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Assessment of the bearing capacity of bored piles with Expander Body technology using pressuremeter test-based methods

Évaluation de la capacité portante des pieux forés avec la technologie Expander Body à l'aide de méthodes basées sur des tests pressiométriques

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ABSTRACT: This study aimed to evaluate the accuracy of various semi-empirical methods for estimating the bearing capacity of bored piles with the innovative Expander Body technology in lateritic soils. The study analyzed the precision and accuracy of different methods based on PMT tests using the Ranking Distance Index (RD). Results showed that methods based on PMT tests were adequate for estimating the load capacity of piles equipped with the Expander Body technology in lateritic soils.

RÉSUMÉ: Cette étude visait à évaluer la précision de diverses méthodes semi-empiriques pour estimer la capacité portante des pieux forés avec la technologie innovante Expander Body dans les sols latéritiques. L'étude a analysé la précision et l'exactitude de différentes méthodes basées sur des tests PMT utilisant le Ranking Distance Index (RD). Les résultats ont montré que les méthodes basées sur les essais PMT étaient adéquates pour estimer la capacité de charge des pieux équipés de la technologie Expander Body dans les sols latéritiques.

Keywords: Expander body; pile load test; pile bearing capacity; pressuremeter; bored piles.

1 INTRODUCTION

The development in the civil construction sector results in increasingly complex buildings, necessitating progressively greater loads in foundations. In order to meet this demand, techniques are developed and refined to enable such constructions. A notable example is the Expander Body (EB) technology, a device installed at the tip of the pile, providing an increase in its bearing capacity. As indicated by Terceros Herrera and Terceros Arce (2016), this technique was conceived in the 1980s by the Swedish engineer Bo Skoberg and subsequently perfected in Bolivia, aiming to enhance the installation process and monitor the soil adjacent to the pile base (Fellenius and Terceros Herrera, 2014; Terceros Herrera and Massarsch, 2014; Fellenius et al. 2018).

The selection of an appropriate foundation type requires carrying out tests to obtain preliminary information into the characteristics of the soil under investigation, with an emphasis on its resistance. These tests include the pressuremeter tests (PMT) and many other in-situ testing procedures.

To estimate the bearing capacity of the pile-soil system, many semi-empirical approaches are used, including those proposed by Ménard (1963), Baguelin *et al*. (1978), and NFP 94-262 (2012). However, the results of these approaches are frequently variable. As a result, it is up to the practitioner to select the best method for calculating the load-bearing capability of the evaluated pile-soil system. Compared to data obtained through pile load testing, acceptability criteria such as the Ranking Distance Index (RD) improve decision-making regarding the most accurate methodology. Orr and Cherubini (2003) proposed the use of a statistical index (RD - Ranking Distance), which assesses both accuracy through the mean and precision through the standard deviation of the ratio Q_p/Q_m (predicted/measured values) of any quantities, as described in the following equation:

$$RD = \sqrt{\left\{1-\left[\mu\left(\frac{Q_p}{Q_m}\right)\right]\right\}^2 + \left[s\left(\frac{Q_p}{Q_m}\right)\right]^2} \qquad (1)$$

Where $\mu(Q_p/Q_m)$ and $s(Q_p/Q_m)$ represent the mean and standard deviation of the values (Q_p/Q_m), respectively. The optimum point occurs when $(Q_p/Q_m) = 1$ and $s = 0$.

Based on PMT test results from the Federal District of Brazil, this study assesses the accuracy and precision of three methods used to estimate the load-bearing capacity of mechanically bored piles equipped with Expander Body (EB) technology. The precision of the pile bearing capacity estimation methods is evaluated by comparing them to the results from pile load tests conducted on mechanically bored piles equipped with EB at the University of Brasilia's experimental field of foundations and in-situ tests.

2 EXPANDER BODY

The Expander Body System (EB) is a 0.12 m wide (initial diameter) by 1 to 2 m long bent steel tube that is inflated (expanded) during the first pressure-grouting stage and discharged over a grouting tube inside the rebar, as depicted in Figure 1. Distinct EB models enable expansion to a diameter of 400 to 800 mm. During the EB expansion process, grout pressure and volume are continuously recorded. The EB bottom tip rises as a result of the lateral expansion of the EB, which causes the EB tube length to shorten by approximately 0.1 m. As a result of this expansion, the soil beneath the EB decompresses, which is compensated by a second grouting stage of the soil at the pile tip (Figure 2).

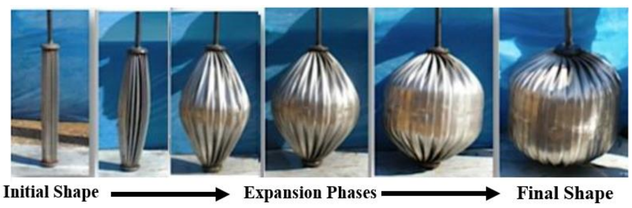

Figure 1. Expander Body expansion in-air.

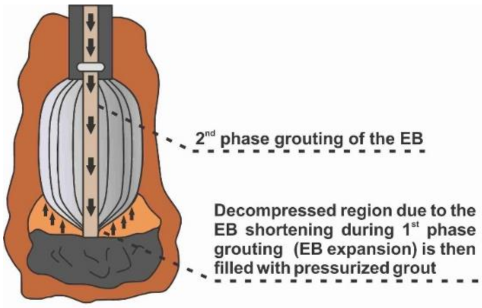

Figure 2. Post-grouting stage after Expander Body expansion.

Bored cast-in-situ piles can be constructed using a variety of techniques. Although each approach has some variation, the overall concept is the same. Drilling mud with permanent or temporary casing are typically combined with a rotary or percussive approach for pile drilling. Drilling ceases as soon as the design depth is achieved. Concrete is subsequently poured into the borehole after the reinforcement cage has been installed. Bored cast-in-situ piles that have EB technology installed use a similar installation process. The installation process of a bored cast-in-situ pile equipped with an EB system is shown in Figure 3.

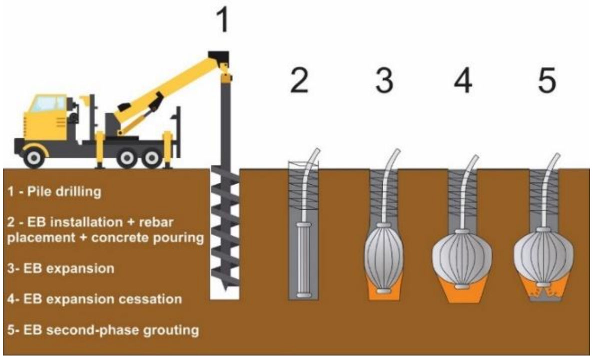

Figure 3. Bored cast-in-situ piles equipped with EB system installation technique.

The installation procedure of bored piles equipped with EB technology can be divided into five steps (Figure 3). Initially, pile drilling is carried out. Secondly, the EB is placed at design depth along with the reinforcement bar, and then, concrete is poured into the borehole. The next step consists of an initial grouting phase, delivered through a hollow schedule tube (EB expansion). After EB expansion ceases, the second-phase grouting step is carried out so that the decompressed region (pile tip) is filled with pressurized grout. Both injection pressure and volume are continuously monitored using a mortar pump and pressure gauge. This equipment not only provides adequate monitoring of the EB expansion but also provides pressure *versus* volume charts. The Expander Body effective diameter (D_{EB}) is determined from calibration curves for each EB model.

3 CASE STUDY

The Federal District is enclosed on the south by the 16°03' parallel and on the north by the 15°30' parallel, with a total area of 5814 km^2. The research location of the UnB geotechnical group has already been thoroughly explored and described in the literature (Cunha, 2011). This research location used various piling techniques, and the piles were horizontally and vertically loaded. Furthermore, several laboratory and in-situ tests have been conducted at this location. Block samples were collected and transferred to the laboratory, where triaxial, direct shear, oedometer, and routine characterization tests were performed. In the upper portion of this region, the soil strata change between clay, silt, and silty sand.

Two bored cast-in-situ piles equipped with EB technology with 8.8 and 10 m length were excavated with a rotating auger at the University of Brasilia experimental site, displayed in Figure 4. More details regarding the pile's geometric characteristics are shown in Table 1.

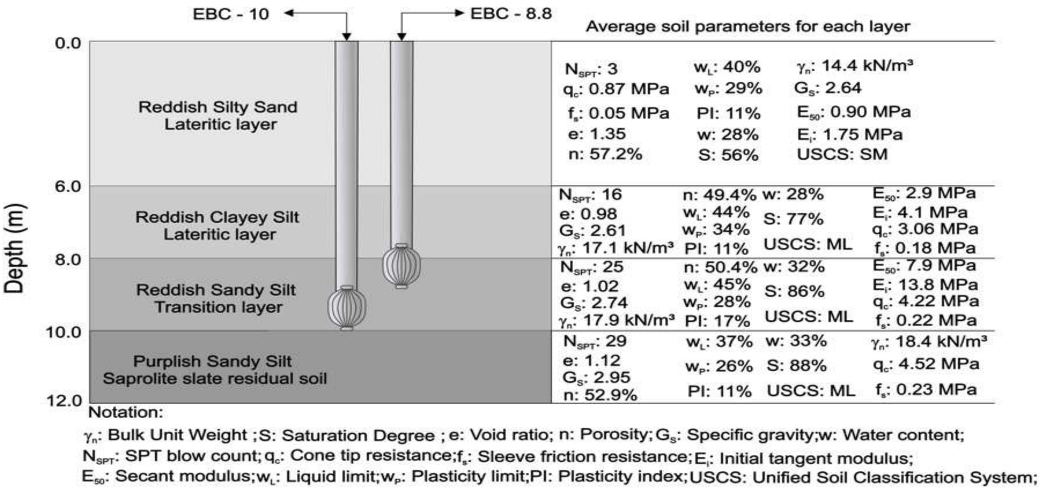

Figure 4. Typical soil profile at the UnB research site.

Figure 5 depicts the pressuremeter curves acquired during PMT tests in the experimental field. It is possible to determine relevant parameters such as limit pressure (p_L) and the coefficient of earth pressure at rest (K_0) from pressuremeter curves to use methods for assessing load-bearing capacity based on pressuremeter tests. The value obtained at a depth of 1 m was discarded due to issues with the test measurement. An increase in effective pressure with depth and a significant development in effective pressure in the saprolitic horizon are noticed.

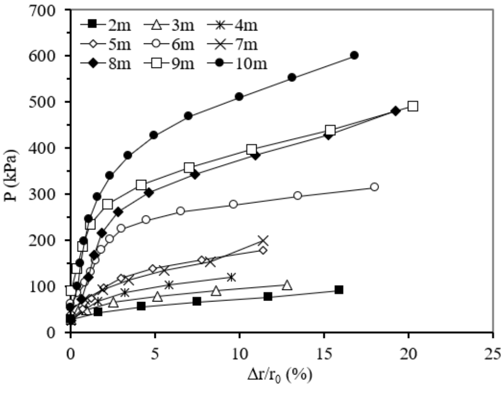

Figure 5. Pressuremeter test (PMT) curves.

A reaction beam, reaction piles, hydraulic jack, loading platform, and calibrated load cell were used to apply load. The spacing between reaction piles was at least three pile diameters. Mechanically bored, cast-in-place piles with the EB System were subjected to compression (Figure 6). The Brazilian Standard ABNT NBR 12131 (2006) specifies four pile load test conditions: slow maintained load, rapid maintained load, combined load, and cyclic load test.

All piles in this study were submitted to slow-maintained load tests, as shown in Table 1.

Table 1. Pile geometric characteristics, load type and velocity.

Test Pile	D (m)	D_{EB} (m)	Load condition	Load increment (kN)
EBC - 8.8	0.30	0.6	Slow maintained	100
EBC - 10	0.30	0.6	Slow maintained	120

The load increments were conducted in ten corresponding load stages, each representing 20% of the working load of the piles analyzed in the study. In the load tests performed, it was observed that the displacement of the piles varied between 52.21 and 66.51 mm, reaching settlements close to the limit of the deflectometer (70 mm), thus noting displacements exceeding 10% of the diameter of the pile shaft. In this work, semi-empirical methods for predicting the load bearing capacity based on the limit pressure (p_L) measurements from the PMT test conducted in Brazil were studied. The methods used were Ménard (1963), Baguelin *et al*. (1978), and NFP 94-262 (2012).

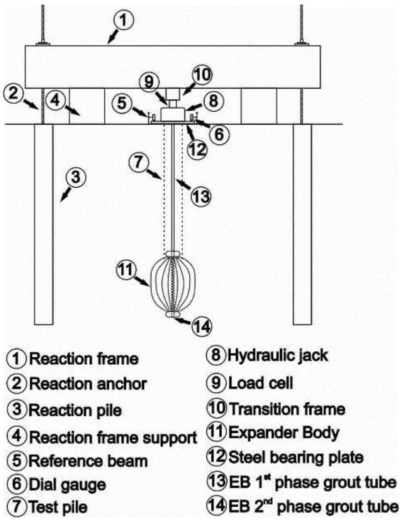

Figure 6. End view of compression pile load test set-up.

4 RESULTS

The load-displacement curves for the analyzed piles are presented in Figure 6. The pile with a length of 10 m, equipped with EB technology, sustained a load of up to 1200 kN, while the pile with a length of 8.8 m, also equipped with EB technology, reached a maximum load of approximately 1000 kN. Based on the displacement levels observed in the load tests, the conventional failure load of each pile can be determined using the 10% criterion of the pile shaft diameter. This criterion, widely adopted in European countries in accordance with Eurocode 7 (ECS, 2004) recommendations, results in interpreted conventional failure loads of 1140 and 823 kN for the bored piles equipped with the EB system, respectively.

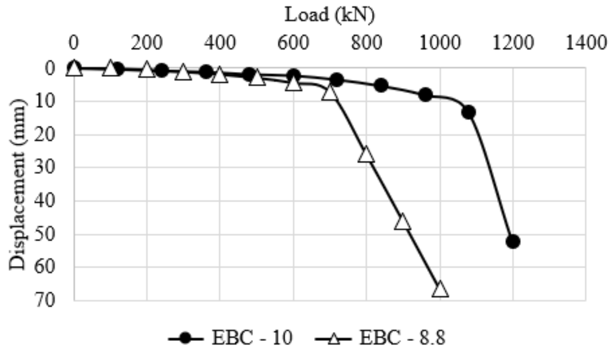

Figure 7. Load-displacement curves of analyzed piles.

Figures 8 and 9 present ratios between predicted and measured load capacities (Q_p/Q_m). Comparing the load capacity estimates from semi-empirical methods with the failure load interpreted from the conventionally determined load for a settlement equivalent to 10% of the pile diameter, it is observed that the methods proposed by Ménard (1963) and NFP 94-262 (2012) showed ratio values (Q_p/Q_m) below the range of ±20% for both piles equipped with the EB technology. While the Baguelin *et al*. (1978) method overestimates the reference values obtained from the interpretation of the pile load test results.

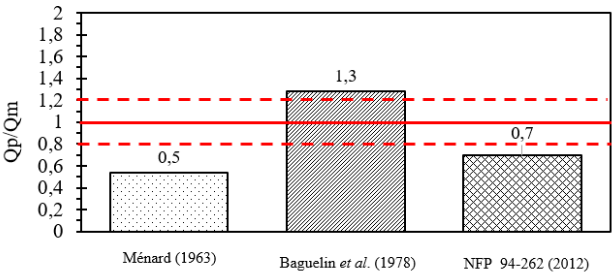

Figure 8. The ratio between predicted and measured load capacities for the EBC – 8.8 pile.

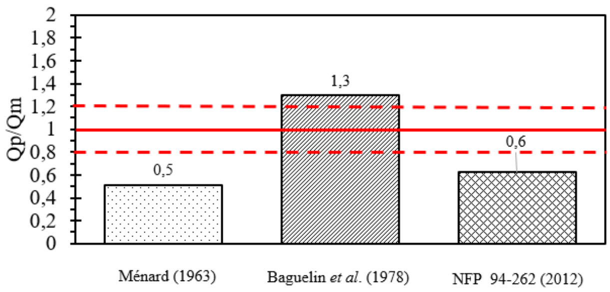

Figure 9. The ratio between predicted and measured load capacities for the EBC – 10 pile.

The semi-empirical methods for bearing capacity, based on pressuremeter tests, often use charts or tables to determine the tip resistance and side friction of piles. These methods require input parameters such as the limit pressure measured during the test, soil type, pile installation process, pile slenderness ratio (L/D), and a load capacity factor (K_p) according to the soil type. The determination of the pile tip load capacity unit requires the use of the load capacity factor (K_p), while the unit side friction resistance is intrinsically linked to the values of the effective limit pressure of the soil layers through which the pile is installed. The determination of the effective limit pressure of the soil layers is influenced by various factors, including soil type, soil density, stress history, degree of saturation, anisotropy, variation of horizontal stress (directly related to the determination of K_0 values), and test depth. The pressuremeter tests in pre-drilled holes (MPM) carried out at the UnB Experimental Field presented effective limit pressure values between 77 and 466 kPa. According to the results obtained from the pre-drilled hole pressuremeter tests (MPM), using curve-fitting techniques, it was found that the K_0 values for the porous clay of Brasília varied between 0.34 and 0.72 along the depth, with an average value of 0.5. The K_p values range from 1.2 to 9.2 for different pile installation methods in the Baguelin *et al*. (1978) method. In the estimate presented in Figures 8 and 9, a load capacity factor (K_p) equivalent to 7.5 was adopted, explaining the likely overestimation of the load capacity of the piles equipped with EB. On the other hand, for other methodologies, the estimates are conservative due to the use of lower load capacity factor (K_p) values (between 1.2 and 2.1).

Table 2 presents the average values and standard deviations for the ratios between predicted and measured load capacity values (Q_p/Q_m) of the analyzed piles in this study. From these values, the Ranking Distance Index (RD) is determined. Low RD values represent an estimation method with high accuracy and precision. As RD values increase, this statistical index characterizes the estimation methodology as less accurate and less precise.

Table 2. Statistical analysis of the Q_p/Q_m ratios for the evaluated methods.

Method	**Average (Q_p/Q_m)**	**Standard deviation (Q_p/Q_m)**	**RD**
Ménard (1963)	0.50	0.0	0.50
Baguelin et al. (1978)	1.30	0.0	0.29
NFP 94-262 (2012)	0.30	0.1	0.35

Among the load capacity estimation methodologies based on PMT tests analyzed in this study, it is observed that the Baguelin et al. (1978) method presents the lowest RD value, making it the most accurate and precise methodology despite the estimated values being overestimated. On the other hand, the method proposed by Ménard (1963) shows the highest RD value, making it the least accurate and precise technique in relation to the data analyzed in this study. However, it was verified that using a load capacity factor (K_p) of magnitude 4 for the three methods results in Q_p/Q_m ratios between 0.8 and 1.0. This suggests, preliminarily, that the bearing capacity estimation using semi-empirical methodologies based on PMT test results for bored piles equipped with Expander Body technology in lateritic soils is satisfactory at the design level.

5 CONCLUSIONS

This work emphasized results obtained from load tests on mechanically bored piles equipped with the Expander Body technology, conducted at the Geotechnical Experimental Field of the University of Brasília. The analyzed foundations were axially loaded under compression, producing load-displacement curves that were interpreted to assess the precision and accuracy of load capacity prediction methodologies for bored piles equipped with the Expander Body system in the tropical soil of the Federal District, based on PMT test results.

Experimental data acquired from load tests and load capacity estimates using the methodologies of Ménard (1963), Baguelin et al. (1978), and NFP 94- 262 (2012) were compared for bored piles equipped with the EB technology, and these were presented and discussed. Although the results are confined to the conditions of the analyses, based on a limited dataset, they allow for preliminary generalizations of the overall behavior. Furthermore, they highlight the fact that the phenomena involved in such processes are considerably complex. In this regard, this research provided a better understanding of some characteristics involved in the loading mechanisms of single piles equipped with EB technology in lateritic soils. It should be noted, however, that some analyses were formulated as hypotheses to explain the results and need further research for a more informed appreciation in the future. Therefore, based on the observed trends in the data and analyses, some general conclusions can be drawn:

- The Baguelin *et al*. (1978) method shows the lowest RD value, making it the most accurate and precise methodology analyzed in this study;
- The method proposed by Ménard (1963) indicates the highest RD value, making it the least accurate and precise method in relation to the data analyzed in this study;

- Based on the experimental results and bearing capacity calculations, it is observed that the bearing capacity estimates, using methodologies reliant on PMT tests and considering a bearing capacity factor (K_p) of magnitude 4, prove to be suitable tools for estimating the load capacity of bored piles equipped with the Expander Body technology in lateritic soils.

It should be emphasized that the described conclusions need to be considered of limited scope and applicability. However, these results, along with the experience gained during the research, can be of great interest to foundation researchers and designers in this region and beyond.

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