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BEARING CAPACITY ASSESSMENT OF ROOT PILES INSTALLED IN SOIL–ROCK COMPOSITE STRATA

AVALIAÇÃO DA CAPACIDADE DE CARGA DE ESTACAS RAIZ EXECUTADAS EM ESTRATOS COMPOSTOS DE SOLO E ROCHA

EVALUACIÓN DE LA CAPACIDAD DE CARGA DE PILOTES RAÍZ EJECUTADOS EN ESTRATOS COMPUESTOS DE SUELO Y ROCA

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ABSTRACT

The bearing capacity of piles is one of the most important estimations in geotechnical engineering. One of the most commonly adopted pile types in foundation design is the micropile, locally known as a "root pile", which is a type of injected pile installed under pressures of up to 500 kPa during shaft formation. The bearing capacity of root piles is typically determined based on static load tests performed after pile installation. Several theoretical, semi-empirical, and empirical methods exist for estimating the bearing capacity of root piles used in Brazil and worldwide; therefore, it becomes essential to verify the efficiency of commonly applied methods and their applicability during the design stage. The objective of this study is to evaluate semi-empirical methods commonly used in Brazilian foundation design practice for estimating the bearing capacity of root piles based on SPT and rotary drilling (coring) data, through comparison with static load test results. SPT and rotary drilling investigations were performed, along with the construction of two root piles with a diameter of 410 mm and a length of 7.7 m. Finally, static load tests were carried out for each pile. Based on this evaluation, the methods proposed by Aoki and Velloso (1975), Décourt and Quaresma (1978), and Williams and Pells (1981) showed the best performance in predicting the bearing capacity of root piles installed in soil–rock stratigraphic profiles in the municipality of Fortaleza, Brazil.

KEYWORDS: *Root pile. Pile load test. Pile bearing capacity. Soil-rock strata. Deep foundations.*

RESUMO

A capacidade de carga de estacas constitui uma das estimativas mais importantes da engenharia geotécnica. Um dos tipos de estaca mais empregados em projetos de fundações é a microestaca, conhecida no Brasil como "estaca raiz", que consiste em uma estaca injetada, executada sob pressões de até 500 kPa durante a formação do fuste. A capacidade de carga das estacas raiz é normalmente determinada com base em provas de carga estática realizadas após a execução das estacas. Existem diversos métodos teóricos, semiempíricos e empíricos para estimar a capacidade de carga de estacas raiz, empregados no Brasil e em outros países. Portanto, torna-se essencial verificar a eficiência dos métodos comumente aplicados e sua adequabilidade durante a fase de projeto.

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O objetivo deste estudo é avaliar métodos semiempíricos usualmente empregados na prática brasileira de projetos de fundações para estimar a capacidade de carga de estacas raiz com base em dados de sondagens SPT e sondagens rotativas com recuperação de testemunhos, por meio da comparação com resultados de provas de carga estática. Foram realizadas sondagens SPT e rotativas e executadas duas estacas raiz com diâmetro de 410 mm e comprimento de 7,7 m. Posteriormente, foram realizadas provas de carga estática em cada estaca. Com base nessa avaliação, os métodos propostos por Aoki e Velloso (1975), Décourt e Quaresma (1978) e Williams e Pells (1981) apresentaram os melhores desempenhos na previsão da capacidade de carga de estacas raiz executadas em perfis estratigráficos compostos por solo e rocha no município de Fortaleza, Brasil.

PALAVRAS-CHAVE: Estaca raiz. Prova de carga em estacas. Capacidade de carga de estacas. Estratos de solo e rocha. Fundações profundas.

RESUMEN

La capacidad de carga de los pilotes constituye una de las estimaciones más importantes de la ingeniería geotécnica. Uno de los tipos de pilotes más utilizados en el diseño de cimentaciones es el micropilote, conocido localmente en Brasil como “estaca raíz”, que consiste en un pilote inyectado ejecutado bajo presiones de hasta 500 kPa durante la formación del fuste. La capacidad de carga de los pilotes raíz se determina normalmente mediante pruebas de carga estática realizadas después de la ejecución de los pilotes. Existen diversos métodos teóricos, semiempíricos y empíricos para estimar la capacidad de carga de los pilotes raíz, utilizados tanto en Brasil como en otros países. Por lo tanto, resulta esencial verificar la eficiencia de los métodos comúnmente aplicados y su adecuación durante la etapa de diseño. El objetivo de este estudio es evaluar métodos semiempíricos utilizados habitualmente en la práctica brasileña de diseño de cimentaciones para estimar la capacidad de carga de pilotes raíz a partir de datos de ensayos SPT y perforaciones rotativas con recuperación de testigos, mediante su comparación con los resultados de pruebas de carga estática. Se realizaron ensayos SPT y perforaciones rotativas, además de la ejecución de dos pilotes raíz de 410 mm de diámetro y 7,7 m de longitud. Posteriormente, se realizaron pruebas de carga estática en cada pilote. Con base en esta evaluación, los métodos propuestos por Aoki y Velloso (1975), Décourt y Quaresma (1978) y Williams y Pells (1981) presentaron los mejores resultados en la predicción de la capacidad de carga de pilotes raíz ejecutados en perfiles estratigráficos compuestos por suelo y roca en el municipio de Fortaleza, Brasil.

PALABRAS CLAVE: Pilote raíz. Prueba de carga de pilotes. Capacidad de carga de pilotes. Estratos de suelo y roca. Cimentaciones profundas.

1. INTRODUCTION

The bearing capacity of piles is one of the most critical parameters during the design stage of deep foundations, directly influencing both the safety and economic feasibility of foundation systems. Over the past decades, several theoretical, semi-empirical, and empirical methods have been proposed for estimating the bearing capacity of root piles used in Brazilian foundation engineering [1-3] and worldwide. Given the diversity of available approaches and the variability of geological conditions under which they are applied, verifying the efficiency of these

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methods and their applicability during the design stage becomes essential. Most methods consider that the total bearing capacity of a pile results from the sum of the shaft (skin friction) resistance and the base (end-bearing) resistance. In particular, piles installed in weak or weathered rock, and those founded directly on rock, develop resistance to loading primarily through skin friction and end-bearing mechanisms at the rock-pile interface [4]. Within this framework, semi-empirical methods occupy a central role. According to Amann [5], such methods can be defined as those derived from established theoretical formulations that allow the maximum shaft and base resistances to be determined through correlations with in-situ test results. Similarly, ABNT [6] defines semi-empirical methods as those in which material properties, estimated from field correlations, are incorporated into theories adapted from soil mechanics. In Brazil, the methods proposed by Aoki and Velloso [1], Décourt and Quaresma [2], and Cabral [3] are the most widely adopted for estimating the bearing capacity of root piles installed in soil profiles, owing to their simplicity and the widespread availability of Standard Penetration Test (SPT) data. However, these methods were originally developed and calibrated primarily for piles embedded entirely in soil, raising questions regarding their applicability to piles that transition into, or are partially socketed in, underlying rock layers.

For piles socketed into rock, a distinct body of literature has addressed the mechanisms governing shaft resistance development. Wyllie [7] examined these mechanisms in detail within the pile–rock system and identified several interrelated factors controlling the bearing capacity and displacement behavior of rock-socketed piles. Geometric aspects, particularly the socket length-to-diameter ratio, play a fundamental role, as do the strength and deformation modulus of the rock mass along both the shaft and the base of the pile. The condition of the materials adjacent to the pile shaft is equally relevant, since surface roughness and the presence of residual drill cuttings or bentonite slurry can significantly alter the rock-pile interface behavior. Likewise, the cleanliness of the excavation base, with respect to the removal of cuttings and other loose debris prior to grouting, influences the development of end-bearing resistance. Finally, the contrast in stiffness between the rock mass and the surrounding soil contributes to the overall load-transfer mechanism along the pile length. Building on these considerations, correlations have been established between the uniaxial compressive strength of rock and the rock-pile interface resistance [8-10]. Within this approach, the shaft (skin friction) bearing capacity of a pile socketed into rock can be related to the uniaxial compressive strength of the rock through the following equation:

$$f_s = \alpha \cdot \beta \cdot \bar{q}_{uc} \cdot E_L \cdot U \quad [1]$$

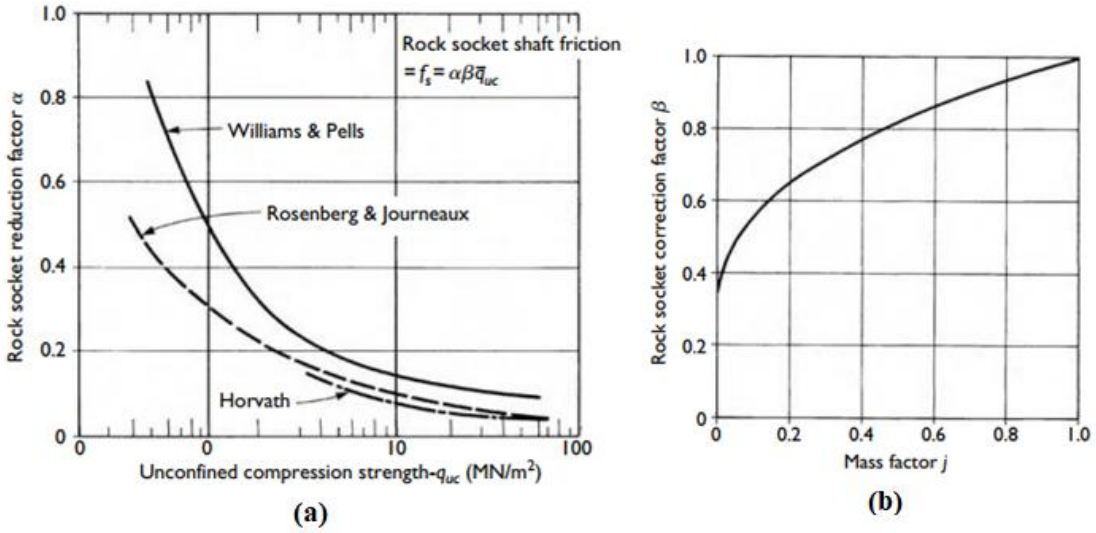
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where α is the reduction factor for rock socket embedment related to the uniaxial compressive strength of the rock; β is the correction factor for rock socket embedment related to the discontinuity spacing within the rock mass; q_{uc} is the uniaxial compressive strength of the rock; E_L is the length of pile embedded in rock; and U is the pile perimeter. The correction values of the Williams and Pells [10] curve in Figure 1a are higher than those of the other two curves, although the α factor is equivalent to unity in all cases for the Horvath [9] and Rosenberg and Journeaux [8] curves. The β factor is related to the j factor, defined as the ratio between the deformation modulus of the rock mass and that of the intact rock, as shown in Figure 1b. The j factor can be approximately obtained from its relationship with the Rock Quality Designation (RQD), as presented in Table 1 [11]. Figure 2 presents a correlation between RQD and the uniaxial compressive strength of rock [12].

Table 1. Relationship between RQD and the *j* factor (Hobbs [11])

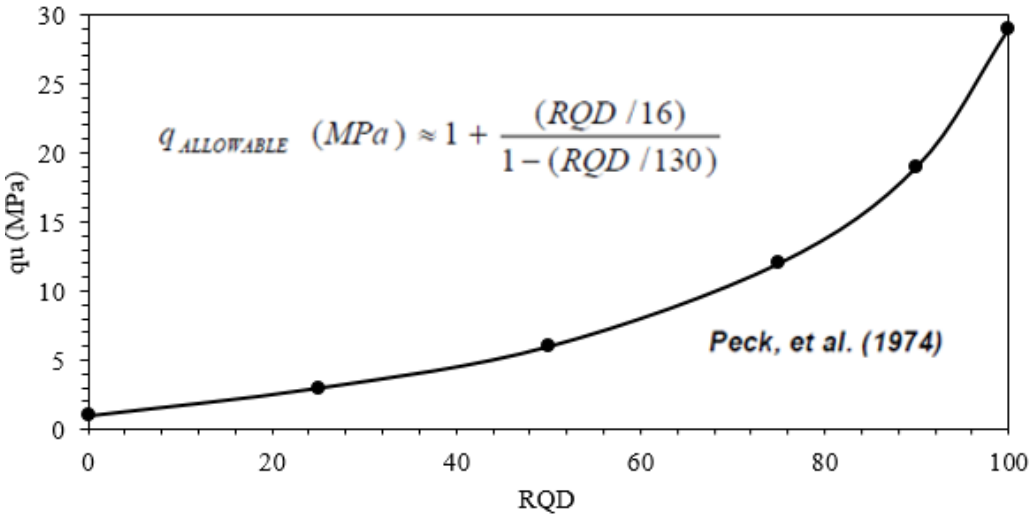
RQD (%)	Factor j
0-25	0.2
25-50	0.2
50-75	0.2-0.5
75-90	0.5-0.8
90-100	0.8-1

Figure 1. (a) α factor; (b) β factor (Tomlinson and Woodward [4])



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Figure 2. Correlation between RQD and the uniaxial compressive strength of rock (Peck *et al.* [12])



The bearing capacity of root piles is typically determined based on static load tests carried out after pile installation. Factors affecting load test results, such as load type, reaction system, hydraulic jack, dial gauge readings, and load cells, have been evaluated by Fellenius [13], who concluded that the estimated error could range between ±10 and 25%, mostly on the order of 15 to 20%, as these values are commonly adopted in foundation engineering practice. Although several semi-empirical methods have been developed and widely applied for estimating the bearing capacity of root piles installed in soil profiles [1-3], and complementary methodologies exist for predicting the side-shear resistance of rock-socketed piles based on rock mass quality indices such as rock unconfined compression strength (q_{uc}) [8-10], these two categories of methods have traditionally been validated and applied independently.

Most existing studies address either soil-founded piles or rock-socketed piles in isolation, with limited attention given to the combined application of soil-based and rock-based semi-empirical methods for piles that are partially embedded in soil and partially socketed into weak-to-very-weak rock, a condition frequently encountered in tropical residual soil profiles such as those typical of northeastern Brazil. Furthermore, most validation datasets for rock-socket methods originate from sedimentary rock formations in temperate regions, and their applicability to tropical weathered rock profiles, characterized by lower uniaxial compressive strengths and higher degrees of weathering, has not been extensively verified. The objective of this study is therefore to evaluate semi-empirical methods commonly used in Brazilian foundation design

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practice for estimating the bearing capacity of root piles based on SPT and rotary drilling results, applied jointly to the soil and rock-socketed segments of the piles, and to compare these estimates with static load test results obtained for root piles founded in soil-rock stratigraphic profiles.

2. ROOT PILE INSTALLATION

The root pile installation process is shown in Figure 3. A rotary drilling technique was used to install the root piles. First, the drill casing was attached to the rotary head, which rotates to advance the borehole into the soil or rock (Figure 3a). Subsequently, a drilling rod (inner rod) was attached to the same rotary head to carry out drilling within the cased section. The drilling rod advanced until the design elevation of the pile was reached. During this process, high-pressure water jets were used to clean the borehole during excavation of the shaft and base of the pile (Figure 3b). Upon reaching the target depth, the inner rod was withdrawn while the casing was temporarily left in place within the soil section. The reinforcement cage was then installed in the borehole (Figure 3c). The excavation was subsequently filled with grout (water–cement ratio of 0.6) until the grout flowed through the annular space between the borehole wall and the outer casing. A cap was installed at the top of the casing, and pressure (compressed air) was applied while the casing was withdrawn (Figure 3d).

Figure 3. Root pile installation process



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3. CASE STUDY

The root piles analyzed were installed for the foundation of a 22-story residential building located in the metropolitan region of Fortaleza, Brazil (Figure 4). Both piles have a length of 7.7 m and a diameter of 0.41 m. An injection pressure of 300 kPa was applied during the construction of both foundations. The geological–geotechnical characterization of the site was based on data obtained from SPT and rotary drilling investigations carried out prior to pile installation.

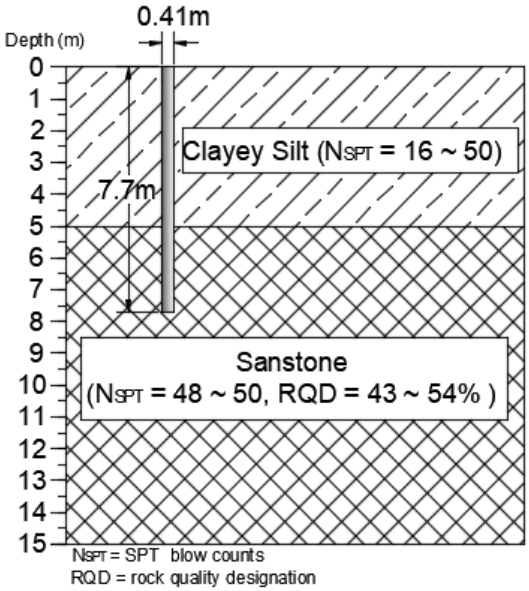
Figure 4. Site location



The groundwater table was encountered at a depth of 3 m. Figure 5 presents a synthesized stratigraphic profile of the site. The subsoil is initially characterized by a clayey silt layer, with N_{SPT} values ranging from 16 to 50, followed by a sandstone horizon with RQD values ranging from 0 to 54%. Within this layer, N_{SPT} values range between 48 and 50. N_{SPT} values were limited to 50, as Robertson [14] reports that the penetration resistance index becomes unreliable above this value due to hammer energy limitations inherent to the SPT test.

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Figure 5. Stratigraphic profile of the studied site



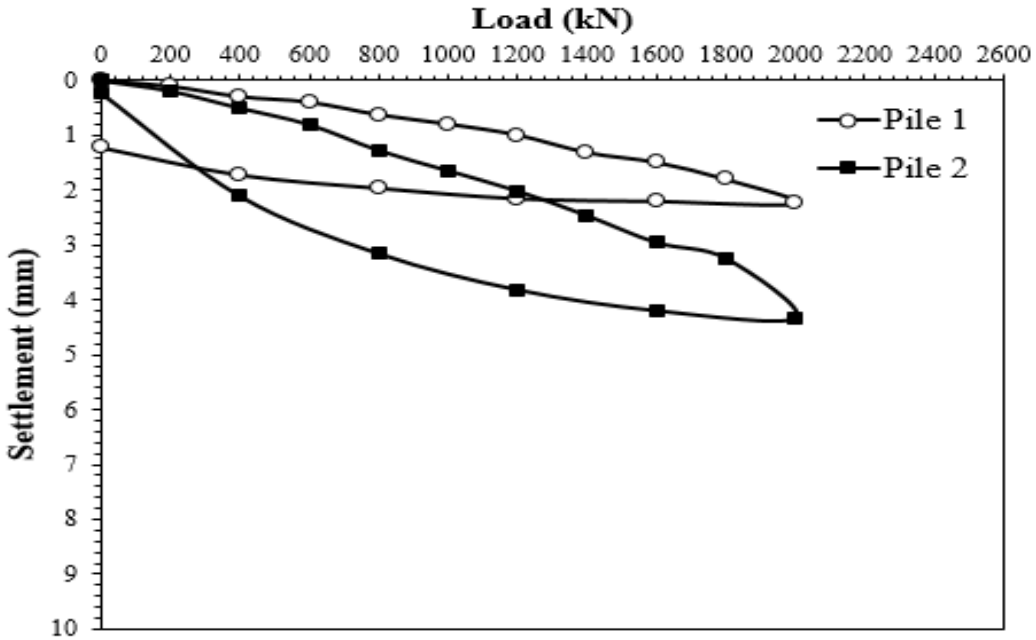
Static load tests were performed on the test piles ten days after installation, in accordance with the guidelines of ABNT NBR 12131 [15]. Pile head displacement was measured using four dial gauges (two on each side of the pile) mounted on two reference beams. The load was applied in increments of 20% of the test load and maintained until the settlement readings between two consecutive measurements differed by less than 5%. After reaching the maximum load, each pile was unloaded in five stages.

4. RESULTS AND DISCUSSION

The test piles reached a maximum applied load of 2000 kN, with maximum recorded displacements of 2.24 mm and 4.32 mm for piles 1 and 2, respectively. Figure 6 shows the load–settlement curves obtained from the static load tests. In both load tests, a distinct failure load (Q_u) was not reached; therefore, the Van Der Veen [16] extrapolation method was applied to determine the failure load of the test piles. The resulting failure loads were 2840 kN and 3060 kN for piles 1 and 2, respectively.

Figure 6. Load–settlement curves for piles 1 and 2

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In this study, semi-empirical methods for predicting bearing capacity were evaluated based on Standard Penetration Test resistance index (N_{SPT}) measurements and RQD values obtained from rotary drilling. The methods employed were those of Aoki and Velloso [1], Décourt and Quaresma [2], Cabral [3], Rosenberg and Journeaux [8], Horvath [9], and Williams and Pells [10]. The bearing capacity of the piles was estimated using methods that account separately for the pile segments installed in soil and those socketed into rock.

The methods of Aoki and Velloso, Décourt and Quaresma, and Cabral are the most widely used for estimating the bearing capacity of root pile segments in soil. The methods of Horvath, Rosenberg and Journeaux, and Williams and Pells are commonly applied in cases where the pile is socketed into rock classified as weak to very weak according to the RQD classification. Initially, the uniaxial compressive strength of the rock was obtained through correlation with the RQD values measured during rotary drilling (Figure 2).

The RQD values obtained from rotary drilling ranged between 0 and 54% (Figure 5) for piles 1 and 2, respectively. Uniaxial compressive strength values between 5 and 7 MPa were obtained and subsequently used to estimate the bearing capacity of the pile segments embedded in rock. It should be noted that N_{SPT} values were limited to 50. Figures 7 and 8 present a comparison between the bearing capacity estimates obtained from the semi-empirical methods

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(estimated values) and the reference values (measured values obtained from the load test results).

Figure 7. Estimated-to-measured bearing capacity ratios for pile 1

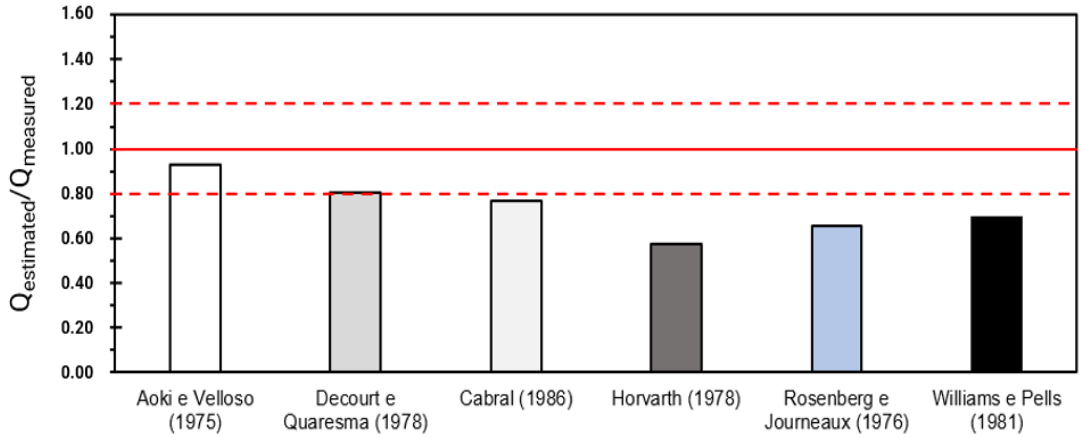
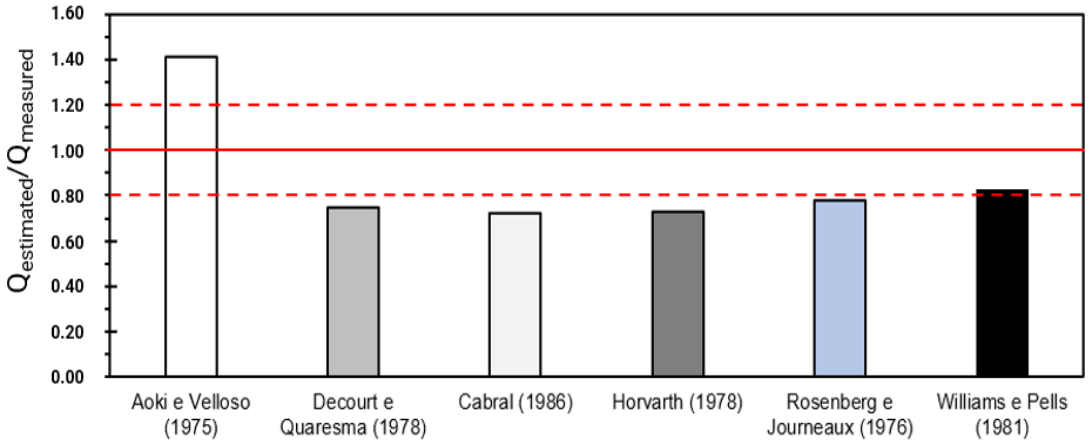


Figure 8. Estimated-to-measured bearing capacity ratios for pile 2



When comparing the bearing capacity estimates from the semi-empirical methods with the failure load determined using the Van Der Veen methodology [16], the semi-empirical methods generally produced conservative estimates, with the exception of the methodology proposed by Aoki and Velloso when applied to pile 2. This discrepancy can be explained by the bearing capacity factor K used in the method, which depends on the soil type present along the pile shaft. Pile 1 is embedded in a stratigraphic profile composed of interbedded siltstone and sandstone, whereas pile 2 is entirely embedded within a sandstone layer. In the Aoki and Velloso

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methodology [1], the K value may range between 220 and 1000 kPa depending on the soil material present. For pile 2, a K factor of 1000 kPa was adopted, corresponding to sand, whereas for pile 1, K values on the order of 400 kPa were considered for the pile segments located within siltstone layers. Variation in the K value affects both the shaft friction and end-bearing resistance estimates, thereby explaining the discrepancies between the estimates obtained for piles 1 and 2 using the Aoki and Velloso methodology [1].

The methods proposed by Aoki and Velloso and Décourt and Quaresma yielded estimated-to-measured ($Q_{estimated}/Q_{measured}$) ratios within ±20% for pile 1, whereas the methodology proposed by Williams and Pells [10] yielded ratios within ±20% for pile 2. It is further observed that the bearing capacity estimates obtained using the Williams and Pells method [10] were higher than those obtained using the Horvath [9] and Rosenberg and Journeaux [8] methods. This can be attributed to the fact that the α correction factor in the Williams and Pells method results in a smaller reduction of the shaft friction bearing capacity than the α factors associated with the Horvath and Rosenberg and Journeaux methods, as shown in Figure 1a. These preliminary results indicate that bearing capacity estimates obtained using semi-empirical methodologies based on SPT and rotary drilling results are satisfactory at the design level for root piles founded in soil–rock stratigraphic profiles in the city of Fortaleza, Brazil.

5. CONCLUSIONS

This study presented results obtained from load tests performed on root piles in the city of Fortaleza, Brazil. The analyzed foundations were axially loaded in compression, producing load–displacement curves that were interpreted to assess the accuracy of bearing capacity prediction methodologies for root piles founded in soil–rock stratigraphic profiles in Fortaleza, Brazil, based on SPT and rotary drilling test results. Experimental results obtained from load tests were compared with bearing capacity estimates derived from the methodologies of Aoki and Velloso, Décourt and Quaresma, Cabral, Horvath, Rosenberg and Journeaux, and Williams and Pells for root piles founded in soil–rock stratigraphic profiles, and the results are presented and discussed herein. Although limited to the conditions analyzed and based on a restricted dataset, these results allow for preliminary generalizations regarding the overall behavior of such piles. Furthermore, they highlight the considerable complexity of the phenomena involved in these processes. Within this context, the present study contributes to a better understanding of some of the characteristics involved in estimating the bearing capacity of root piles founded in soil–rock stratigraphic profiles. It should be noted, however, that some interpretations were formulated as

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conjectures to explain the observed results and require further research for more robust validation in the future. Based on the trends observed in the data and analyses, the following general conclusions can be drawn:

- The semi-empirical bearing capacity methods proposed by Aoki and Velloso, Décourt and Quaresma, Cabral, Horvath, Rosenberg and Journeaux, and Williams and Pells generally provided conservative bearing capacity estimates;
- The method proposed by Williams and Pells provided the most accurate bearing capacity estimates among the methods developed for rock materials;
- The method proposed by Décourt and Quaresma provided the safest and most accurate bearing capacity estimates among the methods developed for piles founded in soil;
- Based on the experimental results and bearing capacity calculations performed, methodologies based on SPT results and RQD values obtained from rotary drilling represent adequate tools for estimating the bearing capacity of root piles founded in soil–rock stratigraphic profiles.

Consequently, it must be emphasized that the conclusions presented herein are of limited scope and applicability. Nevertheless, these results, together with the experience gained during this research, may be of significant interest to researchers and foundation designers in this region and abroad.

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