Monotonic and cyclic axial full-scale testing of reinforced helical pulldown micropiles

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ABSTRACT
Helical piles are increasingly used to support structures subjected to axial compressive loads. This paper presents the results of full-scale field testing of reinforced helical pulldown micropiles (RG-HSP) installed in clayey soils and resting on sandy soils. The piles were tested under monotonic and one way cyclic axial loadings. It was found that the addition of the reinforced grouted column resulted in a significant increase in the failure load of the pile. Also, during 15 cycles of loading, the piles showed no signs of performance deterioration and experienced minimal increase in displacement. The piles' axial stiffness and capacity were not affected after being subjected to 15 cycles of loading. The experimental results show that the reinforced helical pulldown micropile is a viable deep foundation option for axial monotonic and cyclic loading applications.

1 INTRODUCTION

The helical (screw) pile is a foundation system that is used to support several structures such as: buried pipe lines, guyed towers, transmission towers, and residential buildings. It is also used for stabilizing repairs of existing structures. It is made of relatively small galvanized steel shafts fitted with several helical plates (lead section), and can easily be extended to reach the desired depth through a series of extensions and couplings. Helical pile foundation systems can be installed with ease even in difficult and low-accessibility sites thus making them a preferred option for retrofitting existing deficient foundations.

The performance of helical piles has been investigated in several studies including Mooney et al. (1985), Hoyt and Clemence (1985), Rao et al. (1991), Rao and Prasad (1993), El Naggar and Abdelghany (2007a,b), Abdelghany (2008), Livneh and El Naggar (2008), Sakr (2009), Abdelghany and El Naggar (2010), and Merifield and Smith (2010). These studies as well as manufactures of helical piles use one of two main approaches to predict the ultimate compressive or tensile capacity for multi-helix screw plates. The first approach, namely the individual bearing, considers that the plates act separately, while the second approach, namely the cylindrical shear, considers a cylindrical failure surface that extends between the outer edges of the plates. The applicability of these two approaches depends on the soil type, ratio of spacing between helices to their width and loading conditions. Rao and Prasad (1993) reported that for spacing ratios larger than 1.5, the failure surface is not cylindrical for helical piles in clay. For a spacing ratio of 3, El Naggar and Abdelghany (2007a,b) found that for helical piles in clay the load is transferred through a tapered cylindrical shear surface and bearing underneath the lead helix; similar findings were reported by Ben Livneh and El Naggar (2008) for helical piles in sandy soils. Meanwhile, Sakr (2009) suggest that for oil sands, the individual bearing method is more suitable for ultimate capacity calculations.

Helical Pulldown® Micropiles or grouted-helical piles (G-HSP) are helical piles installed with a grout column surrounding the pile central shaft along the extensions. The lead section is first installed, and then a displacement disk is mounted on the pile shaft. Torque is then resumed, creating a cylindrical void with the same diameter as the cutting disk. The hole is continuously filled with the grout mix during installation from a reservoir on top.

This pile system was first introduced by Vickers and Clemence (2000). The grout column was initially implemented to overcome the buckling potential for relatively long piles. Yasser (2008), Abdelghany and El Naggar (2007a and b), experimented several modifications to the G-HSP installed in clayey soils. These modifications include, enhanced grout mix, using steel fibre reinforcement in the grout mix and encasing part of the grout column with relatively rigid fibre reinforced polymer tubes. While the number of tests on each modified helical pile was limited, the results indicated that in all cases, the axial capacity increased compared to the plain helical pile and the cyclic performance is satisfactory. The results also showed that the RG-HSP had the highest ultimate capacity, and was the most favourable under cyclic loading conditions.

To date, the grout column has not been included in the capacity calculation in practice. It is only used as means of overcoming buckling problems for weak soil and/or relatively long piles, and providing additional corrosion protection. This can be attributed to the lack of a thorough experimental data for these modified helical piles. Therefore, a comprehensive study is being undertaken to assess the performance of helical piles and modified helical piles under axial and lateral monotonic and cyclic loads. This study is divided into six main phases. Phase I deals with the monotonic and cyclic axial performance of reinforced helical pulldown micropiles (RG-HSP), where the steel fibres are added to the grout mix before installation. This paper presents the results of the first stage in Phase I, where piles were subjected to axial load, followed by cyclic load, and finally re-subjected to axial loading.

2 TEST PILE DISCRIPTION

2.1 Plain Helical Piles

The test pile is the SS 175 (44.5 mm) square shaft helical pile, manufactured by AB Chance (Centralia, MO) as shown in Figure 1. The lead segment consists of three helices, with 305 mm, 254 mm and 203 mm diameters). The helix pitch is 76 mm and the spacing between the helices is about three times the helix diameter. The helices have true helical shape and therefore, they do not auger into the soil but rather screw into it with minimal soil disturbance. Round square extension segments of 44.5 mm were connected to the lead section through couplings.

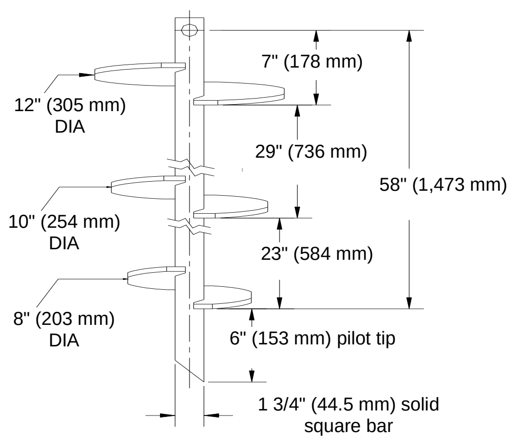

Figure 1. Schematic of a helical pile (after Technical Chance Design Manual, 2007).

2.2 Reinforced Helical Pulldown Micropile (RG-HSP)

The test piles consist of the lead section and extensions with the same configuration above, with a grout column surrounding the pile shaft. After the lead section and the first extension were installed, 152.4 mm (6") diameter hole was created by attaching a displacement disk to the square shaft, as shown in Figure 2. The hole was filled with grout during installation, creating a 4.25 m (14 ft) grout column. All piles were tested after 28 days.

Figure 2. Displacement disk attached to an extension.

3 SITE INVESTIGATION

The piles were installed and tested at the University of Western Ontario Environmental Site, located approx. 8 km north of the City of London Ontario. Two boreholes were performed at the test site. The soil profile is shown in Table 1 and Table 2.

Based on the borehole data, the test piles were installed so that the lead section lies entirely in the dense sand layer, while the grout column lies within the silty clayey till. Depth of test piles ranged from 7 m to 7.5 m.

Table 1. Summary of soil profile from borehole 1 log.

Soil layer	Depth (m)
Compact brown silty sand and gravel.	0-1
Very stiff to hard, brown becoming grey at 3.0 m depth, clayey silt to silty clay till.	1-5.9
Compact to dense sand, trace of some silt.	5.9-7.9
Compact, grey silt.	7.9-8.8

Table 2. Summary of soil profile from borehole 2 log.

Soil layer	Depth (m)
Very stiff to hard, brown becoming grey at 2.5 m depth, clayey silt to silty clay till.	0-5.6
Compact to dense sand, trace of some silt.	5.6-8.8

4 FIELD TESTING

The test setup comprised a main steel reaction beam resting on two wooden cribbing supports one on each end, with the test pile at the center point of its span, as shown in Figure 3. Two secondary reaction beams were aligned perpendicular to the main beam, one at each end, and were supported by four SS 200 reaction helical piles. The load cell and LDTs were connected to the data acquisition system. Once the hydraulic jack advanced against the reaction beam, the load was transferred to the pile and measured by a load cell. Axial displacement was measured by four LDTs mounted on a loading plate, which in turn was resting on the pile shaft.

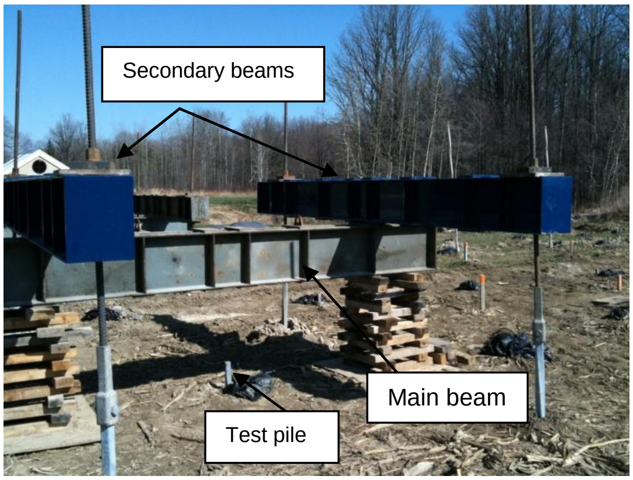

Figure 3. Axial test set-up.

4.1 Testing Procedure

4.1.1 Initial Monotonic Testing

The piles were tested under monotonic compression loads according to the ASTM D-1143 quick test method. The applied load was increased in increments of 30 kN every 4 minutes. The load was increased until continuous jacking was required to maintain the load, a considerable displacement was reached or until the load approached the capacity of the load cell, and/or the reaction system (the main beam).

4.1.2 Cyclic Testing

The cyclic load tests involved one-way compression loading. All piles were subjected to 15 cycles of loading; each cycle was applied over a period of 2 minutes. Initially, one RG-HSP pile was subjected to an average and maximum cyclic loading of 30 % and 48 % of the estimated axial capacity, respectively. The pile's performance was found to be satisfactory and therefore the average and the maximum axial cyclic load were raised, in subsequent tests, to 45 % and 58 % of the estimated axial capacity (Figure 4). The plain helical pile was subjected to the same load ranges of the first loading conditions to serve as a base line.

4.1.3 Final Compression Loading

In order to evaluate the effect of cyclic loading on the pile load carrying capacity, the piles were subjected to axial monotonic loading after the cyclic loading. The load was increased until continuous jacking was required to maintain the load, a considerable displacement was reached or until the load approached the capacity of the load cell, and/or the reaction system (the main beam).

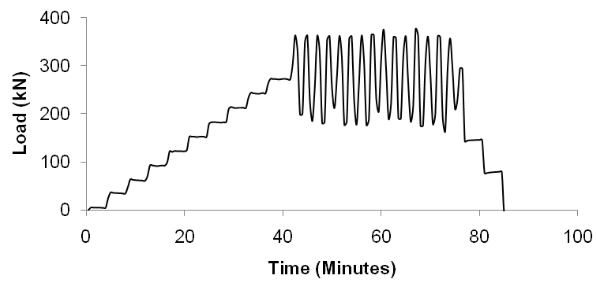

Figure 4. Cyclic testing protocol.

5 TEST RESULTS AND ANALYSIS

Samples of the typical results for one plain pile and four helical pulldown micropiles for the first stage in phase I are reported herein.

5.1 Behaviour of Plain Helical Piles

The axial monotonic behaviour of the plain helical pile is shown in Figure 5. It can be seen that the maximum load of 480 kN was reached at 38 mm displacement. It can also be seen that after a load of 110 kN, the rate of displacement increased with the increase of loading. The ultimate capacity defined as the load corresponding to 25.4 mm (1 inch.) displacement was found to be 350 kN.

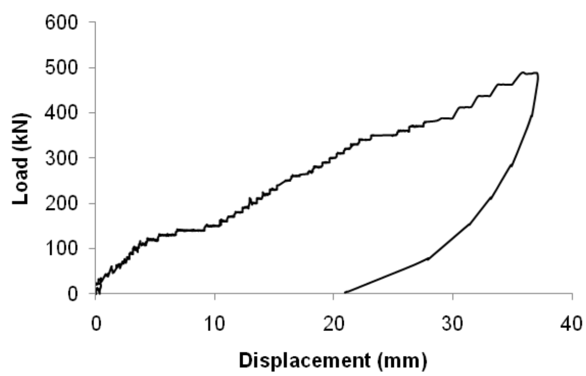

Figure 5. Load vs. deflection for plain helical pile.

Figure 6 shows the load-displacement response of the plain helical pile under cyclic loading. The average cyclic load was 200 kN with a maximum cyclic load of 250 kN (or 57 % and 70 % of the observed ultimate load). As can be seen from Figure 6, the increase in the displacement during cyclic loading was about 4.3 mm. Also, Figure 6 shows that the rate of increase in the pile deflection decreases with cyclic loading, suggesting that the pile system stabilizes after few cycles. After unloading, the pile recovered most of the deflection experienced during cyclic loading.

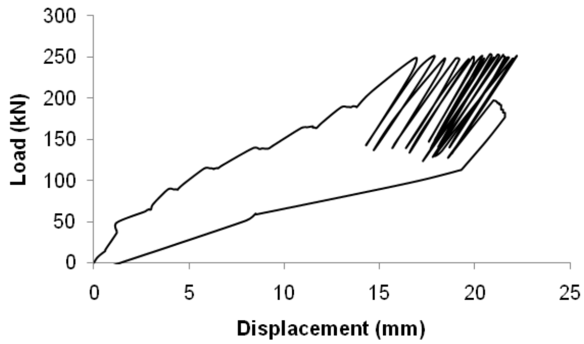

Figure 6. Cyclic load vs. deflection for plain helical pile.

Figure 7 shows the load-displacement curve of the plain helical pile before and after cyclic loading. It can be seen that the pile performance improved considerabely after being subjected to cyclic loading. The stiffness remained almost constant during loading upto failure at 540 kN; buckling was observed in the top extension upon retrieval of the pile.

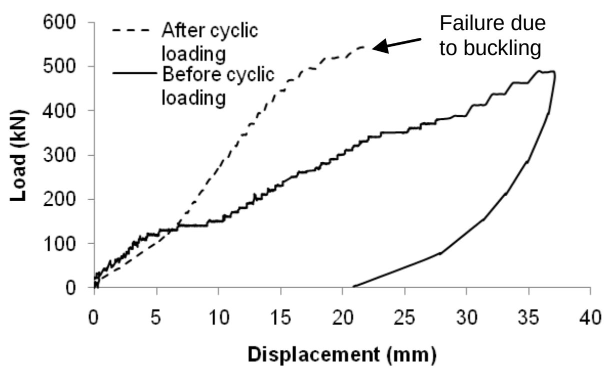

Figure 7. Load vs. deflection before and after cyclic loading for plain helical pile.

5.2 Behaviour of Reinforced Helical Pulldown Micropile (RG-HSP)

The axial monotonic behaviour of the RG-HSP for four test piles under axial monotonic load is shown in Figure 8. It can be seen that the load displacement curve consists of the traditional three regions: initial linear region, curvilinear transitional region, and a semi-linear region up till maximum load. The post yield stiffness for one pile seems to be slightly lower than the other piles. This is highly attributed to the disturbance from the pile hole made prior to installation. In all cases, the piles sustained load levels from 600 kN to 740 kN at a displacement less than 25.4 mm (inch).

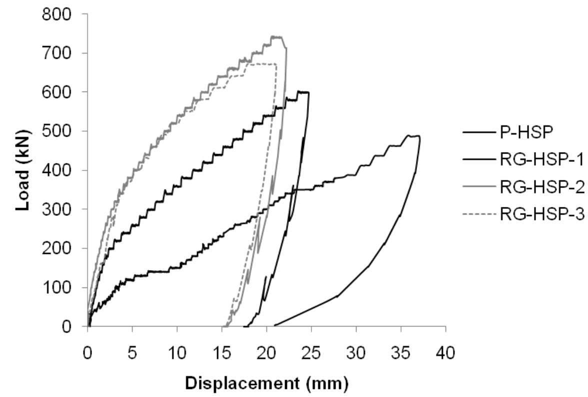

Figure 8. Load vs. deflection for RG-HSP and P-HSP piles.

The load-displacement for the plain pile is plotted in Figure 8 for comparison. As can be noted, the stiffness of the RG-HSP piles is at all times higher than that of the HSP. The load at 20 mm deflection (or 10 % of lead helix diameter) for RG-HSP piles was higher than that of the P-HSP by 180 to 224 %. It is worth noting that the increase in the cost is estimated to be between 5 to 10 %.

5.3 Cyclic Loading Results

Figure 9 and 10 show the cyclic response of Piles 1 and 2 where the average cyclic loading was 200 kN, while Figure 11 and 12 show the results for Piles 3 and 4 subjected to an average cyclic load of 270 kN. As can be seen from the figures, the increase of the displacement during cyclic loading ranged from 0.07 % to 0.23 % of the pile cylinder shaft diameter. The results show that there was no degradation of the pile stiffness during cyclic loading. It can also be noted that the pile displacement stabilizes after a few cycles of loading.

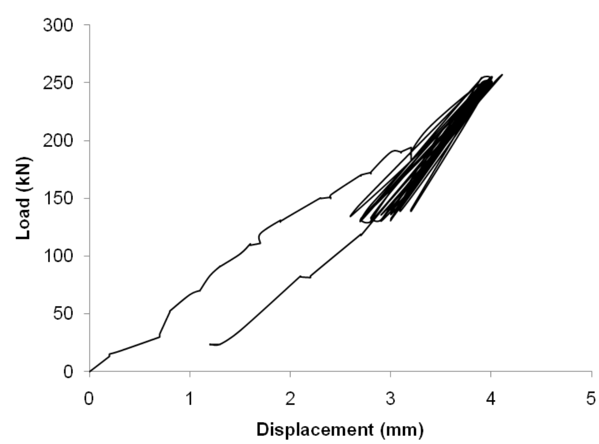

Figure 9. Cyclic load vs. displacement for RG-HSP-1.

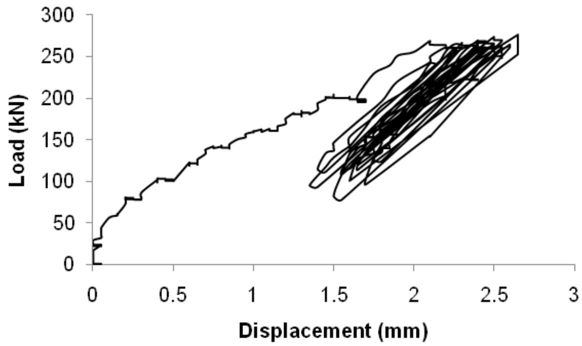

Figure 10. Cyclic load vs. displacement for RG-HSP-2.

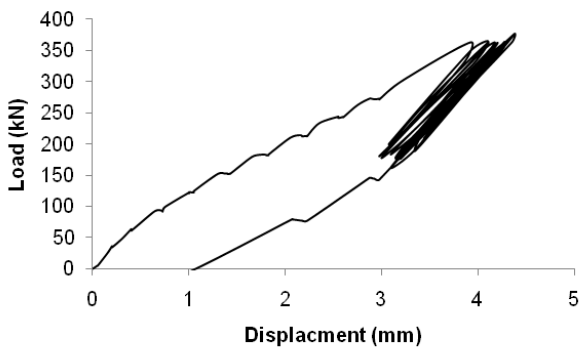

Figure 11. Cyclic load vs. displacement for RG-HSP-3.

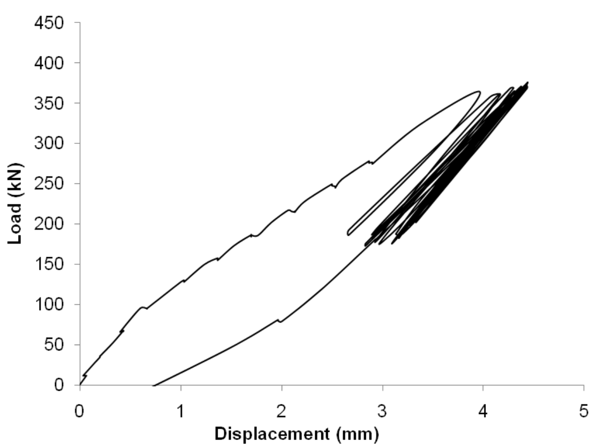

Figure 12. Cyclic load vs. displacement for RG-HSP-4.

5.4 Final Monotonic Results

Figure 13 toFigure 16 show the load-displacement response curves before and after cyclic loading for tested RG-HSP piles. It can be noted that the piles' axial stiffness and capacity were not affected by the cyclic loading. The maximum load reached ranged between 740 kN and 840 kN, which is 137 % to 155 % of that of the P-HSP pile.

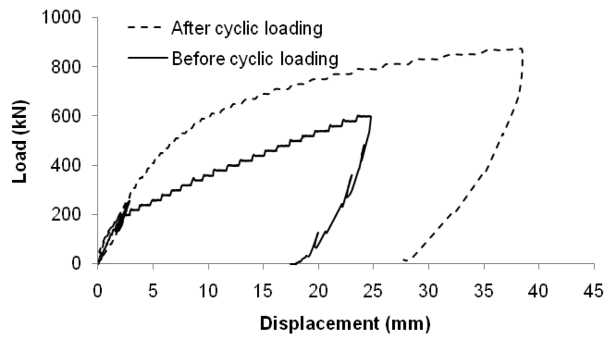

Figure 13. Load vs. displacement before and after cyclic loading for RG-HSP-1.

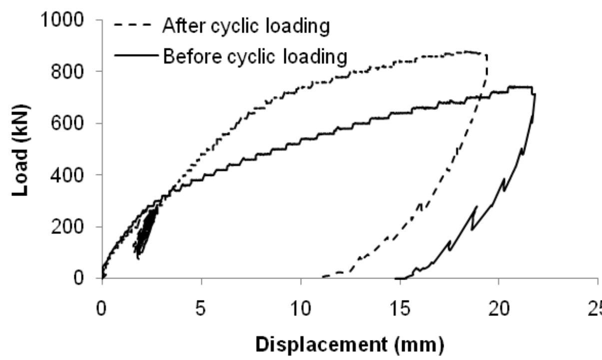

Figure 14. Load vs. displacement before and after cyclic loading for RG-HSP-2.

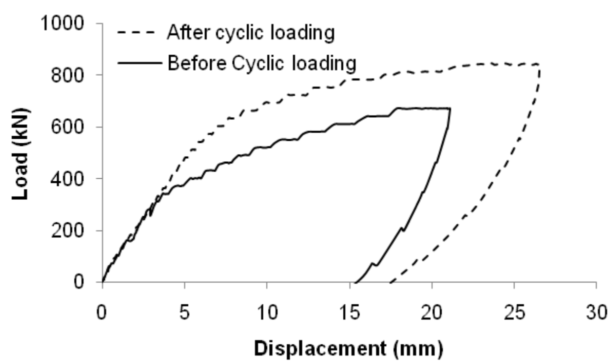

Figure 15. Load vs. displacement before and after cyclic loading for RG-HSP-3

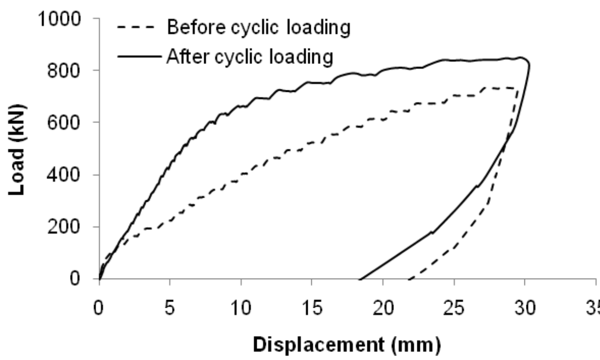

Figure 16. Load vs. displacement before and after cyclic loading for RG-HSP-4

6 CONCLUSIONS

A full scale field experimental program was carried out on plain helical piles and reinforced helical pulldown micropiles (RG-HSP) subjected to monotonic and one way cyclic compression loadings. The lead sections were embedded in dense sand and the shafts were embedded in clayey till. From the experimental results, the following conclusions can be made:

1. The P-HSP pile performs well during cyclic axial loading where the maximum cyclic load is in the order of 70 % of the ultimate load. The cyclic loading has a positive effect on the axial performance of the pile.
2. The performance of RG-HSP under axial loading can be characterized by an initial linear region followed by a curvilinear transitional region, and a semi-linear region until maximum load is reached.
3. The axial monotonic load of the RG-HSP piles at a displacement of 10 % of the lead helix diameter increases by 80 % to 124 % relative to the P-HSP pile.
4. Under cyclic loading with a peak load in the order of 58 % of the ultimate load, the RG-HSP pile performs well during cyclic loading with no deterioration in the performance and a small displacement increase ranging from 0.07 % to 0.23 % of the grout column diameter.
5. Cyclic loading has no effect on the stiffness of the pile or its capacity when subjected to a maximum cyclic load of approximately 45 % of the ultimate capacity.

The experimental results show that the reinforced helical pulldown micropile is a viable deep foundation option for axial monotonic and cyclic loading applications. In addition, the shaft resistance should be taken into consideration for ultimate capacity predictions.

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