Probabilist analysis of the foundation of a shopping center in Brazil

Analyse probabiliste des fondations d'un centre commercial au Brésil

Gusmão A.
University of Pernambuco and IFPE, Brazil

Oliveira P.
Gusmão Engineers, Brazil

Ferreira S.
Federal University of Pernambuco and Unicap, Brazil

Maia G., Amorim M.
Gusmão Engineers, Brazil

ABSTRACT: The Brazilian foundation code that was reviewed in 2010 defined the criteria for the use of probabilistic analysis in the design of foundation, and there is a perspective that such analyzes are increasingly used in practice. The greatest difficulty of the analysis is the small number of load tests available in the works, and particularly in the design phase. This article presents the main aspects of design, execution and control of the construction of a shopping center with 280,000 m^2 area in Recife, Brazil, where they were executed 4,000 continuous flight auger piles type (CFA piles). 40 static load tests were simultaneously performed with the execution of the piles (1% of the total number of piles as recommended by the Brazilian code). With the favorable outcome of the first 15 load tests, the design was reviewed and there was a significant reduction in the number of piles and the total cost of the foundation. It is presented a statistical analysis of results of static load tests, where it was verified the influence of the number of load tests considered on the shape of the curve of resistance, global factor of security, characteristic safety factor and probability of failure. The results showed that when it attained a number of load tests equivalent to 0.4% of the total number of piles, the probability of failure are not showed more substantial changes.

RÉSUMÉ : La norme brésilienne sur les fondations qui a été révisée en 2010 a défini les critères pour l'utilisation de l'analyse probabiliste dans la conception des fondations. Une telle analyse est susceptible d'être de plus en plus utilisée en pratique. La plus grande difficulté de l'analyse est le petit nombre d'essais de chargement disponibles et en particulier en phase de conception. Cet article présente les principaux aspects de la conception, l'exécution et le contrôle de la construction d'un centre commercial de 280 000 m^2 de surface à Recife, au Brésil, où ont été exécutés 4 000 pieux forés en continu (pieux CFA). 40 essais de chargement statique ont été réalisés simultanément à l'exécution des pieux (soit 1% du nombre total de pieux, tel que recommandé par la norme brésilienne). Avec les résultats satisfaisants des 15 premiers essais de chargement, la conception été révisée, entraînant une réduction significative du nombre de pieux et du coût total des fondations. Une analyse statistique des résultats des essais de chargement statique est présentée, permettant de vérifier l'influence du nombre d'essais de chargement considéré sur la forme de la courbe de résistance, le facteur global de la sécurité, le facteur de sécurité caractéristique et la probabilité de ruine. Les résultats ont montré que, quand on atteint un nombre d'essais de chargement équivalent à 0,4% du nombre total de pieux, la probabilité de ruine ne se trouve pas significativement modifiée.

KEYWORDS: Foundation, Statistical Analysis, Probability of Failure.

1 DESCRIPTION OF THE STRUCTURE AND SUBSOIL

The building analyzed is a precast reinforced concrete structure with openings, with approximately 280,000 m2 destined to shopping areas and garages. There are portions of the structure with up to six levels of concrete slabs. A total of 1,283 pillars support permanent vertical loads ranging from 200 to 9,000 kN. The arrangement of the loads also takes into account vertical, horizontal, and moments loads resulting from wind action. The project is designed with a ground floor level, deployed at an elevation of +3.00. From the standpoint of topography, the native terrain does not feature natural unevenness, with a median average of 2.00. From the geological standpoint, the site is located in the fluvial-marine plain, within an marine terrace (Gusmão et al., 1998).

The geotechnical characterization carried out with an arrangement of 61 percussion soundings permits, in a simplified form (Fig.1) characterization of the foundation ground, which is initially composed of a landfill layer of fine silty sand, light brown, soft to moderately compact, to a level of 1.00; followed by layers of sand with organic materials, or silty organic clays, dark gray, very soft, to a level of -3.00. Below this level are found subsequent layers of fine to medium sand, gray, lightly to moderately compacted, interspersed with layers of silty clays, medium, to levels of -21.00 -28.00. After this layer, a layer of silty clays, or silt with very fine sand, gray, compact, extends to the limit of the soundings that were performed (-35.00). The water level was found to vary in levels from 0.00 to +1.50.

2 FOUNDATION DESIGN AND VERIFICATION OF PERFORMANCE

CFA piles (400 and 500 mm diameter) were employed, with allowable loads of 700 and 1,150 kN, respectively. The client indicated that load tests be conducted over the course of the execution of the foundation, due to the time frame for completion and delivery of the project. At first, a total of 15 static load tests were performed, with satisfactory results. At this point, during this first step, 2,563 piles had been placed. Then, from the results of these pilot load tests, the project was revised, and loads for the 400 and 500 mm piles were altered to 800 kN and 1,300 kN (an increase of 14% and 13% respectively).

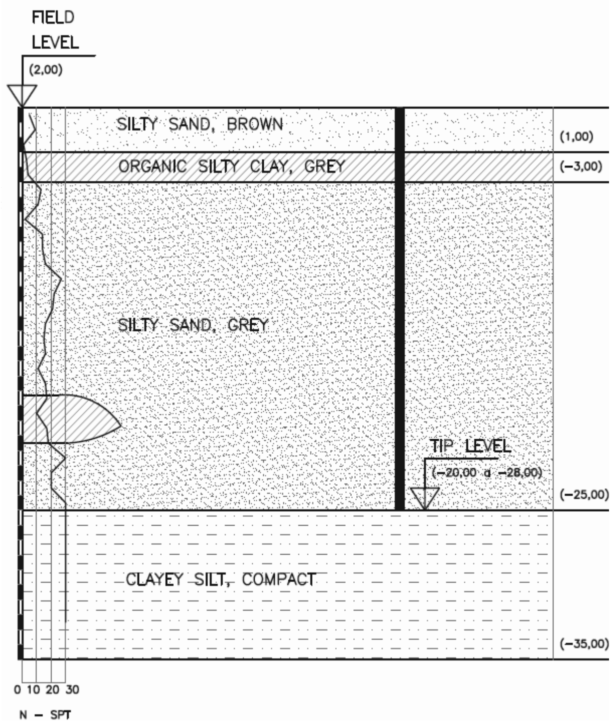


Figure 1. Subsoil profile

The final total of all piles placed, both before and after the revision, came to 3,838. A total of 38 static load tests were programmed throughout the project, 27 for 500 mm piles, 09 for the 600 piles, and 02 for 400 mm piles. However, two of the load tests, specifically the 33rd and 34th, indicated problems in the pile caps, and had to be redone. Figure 2a shows the diagram regarding load versus settlement for the piles analyzed in the study. The Van der Veen equation was used as a criterion for extrapolating the geotechnical rupture load for the load tests.

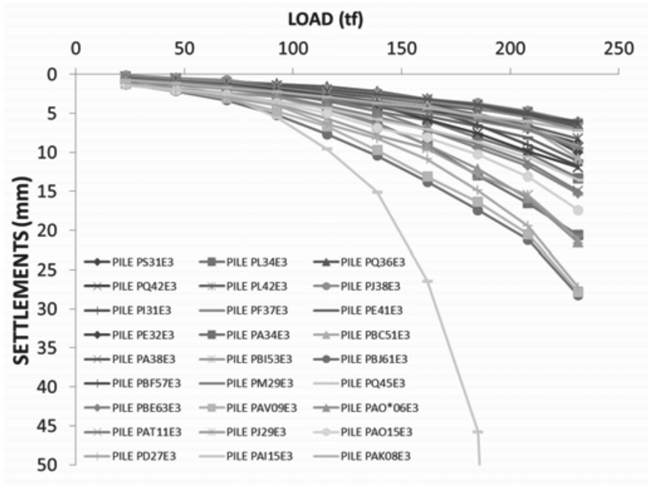
3 STATISTICAL ANALYSIS

A mean value (μR) can be imagined in a representative area where the resistances are distributed, and a standard deviation (σR) can measure the distance this data is from this mean average. Analogically, in designing the details of a project with deep foundations, normally the piles are not designed with expectations to have to withstand maximum admissible loads. Generally, verifiable loads are less than, but close to admissible, presenting an average (μS), and standard deviation (σS)..Since not all locations in the subsoil present the same resistance, it is possible that in a certain location, the resistance is found to be less than that which is required to withstand the load indicated. The likelihood that this phenomenon occurs is called the probability of failure.

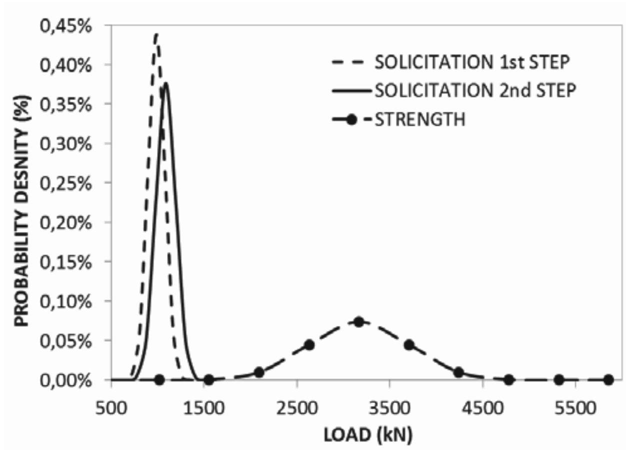
Sample variation can be measured by the ratio between the standard deviation and the mean, this ratio is called the coefficient of variation. Reliability is a concept opposed to variability. The reliability index (β) is defined as the inverse of the coefficient of variation. The reliability index increases as the normal distribution is concentrated to a greater degree around the mean. The concept of a Safety Margin, which is defined as the difference between the requirements demanded, and the actual resistance, also is distributed normally, and through it can be obtained the parameters for analysis of potential for failure.

For the case of the project under study, we studied the probability of failure values before and after revision of the foundation design project for the piles with 500 mm diameters, since the number of samples was greater. This review only changes the curve for requirements, considering that the mean load (μR) per pile was reviewed. For the first step, which preceded the review, mean and standard deviation values were verified for operating loads of 985 and 91.5 kN, respectively. For the second step, values of 1,086 and 106.0 kN, respectively, were determined. Regarding load resistance, values of 536 and 3,167 kN were verified. A standard curve can only be set up using its mean value, and its standard deviation.

From the data obtained, standard curves were plotted for both steps, similarly for the requirements, and the resistances. They are presented in Figure 2b. For the first step, the Reliability Index (β) measured 3.99, and the Probability of Failure (pf) was 1/30,893. For the second stage, β measured 3.79, and the pf measured 1/13,373.



(a)



(b)

Figure 2. (a) Results of load tests for the 500mm piles; (b) Standard curves for the first and second phase compared to the normal curve of resistance.

The load tests carried out for the project were not conducted all at once, thus, during the course of testing, the standard resistance curves could be adjusted to include the last test performed. As each new test is considered, a different pair of mean and standard deviation values is obtained. In such a manner, it is possible to trace standard curves that consider different steps for implementing quality controls for the foundation, or for different quantities of static load test performed, varying the size of the sample until the completion of predictive control for the work.

As the sample increases, dispersion analysis is incorporated. This dispersion arises from the variability of the subsoil profile, the variability of the materials used, and from the uncertainties regarding measurements of the loads and settlement.

Thus, with sample growth, the standard deviation increases, and the probability density around the mean decreases, leaving the curve with a flatter appearance (recalling that the area considered between the standard curve and the abscissa is equal to the unity) . This can be seen in Figure 3, which depicts the variation of the shape of the standard curve, due to the growth of the sample until the final number of load tests performed (N = 27).

In a deterministic analysis, foundation safety is verified by means of the Global Safety Factor (FSg), which is the ratio between the mean resistance and mean requirement. However, for an analysis where the effects of sample dispersion are intended to be considered, as with Probability of Failure, the Safety Characteristic Factor (FSk) must be also considered. This factor is defined as the ratio between the Resistance Characteristic (Rk) and the Requirement Characteristic (Sk). The Resistance characteristic represents the mean resistance increased from Z.σR, as well as the characteristic that is obtained by minimizing the mean requirement in Z. σS (where Z represents the reliability interval, usually equal to 95%, equivalent to Z = 1.65). Figure 3b makes comparison between the Global Safety Factor, and the Safety Characteristic Factor as the sample increases.

As already seen, as sample space increases, population dispersion is incorporated into the sample, and the standard deviation tends to increase. In this manner, as dispersion increases, the reliability index represented by β decreases and eventually the Probability of Failure increases. Thus, on the basis of everything that has been presented, it was verified that with an increase in number of load tests, the probability of failure increased until practically constant between the values of 15 and 20 load tests performed, i.e. 0.35 to 0.48% of the project piles tested. Figure 5 shows the variation of failure probability in function of the increase of the number of load tests, compared with the limits set by the European code EN1990.

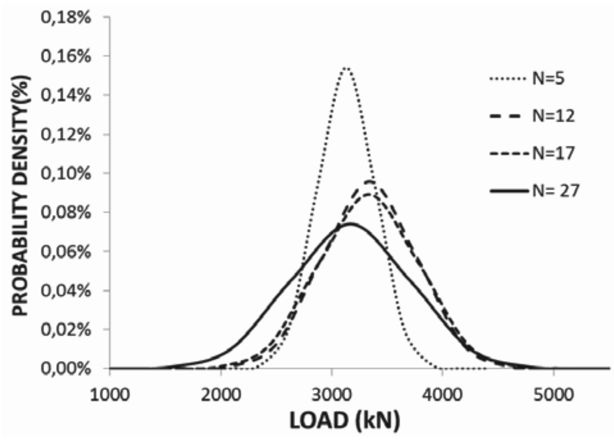


Figure 3. Standard curves varying according to the number of load tests analyzed.

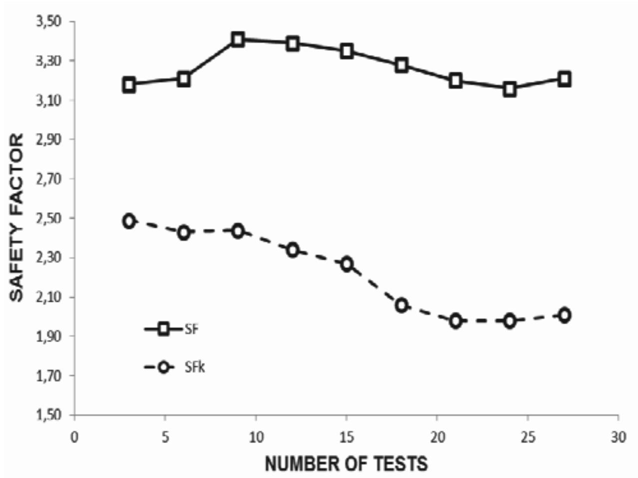


Figure 4. Variation of global and partial safety factors relative to the number of load tests.

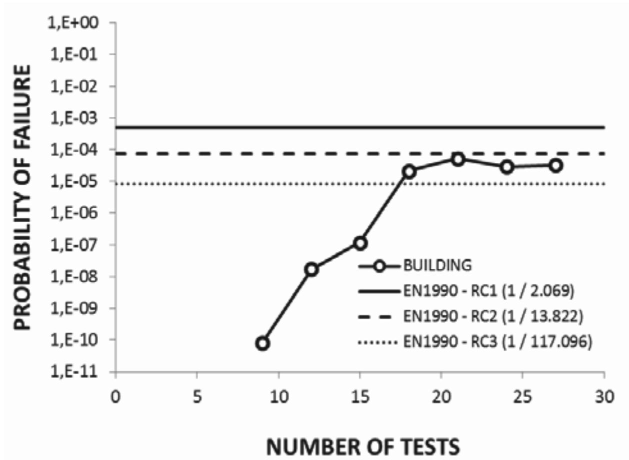


Figure 5. Variation of the probability of failure with an increase in the number of load tests.

3 CONCLUSIONS

With growth of the sample, the standard deviation increases, and probability density around the mean decreases, leaving the curve with a flatter appearance. As sample space increases, population dispersion is incorporated into the sample, and the standard deviation tends to increase. As the dispersion increases, the reliability index represented by β decreases, and probability of failure increases. It was possible to verify that with an increase in the number of load tests, the probability of failure increased until practically constant when reaching 15 and 20 load tests performed, and 0.35 to 0.48% of the project piles having been tested. The safety characteristic factor showed to be, as expected, always less than the global security factor, however, with values remaining above levels permitted by codes.

4 REFERENCES

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