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ANALYSIS OF THE PERFORMANCE OF HELICAL PILES UNDER VARIOUS LOAD AND GEOMETRY CONDITIONS

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ABSTRACT

The study by [7] analyzed the load capacity of moderately sized helical piles, considering configurations such as shaft diameter, plate diameter, and penetration depth. The results showed that increasing the shaft diameter and modifying the helical plates significantly improved load capacity. The configuration of the plates had a greater impact on performance than the shaft diameter. Other studies complemented these findings, such as [8], which emphasized the importance of plate position for pull-out resistance. Study [9] highlighted the impact of helix pitch on lateral load capacity, while [10] examined the spacing between the helices and its effect on load distribution. Helix deflection, as shown by [11], was also a critical factor in pile performance. Additionally, studies on pile groups [13] and pressure grouted helical piles [14] provided valuable insights for optimizing the design of these foundations. Research by [15] on combined loads revealed a positive correlation between helix diameter and load capacity. Overall, the studies demonstrated that geometric factors and soil characteristics are essential for optimizing the performance of helical piles, especially in applications in challenging environments like offshore wind platforms.

I. INTRODUCTION

The load-bearing capacity of helical piles is strongly influenced by various factors, with installation depth and helix diameter being two of the most significant parameters. The depth determines the reach of the piles into the soil, directly affecting the interaction between the soil and the pile. The helix diameter, on the other hand, is related to the area of contact between the pile and the soil, which impacts the load transfer capacity and pullout resistance.

The depth of the helical pile influences both compressive and tensile resistance. The deeper the pile, the greater the resistance provided by the soil in deeper layers, which can increase the load-bearing capacity. However, the depth must also be optimized, as very deep piles can result in higher installation costs and logistical complications. Choosing the ideal depth depends on the soil type, layer distribution, and load conditions, making it essential to consider these variables in foundation design to maximize pile efficiency.

On the other hand, the helix diameter has a direct impact on the area of contact between the pile and the soil. Piles with larger helices generate a greater area of resistance to both pullout and compression, resulting in higher load-bearing capacity, especially in looser soils or conditions of high liquefaction potential.

However, increasing the helix diameter can also lead to higher costs and challenges during installation, such as requiring more torque for drilling. Therefore, balancing the diameter with other pile parameters is crucial to ensure good performance without compromising the economic feasibility of the project.

Thus, the interaction between the depth and the helix diameter is crucial for determining the load-bearing capacity of helical piles. Adjusting these parameters, taking into account local geotechnical conditions and project requirements, allows for the optimization of foundation performance, ensuring greater stability and durability.

II. THEORETICAL REFERENCE

Helical piles have gained recognition as an advanced and versatile foundation solution in both onshore and offshore engineering applications, providing numerous advantages over traditional pile systems. They are particularly appreciated for their ease of installation, minimal environmental impact, and impressive load-bearing capacity. One of the most critical aspects affecting the performance of helical piles is their bearing capacity, which is significantly influenced by various design parameters. Among these, the depth of installation and the diameter of the helical plates are considered key factors that govern the efficiency of these foundations.

According to [1], helical piles are defined as a type of pile foundation equipped with one or more helices that are attached to the shaft at specific intervals. These helices serve to enhance the load distribution and resistance of the pile by engaging a larger volume of soil compared to conventional piles. The geometry of the helical plates, including their diameter and spacing, plays a direct role in influencing the load transfer mechanism, which ultimately affects the overall bearing capacity of the pile. The arrangement of the helix diameters is particularly important; experimental studies by [1] showed that a progressive increase in helix diameter, such as 6 cm, 8 cm, and 10 cm from top to bottom, leads to a more effective load transfer and improved bearing capacity compared to a decreasing diameter configuration. This progressive design allows for a more optimal distribution of end-bearing and shaft friction contributions, resulting in superior overall performance in comparison to other configurations.

Further studies have examined the influence of the number of helices and the spacing between them on the bearing capacity and failure mechanisms of helical piles. In a numerical study conducted by [2], the effects of helix diameter and spacing were investigated, revealing that both parameters play a critical role in the transition between different failure modes, such as cylindrical shear to individual bearing failure. When the spacing-to-diameter ratio approached two, the pile transitioned to an individual bearing failure mechanism, which significantly increased the efficiency of the pile. This transition was shown to enhance the load-bearing capacity, particularly in piles with a larger number of helices and greater spacing. The study further emphasized that conventional methods of calculating bearing capacity often fail to account for these geometric parameters, suggesting the need for advanced modeling techniques to more accurately predict the behavior of helical piles. These findings underscore the importance of considering the geometric configuration of helical plates when designing pile foundations.

Depth is another critical factor that plays an essential role in optimizing the performance of helical piles. As the pile is embedded deeper into the soil, it engages denser and more stable soil strata, thereby enhancing both compressive and tensile resistance. Studies by [3] have highlighted the importance of increasing the embedded depth of helical piles, especially in loose sandy soils, where deeper embedment leads to improved interaction between the helix and surrounding soil. This deeper engagement helps distribute the load more efficiently, contributing to enhanced pile stability and reduced settlement. Numerical simulations have corroborated these findings, revealing that deeper installation depths result in lower displacement and improved load-carrying capabilities, particularly when combined with optimal helix spacing and diameter configurations. In these cases, the pile's ability to resist both vertical and lateral forces is enhanced, making them more reliable and effective for use in a variety of soil conditions.

Additionally, research by [4] examined the impact of the number of helices on the bearing capacity of helical piles. This study involved static loading tests on different types of helical piles, including single shaft piles, piles with identical diameter helices, and piles with helices of varying diameters. The study concluded that adding more helices significantly increased the bearing capacity, with helical piles exhibiting a 252% to 369% increase in capacity compared to the single shaft. Furthermore, the research compared the performance of helical piles with the same diameter helices to those with varying diameters, highlighting how the configuration of helices can further influence pile performance. These findings are significant for understanding how to optimize the number and arrangement of helices in order to maximize the load-bearing capabilities of helical piles.

The performance of helical piles in partially saturated soils has been a subject of limited research compared to their performance in dry or fully saturated conditions. The study by [5] focused on this gap by testing small-scale models of steel piles with single, double, and triple helices embedded in cohesionless soils under varying soil saturation conditions. The results indicated that helical piles in partially saturated soils exhibited an increased bearing capacity, ranging from 1.5 to 1.8 times greater than that of piles in fully saturated soils. Additionally, the study demonstrated that the addition of helices significantly improved bearing capacity, with single, double, and triple helix configurations showing improvements of 33.3%, 45.0%, and 108.3%, respectively, over the shaft pile only. This research underscores the potential advantages of using helical piles in soils with intermediate levels of saturation, offering insights into their performance in real-world conditions that may not always be fully saturated or dry.

Lastly, a study conducted by [6] explored the behavior of helical piles in Iraq using the finite element method. This study used Plaxis 3D software to model the geometry of helical piles and performed parametric analyses to examine the effects of various factors such as the number of helices, spacing between helices, helix diameter, and helix configuration. The results showed that increasing the number of helices significantly enhanced the bearing capacity, with the maximum pile capacity for a three-helix configuration increasing by 115.4% compared to the case without helices. The study also found that increasing the spacing between the helices led to a 130.7% increase in pile capacity when the spacing was increased from 0.5D to 3.5D. Furthermore, the study highlighted that displacement values decreased with increasing spacing between the helices, which suggests that optimal helix spacing can improve pile performance by reducing settlement.

Overall, the literature consistently highlights the importance of geometric factors such as helix diameter, pile depth, and helix configuration in determining the bearing capacity of helical piles. These factors, when optimized according to the specific soil conditions and load requirements, contribute significantly to the stability and efficiency of helical pile foundations. The studies also emphasize the need for advanced modeling techniques and experimental validation to accurately predict the behavior of helical piles, ensuring their reliable performance in a variety of engineering applications.

III. MATERIALS AND METHODS

.The methodology adopted in this study was primarily based on a bibliographic research approach, aimed at gathering and analyzing the main studies and scientific articles that address the behavior and performance of helical piles. The research was conducted across major scientific databases such as Google

Scholar, Scopus, Science Direct, and Web of Science, focusing on recent and relevant publications on the subject. The selection of articles was made with great care, considering the quality of the publications, the reputation of the journals, and the relevance of the studies regarding the load-bearing capacity and performance of helical piles under various soil conditions. Additionally, research analyzing different design parameters, such as helix diameter, embedment depth, and the number of helices, was included.

This study is characterized as exploratory and qualitative research, focusing on the analysis of secondary data from previously conducted studies. The exploratory research allows for an in-depth examination of various aspects of the behavior of helical piles, including variables such as helix geometry and installation conditions, providing a broad view of the different analysis methodologies and experimental tests applied to the subject. Furthermore, the qualitative nature of the research enabled the identification of key trends and gaps in the literature on the performance of helical piles, highlighting the importance of specific parameters, such as helix configuration and installation depth, for the success of these foundations in various soil types.

Finally, the bibliographic research conducted was not limited to a simple data collection but involved a critical and comparative analysis of the methodologies used in the selected studies. Not only were the results obtained evaluated, but also the experimental and numerical approaches employed to simulate the loading conditions and behavior of helical piles in different scenarios. This analysis allowed for the identification of best practices and the suggestion of recommendations for the application of helical piles in foundation projects, considering the particularities of sandy, cohesive, and partially saturated soils, among others.

IV. RESULTS AND DISCUSSIONS

The study conducted by [7] aimed to estimate the load capacity of moderately sized helical piles, considering various configurations such as shaft diameter, plate configuration, and penetration depth. Six different types of helical piles were constructed with shaft diameters ranging from 73 mm to 114 mm, support plate diameters varying from 400 mm to 250 mm, and different numbers of helical plates (one or three). Field loading tests were carried out to assess the impact of these configurations on the load capacity of the helical piles. The results indicated that both the increase in shaft diameter and changes in the number or diameter of the helical plates significantly improved the load capacity of the pile. Notably, the configuration of the helical plates was found to be more critical than the shaft diameter in enhancing the pile's load capacity.

In another study, [8] analyzed the load capacity and resistance to pull-out of helical piles. The research used both model tests and numerical modeling to investigate the impact of factors such as the number, size, and position of the helices on pile performance. The results showed that increasing the number and diameter of the helices improved both the load capacity and pull-out resistance of the pile. Furthermore, when the helix was installed near the base of the pile, performance was significantly improved. The study also included an economic analysis, highlighting the importance of considering the installation position of the helix to optimize performance and cost-effectiveness of the helical piles. Based on these findings, the research suggested that the helical pile design could be substantially enhanced by adjusting these parameters.

The research conducted by [9] focused on the influence of thread pitch and helix diameter on the lateral load capacity of a single-helix helical pile, with an emphasis on installation effects. This study, which included laboratory tests, revealed that the helix diameter had a negligible effect on the lateral load capacity of the pile. However, the thread pitch significantly influenced pile performance due to the increased soil disturbance around the pile. The results from the single-helix pile were compared with those of steel tube piles and other foundation methods, offering valuable insights into the behavior of helical piles for applications such as offshore wind turbine foundations. The study reinforced the importance of considering thread pitch when designing helical piles for optimal lateral load performance.

In another study, [10] investigated the effects of helix spacing on the behavior of helical piles through compressive axial load tests on instrumented piles with strain gauges. The test piles, which had two helices with variable spacing between them, were installed in a homogeneous clay layer with an average undrained shear strength of 65 kPa. Failure mechanisms of the piles were determined by comparing the measured load distributions with those predicted by cylindrical shear and individual load models. The results indicated that for piles with a helix spacing-to-diameter ratio of 1.5 or greater, the individual load model dominated the pile behavior. The study also evaluated the load capacity factor of the helices and the shaft adhesion factor, comparing measured resistances with theoretical estimates, and concluded that the recalculated load capacity and adhesion factors were lower than those typically used in helical pile design. Additionally, the research analyzed the impact of the soil setup on pile behavior by comparing load and settlement responses of piles tested immediately after installation with those tested days later.

Another relevant study by [11] investigated the effect of helix deflection on the load-settlement behavior and ultimate load capacity of helical piles. Recognizing that these piles have greater ultimate load capacity due to the presence of larger helices relative to the central shaft, the study aimed to understand the limitations imposed by helix deformation under high load conditions. To this end, load tests were performed on models with different helix-to-shaft diameter ratios and varying helix thicknesses to assess the behavior of the piles with and without significant deformations. The tests were conducted on dense, dry Toyoura sand. The results showed that helix deflection began to negatively affect the load-settlement response once it exceeded a critical value. It was further observed that the ratio of critical deflection to projection length decreased as the helix-to-shaft diameter ratio increased, and this relationship was presented in the study. Furthermore, Roark's formula for flat circular plates under uniform load on a very small area with fixed edges showed good agreement with the measured helix deflection, enabling the development of a modified equation to estimate the optimal helix thickness based on the critical deflection.

The study conducted by [12] investigated the geotechnical behavior of helical piles through experiments using the frustum confining vessel (FCV) method. This device was chosen due to its special geometry, which allows for a linear distribution of vertical and lateral stresses along its height, effectively simulating field conditions. The research focused on small-scale helical piles made of 4 mm thick steel plates, with a shaft diameter of 32 mm and helices ranging from 64 to 89 mm in diameter. The results indicated that the performance of helical piles strongly depends on geometric characteristics such as the spacing ratio between helices (S/D) and helix diameter. It was observed that failure could occur either near the individual helices or along a cylindrical shear surface, directly affecting the load capacity. Additionally, the helical piles demonstrated the ability to support axial uplift loads comparable to conventional steel piles with the same helix diameter, and their compressive load capacity was sufficient to classify them as medium-capacity piles.

In the study conducted by [13], the results of a field load testing program were presented to investigate the group effects on the pull-out capacity of deep single-helix helical piles installed in sand. Due to their high pull-out capacity and quiet installation process, helical piles have become a viable alternative to conventional deep foundations, especially in offshore applications for renewable energy structures. Considering new applications in marine environments, the use of helical pile groups to resist structural loads is being evaluated. While it is known that group interaction effects occur in this type of foundation, there is still a lack of field data on performance in sand under pull-out loading. The study involved the installation and load testing of round-shaft piles with a 152 mm diameter, tested individually and in groups, embedded at depths equivalent to 12 and 18 times the helix diameter. Variables such as pile spacing, group configuration (number of piles), and soil strength (determined by CPT tests) were analyzed. The results showed group efficiencies ranging from 0.6 to 1.0 for horizontal spacings of 2 to 3 times the helix diameter, in sands with friction angles between 39° and 44°. The obtained data are also valuable for calibrating and validating numerical models to further analyze group interactions in helical pile systems.

The study by [14] investigated the performance of pressure grouted helical piles (PGHPs), which are reinforced piles installed using the simultaneous drilling and grouting technique. This method promotes the formation of a soil-cement column around the pile, whose geometry is influenced by various installation parameters, such as the number and size of the helices and the drilling speed. To analyze the axial behavior of these piles and the load transfer mechanism, small-scale model tests were conducted in clay. The results showed that the final compressive load capacity of PGHPs was between 260% and 293% greater than that of ungrouted helical piles. Additionally, the load capacity increased proportionally with the number and size of the helices but decreased with an increase in drilling speed. The adhesion between the soil-cement column and the surrounding clay varied between 0.8 and 1.2, and the diameter of the cement column was approximately 1.26 to 1.35 times the size of the helix. These results demonstrate the effectiveness of the simultaneous drilling and grouting technique in improving the axial performance of helical piles compared to traditional ungrouted piles.

The study conducted by [15] investigated the performance of hollow-shaft and single-helix helical piles under combined loading, a common condition in offshore structures due to the simultaneous action of wind, waves, currents, and the structure's own weight. Although these piles are widely used in onshore foundations due to their quick installation and high load capacity, their behavior under combined loading is not well understood. To address this gap, the study used finite element method (FEM) analysis in 561 different cases, considering various ratios of helix to shaft diameter, as well as helix positions. The results showed a positive linear correlation between the helix-to-shaft diameter ratio and load capacity, while the influence of helix position exhibited a more complex and nonlinear behavior. Based on these analyses, a predictive formula was developed to estimate the load capacity of helical piles under combined loading, significantly contributing to their application as an alternative to monopile foundations in offshore wind turbines.

Finally, the study by [16] investigated the uplift capacity of helical piles, focusing on the effect of helix size. Helical piles, widely used for low-load applications, consist of helical plates attached to a central shaft, with both the shaft and helix diameters varying in size. When installed in appropriate soil layers, helical piles can resist both compressive and tensile loads. The total capacity of the pile is defined as the sum of the capacities of each individual helical plate. This study specifically explored the influence of helix size on uplift capacity, performing uplift load tests on two types of helical piles — with uniform and variable-sized plates — installed in clayey soil. The helix diameters used in the tests were 15 cm, 20 cm, and 25 cm, with a spacing ratio (S/D) of less than 3 for the larger helix diameters. The results revealed that variations in helix size significantly influenced the uplift capacity, with capacity increasing by up to 50% as the helix diameter increased. This study provides valuable insights into the effect of helix size on the uplift capacity of helical piles.

The results presented by the studies discussed above provide a comprehensive view of the performance of helical piles under various loading conditions and geometric variables. While each study focused on different aspects of helical piles, they all converge on the idea that the geometric configuration and soil characteristics have a significant impact on the load-bearing capacity and behavior of the piles.

The study by [7] emphasizes the importance of the configuration of the helical plates, showing that both an increase in the shaft diameter and variations in the number or diameter of the helical plates result in significant improvements in load capacity. However, a crucial finding was the observation that the configuration of the helical plates is more critical to the pile's performance than the shaft diameter, an important insight for the design of helical piles in terms of optimizing load capacity.

In a complementary study, [8] not only investigated the load capacity but also the pull-out resistance of helical piles, analyzing how the number and size of the helices influence these properties. The study also highlighted the importance of the helix position to improve pile performance, emphasizing that installing the helices closer to the base resulted in significant improvements in pull-out resistance and load capacity. This suggests that optimizing the design of piles should consider the position of the helices, in addition to their number and size, for optimal performance under different soil conditions.

The research by [9], in turn, revealed that the pitch of the screw has a more significant impact on the lateral load capacity of the pile than the helix diameter. This study is particularly relevant for applications in terrains with high lateral loads, such as offshore wind farm foundations, where helical piles are frequently used. The discovery that increasing the pitch results in greater soil disturbance and consequently better performance under lateral load provides valuable guidance for the design of these foundations.

Another relevant study by [10] investigated the effect of helix spacing on the behavior of helical piles. The results indicated that the pile behavior can be more accurately modeled when the ratio of helix spacing to helix diameter is greater than 1.5. This finding suggests that optimizing the spacing between helices can directly influence load distribution and performance efficiency, especially in homogeneous soil conditions like clay.

Studies by [11] and [12] analyzed the deflection of the helices and the impact of geometric characteristics on the load capacity of helical piles. Study [11] concluded that excessive deflection of the helices can compromise pile performance, with important implications for the design of the helices and the sizing of their thicknesses. On the other hand, [12] investigated the geometric characteristics of small-scale piles, revealing that failure in helical piles can occur both near individual helices and along a cylindrical shear surface, reinforcing the importance of helix distribution and size.

Regarding the performance of helical piles in groups, study [13] provided valuable insights into the group effects on the performance of helical piles installed in sand. The research indicated that group efficiencies vary with pile spacing and soil resistance, with direct implications for the design of foundations in high-traction environments, such as offshore structures.

Additionally, the study by [14] on pressure grouted helical piles (PGHPs) highlighted the impact of the grouting technique on pile load capacity, showing that combining larger helices with grouting can result in a substantial increase in load capacity. This offers an interesting alternative to enhance the performance of helical piles in soils with low resistance.

Finally, the study by [15] addressed combined loading, an important condition for offshore structures, showing that the ratio of helix diameter to shaft diameter has a positive correlation with load capacity, while the position of the helices has a more complex effect. These findings are essential for the design of helical piles for applications in structures subjected to multiple types of simultaneous load.

In summary, the studies discussed demonstrate the importance of a detailed analysis of geometric variables, soil characteristics, and group effects on helical piles, highlighting that pile design should be carefully adjusted to optimize performance under different loading and soil conditions. The combination of different optimization strategies, such as adjusting the number and size of the helices, modifying the screw pitch, and considering the spacing between the helices, is essential to ensure the success of helical piles in modern foundation projects, including those in challenging environments such as offshore wind farms and other submerged structures.

V. CONCLUSIONS

The research on the performance of helical piles under various load conditions and geometric characteristics reveals that factors such as shaft diameter, helix configuration, and penetration depth play crucial roles in the load capacity of these piles. The studies showed that both increasing the shaft diameter and modifying the number and size of the helical plates significantly improved load capacity. However, the configuration of the helical plates was found to be more important than the shaft diameter in optimizing the pile's load-bearing capacity.

Additionally, the results indicated that positioning the helical plates near the base of the pile improves pull-out resistance, which is an important consideration for designs in more challenging soils. The research also highlighted the importance of the spacing distribution between the helical plates and the shaft thickness, as factors that can negatively impact pile performance if not properly dimensioned.

In specific conditions, such as soils subject to high lateral loads, modifying the helix pitch was crucial to improving lateral load capacity. This finding is particularly relevant for the use of helical piles in offshore wind turbine foundations, where lateral load conditions dominate.

Studies on helix deflection indicated that excessive deformations could compromise pile efficiency, emphasizing the need to consider critical deflection limits during design. The combination of different optimization strategies, such as adjusting the number and size of the helical plates, and a detailed analysis of group interactions, ensures more efficient and safer performance.

In summary, these studies provide valuable insights into improving the design of helical piles, being essential for applications in challenging environments, such as offshore platforms and submerged structures. Ongoing research on the behavior of helical piles will allow for the adaptation of foundations to different soil types and load conditions.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Eliomar Gotardi Pessoa.
Methodology: Eliomar Gotardi Pessoa.
Investigation: Eliomar Gotardi Pessoa.
Discussion of results: Eliomar Gotardi Pessoa.
Writing – Original Draft: Eliomar Gotardi Pessoa.
Writing – Review and Editing: Eliomar Gotardi Pessoa.
Resources: Eliomar Gotardi Pessoa.
Supervision: Eliomar Gotardi Pessoa.
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