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Numerical Modeling of Helical Piles: A State-of-the-Art Literature Review

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Abstract- This paper presents an encompassing literature review on the utilization of numerical modeling techniques in the domain of helical pile engineering. The review showcases the progression and insights gained through numerical methodologies, providing valuable perspectives on helical pile behavior under varying conditions. The integration of Finite Element Analysis and other numerical approaches enables accurate prediction of load-bearing capacities, deformation characteristics, and failure mechanisms. Additionally, the review highlights the synergy between numerical simulations and experimental validation, emphasizing their potential to refine design guidelines. By addressing factors like soil heterogeneity and dynamic effects, numerical models contribute substantially to optimizing helical pile design. Although the field has advanced, ongoing research is essential to further enhance the accuracy and applicability of these models, ultimately facilitating the efficient and sustainable use of helical piles in diverse geotechnical scenarios.

Keywords- Numerical modelling, Literature review, helical piles, PLAXIS 3D.

I. INTRODUCTION

A circular or square shaft that is fixed with one or more helices forms the basis of a deep foundation structure known as a helical pile. During the latter half of the 19th century, helical piles emerged as a significant breakthrough in foundation engineering and are commonly employed by engineers and designers [1], a helical/screw pile consists of a cylindrical shaft having attached helical plates that have larger diameters compared to the shaft. These helical plates enable the pile to possess both end bearing and shaft frictional capabilities, ensuring it can effectively bear loads and achieve the desired bearing capacity [2].

Alexander Mitchell is credited with inventing helical piles, also known as screw piles or helical anchors, in 1836. Although the concept of helical piles existed earlier, with some evidence of their use dating back to the 19th century, it was not until the mid-20th century that they were specifically developed and widely adopted for foundation applications. Helical piles are composed of helical-shaped steel plates or shafts that are rotated into the ground to provide support for foundations. They have become a common choice in construction projects for reinforcing various structures like buildings, bridges, and other foundation types. It's important to note that while Alexander Mitchell made significant contributions to civil engineering, his focus was primarily on screw-pile lighthouse foundations rather than helical piles for building foundations. Then, until 1985 [2], Helical piles were employed for anchoring purposes. Numerous loads, including wind load, earthquake, uneven earth pressure, Pipe-line thrust, and load eccentricity, have an impact on the foundation. Helical piles will be utilized in place of other conventional piles to resist these loads [3].

In the past, researchers have analyzed the piles through numerical models. Numerous numerical analyses of the helical piles were conducted [1-6] in majority of those investigations, the helical blades were thought to be flat discs [7-9]. Few perimeters are covered by research that accommodate its appropriate geometry [10-11]. Through numerical study we can apply the effects of parameters on bearing capacity, experimentally this study is difficult to conduct. Software like PLAXIS, ABAQUS and L-PILE were used to model piles numerically. Helical piles represent a subset of deep foundation piles used to provide support for foundations placed under marine loads, serving in both tension and compression roles. Moreover, they find application as lateral tension elements, lending support to retaining walls and earth embankments to safeguard against potential collapses. The structural configuration of a helical pile involves helical plates featuring a diameter exceeding that of the central shaft. These plates are affixed to the hollow shaft and incorporate specialized helix plates, contributing to both end-bearing capability and shaft frictional capacities. This intricate arrangement culminates in the achievement of the overall bearing capacity [12].

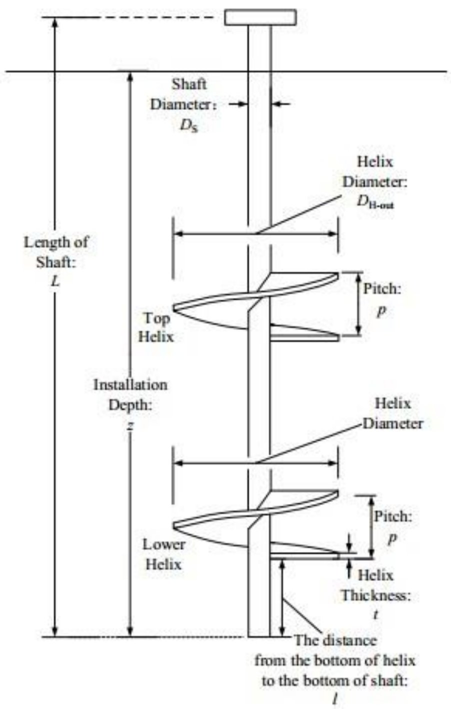


Fig. 1 The definitions of Helical Pile [13]

Construction of both lightly and strongly loaded structures can be done using the deep foundation technology of the helical pile because it is innovative, quick, economical, and not harmful to the environment. In recent times, there has been a notable rise in the utilization of helical anchors, both offshore and onshore, primarily due to the numerous benefits they offer in comparison to traditional piles. The increased adoption is primarily attributed to the advantages arising from the installation process. The method of installing helical anchors from the ground surface includes substantial plastic deformation, contact, and material separation, making it unsuitable for modeling through conventional finite element approaches. To address this challenge, the assumption is made that the anchor is already partially embedded in the soil, leading to the omission of the initial penetration phase in the installation process [14].

In spite of the various benefits linked to this particular foundation type, certain gaps in understanding still persist. Within the existing body of literature, it's commonplace to come across discussions about the notable disparities between theoretically predicted outcomes and the results obtained from load tests. Consequently, this discrepancy has the potential to negate the economic viability of this solution, as a reliable design hinges on the execution of load tests across numerous piles. As a result, there exists a pressing necessity to undertake additional research into this foundation type, aiming to discover more precise techniques for assessing pile capacity. Other names for helical piles include screw foundations, helical piers, and helical anchors. Although some naming techniques may have slight variations, these names are frequently used interchangeably. The fundamental idea behind each of these remains the same, at all times. All the research studies' literature reviews are consolidated in the final part of this document, presented in a tabular format encompassing comprehensive particulars.

II. IMPORTANCE

There is no restriction on the load because helical pile has ability to bear the load immediately after the construction. The transportation of this type pile is not a difficult issue it transfers from one to another place easily. Soil condition and whether condition do not affect the helical pile installation [15]. Both lateral and compressive helical piles provide the highest level of resistance compared to other types of piles. [16]. As foundations for offshore wind farms (which generate clean and renewable energy) [17], bridges, broken building foundations, residential and commercial buildings, and dangerous constructions [18], helical piles excel in a wide range of practical applications. The utilization of helical piles for supporting transmission towers is experiencing a constant increase. A transmission tower has been erected atop a concrete pile, which is reinforced by multiple helical piles. These benefits include cost effectiveness, the ability to withstand loads right away after installation, a lack of vibration during installation, the use of fewer workers and equipment, the light weight of construction machinery, and the simplicity of installation in all types of weather. The helical piles do not affect the near located building and its installation is free from vibration so that's why it is friendly related to environment [15].

III. TESTING OF HELICAL PILES IN THE FIELD

Many of researchers analyzed the helical piles through its lateral capacity and compressive capacity. The testing of the helical pile in the field is very challenging and not easy because it required the huge cost and trained labors Extensive field testing was done to determine the longitudinal and axial capabilities of helical piles. These tests played a vital role in assessing and understanding the performance of helical piles. Türedi and Örnek (2019) performed the test on the screw pile to examine the helical pile's response to compressive capacity in sandy soil. Thirty laboratory model tests conducted on the helical pile for changing the helical plate diameter, number of helices, helix diameter and spacing ratios s/d. They further conclude that using double helical piles instead of single helical piles results in twice the capacity. Unlike the non-linear compressive load increase, the diameter of the pile's helix increases proportionally. This implies that when the compressive load increases threefold, the helix diameter doubles. Detail of helical pile and model helical pile as given in the (Fig-2)

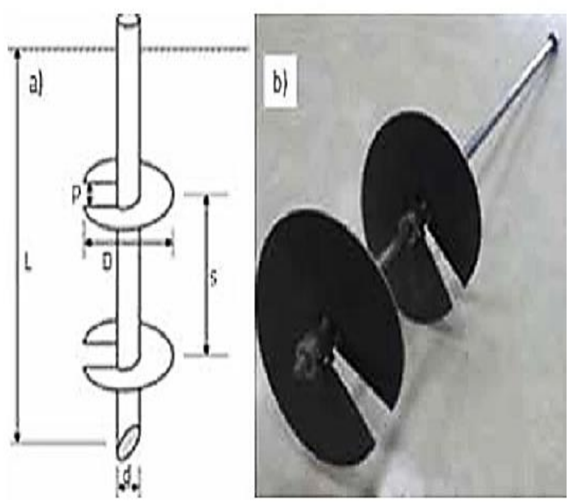
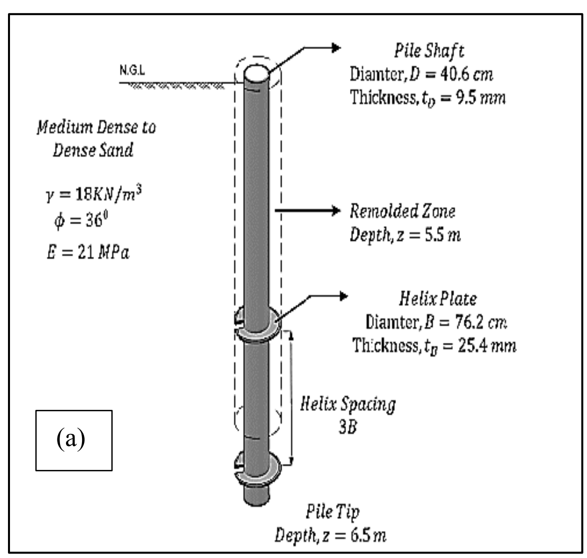


Fig. 2 (a) Helical Pile Detail (b) Model Helical Pile [15]

Sakr (2010) after conducting various experiments in various locations throughout northern Alberta, Canada, carried out experiments to assess the sideways resistance of high-capacity helical piles. Sites 1 and 2 have cohesion-less soil (sandy soil) while Sites 3 and 4 have cohesive soil (clay till soil). All piles have round shaft varying diameter. Some piles containing single helix while some having double helices. Some piles installed after predrilling while other installed without predrilling [18].

Fig. 3 Testing Setup for Helical Pile Lateral Capacity [18]

The result of Sakr (2010) test shows that the capacity of the helical piles against lateral load is affected by the predrilling phenomena. The piles without predrilling show excellent result. Concluded that pile have more shaft diameter installed through predrilling process having less lateral capacity than the pile installed without predrilling phenomena. Akl (2016) performed tests on helical pile having double helices. Field 1 shows the cohesive soil have fine grained sand to silty sand which was dense to very dense and Field 2 show the similar property of Field 1 but it includes sandy silt and glacial till. Predrilling occurs in the Field 1 while Field 2 was without predrilling. Field 1 test pile and Field 2 test pile shown in the (Fig-4)



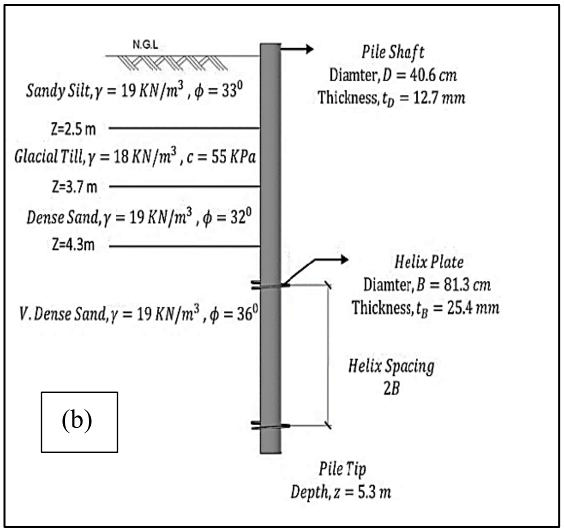


Fig. 4 Helical Piles Test (a) Field 1 (b) Field 2 [17]

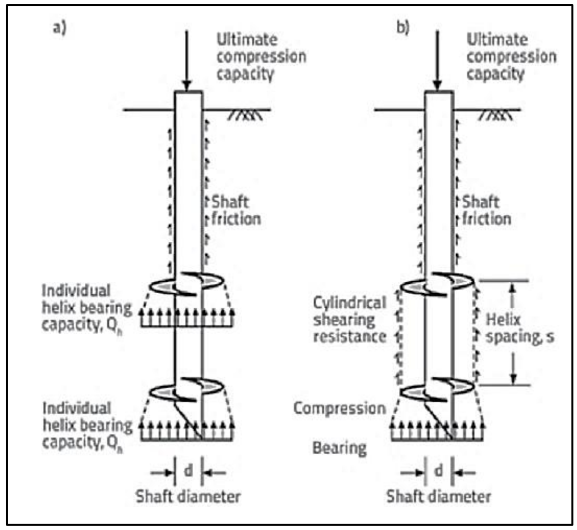


Fig. 5 Individual bearing method (b) cylindrical shear method [21]

Actually, this test was performed to verify the test results of Sakr (2010). The test's findings show that predrilling has an impact on the helical pile's lateral strength. At the Amherst Campus of the University of Massachusetts helical piles underwent both dynamic and static loading tests at the national site of geotechnical experiments. The analysis involved the use of seven helical piles. According to the results, there was a significant correlation between Davisson's assessment of the static pile load test results and those from the dynamic load test. Moreover, the load d-displacement curves exhibited identical fundamental patterns in both tests [19]. Similarly, Alzawi and Phang (2013) analyzed the parameters like Shaft diameter, Helix diameter and Pile length.

IV. Methods For Finding Bearing Capacity

A popular design approach for evaluating the performance of helical piles uses both the individual bearing model/method and the cylindrical shear model/method. This method, which is frequently used in the field, makes it possible to assess a material's ability to support loads and resistance to shear pressures. This design approach provides a thorough evaluation of the capabilities of helical piles by taking into account both the individual bearing capacity and the cylindrical shear behavior [19].

The cylindrical shear failure was introduced by Mitsch and Clemence (1985), while the Individual bearing equation was first introduced by Trofimenkov and Maruipolshii in 1965. Capacities of all the helical blades and shaft resistance is used to define the individual bearing technique failure mechanism [7, 24-25]. The mathematical expression for the compression or tension capacity [15, 18] is given as:

$Q_{c,t} = Q_{helix} + Q_{shaft} + Q_{bearing}$

$Q_{c,\,t}$ = ultimate compressive or uplift capacity of pile

Q_{helix} = shearing resistance along the cylindrical failure surface

$Q_{bearing}$ = piles end bearing capacity in compression

$Qshaft$ = resistance mobilized along the steel shaft

Adams and Klym, (1972) Postulated that if the inter-helix distance is significantly large, each plate will behave individually. This method can be used for both tension and compression load on single- and multi-helix screw piles with an inter-helix spacing of 3.0 or more [25, 27]. In cohesive or non-cohesive soils, the addition of the bearing capacities of individual bearing plate and shaft resistance defines the total tensile capacity [28-29], given as;

$Q_{c,t} = Q_{shaft} + \sum Q_{bearing}$

Where, $Q_{c,}$ = total bearing capacity of plates

$Q_{bearing}$ = individual bearing capacity of plates in tension or compression.

Q_{shaft} = skin friction along the shaft

V. Numerical Modeling Of Helical Pile

Accurately depicting the interaction between a helical pile system and the surrounding soil is crucial

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in modeling. There are several software programs available for this purpose, each with its own set of advantages and limitations. While some software options yield excellent results, they may come with certain drawbacks that need to be considered. In particular, defining the properties of the helical pile within these programs can pose challenges compared to other software alternatives. Therefore, when choosing software for modeling helical piles, two key factors should be taken into account. Firstly, the selected software must be capable of providing the desired results, accurately capturing the behavior and performance of the helical pile system in relation to the soil. This ensures that the modeling outcomes align with the real-world scenario. Secondly, the software should be user-friendly and easy to navigate. A simple and intuitive interface allows users to efficiently work with the software, minimizing the learning curve and maximizing productivity. This aspect is essential for both experienced professionals and those new to helical pile modeling. There are many software's used for modeling of helical pile some are as:

- PLAXIS 2D and PLAXIS 3D
- LPILE
- DeepFND
- ABAQUS
- MIDAS
- HeliCAP

ElSawy (2017) Proved that the mechanism changed from cylindrical shear to individual plate bearing failure at S/D = 1.58 using Finite Element (FE) simulations. Kurian and Shah (2009) use FE analysis to assess how helical piles behave when subjected to axial loading. As a shell foundation, axisymmetric circumstances were used to model the tensile capabilities. A 3D computational study of the helical anchor installation procedure in clay was described in [31]. By utilizing the correlation between torque capacity and the findings of their research, it becomes possible to anticipate the connection between installation torque and the expected force, taking into account factors such as screw pitch, roughness, and width. Furthermore, Nowkandeh and Choobbasti (2021) makes it abundantly evident that the upward pullout in axisymmetric circumstance present in PLAXIS 2D is capable of accurately simulating the pullout behavior of helical piles. A horizontal force is supplied to the absorbent border in order to imitate the horizontal orientation.

Ahmed (2022) used PLAXIS 3D to mathematically verify the experiment's findings. Numerous helical piles that were embedded at varying depths were the subject of their inquiry. Helical pile were effectively model by some of the researchers [13, 34-35]. An evaluation was done to find out how different anchor plate forms affected the axial strength of horizontally anchored structures in undrained clay using three-dimensional (3D) finite element modelling [36]. A load-transfer process of the thin helical piles with square shafts using 3D finite element models were studied [11]. Axisymmetric and three-dimensional finite element (FE) models were used to assess the axial capacity of helical piles in drained cohesive soils [14].

Rawat and Gupta (2017) modeled the helical Pile by changing the number of helix and spacing between helix to check the pullout capacity of helical pile as shown in (Fig 6).

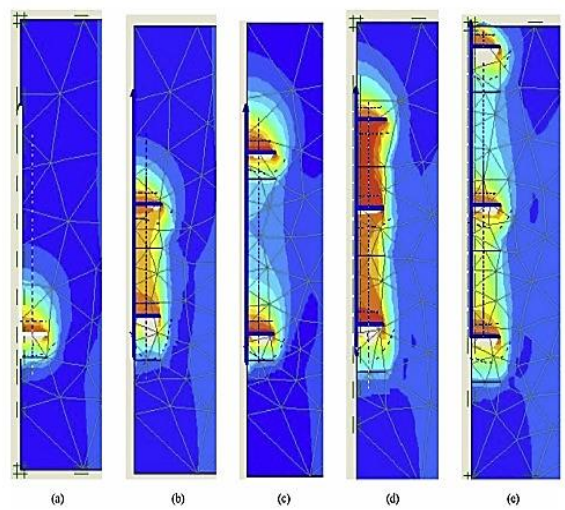

Fig. 6 Helical Pile Modeling changing spacing and number of helices using PLAXIS 2D [37]

Türedi and Örnek (2019) used PLAXIS 2D to simulate the helical pile that was subjected to axial compression by altering the distance between the helix. The axial capacity of a helical pile was also tested experimentally, and the results were compared to those obtained by numerical modelling a helical pile that yielded the identical results in the test. George (2017) use PLAXIS 3D to examine the helical Pile in cohesion-less soil by adjusting various parameters. The installation depth, helical blade diameter, shaft diameter, and helical blade pitch all have an influence on the helical pile in the analysis.

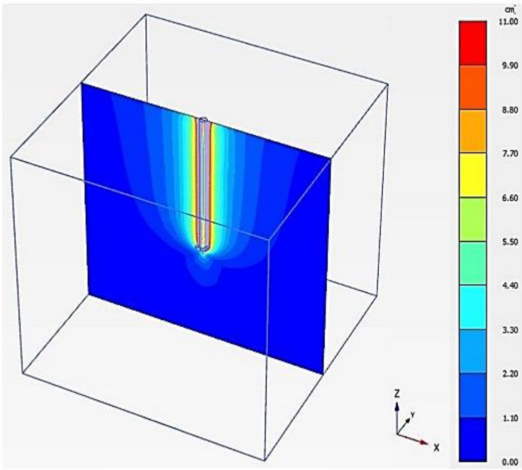

Fig. 7 Numerical Modeling of Helical Pile in Cohesionless soil [38]

To determine the axial capacity of the helical Pile, a numerical model was created. A helical pile's axial capacity is influenced by changing the number of helixes and the space between them [12].

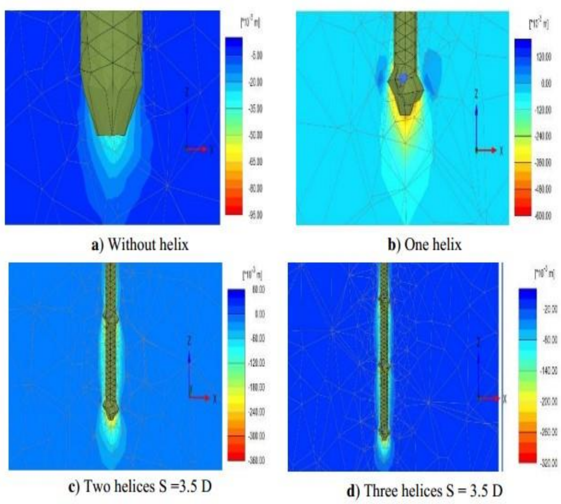

Fig. 8 Numerical Modeling of Axially Loaded Helical Pile [12]

Sakr (2010) calculates the lateral capacity of the screw Pile in the four different sites using LPILE PLUS 5. Using LPILE PLUS 5 changing the shaft diameter in the 4 different sites having different soil type analyze the helical Pile. Different installation torque values are needed depending on the site and soil type. Using p-y analysis, it is possible to evaluate how predrilling affects the helical pile's lateral capacity. The LPILE PLUS 5 software's analysis was quite straightforward. Using PLAXIS 3D, a numerical model was created by Beim and Luna (2012), validating the results of Sakr (2010). Without predrilling, the helical Pile's capacity is unaffected, the predrilling phenomenon affects its lateral capacity.

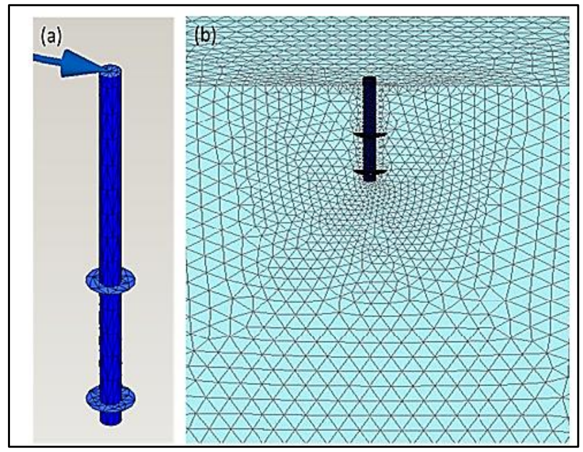

Fig. 9 PLAXIS 3D Analysis of helical Pile [17]

The relation between lateral deflection and lateral load was done using LPILE [17]. The y multiplier used in the analysis to check the lateral capacity of helical Pile that how much it affects its performance. To confirm the results and demonstrate the best work of the LPILE programs to model the helical Pile without experimental work, they also compare the results of experimental work and numerical modelling technique.

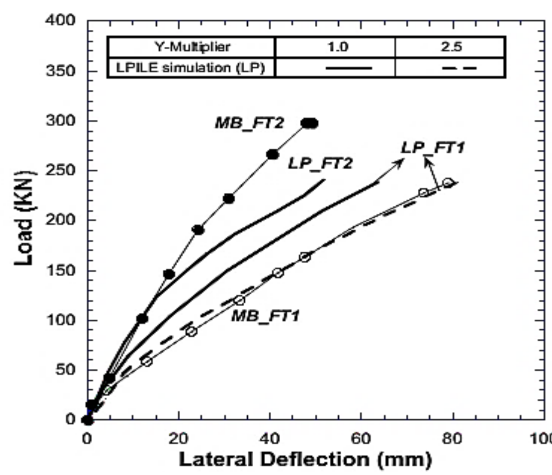

Fig. 10 Comparison of LPILE Modeling and field test after [18]

The seismic load analysis of helical pile using LPILE modeling done by [39]. The primary goal of the analysis was to assess how the soil reacts in the presence of a helical pile. This was achieved by inserting the helical pile into dry sand, and the analysis focused on examining dynamic p-y curves and seismic loading data. Dynamic p-y curves represent how the soil laterally responds when the pile undergoes movement. Analyzing these curves enabled the identification of various factors associated with the behavior of the helical pile. These factors encompassed aspects such as the method of installation, the number of helices (the spiral-shaped plates on the pile), the magnitude of the applied load, the shape of the pile shaft, and the type of coupling used. In order to visually represent the analysis, a figure labeled as Figure 11 depicted the modeling process utilizing the LPILE software. LPILE is a commonly utilized software program employed for the analysis and design of deep foundations, including helical piles. Fig-11 show the modeling done by ElSawy et al., (2019) using the LPILE.

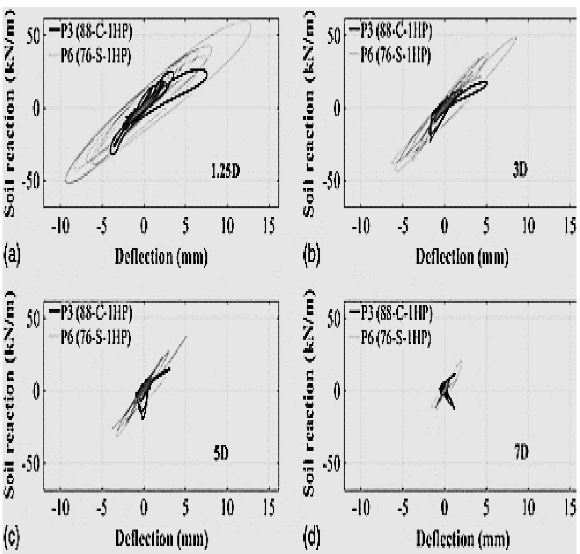

Fig. 11 Soil reaction against seismic load helical Pile as foundation using LPILE [30]

Naggar and Elsherbiny (2013) studied the group pile analysis using ABAQUS to simulate the experimental program. They have done both group pile analyses experimentally and numerically. They compare result of experimental work with numerical model. In modeling using ABAQUS analyzed the helical group Pile by parameter spacing Centre to Centre spacing between Pile which affect the capacity of helical Pile.

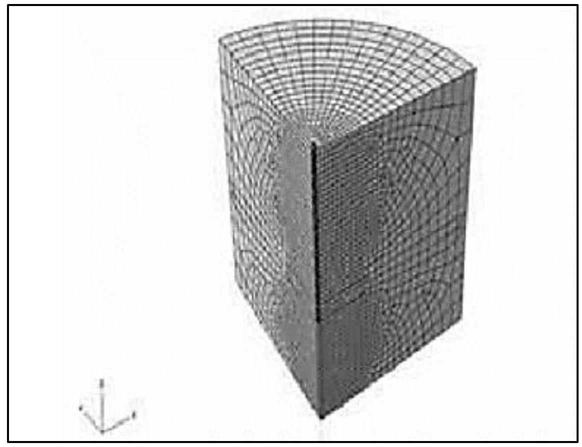

Fig. 12 Numerically Model helical Pile subjected to axial load using ABAQUS [8].

Because ABAQUS is the most sophisticated and intricate software, it was used to simulate the helical Pile in great detail. Although it provides us with a very detailed output, the property defining in this software is really challenging. Akl (2017) models the bearing characteristics of helical pile foundations for offshore environments with sandy soil. The capacity of the helical pile was compared to that of a mono-pile by focusing on the number of blades, the length of the pile, the diameter of the blades, the pitch, and the distance between the blades and the pile's bottom.

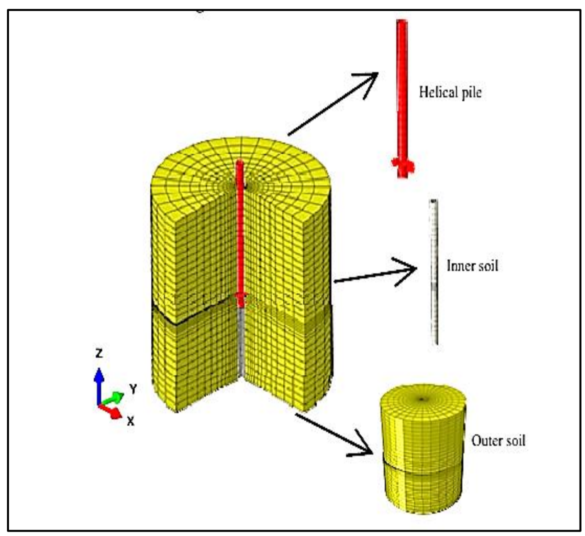

Fig. 13 Single helical Pile Model using ABAQUS [16]

One of analysis was the relation of deformation of helical Pile and mono-pile. In modeling the helical Pile show more resistance than mono-pile. The displacement finite element program ABAQUS were used to perform all of the numerical simulations. Without any published works on numerical modelling of HP, a single axially loaded pile's compression responses were used to validate simulation results [31]. Two separate 3D models were employed to examine the axial capacity of individual helical piles and groups of helical piles [32].

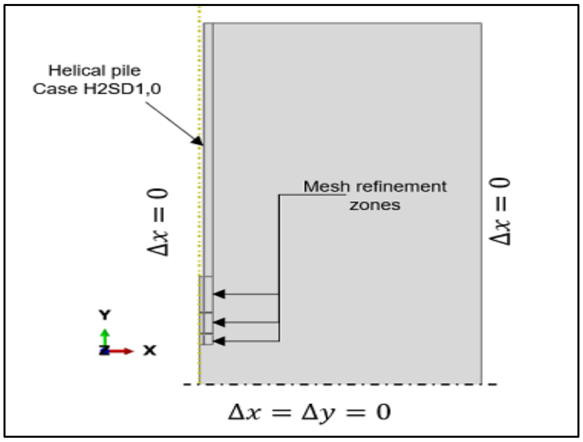

Fig. 14 ABAQUS Helical Pile Model [31]

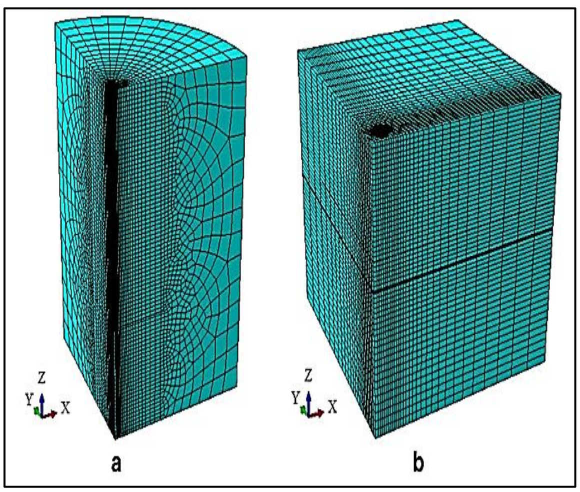

Fig. 15 ABAQUS Model of (a) Single Helical Pile (b) Group Helical Pile [32]

Similarly helical pile performance under cycle load using PLAXIS 3D software (PLAXIS 2020) were investigated by [40]. Alwalan and Naggar (2019) Also performed dynamic analysis using PLAXIS 2D.

VI. Conclusion

- The reviewed literature points out the potential for combining numerical modeling with experimental validation to enhance the accuracy and reliability of predictions, leading to more robust design guidelines for helical pile applications
- Both lightly and heavily loaded structures can be constructed using the modern deep foundation technology of helical piles. This approach is fast, cost-effective, and environmentally friendly.
- Helical piles can carry loads right after installation, without limitations. Transporting them is easy, and their installation isn't affected by soil or weather conditions.
- From the literature, it's evident that numerical modeling offers valuable insights into the load-bearing capabilities, deformation characteristics, and response mechanisms of helical piles, enabling engineers to optimize their design and deployment
- An aspect of the analysis involved examining the deformation behavior of both helical piles and mono-piles. The modeling revealed that helical piles exhibited greater resistance to deformation compared to mono-piles.

VII. Research Gap

Research in the field of "Numerical Modeling of Helical Piles" has made significant strides in understanding the static behavior and load-carrying capacity of these innovative foundation elements. However, a notable research gap exists when it comes to comprehensively exploring the long-term dynamic performance of helical piles under the influence of cyclic loads and environmental factors. Currently, the literature predominantly focuses on the short-term, static behavior of helical piles, often overlooking the complexities of their response to prolonged dynamic loading conditions, such as those encountered in offshore structures, wind turbines, or other applications exposed to environmental fluctuations. This research gap underscores the need for advanced numerical models that can simulate the fatigue life, deformation, and failure mechanisms of helical piles under dynamic loading scenarios. Understanding the long-term performance and behavior of helical piles in dynamic conditions is essential to ensure their reliability and structural integrity over time.

By addressing this research gap, future studies in the field of numerical modeling of helical piles have the potential to offer valuable insights into the design, durability, and maintenance of these foundations in real-world engineering applications. Exploring the dynamic aspects of helical pile behavior can enhance their safety, sustainability, and economic viability, ultimately contributing to the advancement of geotechnical engineering and the broader construction industry.

Table 1: Overview of Previous Papers

S #	Reference No.	Year	Soil Type	Load Type	Software	Single/ Group Pile Test	Parameters
1	[18]	2010	Cohesion less and cohesive soil	Lateral	LPILE	Group Pile	No of helix, Helix Diameter, Shaft Diameter, Shaft Thickness,Embedment Depth,
2	[19]	2012	Cohesive Soil	Dynamic and static		Group Pile	Pile length, Pile diameter
3	[8]	2013	Dry sand and saturated clay	Compressive	ABAQUS	Group Pile	Inter helix spacing ratio, Centre to center spacing between Piles.
4	[20]	2013	Cohesive soil	Dynamic		Single	Shaft diameter, Pile length, Helix diameter
5	[17]	2016	Sand, Sandy Silts, Glacial Till	Lateral	LPILE and PLAXIS 3D	Group Pile	No of helix, Helix Spacing, Pile tip Depth, Helix Diameter, and Helix to pile Diameter Ratio.
6	[35]	2017	Clay	Compressive	Midas GTS NX PC	Single Pile	Length of Pile, Shaft diameter, Blade diameter, Distance between Blades,
7	[38]	2017	Cohesion less soil	Axial	PLAXIS 3D	Single Pile	Depth of installation, Shaft diameter, Helical blade diameter, Helical blade pitch.
8	[37]	2017	Saturated completely decomposed granite (CDG) soil	Pullout	PLAXIS 2D	Single Pile	Number of helices, Spacing ratio
9	[15]	2019	Dry Sand	Axial	PLAXIS 2D	Single Pile	No of Helix, Helix Spacing, Helix Diameter, Settlement Ratio(s/D) Helix spacing to Diameter of helix
10	[34]	2019	Cohesive and cohesion less soil	Dynamic	PLAXIS 2D		Number of helices, spacing between helices, Hammer drop height, Hammer weight
11	[30]	2019	Dry sand	Dynamic	LPILE	Group Pile	Number of helices, Pile shaft shape, Installation method
12	[32]	2021	Cohesive and cohesion less soil	Compressive	ABAQUS	Single and group Pile	Soil parameters, Pile length, Shaft diameter, inter helix spacing,
13	[36]	2021	Cohesive and cohesion less soil.	Compressive		Group Pile	Shaft shape, Shaft diameter, spacing between Piles, number of helices, Embedment depth, Embedment ratio, Helix diameter, Helix to shaft diameter ratio (wing ratio), Helix Pitch, Soil type
14	[41]	2021	Cohesive and Cohesion less soil	Lateral		Single Pile	Shaft shape, Shaft diameter, Helix diameter, Embedment length and embedment ratio, Number of helices, Vertical spacing ratio, Helical depth ratio, Height of applied load, Relative density, Pitch of helical blade.
15	[16]	2022	Sandy soil	Compressive and Tensile	ABAQUS	Single Pile	Pitch of helix, Blade diameter, Number of Blades, Blade spacing,
16	[40]	2022	Cohesion less soil	Dynamic	PLAXIS 3D	Single	Number of helices,

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