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Uplift performance of helical piles with cement injection in residual soils

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ABSTRACT

Helical piles have been widely used in Brazil to resist uplift forces of transmission line towers due to certain advantages compared to other foundations, such as resistance to both compressive and tensile loads, easy transport to remote sites, possibility of installation at batter angles, rapid installation with small equipment, and no need for concrete and formwork. However, in some sites the appropriate soil layer for the installation of the pile helices is too deep or too hard to be penetrated. In these cases, the use of helical foundations is not economically and/or technically viable. One possible solution for this problem is to install the pile in a soil with low bearing capacity improved with cement injection. To evaluate the applicability of a soil-treatment method for helical piles, two different procedures of injection were tested in typical Brazilian residual soils of different geologic origin. For this investigation, 41 multi-helix piles (15 conventional piles and 26 with cement injection) were installed and submitted to tensile loading tests. The results reveal that both techniques can improve the tension capacity and produce a stiffer load-displacement response of helical piles under uplift loads.

**Key words:** helical piles, uplift capacity, tropical residual soils, cement injection, full-scale pile load tests
INTRODUCTION

Helical piles are made of steel and consist of one or more helical plates welded to a central shaft (Figure 1). The size and number of helices vary according to the pile load capacity defined in the design phase, and with the soil conditions. The shaft diameter usually ranges from 73 to 965 mm, while the helix diameter ranges from 150 to 1220 mm (Sakr 2009).

This type of pile is screwed into the ground by the application of torque at the top of the shaft using a hydraulic motor. The pile penetrates into the ground in a smooth and continuous manner, with the rate of advance of one helix pitch per revolution, and rotational speed between 5 and 20 rpm. Sufficient pull down pressure is applied to ensure that the pile advances uniformly into the ground (A.B. Chance 2010). The torque required to install the pile varies with the soil characteristics and pile geometry.

The use of helical piles in Brazil as foundations of towers of transmission lines (for hydroelectric power and wind energy) has been increasing considerably during the last ten years, mainly because this type of foundation can: (i) support tensile and compressive forces, (ii) be installed using small equipment, (iii) have the ultimate capacity evaluated by the final installation torque, (iv) be installed below the groundwater table, (v) be installed at any inclination angle, and (vi) be loaded immediately after the end of the installation.

A large number of helical foundations in Brazil, used for transmission tower structures of extensive and numerous transmission lines, have been installed in unsaturated tropical residual soils. Weathered tropical soils with high void ratios lose much of their natural structure during the installation of helical piles, and, as consequence, in these soils the pile uplift capacity is lower than expected (Tsuha et al., 2015).

In tropical regions, the weathering of primary minerals occurs at greater depths than elsewhere (Fookes 1997). Therefore, thick layers of residual soils of insufficient capacity to the use of helical piles are found in many areas in Brazil, where power transmission lines should be constructed. In these cases, the helical piles should be installed at very deep soils to ensure a good foundation performance. However, the use of very deep piles is not economically feasible for tower foundations. Additionally, this type of pile is technically unfeasible in sites where weakly bonded tropical soils overlay an impenetrable material (rock or partially weathered rock).

The extensive use of helical foundations in Brazilian transmission lines, together with the problems cited above, detailed in Tsuha et al. (2015), have motivated the current study, which was designed to evaluate the use of cement injection for soil improvement, to make possible the use of helical piles in soils with low bearing
capacity. For the present investigation, two different procedures of cement injection were developed and evaluated by field experiments. This paper presents a comparison between the performance of helical piles with and without soil treatment installed at three different test sites.

HELICAL PILE INJECTION

Previous investigations

Few studies have been published to date on the effect of the cement injection on the behaviour of helical foundations. The most studies were conducted on reduced pile models in laboratory, tested at 1g or in a centrifuge. The first study on this topic was presented in Manke (2004) and in Laefer et al. (2007). In this work, reduced models of helical piles with two helices, in the scale 1:8, installed in sand, were injected with grout during installation, and tested. The grout penetrated the soil by a hole located closer to the pile tip. The objective of this investigation was to evaluate the behaviour of groups of drilled shaft reinforced using helical piles with and without grout injection. The results of the model tests showed a slightly superior performance of the conventional helical pile compared to the grouted case. Laefer et al. (2007) concluded that this unexpected result may be caused by the extreme soil dryness and uniformity. These authors also mentioned that for grouted helical piles in non-uniform soils, with some water content, the helix carved path is able to remain open and the grout can fill it, and in the laboratory tests the dry sand did not allow the helix carved path to stay open, which caused loosening of the soil around the pile.

Bian (2006) performed centrifuge tests on reduced models of single-helix piles with grout injection in sand. The main conclusions found from this study can be summarized as follows: smaller water-cement ratio can produce larger soil–grout bulbs; the pile rotation during injection provides an increase in the bulb diameter of 60 to 100%; and higher injection pressure resulting in larger grout bulbs.

Khazaei and Eslami (2016) performed tensile and compression tests on double-helix pile models, installed in a calibration chamber filled with sand. The cement slurry injection was done in three different parts of the pile: from pile toe, from shaft body between the two helices, and under the upper helix. The results obtained showed an increase of 25-50% in the pile capacity of the injected piles compared to the conventional piles, and the improvement was greater when the injection was performed under the upper helix. These authors
concluded that the post-grouting procedure can improve the performance of helical piles and compensates the installation effects on the pile capacity.

Sanchez (2014) carried out the first field study on helical piles with cement injection in Brazil. This author conducted pull-out loading tests on four three-helix piles (two conventional and two injected piles) installed in a clayey-sandy silt. The piles were constructed with two levels of injection holes in the shaft body, one under the bottom helix and other under the second (middle) helix. The results of pile tests showed that the values of uplift capacity of the injected piles were approximately 104% higher than the ones obtained with the conventional piles. In this cited work, the exhumation of the injected pile indicated that the cement slurry filled the void space left by the passage of the helices during installation.

Field tests on grouted and un-grouted helical piles were carried out in Nabizadeh and Choobbasti (2016). They installed and performed axial compressive load tests on helical piles with one, two and three helical plates at two different experimental sites. Gains in pile capacity, varying from 8-28%, were observed for the grouted piles installed in clay, and of 14-24% for the cases installed in sand. Nabizadeh and Choobbasti (2017) presented new results of tensile and compression tests performed on grouted helical piles with the same configurations and installation procedure of the cases presented in Nabizadeh and Choobbasti (2016). The results of compression tests on the grouted piles indicated gains of 20% for the single-helix pile, 29% for the two-helix pile, and 25% for the three-helix pile compared with the conventional helical piles. However, the results of pile tensile tests indicated that the gains provided by the grout injection were reduced.

Cement injection procedures

The installation process of helical piles disturbs the soil penetrated by the helices. The effect of installation on the uplift performance of helical piles have been observed by different authors (Weech 2002, Tsuha et al. 2012; Clemence and Ghaly 2013; Lutenegger et al. 2014; Lutenegger and Tsuha 2015; Tsuha et al. 2015; Perez et al. 2017). Therefore, the objective of the current investigation was to evaluate a procedure of cement injection to repair the disturbance caused by the helical pile installation in residual tropical soils, by improving the mechanical properties of the soil above the helices.

For this investigation, the cement slurry was injected through holes at the pile shaft close to the helices. The efficiency of the improvement process was verified experimentally in this work using two different
injection procedures. The first one consists of simple injection, and the second of the use of an inflatable packer to improve the performance of the reinforced zone in the region of the helices.

Due to the passage of the helices during pile installation, when the soil has some cohesion, a preferred path for the cement flow is created, as observed previously in Sanchez (2014). This phenomenon was also noted in the present investigation, and is responsible for limiting the volume of injected slurry and of the injection pressure, and consequently influences the efficiency of the soil treatment process. Therefore, in the current work an inflatable packer was developed to prevent the rise of the cement slurry to the ground surface through empty spaces along the pile-soil interface, and to force the movement of the cement slurry to the region of the helices.

The inflatable packer used in this work consists of a cylindrical rubber membrane with the thickness of 10 mm, and internal diameter equal to the external pile shaft diameter. As illustrated in Figure 2a, the steel rings provide sealing and control the expansion at the device extremities. The device is installed in a helical pile extension with holes under the rubber membrane (Figure 2b), which allows the membrane to be filled with the cement slurry. At one section of this device, there is also an internal valve (activated by reaching a pre-determined pressure of 400 kPa), which allows the membrane to be inflated by the pressurized slurry before the infiltration of the slurry in the soil.

The current paper compares the uplift performance of injected (with and without inflatable packer) and conventional (no-injected) helical piles installed at three different sites of residual soils in Brazil. Figure 3 illustrates the three types of helical piles tested in this study.

**TESTING PROGRAM**

**Test piles**

For the current study, four different pile configurations were tested: two different shaft diameters and piles with four and six helices (Table 1). The piles were fabricated with helical plates spaced three diameters apart along the pile shaft. The six-helix piles were composed of a lead section with four helices and an extension with two helices (i.e., helix thickness of 12.5 mm with a pitch of 90 mm). For the helical piles with cement injection, 12 holes were drilled along the shaft above the first three helices. Four holes were drilled
above each helix in two different and perpendicular positions (150 mm and 240 mm above the helix), as illustrated in Figure 4.

The helical piles in the current work are named according to the site tested (S1, S2, or S3), type of injection (conventional pile: CP, free injection: FI, or injected with an inflatable packer: IP), shaft diameter (dimensions in mm), number of helices, embedded length (in meters), and test number; for example: S1-FI-88.9-4H-9.5m-T2 (site 1, free injection, shaft diameter of 88.9 mm, four helices, with an embedded length of 9.5 m, second identical pile tested). Table 2 describes the characteristics of all helical piles tested for the current investigation.

The improvement caused by the cement injection was verified in three different test sites (sites 1, 2 and 3) in Brazil (Figure 5). In all sites, conventional and injected helical piles with the same configuration (same shaft and helices diameters and number of helices) were installed in similar conditions for the comparison of the pile uplift performance. In Table 2, for each site tested, piles of identical geometry with similar final torque (sites 1 and 2) or identical embedded depth (site 3) are grouped into different groups (G1 to G10).

Table 2 shows that in the sites 1 and 2, the embedded lengths of the piles of the same group are similar, but not identical. For these first two sites tested, as the uplift capacity of helical piles is directly proportional to the final torque (Hoyt and Clemence, 1989), the criteria chosen to evaluate the gain in capacity provided by the injection was to compare piles of identical geometry (same shaft and helices diameters) installed with similar final torque. However, as shown in Table 2, the identical piles of sites 1 and 2 also present similar embedded length. For the site 3, a different criteria was used, and in this case piles of identical geometry (injected or not) were installed at the same embedded length for comparison. Additionally, as illustrated in Table 2, for the most types of pile configuration, two identical piles were tested (T1 and T2). The second experiment was devoted to the evaluation of the repeatability of the results of pile uplift response.

Figures 6 to 8 illustrate the location of the piles at the three sites. The minimum distance between the tested piles was 1.50 m (4.2 times the larger helix diameter). As mentioned in Perko (2009), four times the helix diameter should be used to avoid group effects. Additionally, as shown later in this paper, the results of the piles exhumations indicate that the cement slurry filled the cylindrical zone penetrated by the helices during installation. Therefore, the distance between the tested piles is supposed to be enough to eliminate any effect on the boundary conditions of the tested piles.
Site 1

The first tests of this experimental research were carried out at the same site investigated in Tsuha et al. (2015), in a region between São Carlos and Itirapina city, inland of São Paulo State, Brazil (Figure 5). The area is dominated by a 7 m deep layer of highly porous (high void ratio and low density) and colluvial sandy clay (lateritic soil), which overlay a residual soil formed by the decomposition of diabase rock (saprolitic sandy clayey silt).

The results of SPT and CPT tests performed in this area are presented in Figure 6a. The groundwater table was not reached at the tests. More details of the soil characteristics are found in Tsuha et al. (2015). In this cited work, the results of uplift capacity of single-helix and multi-helices piles, installed vertically at a depth of 10 m from the ground surface, were lower than expected due to the effect of helix penetration on the weakly bonded soil. For a better understanding of the installation effects on the uplift capacity of helical piles in this case of sensitive soil structure, these authors performed static tension and compression pile load tests, complemented by in situ and laboratory testing.

For the current investigation in this site, six helical piles (two conventional and four injected piles) with embedded length varying from 8.0 to 10.5 m, with similar value of final installation torque, were installed with an inclination angle of 40°. In this site, the effect of the pile injection was evaluated for four-helix and six-helix piles (piles groups G1 and G2), as illustrated in Table 2.

The locations of the piles and of three standard penetration tests (SPTs) and three cone penetration tests (CPTs) are illustrated in Figure 6b. As indicated in Table 2, in the site 1 the helical piles were injected without inflatable packer. This device, used for the improvement of the soil treatment with cement injection, was developed during the period of tests in the site 2; therefore, it was only evaluated in the sites 2 and 3.

Site 2

The second test site is located in Betim city, Minas Gerais State, Brazil (Figure 5). The top layer of this area is composed of unsaturated residual soils (weathered granitoids), illustrated in Figure 7a. The groundwater table was not found at the site. In this area, 18 helical piles (six conventional piles, ten injected piles without
and two with an inflatable packer), with embedment lengths ranging from 10.5 to 13.5 m, were installed vertically into the ground. The locations of the SPT tests and the tested piles are indicated in Figure 7b.

As shown in Table 2, for each configuration of conventional helical piles, two identical piles with cement injection (same shaft and helices diameters and number of helices, installed with similar final torque) were tested for comparison. In this site the injection with the inflatable packer was tested for the first time in two identical helical piles, which have same geometry and similar final torque of conventional and injected helical piles without this device (pile group G7 of Table 2) for comparison.

The pile tests carried out at the site 2 were grouped into five groups (G3 to G7) as presented in Table 2. The pile tests of the four first groups (G3 to G6) were proposed to evaluate the effect of the number of the helices and of the shaft diameter (tested piles with four or six helices, and with shaft diameter of 88.9 mm or 101.6 mm) on the gain in uplift capacity of helical piles caused by the cement injection. The group G7 was designed to investigate the effect of the type of injection (with or without the inflatable packer) on the improvement of the pile performance.

Site 3

The third test site is located in São Carlos city, Brazil (Figure 5). The soil profile at the test site, described in Figure 8a, is composed of a sandstone residual soil (red clayey fine sand) covered by a colluvial lateritic clayey sand layer, separated by a layer of pebbles. The top layer is a typical tropical unsaturated porous soil of collapsible nature. The groundwater table varies seasonally from 9 to 12 m below the ground surface (Schiavon et al., 2019). For the current study, no new soil investigations were performed at the site 3 since several SPT and CPT tests were conducted before at this experimental site (Giacheti et al. 2006), as illustrated in Figure 8a. For this reason, the locations of SPT boreholes and CPT soundings are not included in Figure 8 to avoid excessive number of points.

In this site, 17 helical piles were installed vertically with embedment lengths of 8 m and 16 m. The experiments at this site were organized into three groups (G8 to G10) to evaluate the effect of the number of helices (tested piles with four or six helices), type of injection (with and without an inflatable packer) and pile length (8 m or 16 m) on the gain in uplift capacity of helical piles due to the cement injection. In each group described in Table 2, a particular configuration of a conventional helical pile was compared to identical injected
piles (same geometry and embedded length), with or without an inflatable packer. However, for the pile cases of 16 m length (group G10), only injected piles without inflatable packer were installed and tested for comparison with conventional piles. The pile locations are illustrated in Figure 8b.

**Pile installation and injection**

The helical piles evaluated in this work were installed into the ground with the application of torque by the driving tool illustrated in Figure 9a. The results of the torque readings, collected by a digital torquemeter (Figure 9b), were recorded every 50 cm during pile installation.

After the installation of all helical piles, the cement injection was performed in a single stage through the inside of the pile shaft. The material injected was a mixture of Portland cement and water, with a water/cement mass ratio equal to 0.5.

The cement slurry was prepared in a blender and injected using a piston pump. The volume of injected slurry was variable, being limited to 300 kg of cement per pile (Table 2). Figure 10 shows the equipment used for the injection process. Injection pressures of approximately 3000 kPa were achieved in the piles injected without inflatable packer, and 4000 kPa in the piles with inflatable packer. The pressure was higher for the piles injected with the inflatable packer due to the flow strangulation when the slurry pass through the valve. Furthermore, after the valve is activated, the inflated packer prevents the rise of the injected slurry toward the ground surface. In the present work, the injection procedure was stopped when the slurry returned to the ground surface or when reached a maximum cement volume specified.

**Static tension load tests**

Tensile load tests were performed on all piles identified in Table 2. For the injected piles, the tests were conducted seven days after the injection. Seven days is the minimum curing time recommended by the Brazilian standard ABNT NBR-12131 (ABNT 2006a) for ties anchored in soil when common cement is used for injection.

The axial load was applied using a 900 kN hydraulic jack, in increments of 5% of the predicted pile ultimate load in 5 min intervals, as stated in the Brazilian standard ABNT NBR-12131 (ABNT 2006b). The
pile ultimate load was calculated using the torque correlation method \( Q_u = K_T T \), where \( Q_u \) is the pile uplift capacity, \( K_T \) is the torque factor, and \( T \) is the final installation torque, as shown in Hoyt and Clemence (1989). For the first site tested (site 1), the value of the torque factor \( K_T \) was determined using the equation proposed in Perko (2009). However, for the sites 2 and 3, higher values of \( K_T \) were used, as the results of the load tests on the injected piles in the site 1 showed that the measured \( K_T \) values are superior than the value used for the first prediction.

As illustrated in Figure 11, a reaction beam supported by wood cribbing was used for the pile load tests conducted at the sites 2 and 3. In the site 1, the load tests were carried out with the same inclination angle of the piles, and a tripod with a backhoe for balancing the horizontal forces were used for this purpose (Figure 11a). For all tests, the load at the pile head was recorded using a digital load cell with a maximum capacity of 1000 kN and 0.1 kN accuracy, manufactured by Alfa Instrumentos (São Paulo, Brazil). During the load tests, the pile head movement was monitored using four supported dial gauges (0.01 mm accuracy, 50 mm travel) manufactured by Mitutoyo Corporation.

In the current work, the uplift capacity of helical piles were determined from the load-displacement curves using the criteria proposed in Livneh and El Naggar (2008) (load equivalent to the pile head movement equal to 8% of the largest helix diameter plus the elastic deflection of the pile).

**Pile exhumation**

In the current work, two short double-helix piles were installed at the site 3, with 3 m embedded length, and exhumed for observation. The goal of the pile exhumation was to examine the spreading of the cement slurry injected into the piles, with and without an inflatable packer. These piles were fabricated with shaft diameter of 101.6 mm, and with four holes drilled above the bottom helix in two different and perpendicular positions (150 mm and 240 mm), as indicated in Figures 12a,b (in millimeters). The horizontal distance between these two piles was 2.0 m. After pile injection, the soil around the piles was carefully excavated (Figure 12c) to provide a clean-cut vertical section of the soil for visual observation of the injected material.

**RESULTS**
Installation torque

The results of the torque readings, recorded during the piles installation, are shown in Figures 13 to 15. The values of final torque (average value recorded during the last one meter of installation) are presented in Table 2. Figures 13 to 15 indicate that in the three test sites of this research, the installation measurements of piles with the same shaft diameter and number of helices (same pile group), installed at the same site, show similar values of torque along the depth. This fact indicated that the three sites are homogeneous horizontally, which is fundamental for a good comparison between the uplift performance of different piles (injected or not) installed in the same site.

In the sites 1 and 2, each pile group of identical geometry (G1 to G7) were installed with similar final installation torque for comparisons between the performance of conventional and injected piles. Figure 13a illustrates the installation torque of the pile group G1 (four-helix piles) and Figure 13b of the pile group G2 (six-helix piles). The piles of the both groups, installed with an inclination angle of 40° at the site 1, present similar final torque; however, for the case of six-helix piles the final embedded length is slightly inferior.

Figure 14 shows the installation torque results of the pile groups installed vertically at the site 2 (G3 to G7). As observed in the site 1 (Figure 13), the final torque of the piles in the same group are similar, and the final embedded depth of all piles are also similar.

The comparisons between Figure 14a (G3) and 14b (G4), and between Figure 14c (G5) and 14d (G6), indicate that the piles with four and six helices (with same shaft diameter) have similar final installation torque and embedded depth. Therefore, the fact of adding more two helices to the pile did not influence the installation torque results. Probably it occurs because of the two upper helices (fifth and sixth helices) of the six-helix pile (which have the same diameter of the fourth helix) penetrate a soil considerably disturbed by the penetration of first four helices, and for this reason the results of installation torque of the four-helix and six-helix piles are similar (Table 2).

The comparisons between Figures 14a,b (piles of the group G3 and G4) and Figures 14c,d (piles of the group G5 and G6), and the results of final torque in Table 2, show that the piles with shaft diameter of 101.6 mm presented higher installation torque than the piles with shaft diameter of 88.9 mm. This difference is explained by the higher shaft surface area in contact with the soil during installation.
Figure 14e illustrated the torque results of the piles of the group G7, which were installed closer the SPT borehole named SP-02 (Figure 7). As shown in Figure 7, the results of $N_{60}$ of the SP-02, obtained at the depths from 9 to 12 m, are reduced compared to the values of the SP-01. Therefore, the piles of this group were installed with lower values of final torque compared to the groups G3 to G6. The purpose of this choice was to evaluate the injection performance using the inflatable packer in piles installed in soils of low strength. The two first piles with inflatable packer installed and tested in the current study belong to the group G7.

The measurements of installation torque of the piles tested in the site 3 are presented in Figure 15. Figures 15a (four-helix piles) and 15b (six-helix piles) show the results of the piles installed with and identical embedded depth of 8 m. These figures indicate that the six-helix piles presented slightly higher values of torque compared to the four-helix piles with the same shaft diameter. In this case, different from the trend observed in the site 2, the fact of adding two more helices slightly increased the installation torque. Therefore, from the torque measurements of this study, it can be concluded that the effect of adding more helices to a multi-helix pile can increase the installation torque or not, according to the degree of the disturbance of the soil penetrated by the additional helices. Figure 15c presents the installation torque results of identical four-helix piles installed to a depth of 16 m (pile group G10). The final torque values measured for the group G10 are approximately 2.5 times the values obtained for identical four-helix piles installed to a depth of 8m (piles group G8).

Load-displacement curves

The load–displacement curves of all tensile load tests carried out for the current study are shown in Figures 16-18 (tests in site 1, site 2, and site 3, respectively), and the results of uplift capacity are presented in Table 2.

Figure 16 compares the load-displacement behaviour of four-helix (Figure 16a) and six-helix (Figure 16b) piles, with and without injection, installed at the site 1. The results show clearly that the cement injection improved considerably the pile uplift performance. Additionally, the curves of the tests on injected helical piles with the same number of helices (four or six) are almost identical, indicating good reproducibility of the injection technique.

Although the helical piles of Tsuha et al. (2015), also tested at the site 1, were constructed with an inferior number of helices and installed slightly deeper compared to the current investigation, for both cases
the results indicate that for this type of soil the increase in the number of helices of conventional multi-helices piles (no-injected) practically does not improve the uplift load-displacement performance under displacements lower than 10% of the mean helix diameter. Additionally, in the current study, as shown in Figure 16, the performance of a conventional four-helix pile was slightly superior compared to the six-helix pile. This finding indicates that the cylinder of soil above the fifth and sixth helices of the six-helix pile is completely disturbed and does not contribute to the pile uplift capacity.

The plots obtained from the pile load tests at the site 2, presented in Figures 17a,b,c,d are separated by groups of helical piles with identical geometry and similar final installation torque, without and with cement injection (without inflatable packer) as shown in Table 2. These results, as observed in the site 1, indicate that the procedure of cement injection can improve the pile uplift behaviour. In addition, as occurred in the site 1, the curves of identical injected helical piles are similar, showing good repeatability of the injection procedure.

Figures 17a to 17d compare the effect of the number of helices and of the shaft diameter (tested piles with four or six helices, and shaft diameter of 88.9 mm or 101.6 mm) on the improvement of the load-displacement performance caused by cement injection. As discussed later in this paper, the number of helices influences the amount of gain in pile performance caused by the pile injection, although for the range of shaft dimensions tested no effect of the shaft diameter was observed. Figure 17e compares pairs of conventional helical piles with pairs of injected piles, with and without inflatable packer. The results of this comparison show that the improvement on the pile performance caused by cement injection is even better in the case of the injection with an inflatable packer.

Figures 18a,b compares identical helical piles (with and without injection) with embedment length of 8 m. The curves of these figures illustrates that for piles with four helices (Figure 18a) and with six helices (Figure 18b) the uplift performance is improved after cement injection. The curves of Figure 18a and the results of uplift capacity shown in Table 2 indicate that for the case of four-helix piles, the injection with an inflatable packer were more advantageous compared to the procedure without this device (average increase in capacity of approximately 42 %). However, for the six-helix piles (Figure 18b), the gain in using the inflatable packer compared to the cases of free injected piles was reduced (average increase in capacity of approximately 16 %). It occurs probably because for the piles with embedded length of 8 m, the depth of the inflatable packer of the six-helix pile (located above the sixth helix) is closer to the ground surface compared to the case of the four-helix pile, and in this case, the use of an inflatable packer close to the ground surface was not advantageous.
The curves obtained from the tests on the helical piles of 16 m length are shown in Figure 18c. In this case, only conventional piles and piles injected without inflatable packer were tested. The results indicates that the cement injection has improved considerably the pile capacity and the load-displacement behaviour.

Pile exhumation

The manual excavation of the helical pile injected without the inflatable packer confirms the formation of helical "cement plates" along the entire length of the pile, as shown in Figure 19a. The plates were formed due to the filling of the space left by the passage of the pile helices during the installation in a soil with some cohesion. The cement plates have the same diameter of the helices and a constant thickness of approximately 20 mm (Figure 19b). The cement plate thickness was greater than the helix thickness (12.5 mm) probably due to the expansion caused by the injection process.

The exhumation of the pile injected with the inflatable packer shows the formation of cement plates below the device (Figure 20a) similarly to the other pile. Two subvertical lenses (with approximately 6-10 mm thick) were formed from the base of the inflatable packer and projected radially (Figure 20b). In this case, no cement plates were found in the region above the device (Figure 20c). No great expansion of the inflatable packer was observed, although, it could have expanded and returned to its original shape with pressure relief as soon as the injection process was finished. In any case, there is no doubt that it prevented the flow of cement slurry through the region of disturbed soil above the top helix, and provided an increase in the injection pressure and the volume injected. Additionally, it was also verified in both exhumed piles that there was no flow of slurry to the region of soil below the pile tip.

Although in the two other sites tested, the injected piles were not exhumated and visually analyzed, the slurry flow path may be similar to that observed at the site 3 and in Sanchez (2014), as the injected piles in these sites were installed in unsaturated and cohesive soils. However, the slurry movement observed in the present study is valid for sites of similar soil conditions (soils with some cohesion). In the case of injected helical piles in no-cohesive soils, as mentioned in Laefer et al. (2007), the helix carved path is closed after the passage of the helix and the injection phenomena is different from that of the current study, in which the cement slurry filled the void space left by the helices during installation. Additionally, the injectability (slurry penetrability) is higher in sandy soils than in clayey ones.
DISCUSSION

Improvement of the uplift capacity

Table 2 show that the results of uplift capacity of all injected piles are greater than the values found for similar conventional helical piles (with same geometry and similar final torque and embedded length). The gains caused by the cement injection is due to the fact this procedure can repair the soil disturbed by the pile installation, which is mobilized when the pile is loaded in tension. Additionally, the results of Table 2 also indicate that there is no clear relationship between volume of injected cement and gain in pile uplift capacity. The effect of volume injected should be only important when the cement slurry fills the soil disturbed zones that resist the uplift loading. When the excess of volume injected fills the soil near the ground surface or cavities outside the cylindrical zone penetrated by the helices, no gain in uplift capacity will occur.

The frequency histogram of Figure 21a shows the distribution of the ratio of the uplift capacity of injected to conventional piles ($Q_{u\text{ inj}}/Q_{u\text{ conv}}$) of the same pile group described in Table 2 (with identical geometry, installed at the same site, and with similar final torque or embedded length). This figure shows that the mean value of the improvement ratio ($Q_{u\text{ inj}}/Q_{u\text{ conv}}$) of all injected piles tested in this study is 2.11, with a coefficient of variation of 19.1%. These results show that the injection procedure tested in helical piles installed in different sites, with different embedded lengths, final installation torque, number of helices, and injection process (with and without the inflatable packer) provided similar improvement in uplift capacity (a coefficient of variation of 19.1% is reasonable for geotechnical engineering).

Considering that the embedded length of the piles of the sites 1 and 2 are similar, but not identical, Figure 21b presents the distribution of the ratio of uplift capacity normalized to the embedded length ($Q_u/L$) of injected to conventional piles. The frequency histogram of Figure 21b presents a mean value of $(Q_u/L)_{\text{inj}}/(Q_u/L)_{\text{conv}}$ of 2.02 with a coefficient of variation of 17.9% (similar mean and coefficient of variation observed in Figure 21a). Therefore, the small differences in pile lengths did not influence the values of the improvement ratio ($Q_{u\text{ inj}}/Q_{u\text{ conv}}$) obtained in this study.

The results of final torque of piles of the same group (Table 2) are also similar, but not identical. Therefore, to evaluate the effect of the differences in final torque, Figure 21c illustrates the distribution of the
ratio of uplift capacity normalized to the final torque ($Q_u/T$) of injected to conventional piles. The mean value and coefficient of variation of 2.13 and 21.1\%, respectively, obtained for this ratio, indicate that the slight differences in final torque did not affect the results of the improvement ratio ($Q_{u,\text{inj}}/Q_{u,\text{conv}}$).

**Effect of the number of helices**

The gains provided by the injection tend to increase with the increase in the number of pile helices. This trend can be observed in Figure 22a, which compares the ratio of the uplift capacity of injected to conventional piles ($Q_{u,\text{inj}}/Q_{u,\text{conv}}$) of identical geometry, installed at the same site (of the same group described in Table 2). The mean value of the improvement ratio ($Q_{u,\text{inj}}/Q_{u,\text{conv}}$) found for the injected four-helix piles was 2.00 with a coefficient of variation of 19.9\%, and for the six-helix piles these values were 2.28 and 15.8\%, respectively. For the cases of injected six-helix piles (10 piles), the mean value of the improvement ratio is higher with a lower coefficient of variation compared to the cases with four helices (16 piles).

The trend shown in Figure 22a can be explained by the cumulative effect of the soil disturbance caused by the passage of the helices during installation. The degree of disturbance of soil above the upper helices is significant, and as consequence the contribution of these helices to the pile uplift capacity is irrelevant for conventional helical piles. However, when the pile is injected, the soil above all helices is improved, and the upper helices contribute more significantly to the pile uplift capacity.

Another way to compare the efficiency of the cement injection is by the ratio of the uplift capacity to the final installation torque ($Q_u/T$), known as torque factor $K_T$. The torque factor relates the pile capacity to the installation forces; therefore, for pile cases with higher values of $K_T$, the relative gain in capacity is greater. Figure 22b compares the ratio of the torque factor of the injected to conventional piles obtained for the four-helix and six-helix piles tested in the current work. The mean value of the ratio $K_{T,\text{inj}}/K_{T,\text{conv}}$ obtained for the injected four-helix piles was 2.07 with a coefficient of variation of 23.7\%, and for the six-helix piles these values were 2.21 and 17.0\%, respectively. These results also indicate that the injection process was more advantageous for the pile cases with six helices compared to cases of piles with four helices.

**Effect of the type of injection procedure**
Figure 23a compares the ratio of the uplift capacity of injected to conventional piles \( (Q_{u\text{ inj}} / Q_{u\text{ conv}}) \) of identical geometry and installed at the same site, for injected piles with and without the inflatable packer.

The mean value of the improvement ratio \( (Q_{u\text{ inj}} / Q_{u\text{ conv}}) \) found for the piles injected without the inflatable packer was 2.01 with a coefficient of variation of 19.5 %, and for the piles injected with the inflatable packer these values were 2.44 and 9.7%, respectively. For the few cases of injected pile with the inflatable packer (6 piles), the mean value of the improvement ratio is higher with a lower coefficient of variation compared to the cases of piles injected without the device (20 piles). Therefore, although the number of tested piles injected with the inflatable packer was reduced compared to the quantity injected without this device, the current study indicates that the use of the inflatable packer seems to be more advantageous.

Figure 23b presents the values of the ratio \( K_{T\text{ inj}} / K_{T\text{ conv}} \) for pile cases injected with and without the inflatable packer. The mean value of the ratio \( K_{T\text{ inj}} / K_{T\text{ conv}} \) obtained for the piles injected without the inflatable packer was 2.00 with a coefficient of variation of 19.9 %, and for the piles injected with this device these values were 2.54 and 14.1 %, respectively. These results also demonstrate that the use of the inflatable packer was advantageous for the injected piles tested in this research.

The mean improvement ratio \( (Q_{u\text{ inj}} / Q_{u\text{ conv}}) \) obtained in the current investigation for the piles injected without the inflatable packer is similar to the value observed in the work of Sanchez (2004). In this cited study, the uplift capacity of three-helix injected piles (without an inflatable packer), with a length of 4 m installed in an unsaturated soil (clayed sandy silt), was approximately 2 times the values found for conventional helical piles of identical geometry.

**Improvement of the load-displacement performance**

The results of load–displacement curves presented in the current study indicate that the use of cement injection can also improve the serviceability of the helical piles. Normally, for the foundations of guyed towers of transmission lines in Brazil, a typical allowable uplift displacement of 30 mm is accepted. The values of allowable uplift capacity \( (Q_{ua}) \), related to a displacement of 30 mm, obtained from the curves of Figures 16 to 18, were used to calculate the values of the ratio of the allowable uplift capacity of injected to conventional piles \( Q_{ua\text{ inj}} / Q_{ua\text{ conv}} \) illustrated in Figure 24. This figure shows that the gain in allowable uplift capacity is comparable to the gain in uplift capacity obtained for injected piles with and without inflatable packer,
presented in Figure 23, and mentioned above. Additionally, the curves presented in Figures 16 to 18 indicate that the injection procedures presented in this work are also beneficial and advantageous for the helical foundations under service loads due to its efficiency in minimizing the uplift displacements of the helical piles.

CONCLUSIONS

This paper describes the results of a field investigation carried out to evaluate the use cement injection to improve the uplift performance of helical piles in tropical residual soils. The aim of this procedure was to improve the disturbed soil in the region above the helices caused by the pile installation, by injecting cement slurry under pressure. In order to make this injection procedure more efficient and uniform, an inflatable packer has been developed and tested, which can be connected to the pile at any time during the installation, and is intended to prevent the upward flow of the cement slurry injected. Forty-one tensile loading tests were performed on conventional and injected helical piles, in three different experimental areas, to investigate the improvement caused by the injection without and with the inflatable packer. Additionally, short injected piles for exhumation were installed to permit the evaluation of the spreading of the cement injected into the soil mass, for the two types of injection procedures tested (with and without inflatable packer).

The results showed that the two injection procedures investigated improved the uplift capacity and the load-displacement performance of helical piles in the soils tested in this study. However, although the number of tested injected piles with the inflatable packer was inferior compared to the case of the piles injected without this device, the results described in this paper show that the use of an inflatable packer can improve the performance of injected helical piles.

The experiments indicated that cement injection procedure is more advantageous for helical piles with a larger number of helices. It occurs because for the injected piles, the improved soil above all helices presents similar bearing capacity to tensile loadings, while for the cases of conventional multi-helix piles, the capacity of the upper helices are reduced because the soil above the upper helices are penetrated and disturbed more times compared to the lower helices. Therefore, the effect of adding more helices to a helical pile is more significant for injected piles than for conventional ones.

Finally, further experiments are necessary to confirm the improvement caused by cement injection on helical foundations observed in this study. Furthermore, the amount of gain in performance caused by the
cement injection, and the findings presented here are valid for piles installed in similar soils. Additionally, the observed improvement caused by the use of an inflatable packer should occur in cases of injected helical piles in which the location and the dimensions of the proposed device are similar to that tested in the current work.

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Table 1. Summary of pile dimensions.

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<tr>
<th>Pile type</th>
<th>Shaft diameter x thickness (mm)</th>
<th>Nº of helices</th>
<th>Bottom helix diameter (mm)</th>
<th>Second helix diameter (mm)</th>
<th>Third helix diameter (mm)</th>
<th>Fourth helix diameter (mm)</th>
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Tabela 2. Description of the piles tested, volume of cement injected, and results of final installation torque, uplift capacity, and torque factor.

<table>
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<tr>
<th>Site</th>
<th>Groups of similar piles</th>
<th>Pile tested</th>
<th>L, embedded length (m)</th>
<th>Volume of cement injected (number of bags of 50 kg)</th>
<th>T, final torque (kN.m)</th>
<th>Q, uplift capacity (kN)</th>
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Figure 1. Photograph of a four-helix pile tested in the current study.
Figure 2. (a) Photograph of the inflatable packer used in this study; (b) inflatable packer before and after expansion.
Figure 3. Types of helical pile tested: (a) conventional, (b) injected without inflatable packer, and (c) injected with inflatable packer.
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Figure 7. (a) Soil characteristics of the site 2; (b) test layout of pile load and in situ tests.
Figure 8. (a) Soil characteristics of the site 3 (adapted of Giacheti et al. 2006); (b) test layout of pile load tests.
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Figure 14. Torque readings measured during the installation of helical piles at the site 2.
Figure 15. Torque readings measured during the installation of helical piles at the site 3.
Figure 16. Applied load at pile head versus displacement for tension pile load tests at the site 1.
Figure 17. Applied load at pile head versus displacement for tension pile load tests at the site 2.
Figure 18. Applied load at pile head versus displacement for tension pile load tests at the site 3.
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Figure 20. Excavation of the helical pile injected with the inflatable packer.
Figure 21. Comparison between the results of injected and conventional helical piles: (a) uplift capacity, (b) uplift capacity normalized to the embedded length (L), and (c) uplift capacity normalized to the final torque (T).
Figure 22. Effect of the number of helices on the improvement of the: (a) uplift capacity, and (b) torque factor.
Figure 23. Effect of the type of injection procedure on the: (a) uplift capacity, and (b) torque factor.
Figure 24. Effect of the injection procedure on the gain in allowable uplift capacity ($Q_{ua}$).