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HELICAL SCREW PILES (HSP) CAPACITY FOR AXIAL CYCLIC LOADINGS IN COHESIVE SOILS

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ABSTRACT

The use of helical anchors has gained popularity and has evolved into several innovative applications, including Helical Screw Piles (HSP). A comprehensive research program is being undertaken to explore the use of HSP for the seismic retrofitting of the foundations of existing structures and for implementation of new buildings in seismic areas. The research is motivated by some needs arisen from the recent upgrade of the Canadian seismic code. This paper focuses on the seismic performance of HSP capacity for axial cyclic loadings in cohesive soils. The main objectives of the paper are to evaluate the geotechnical capacity of this foundation system and to understand its cyclic behavior and load transfer mechanism. A filed testing program was conducted involving monotonic and cyclic load testing of three instrumented HSPs in cohesive-frictional soil. The piles performed well in terms of both pile capacity and displacement under cyclic loading. It was found that 15 cyclic loadings on the piles reduced the axial compression capacity of the pile by less than 10%.

Keywords: Helical Screw Piles, Seismic Analysis, Axial Cyclic Field Testing, Cohesive Soils.

INTRODUCTION

The social order anticipates that infrastructures and other structures are safe and comfortable for their occupants, dwellers and for those who are in their vicinity or area of influence. Among the natural disasters, several earthquakes hit the world every year, including some with large magnitudes resulting in too many casualties and severe social and economic crises. Samardjieva and Badal (2002) analyzed the human losses after strong earthquakes that occurred in the world during the twentieth century and they offered a quantitative model for a preliminary assessment of casualties based on worldwide data. It consists of a correlation between the number of casualties and the earthquake magnitude as a function of population density. To minimize causalities during earthquakes, especially in densely populated areas, structures foundations must be designed to withstand such earthquakes.

RESEARCH MOTIVATION

The upgraded seismic loading proposed in the revised national building code of Canada (NBCC 2005) postulates an increased seismic hazard in Canada (Adams et al. 2004). Existing structures were designed and constructed prior to these new design guidelines and are still susceptible to earthquake damage. The seismic risk to Canada's economic core is significant in view of the population density and concentrations of critical infrastructure facilities (eg. nuclear power plants, bridges, etc.) in western and eastern Canada, and these structures have to adhere to the new seismic loading provisions.

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In addition, failures of buildings during recent earthquakes due to excessive settlement and/or rotation of foundations, not due to liquefaction, have highlighted the importance of designing foundations that can withstand the seismic forces acting on the supported structure. This has been emphasized in the seismic provisions of the new code (NBCC 2005). Therefore, there is a need to accurately characterize the seismic risk for critical infrastructures and to provide novel solutions for seismic resistant foundations for new and existing structures

The increased seismic forces postulated in the NBCC (2005) imply that all structures designed before 2005 have to be modified to comply with the new code. Retrofitting foundations to enhance their resistance to seismic loads can be achieved by installing helical piles, which represent an attractive option because of their efficiency and non vibratory easy installation procedure.

OBJECTIVES AND SCOPE OF WORK

The use of helical anchors has gained popularity and has evolved into several innovative applications, including Helical Screw Piles (HSP). Numerous investigations of static performance of HSP and their stability against uplift forces are reported in the literature. However, their cyclic performance has not been investigated. The purpose of this study is to explore the use of HSPs for the seismic retrofitting of the foundations of existing structures and for its implementation in new buildings in seismic areas. Recent research effort has been directed towards the development of the innovative helical screw pile and investigating its seismic performance to address some needs arisen from the recent upgrade of the Canadian seismic code. Cyclic field testing of HSPs was performed to evaluate their seismic performance in different soil profiles and the results are reported herein.

SEISMIC REGIONS OF CANADA

The (NBCC 2005) presents the seismic hazard for Canada in terms of a probabilistic based uniform hazard spectrum, replacing the probabilistic estimates of peak ground velocity (PGV) and peak ground acceleration (PGA) in the earlier codes (Adams and Halchuk, 2004). Spectral acceleration at 0.2, 0.5, 1.0 and 2.0 second periods and peak acceleration form the basis of the seismic provisions of NBCC 2005. Eastern and western Canada are treated slightly differently because of the different properties of the crust in these regions. Figure 1, illustrates the earthquakes and the regionalization used and identifies, in general, the low seismicity central part of Canada defined as “stable Canada”.

Figure 2 shows the spectral acceleration parameters denoted as Sa (T), where T is the period for different soil conditions. Seismic hazard values were calculated for a grid extending over Canada and used to create national contour maps such as Figure 3, which shows the Uniform Hazard Spectra (UHS) for a few major cities to illustrate the range and period dependence of seismic hazard across Canada. The seismic hazard characterized in Figures 2 and 3 is significantly higher than the values included in the seismic provisions of the previous building code, especially for Eastern Canada. In some cities, the seismic hazard in the new code represents an increase of more than 200%. This is undoubtedly a serious concern, especially for public buildings such as municipals, universities, hospitals and schools.

Figure 1. Map of Canada showing the earthquake catalogue used for the 4th Generation Model (Adams and Halchuk, 2004)

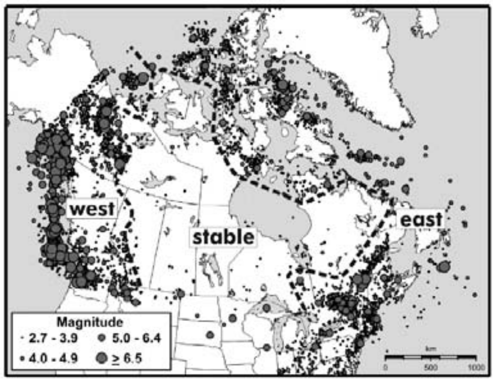


Figure 2. Sa (0.2) for Canada (median values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years) (Adams and Halchuk, 2004)

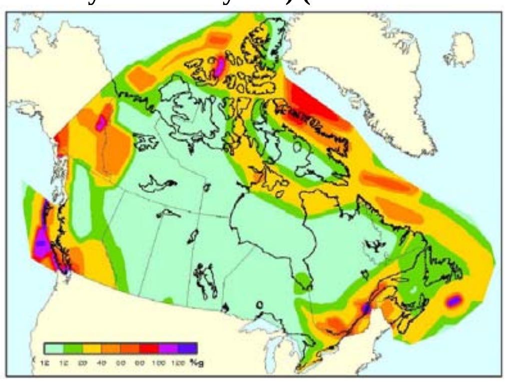
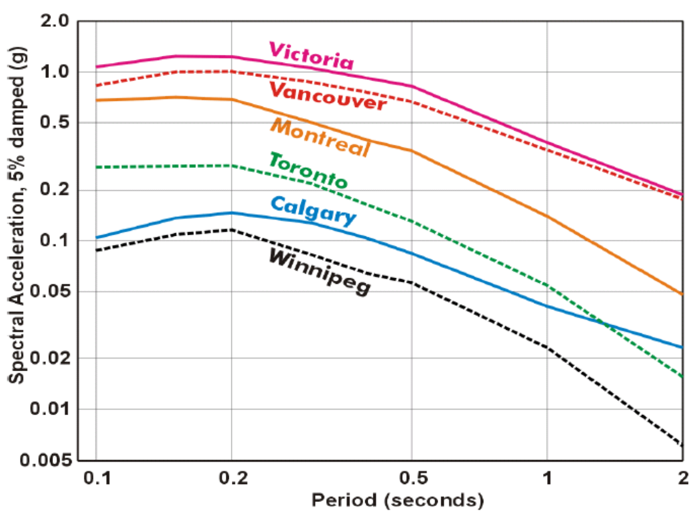


Figure 3. Uniform Hazard Spectra for median 2%/50 year ground motions on Site Class C for key cities (Adams and Halchuk, 2004)



HELICAL SCREW PILES PREVIOUS RESEARCH

Foundation rocking during an earthquake contributes significantly to its response and may involve both uplift at one end and yield (bearing capacity failure) at the other. This mechanism contributes most of the permanent settlement of foundations during seismic events. The helical (screw) pile is a foundation system that is used to support new residential and commercial buildings. It is also used for stabilizing repairs of existing structures. It is made of relatively small galvanized steel shafts fitted with one or more helical plates. Helical pile foundation systems can be installed with ease even in difficult and low-accessibility sites thus making them a preferred option for retrofitting deficient existing foundations. However, there is no guidance for their implementation in seismic applications.

The majority of research on helical foundations focuses on their load carrying capacity with little effort to characterize their response to other loading modes such as axial cyclic and/or lateral loading. Several researchers have studied the performance of single screw anchors and group action with regard to their installation (vertical and inclined), uplift resistance, compressive resistance experimentally (field or laboratory testing) and theoretically. Among these studies are Clemence and Samuel (1983), Clemence (1984), Mooney et al. (1985), Hoyt (1989), Hoyt et al. (1995), Puri and Vijay (1984), Huang et al. (1995), Johnston et al. (1999), Perko (2000), Pack (2000), Rao et al. (1993), Prasad et al. (1994), Shaheen et al. (1995) and Frangoulides (2000). Vickars et al. (2000) studied the performance of helical piles with grouted shafts experimentally. Carville et al. (1995) presented a review study of design parameters and criteria and provided information on installation techniques and equipment. Applications of screw anchor include installations where lightly and moderately loaded buildings and structures that have suffered distress or damage from fill soil settlement, expansive soil heave, earthquake shaking or slope instability failure.

FIELD TESTING AND THEORETICAL STUDY

HSPs Physical Description

The “SS175 Chance foundation system” is a segmented deep foundation system with helical steel bearing plates welded to a central steel shaft. Load is transferred from the shaft to the soil through these bearing plates. The Chance SS175 helical foundation system is intended for use as a deep foundation system to support various moderate weight constructions such as commercial and residential low-rise buildings, houses, cottages, carports, sunrooms and decks. This foundation system is considered in this study as a seismic retrofitting option for existing foundations and for implementation in new buildings in seismic areas.

The system consists of a lead section with helical plates, shaft extensions, and a foundation support bracket. The lead section is placed in the soil with mechanical rotation. Depending on the application, the depth of the lead section of the helical foundation system in the soil is extended to the required depth by adding one or more shaft extensions coupled to the lead section. Segments or sections are joined with bolted couplings. The bolts used to connect the central steel shaft sections together are 22mm diameter bolts per ASTM A193 Grade B7, which also conforms to CAN/CSA-G40.21-M98, 350 MPa. Installed depth is limited only by soil resistance and practicality based on economics. A helical bearing plate or helix is one pitch of a screw thread. All helices, regardless of their diameter, have a standard 75mm pitch. The helices have true helical shape and therefore, they do not auger into the soil but rather screw into it with minimal soil disturbance. The lead section has a shaft with round-corner square (RCS) cross-section of 45mm and contains three helices. The diameter of the helices of the lead section, tested as part of this study, is 200mm, 250mm and 300mm. Helical plates are 9.5mm thick and are spaced at a distance far enough apart, nominally three times the lower helix, such that they function independently as individual bearing plates. Plain extensions can be added in standard lengths of 0.90m, 1.5m, 2.1m and 3m.

Static Performance of Helical Screw Piles

El Naggar (2006) reported on a comprehensive investigation of the Chance SS175 helical foundation system. It involved a theoretical study as well as an experimental load testing program at the test site of the University of Western Ontario at the request of Hubbell Canada Incorporated. Thirteen test helical piles and twenty one reaction helical piles were installed as part of this experimental program. Eight piles were tested in compression and five piles were tested in tension. Ten test piles were installed in cohesive soils (Site 1) and three test piles were installed in cohesionless soils (Site 2). Six of the test piles in Site 1 were installed such that the helical bearing plates rested within the upper clay layers (depth of 5m below ground surface), and four piles were installed such that the helical bearing plates rested within the lower silt layer (9m below ground surface). The piles situated in Site 2 were installed to a total depth of 7.8m. The installation records for all piles contain the values of the installation torques at 300 mm (1 ft) intervals.

Based on the results of the comprehensive study, it was determined that the steel shaft, the blades and accessories of the SS175 Chance HSF conform to CAN/CSA-G40.21-M98, 350 MPa. They have a galvanic coating that meets the requirements of CAN/CSA G164, 610 g/m^3. Based on the load test results and maintaining a minimum factor of safety of 2, the allowable compressive load is 335 KN (75 kip) and the allowable tensile (uplift) load is equal to 223 KN (50 kip). The ultimate capacity values established using these criteria for piles tested in compression are shown in table 1, together with the average of the installation torque over the last 1m of the installation. (Eq.1) after (Hoyt and Clemence, 1989) was used for proposed the following formula for the torque/screw foundation capacity relationship:

$$Q_{ult} = K_t T \qquad (1)$$

Where: Q_{ult} = ultimate capacity [kN (lb)]
Kt = empirical torque factor [m-1 (ft-1)]
T = average installation torque [kN.m (lb.ft)]

Table 1 Pile Capacity and Installation Torque for Piles Tested In Compression (El Naggar, 2006)

Pile No.	Soil Type	Pile Capacity kN (kip)	Average torque over last 1m kN.m (lb.ft)	Kt m-1 (ft-1)
1	Clayey silt	450 (101)	11.76 (8666)	38 (11.6)
2	Clayey silt	480 (107.7)	11.54 (8500)	41 (12.5)
3	Clayey silt	310 (69.6)	13.80 (10166)	22.5 (6.8)
4	Silty clay	350 (78.6)	9.95 (7333)	35 (10.6)
5	Silty clay	300 (67.4)	8.73 (6433)	34 (10.2)
6	Silty clay	320 (71.8)	8.6 (6333)	37 (11.3)
13	Sand	600 (134)	11.31 (8333)	53 (16.2)
14	Sand	600 (134)	10.63 (7833)	56 (17.2)

Cyclic Performance of Helical Screw Piles

Piles Instrumentation

The tested HSP pile systems, each consisted of one lead section, 5ft in length, with three helical and one shaft extension, 7ft in length. The lead sections were instrumented to track the response of the HSP through a data acquisition system during testing in order to evaluate their capacities prior to and after cyclic loading. The strain gauges and their lead wires were placed inside minor grooves on the helical lead sections in the spacing between the helical plates for protection. Each pile was instrumented with six strain gauges of type (N11-FA-10-120-11) manufactured by Showa Measuring Instruments co., two of which were placed very close to the helical plates one on each side. The gauges manufacturer's guidelines were followed for placing them in terms of preparing piles surfaces, proper alignment, etc. Afterwards, protection and water proofing were applied to strain gauges. The lead wires and strain gauges were covered by multiple types of tapes. Strain gauges were tested before installation and after installation (prior to load testing) to ensure proper performance.

Piles Installation and Field Testing

During an earthquake, the soil, foundations and supported structures are subjected to the propagating seismic waves. The vibration of a structure due to the foundation input motion creates inertial forces which are transmitted to the piles. These forces are cyclic in nature. The seismic forces are mainly horizontal. However, due to the rocking of the structure, the supporting pile foundation will be subjected to axial cyclic loading. In addition, the ground motion during most earthquakes would have a vertical component that will induce axial cyclic loading to the piles. Therefore, it is important to evaluate the cyclic axial performance of foundation systems as part of its seismic performance characterization. The average number of "effective" load cycles of an earthquake is about fifteen. Thus, in this study, the HSPs were subjected to 15 cycles of axial loading.

The HSPs were installed in The University of Western Ontario environmental test site. Two boreholes performed at the test site indicated cohesive soil layers as shown in Table 2. The water table was encountered at 2.4m and 2.6m below the ground surface, for boreholes 1 and 2, respectively. The field testing consisted of two loading arrangements: one for compressive loading and one for cyclic loading. Each pile was subjected to 15 cycles of axial loading according to ASTM standards for cyclic loading, followed by axial compressive loading to failure. The compression axial loading was conducted to evaluate the pile performance after cyclic loading.

The cyclic loading was applied in the following manner: the load is applied through a hydraulic jack from an initial load of almost 0 kN to 130 kN, in increments of 10 kN. Each increment was maintained constant for 2.5 minutes. Once the load applied to the pile reached 130 kN, it was decreased to 70 kN in 10 kN intervals, each held constant for 2.5 minutes. In the following repetitive cycles, the load was varied from 70-130 kN and vice versa. The displacement was recorded using four LVDTs' connected to the data acquisition system which is calibrated to take one reading per second. The average displacement for the four LVDTs' was recorded at the end of each load interval.

After the cyclic loading was completed, the piles were tested in axial compression in increments of 10 kN, each maintained for 2.5 min, till failure. This load testing was performed in order to evaluate the effect of 15 cycles of loading on the axial compressive capacity of the pile. In addition, a conventional axial compression test (with no cyclic loading) was performed on one of the piles to validate the empirical piles capacity formula (Eq.1).

Table 2. Borehole No. 1 Soil Layers Description

Soil Layer	Soil Layer	Depth (m)
A	Brown sandy clayey silt embedded gravel.	0 — (2.4)
B	Brown clayey silt	(2.4) – (4.1)
C	Grey clayey silt	(4.1) – (5.8)
D	Grey sandy clayey silt, embedded gravel	(5.8) - (7.3)
E	Dense grey silt (saturated)	(7.3) – (8.1)

RESULTS AND ANALYSIS

Torque installation curves for the tested piles are shown in Figure 4. Using the piles installation torque-pile capacity relationship for pile installed in cohesive soils (See Table 1 and Eq. 1), the ultimate capacity of the tested piles was calculated. The calculated pile capacities were approximately 300 kN as shown in Table 3.

Figure. 4. Torque versus Installation Depth for Tested Piles

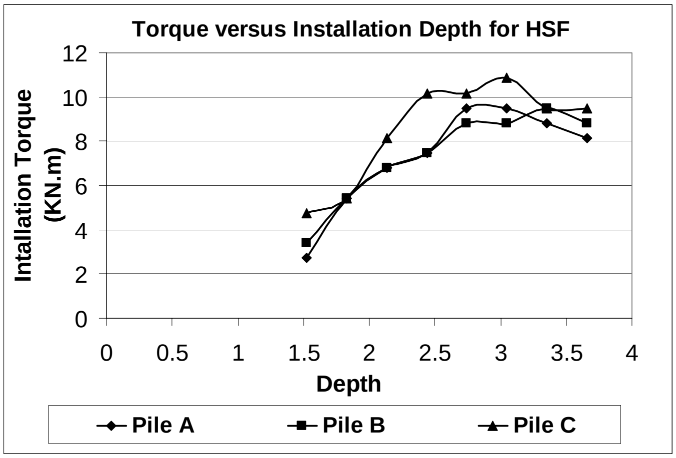


Table 3. Piles Capacities Calculated Using Eq. 1

Pile No.	Soil Type	Pile Capacity kN (kip)	Average torque over last 1m kN.m (lb.ft)	Kt m-1 (ft-1)
A	Stiff to V. Stiff Clayey silt	291 (65.35)	8.81 (6500)	33 (10)
B	Stiff to V. Stiff Clayey silt	298 (67.06)	9.04 (6667)	33 (10)
C	Stiff to V. Stiff Clayey silt	328 (73.74)	9.94 (7333)	33 (10)

The performance of Pile A during 15 cycles of loading at an average cyclic load of 100 kN (1/3 of the pile estimated capacity) is shown in Figure 5. The axial compressive loading performed after the completion of the cyclic loading was used to evaluate the effect of cyclic loading on the piles ultimate capacity. The ultimate load (capacity) of the pile was determined as the load applied at the pile head that corresponds to a settlement at the head equal to 8% of the diameter of the largest helical plate (300mm). The calculated piles axial capacities were 278 and 276 kN for piles A and C, respectively.

The average displacement for each load increment during the axial compressive loading phase is plotted in Figures 6 and 7, for piles A and C, respectively. Pile B was subjected to axial compression testing without prior cyclic loading and the load-displacement curve is presented in Figure 8. it is noted that the capacity of pile B estimated using the average displacement of the four LVDT was 280 kN, which is in reasonable agreement with the capacity estimated using Equation 1 (298 kN). It is also noted that using the average displacement given by LVDT 1 and 2, the capacity would be 300 kN. Comparing the measured capacity of Piles A, B and C, it can be interpreted that cyclic loading reduced the ultimate capacity of helical screw piles by less than 5-10%.

Figure 5. Measured Load and Displacement During Cyclic Loading of Pile A

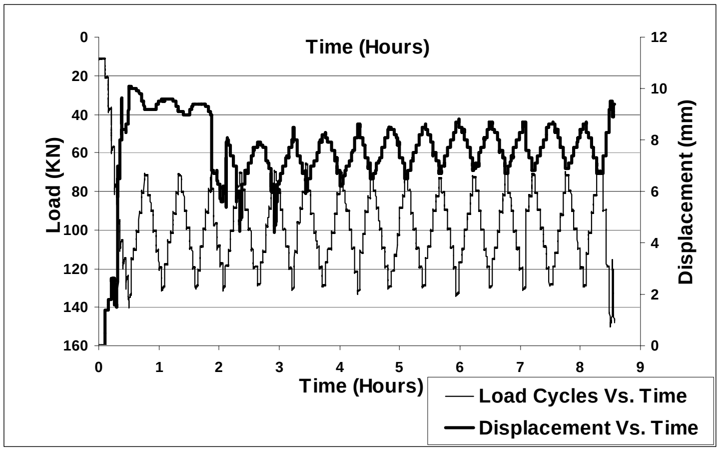


Figure 6. HSP (A) axial compression field testing after 15 cycles of loading

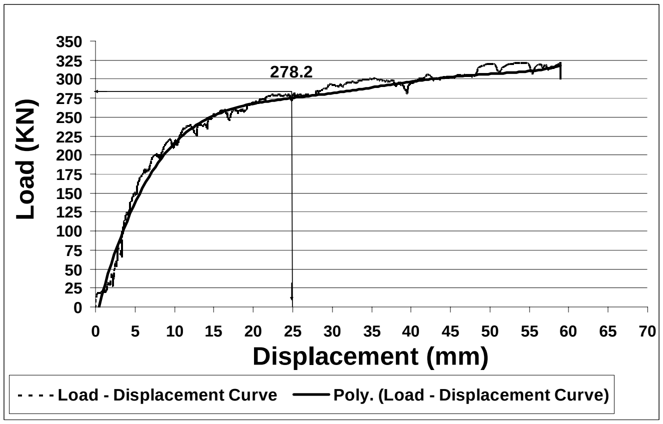


Figure 7. HSP (C) axial compression field testing after 15 cycles of loading

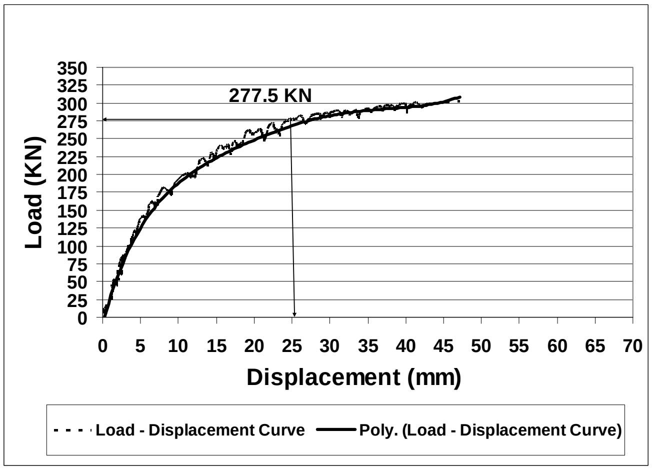
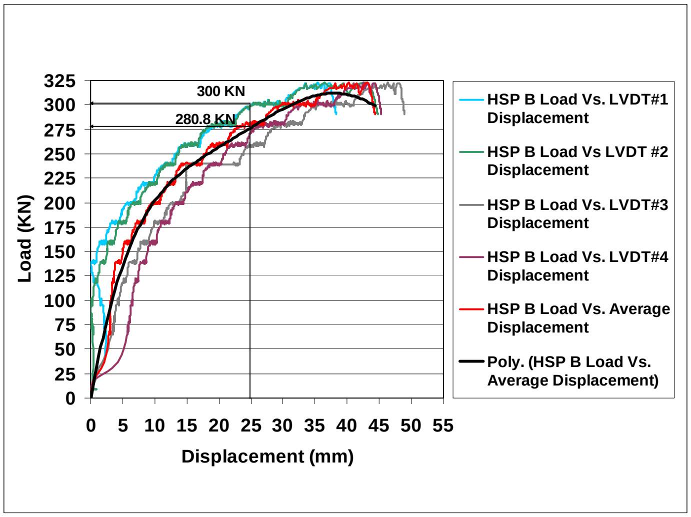


Figure 8. HSP (B) axial compression field testing before cyclic loading



The load transfer along the pile was evaluated using the readings of the strain gauges placed on each helix side of the three helices plates located at the lead section. The load transfer mechanism of the helical screw piles A and C is illustrated in Figures 9 and 10, respectively. Examining theses figures reveals that the load transfer to the soil is predominantly through a cylindrical shear failure surface over the inter-helices soils; and the bearing capacity of the lead (bottom) helix. The distribution between these two mechanisms was approximately 50% and 40% for Pile A and 63% and 27% for Pile C. This reflects that most of the load is transferred to the soil through helical plates and the soil enclosed between them, with a small percentage (10%) of the load transferred to the soil through slender shaft above the helices.

Figure 9. HSP (A) Load transfer curve Vs. Depth

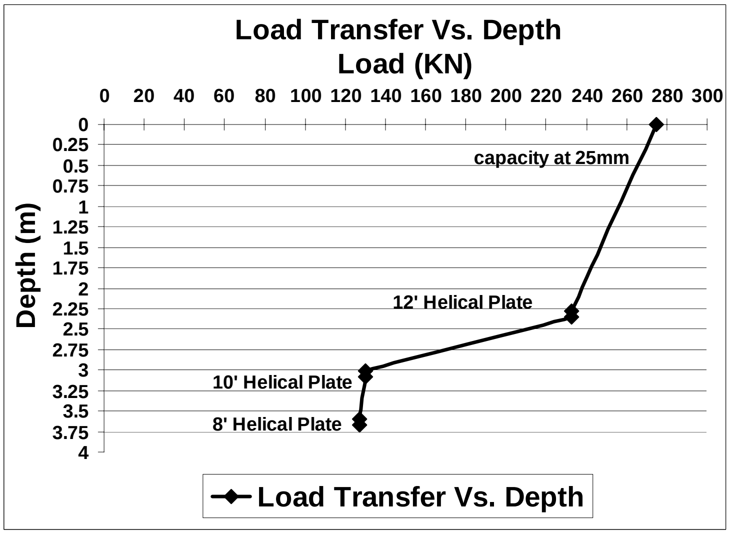


Figure 10. HSP (C) Load transfer curve Vs. Depth

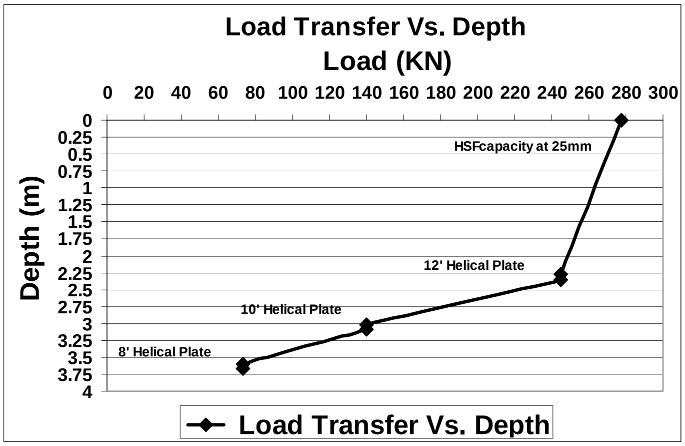


Figure 11 shows the cyclic load-displacement performance of Pile A. The variation of the pile stiffness with the number of cycles is shown in Figures 12 and 13 for piles A and C, respectively. Figure 12 shows that pile A experienced some degradation of its stiffness as the number of cycles increased. On the other hand, Figure 13 shows that the stiffness of Pile C fluctuated as the number of cycles increased with no indication of stiffness degradation. Based on these limited results, it may be suggested that the cyclic behavior of HSP is satisfactory and warrants a consideration for seismic applications.

Figure 11. HSP (A) Load cycles Vs. Displacement

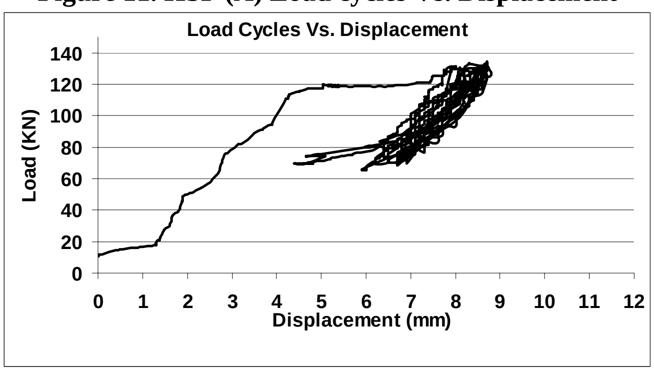


Figure 12. HSP (A) Stiffness Vs. Load Cycles

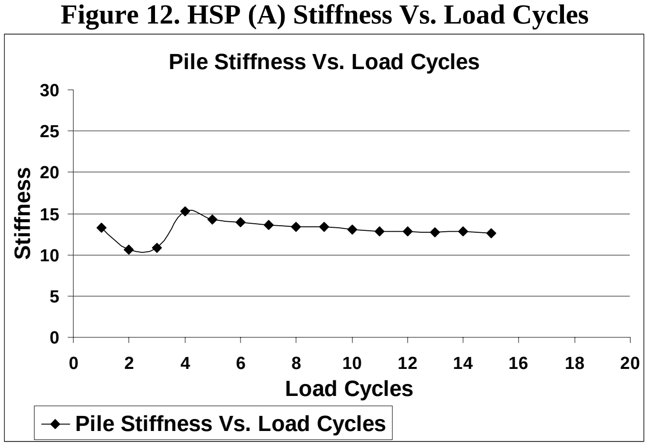
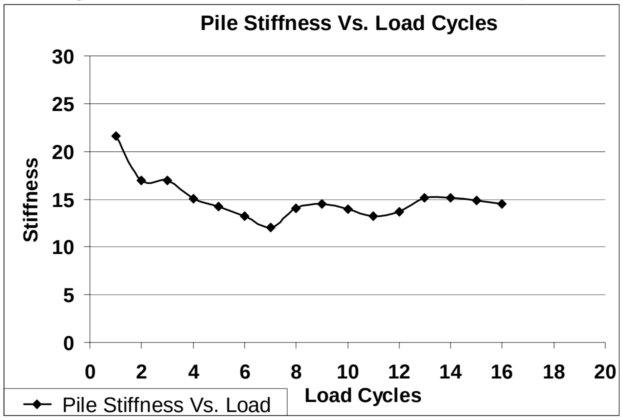


Figure 13. HSP (C) Stiffness Vs. Load Cycles



CONCLUSIONS

In this paper, the cyclic performance of helical screw piles was evaluated. The results show that, in general, the seismic performance of these piles is satisfactory. The specific conclusions that may be drawn are:

1. Fifteen cycles of axial loadings reduced the axial pile capacity by less than 5-10%.
2. The research confirmed the appropriateness of the empirical formula relating the ultimate axial capacity of the pile capacity and its installation torque.
3. The load transfer involves shear failure of an inter-plates soil cylinder and bearing failure underneath the bottom helix.
4. The effect of cyclic loading on the stiffness of HSPs is negligible.

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