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Development of Modified p-y Curves to Characterize the Lateral Resistance of Helical Piles

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ABSTRACT

Recognizing the pressing issues of global climate change, the government of South Korea continues its efforts to incorporate sustainable development strategies to push forward the goal of a carbon-neutral society by 2050. To achieve this feat, renewable and clean energy sources such as solar and wind power generation should become core energy generating systems. Shallow foundations due to its design feature of having a wide base, is excellent to transmit and distribute the structural loads of these renewable energy systems to the supporting soil. An ideal solution for most infrastructure projects, but is not environmental friendly. With this taken into consideration, an alternative solution is by helical pile foundation. This study develops a soil resistance multiplier to modify the soil resistance in areas covered by the zone of influence from the concept of p-multipliers originally used as a reduction factor for piles in-group action. The predicted lateral displacements of the various pile diameters generated through the numerical analysis method shows good agreement to the recorded field test results.

1. INTRODUCTION

Numerous research conducted on helical piles under lateral loading are present in literature. Among them are Prasad and Rao (1996) and Sakr (2009) who investigated the lateral capacity embedded in clay soils, Mittal et al. (2010) studied the static equilibrium of helical piles on cohesionless soils and Zhang (1999) carried out in-situ lateral load tests in both clay and sand. A common conclusion was reached that it exhibits greater lateral resistance compared to traditional single straight-shafted piles by observing its lateral displacement. Despite of the various research accounts pertaining to its lateral resistance, the lack of proper design criteria has impaired the confidence of

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the usage of helical piles for large-scale infrastructure projects.

To increase global trade and to develop residential and commercial areas in South Korea, land reclamation projects such as the Songdo international business district project and Saemangeum development project have been initiated in the country (Kim et al, 2020). The Saemangeum Onshore Solar Farm houses the pilot 100MV photovoltaic power generation project.

2. GEOTECHNICAL PROPERTIES

The Saemangeum Onshore Solar Site (100MW), nearby BB-6, BB-7 and BB-8 where Standard Penetration Test (SPT) was performed with blow counts varied between 5~6 blows per 300mm penetration until a depth of 3m indicates a loose fine grained silty sand layer, and blow counts 1~7 from depth 3.0 to 9.0m indicating a loose to very loose silty clay layer. The value taken for hammer correction is 60%, borehole and sampling factor taken as one. Rod length correction factor varies as depth of penetration increases as well as overburden correction. The helical pile embedment length is 3m and applying all these corrections results to the corrected values shown in Fig. 1

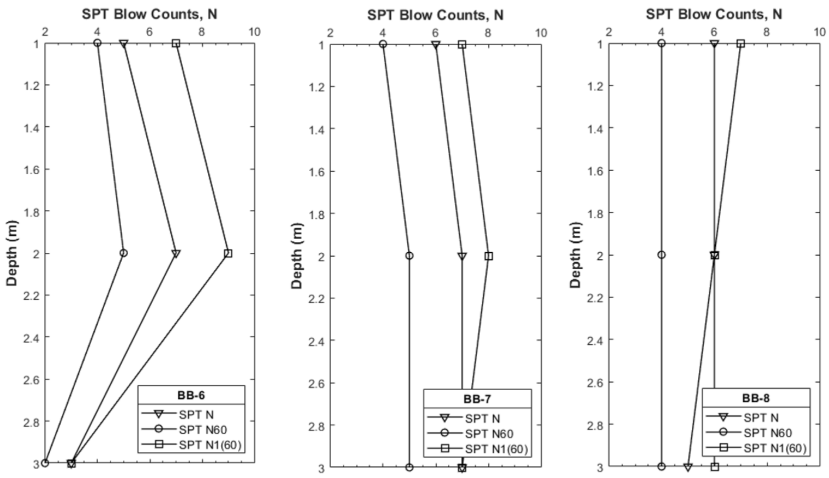


Fig. 1. SPT Blow Counts for BB-6, BB-7 and BB-8

The p-y curve parameters needed for sandy soils require the best values for friction angle and soil unit weight (Matlock and Reese, 1960). The friction angle (ϕ), of granular soils have been correlated with N_{60} or $(\mathrm{N}_1)_{60}$. $(\mathrm{N}_1)_{60}$ is the corrected value of N_{60} for granular soil affected by effective overburden pressure. Hatanaka and Uchida (1996) provided a simple correlation between ϕ and $(\mathrm{N}_1)_{60}$ that can be expressed as shown in Eq. 1.

$$\phi = \sqrt{20\,(\mathrm{N}_1)_{60}} + 20 \qquad \text{(Eq. 1)}$$

The saturated unit weight for sands, according to “The Foundation Engineering Handbook” by Manjriker Gunarante, is a function of N_{60} ranging from 15.7-19.6 $\mathrm{kN/m^3}$.

Using SPT Correlations Software—NovoSPT, correlations for friction angle and saturated unit weight for silty sand soils are obtained and plotted per 1m depth of penetration to the ground as shown in Fig. 2. For friction angle, Hatanaka and Uchida (1996) equation is used and Kulhawy and Mayne (1990) for the saturated unit weight.

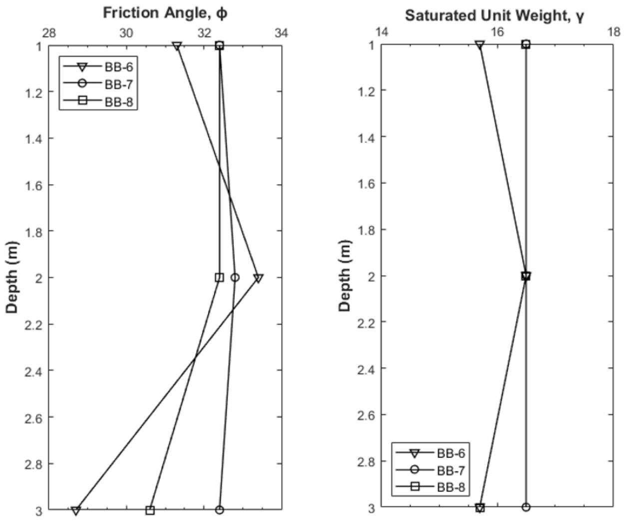


Fig. 2. Correlated friction angle and saturated unit weight for BB-6, BB-7 and BB-8

3. FULL SCALE LATERAL LOAD TEST

The lateral load tests were conducted in compliance to Procedure A (Standard Loading) and in accordance with the technical specifications stated in ASTM D3966-07, Standard Test Methods for Deep Foundations Under Lateral Loading.

The load applied on the test pile is delivered by a hydraulic jack which is approximately 0.2m above ground level connected to a H-beam which acts as a compression member and is then supported by the reaction pile. The compression member was securely fastened to eliminate the possibility of eccentric loading on the pile surface, it is important that the applied load pass the vertical central axis to avoid warping of the shaft section. An electronic load cell was used to monitor the load applied on the test pile. To measure the lateral displacement of the test pile, 2-LVDTs (linear variable differential transformer) were installed at 0.2m and 0.4m respectively, attached to one side of the pile and the other end attached to an external sturdy metal box.

The design load selected for the lateral test was 6.59kN, in compliance with the standard specifications stipulated on ASTM D3966-07 under procedure A. Lateral loads were applied in increments; each increment was maintained for a period of 10-20 minutes for most load steps except for the 200% increment held up for 60 minutes.

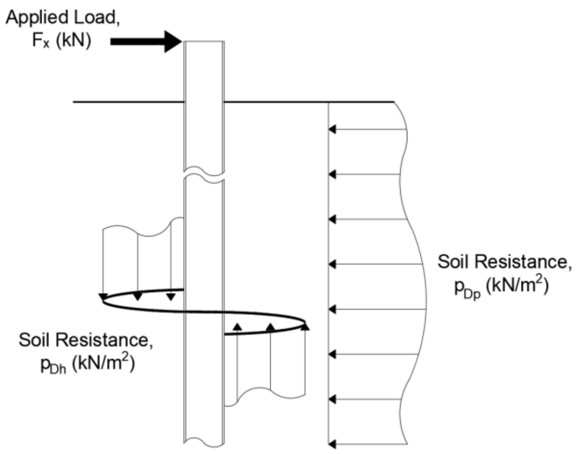
4. HPCAP PROGRAM

To analyze a laterally loaded helical pile, the geotechnical research team of Kunsan National University developed a computer program HPCAP (Helical Pile

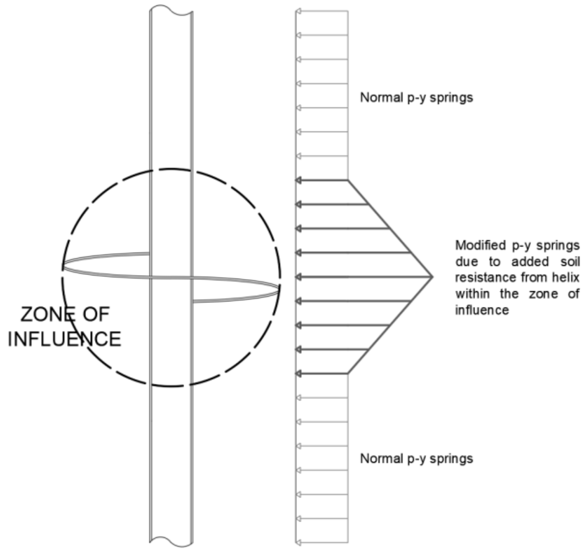
CAPacity) for its analysis. The computer program is capable to analyze both the axial and lateral capacity of the helical pile though modified non-linear curves from single piles. The solution is based on the finite difference method, which utilizes the fourth-order differential equation shown in Eq. 2 derived by Hetenyi (1946) and coded using Mathlab R2021a. The program uses five hundred nodes to accurately capture the behavior of the pile element and is also capable to analyze multilayered soil up to five layers.

$$EI\frac{d^4y}{dx^4} + P_x\frac{d^2y}{dx^2} = q + p \qquad \text{(Eq. 2)}$$

The original p-multiplier concept was used as a reduction factor for piles acting in group action (Fayyazi et al, 2012). In this study, the p-multiplier will be modified to account for the presence of the helices on the pile, not as a reduction factor but as a reinforcement factor, which is a function of helix diameter and zone of influence. As shown in Fig. 3a, the lateral resistance is offered not only by the shaft length and diameter, but also with the additional soil resistance coming from the helix blades. It is hypothesized that, the equilibrium of the forces acting on the helices will provide additional pile stiffness that will substantially decrease the lateral deflection of a helical pile compared to a normal pile. The traditional p-y springs will be modified using the p-multiplier concept by introducing a stiffness factor that accounts for the presence of the helices as a function of zone of influence as shown in Fig. 3b. The distribution of the modified p-y springs is linear, with maximum value near the center and gradually decreasing towards a minimum value bounded by the zone of influence. The minimum value is fixed at value = 1, which means that the traditional p-y springs are applied and is not outside the zone of influence.



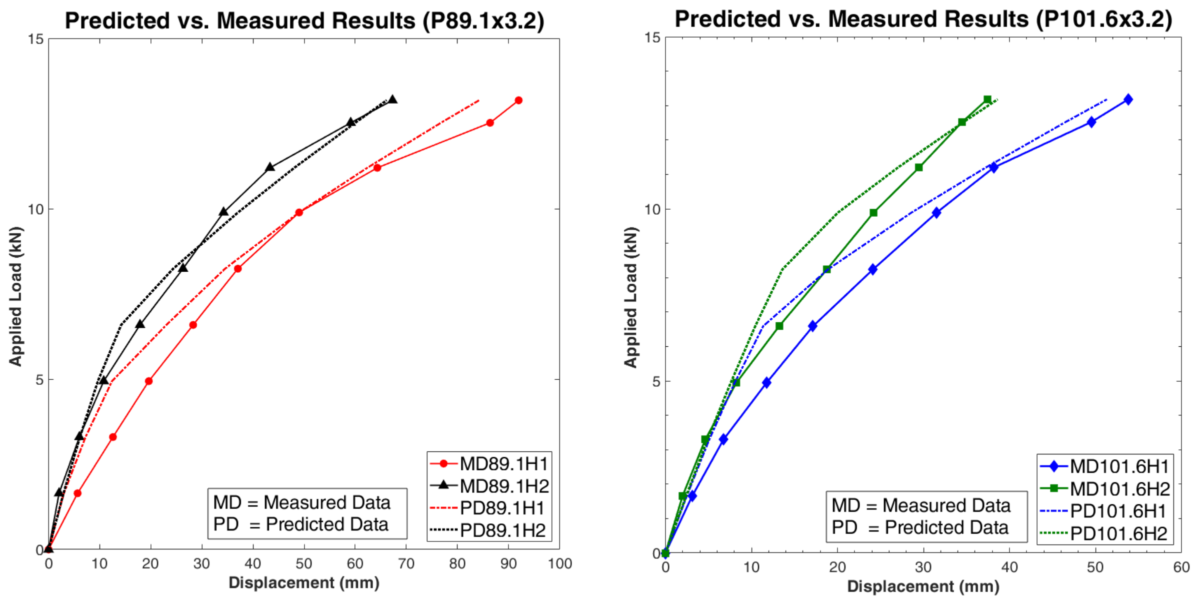
(a) Helical pile under lateral loading



(b) Distribution of p-y springs for helical piles

Fig. 3 Soil resistance concept for laterally loaded helical piles

Displayed in Fig. 4, the numerical analysis results are in good agreement with the measured field test data. MD refers to test data, while TP refers to predicted data. This proves that the numerical program predicts the lateral resistance of helical piles accurately.



(a) Pile Diameter 89.1mm x 3.2mm (t) (b) Pile Diameter 101.6mm x 3.2mm (t)

Fig. 4. Predicted versus Measured Test results

5. CONCLUSION

Presented in this study is the development of modified p-y curves to characterize the lateral resistance of single helical piles embedded in reclaimed soils. A numerical method of analysis is proposed and demonstrated to account the presence of helices attached to the central shaft of a single pile and its significance to the lateral resistance of a laterally loaded helical pile. The method is based on the theory of a Winkler foundation, an embedded pile element connected to the soil medium via non-linear springs supplemented by the concept of modified p-multipliers to account the presence of helices around the central shaft, originally used for pile group analyses. The p-y curves along the embedded pile length are modified using the concept of p-multipliers to increase the stiffness of the areas under the zone of influence. The input soil properties are obtained and correlated from SPT-N in situ tests. The soil unit weight used for analysis must be the effective unit weight.

Established in this study are the following observations and key points necessary to determine the behavior of a laterally loaded helical pile:

1. The zone of influence of a helical plate is 1.75 times the diameter of the helix plate.

2. The pile coefficient differs from various pile shaft diameters and is a function of the ratio length of embedment to the pile shaft diameter.
3. The stiffness offered by the helical plate for the lateral resistance of a helical pile is linearly increasing and not constant. With maximum stiffness offered at the central location of the helix position and linearly decreasing away from the center to a minimum value of one, which implies the boundary of the zone of influence is reached.

The predicted lateral displacements of the various pile diameters generated through the numerical analysis method shows good agreement to the recorded field test results.

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