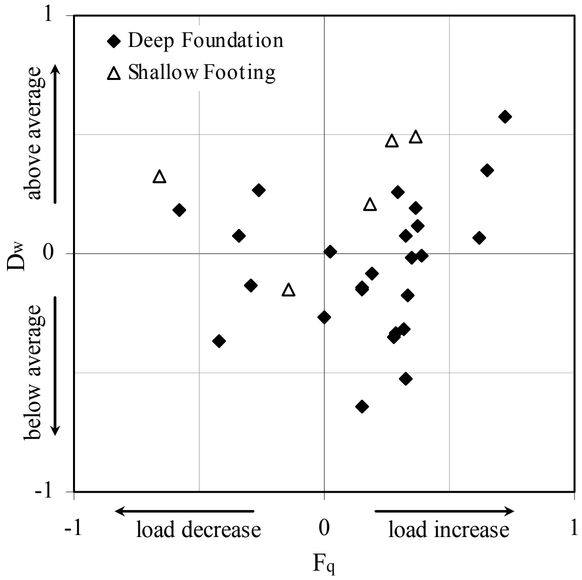

Figure 5 – Load redistribution in function of the settlement dispersion for firth floor

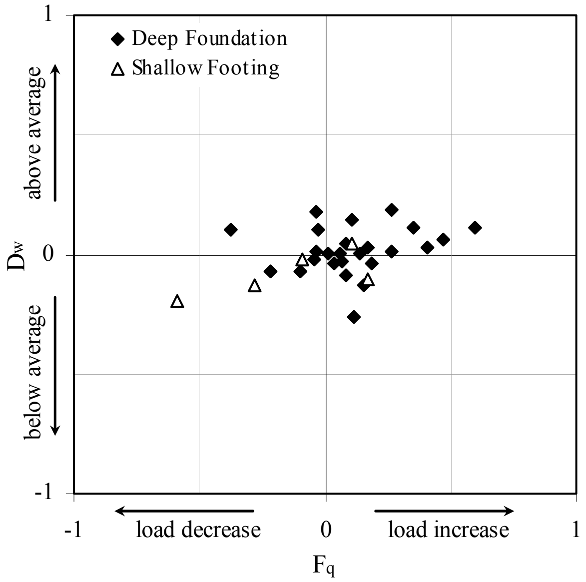

Figure 6 – Load redistribution in function of the settlement dispersion for third floor.

Figures 6 to 8 shows that in the beginning of the construction, considerable pillar load redistribution occurs associated with settlement dispersion. It justifies itself by the low structure rigidity that allows the differential displacement between the pillars. As the construction goes on, the rigidity of the building increases and therefore the load redistribution decreases with increase in settlement dispersion. After the placement of the fifth floor it is observed that more significant settlements dispersions does not occur and the loads redistribution are less than 20%, approximately. This effect occurs in independent form of the foundation type.

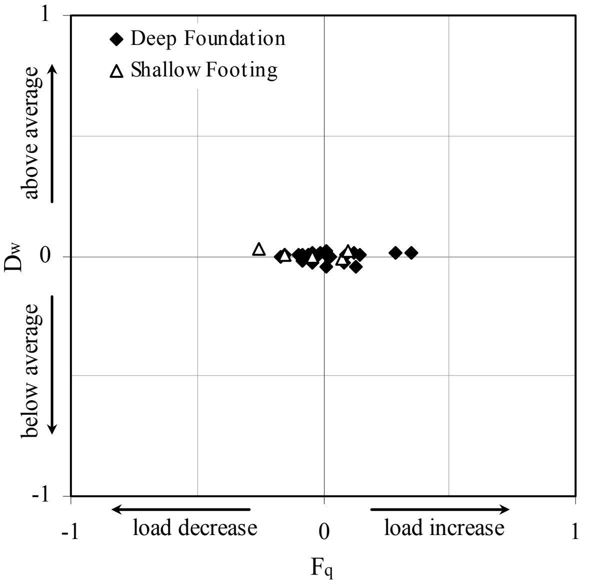

Figure 7 – Load redistribution in function of the settlement dispersion for fifth floor

Figure 8 presents the variation of the average, maximum and minimum settlement rate with the construction time. It is verified that the beginning of the construction is marked by great settlement rate. After the fifth floor has been placed, the reduction in the settlement rate is verified. This has been justified by the typical behavior of the continuous flight auger in the study region. In this in case that the piles are long and therefore works essentially with tip load that needs considerable deformations for the whole mobilization of load capacity (Simons and Menzies, 1981). Moreover, it is observed that after beginning of masonry insertion, that increases significantly the structure rigidity, no modification of the settlement rate trend reduction with construction time was verified. In this way, one can concluded that the average settlement rate was not significantly affected by soil-structure interaction. However the introduction of masonry provokes uniformity on settlement rate among pillars. This can be verified by the less discrepancy amongst values of maximum and minimum settlement rates (Figure 8).

5 CONCLUSIONS

The results indicate that the applied methodology and Terzaghi water level developed for settlement monitoring had allowed the evaluation of the soil-structure interaction in studied case. It's important to highlight that the used equipment showed good relation cost benefit.

The results have allowed the determination of factors that quantify the loads redistribution and the settlement dispersion due to soil-structure interaction. The analysis of these factors has indicated that the foundation behavior was strongly influenced by soil-structure interaction. Moreover, a significant reduction in soil-structure interaction takes place when small addition in the rigidity of the structure occurs. In this case, it was verified that the small loads redistribution and the settlement dispersion occur after the masonry introduction.

The mean settlement rate is not much influenced by increase in structure rigidity. However, the discrepancy between minimum and the maximum rate is reduced, due to the increase in structure rigidity.

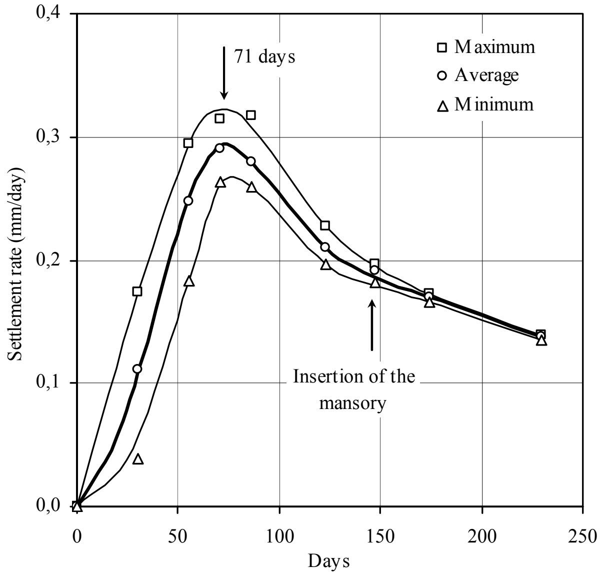

Figure 8 – Variation of the settlement rate with the construction time

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REFERENCES

ABNT, 1996. Design and construction of Foundations (in Portuguese). Brazilian technical norm designation: NBR 6122/96, 33 p.

CHAMECKI, S. 1954, Consideration of structural rigidity on determination of settlement foundation (in Portuguese). *Primeiro Congresso Brasileiro de Mecânica dos Solos*, ABMS, Vol. I, Porto Alegre, Brasil,.pp. 35-80.

DANZIGER F. A. B.; DANZIGER B. R.; CRISPEL F. A. 2000. The settlement monitoring since construction beginning for a foundation quality control (in Portuguese). *Seminário de Engenharia de Fundações Especiais e Geotecnia* – SEFE IV, pp. 191-202.

GUSMÃO FILHO, J. A. 2002. Foundation – Geological knowledge to engineering practice (in Portuguese). UFPE Editor., 345 p.

GUSMÃO, A. D. 1994, Relevant aspects of soil-structure interaction of buildings (in Portuguese). *Soil and Rocks*, vol. 17, no. 1, p. 47-55.

GUSMÃO, A. D. E GUSMÃO FILHO, J. A. 1994, Construction sequence effect on settlements of buildings. Proc., XIII ICSMEFE, New Delhi, Vol. 2, pp. 1803-1806.

LUCENA, A. E. F. L.; BEZERRA, R. L.; GUSMÂO, A. D. 2004. Settlement measurement of buildings on shallow foundations since the beginning of the construction and analysis of the soil-structure interation (in Portuguese). *Soil and Rocks*, v. 27, no. 3, p. 215-230.

MAIA, P. C. A.; BARROS R. A.; SABOYA, F. 2004. Settlement monitoring of flight auger foundation in Campos dos Goytacazes region. *V Seminário de Engenharia de Fundações Especiais e Geotecnia*, Vol. 2, São Paulo, Brasil, pp. 441-449.

SIMONS N. E.; MENZIES, B.K. 1981, Introduction of Foundation Engineering (in Portuguese). Ed. Interciência, Rio de Janeiro, Brazil, 199 p.

SKEMPTON A. W.; MACDONALD D. H. 1956, Allowable settlements of buildings. Proc., Institution of Civil Engineers, London, Part 3, vol. 5, pp. 727-768.

VELLOSO, D. A.; LOPES, F. R. 2002. *Foundation* (in Portuguese). vol. 1, COPPE/UFRJ, Rio de Janeiro, Braisl, 290p.