

Numerical Analysis of Screw Anchor Piles: A Comprehensive Review

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Abstract - Screw anchor piles are widely used in offshore, marine clay, and soft soil conditions due to their high uplift capacity and ease of installation. Numerical modelling techniques such as finite element analysis are widely used to evaluate the behaviour of screw anchor piles under vertical and uplift loading conditions. This review paper summarizes recent research studies focusing on numerical analysis of screw anchor piles considering plate geometry, embedment depth, spacing, and soil type. The review also highlights the influence of different plate configurations such as circular, helical, square, and star plates. Based on the reviewed literature, research gaps are identified and objectives of the present study are formulated.

Key Words: Screw anchor pile, Helical pile, Numerical modelling, Uplift capacity, MIDAS GTS NX

1. INTRODUCTION

Screw anchor piles are deep foundation elements consisting of a steel shaft and one or more helical plates attached to the shaft. These piles are installed by applying torque into the soil. The load transfer mechanism occurs through bearing resistance of plates and shaft friction. Screw anchor piles offer several advantages over conventional foundation systems. They provide high uplift resistance due to the presence of helical plates, which increase the bearing area and improve load transfer.

These piles can carry load immediately after installation, eliminating the need for curing time as required in cast-in-situ piles. The installation process causes minimal soil disturbance because the piles are screwed into the ground rather than driven or bored. Screw anchor piles are particularly suitable for marine clay and soft soil conditions where conventional foundations may experience excessive settlement. Additionally, they are easy to install, require less equipment, and can be removed or reused if necessary.

Screw anchor piles are widely used in various engineering applications. They are commonly employed in transmission tower foundations where uplift forces are significant. These piles are also used in offshore structures and marine foundations due to their excellent performance in soft and saturated soils. In retaining structures, screw anchor piles act as anchoring elements to resist lateral earth pressure. Furthermore, they are increasingly used in wind turbine foundations where both uplift and overturning loads are critical.

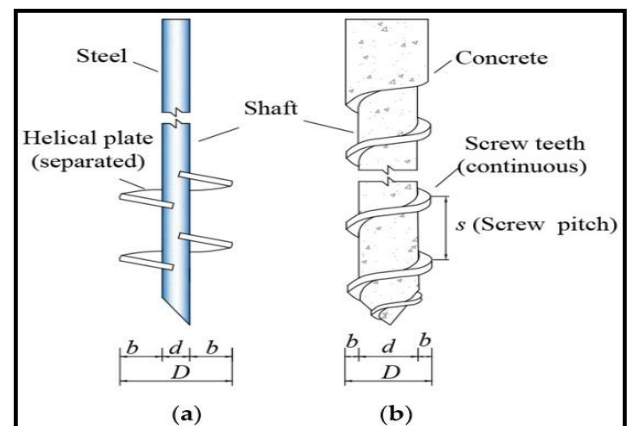


Fig -1: Screw Anchor Pile Geometry

2. MOTIVATION

Screw anchor piles have gained considerable attention in geotechnical engineering due to their ease of installation, minimal soil disturbance, and high load-carrying capacity under both compression and uplift loading conditions. Their performance is significantly influenced by plate geometry, spacing, and soil-structure interaction, which control the load transfer mechanism and overall stability. While numerous studies have focused on conventional circular and helical plate anchors, limited research is available on alternative plate shapes such as square and star configurations, and their comparative performance has not been fully explored.

In addition, numerical modelling techniques provide an efficient approach to simulate anchor behaviour. However, only a few studies have investigated different plate geometries under varying loading conditions using advanced finite element analysis. Therefore, a comprehensive review is

required to understand the influence of plate shape, highlight existing research gaps, and provide a structured foundation for future studies on screw anchor piles under vertical and uplift loading conditions.

3. OBJECTIVE

The objective of this review paper is to provide a comprehensive understanding of the numerical analysis of screw anchor piles under different loading conditions. The paper aims to review various design approaches and numerical modelling techniques available for analysing screw anchor piles, particularly focusing on vertical and uplift loading behaviour. In recent years, screw anchor piles have gained increasing attention due to their high uplift resistance, ease of installation, and suitability for soft soil conditions; however, their design and analysis procedures are still not fully standardised. Many researchers have conducted studies using different numerical tools and plate configurations, but the available information is scattered across various publications. Therefore, this review attempts to compile and critically analyse the existing literature to improve clarity regarding the behaviour of screw anchor piles.

4. LITERATURE REVIEW

4.1 Numerical Modelling of Screw Anchor Piles

Emirler (2024) conducted both physical testing and three-dimensional finite element modelling to evaluate the capacity of helical piles in weak soils [1]. The study concluded that three-dimensional numerical models provide significantly better agreement with physical test results than simplified two-dimensional approaches, and that pile geometry and soil parameters jointly govern load-bearing capacity. The findings underscore the importance of using full 3D models when analysing helical pile systems.

Gil-Hernandez et al. (2024) performed a detailed parametric study using finite element modelling to evaluate the compression and tension behaviour of helical piles [2]. Their results demonstrated that helix spacing, embedment depth, and helix diameter all significantly affect axial capacity and displacement response. Notably, the study identified that optimising the spacing-to-diameter ratio is critical to achieving efficient load transfer between helices.

Arun Kumar et al. (2024) investigated RCC helical piles under combined loading using numerical methods [3]. The study highlighted that shaft material and cross-sectional configuration influence both stiffness and capacity under simultaneous axial and lateral loads, a finding relevant to wind turbine and retaining wall applications.

Taghavi et al. (2024) applied numerical analysis to evaluate the use of helical anchors in deep excavation support systems [4]. The results confirmed that helical anchors provide reliable lateral resistance and can be effectively modelled using finite element software for support design verification.

Li (2023) carried out finite element modelling of screw anchor piles and reported that increasing helix diameter improves uplift capacity, while excessive spacing between helices reduces their interaction and diminishes the capacity

gain [18]. Wang (2023) studied the compression behaviour of helical piles and observed that screw anchor piles exhibit higher stiffness and lower settlement compared to conventional bored piles under equivalent loading conditions [19].

Al-Kaabi and Karkush (2023) investigated screw piles under seismic loading using numerical modelling and reported that helical piles demonstrate satisfactory performance under dynamic conditions, with plate geometry influencing the seismic response [10]. Wang (2022) conducted a numerical study of helical piles in layered soil and found that soil stratification significantly affects load distribution along the shaft and the relative contribution of individual helices to total resistance [17].

4.2 Uplift Capacity of Screw Anchor Piles

Uplift capacity is widely considered the governing design criterion for screw anchor piles used in transmission tower foundations, offshore anchoring systems, and wind turbine bases. Failure under uplift typically involves shear failure of the soil mass above the uppermost helix plate, forming either individual plate failure surfaces or a combined cylindrical shear failure surface depending on the spacing ratio.

Hoyt and Clemence (1989) established foundational relationships between embedment depth, helix diameter, and uplift capacity, identifying the transition between individual plate failure and cylindrical shear failure as a function of the spacing-to-diameter ratio [12]. These early findings continue to underpin current design methods.

Cogent Engineering (2023) studied the uplift capacity of helical anchors in cohesionless soil and reported that torque resistance measured during installation can be correlated with ultimate uplift capacity [9]. The study also confirmed that helix diameter is the dominant geometric variable governing uplift resistance in sandy soils.

Chen et al. (2024) investigated uplift screw shaft piles and found that blade spacing, pitch angle, and soil density collectively influence uplift capacity and displacement characteristics. Their results indicated that closer blade spacing improves capacity in dense soils but has a diminishing effect in loose cohesionless conditions.

Sharma (2024) examined the uplift behaviour of helical anchors in clay and reported that undrained shear strength and overburden pressure are the primary soil parameters controlling capacity in fine-grained soils [21]. The study also noted that the failure mechanism transitions from individual plate failure to general shear failure at greater embedment depths.

Rao (2011) investigated the pullout capacity of helical anchors and established empirical relationships between helix geometry and uplift resistance that have been widely adopted in practice [16]. Livneh and Naggar (2008) studied the axial behaviour of helical piles and confirmed that both compression and tension capacity increase with embedment depth, with a nonlinear relationship observed between capacity and the number of helices [14].

4.3 Behaviour in Soft Clay and Marine Soil

Soft clay and marine soil conditions present significant challenges for conventional foundation systems due to their low shear strength, high compressibility, and sensitivity to disturbance during installation. Screw anchor piles are considered particularly effective in such environments owing to their ability to mobilise bearing resistance across the plate area without requiring driven or bored installation.

Ocean Engineering (2023) studied the group behaviour of helical piles in soft clay under combined uplift and lateral loading [7]. The results showed that pile spacing greater than three times the helix diameter effectively reduces group interaction effects and allows piles to be treated as independent elements for design purposes. Below this spacing threshold, group efficiency decreases notably, particularly under uplift loading.

Marine Georesources and Geotechnology (2023) reported on the load–settlement response of helical piles installed in soft clay, finding that the bearing capacity factor and failure mechanism depend strongly on the undrained shear strength profile and the depth-to-diameter ratio [8]. The study observed that helical piles in soft clay exhibit a relatively ductile load–displacement response, with gradual mobilisation of resistance rather than sudden failure.

Alnmr et al. (2023) analysed helical piles in expansive soil and concluded that screw anchor piles effectively reduce heave-induced settlement by providing an anchoring force below the active zone of moisture change [6]. The study recommended helical piles as a viable foundation solution in regions with seasonally active expansive soils.

Sakr (2009) evaluated the performance of helical piles in oil sand and found that installation torque is a reliable predictor of pile capacity in such conditions [13]. The study highlighted the versatility of helical pile systems across a wide range of soil types beyond conventional clay and sand.

4.4 Effect of Plate Geometry

Plate geometry is a primary determinant of screw anchor pile performance, influencing stress distribution, failure mechanism, bearing area, and load transfer efficiency. The most commonly studied configurations are circular and helical plates, though recent research has begun to examine square and star plate geometries.

Materials Journal (2024) investigated the influence of helix position on screw pile capacity and found that the location of the uppermost helix relative to the ground surface significantly affects the failure mode and overall capacity [5]. Piles with helices positioned at greater depth exhibited higher capacity due to increased overburden confinement.

Zhang et al. (2018) performed numerical modelling of helical piles in sand and concluded that plate geometry directly influences the stress distribution around the helix and the shape of the failure surface [15]. Circular plates generated a more symmetric failure zone, while non-circular geometries produced irregular stress concentrations that affected both capacity and displacement at failure.

Lingden (2025) conducted a comparative study of different screw anchor configurations using finite element modelling

and reported that plate shape significantly affects load–displacement behaviour [20]. The study noted that continuous helix configurations provide higher axial and uplift performance compared to discrete plate arrangements under equivalent embedment conditions.

Kumar (2023) performed finite element modelling of helical piles in sand and examined the role of plate thickness and diameter-to-shaft ratio on capacity [23]. The results indicated that thicker plates with larger diameter ratios improve bearing resistance but also increase installation torque requirements, presenting a practical design trade-off.

R.R. Badnakhe (2020) conducted a numerical study using MIDAS GTS NX to compare the pullout and lateral capacities of circular, square, helical, and star plate anchors embedded in clay [22]. Eight configurations were analysed by varying embedment depth, number of plates, and spacing-to-diameter ratio (Sp/D) using the Mohr–Coulomb model. The results showed that uplift and lateral capacities increase with embedment depth and Sp/D ratio. Among all configurations, helical plate anchors provided the highest capacity. The study established a comparative FEM framework for evaluating different plate geometries.

4.5 Load–Displacement Behaviour

The load–displacement response of screw anchor piles provides essential information for serviceability limit state design and is used to calibrate numerical models against experimental data.

Perko (2009) provided a comprehensive treatment of helical pile design including load–displacement prediction methods, establishing that screw anchor piles typically exhibit an initial stiff linear response followed by a nonlinear transition zone and ultimate capacity plateau [11]. This characteristic behaviour distinguishes helical piles from conventional piles, which often show a more gradual capacity mobilisation.

Wang (2023) observed that screw anchor piles exhibit higher initial stiffness and lower settlement at working loads compared to conventional piles, attributing this to the confinement effect of helical plates on the surrounding soil [19]. Bearing capacity studies of screw-groove piles confirm that axial force distribution and settlement behaviour are strongly influenced by helix geometry and shaft resistance, with the relative contribution of each component varying with embedment depth and soil stiffness.

Li (2023) reported nonlinear load–displacement behaviour in finite element models of screw anchor piles, with stiffness degradation becoming more pronounced beyond approximately 50% of ultimate capacity [18]. The study noted that the Hardening Soil constitutive model captures this nonlinearity more accurately than the simpler Mohr–Coulomb model, particularly at larger displacement levels.

Gil-Hernandez et al. (2024) highlighted that the load–displacement relationship is sensitive to helix spacing, with closely spaced helices producing a stiffer initial response but a less ductile post-peak behaviour [2]. State-of-the-art reviews confirm that axial and uplift capacity, as well as the shape of the load–displacement curve, depend jointly on soil type, helix geometry, and embedment depth, reinforcing the

need for case-specific numerical analysis rather than purely empirical design approaches.

5. DISCUSSION

The reviewed literature demonstrates that the performance of screw anchor piles is governed by a combination of geometric, material, and loading-related parameters. A synthesis of the available studies reveals both consistent findings and unresolved questions that warrant further investigation.

5.1 Influence of Plate Geometry on Load-Carrying Capacity

Plate geometry emerges as the most critical design variable across reviewed studies. Circular and helical plate configurations have received the greatest research attention and are generally found to deliver efficient stress distribution and high bearing capacity due to the increased contact area between the plate and surrounding soil. Emirler (2024) confirmed that pile geometry significantly influences load-bearing behaviour, while Gil-Hernandez et al. (2024) demonstrated that helix diameter and spacing directly affect both axial capacity and displacement response. Li (2023) further reported that increasing helix diameter improves uplift capacity, although excessive plate spacing reduces inter-helix interaction and diminishes this benefit.

By contrast, square and star plate configurations remain poorly understood. Only isolated studies such as Lingden (2025) have examined alternative plate shapes, and direct performance comparisons under identical soil and loading conditions are largely absent from the literature. This is a significant gap given that non-circular plates may offer practical fabrication advantages and potentially different failure mechanisms under oblique or combined loading. Without systematic comparative studies, it is not possible to determine whether circular plates are genuinely superior or simply better studied.

5.2 Effect of Soil Conditions

Soil type and strength properties play a fundamental role in governing screw anchor pile behaviour. In soft clay and marine soils, helical piles consistently outperform conventional driven piles by mobilising bearing resistance across the plate area rather than relying primarily on shaft friction. Studies reviewed under Section 4.3 indicate that pile spacing greater than three times the helix diameter effectively eliminates group interaction effects, a finding with direct implications for offshore and marine foundation design. Alnmr et al. (2023) extended these observations to expansive soils, reporting that screw anchor piles reduce heave-induced settlement through improved load distribution. However, the behaviour of screw anchor piles in layered or heterogeneous soil profiles common in real field conditions has received comparatively little attention, and generalising findings from homogeneous soil models to such conditions requires caution.

5.3 Numerical Modelling Approaches

Finite element analysis is the dominant method used across reviewed studies, with PLAXIS 3D, ABAQUS, and MIDAS GTS NX being the most frequently adopted platforms. Three-dimensional models consistently show better agreement with physical test results than two-dimensional axisymmetric approximations, particularly when modelling helical plate interaction and non-symmetric plate geometries. The Mohr–Coulomb model remains widely used for its simplicity, though studies employing the Hardening Soil Model report improved accuracy in capturing nonlinear load-displacement behaviour at larger deformations. A notable limitation is that MIDAS GTS NX — despite its growing use in geotechnical practice — has been applied in very few published studies on screw anchor piles, meaning benchmark validation data for this platform remains sparse.

5.4 Conflicting Findings and Limitations of Existing Work

Several areas of inconsistency exist across the reviewed literature. The relationship between plate spacing ratio and uplift capacity varies between studies, likely due to differences in soil type, plate diameter, and the constitutive models used. Similarly, the optimum embedment depth for maximum uplift efficiency is reported differently depending on the failure mechanism assumed individual plate failure versus cylindrical shear failure. Many studies also model idealized, homogeneous soil conditions that do not fully represent field variability, limiting the direct applicability of numerical findings to real projects. Furthermore, combined loading conditions — vertical plus lateral or moment loading remain underexplored relative to pure vertical and uplift cases, despite being highly relevant to wind turbine and transmission tower foundations.

Overall, the reviewed literature establishes a strong foundation for understanding screw anchor pile behaviour under vertical and uplift loading in relatively simple soil conditions. The convergence of findings around the importance of plate geometry, embedment depth, and helix spacing provides a reliable basis for design. However, the lack of comparative studies on alternative plate shapes, the limited use of MIDAS GTS NX, and the absence of studies addressing combined loading and heterogeneous soils represent clear directions for future work. The present study is positioned to address these gaps through systematic numerical analysis of circular, helical, square, and star plate configurations under both vertical and uplift loading conditions using MIDAS GTS NX.

6. CONCLUSION

This review paper presents a comprehensive overview of the numerical analysis of screw anchor piles and their performance under different loading conditions. Based on the reviewed literature, screw anchor piles have been found to provide significant advantages such as high uplift resistance, immediate load-carrying capacity, minimal soil disturbance, and suitability for soft clay and marine soil conditions. The

load transfer mechanism of screw anchor piles primarily depends on end bearing of the helix plate, shaft friction, soil confinement, and plate interaction effects. Under uplift loading, failure generally occurs above the helix plate forming a conical soil failure surface.

The review also highlights that finite element modelling is widely used to analyse screw anchor piles, with software such as MIDAS GTS NX, PLAXIS 3D, ABAQUS, and FLAC 3D being commonly adopted. Different soil constitutive models including Mohr–Coulomb, Hardening Soil Model, and Modified Cam Clay Model are used to simulate soil behaviour. The performance of screw anchor piles is significantly influenced by plate geometry, embedment depth, spacing, and soil properties. Among different configurations, circular, helical, square, and star plate anchors show varying load-displacement behaviour depending on soil conditions and loading type.

From the literature, it is observed that limited studies are available comparing different plate shapes under both vertical and uplift loading conditions. Research on star plate anchor piles is very limited. Additionally, numerical modelling using MIDAS GTS NX software has not been extensively explored. Therefore, further comparative numerical analysis considering multiple plate geometries is required. The findings of this review provide a useful reference for researchers and geotechnical engineers and help in understanding the behaviour of screw anchor piles for foundation applications.

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