Bearing capacity assessment of bored piles equipped with expander body systems using the mechanics of unsaturated soils

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Abstract. Bearing capacity of single piles are occasionally predicted using the renowned theoretical methods (α and β methods). These methods are based on laboratory tests, which can be time-consuming, but also applicable in foundation engineering practice for unsaturated soils. Full-scale pile load tests were carried out on bored piles equipped with Expander Body Systems in the Federal District of Brazil, known for its unsaturated, collapsible and porous soil. This paper has the aim to assess the applicability of the β method, considering the contribution of soil matric suction, in order to estimate the bearing capacity of these piles subjected to uplift and compression loads in unsaturated soils. Based on the experimental results, it is indicated that the use of the β method considering the matric suction, can be a useful tool for bearing capacity estimation of bored piles equipped with Expander Body Systems in unsaturated soils.

1 Introduction

Single piles bearing capacity is usually computed using semi-empirical methods; however, renowned theoretical methods (α and β methods) have also been employed in pile foundation engineering for many years [1]. Pile foundation behavior can be influenced by several aspects, such as soil shear strength parameters, soil saturation degree, soil compressibility, soil stress history and age, as well as pile installation technique. Many pile foundations are located above the groundwater table zone. Therefore, soil-pile interaction can also be influenced by matric suction in these unsaturated soils. Also, the development of novel pile installation methodologies subsidized growing appeals for analyzing the applicability of theoretical bearing capacity methods. The Expander Body System is an innovative technology that can be attached to the toe of bored and driven piles. This system has been widely adopted as a pile foundation solution in prominent urban centers such as Santa Cruz de la Sierra, Bolivia [2].

In Bolivia, more than 3000 pile foundation elements equipped with Expander Body technology have already been installed in 35 different engineering projects such as bulk silos, industrial facilities, residential buildings and bridges. Many other countries, such as Sweden, Norway, Germany, Japan, Paraguay, Peru United States of America, South Korea and now Brazil, have implemented this building technology as a viable pile foundation solution.

This paper has the aim to assess the applicability of the β method, considering the contribution of soil matric suction, in order to estimate the bearing capacity of bored cast-in-situ piles equipped with the EB technology subjected to uplift and compression loads in lateritic, porous and unsaturated soil.

2 Bearing Capacity of Single Piles using the β Method

Pile foundation design has been commonly performed based on saturated soil mechanics. However, a significant amount of attention can be attributed to pile foundation design for engineering fundamentals, in which the mechanics of partly saturated soils have been widely applied [3-5].

The following equation gives the ultimate pile bearing capacity:

$$Q_u = Q_T + Q_S \tag{1}$$

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The conventional β method [6-7] establishes that skin friction resistance (Q_S) and toe resistance (Q_T) can be given:

$$Q_S = \int_L^0 P_S \cdot (c' + \beta\sigma'_z)\, dz \qquad (2)$$

$$Q_T = A_T \cdot \sigma'_{vp} \cdot N_t \qquad (3)$$

where: Q_T is the toe resistance, Q_S is the skin friction resistance, c' is the effective soil cohesion, , β is the Bjerrum-Burland coefficient, N_t is the toe bearing capacity coefficient, σ'_{vp} is the effective overburden stress at the pile toe, σ'_z is the effective overburden stress, A_T is the pile toe area, P_S is the pile shaft perimeter at depth z.

The Machado e Vilar (1998) [8] proposal was adopted in order to evaluate the matric suction contribution on soil cohesion, which directly influences pile skin friction resistance. This proposal adjusts the cohesion variation and matric suction by hyperbolic functions using the least-squares method.

$$c = c' + \frac{(u_a - u_w)}{a + b \cdot (u_a - u_w)} \qquad (4)$$

where: c' is the effective soil cohesion obtained in CU triaxial and direct shear tests, $(u_a\text{-}u_w)$ is the matric suction, c is the apparent cohesion given a matric suction value, a and b are adjustment coefficients. In this research, a and b values of 3.725 and 0.012 were considered (as reported in [9]), respectively.

3 The Expander Body System

The Expander Body System (EB) is a bent steel tube, which is inflated (expanded) by an initial pressure-grouting process, discharged discharged via a grouting tube that goes down through the re-bar cage. Distinct models allow an expansion from 0.4 to 0.8 m in diameter. Grout pressure and volume are registered continuously during the expansion of the EB. Figure 1 depicts the EB expansion stages during the pressure grouting step.

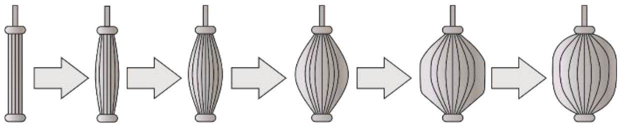

Fig. 1. Expander Body Expansion Stages.

The Expander Body (EB) system is commercially available in different dimensions depending on design requirements. The EB models have lengths between 1 and 2 m, as well as widths between 0.10 and 0.13 m in the stages before the expansion (initial stage). The models allow expansion, obtaining effective diameters between 0.4 to 0.8 m. During EB expansion stage, the relationship between injection pressure and volume can be registered by a data acquisition system. The lateral expansion of the EB induces an EB tube length shortening by almost 0.2 m, displayed as a rising of the EB bottom-tip. This expansion causes a soil decompression beneath the EB, which is compensated by a second grouting stage of the soil at the pile tip (Figure 2). The second grouting stage is discharged to the pile tip over a distinct grout tube inside the grout tube (Figure 3) employed for the initial grouting stage (passing the EB inner section).

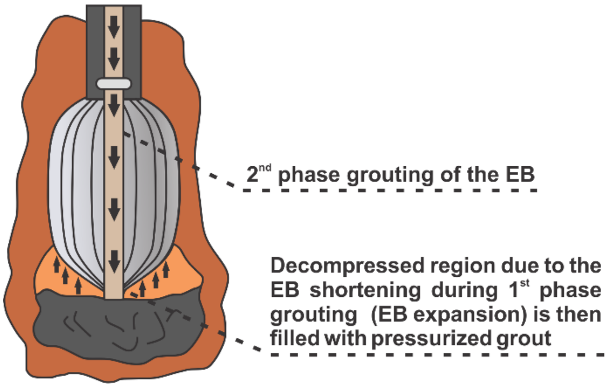

Fig. 2. Post-grouting stage after EB expansion.

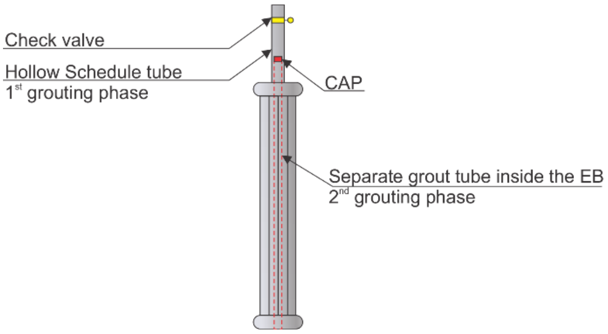

Fig. 3. Grout tube passing the EB inner section.

4 Materials and Methods

4.1 Pile installation

Diverse methods can be employed to build bored cast-in-situ piles. The principle is essentially the same; there is, however, a slight variation between these approaches. Pile drilling excavation is usually performed utilizing a percussive or rotary method with the use of permanent or temporary casing or drilling mud. Once design depth is reached, the drilling process is ceased. The reinforcement cage is placed, and the borehole is then filled with concrete. The installation procedure of bored cast-in-situ piles equipped with Expander Body technology follows a similar approach. Figure 4 depicts the installation procedure of bored cast-in-situ pile equipped with the

Expander Body system. The Expander Body's pre-loading effect specifically decreases required deformations to mobilize toe resistance when compared to traditional bored piles.

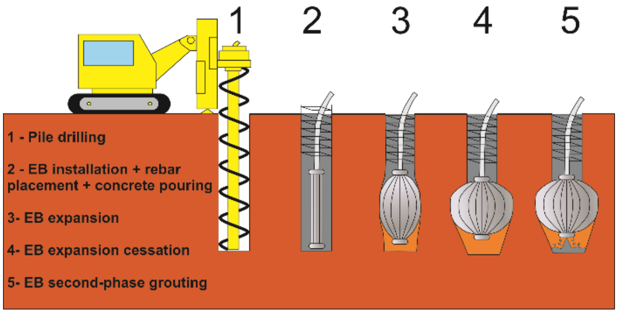

Fig. 4. Bored cast-in-situ piles equipped with EB system installation procedure.

The installation procedure of bored piles equipped with EB technology can be divided into five steps (Figure 4). Initially, pile drilling is carried out. Secondly, the EB is placed at design depth along with the reinforcement bars, and then, concrete is poured into the borehole. The next step consists of an initial grout phase, delivered through a hollow schedule tube (EB expansion), as described in Figure 4. After EB expansion ceases, the second-phase grout 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 mortar pump and pressure gauge. These equipments not only provide adequate monitoring of the EB expansion, but also provides pressure-volume charts.

4.2 Soil stratigraphy

The Federal District is limited in the south by the parallel 16 ° 03 'and in the north by the parallel 15 ° 30', presenting a total area of 5814 km^2. The University of Brasília (UnB) campus is situated within Brazil's Federal District, in an area most widely recognized as the "north wing" due to its aircraft shape. UnB geotechnical group research site has already been intensively investigated and presented in literature [10]. The soil stratigraphy varies between clay, silt, and silty sand in the upper portion of this region. For instance, occurrence of large areas (more than 80% of the Federal District area) covered by a tertiary-quaternary age weathered laterite is typical. This lateritic soil has undergone extensive leaching and presents a variable thickness ranging from a few centimeters to about 40 meters. The high porosity produced by aggregation and cementation resulting from processes such as leaching, hydrolysis and cementitious agents deposition is observed in many weathered tropical soils in Brazil. As a consequence, both soil void ratio and porosity are high. In situ standard penetration tests (SPT) and cone penetration tests (CPT), as well as, usual characterization laboratory tests were conducted to evaluate main parameters of the lateritic, unsaturated and collapsible soil site.

Figure 5 depicts a simplified soil stratigraphy, average SPT blow counts, cone tip resistance and sleeve friction, as well as soil parameters obtained in laboratory tests. The simplified geotechnical-geological soil profile is characterized by a superficial laterite (silty sand) layer that overtops a transition zone (clayey silt) and a saprolite soil (sandy silt) that originates from the region native rock. In situ tests were carried out to a depth of 18 m, although, the water table level was not reached. Triaxial tests on undisturbed block samples were performed at depths of 3, 6, and 9 m. Initial tangent modulus (E_i), secant modulus at 50% of the failure stress (E_{50}), soil effective cohesion and friction angle were acquired performing triaxial CD tests at cell pressures of 50, 100, and 200 kPa on each depth. The lateritic soil was classified as silty sand (SM), while the residual soil was identified as low plasticity silt (ML) according to USCS.

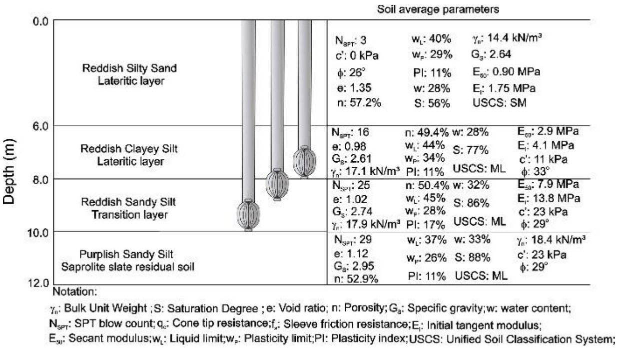

Fig. 5. Soil stratigraphy and average parameters.

4.3 Pile load test

Test pile drilling excavation was performed with a rotating hollow flight auger at the UnB research site. Once design depth was attained, the drilling process was ended, and the reinforcement cage was placed**.** Subsequently, the EB was placed at design depth alongside 3 m length pile rebar, and then, the borehole was filled with concrete. Thereafter, an initial grout phase was delivered through a hollow schedule tube attached to the EB (EB expansion). Lastly, a second-phase grout step was carried out using a high-pressure flexible hose that passes inside the EB to the pile toe. In addition, both injection volume and pressure were continually monitored using mortar pump and pressure gauge. These instruments not only provide appropriate monitoring of EB expansion but also provide pressure *versus* volume records. The reinforcement cage consisted of primary CA-50 steel longitudinal rebars ($\varnothing_{rebar}$ = 16 mm) and transverse CA-50 steel spiral stirrups rebars ($\varnothing_{rebar}$ = 6.3 mm). The test piles were installed using 20 MPa concrete and 210 MPa steel reinforcement. A water/cement ratio between 0.4 and 0.5 was employed during the primary and secondary grout injection phase. In piles subjected to uplift load tests, only the main grout injection phase (EB expansion) was performed. Bored cast-in-situ reaction piles were installed with 0.3 m in diameter and 12 m long, with 47 mm Dywidag reaction anchors of 14.5 m.

Four static load tests were carried out using a reaction system composed of reaction piles, reaction frame and reaction frame support. Both compression and uplift reaction systems set-up are displayed in Figures 6 and 7. The required duration to stabilize the displacements was spent after each axial load increment. In compliance with the Brazilian Standard NBR 12131 [11], all intervals were maintained for at least 30 minutes until the Brazilian standard criterion was accomplished. A 3.1 m center-to-center distance between the test pile and reaction piles was adopted.

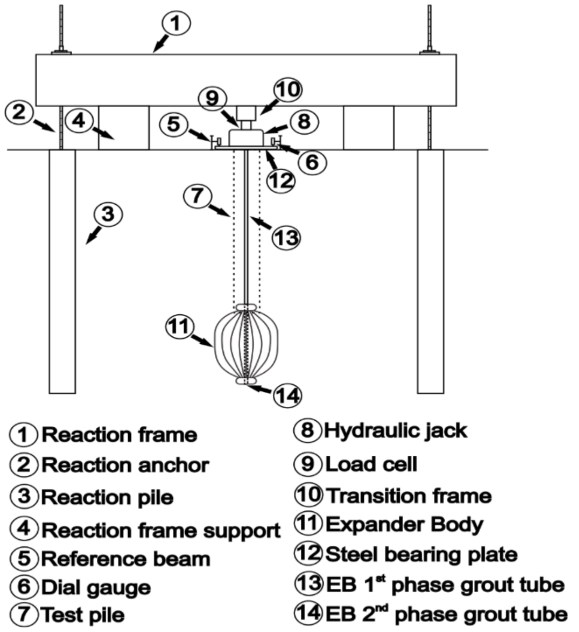

Fig. 6. End view of compression pile load test set-up.

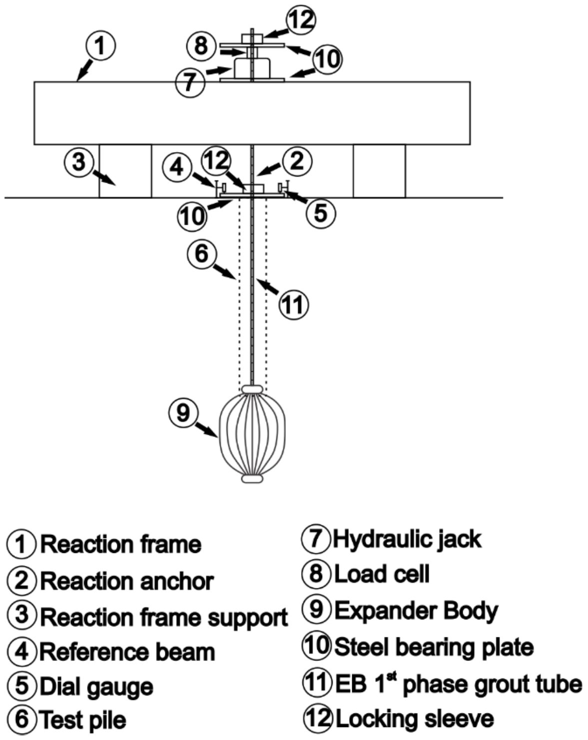

Fig. 7. End view of uplift pile load test set-up.

The compression load tests set-up displayed an H-shaped reaction system, using two 3.2 m long secondary reaction frames and a 6 m long main reaction beam (Figure 8). While uplift load tests reaction system scheme was composed with an H-shaped reaction system, consisting of a 3.6 m long main reaction frame and two concrete reaction frame supports that were placed on the ground level (Figure 9). Load measurements at pile top were conducted with a 2000 kN load cell, while displacement measurement were performed using 50 mm dial gauges. Table 1 presents geometric characteristics of the test piles, as well as test pile load type.

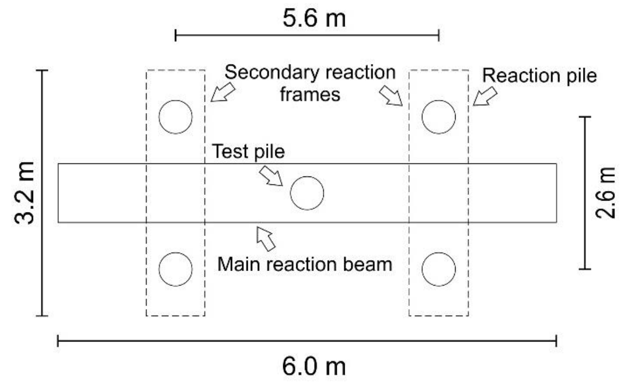

Fig. 8. Top view of compression pile load test set-up.

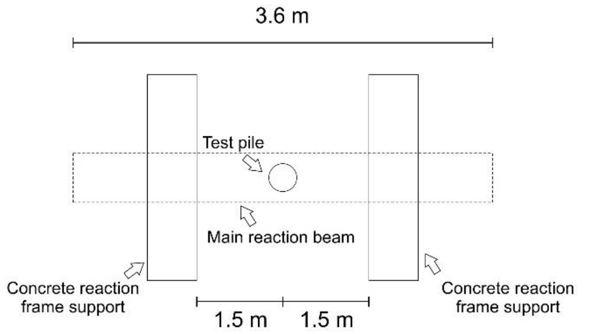

Fig. 9. Top view of uplift pile load test set-up.

Table 1. Pile geometric characteristics and load type.

Test Pile	$\varnothing$ (m)	$\varnothing_{EB}$ (m)	L (m)	Load Type
EBC-8.8	0.30	0.6	8.8	Compression
EBC-10	0.30	0.6	10.0	Compression
EBU-10	0.25	0.6	10.0	Uplift
EBU-8	0.25	0.6	8.0	Uplift

Note: EBC = Bored pile with Expander Body System subjected to compression load; EBU = Bored pile with Expander Body System subjected to uplift load; $\varnothing$ = pile diameter; $\varnothing_{EB}$ is the EB effective diameter after expansion.

All load tests attended the slow maintained test procedure (ABNT, 2006) [11] with load increments ranging from approximately 55 and 120 kN. A summary of load test increments and pile ultimate load values of all tested piles is presented in Table 2. Load versus pile head displacement curves are presented in Figure 10.

Table 2. Summary of test piles load and displacement data.

Test Pile	**$\varnothing$ (m)**	**$\varnothing_{EB}$ (m)**	**Displacemet criterion**	**Load increment (kN)**	**P_{ult} (kN)**
EBC-8.8	0.30	0.6	10% $\varnothing$	100	820
EBC-10	0.30	0.6	10% $\varnothing$	120	1120
EBU-10	0.25	0.6	10% $\varnothing$	98	880
EBU-8	0.25	0.6	10% $\varnothing$	63	580

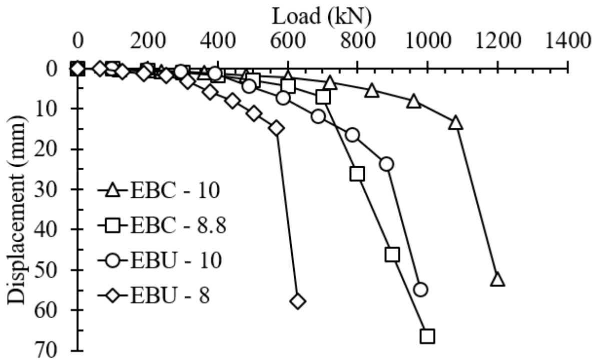

Fig. 10. Pile load-displacement curves.

4.4 In-situ and Laboratory tests

The soil-water characteristic curve (SWCC) was determined using the filter paper method on undisturbed samples retrieved at depths ranging from 1 to 10 m (Figure 11). Several moisture measures were carried out during in-situ tests performance. Soil matric suction was then determined using both soil-water characteristic curve and soil saturation degree along the pile length. Moisture measures (Figure 12), as well as soil characterization tests (moisture content, Atterberg limits, specific gravity of soil and dry density of soil) results, were used in order to obtain soil saturation degree at each meter depth.

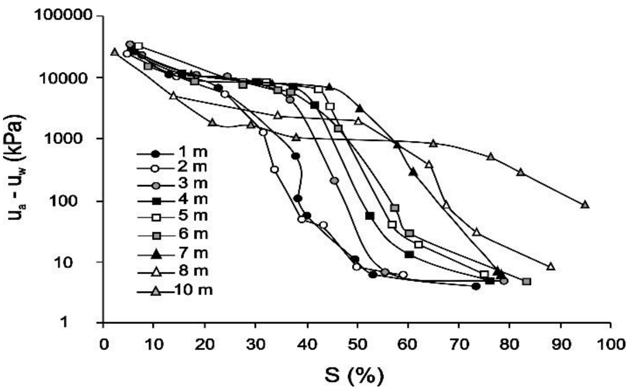

Fig. 11. Soil-water characteristic curves at the UnB geotechnical group research site ([12] – modified).

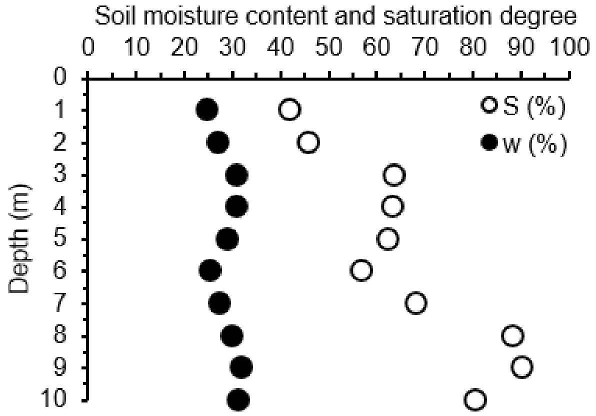

Fig. 12. Soil moisture content and saturation degree for different depths.

5 Results and discussions

In this research, both toe and skin friction capacity of in-situ single piles equipped with the Expander Body System were predicted using the conventional β method, the β method considering matric suction contribution and the conventional β method considering Nt and β values proposed by Fellenius, 2020 [13]. The toe bearing capacity estimates for piles subjected to uplift load was neglected; therefore, the bearing capacity of piles subjected to uplift load was considered to be equal to pile shaft resistance. The pile bearing capacity estimates were computed by dividing the pile length into ΔL segments. β values were computed using Poulos, 1989 [14] recommendation, as described in the following equation for analyses using the conventional β method and the β method considering matric suction contribution.

$$\beta = (1 - \sin\phi') \cdot \tan\phi' \cdot (OCR)^{0.5} \tag{5}$$

where: ϕ' is the effective soil internal friction angle and OCR is the over-consolidation ratio.

The corresponding matric suction (u_a-u_w), for each saturation degree value along pile length, is determined from the respective soil-water characteristic curve (SWCC). Predicted (Q_p) and measured (Q_m) pile bearing capacity ratios for each employed method are depicted in Figures 13, 14, 15 and 16. For piles under compression loads, a possible shaft resistance descrease immediately above the enlarged EB was neglected. As for piles under uplift loads, a potential pile skin friction increase was disregarded. The Expander Body system is expanded after pile installation, applying radial stresses along pile tip and immediately above the enlarged part. This expansion might lead to different stress-strain soil conditions from conventional enlarged base piles, where this effect has been previously analyzed. Moreover, Fellenius *et al.* 2018 [15] verified that equipping the pile toe with the EB with post-installation grouting considerably increased the pile stiffness response to applied load. Therefore, the pile shaft increase or decrease mechanism due to EB expansion is yet undetermined.

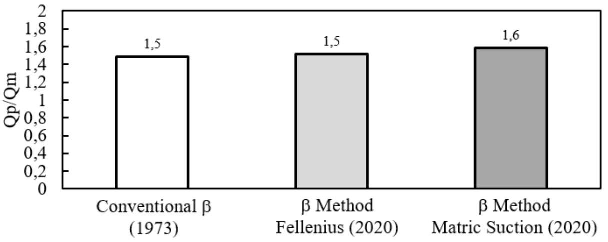

Fig. 13. Pile bearing capacity ratios – EBC – 8.8.

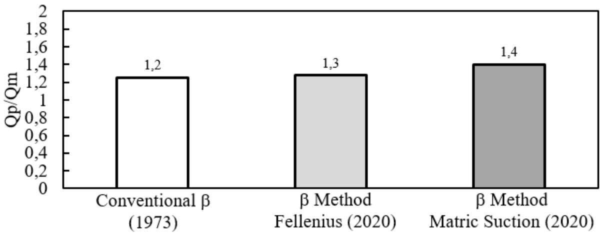

Fig. 14. Pile bearing capacity ratios – EBC – 10.

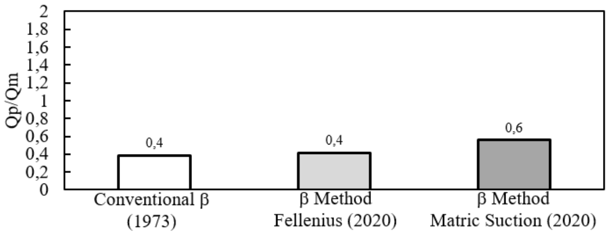

Fig. 15. Pile bearing capacity ratios – EBU – 10.

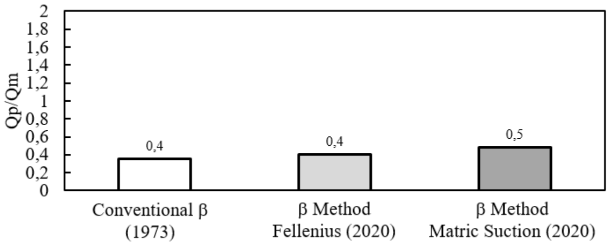

Fig. 16. Pile bearing capacity ratios – EBU – 8.

The β method considering matric suction yields slightly better bearing capacity estimates for piles subjected to uplift loads, when compared to the conventional β method. On the other hand, conventional β method presented better estimates when analyzing piles under compression, however, all methods overestimated pile bearing capacity. These findings can be attributed to the fact that for compression piles, the toe bearing capacity has been considered, when estimating the total pile bearing capacity, in contrast, piles under uplift loads showed an opposite trend, underestimating pile bearing capacity, since only pile shaft resistance was taken in consideration. Consequently, it can be speculated that pile tip resistance is overestimated, while, pile skin friction resistance is underestimated when analyzing all examined methods in this research.

The skin friction resistance estimated by using the β method considering matric suction is approximately 10% higher in comparison to the conventional β method for piles under compression, while in piles subjected to uplift loads, shaft capacity prediction is nearly 40% higher as well. Despite different embedment depths and slenderness ratio, the piles under compression and uplift loads presented a similar behavior for all analyzed methods. Despite the limited data, it can be recommended that the total pile bearing capacity should be reduced by nearly 33% for piles under compression when predicting the bearing capacity of bored cast-in-situ piles equipped with the Expander Body System using either the conventional β method or the β method considering matric suction. While for piles subjected to uplift loads, an increase of approximately 40% is suggested.

6 Conclusions

The main objective of this research was to assess the applicability of the β method, considering the contribution of soil matric suction, in order to estimate the bearing capacity of bored cast-in-situ piles equipped with the EB technology subjected to uplift and compression loads in lateritic, porous and unsaturated soil. This article emphasized four full-scale maintained static load test on bored cast-in-situ piles equipped with EB system at the UnB (University of Brasília) foundation research site. This paper provides a comparison between the estimated total pile bearing capacities of bored cast-in-situ piles equipped with EB system using both the conventional β method and the β method considering suction. The matric suction influence on the skin friction capacity of a single pile was estimated by using the Machado e Vilar (1998) [8] proposal, in order to assess the cohesion component increase.

The findings show that matric suction has a slight influence on the bearing capacity of bored cast-in-situ piles equipped with EB system since its behavior is mostly governed by pile toe resistance when analyzing piles under compression loads. For piles subjected to uplift loads, matric suction influence increases, and pile toe resistance should be neglected for practical purposes. Based on the experimental results, it is indicated that the use of the β method considering the matric suction, can be a useful tool for bearing capacity estimation of bored piles equipped with Expander Body Systems in unsaturated soils.

Full-scale pile load testing analysis often raises limitations associated with sample size, making it difficult to identify meaningful relationships from analyzed data, because statistical analyses usually require a larger sample size to ensure a representative population distribution. Hence, the need for future research on this innovative building technology in typical tropical, unsaturated and lateritic soils of substantial occurrence in Brazil should be emphasized.

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