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Experimental and Numerical Modelling of Helical Piles Subjected to Lateral Loading

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Abstract

Foundation is one of the most important parts of a building and infrastructure in the construction industry. The increase in demand of high-rise buildings and infrastructure due to limited land availability, increases the demand for efficient foundation systems. Researchers have performed various numerical and experimental studies to investigate the most viable foundation type for high rise buildings. Helical pile raft foundation, is one of the main focus of the current research study. In helical pile, some load is taken by skin friction, end bearing and some is taken by the helix attached. In case of helical pile raft, apart from the above-mentioned phenomenon, raft also contributes towards the bearing capacity of a foundation. The current study is carried out to investigate the settlement and load carrying capacity of helical pile and helical pile raft (HPR) foundation. In this study, small scale models of helical pile raft foundation is prepared and placed in a rectangular box filled with cohesionless soils. Instrumentation of the model is carried out using settlement transducers and load cells to record the settlement and load applied, respectively. Results of different HPRs with varying number of piles are compared, and it was concluded that the HPR foundation has greater load carrying capacity than the conventional pile raft foundation. In addition, it was concluded that the HPR foundation is more efficient in controlling the settlement behaviour.

Keywords: Helical Pile; Screw Pile; Lateral Capacity; Deep Foundation; Numerical Modelling.

1. Introduction

Helical foundations are used commonly in areas, where seasonal fluctuations of moisture significantly affect the active zone of soil. Swelling and shrinking of expansive clay due to change in moisture content causes serious damage to foundations that are not designed and constructed to mitigate these effects (Pack, 2006).

Helical piles are driven in parts extending from 3 to 7 feet long, (see Figure 1). In some cases, helical plates are attached to additional parts, where the leading part is not long enough to attach more plates, to generate the required design resistance.

While helical anchors are becoming more popular, helical pile foundations have been implemented since the early 1800s. In 1833 the screw pile was officially patented in London, credited to Alexander Mitchell; an example is shown in Fig. 2. These screw piles were successfully used to support lighthouses in sandy soils. The Maplin Sands lighthouse was constructed on the River Thames in England in 1838. The foundations consisted of eight wrought-iron screw piles in an octagonal arrangement surrounding one center pile. Each helical anchor consisted of a four-foot helical plate on a five-inch shaft as shown in Fig. 3.

There are many practical applications of helical piles like they can be used as a guy wire anchors for electrical transmission towers. They can be used in foundation of new building as well as retrofitting of old buildings. They are also used for decks and gazebos construction. In Japan they are used for retrofitting of bridge pier. Helical pile is a fast foundation technique as compared to footing-type foundations for residential additions (Soth and Sailer, 2004). One of the best application of helical pile is its use in frost heave and expansive soils. The long central shaft of helical pile bounds the upward stresses due to soil heave, while uplift forces were resisted by helical bearing plates. The use of helical pile is enormous. They can be used for construction of board walks, bill boards construction, solar farms etc. There vibration free ability makes it more feasible for residential constructions. Helical piles can also be used for the foundation of industry in which high vibratory machines might work. Similarly for heavy construction helical piles are widely used in groups to resist more loads. The International Building Code, Chapter 18, states that the tops of all types of piles need to be laterally braced. Hence to achieve this a minimum of three piles in a group might be used to support footing of column for resisting large loads. In this way, helical piles have been used in a variety of low to high-rise commercial construction projects. (Perko, 2009). Helical piles are also known as screw piles, helical anchors, helical piles and helical piers (Merrifield, 2013). The soil strength is found to affect the capacity in both individual bearing failure and in cylindrical shear failure (Davis, 1982).

Several other researchers (Meyerhof and Adam, 1968, Mooney et al. 1985, Prasad et al. 1993, Prasad et al. 1996, Mitsch and Clemence, 1995, Perko, 1999 and Lutenegger, 2009, 2011) also investigated the axial and lateral capacities of helical piles. However, further experimental model tests and numerical modelling techniques are necessary to investigate the lateral capacity of helical piles. The current study is focused on understanding the lateral capacity of helical piles.

2. Testing Overview and Sample Preparation

First the soil box was filled with the sand up to the top from the base and was leveled properly. The sand was compacted to a medium dense state. A sand sample was collected from a known location and dry sand was used for the test to eliminate the chances of corrosion and effect of water on the results. The specific gravity of the sample was determined in laboratory using pycnometer, which was found to be 2.66, direct shear test and sieve analysis were also conducted in the laboratory. The results of the direct shear test showed the cohesion equal to 0 and frictional angle value of 37o. Based upon the sieve analysis results, the sample was categorized as poorly graded. The gradation curve is shown in Figure 4 and the basic properties of the soil are summarized in Table 1. Based on the values of coefficient of uniformity and curvature, the soil was classified as poorly graded sand based on USCS.

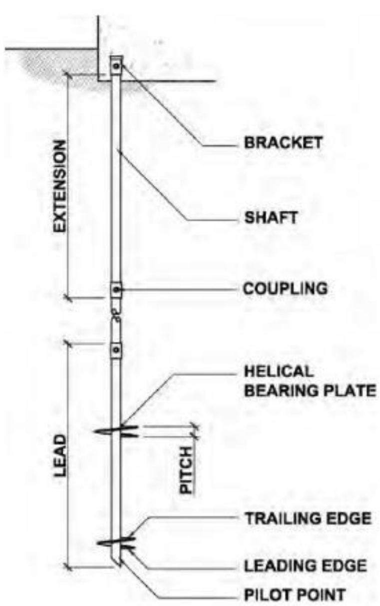

Fig. 1. Components of Helical Pile (Perko, 2009)

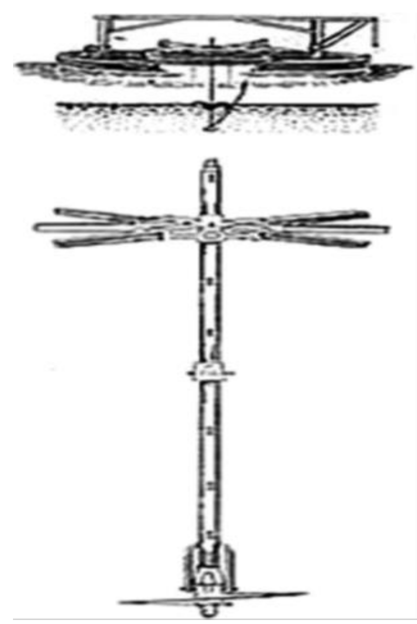

Fig. 2. Light House Foundation (Mitchell, 1833)

Positions of piles are marked in the sand box at the mid to ensure that the pile raft are equidistant from the walls of the sand box. Sand box is a rectangular shape box made of iron sheets. It depicts the side condition of a sand. Sand is retained in a sand box having almost same relative density as in site. The dimensions of the box were selected, to avoid any significant effects of pressure bulb and boundary conditions. In this study, we chose dimensions of box as 4ft x3ft x5ft. Helical pile was then retained in the sand to perform tests as shown in the Fig. 5.

Fig. 6 and Fig. 7 show different elements of Pile Raft foundation such as piles, nut and bolts, strain gauges and Raft. The piles are driven into the sand such that the medium dense state of the sand remained unchanged, and the strain gauges are aligned parallel to the lateral load application. Raft is then placed over the piles and is fitted using bolts as shown in Fig. 8.

Two LVDTs are attached to the top of the raft at both corners parallel to the application of loads to find the lateral deflection. Linear vertical displacement transducer (LVDT) is a device, which measures the vertical displacement. Linear displacement is the movement of an object in one direction along a single dimension. The output signal of the linear displacement sensor measures the distance an object traveled in units of millimeters (mm), or inches (in.). Spring type displacement transducer was used while performing the experimental work. Figure 9 shows the LVDT used in this study during experimental work. Two LVDTs were used for the measurement of lateral displacement having the maximum capacity of 25mm or 1 inch. LVDTs were attached to pile cap opposite to the load application.

The load cell is placed over the raft to measure a constant axial load. It is a device which is used to measure the applied load. Signals from load cell are send to the data logger which is then transferred to MATLAB software. Data logger is an electronic device which that records data over time interval of almost 0.1 second. Strain gauges, LVDTs and load cell wires are connected to the data logger as shown in Fig. 11. A communication wire from data logger is connected to laptop which is read by using MATLAB software. There are total of 30 channels in a data logger used in this study. Channel from 1 to 16 measures the displacement directly in mm; from 17 to 29 measures the strain in micro-strain and channel 30 measures load in micro-strain.

Strain is a quantity of deformation – elongation or contraction of a material in proportion to the applied external load (Fig. 10). Strain gauge detects the strain caused in material due to the load in a form of electric signals. These signals are detected by the data logger and then is transferred to MATLAB to give result. To attach a strain gauge to a material, first undulations are removed from a material surface then glue is applied to the surface and the gauge is attached. The gauge is made fixed by a tape to not allow any disturbance. There are some disturbances in the reading due to temperature, humidity, and axial load; to accommodate these variations a stone wheat bridge is designed.

Fig. 3. Light House (Lutenegger,2003)

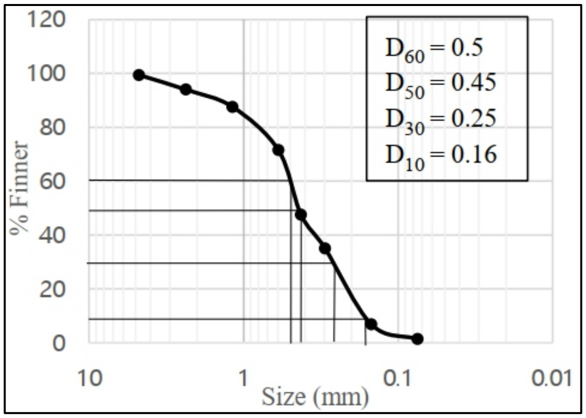

Fig. 2. ANFIS model structure


Fig. 5 Sand Box with Lateral Load Cell.


Fig. 6. Single Helix and Double Helix pile.

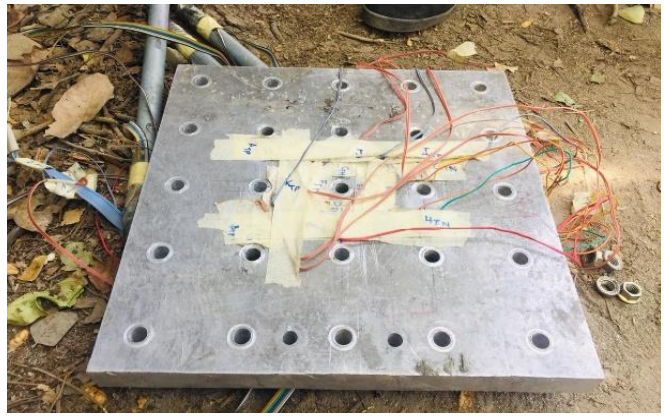
Fig. 7. Pile Raft.


Fig. 8. Pile Raft Setup.


Fig. 9. LVDTs attached to Single Pile with help of Plate.

Table. 1 Basic properties of soil.

C_u	C_c	Sand Fraction	Gravel Fraction	Fine Fraction	[redacted]	[redacted] (kN/m^3)	G_s
3.125	0.661	97.96	0.65	1.39	36^o	17.04	2.64

Before using, calibration of load cell was completed. The lateral load cell calibration came out to be 0.018894. The data logger data is then divided by this factor. There are different types of load cell available. In our study, we used hydraulic type of load cell as shown in the Figure 12 and Figure 13. Load cell is attached to the lateral load pump to measure lateral load. They are attached to a laptop through data logger.

We applied a static axial load 5150 N (Fig. 15). The hydraulic pump is turned on which applied lateral load and the data from the strain gauges is captured in the laptop. The load is increased incrementally at a very slow rate which can be assumed as static. The LVDTs are used to measure the raft lateral deflection as shown in the Fig. 14.

Numerical simulation of all experimental work was carried out through PLAXIS 3D. The input parameters used in PLAXIS 3D have been presented in Table 2 and numerical model has been shown in Fig. 16. The results of PLAXIS 3D were compared with those obtained from experimental tests. The numerical results were in good agreement with experimental tests.

3. Results and Discussion

Helical piles can be made up of number of helixes attached to it. In this study, experimental model tests of two types of helical piles are tested i.e., single helix single pile and double helix single pile.

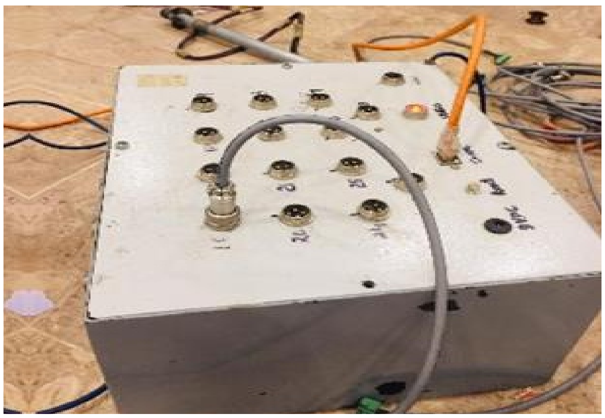

Fig. 10. Strain Gauge.

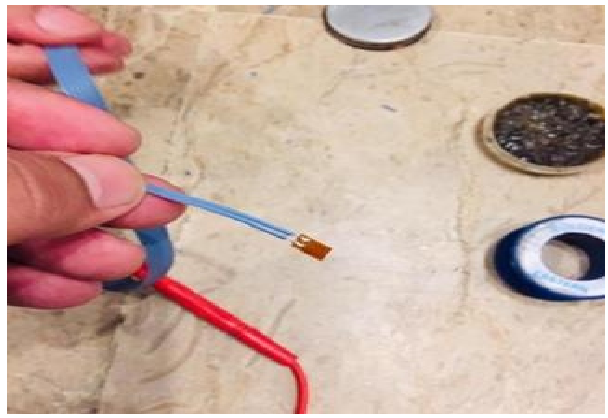

Fig. 11. Data Logger.

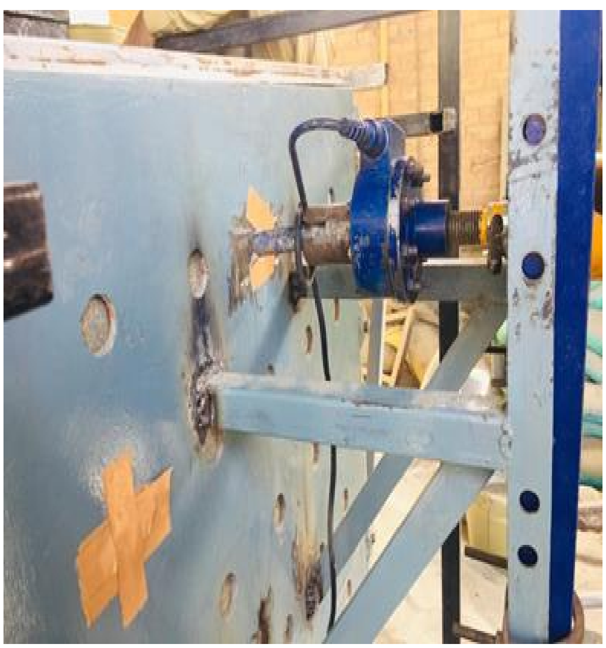

Fig. 12. Lateral Load Cell.

Fig. 13. Axial Load Cell.

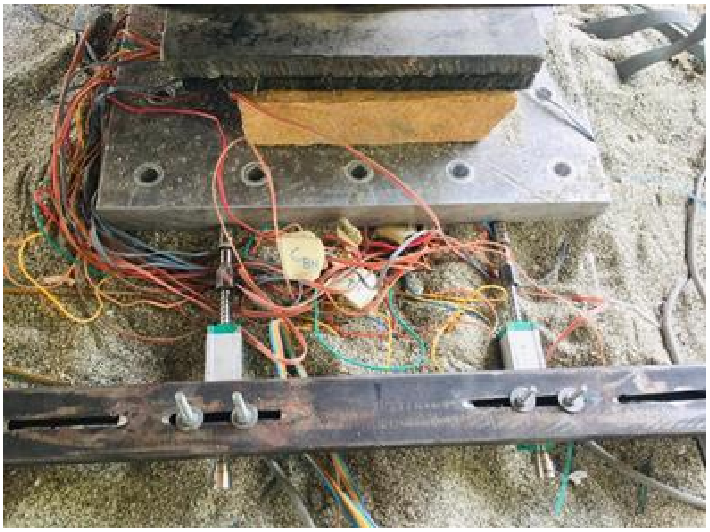

Fig. 14. LVDTS attached to Pile Raft

Fig. 15. Axial Building Load 5150N.

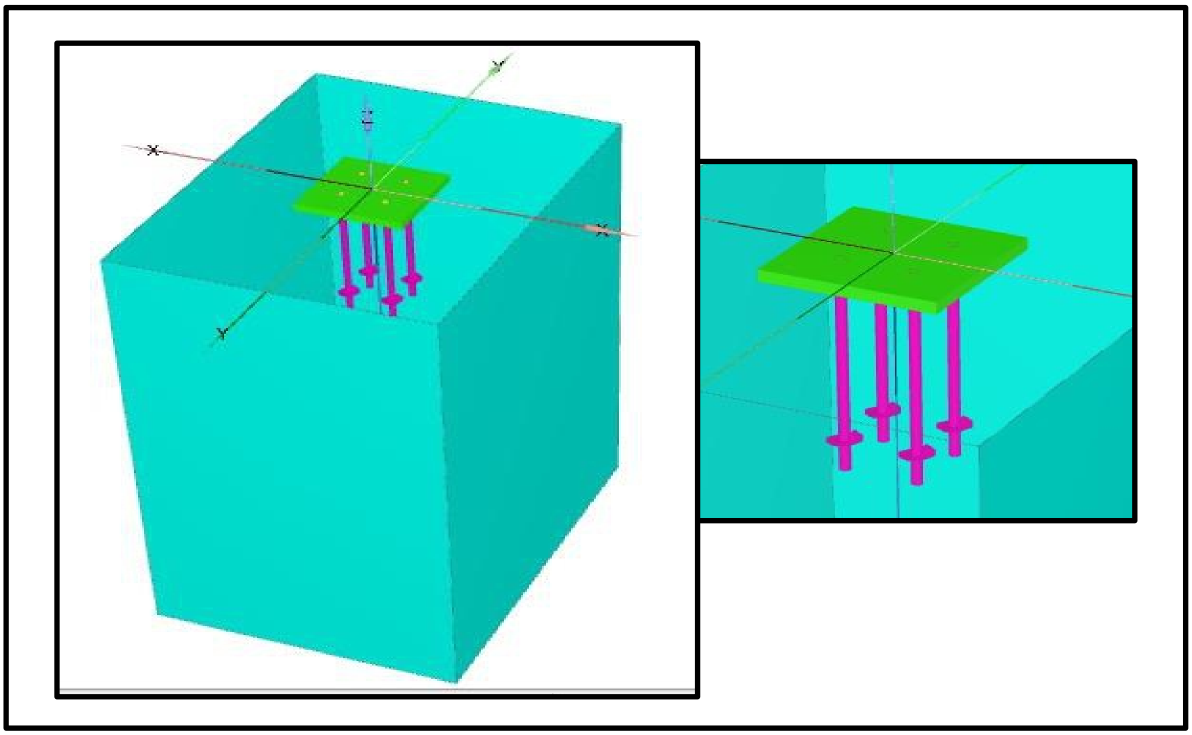

Fig. 16. PLAXIS 3D Numerical Model

Table. 2 Input Parameters for Numerical Modelling in PLAXIS 3D.

Material	**Soil**	**Raft**	**Pile**	**Helix**
Parameter	Sand	Aluminum	GI Pipes	GI plates
E	30 MPa	70GPa	200GPa	200GPa
Cohesion (kPa)	0	-	-	-
Friction Angle	34	-	-	-
Model	MC	Linear Elastic	Linear Elastic	Linear Elastic
γ (kN/m3)	17	26.4	77	77
Poisson ratio ν	0.3	0.27	0.27	0.27
Strength Reduction factor R	0.6			

3.1 Single Helix Single Pile

First, a pile with single helix attached to it was tested experimentally to find the lateral capacity against the lateral displacement. Table 3 shows the experimental data from single pile and lateral vs lateral displacement plotted as shown in Figure 17, a comparison is done with Numerical modelling as show in Figure 18. The maximum lateral resistance offered by single helical pile is 329.69 N corresponding to 19.54 mm lateral displacement while by numerical modelling it is 380.4 N. By comparing a single pile with single helix to sample conventional pile the lateral capacity of single helical pile is approximately 10% more than conventional pile. A helix attached to pile increases the bearing area and hence increases the lateral capacity as well as bearing capacity against lateral loading.

3.2 Double Helix Single Pile

Second, double helix single pile is tested for bearing capacity against the displacement. Data extracted experimentally is shown below in Table 4, force displacement graph is plotted (Fig. 19) and a comparison is done with Numerical Analysis as show in the Figure 20. The maximum lateral resistance offered by double helical pile is 359.57 N corresponding to 22.64 mm lateral displacement while by numerical modelling it is 406.51 N. By comparing a single pile with double helix to sample conventional pile the lateral capacity of single helical pile is approximately 19% more than conventional pile. A helix attached to pile increases the bearing area and hence increases the lateral capacity as well as bearing capacity against lateral loading.

Table. 3. Single Helix Single Pile Experimental Data.

Lateral Displacement (mm)	Lateral Load (N)
0.52	11.69
1.51	22.59
3.19	92.74
9.4	259.54
19.54	329.69
20.32	309.20

Table. 4. Double Helix Single Pile

Lateral Displacement (mm)	Lateral Load (N)
0.129	3.2
2.16	66.07
5.67	184.94
12.47	314.94
22.64	364.51
23.1	359.57

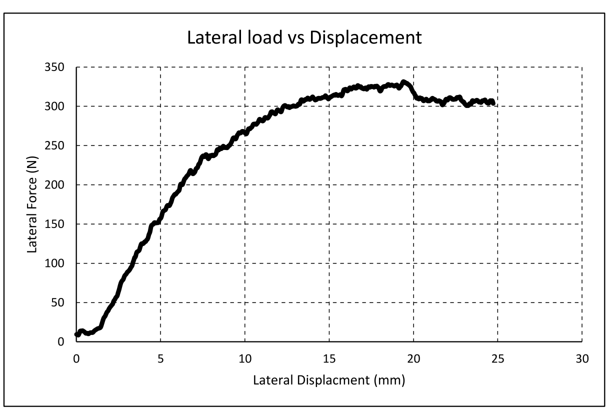

Fig. 17. Single Pile Singe Helix Load vs Displacement.

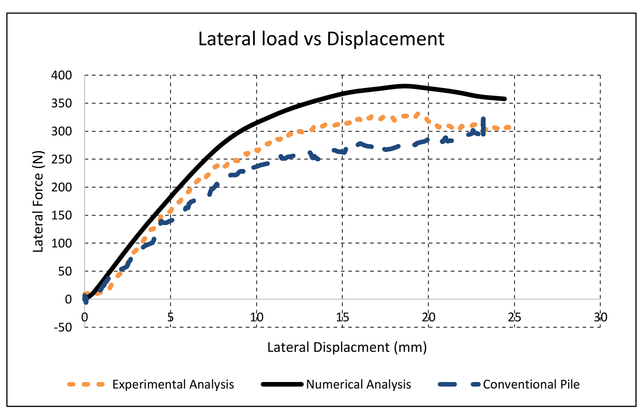

Fig. 18. Comparison between Experiment & Numerical Modelling.

From Fig. 21 the maximum load taken by a single helix single pile by physical modelling is 329.69 N against the displacement of 19.54 mm while by numerical modelling 380.4 N. In contrast, double helix single pile bearing capacity is calculated as 359.57 N against the displacement of 22.64 mm by physical modelling while by numerical modelling is 406.51 N.

The load taken by single helix pile against 20mm lateral displacement is 309.52 N; in contrast, double helix load taking capacity is 350.25 N against the same displacement.

It is concluded that adding helixes to a pile contribute to the bearing capacity of a pile.

3.3. Test Data for Helical Pile Raft

When the raft of foundation is attached to ground, it is called raft foundation. In this experimental modelling two types of pile rafts is tested. One, double helix two pile raft, second, double helix four pile raft. In case of pile raft axial static load is applied on pile raft as a building load and medium state relative density of sand is achieved to simulate the site condition.

3.4. Test Data for Double Helix Two Pile Raft

Two piles were attached to the raft in front of each other. Axial load of 5150 N is applied on the raft as a building load. Lateral load is applied on the raft and data is collected using Data logger. In case of pile raft, portion of the load is taken by piles and some load is taken by the raft. Table 5 shows data collected from experimental work and load vs displacement graph is shown below in Fig. 22.

3.5. Test Data for Double Helix Four Pile Raft

Double helix four piles were attached to the raft for lateral load testing. Same static axial load of 5150 N is applied on the raft as a building load to simulate the site condition. Data logger is used for collection of data. As in case of two pile raft, the same procedure as followed for the collection of data. Data from the two piles is placed in front of each other is collected. The same data is than used for the other two piles in this case. Table 6 shows the data collected during Experimental work and graph are shown below in Fig. 23.

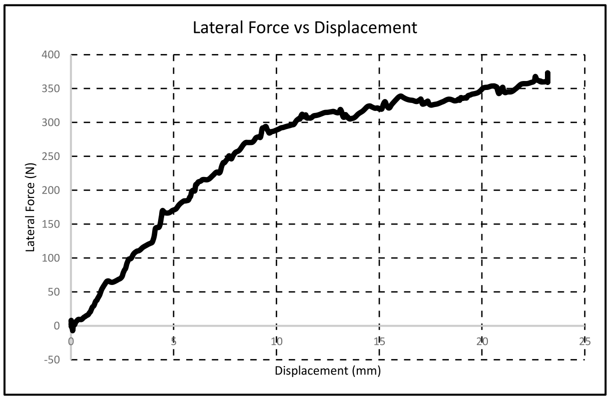

Fig. 19. Double Helix Single Pile.

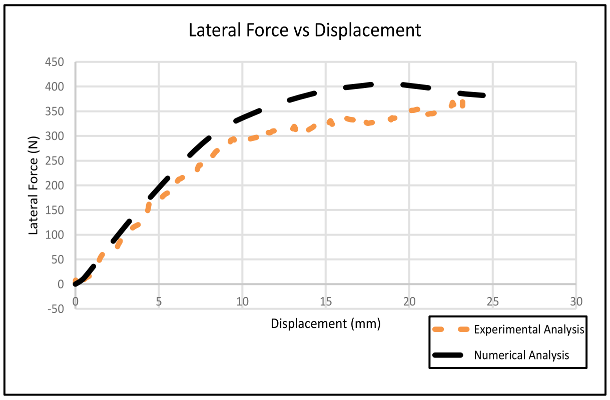

Fig. 20. Comparison between Experimental and Numerical Modelling.

Table. 5. Double Helix Two Pile Raft.

Lateral Displacement (mm)	Lateral Load (N)
0	381.62
0.15	1055.44
5.79	1773.11
12.19	2024.28
18.01	2346.92
18.20	2302.70

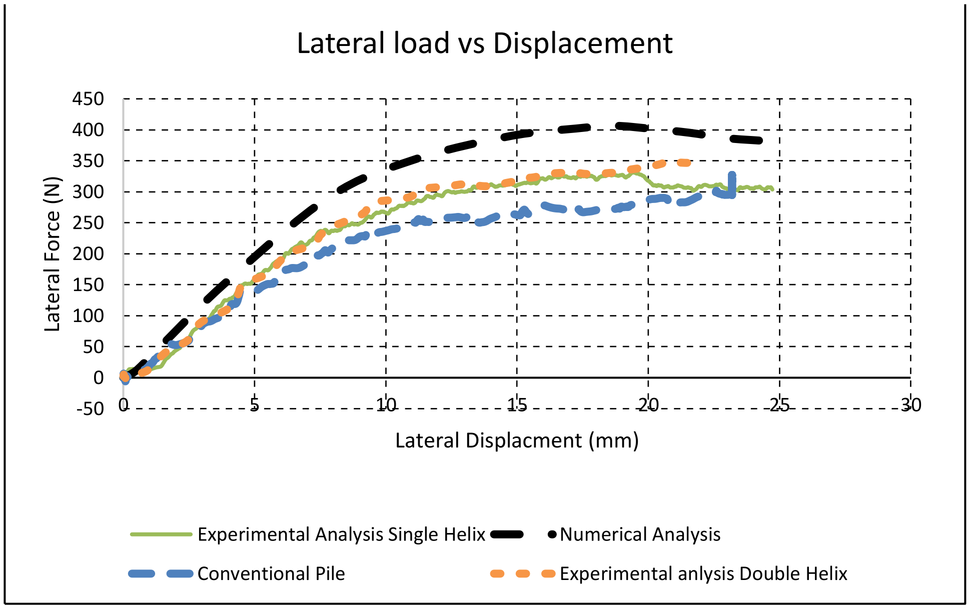

Fig. 21. Comparison of Single Helix and double Single Piles

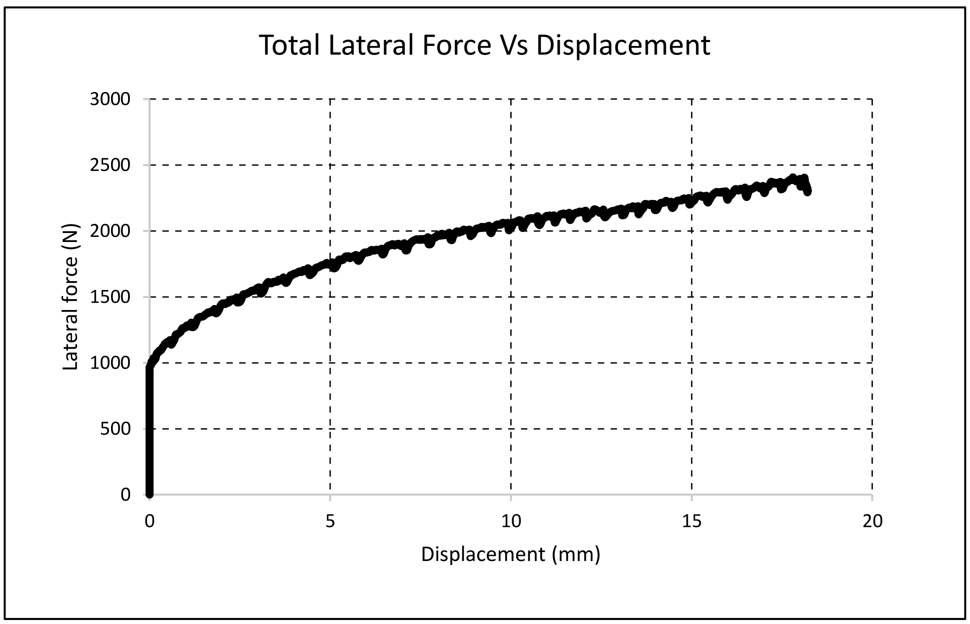

Fig. 22. Double Helix Double Pile Raft Total Capacity.

Table. 6 Double Helix Four Pile Raft

Displacement (mm)	Load (N)
0.05	121.97
1.32	683.97
6.95	1678.97
10.52	2146.43
15.95	2841.58
16.2	2802.12

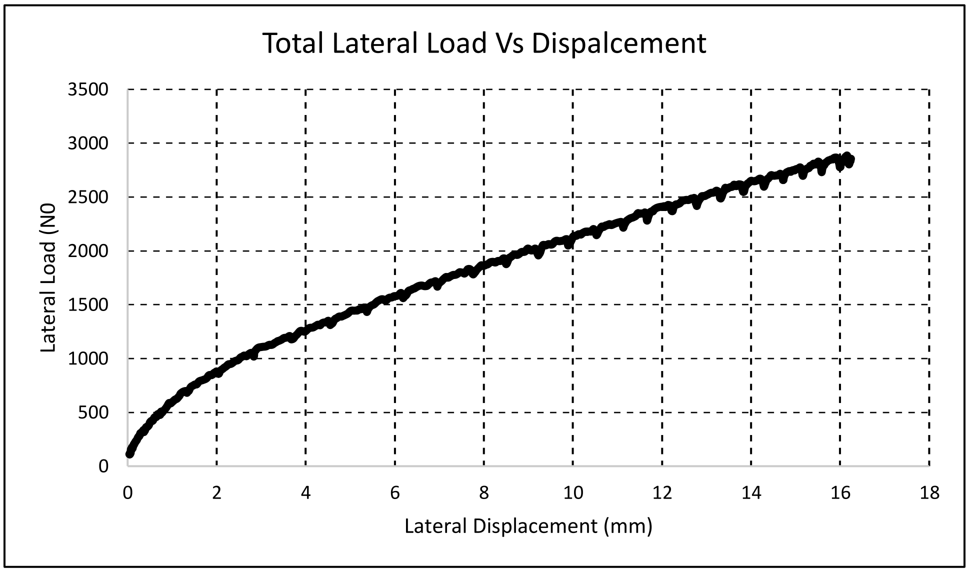

Fig. 23. Total Capacity of Double Helix Four Pile Raft

A comparison is done between 2 pile raft and four pile rafts. Corresponding to 10 mm lateral displacement two pile raft taken the load of 2004.61 N and load taken by 4 pile raft is 2151.54 N.

4. Conclusions

In the current study, the maximum load taken by single helix pile is 329.69 N, while the maximum load taken by double helix single pile is 364.51 N. In case of double helix, two piled raft maximum load is 2346.92 N, while for double helix and four pile raft took the maximum load of 2841.58 N. After performing a number of experiment model tests, it is concluded that adding helix to a conventional pile increases bearing capacity of a conventional pile. In addition, it is observed that number of helixes affected the bearing capacity of a pile. Previous research shows that number of helixes increased the bearing capacity of a pile up to a certain limit. Furthermore, adding more helixes do not significantly affect the bearing capacity. In design, previous studies did not consider the effect of raft while designing. After the experiments, it is found that the raft significantly contributes to the bearing capacity of a raft foundation (e.g., 40%). The results and findings from the current study may add value to the construction industry and significantly affect the economy of buildings and infrastructures.

Acknowledgments

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Author's Contribution

Muhammad Safdar, proposed the main concept and involved in write up, Tauseef Shaukat assisted in establishing field data and did provision of relevant literature, Zakria Khan review and proof read of the manuscript. Wali ullah and Irfan Jamil did technical review before submission and proof read of the manuscript. Muhammad Waseem did collection of field data. Naveed Ahmad, was involved in preparation of illustration and plates of figures.

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