Lateral resistance of helical monopole bases

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ABSTRACT
A Helical Monopole Base (HMB) is a two-section steel pipe shaft with a helix or more near the bottom of each shaft section. HMBs are used regularly in Alberta as foundation pockets for single and double circuit distribution power line poles. The results of a comprehensive lateral pile load test program and field monitoring of HMBs installed in organic soil (muskeg) over soft clay are presented in this paper. A total of eight full scale lateral load tests were carried out including six tests using HMBs with different diameters and embedment depths and two tests using single shaft helical piles. The prime objective of the study was to evaluate the lateral performance of helical monopole bases and to compare the lateral resistance of HMBs to straight shaft helical piles. This paper summarizes the helical pile installation, test setup and discusses the test results. The results of the load tests are compared to a theoretical model using LPILE Plus 5, a program widely used to estimate the lateral pile resistance based on the p-y curves.

RÉSUMÉ
A Helical Monopole Base (HMB) est une section de deux tuyaux en acier avec un arbre d'hélice ou plus près de la base de chaque arbre de la section. HMBs sont régulièrement utilisés en Alberta en tant que fondement de poches simple et double circuit de distribution électrique pôles. Les résultats d'un essai de charge latérale pile de programme et de surveillance sur le terrain de HMBs installé en sol organique (muskeg) sur argile molle sont présentés dans le présent document. Un total de huit à grande échelle des tests de charge ont été effectuées, dont six HMBs tests à l'aide de différents diamètres et l'incrustation des profondeurs et de deux tests en utilisant directement l'arbre d'hélice piles. L'objectif principal de l'étude était d'évaluer la performance de l'hélice latérale monopole de bases et de les comparer à la résistance latérale de droite à HMBs arbre d'hélice piles. Le présent document résume les helical pile installation, essai et analyse les résultats du test. Les résultats des tests de charge sont comparées à un modèle théorique utilisant LPILE plus 5, un programme largement utilisé pour évaluer la résistance latérale pile sur la base des courbes p-y.

1 INTRODUCTION

Despite the extensive research on the axial behaviour of helical piles (Meyerhof and Adams 1968; Vesic 1971: Mitsch and Clemence 1985; Das 1990; Zhang 1999; Livneh and El Nagger 2008), a very little information is available on their lateral behaviour. This mainly due to that helical piles were historically used either as anchors to resist uplift loads or as a foundation for residential housing to resist small compressive loads and their shaft were either square or rounded with small diameters between 45 mm and 114 mm. Large diameter helical piles have been recently used to resist large axial loads. The availability of high torque heads facilitated the installation of large diameter helical piles. To date helical piles with shaft diameters up to 914 mm were installed in western Canada in soft clays. In hard clay tills and dense sands, helical piles with shaft diameters up to 508 mm were successfully installed. With these relatively large diameter helical piles, their lateral resistance has become a considerable component.

There are several sources that contribute to horizontal (or lateral) loading and moments to piles, such as wind loading, axial thrust on pipelines, and load eccentricity. Moreover with the recent rehabilitation and upgrades for a variety of transmission and distribution power lines, more cables and high voltage lines are required and therefore larger lateral loads and moments are exerted on the foundation system.

A Helical Monopole Base (HMB) is a steel pipe shaft with two shaft sections and a helix or more near the bottom of each shaft section. The upper shaft section of the HMB is larger in diameter (typically about 0.6 m to 0.9 m) than the lower shaft section (about 0.3 m). The top section provides the required lateral resistance while the lower section provides most of the axial capacity. HMBs are regularly used in western Canada as foundation pockets for wooden poles or bases for structures that are supporting single or double circuit distribution power lines. The main advantage of HMBs include their ability to resist large lateral loads and moments, easy and quick installation process, and their cost effectiveness compared to large diameter straight-shaft driven piles. In addition to that, HMB installation is a vibration-free process, which is advantageous on urban sites and environmentally sensitive areas.

The objectives of the present study were to evaluate the lateral resistance of HMBs installed into very soft organic soil (Muskeg) overlying soft clay soils and to compare between the measured and estimated lateral resistances of helical piles using p-y curves. In order to achieve these objectives, eight full scale lateral tests were carried out using helical piles with different configurations including two-section and one-section helical piles. Details of pile configuration, testing set up and load test results are provided in the following sections.

2 SITE DESCRIPTION

The testing site is located on an access road near Conklin, in northern Alberta, Canada. The ground surface at the test location was flat lying and covered with grass. The surface was very wet and groundwater level was at ground surface.

2.1 Subsurface Soil Conditions

Subsurface soil exploration program for the test site consisted of two Cone Penetration Tests (CPT). The locations of the CPT tests and pile load test layout are shown in Figure 1. CPT data for both test locations are presented in Figure 2. The generalized stratigraphy at the pile load test site established using the CPT data indicated that the uppermost layer was organic soil (muskeg) extending to depth of about 0.9 m over very soft to soft clay extending to depth of about 6.9 m underlain by compact sand that extended to the end of the CPT tests at depth of about 8.0 m. Silt and sand lenses were encountered within the clay at various depths as shown on the CPT test logs. The data obtained from the CPT testing was used to estimate the undrained shear strength and frictional resistance angler of different soil layers and summary of soil parameters are presented in Table 1.

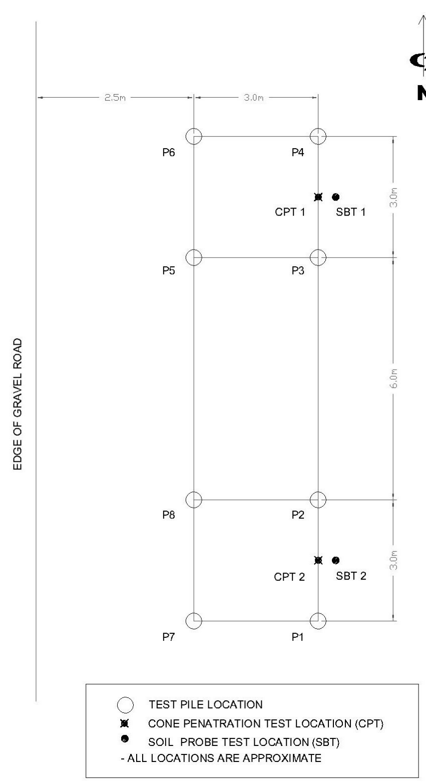

Figure 1. Layout of pile load tests

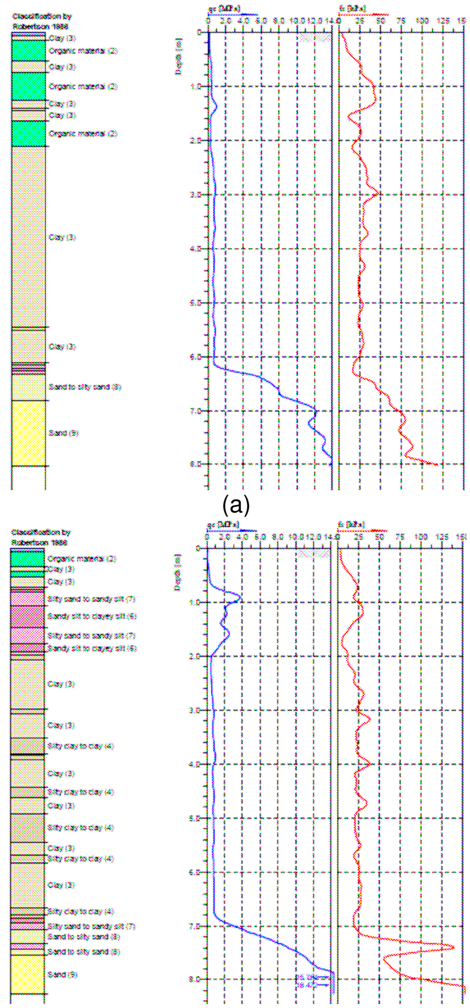

Figure 2. Cone Penetration Test (CPT) results: (a) CPT1 and (b) CPT 2

Table 1. Summary of estimated soil parameters

Soil Type	Depth m	Undrained Shear Strength, C_u, kPa	Friction angle, (°)
Muskeg, very soft	0 – 0.9	10	-
Clay, very soft to soft	0.9 – 6.9	30	-
Sand, compact	6.9 – 9.0	-	32

3 TEST PILE CONFIGURATION

A summary of pile configurations for the load test program are presented in Table 2. Details of test pile configurations are also shown in Figure 3. The helical piles tested in this program were manufactured and installed by ALMITA Manufacturing Ltd of Ponoka, Alberta. The pile installation equipment comprised a drive unit mounted on a tracked Excavator. The drive unit contained a hydraulic motor that provided the torque for rotation of screw pile into the ground to a maximum torque of 156,000 ft.lbs (211.5 m.kN).

Piles odd-numbered (i.e. P1, P3, and P5) had top section of 762 mm in diameter and while piles even-numbered (i.e. P2, P4, and P6) had top section of 610 mm in diameter. The length of the top section varied between 3.65 m and 9.1 m. Piles P1 through P6 had lower sections of 324 mm in diameter and were 3.1 m long while piles P7 and P8 were single section helical piles, 9.1 m long and 762 mm and 610 mm in diameter.

Table 2. Summary of tested helical pile configuration

Pile ID	Length (m)	Top shaft diameter, D_t (mm)	Length of top segment, L_t (m)	Helix diameters (upper/lower) (mm)	Number of helixes
P1	6.65	762	3.65	914/610	2
P2	6.65	610	3.65	762/610	2
P3	7.6	762	4.6	914/610	2
P4	7.6	610	4.6	762/610	2
P5	9.1	762	6.1	914/610	2
P6	9.1	610	6.1	762/610	2
P7	9.1	762	9.1	1067	1
P8	9.1	610	9.1	914	1

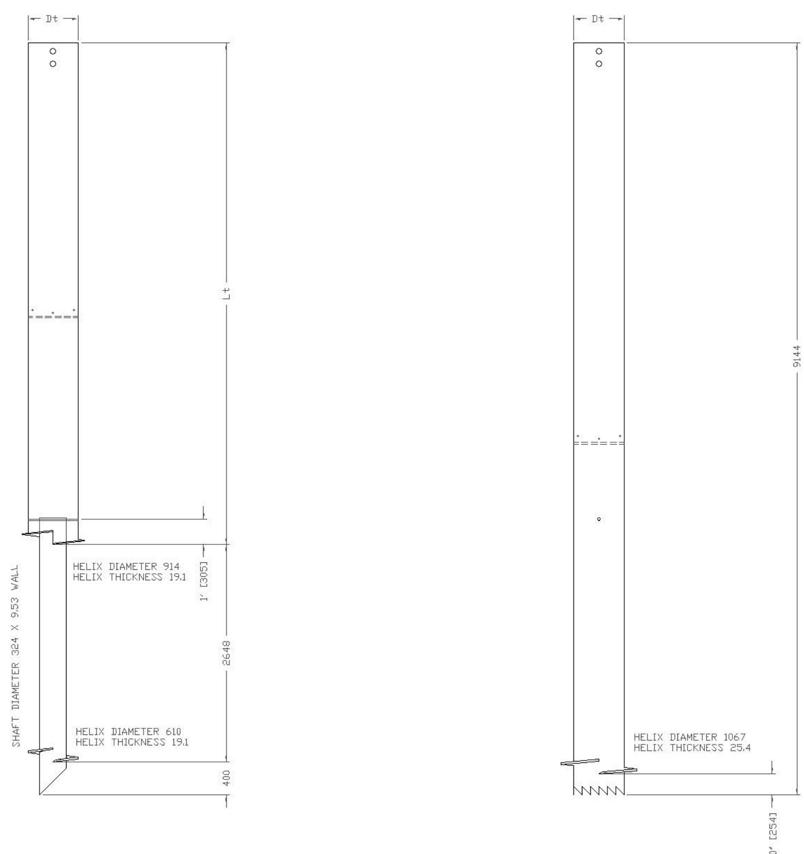

Figure 3. Pile configurations for lateral load tests

4 INSTALLATION MONITORING

Field monitoring of pile installations including the torque recorded at the end of pile installation and depth of embedment are summarized in Table 3. Figure 4 shows a typical helical pile installation. A significant increase of torque values were observed during pile installation at depth of about 7 m below existing ground level which confirm the presence of a compact sand layer at that depth. It can be seen from Table 3 that the measured torque values for piles with top section of 762 mm in diameter (i.e. P1, P3, P5 and P7) were about 14% to 29% higher than those values for piles with top section of 610 mm in diameter with an average increase of about 21%. The average increase in torque values for piles with larger diameters (21%) agreed reasonably with the ratio of top section diameters of both shaft sizes (about 25%) which confirms that the torque is function of shaft diameter. Moreover piles P7 and P8 with single shaft size required about 20% more torque to install than the two-section piles P5 and P6 with the same embedment length.

Figure 4. Typical helical pile installation

Table 3. Summary of pile installation

Pile No	Installation Torque at end of installation kN.m (ft.lbs)	Embedment Depth m
P1	77.6 (57200)	6.1
P2	59.9 (44200)	6.2
P3	84.6 (62400)	7
P4	74.0 (54600)	7.1
P5	162.2 (119600)	8.7
P6	134.0 (98800)	8.7
P7	193.9 (143000)	8.7
P8	162.2 (119600)	8.7

5 TEST SETUP

Lateral load tests were carried out in the present testing program in pairs so each test setup included testing two piles at the same time in opposite directions. This arrangement reduced the amount of time required to carry out the testing program. However it required special care in choosing each pile pairs so that lateral deflection compatibility can be achieved. Therefore for all tests, each tested pile pairs had similar lengths and top section shaft diameters of 610 mm and 762 mm.

The lateral load tests were carried out in accordance of ASTM D3966, Standard Method of Testing Piles under Lateral Loads. An oblique view of the lateral load test setup is shown in Figure 5. The lateral load test setup consisted of testing two piles simultaneously installed at about 3 m away from each other by application of compressive loads using a hydraulic jack between piles. Loads were applied at distance of about 200 mm above ground level using an 800 kN hydraulic jack. The hydraulic ram acted directly against a steel strut placed between the base of the jack and load cell. The load was placed such that it acted directly against the second pile so that the hydraulic jack, strut, and load cell were all in horizontal alignment in-line-of load application. Loads were applied in 10 kN increments and each load increment was maintained for 10 minutes.

Pile lateral movements were monitored at three points during the test, using independently supported Linear Displacement Transducers (LDTs) with 0.05 mm accuracy and 150 mm travel. The LDTs were set so that two of them were near the pile head in opposite directions at distances of about 400 mm above ground and the third LDT was positioned in the opposite direction to the point of load application at distance of about 200 mm above ground. The LDTs were positioned to facilitate measuring lateral deflections at points corresponding to the height of load application and near the pile head. All LDT readings were recorded automatically at the same time increments (30 seconds) throughout the test duration.

Figure 5. Lateral load test setup

6 TEST RESULTS

The results of lateral load tests are presented in the form of load deflection curves (Figures 6 through 9). Each figure present the results of a pile pair with the same configuration and embedment depth except that the top shaft section diameter was either 762 mm or 610 mm. For example, Figure 6 presents the results for pile pairs P1 and P2 with the same configuration and embedment depths (i.e. two sections of 3.6 m over 3 m long) and the only difference is the diameter of the upper section. It can be seen from Figures 6 through 9 that the lateral responses of all piles were nonlinear. Gaps were formed behind the piles during testing indicating a plastic deformation of the soil in front of the pile within the upper soil layers. Figure 10 shows the typical gap that formed behind piles during testing.

6.1 Load Deflection Curves

Piles P1 and P2 (Fig. 6) were loaded to maximum loads of about 135 kN which corresponded to maximum deflections of about 62 mm and 76 mm, respectively. When piles rebounded to zero load, the net or permanent deflections for piles P1 and P2 were 20 mm and 38 mm, respectively. A Comparison between the response of piles P1 and P2, indicate that pile P1 showed slightly higher lateral resistance than pile P2. The lateral resistance of pile P1 was about 6% to 8% higher than that of pile P2. The slight increase of the lateral resistance of P1 despite its larger diameter is likely due to the short length of piles.

The maximum lateral load applied for piles P3 and P4 (Fig. 7) were about 127 kN and the corresponding lateral deflections were 46 mm and 62 mm, respectively. Permanent lateral deflections for piles P3 and P4 were 22 mm and 26 mm, respectively. It can be seen from Fig. 7 that the lateral resistance of pile P3 was higher than that of P4 and pile P3 resisted on average about 22% to 42% higher loads than pile P4. At load level of approximately 110 kN, a load cycle was carried out in which the load was decreased to zero and increased again in four steps. This step indicated that cyclic loading had a minor effect on the lateral resistance and both piles continued to follow the same load path at higher deflection levels.

The maximum lateral load at the end of the test for piles P5 and P6 (Fig. 8) was about 132 kN and the corresponding deflections were 17 mm and 29 mm respectively. It can be seen from Fig. 8 that on average, pile P5 resisted about 12% to 30% higher loads than P6, at the same deflection level. At the end of test, permanent deflections of about 6 mm and 9 mm were recorded.

The maximum load applied at the pile head for piles P7 and P8 (Fig. 9) was 235 kN and the corresponding lateral deflections were 47 mm and 70 mm, respectively. Similar observations were also observed for P7 and P8 in terms of higher lateral loads were resisted by pile P7 compared to P8 at the same deflection levels (P7 resisted about 34% to 41% higher loads than P8). The permanent lateral deflections at the end of the test for piles P7 and P8 were about 16 mm and 18 mm respectively.

It can be also seen from Figs. 6 through 8 that increasing the length of the top section resulted in increasing their lateral resistance at the same deflection level. For example at deflection level of 12 mm, the lateral resistance of piles P1, P3 and P5 were 56 kN, 73 kN and 93 kN, respectively. It should be noted that the lateral resistance of piles P5 with two shaft diameters (Fig.7) and P7 with single shaft diameter (Fig. 9) and the same total length, were very similar at 93 kN and 96 kN, respectively. Similar responses were also observed for piles P2, P4, P6 and P8. This behaviour can be explained by the fact that the load transfer mechanism for all piles was rotational and therefore, the longer the pile, the higher the lateral resistance. Comparing Figs. 6 through 9 also indicates that plastic deformations at the end of tests were smaller for piles with large top section diameter (i.e. piles P1, P3, P5 and P7) versus piles P2, P4, P6 and P8.

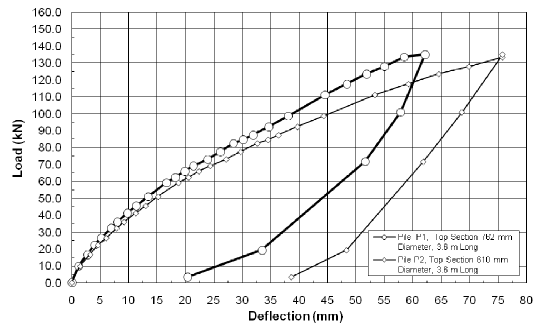

Figure 6. Lateral load-deflection curves for P1 and P2

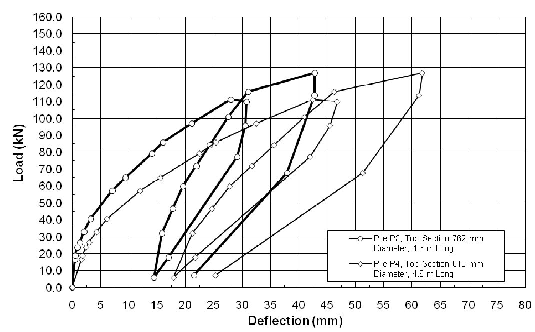

Figure 7. Lateral load-deflection curves for P3 and P4

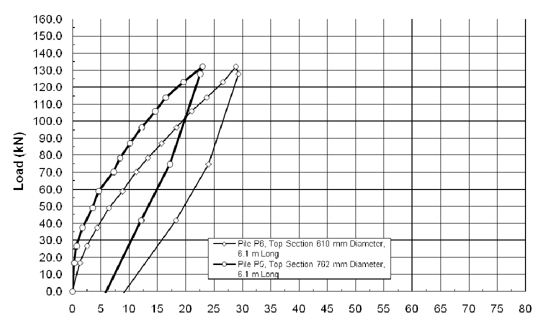

Figure 8. Lateral load-deflection curves for P5 and P6

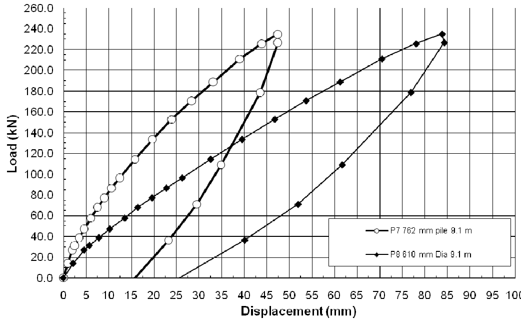

Figure 9. Lateral load-deflection curves for P7 and P8

Figure 10. Typical gap formed behind piles during lateral load tests.

6.2 Lateral Capacity of Tested Piles

As identified in the Canadian Foundation Engineering Manual (2006), the lateral capacities of piles may be limited by the following factors: the capacity of soils, excessive bending that exceeds the structural capacity of the pile, or deflection at the pile heads. For the relatively short rigid piles installed in soft clay considered in the present study, failure usually occurs by rotation of the pile within the soil. In this case, a large deflection is required to mobilize the passive resistance of the soil near the pile head and at the pile toe. Therefore, the ultimate lateral load of piles may be specified to satisfy a limiting lateral deflection criterion that meets the structural requirements for the superstructure.

The lateral loads at deflection levels of 6 mm, 12 mm, 25 mm, 51 mm and 76 mm are presented in Table 4. It can be seen from Table 4 that despite the soft soil conditions all piles continued to resist higher loads at high deflection levels. The lateral resistance of piles increased with increasing either the embedment depth or the diameter of the top section. Moreover, Table 4 indicates that the lateral resistance of both piles P5 and P6 were comparable to piles P7 and P8. Therefore, the use of monopole base type (P5 and P6) is preferred over single section pile in terms of economic savings.

Table 4. Summary of lateral load test results

Pile ID	Lateral load at different deflection levels (kN)				
	6 mm	12 mm	25 mm	51 mm	76 mm
P1	38	48	75	123	-
P2	36	44	70	108	135
P3	50	73	105	-	-
P4	40	57	86	119	-
P5	62	93	-	-	-
P6	48	72	118	-	-
P7	57.5	96	158	-	-
P8	43	68	114	190	-

6.3 Comparing between Measured and Estimated Lateral Resistances

The computer program LPILE Plus 5 (ENSOFT INC., 2005), based on the p-y curves developed by Reese et al. (1974), is widely used to predict the response of laterally loaded piles. In LPILE Plus 5 program, the load-displacement curves (i.e. p-y curves) are established using Matlock's model for soft clays and Reese's model for sand. LPILE Plus 5 was used to estimate the load-displacement curves for different piles.

The selected soil parameters for LPILE Plus 5 are presented in Table 5. The soil parameters were selected based on CPT data and the recommended values by ENSOFT Technical Manual. For example, the strain parameter, E_{50}, defined as the axial strain at 50 percent of the undrained strength, was chosen as 0.02. For sand layer, the shape of the p-y curve can be defined using the initial modulus of subgrade reaction (k) which is a function of friction angle. These values were specified based on correlations with soil consistencies from the available CPT data. The loads were applied at about 0.2 m above ground surface to simulate lateral load point of application for free head condition.

Table 5. Selected soil parameters for LPILE analysis

Soil type	Effective unit weight (kN/m^3)	Strain factor, E_{50}	p-y modulus, k, kN/m^3
Muskeg, very soft	4	0.02	-
Clay, soft	10	0.007	-
Sand, compact	10.2	-	16300

The estimated lateral loads using LPILE Plus 5 are presented in Figures 11 and 12 for piles with top shaft diameter of 762 mm and 610 mm, respectively. The measured load-deflection curves are also plotted in

Figures 11 and 12 to facilitate direct comparison between measured and estimated deflections at different load levels. It can be seen from Figures 11 and 12 that a reasonable agreement was obtained between measured and estimated lateral resistances especially at low deflection levels (i.e. below 40 mm). However at high deflection levels, LPile Plus 5 software underestimated the lateral resistance of different piles by about 10%. Therefore a slight modification to p-y curves may be required to improve the agreement at high deflection levels.

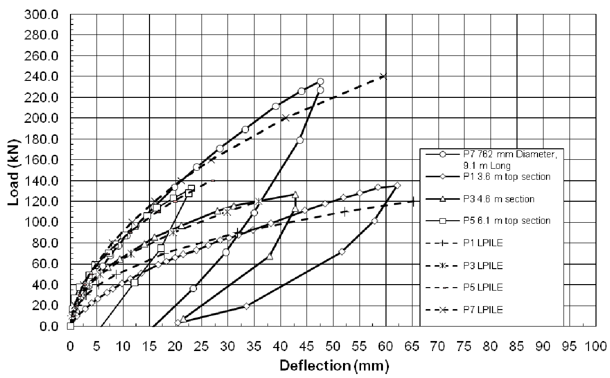

Figure 11. Comparing between measured and estimated load-deflection curves for piles P1, P3, P5 and P7

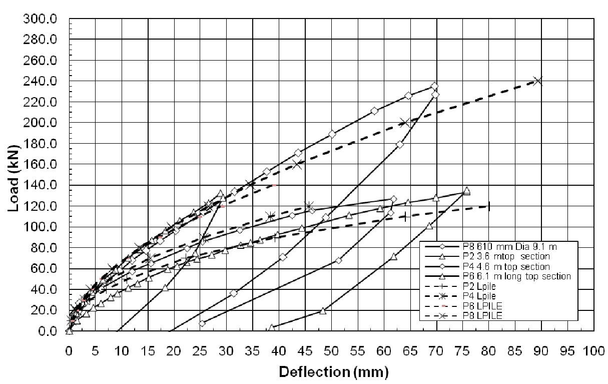

Figure 12. Comparing between measured and estimated load-deflection curves for piles P2, P4, P6 and P8

6.4 Lateral Deflection Profile

The lateral deflection profiles along the pile depth at different loads established from LPILE Plus 5 analyses are provided in Figures 13 and 14 for piles P1 and P5. It can be seen from Figs 13 and 14 that both piles had undergone rotational movement. As the top section increased in depth for pile P5, the centre of rotation moved down towards the bottom of the soft clay layer and pile P5 resisted higher loads than that of pile P1. For example at lateral load of 40 kN, the centre of rotation for pile P1 was about 4.5 m while for pile P5, the centre of rotation was at 5.5 m below ground surface. It can be seen also from Figs 13 and 14 that as the load level has increased, the centre of rotation also has increased. For example, the centre of rotation for pile P5 at load level of 20 kN was about 5.2 m while at load level of 140 kN, it increased to 5.8 m. Comparing between Figs 13 and 14 also indicates that the effect of embedding the bottom portion of helical piles into compact sand had caused a partial fixity to the bottom. This partial fixity is likely also to improve the load-deflection pattern at the pile head.

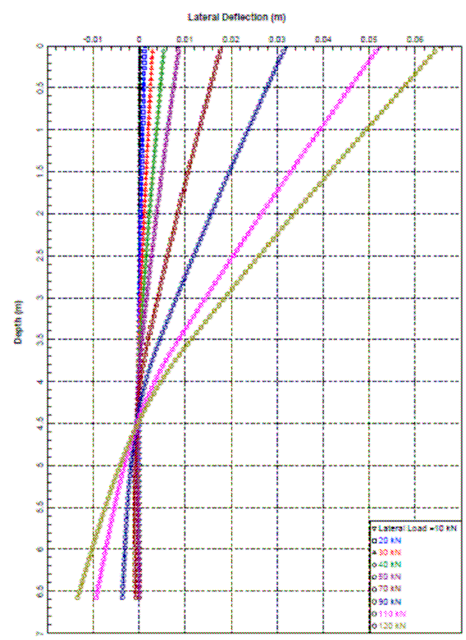

Figure 13. Deflection profile at different load increments for pile P1

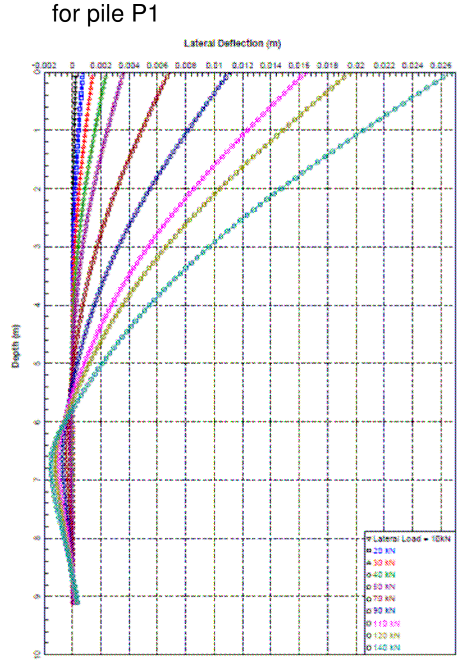

Figure 14. Deflection profile at different load increments for pile P5

7 CONSLUSIONS

The results of eight lateral pile load tests carried out using different pile configurations including two-section (HMB) and single shaft helical piles tested in organic soil (muskeg) layer over soft clay are presented in this paper. The test results are summarized as follows:

1. The effect of a larger top section diameter resulted in increasing the lateral resistance anywhere between 8% to 42% depending on embedment depth.

2. Increasing the top section length resulted in increasing the lateral resistance by values varied between 14% and 29%.

3. The two-section helical piles with bottom section with smaller shaft size offered similar resistance to a single shaft helical piled. Therefore the use of two-section helical piles are preferred since it will provide a cost saving without sacrificing their lateral performance.

4. The predicted lateral resistance of different piles using LPILE Plus 5, agreed well with measured resistance especially at low deflection levels. Therefore LPILE may be used to estimate the lateral resistance of monopole bases in absence of load test data with reasonable accuracy.

5. The load transfer mechanism was rotational and the centre of rotation has shifted down into the soil as top section has increased. The top portion of the soil resisted the lateral forces and soil reactions reached their limiting values near the top section.

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