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Uplift Performance of Large-Capacity Helical Piles in a Tropical Residual Soil

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Abstract. Helical foundations have been frequently used in Brazil for the construction of transmission line towers to resist uplift and compressive forces. However, in recent years the height of the towers has increased and consequently the loads on the foundations are also of greater magnitude. Normally, for these higher towers the loads are supported by groups of small-capacity helical piles, which are typical in Brazil (shaft diameters from 73 to 100 mm). In these cases, an advantageous alternative to reduce the number of piles and the costs of the foundations is the use of large-capacity helical piles. However, helical foundations of large dimensions have never been investigated before in Brazilian tropical residual soils. Therefore, to address the need of examining the performance of large-capacity helical piles in typical Brazilian residual soils a field-testing program was carried out at the Experimental Site of the University of São Paulo in São Carlos City. For this study, a single-helix and a double-helix instrumented large-capacity helical piles, with shaft diameter of 168.3 mm, were installed and tested under tensile loads. The load-transfer mechanisms of the large capacity helical piles were evaluated and discussed in this paper. The results of this study showed that although the uplift bearing capacity of the second helix of a pile is more impaired by the installation procedure compared to the bottom helix, the use of a double-helix pile is still more advantageous because it leads to a shorter pile resisting the same capacity of a longer single-helix pile of same shaft diameter.

Keywords. Helical piles, uplift capacity, tropical residual soils.

1. Introduction

Helical piles are composed of one or more helical plates welded to a circular or square steel shaft. The side of the square section varies from 40 to 50 mm, while the diameter of the circular section ranges normally from 73 mm to 965 mm, and the helices diameter from 152 mm to 1219 mm [1]. In Japan and other Asian countries helical piles are fabricated with shaft diameters up to 1600 mm [2].

This type of pile is installed into the ground by the application of a rotational torque by a hydraulic motor (Figure 1). The penetration rate is equal to the helix pitch for each complete revolution to minimize soil disturbance. If necessary, extension sections of the central shaft (with or without helices) are used to extend the lead section of the pile to greater depth. Before 2005, the hydraulic motors for the installation of helical piles provided maximum torque up to 110 kN.m; however, at the end of the 2000s decade, engines with a torque capacity up to 340 kN.m were used for larger piles [3, 4].

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The use of helical foundations has increased considerably in Brazil over the last decade. Helical piles are frequently used for the construction of Brazilian power transmission lines when deep foundations is needed. This increase in recent years has been due to the many advantages offered by this type of pile as supporting of compressive and tensile loads, installation at a batter angle, easy transportation to remote sites, rapid installation, etc.

Figure 1. Helical pile installation in a Brazilian transmission line.

In the beginning, helical piles were used in Brazil for transmission lines with operating voltage of 69 and 138 kV, to resist uplift loads of the towers that rarely exceeded 200 kN. More recently, the application of helical foundations has been extended to projects with operating voltage from 230 to 500 kV, currently reaching 800 kV, which is the highest voltage transmission in Brazil. For these cases, due to the increase of the average height of the towers. the foundations are required to resist larger tensile loads (up to 900 kN), and consequently groups of small dimeter helical piles are used for this end in the place of a single pile. The increase in the number of piles for a single tower considerably increases the cost of the towers foundation. This fact has resulted in a loss of competitiveness of helical foundations in comparison with other types of piles. In order to face this problem, the current work was designed to investigate the use of larger helical piles to support higher loads.

For the present study, the performance of large-capacity helical piles was evaluated by tensile loading tests performed on two instrumented piles installed in the Experimental Test Site at the University of São Paulo in São Carlos, Brazil. The soil at this site is a typical Brazilian residual tropical soil, and represents the condition of many transmission line towers in Brazil. The installation of this type of pile causes the breakdown of natural soil structure, and consequently affects the uplift capacity of helical foundations in residual structured soils. The amount of this effect on the behavior of conventional helical piles in Brazilian residual soils have been investigated in [5, 6, and 7]. However, the installation effect on the uplift capacity of helical piles of larger dimensions in residual Brazilian soils has not been investigated yet.

2. Experimental programme

2.1. Test site

The experiments of this investigations were carried out in the Experimental Test Site at the University of São Paulo in São Carlos, Brazil. Figure 2 shows the results of standard penetration tests (SPT) and cone penetration tests (CPT) done at the test site. The soil is composed of a sandstone residual soil layer covered by a superficial lateritic clayey sand layer (collapsible soil). A layer of pebbles separates the top layer from the residual soil. The level of the ground water table varies seasonally from approximately 9 to 12 m below the soil surface.

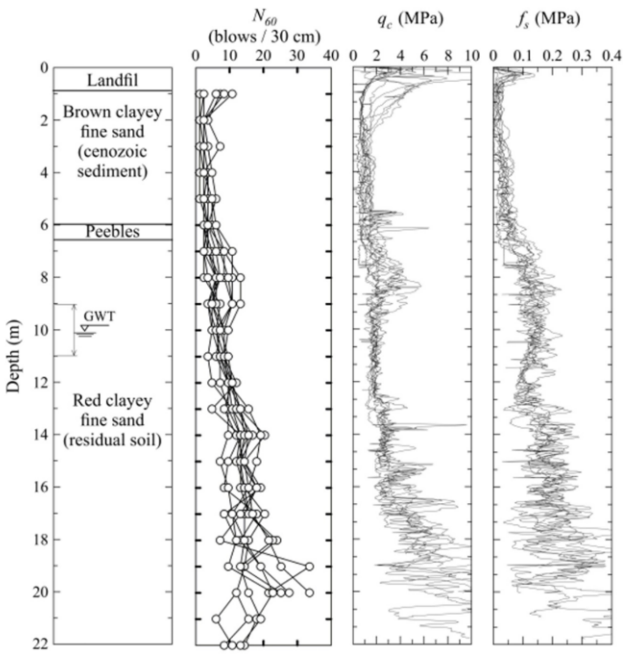


Figure 2. Soil profile at the test site ([8]).

2.2. Test piles

For the current study, two helical piles were tested: a single-helix and a double-helix pile, both with shaft diameter of 168.3 mm (wall thickness of 9.5 mm). The single-helix pile (E1) was fabricated with a single helical plate of 635 mm diameter, and the double-helix pile (E2) was constructed with two helical plates with diameters of 510 mm (bottom helix) and 635 mm (top helix). The wall thickness of the helical plates of both piles was 25 mm. Figure 3 illustrates the helical lead sections of piles E1 (single-helix) and E2 (double-helix).

For a better understanding of the helical pile uplift performance, and to investigate the installation effect on the helix bearing resistance of a large helical pile in a Brazilian residual soil, the guide sections of the piles were instrumented to separate the shaft resistance and the helix bearing resistances during the pile load tests. For the instrumentation, strain gages were installed above the helices of both piles, as illustrated in Figure 4. The strain gauges were fixed on the pile shaft and a thin steel plate was used to protect them. The electric cables connected to the gauges were placed inside the piles.

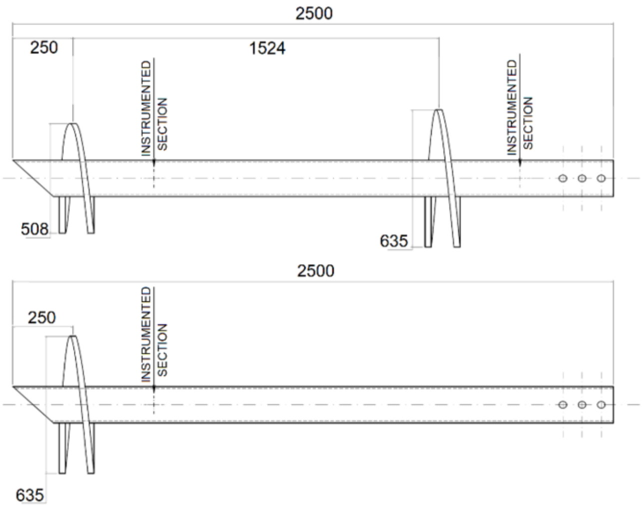


Figure 3. Dimensions of the lead sections of the tested piles E1 and E2 (millimeters).

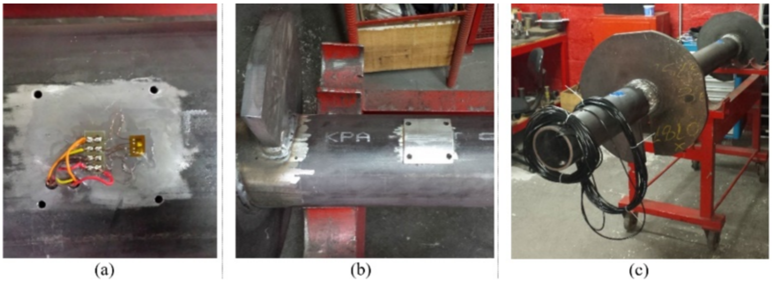


Figure 4. Details of pile instrumentation: (a) strain gages, (b) mechanical protection of sensors, and (c) cables connected to the strain-gages (cables passing through the shaft).

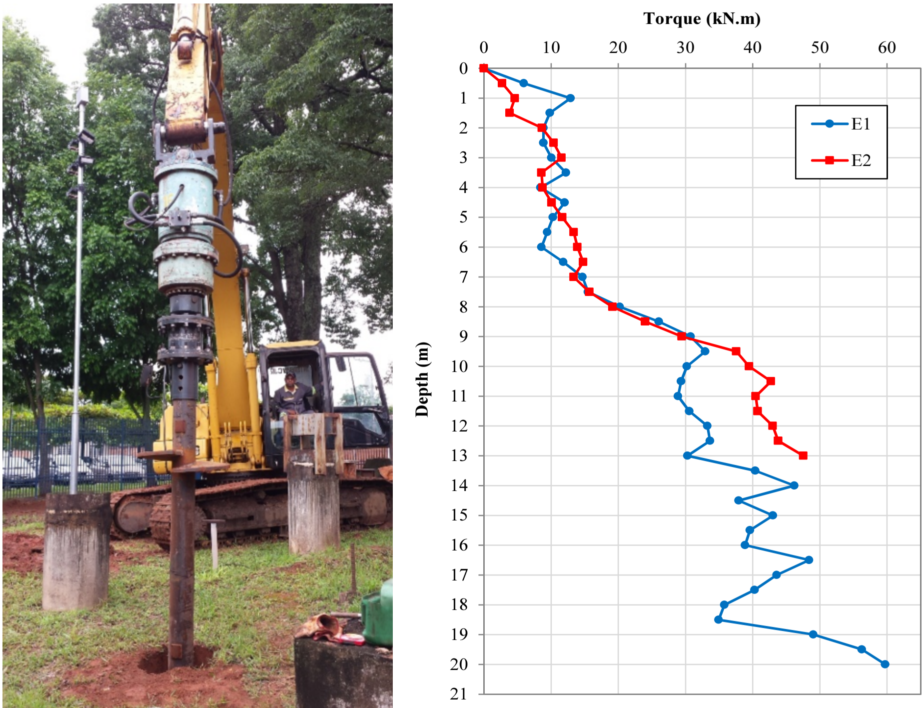
The helical piles were installed into the ground by a hydraulic motor (Figure 5a). The torque required to install the piles was measured during the installation by a torquemeter. This measurement is a typical procedure used for pile capacity control during installation. The final depth of helical foundations is controlled by the installation torque because the pile capacity is correlated empirically with the final installation torque by means of an empirical factor, K_T [9]. Figure 5b shows the results of installation torque along the installation depth. Table 1 describes the installation data of piles E1 and E2.

The aim of the study was to compare the performance of a single and a double-helix pile with uplift capacity of approximately 575 kN. Therefore, to estimate the value of a final torque to provide the target capacity, the K_T factor (K_T = uplift capacity/final torque), which is unique for helical piles of same shaft diameter, was estimated based on the recommendation of [10]:

$$K_T = \lambda_k / d_{eff}^{0.92} \quad (1)$$

where λ_k = fitting factor equal to 22 in$^{0.92}$/ft [1433 mm$^{0.92}$/m] and d_{eff} = effective shaft diameter.

For the shaft diameter of 168.3 mm, using the K_T factor obtained from Eq. (1) (K_T = 12.8 m^{-1}) a final torque value of 45 kN.m was determined for the current work (averaged over the final penetration of three times the helix diameter). As shown in Figure 5, the pile with two-helix reached the target torque value before the pile with one helix. This occurs because the installation torque increases with the pile surface area; therefore, to install a pile with a greater number of helices a higher torque is necessary.



(a) (b)

Figure 5. (a) Pile installation and (b) results of installation torque.

Table 1. Final depth and installation torque of piles E1 and E2.

Final depth (m)	Value
Pile E1	20
Pile E2	13
Average final torque (kN.m)	
Pile E1	47.1
Pile E2	43.1

2.3. Pile load tests

Figure 6 shows the general layout of the setup for the tensile loading tests. The load was applied by a hydraulic jack (capacity of 900 kN) and a reaction beam, and measured using a calibrated load cell (capacity of 1.000 kN). The vertical displacements of the pile were measured using mechanical extensometers with 0.01 mm sensitivity. The load was applied in increments of 5% of the predicted pile uplift capacity in 5 min intervals, as specified in the Brazilian standard ABNT NBR-12131 [11].

Figure 6. Load test set-up.

3. Results

The results of the two loading tests performed for the current study are presented herein in terms of load-displacement curves in Figure 7. Before both loading tests, a small alignment (preload) was applied to the piles, and for this reason the initial load shown in the curves is greater than zero.

Figure 7 shows that for displacements less than 80 mm, the performance of the double-helix pile of 13 m depth is better compared to the single-helix pile of 20 m. However, for greater displacements the single-helix pile shows greater capacity. This occurs because the helix of pile E1 is installed in a deeper soil layer of greater capacity.

Using a failure criteria in which the uplift capacity is assumed as the load equivalent to a displacement of 10% the mean helix diameter, the values of uplift capacity is similar for both piles (Table 2). This fact indicates that the K_T factor is comparable for helical piles of same shaft diameter and different number of helices. As shown in Table 2, the measured value of the K_T factor is lower than the value calculated using Equation 1. However, if the K_T factor was estimated using the peak load instead the load equivalent to the displacement of 10%D, the measured value of K_T factor would be greater than the one found from Equation 1. The K_T factor varies with the failure criterion used.

Figure 8 illustrates the fractions of helix bearing capacity and shaft resistance obtained from the pile instrumentation using strain-gages (Figure 4). For both piles, the portion of helix bearing resistance is more important compared to the shaft resistance. This figure also indicates that the bearing capacity of the single helix of pile E1 is comparable to the sum of the bearing capacities of the two helices of pile E2.

Figure 9 illustrates the bearing pressure resisted by the helices of pile E1 and E2 and shaft unit skin friction. Figure 9a shows that the mobilization of helix bearing resistance increases with pile displacement, and no failure trend was observed. However, the curves of the helix bearing resistances of pile E2 (Figure 9b) indicates that after a displacement of around 60 mm, the rate of displacement increases rapidly with increasing the applied load.

Additionally, Figure 9b shows that the bottom helix of pile E2 supports a greater amount of load compared to the top helix. This fact indicates that the disturbance in the soil above the second helix (penetrated two times during installation) is more important compared to the soil above the bottom helix (penetrated only one time). However, although the soil disturbance caused by installation is more important above the second helix, the results of this study show that the double-helix pile provide similar uplift response of a (7m) longer single-helix pile; therefore, the use of a double-helix pile is more advantageous.

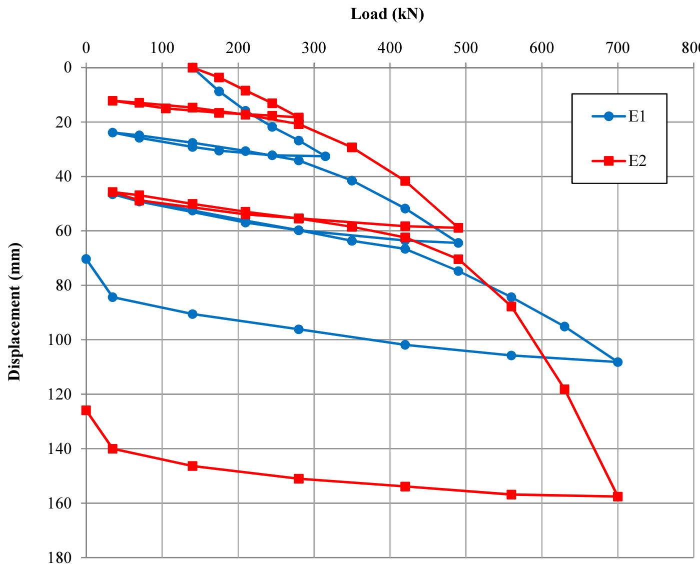


Figure 7. Applied load at pile head versus displacement for axial tension pile load tests.

Table 2. Uplift capacity and K_T factor of piles E1 and E2.

Uplift capacity (kN)	Value
Pile E1	482
Pile E2	483
K_T factor (m^{-1})	
Pile E1	10.2
Pile E2	11.2

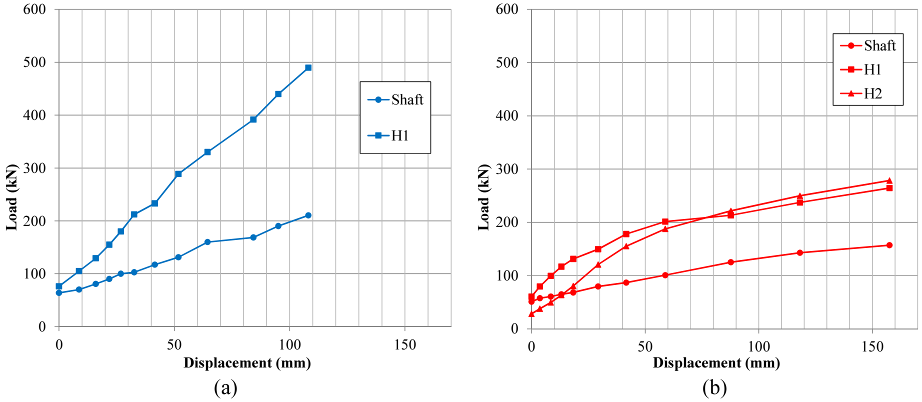


Figure 8. Fractions of helix bearing and shaft resistances during the loading tests om piles E1 and E2.

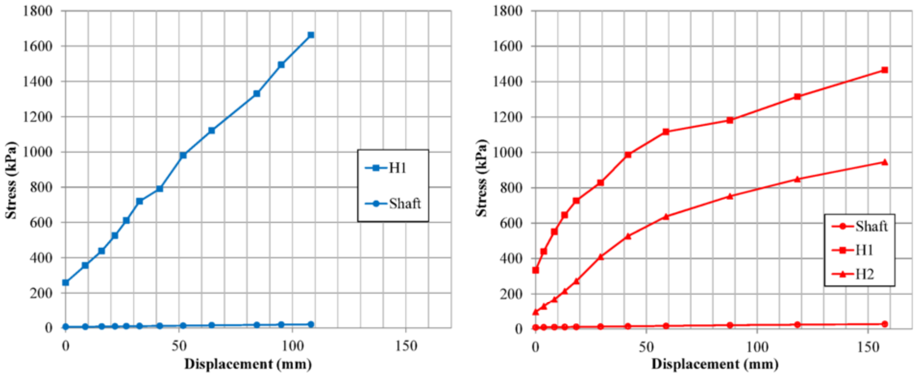


Figure 9. Helix bearing pressure and shaft skin friction during the loading tests on piles E1 and E2.

4. Conclusions

This paper presents a field study on the behavior of large helical piles in a tropical residual soil. The results indicated that the use of a double helix-pile is more advantageous compared to a single-helix pile in the site investigated.

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