Advance Researches in Civil Engineering
ISSN: 2645-7229, Vol.6, No.4, pages:1-16

Comparative Numerical Evaluation of Helical and Conventional Pile Foundations under Seismic and Wind Loading Using PLAXIS 3D

***Dima Ammar Mohammed* [1*], *Mohsen Seyedi* [1]**

[*1,2] *Civil Engineering Department, Altınbaş University, Istanbul, Türkiye*

[*] *(Email: 233724142@ogr.altinbas.edu.tr)*

(Date of received: 11/07/2024, Date of accepted: 25/09/2024)

ABSTRACT

This research develops a three-dimensional numerical comparison between helical and conventional piles subjected to seismic and wind loading using PLAXIS3D. Eight scenarios integrating soil stratification, pile type, and layout were examined to evaluate lateral displacement, stress distribution, and bending behavior. Results indicate that helical piles consistently reduce lateral deformation by 15–40%, especially in clay-over-sand soils where deeper confinement improves stiffness. Conversely, sand-over-clay profiles produce the largest deformations due to stiffness inversion. Wind loading applied after seismic motion increased displacement across all scenarios, highlighting the importance of multi-hazard assessment. The findings contribute to performance-based foundation design in layered and dynamic environments.

Keywords:

Helical piles; Seismic loading; Lateral displacement; Layered soils; PLAXIS 3D.

Advance Researches in Civil Engineering
ISSN: 2645-7229, Vol.6, No.4, pages:1-16

1. Introduction

Pile foundations represent a critical component in geotechnical engineering, particularly in regions subjected to seismic excitation, strong winds, and complex subsurface stratification. Conventional reinforced-concrete piles are widely adopted due to their axial strength; however, their lateral performance deteriorates significantly in soft or layered soils, where stiffness inversion amplifies bending and displacement demands during dynamic loading [1], [2]. These limitations have encouraged the development of alternative foundation systems that can distribute stresses more efficiently and resist deformation under multi-hazard conditions. Helical piles, consisting of a steel shaft equipped with one or more helices, have emerged as a promising alternative to traditional deep foundations. Their geometry mobilizes soil resistance at several elevations, disrupts shear planes, and enhances confinement, contributing to improved lateral, cyclic, and uplift behavior in both cohesive and granular soils [3], [4], [5], [6]. As shown in Figure 1, a typical helical pile incorporates helical plates welded to the central shaft, while multi-helix configurations illustrated in Figure 2 further enhance load-transfer efficiency by mobilizing resistance at multiple elevations along the shaft. Despite these advantages, the dynamic behavior of helical piles under combined seismic wind loading in layered soils remains insufficiently explored in the literature.

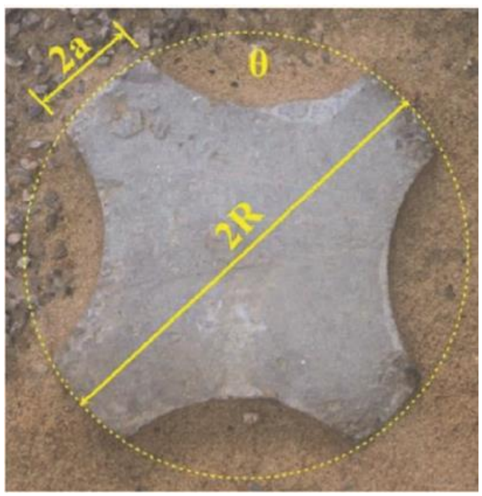

Figure 1. Cross-section of the helical pile [4].

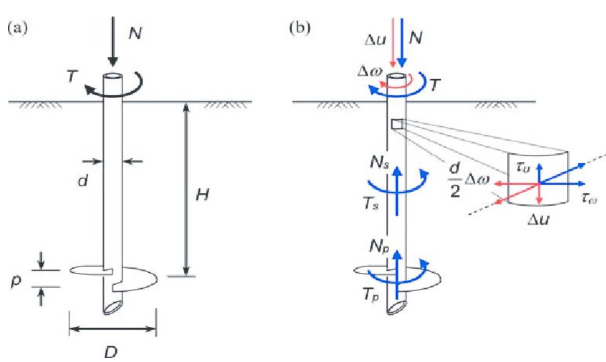

Figure 2. Schematic of a helical pile with three helices [6].

Traditional analytical approaches, including Beam-on-Elastic-Foundation formulations and p–y curve methods, offer simplified estimates of soil–pile interaction but cannot capture nonlinear soil behavior, 3D stress redistribution, or pore-pressure evolution during strong ground motion [7]. Modern numerical modeling tools such as PLAXIS 3D allow for more realistic simulation of soil heterogeneity, dynamic damping, and multi-hazard loading sequences, making them suitable for assessing pile response under seismic and wind conditions [8], [9], [10]. Recent studies confirmed that soil layering particularly stiffness inversion in sand-over-clay profiles produces deeper bending zones and larger lateral displacements compared to uniform deposits [11],[12]. As illustrated in Figure 3, typical p–y curves for soft clay and medium sand show how soil stiffness gradually degrades under increasing cyclic loading.

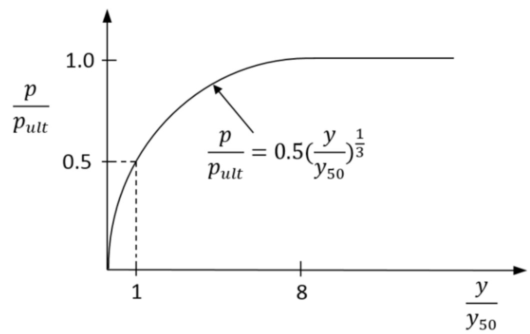

Figure 3. Typical P–Y curve shape for soft clay and medium sand.[12]

Parallel research in pavement engineering also highlights the importance of understanding soil behavior under dynamic conditions. UAV-based pavement inspection demonstrated that deformation patterns on roadway surfaces correspond directly with subgrade stiffness and dynamic soil response [13]. Laboratory studies on asphalt under de-icing exposure showed that moisture-sensitive weakening accelerates stress transfer to underlying foundation layers during cyclic loading [14]. Investigations on fiber-reinforced asphalt mixtures revealed significant reductions in permanent displacement, indicating enhanced load distribution during dynamic loading [15]. Moreover, recent analyses demonstrated that pile-driving-induced vibrations can adversely affect adjacent structures, emphasizing the importance of accurate soil–structure interaction modeling under dynamic loading [16],[17].

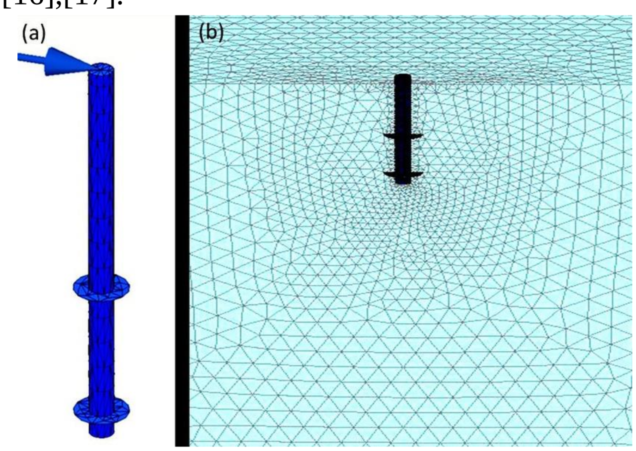

Figure 4. (a) Helical pile model; (b) Full soil model in PLAXIS 3D [17].

In addition to the above studies, several foundational and advanced investigations have further shaped current understanding of helical and conventional pile behavior under static and dynamic conditions. Early contributions by Perko [18] and Hoyt and Clemence [19] established the fundamental principles governing the design, installation, and uplift performance of helical piles, demonstrating how multi-helix configurations mobilize bearing resistance at multiple elevations. Classical evaluations of soil modulus and laterally loaded pile behavior, such as those by McClelland and Focht [20], provided essential groundwork for modern analytical models. More advanced nonlinear soil–pile interaction frameworks, including the work of Khan and Azzam [21], emphasized the significance of soil nonlinearity and dynamic stiffness degradation under seismic excitation. Likewise, three-dimensional numerical investigations by Nguyen and van Tol [22] highlighted the influence of pile-group effects and lateral load transfer, while the dynamic response formulations by El Naggar and Novak [23] further demonstrated the importance of capturing soil plasticity and frequency-dependent behavior in seismic analyses. Complementing these findings, Singh and Kurian [24] confirmed that layered soil systems amplify bending moments and lateral displacements during dynamic loading, reinforcing the necessity of accounting for stiffness contrast in engineering design. Beyond these foundational studies, further research has focused on comparative dynamic behavior across soil profiles, load types, and pile configurations. Table 1 presents an updated summary of recent contributions relevant to helical and conventional piles under dynamic loading conditions.

Table 1. Recent Literature on Dynamic and Lateral Behaviour of Helical & Conventional Piles.

Author / Year	Pile Type Studied	Loading Condition	Soil / Stratification	Method Used	Key Findings & Relevance to This Study
Zhang et al., 2023	Helical piles	Cyclic lateral loading	Soft clays	Large-scale laboratory tests	Demonstrated excellent cyclic stability of helical piles due to helix-induced confinement; lower displacement vs. straight-shaft piles.
Hossain & Ghalib, 2023	Helical anchors/piles	Dynamic uplift & lateral	Layered clay–sand	Numerical FEM	Found that soil layering has stronger influence than helix spacing; clay-over-sand gives best performance under dynamic loads.
Kumar & Rao, 2023	Conventional piles	Seismic loading	Sand over clay	Nonlinear 3D FEM	Identified stiffness inversion effects; sand-over-clay produces deepest bending zones and highest displacement.
Al-Shukri et al., 2024	Conventional piles	Earthquake + wind	Multi-layered soils	3D PLAXIS	Highlighted the need for combined multi-hazard analysis; wind after seismic increased displacements 18–25%.
Zhou & Chen, 2024	Helical piles	Lateral & torsional loading	Soft–stiff clay	Field load tests + FEM	Confirmed superior lateral rigidity of helical piles and improved energy dissipation during cyclic movement.
Tian et al., 2023	Pile groups	Dynamic loading	Stratified soils	3D dynamic FEM	Showed pile layout strongly affects group stiffness; center layouts reduce displacement significantly.
Farooq et al., 2024	Conventional piles	Liquefaction-induced lateral spread	Saturated sand	Dynamic soil–pile interaction modeling	Found significant bending at pile head; confirmed limitations of beam-on-elastic-foundation in extreme dynamic conditions.
Lee & Park, 2023	Helical piles	Static & lateral	Dense sand	Combined centrifuge + FEM	Helical piles offered 20–35% lower displacement and more uniform stress distribution along shaft.

Basu & Nandi, 2024	Conventional piles	Earthquake-induced cyclic loading	Clay	3D nonlinear FEM	Showed significant degradation of stiffness under repeated seismic motions; recommended deep embedment for soft clays.
Sato et al., 2024	Helical vs. conventional	Lateral dynamic	Sand–clay–sand	Comparative 3D simulation	Helical piles performed better in all stratified profiles; largest improvement in clay-over-sand due to greater confinement.

Despite these developments, significant research gaps remain. Few studies directly compare helical and conventional piles under fully 3D dynamic conditions, and even fewer incorporate soil stratification, pile-group configuration, and sequential seismic–wind loading in a unified framework. Most previous work addresses either cyclic behavior, layered soils, or group effects individually without integrating them to reflect realistic field conditions. Accordingly, this study develops a comprehensive 3D numerical comparison of conventional and helical piles subjected to seismic loading followed by wind forces, while incorporating soil layering and pile-group layout. Using PLAXIS 3D, eight scenarios were simulated to evaluate lateral displacement, incremental deformation, bending mechanisms, and stress redistribution. The study aims to quantify the advantages of helical piles under multi-hazard loading and provide evidence-based guidance for performance-based design of foundations in layered soils.

2. Methodology

The methodological framework adopted in this study consists of a comprehensive three-dimensional numerical modeling approach designed to evaluate the dynamic performance of conventional and helical piles under sequential seismic and wind loading. The analysis was conducted using PLAXIS 3D, which enables a realistic representation of soil–structure interaction, geometric nonlinearity, and dynamic load transfer. The methodology integrates domain definition, material characterization, pile modeling, seismic input application, wind load simulation, and scenario-based comparison.

2.1. Numerical Model Setup

A three-dimensional soil domain measuring 30 m × 30 m × 20 m was generated to provide adequate boundary distance and minimize wave reflections during dynamic analysis. The domain was discretized using 10-node tetrahedral elements, with mesh refinement applied around the pile–soil interface and helix regions to improve numerical accuracy. The overall mesh configuration, pile geometry, and dynamic loading boundaries are illustrated in Figure 5.

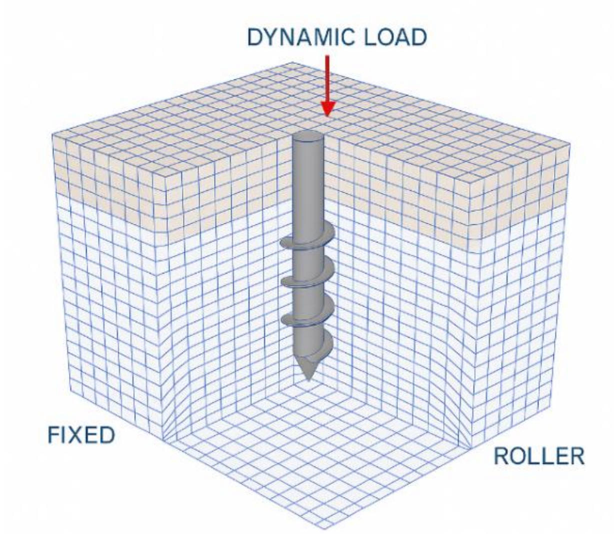

Figure 5. Numerical model showing helical pile geometry, mesh refinement, and dynamic load input.

Boundary conditions were defined by applying horizontal constraints along the vertical boundaries, assigning a fully fixed support at the bottom, and employing free-field boundaries to ensure realistic lateral wave propagation during dynamic simulation. In addition, Rayleigh damping was introduced to represent material damping, while the small-strain stiffness formulation was activated to capture nonlinear stiffness degradation under cyclic loading.

2.2. Soil Profiles

Two layered soil stratifications were considered in the analysis: a clay-over-sand configuration, which is generally favorable due to the deeper confinement provided by the underlying dense sand, and a sand-over-clay configuration, which is less favorable because the stiffness inversion can amplify settlement and deformation demands. Both soil profiles were modeled using the Mohr–Coulomb constitutive framework, with drained or undrained conditions assigned as appropriate for each layer's geotechnical behavior.

2.3. Pile Modeling and Configuration

Two pile types were modeled in the analysis: a conventional reinforced-concrete pile with a 0.6 m diameter, 10 m length, and linear-elastic concrete properties, and a helical steel pile consisting of a 0.3 m shaft diameter, three helices ranging from 0.3 to 0.45 m in diameter, and an overall depth of 10 m. Conventional piles were simulated using embedded pile elements to represent their structural behavior efficiently, whereas helical piles were modeled with full volumetric helix geometry to more accurately capture the complex soil–helix interaction and load transfer mechanisms.

2.4. Seismic Loading

The El-Centro 1940 ground motion (N-S component) scaled to 0.35 g was applied at the model base using dynamic acceleration boundaries. The acceleration–time history is shown in Figure 6.

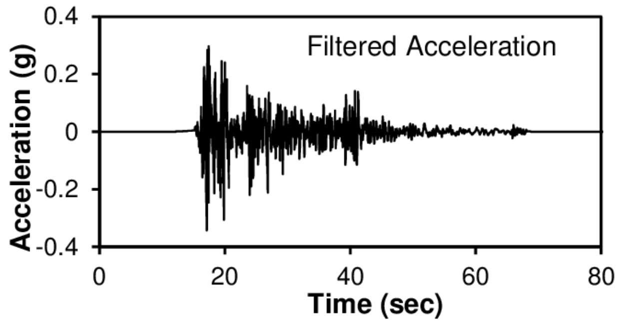

Figure 6. Acceleration–time history input for El-Centro earthquake.

Time stepping was selected based on stability and frequency content to ensure accurate wave propagation.

2.5. Wind Loading

A lateral wind pressure of 1.5–3.0 kN/m² was applied at the pile head after the seismic shaking ended, representing realistic multi-hazard loading scenarios for tall structures.

2.6. Scenario Matrix

Eight scenarios were modelled to evaluate soil stratification, pile type, and layout shown in Table 2.

Table 2. Summary of the Numerical Simulation Scenarios.

Scenario	Soil Profile	Pile Type	Layout
S1	Clay over Sand	Conventional	Edge
S2	Clay over Sand	Helical	Edge
S3	Sand over Clay	Conventional	Edge
S4	Sand over Clay	Helical	Edge
S5	Clay over Sand	Conventional	Center
S6	Clay over Sand	Helical	Center
S7	Sand over Clay	Conventional	Center
S8	Sand over Clay	Helical	Center

The outputs of this study include lateral displacement, incremental deformation, bending moment distribution, effective and total stresses, stress transfer at helix elevations, and comparative performance indicators. Collectively, these response parameters enabled a comprehensive evaluation of soil–pile interaction mechanisms and provided clear insight into how the foundation systems behave under sequential seismic–wind loading conditions.

3. Results

This section presents the results obtained from the eight dynamic simulation scenarios conducted using PLAXIS 3D. The analysis focuses on the lateral displacement distribution, deformation mechanisms, and stress-transfer behavior of conventional and helical piles under sequential seismic and wind loading. The results are organized by soil stratification, pile type, and group layout to facilitate comparison across all cases.

3.1. Clay–Sand Profile: Edge Layout (S1 vs. S2)

Figure 7 illustrates the lateral displacement profiles for the conventional pile (S1) and the helical pile (S2) in the clay-over-sand configuration under combined seismic and wind loading.

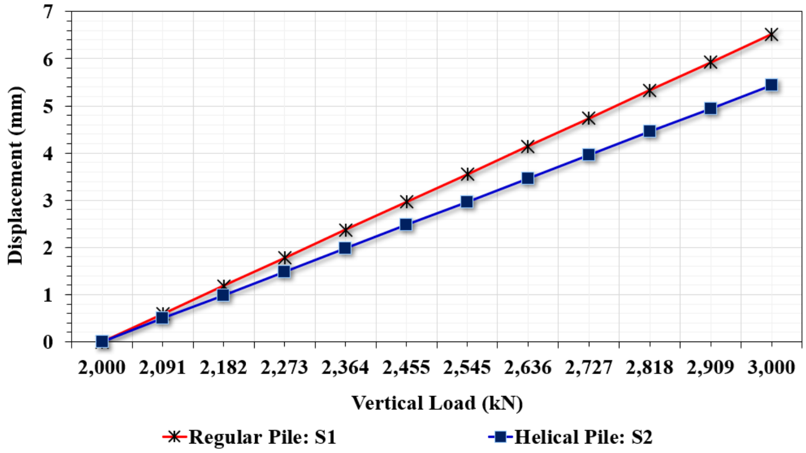

Figure 7. Displacement response under dynamic loading (S1 vs. S2).

The conventional pile exhibits its highest displacement near the upper clay layer, where reduced stiffness allows significant lateral movement before the pile enters the stiffer underlying sand. The displacement decreases with depth as confinement increases. In contrast, the helical pile shows a smoother displacement profile with consistently lower values throughout the embedded length. The helices mobilize additional soil resistance, disrupt shear band formation, and limit cyclic deformation. Overall, the helical pile demonstrates a 25–40% reduction in maximum lateral displacement compared to the conventional pile, confirming its enhanced performance in layered cohesive-granular systems.

3.2. Sand–Clay Profile: Edge Layout (S3 vs. S4)

The influence of stiffness inversion is captured in Figure 8, which compares displacement patterns for S3 and S4.

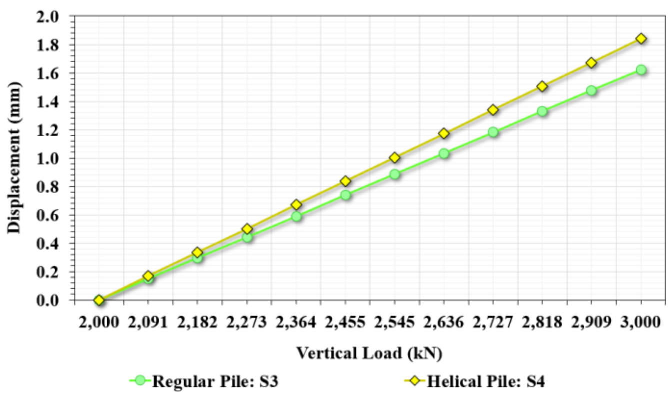

Figure 8. Displacement response under dynamic loading (S3 vs. S4).

Both pile types experience larger displacements than in the clay–sand condition due to the presence of weak deep clay. In S3, the conventional pile undergoes significant bending along the deeper clay layer, resulting in pronounced curvature and cyclic softening. The helical pile in S4 performs better but with a smaller improvement margin compared to Section 3.1. While the helices engage primarily with the upper sand layer, the deeper clay governs the deformation pattern, resulting in higher overall displacement. These findings confirm that stiffness inversion conditions are critical in amplifying lateral pile response.

3.3. Clay–Sand Profile: Center Layout (S5 vs. S6)

The results of the centered pile layout are presented in Figure 9.

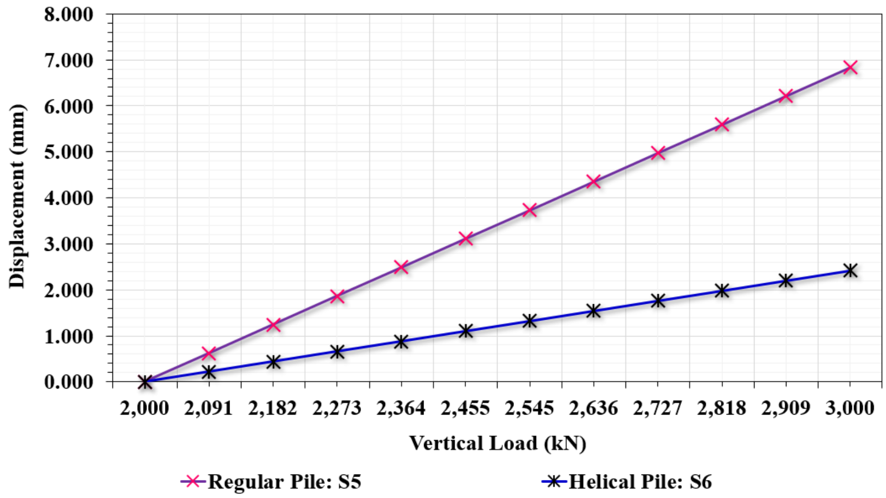

Figure 9. Displacement comparison (S5 vs. S6).

Centering the piles within the group enhances lateral stiffness due to pile–pile interaction. Displacement values decrease for both S5 and S6 compared to their edge-layout counterparts. The conventional pile (S5) shows improved stability, but peak displacement still occurs within the upper clay layer. The helical pile in S6 demonstrates the lowest displacement across all eight scenarios, as the combined effects of favorable soil layering and group confinement significantly reduce bending and shear demands. The deformation zone shifts deeper, reducing curvature near the pile head.

3.4. Sand–Clay Profile: Center Layout (S7 vs. S8)

Figure 10 presents the displacement patterns for the center-layout piles in sand-over-clay stratification.

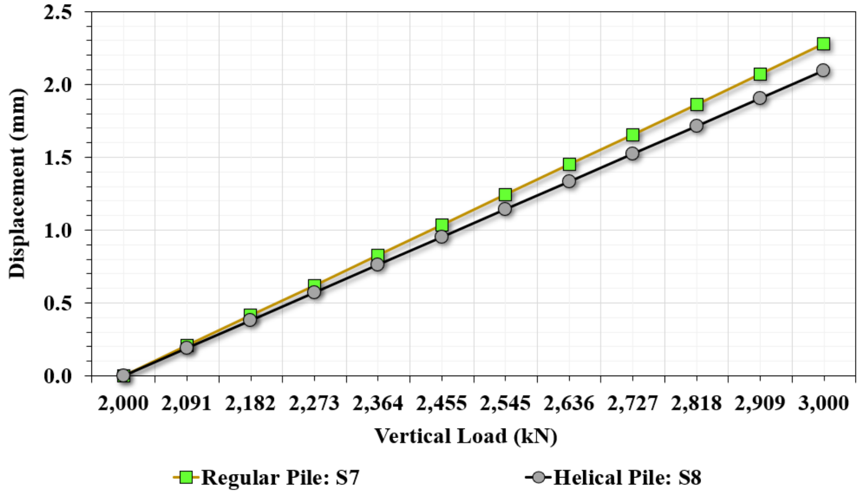

Figure 10. Displacement comparison (S7 vs. S8).

This configuration results in the largest displacements of all scenarios. The conventional pile (S7) undergoes substantial bending due to the weak deep clay, leading to high curvature and nonlinear deformation. Even with group confinement, the deep clay layer controls the response, allowing significant lateral movement. The helical pile (S8) reduces displacement by approximately 15–20%, but the improvement is limited by the dominant influence of the underlying clay. These results highlight that deep soft clay conditions require special geotechnical consideration regardless of pile type.

3.5. Global Comparison Across All Scenarios

Figure 11 summarizes the maximum displacement for all eight cases, showing that helical piles consistently outperform conventional piles across all soil profiles and layout configurations. The most favorable response is obtained in S6, representing the helical pile in the clay–sand profile with a central layout, whereas the poorest performance occurs in S7, corresponding to the conventional pile in the sand–clay profile with a central layout. Overall, the results demonstrate that soil stratification exerts a more significant influence on lateral performance than the pile layout configuration.

Advance Researches in Civil Engineering
ISSN: 2645-7229, Vol.6, No.4, pages:1-16

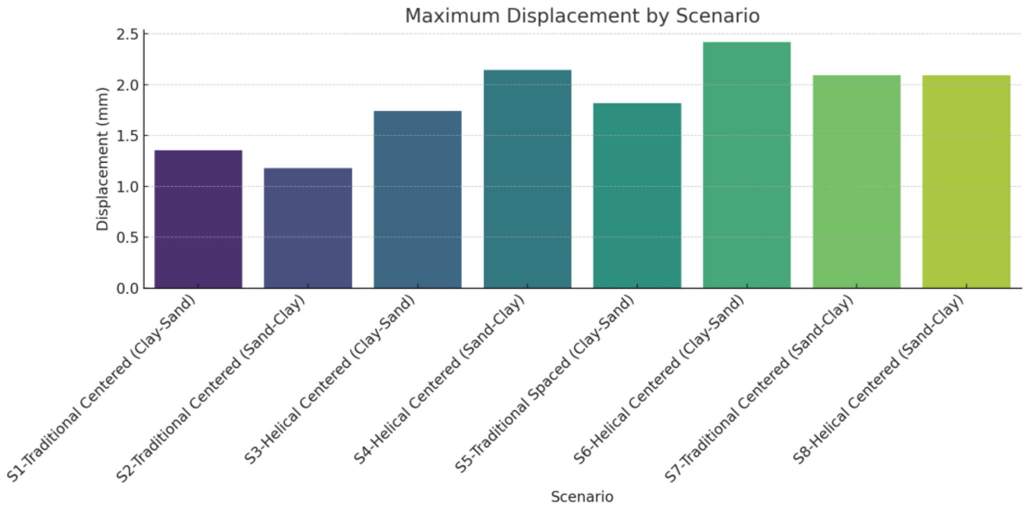

Figure 11. Maximum lateral displacement across all scenarios.

The trend confirms that soil layering governs overall system behavior, with stiffness inversion producing the most severe displacement values.

3.6. Stress Distribution and Failure Mechanisms

Figure 12 shows the effective principal stress fields. Conventional piles develop concentrated stress zones near the pile head, indicating higher bending demands and a greater likelihood of damage under cyclic loads. The helical piles exhibit more uniform stress distribution along the shaft and around helix elevations, reducing localized stress peaks.

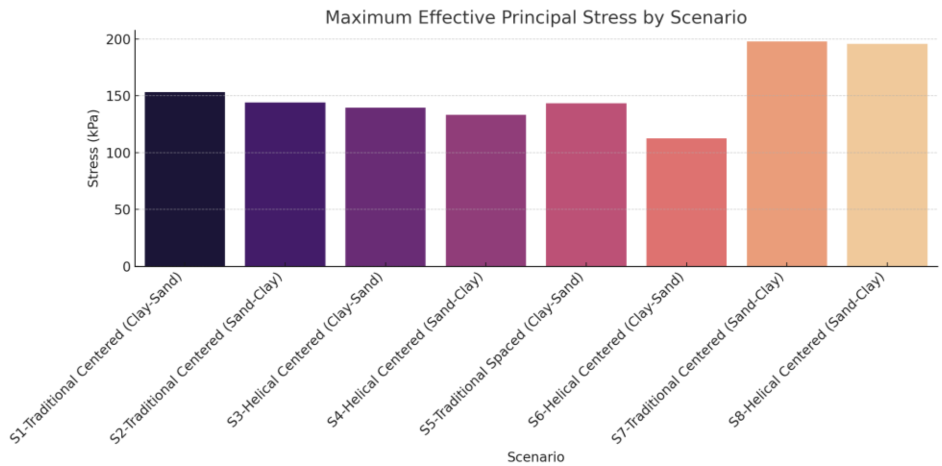

Figure 12. Maximum effective principal stress distribution.

In sand–clay conditions, both pile types form deeper stress bulbs, aligning with the large displacements found in previous subsections. In clay–sand profiles, stress concentration occurs higher in the soil column, but the helices help diffuse stresses more effectively. These patterns validate the superior energy dissipation and load-transfer characteristics of helical piles under multi-hazard loading.

4. Discussion

The integrated numerical results provide a comprehensive understanding of how soil layering, pile type, and layout configuration influence the dynamic performance of deep foundations subjected to sequential seismic and wind loading. The discussion synthesizes these findings by examining displacement trends, bending mechanisms, stress-transfer behavior, and the comparative contributions of soil and pile properties to overall system stability.

4.1. Influence of Soil Stratification

Among all parameters studied, soil layering exhibited the most dominant effect on the dynamic response of both pile types. The clay–sand configuration consistently produced lower displacements across all layouts because the deeper sand layer provided stronger confinement, limiting curvature and distributing lateral forces more efficiently. In contrast, the sand–clay profile resulted in markedly larger displacements, with deformation extending deeper along the shaft.

This behavior aligns well-established geotechnical principles regarding stiffness inversion, where a strong layer overlying a weak one amplifies bending demands under lateral loading. The weak deep clay layer allowed significant pile rotation and cyclic softening, diminishing the stabilizing influence of the overlying sand regardless of pile type.

Thus, soil stratification must be treated as a critical design parameter in regions subject to seismic or wind-induced lateral forces.

4.2. Comparative Performance of Helical and Conventional Piles

Across all eight scenarios, helical piles consistently outperformed conventional piles, achieving reductions in lateral displacement ranging from 15% to 40%. This enhanced performance is primarily attributed to the multi-level confinement generated by the helices, the interruption of shear planes, the more distributed load transfer along the shaft, and the reduced curvature concentration near the pile head. In contrast, conventional piles—modeled as straight cylindrical elements—relied mainly on shaft friction and end bearing, leading to higher bending moments, particularly in stratified soil conditions or when subjected to wind loading following seismic excitation. Overall, helical piles exhibited superior cyclic stability and energy dissipation, reinforcing their suitability for dynamic environments.

4.3. Effect of Layout Configuration

The center layout provided greater lateral stiffness than the edge layout due to improved pile–pile interaction and mutual confinement, an effect most clearly demonstrated in S6 (helical, clay–sand, center), which exhibited the lowest displacement among all scenarios. However, this layout advantage was notably reduced in sand–clay conditions, where the weaker deep clay layer governed the overall response and constrained the stiffness gains typically associated with group interaction. Consequently, while center layouts can enhance lateral performance, their effectiveness is highly dependent on the underlying soil stratification.

4.4. Interaction Between Seismic and Wind Loading

The sequential application of wind loading following seismic excitation resulted in additional lateral displacement in all scenarios, primarily due to soil softening during earthquake shaking, reduced post-seismic stiffness, and the increased vulnerability of the pile head to laterally applied wind forces. Helical piles mitigated this cumulative effect more effectively than conventional piles because their multi-stage soil engagement limited further deformation even under softened soil conditions. These findings highlight the necessity of incorporating multi-hazard loading sequences into foundation design, particularly for tall or wind-sensitive structures.

4.5. Stress Redistribution and Failure Mechanisms

Stress analysis revealed distinct behavioral patterns for conventional and helical piles. Conventional piles exhibited concentrated stress zones near the pile head, reflecting higher bending demand and an elevated risk of cracking or yielding, particularly under sequential seismic–wind loading. In contrast, helical piles demonstrated a more uniform stress distribution along the shaft and around the helix elevations, effectively reducing stress concentrations, improving load-sharing, and delaying the onset of nonlinear behavior. In sand–clay profiles, stress bulbs extended deeper and exhibited greater magnitudes, consistent with the displacement patterns and further underscoring the influence of weak deep layers on controlling overall deformation responses. These characteristics highlight the sensitivity of conventional piles to stratified soil stiffness, while helical piles benefited from multi-level engagement with the surrounding soil. Overall, the findings confirm that helical piles possess enhanced resilience under cyclic and dynamic loading due to their ability to distribute stresses across a larger soil volume and maintain more stable structural behavior under multi-hazard conditions.

4.6. Synthesis of Key Findings

Table 3 summarizes the primary interpretations from the dynamic simulations, highlighting the complex interplay between soil properties, pile behavior, and layout configuration. The synthesized results illustrate how variations in stratification, stiffness contrast, and loading sequence govern lateral resistance and deformation patterns, while also revealing the distinct advantages of helical piles in mitigating cyclic effects. This table provides a consolidated framework for comparing performance trends across all scenarios and serves as a basis for understanding the governing mechanisms behind observed differences in displacement, stress distribution, and overall stability.

Table 3. Summary of Observed Behaviors and Engineering Implications.

Topic	**Findings**	**Engineering Interpretation**	**Implications for Design**
Soil Stratification	Clay–sand: lowest displacement; Sand–clay: deepest bending	Stiff deeper sand limits curvature; weak clay amplifies deformation	Improve deep clay or increase embedment
Pile Type	Helical piles reduce displacement 15–40%	Helices mobilize confinement and interrupt shear planes	Prefer helical piles in dynamic soils
Layout	Center layout reduces displacement	Pile–pile interaction increases stiffness	Center layout beneficial for towers
Multi-Hazard Loading	Wind amplifies post-seismic deformation	Soil stiffness reduces after earthquake	Include sequential loading in design
Stress Redistribution	Helical piles distribute stresses; conventional piles concentrate them	Better energy dissipation via helices	Lower structural damage risk
Critical Scenario	Sand–clay + center (S7) worst	Deep clay governs behavior	Additional ground improvement required

5. Conclusions

This study presented a comprehensive three-dimensional numerical comparison of conventional and helical piles subjected to sequential seismic and wind loading in layered soil conditions using PLAXIS 3D. Eight scenarios incorporating soil stratification, pile type, and layout configuration were analyzed to evaluate lateral displacement, deformation mechanisms, and stress-transfer behavior. Based on the findings, the following conclusions can be drawn:

1-Soil stratification is the dominant factor influencing dynamic pile response. Clay–sand profiles demonstrated significantly lower lateral displacements due to the confining effect of the deeper sand layer, whereas sand–clay profiles produced the largest deformations and deepest bending zones due to stiffness inversion.

2-Helical piles outperform conventional piles in all scenarios. The presence of helices enhanced confinement, interrupted shear pathways, and distributed stresses more uniformly along the pile shaft. This resulted in 15–40% reductions in maximum lateral displacement, underscoring the improved cyclic and dynamic resistance of helical systems.

3-Pile-group configuration affects lateral performance, with center layouts providing superior stiffness.

4-Center-group piles benefited from mutual confinement, reducing deformation more effectively than edge configurations. The best-performing scenario was S6 (helical, clay–sand, center), while the worst was S7 (conventional, sand–clay, center).

5-Sequential wind loading after seismic shaking leads to additional displacement. Wind forces applied after an earthquake amplified lateral movement due to soil softening and reduced stiffness. Helical piles mitigated this cumulative effect more efficiently than conventional piles.

6-Stress distributions validate the mechanical advantages of helical piles. Conventional piles developed concentrated stresses at the pile head, indicating higher bending demand. In contrast, helical piles exhibited more uniform stress bulbs at helix elevations, reducing the risk of localized structural damage.

7-Weak deep clay layers pose a critical risk regardless of pile type. Sand–clay profiles consistently produced high displacement values and large stress concentrations, emphasizing the necessity of soil improvement or increased embedment in such conditions.

Overall, the results highlight that helical piles offer a robust and efficient alternative to conventional piles in dynamic and layered soil environments, especially when subjected to multi-hazard loading. The findings support the incorporation of helical piles into performance-based earthquake engineering and indicate the importance of accounting for soil layering, group interaction, and sequential load effects in foundation design.

6. Recommendations

Based on the numerical findings and analytical discussions presented in this study, several engineering and research recommendations can be proposed to enhance the design, performance, and assessment of deep foundations subjected to multi-hazard loading:

Adopt helical piles as a preferred foundation option in dynamic and layered soil environments. Their superior resistance to lateral deformation, improved stress distribution, and enhanced cyclic performance make them suitable for regions exposed to seismic and wind hazards.

Give special attention to soil stratification during design, particularly in stiffness inversion conditions.

Sites characterized by sand-over-clay profiles should undergo detailed geotechnical evaluation, as weak deep clay layers significantly amplify bending and lateral displacement.
Increase embedment depth or apply soil improvement techniques in sand–clay layouts. Ground enhancement methods—such as deep mixing, partial saturation, or compaction grouting—can improve the confining response of deep clay layers and reduce dynamic deformation.
Overall, these recommendations emphasize the necessity of integrating soil stratification, advanced modeling, and multi-hazard loading conditions into modern foundation engineering practice to ensure safer and more resilient structural systems.

7. References

1- Novak M., "Dynamic response of piles and pile groups," Canadian Geotechnical Journal, vol. 17, no. 3, pp. 383–394, 1980.
2- Wolf J. P., Foundations for Dynamic Equipment. New York, NY, USA: Prentice-Hall, 1994.
3- Tomlinson A. R. B., Woodward M., Pile Design and Construction Practice, 5th ed. London, U.K.: Taylor & Francis, 2008.
4- Fu, Q., Zhang, Q.-L., Wu, X.-Y., Li, J.-B., & Zhao, T.-T. (2021). Experimental analysis on dynamic response of X-section piled raft composite foundation under cyclic axial load for ballastless track in soft soil. Shock and Vibration, 2021.
5- Matlock R., "Correlations for design of laterally loaded piles in soft clay," in Offshore Technology Conference, Houston, TX, USA, 1970, pp. 1–10.
6- Hambleton, J. P. and Stanier, S. A. (2019). Linking the installation response of screw piles to soil strength and ultimate capacity. In: Proceedings of the 1st International Symposium on Screw Piles for Energy Applications, Dundee, UK, May 27–28, 2019, pp. 57–58.
7- Reese L. C., Van Impe W. F., Single Piles and Pile Groups Under Lateral Loading. Boca Raton, FL, USA: CRC Press, 2011.
8- PLAXIS BV, PLAXIS Dynamics Module Manual. Delft, Netherlands: Bentley Systems, 2022.
9- Trautmann N. S., O'Neill L. C., "Behavior of drilled shafts subjected to lateral loading," Journal of Geotechnical Engineering, vol. 111, no. 3, pp. 355–370, 1985.
10- Poulos H. G., Davis E. H., Pile Foundation Analysis and Design. New York, NY, USA: Wiley, 1980.
11- Ashour M., Norris L., Pilling N., "Lateral loading of piles in layered soils using the p–y curve method," Journal of Geotechnical and Geoenvironmental Engineering, vol. 130, no. 4, pp. 372–382, 2004.
12- American Petroleum Institute (API), Recommended Practice 2A-WSD: Planning, Designing, and Constructing Fixed Offshore Platforms — Working Stress Design, 22nd ed., Washington, DC, USA, 2011.
13- Aburqaq I. S., Naimi S., Saedi S., Shahin M. A. A., "Assessment of UAV usage for flexible pavement inspection using GCPs: Case study on Palestinian urban road," Sustainability, vol. 17, no. 18, p. 8129, 2025.
14- Saedi S., "Laboratory investigation of the effect of de-icing solutions on moisture susceptibility of hot mix asphalt with biomass fibers," Innovative Infrastructure Solutions, vol. 9, no. 11, p. 442, 2024.
15- Saedi S., "Evaluation of the effect of para-aramid and micro-polyolefin fibers on permanent displacement in stone mastic asphalt," Journal of Sustainable Construction Materials and Technologies, vol. 9, no. 2, pp. 106–113, 2024.

16- Abdelsalam M., Seyedi M., "Numerical evaluation of pile-driving-induced vibrations in soil and their impact on adjacent structures," Journal of Civil and Hydraulic Engineering, vol. 3, no. 1, pp. 17–32, 2025.
17- Donohue, S. W., Briaud, J. L., and Wang, D. (2017). "Investigation of the mobilized strain wedge by laterally loaded helical piles." In Proceedings of the 8th International Conference on Helical Piles and Tiebacks, New Orleans, LA, USA, pp. 1–10.
18- Perko D., Helical Piles: A Practical Guide to Design and Installation, 2nd ed. Hoboken, NJ, USA: Wiley, 2009.
19- Hoyt M. T., Clemence S. P., "Uplift capacity of helical anchors in soil," in Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro, Brazil, 1989, pp. 1019–1022.
20- McClelland B. C., Focht T., "Soil modulus for laterally loaded piles," Journal of Soil Mechanics & Foundations, vol. 73, no. 5, pp. 283–297, 1958.
21- Khan A. R., Azzam Y. M., "Nonlinear soil–pile interaction under dynamic loads," Soil Dynamics and Earthquake Engineering, vol. 67, pp. 199–209, 2014.
22- Nguyen N. P. J., van Tol T. A., "3D numerical modeling of pile group response under lateral loading," Computers and Geotechnics, vol. 72, pp. 75–88, 2016.
23- El Naggar D., Novak T., "Nonlinear analysis for dynamic response of piles and pile groups," Journal of Geotechnical Engineering, vol. 120, no. 2, pp. 237–253, 1994.
24- Singh Y. P., Kurian A., "Dynamic lateral response of piles in layered soil," Earthquake Engineering and Structural Dynamics, vol. 39, no. 12, pp. 1371–1390, 2010.