ICIC Express Letters
Part B: Applications
Volume **11**, Number **3**, March **2020**

ICIC International ©2020 ISSN 2185-2766
pp. 253–260

NUMERICAL ANALYSIS OF BEHAVIOR OF HELICAL PILE WITH SINGLE HELIX VARYING HELIX LOCATIONS

Jonghwan Bae[1], Sehee Shin[1], Junwon Lee[1], Kicheol Lee[1]
Byung Soo Kim[2] and Dongwook Kim[1,*]

[1]Department of Civil and Environmental Engineering
[2]Department of Industrial and Management Engineering
Incheon National University
119 Academy-ro, Yeonsu-gu, Incheon 22012, Korea
{ bjh0989; couplions36; wnsdnjs0530 }@naver.com; wlq4619@gmail.com; bskim@inu.ac.kr
*Corresponding author: dwkim@inu.ac.kr

Received August 2019; accepted November 2019

Abstract. *As economical energy resources are being depleted around the world, interest in developing energy resources in cold regions is stiffly increasing. Accordingly, the increasing number of energy plant constructions accelerates the demand of efficient foundations supporting the plants. The typically-used cast-in-place piles and driven piles in inland are not suitable types of foundation in extreme cold regions. Therefore, helical piles are attempted to be used for their advantages of easy and simple construction process. The helical pile has helix attached to the central shaft and is rotationally penetrated. The helix plays an important role in both bearing capacity and constructability. In this study, the behavior of the helical pile varying the helix location was analyzed. To achieve the goal, laboratory model tests and numerical analyses were carried out. It was found that the helical pile with a helix at the uppermost location produced the greatest ultimate load.*

Keywords: Helical pile, Helix, Axial behavior, Shear strength, Frictional soil, Numerical analysis

1. **Introduction.** As global demand of energy continues to increase, many plant constructions are planned for the energy resource developments. In particular, more than 70 percent of the undiscovered oil and natural gas are estimated to be found in cold regions such as Alaska, Siberia, and Greenland; the plant construction in cold regions is getting attention [1]. Cold region is defined as a region where the monthly average temperature is below −30°C. The plants located in the cold regions may experience ground deformation due to the freezing and melting of the ground. The heat transferred from the superstructure to substructure during the construction and operation of the plant may also influence the behavior of foundations. Therefore, design and construction of the foundations must be conducted accurately in the cold region. Especially, the foundations in the cold regions require rapid construction and easy of pull out for recycling to prevent environmental problems after termination of plant use.

The typically-used piles in inland are cast-in-place piles and driven piles. However, under the cold region environment, cast-in-place piles require longer construction periods and higher installation costs. Furthermore, it is difficult to control the curing temperature of concrete under cold region environment. Installation of driven piles is possible using a piece of large equipment. Moving a piece of heavy installation equipment is practically and significantly difficult in cold regions as most of the surface grounds of the cold regions are organic soils. These two types of piles require significant restoration cost after complete operation of plants due to higher expenses to pullout.

DOI: 10.24507/icicelb.11.03.253

A helical pile has attracted attention as an optimal foundation of plants in cold regions. The helical pile consists of steel central shaft and helix plate (or helix plates) attached to the shaft. The helical pile penetrates into ground by rotation under small vertical forces applied to the pile head [2]. The helical pile can be installed using relatively small equipment. In addition, helical pile is able to be pulled out if reverse rotation is applied to the pile head. This enables easy recycling of helical piles, which is environmental and economic advantage.

Because of these advantages, studies of helical piles have been steadily conducted. Studies on helical piles have focused on the number, diameter, and pitch of helices. Lee et al. [3] analyzed the bearing capacity of moderate-size helical pile varying number and diameter of helices. Bak et al. [4] studied helical pile behavior in sands varying helix pitch based on the numerical analysis results. They confirmed that the bearing capacity of the helical pile increased with longer helix pitch. However, there is a lack of research on the behavior of helical pile varying the location of helix to understand helix contribution on pile resistance.

In this study, numerical analyses were performed using the ABAQUS/CAE [5]. For the reliability of numerical analysis results, the laboratory model tests of the helical piles were conducted for the comparison between experimental and numerical analyses results varying the helix location. As a result, the behavior of the helical piles such as the ultimate loads and bending of helix was analyzed varying helix location.

2. **Bearing Capacity of Helical Pile.** There are several criteria to determine the ultimate loads of the helical piles. Davisson's criterion [6] is a method widely used for estimating the bearing capacities of piles from the pile load test results. O'Neill and Reese [7] defined the ultimate load as the resistance corresponding to the pile settlement of 5% of the pile diameter. Livneh and El Naggar [8] proposed the ultimate load equation based on the results of the laboratory tests and the numerical analyses of helical piles.

Kulhawy [9] recommended a reasonable method to determine the ultimate load of a helical pile. Kulhawy [9] classified the load-settlement curve of a helical pile into three regions: 1) linear region, 2) transition region, and 3) final linear region as shown in Figure 1. The linear region is the section where the axial load is transferred from the shaft to the end of the helical pile. As a result, both the shaft frictional resistance and the end-bearing resistance start to be mobilized. During the transition region, the shaft frictional resistance increases and reaches the maximum; while the soils near the helix are

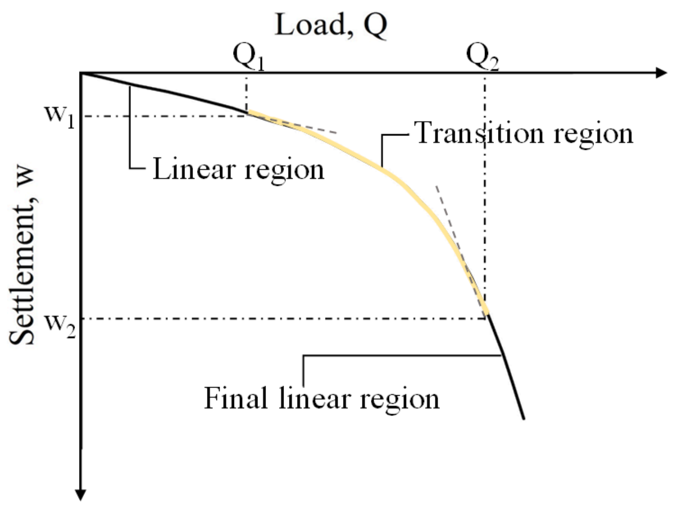
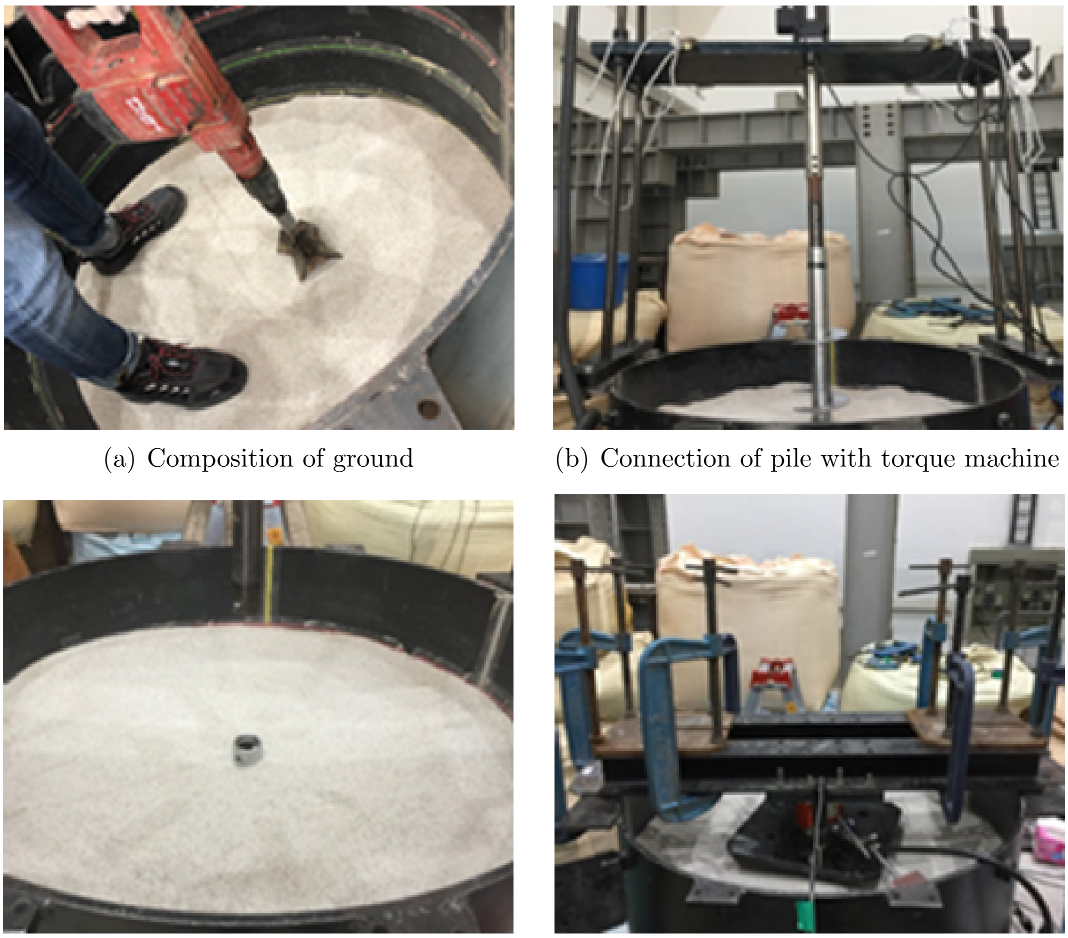


Figure 1. The load-settlement curve of the helical pile (modified after Kulhawy [9])

pushed gradually producing increase of passive resistance. The starting point of the final linear region is the point at which the yielding of helical pile occur. Typically, the load in the final linear region exceeds the ultimate bearing capacity of the helical pile. The loads Q_1 and Q_2 are the loads at the beginning of the transition and final linear region, respectively. And settlements w_1 and w_2 represent the settlements corresponding to Q_1 and Q_2, respectively.

3. **Laboratory Model Test.** The purpose of this study is to analyze the behavior of helical piles varying helix location. From a small-scale model experiment, it is difficult to confirm the quantitative behavior of the helical pile and helix. However, in order to ensure the reliability of the numerical analysis qualitatively, the laboratory model tests of the helical piles were performed prior to the numerical analyses. The helical piles used for the laboratory tests and numerical analyses have the shaft length of 750 mm, the shaft diameter of 50 mm, the helix diameter of 100 mm, and the helix pitch of 50 mm. The chamber used in the laboratory model tests is a cylindrical tank with the diameter of 1 m and the height of 1.2 m. Crushed sands (silica sands) were used to compose the ground (soil layer).

The procedure of the laboratory model test is shown in Figure 2. To construct a high-density homogeneous sand layer, compaction was conducted on every 200 mm thick sand layer (Figure 2(a)). Then, the helical pile is combined to the torque machine installed on the chamber and is installed to the target embedment depth of 680 mm under axial load of 85 kg and rotation speed of 30 rpm (Figure 2(b)). Figure 2(c) shows the helical pile



(a) Composition of ground (b) Connection of pile with torque machine

(c) Completion of helical pile installation (d) Measurement of load and settlement

Figure 2. Procedure of the laboratory model test

when its installation is completed. After positioning a reaction force beam on the top of the chamber, a hydraulic jack is installed between the ground and the reaction force beam. The hydraulic jack and displacement meter (LVDT) were used to the measure load and settlement of the helical pile (Figure 2(d)).

4. **Numerical Analysis.** To accurately assess the helical pile behavior from location to location, three dimensional numerical analyses were performed because two dimensional analyses are not sufficient to analyze the overall behavior of the solid helix's spiral structure. The numerical models of helical pile and the ground are shown in Figure 3.

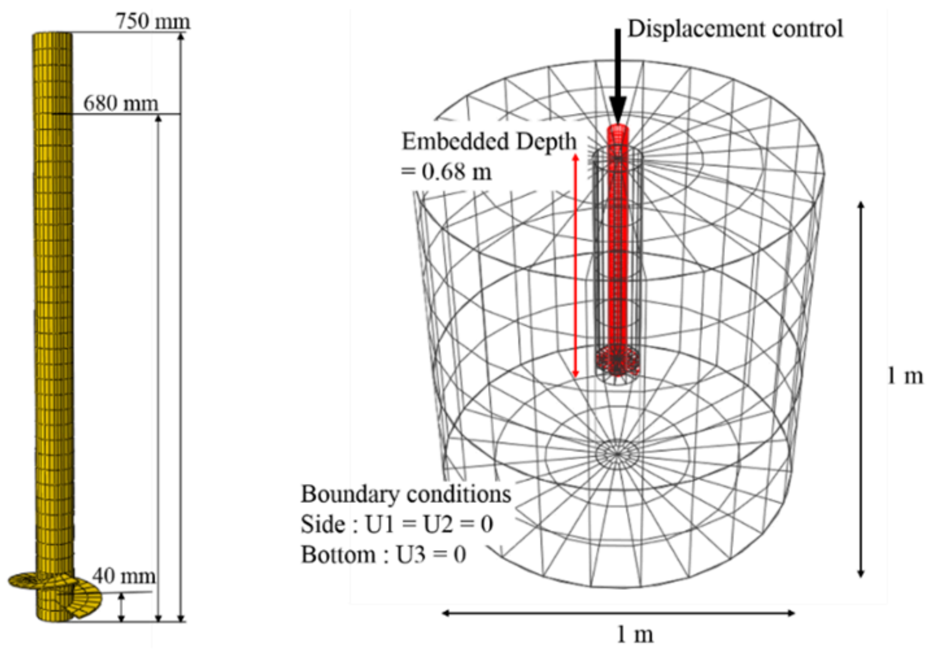


FIGURE 3. Helical pile and ground modeling

The procedure of the numerical analysis is as follows. 1) In the setting step of the boundary conditions, the contact surface between the helical pile and the ground is set as the 'constraint-tie' considering the rotational penetration. Since the sides and bottom of the ground are constrained by the chamber in the laboratory test, the sides (x-axis and y-axis) of the ground are set to "U1 = U2 = 0" and the bottom (z-axis) is set to "U3 = 0". 2) Since the ground and pile deformation can occur due to gravity, the stabilization of the ground and pile is achieved through the 'geostatic' process. 3) The load of each step was confirmed by controlling the displacement of the head of the helical pile. In other words, the load was calculated by the reaction force according to the displacement control.

Table 1 summarizes the material properties of the helical pile and the soil used in the numerical analyses. The helical pile is made of stainless steel. And, the elastic modulus, cohesion, friction angle and Poisson's ratio of the soil were estimated by the direct shear and uniaxial compression test results.

4.1. **Comparison between laboratory model test and numerical analysis results.** The load-settlement curves of the helical pile from laboratory model test and numerical analysis are shown in Figure 4. Despite slight difference between laboratory model test and numerical analysis results at the initial stage, overall similarity between the results is observed with increasing load or settlement. The difference in behavior may result from imperfect construction process of ground and installation of the helical pile in the laboratory test.

Table 1. Material properties of helical pile and soil

	Helical pile	Soil (Sand)
Material	Stainless steel	Silica sand
Density (t/m^3)	7.800	1.391
Elastic modulus (MPa)	190,000	15
Poisson's ratio	0.27	0.25
Friction angle (degree)		32.77
Dilation angle (degree)		2.77
Cohesion (kPa)		1.0

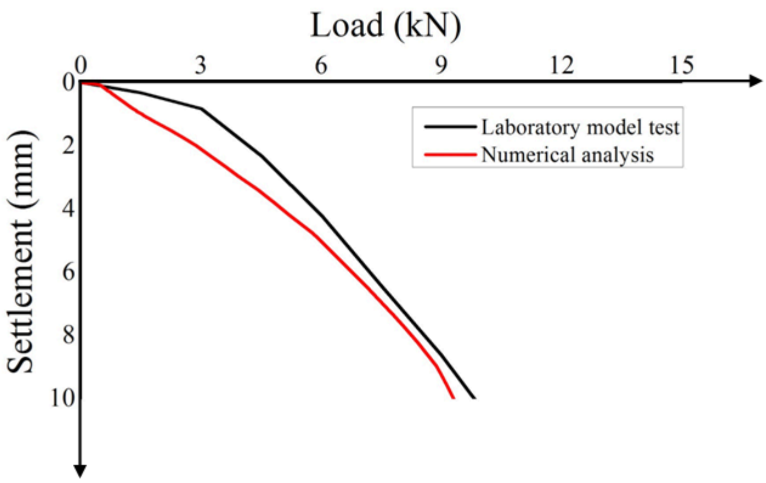
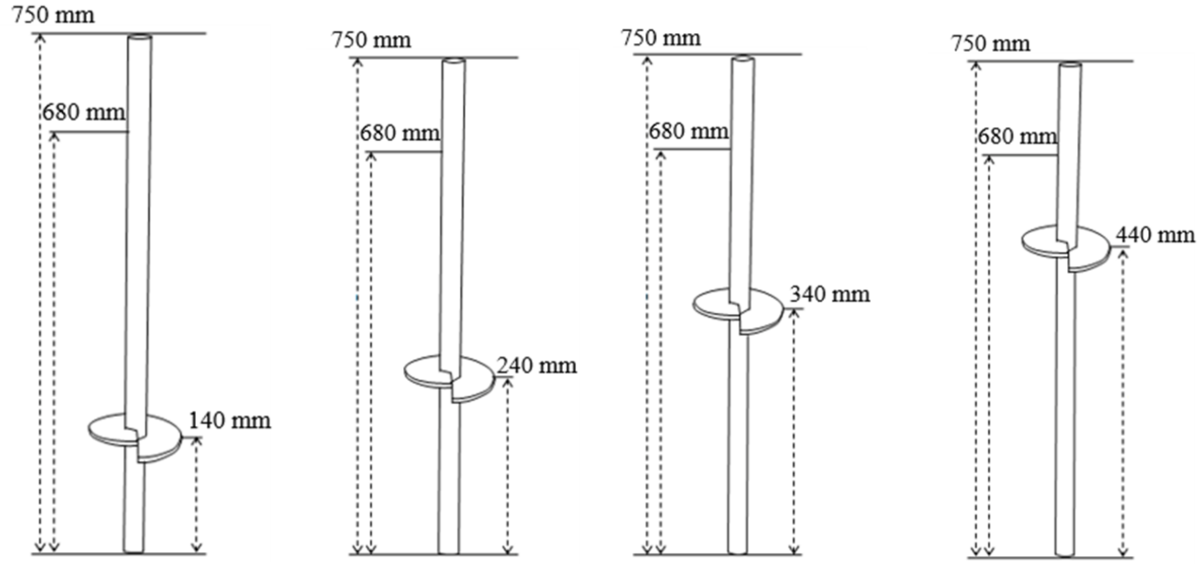


Figure 4. Load-settlement curves of numerical analysis and laboratory model tests

4.2. **Analysis of helical piles behavior varying helix location.** The central shaft of the helical pile has the length of 750 mm, the diameter of 50 mm, and the thickness of 1 mm. The diameter and thickness of the helix are 150 mm and 2 mm, respectively. The pitch of the helix was fixed at 50 mm. In order to analyze the behavior and the ultimate loads of the helical piles for different helix locations, the following analysis cases were planned (Figure 5): The locations of the helix, which is a variable in the case of the numerical analysis, are set at 140 mm (Figure 5(a)), 240 mm (Figure 5(b)), 340 mm (Figure 5(c)), and 440 mm (Figure 5(d)) from the bottom of the shaft.

The results of the analyses are shown and summarized in Figure 6 and Table 2, respectively. The ultimate loads of the helical piles were determined based on the criterion proposed by Kulhawy [9]. The ultimate load and the corresponding settlement tended to increase with increasing helix distance from the helical pile end. When the helix is attached to a higher level of central shaft, a larger bearing capacity is obtained. It is inferred that the uppermost helix starts to mobilize resistance earlier at a lower applied load, compared with the deeper helix locations.

The bending displacements of the helices were analyzed to determine the behavior of the helix according to the helix location (Figure 7). The analyses results are summarized in Table 3. The bending displacement can be obtained by calculation of the difference between displacements of the central shaft and the helix. For example, if the displacement of the central shaft is equal to the displacement of the helix, the bending displacement is zero. If the displacement difference between shaft and helix is large, the distortion of helix occurs. The results of the analysis according to Table 3 show that bending increases with decreasing helix distance from the helical pile end.



(a) Helix distance of 140 mm (b) Helix distance of 240 mm (c) Helix distance of 340 mm (d) Helix distance of 440 mm

FIGURE 5. Modeling of helical piles with helix location from bottom of pile

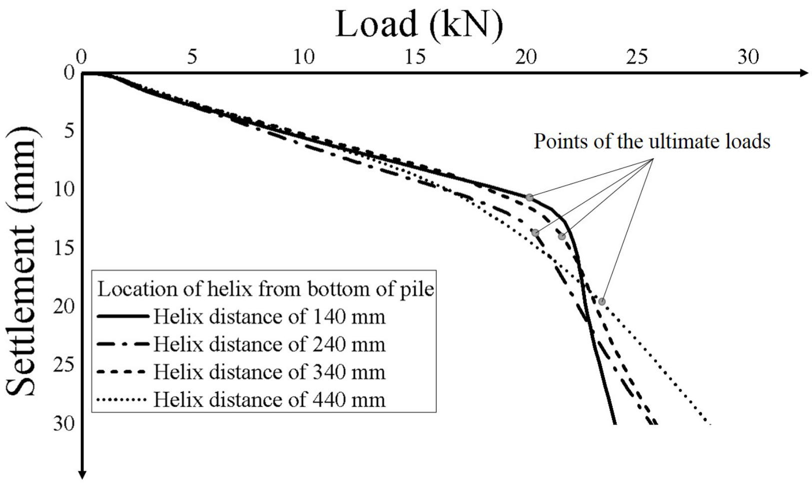


FIGURE 6. The load-settlement curves of helical piles varying helix locations

TABLE 2. Summary of numerical analyses results of helical piles varying helix locations

Cases	Location of helix from pile end (mm)	Ultimate load (kN)	Settlement (mm)
Case (a)	140	20.52	12.35
Case (b)	240	21.65	14.14
Case (c)	340	21.93	14.68
Case (d)	440	22.51	17.82

5. **Conclusions.** Numerical and experimental analyses were conducted to analyze the behavior of the helical piles varying the helix location. To ensure the reliability of the numerical analysis of the helical pile, the numerical analysis results were overall matched with the laboratory model test results by changing the soil parameters reasonably. Interesting results were found that the ultimate load increases and bending decreases with

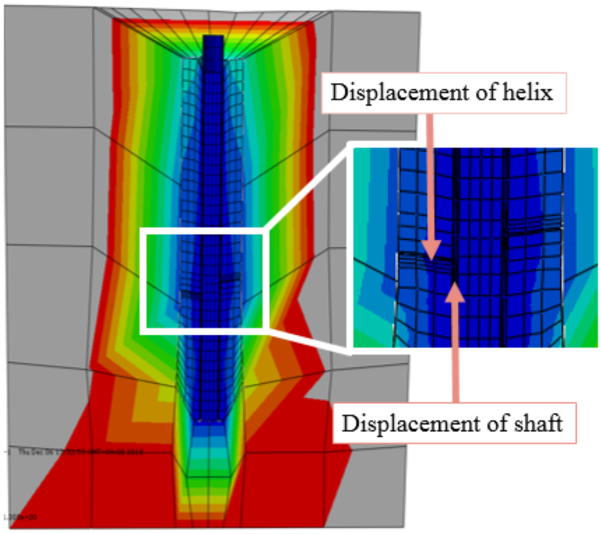


Figure 7. Displacement field near helix to assess behavior of soil and helix

Table 3. Bending displacements of helices at different helix locations

Cases	Location of helix from pile end (mm)	Displacement of helix (A) (mm)	Displacement of shaft (B) (mm)	Bending displacement (B − A) (mm)
Case (a)	140	36.27	39.57	3.30
Case (b)	240	24.90	27.98	3.08
Case (c)	340	24.32	27.08	2.74
Case (d)	440	20.68	23.39	2.71

increasing helix distance from the helical pile end. In this study, the single helix was implemented to assess local behavior of helical pile and to examine resistance contribution of each helix to the total helical pile resistance. The results in this study can be used as the preliminary research to investigate the behavior of the helical pile with multiple helices for future study.

Acknowledgment. This work was supported by the Incheon National University Research in 2017-2018.

REFERENCES

[1] K. J. Bird, R. R. Charpentier, D. L. Gautier, D. W. Houseknecht, T. R. Klett, J. K. Pitman, T. E. Moore, C. J. Schenk, M. E. Tennyson and C. R. Wandrey, *Circum-Arctic Resource Appraisal: Estimates of Undiscovered Oil and Gas North of the Arctic Circle*, No. 2008-3049, Geological Survey (US), 2008.
[2] N. P. Kurian and S. J. Shah, Studies on the behaviour of screw piles by the finite element method, *Canadian Geotechnical Journal*, vol.46, no.6, pp.627-638, 2009.
[3] J. Lee, D. Lee, H. Kim and H. Choi, Effect of configuration of shaft and helix plate on bearing capacity of moderate-size helical pile: I. test-bed construction and field loading test, *Journal of the Korean Geosynthetics Society*, vol.13, no.2, pp.31-39, 2014.
[4] J. Bak, K. Lee, B. Choi and D. Kim, Analysis of helical pile behavior in sands varying helix pitch based on numerical analysis results, *Journal of the Korean Geosynthetics Society*, vol.17, no.4, pp.29-40, 2018 (in Korean).
[5] SIMULIA, *6.14 Documentation Collection*, ABAQUS/CAE User's Manual, 2014.
[6] M. T. Davisson, High capacity piles, *Innovations in Foundation Construction: Proc. of the Lecture Series*, Illinois, 1973.
[7] M. W. O'Neill and L. C. Reese, *Drilled Shaft: Construction, Procedures and Design Methods*, FHWA-IF-99-025, 1999.

[8] B. Livneh and M. H. El Naggar, Axial testing and numerical modeling of square shaft helical piles under compressive and tensile loading, *Canadian Geotechnical Journal*, vol.45, no.8, pp.1142-1156, 2008.

[9] F. H. Kulhawy, On the axial behaviour of drilled foundations, *GeoSupport Conference 2004: Drilled Shafts, Micropiling, Deep Mixing, Remedial Methods, and Specialty*, Orlando, Florida, US, 2004.