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Study on Rectangular Winged Pile with Toothing System Subjected to Static and Dynamic Loadings

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Abstract Events like earthquakes, waves and wind can exert significant lateral pressure on pile foundation supporting structures, including towering buildings, transmission towers, offshore constructions, and bridges. The present study illuminates the notable improvements in the ability of monopile foundations to withstand lateral cyclic, static, and axial loads by implementing toothing system in rectangular wing design. Furthermore, findings serve as valuable information for optimizing foundation configurations in structures that face lateral and axial loads. In particular, this research delves into the structural behaviour of a novel pile foundation design that features rectangular wing with toothing system. The study compares the behaviour of traditional monopile to rectangular winged pile with toothing system, subjected to static, cyclic, and axial loads. The numerical simulations were performed to evaluate the effectiveness of piles when subjected to cyclic lateral loads, static loads, and axial loads using ANSYS software. The static load simulations incorporated displacements ranging from 2 mm to 10 mm. The results revealed that the rectangular winged pile toothing system displayed a 35% improvement in resistance against static lateral loads compared to the monopile. In cyclic loading, rectangular winged pile with a toothing system showed significant improvements in load resistance, surpassing the monopile by 71.62% in positive direction and 74.29% in negative direction and 103.53% for axial loading when compared with conventional monopile.

Keywords Rectangular Pile Wing, Toothing System, Cyclic Loading, Static Loading, Axial Loading, Numerical Simulation

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1. Introduction

Pile support is used to support a large number of bridges, tall buildings, and transmission towers. Large lateral loads from events like earthquakes and strong winds could be applied to these structures. Within these piles that will have little lateral resistances under load, improvement is necessary. Pankaj, et al. [1] stated that the monopile foundations are an essential component in the construction of offshore structures like wind turbines that must withstand powerful external forces, including wind, waves, hurricanes, and earthquakes. Nevertheless, foundations for offshore structures must endure significant environmental stresses from wind, waves, and currents, which can result in lateral loads equal to or greater than one-third of the vertical loads. Taha K. Mahdi [2] studied that these external forces may lead to a decrease in the lateral resistance of commonly used pile foundations, necessitating their improvement to withstand the imposed loads more effectively. Improved resistance against horizontal or lateral stresses is necessary for mono piles because they support the weight and forces of above-water constructions. J Peng [3] investigated that to enhance the lateral capacity of piles, it is vital to consider aspects such as pile geometry, soil properties, and the type of loading. Studies on single piles have been conducted to examine the lateral capacity, the impact of rigidity, and novel pile foundations like tapered piles [4] and fin piles, tripod, and helical piles are used [5-7]. Richards et al. [8] studied the rotational behavior of monopiles subjected to complicated cyclic lateral loading in sand and reported that large-diameter open-ended steel piles have grown in size over time to support greater OWTs and in deeper water. Sung-Ha Baek and Joonyoung Kim [9] studied the effect of soil properties, specifically the existence of silt in the sand matrix, on the response of piles to cyclic loading and investigated how variations in soil composition, density, and moisture content can affect the magnitude and distribution of lateral soil pressure along the pile shaft, ultimately influencing its structural response and stability. A three-dimensional analysis of laterally loaded fin piles was investigated by J Peng [10]. Plotting the lateral resistance against the movement of the pile head shows how adding fins to a pile increases its lateral resistance. The lateral resistance rises as fin length grows, according to numerical study. When the fin length is half the pile length, a fin pile operates at its most efficient level. A pile's lateral load capacity increases as the diameter at the pile head increases. It has been established that adding wings close to the seafloor increases the pile's ability to support lateral loads. According to research by Hocine Haouari and Ali Bouafia [11], the pile deflection (Y0) at the mudline shows a cumulative increase in logarithmic form, whereas the maximum bending moment (Mmax) increases logarithmically with the number of loading cycles (N) and the absolute stiffness of the pile degrades as a power function with the number of cycles, indicating a reduction in pile stiffness over successive loading cycles. Min Yang et al. [12] studied the importance of shear force tangent to the monopile circumference as a crucial component of soil resistance to lateral loading. Ignoring these shear forces can lead to significant discrepancies in force and moment equilibrium. Duhrkop and Grabe [13] introduced the idea of piles with wings attached to the pile head to boost lateral stiffness and capacity. The combination of the soil, the wings, and the pile shaft's stiffness determines how effective the wings are. To get the same benefit from adding to the pile section in stiff soil, the wings' stiffness needs to be higher than it is in weak soil. It has been demonstrated that winged or finned piles are more effective than other conventional techniques like strengthening shallow soils or enlarging pile diameters [14]. The pile's wings, or fins, will increase its bearing capacity, enabling it to be used in deeper water or permitting the designer to reduce the pile's size in order to reduce costs associated with manufacturing, transportation, and installation; additional benefits include reduced drive times and fewer operating site hazards. The research of laterally loaded circular piles has been effectively conducted using finite element methods computer codes, such as LPILE, PLAXIS, ANSYS, and ABAQUS [15-16]. Xinglei Cheng et al. [17] investigated the behavior of large diameter monopiles under cyclic lateral loading conditions, a scenario often encountered in offshore applications due to factors like wave and wind forces. Three-dimensional (3D) finite element analysis was analysed by Chik, Taha, Kim and Jeong [18-20] as a way to use the PLAXIS tool to simulate a lateral load test. The finite element (FE)-based numerical modelling techniques offer flexible tools that can be used to represent 3D boundary conditions, soil continuities, soil nonlinearities, and soil–pile interface behaviour. Thus, using the 3D nonlinear computer program PLAXIS 3D Foundation, a number of FE analyses were performed on model-scale and prototype-scale piles exposed to lateral stress and soil conditions as in the model tests.

This paper addresses the enhancement of lateral load capacity in monopiles, vital foundation structures in offshore wind turbines, and marine construction by integrating rectangular wings with toothing system on all four sides of the pile. The study aims to bolster the structural resilience of these singular steel piles driven into the seabed. The efficacy of a novel foundation design in comparison to rectangular winged pile with toothing system is examined. Through extensive testing under a range of loading circumstances such as lateral cyclic loading, static loading, and axial loading, ANSYS software is used to precisely simulate the models and evaluate the performance and outcomes. An extensive comparative analysis of the results provides valuable insights into the structural behaviour and performance characteristics of each model at different loading scenarios.

2. Methodology

This study employs a systematic approach to analyzing monopiles using ANSYS. The monopile models, with specified dimensions and embedded length, include rectangular wings with a toothing system to evaluate structural behavior under various loading scenarios. The soil model, scaled to reflect highly porous conditions, supports the pile at a specified depth. The finite element analysis involves detailed modeling, meshing, and application of realistic boundary and loading conditions to simulate static, cyclic, and axial forces. The approach integrates scaled-down material properties and nonlinear behavior to ensure accurate representation and evaluation of the monopile's performance under different scenarios. The flowchart of the analysis is depicted in Figure 1.

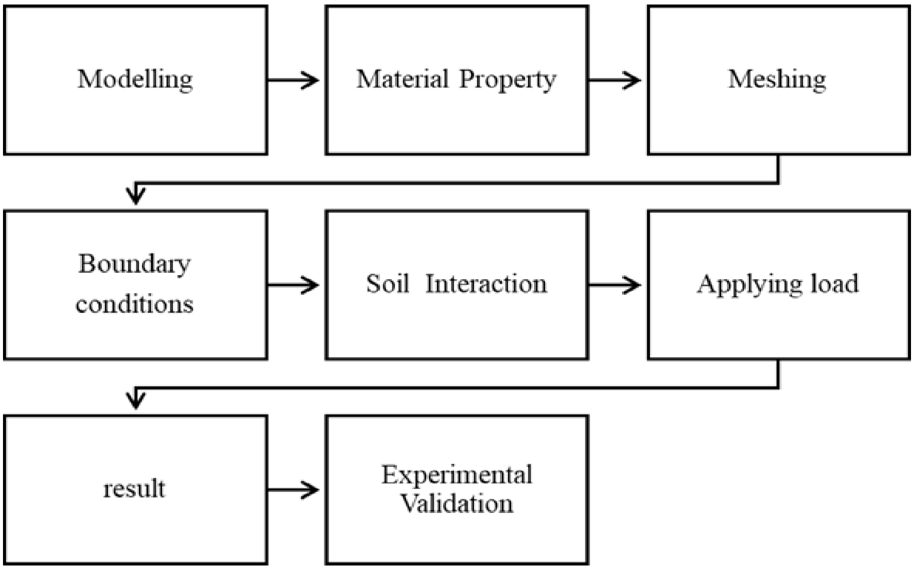


Figure 1. Flowchart of analysis

2.1. Modelling of Monopile

The dimensions of the piles under investigation in this study are consistent, with an embedded length of 280 mm, an outer diameter of 45 mm, and an inner diameter of 40 mm. The rectangular wing with toothing system is connected to all four sides of the pile with dimensions of 70 mm in length, 5 mm in thickness, 25 mm in breadth, length of the teeth is 10mm and spacing between the teeth is equal to the thickness of the pile as shown in Figure 2. These design details are an essential component of the experimental setup that allows for a comprehensive analysis of the structural behaviour of the piles under various loading scenarios. The height of the soil model is equal to the pile length (LP) plus an extra 0.7LP below the pile-toe level, and whose sides are 26 times the diameter of the pile [21-22]. Nevertheless, the greatest pile displacement in this investigation is constrained to 20 mm. As a result, as shown in the Figure 4, the model is built using the pile size and maximum displacement. In the middle of the soil model, the pile is driven. To shift the pile head, the pile is exposed 70 mm above the ground as shown in figure 3 [23]. 3D models of the piles are depicted in Figure 3 and the properties of monopile are tabulated in Table 1. Since the pile model is scaled down in the ratio 1:100, the material property of the pile is also scaled down. By scaling down the material properties in proportion to the model size reduction, nonlinear behaviour is applied in the analysis. This nonlinear behaviour arises because the scaled-down material properties affect the stiffness, strength, and other characteristics of the pile differently than they would at full scale.

2.2. Modelling of Soil

Highly porous soil is used for the investigation of lateral and axial load capacity of the monopiles. The dimensions of the soil model are 800x800x800 mm, and the pile is positioned in the middle of it. Precisely reaching the top of the pile wing, the piles are driven to a depth of 210 mm as shown in Figure 4. This arrangement seeks to replicate real-world circumstances and permits the examination of the interaction between the unique pile designs and the specified loose, extremely porous soil. The properties of soil are tabulated in Table 2. The soil may initially exhibit linear behavior similar to an elastic material under minor lateral displacements. This suggests that the soil stretches directly in response to the imposed stress and returns to its initial shape when the force is released. Scaling down the soil parameters is necessary to accurately capture the nonlinear impacts, if the soil shows nonlinear behavior under the specified loading conditions. Moreover, the interaction between the monopile and the surrounding soil can introduce nonlinearities. As the monopile deflects laterally, it may trigger additional soil resistance, resulting in nonlinear responses such as heightened stiffness or resistance at increased displacements.

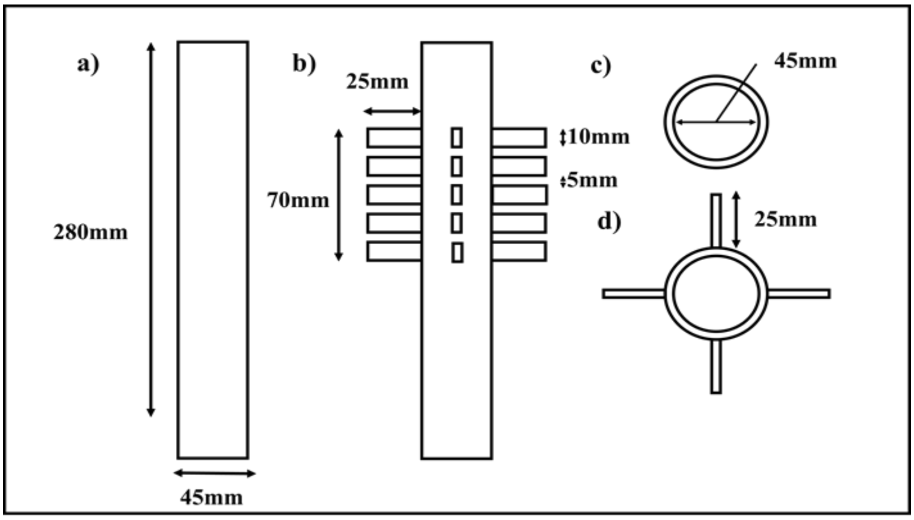


Figure 2. Schematic representation of pile models a) conventional monopile b) rectangular winged pile with toothing system c) top view of monopile d) top view of rectangular winged pile with toothing system

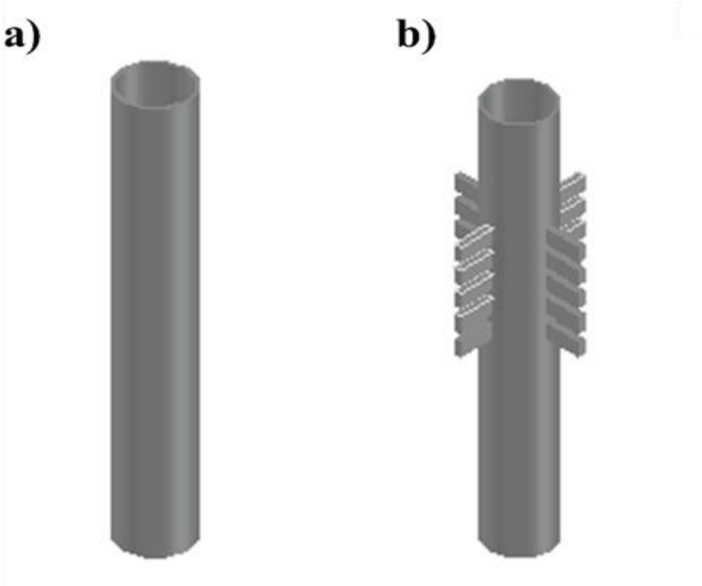


Figure 3. 3D view of modelled pile a) conventional monopile b) rectangular winged pile with toothing system

Table 1. Properties of monopole

S.no	Property	Value
1	Density	7850 KPa
2	Young's modulus	2000 MPa
3	Poisson Ratio	0.3
4	Shear modulus	7.6 MPa
5	Bulk modulus	1.6 MPa
6	Yield strength	2.5 MPa
7	Tangent Modulus	MPa

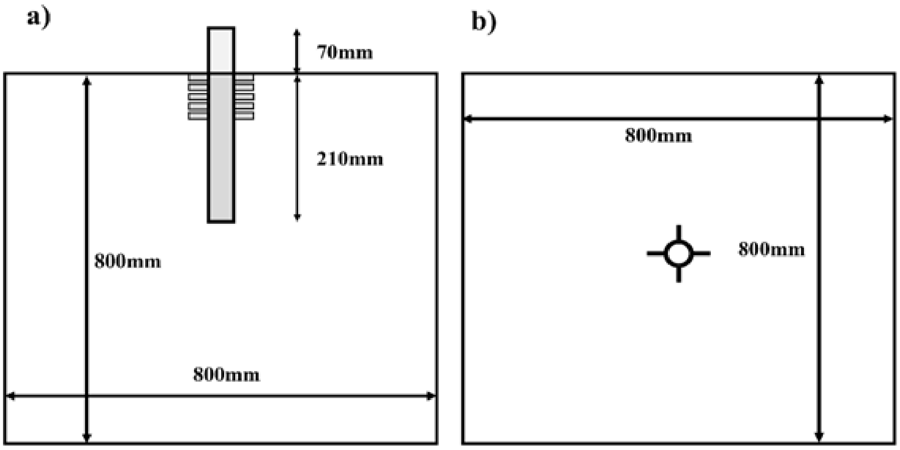


Figure 4. Schematic representation of soil models a) Cross section of the soil model, b) top view of the soil model

Table 2. Properties of soil

S.no	Property	Value
1	Coefficient of thermal expansion	1.23×10^{-5}
2	Young's modulus	0.75 MPa
3	Poisson Ratio	0.33
4	Bulk modulus	7.35 MPa
5	Shear modulus	2.81 MPa
6	Dilatancy angle	0.087 rad
7	Initial friction angle	0.61 rad
8	Initial cohesion	$X\ 10^{7}$

2.3. Numerical Simulation

The study demonstrates the significance of ANSYS as a finite element analysis tool, enabling a comprehensive examination of pile behaviour in offshore structures. Complex models with assigned geometric features and material qualities are meticulously developed using ANSYS. The research aims to evaluate the effects of wing incorporation with a toothing system on monopiles under axial, cyclic, and static loading scenarios. By utilizing ANSYS's advanced modelling capabilities to simulate pile behaviour under various loading circumstances, the load bearing capacity of pile models is examined.

2.4. Meshing

In numerical simulations, the process of discretizing a geometric model into smaller, interconnected components to describe the physical behaviour of the structure or component under study is known as finite element meshing. The intricate interactions and responses that occur within the system must be precisely captured by means of this procedure, which is called finite element meshing. A finite number of elements must be created during the meshing process in order to cover the entire domain and ensure that the model accurately captures the structural features and properties. Triangular or quadrilateral components are frequently employed for 2D problems, such as plane stress or plane strain analysis, while tetrahedral or hexahedral elements are chosen for 3D problems in order to reflect the volumetric domain. The element type used is determined on the geometry and complexity of the problem being analyzed. The quality and density of the mesh have a significant impact on the simulation results' correctness. More accurate results can be obtained by using finer meshes with smaller pieces because they can capture minute nuances and variations in the structural behavior. On the other hand, creating overly fine meshes may result in longer computation times and inefficiencies. For accurate and effective simulations, then, a compromise between mesh density and processing resources needs to be made. Refinement techniques for meshes, including adaptive meshing or local refinement, can be used to maintain a reasonable mesh density elsewhere and concentrate computational efforts on areas of relevance. Mesh independency of the model is depicted in Figure 5.

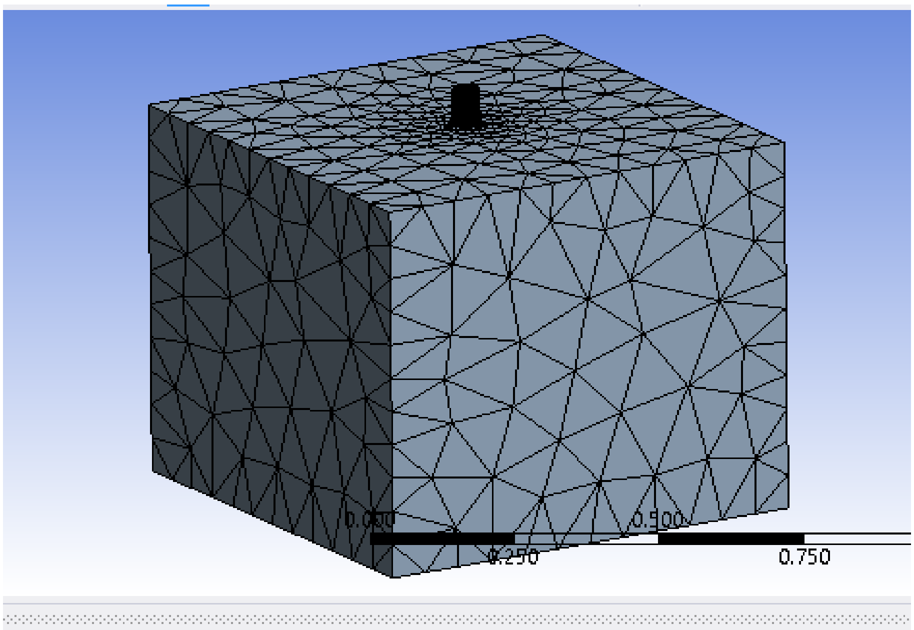


Figure 5. Meshing

2.5. Boundary Conditions

To replicate the behaviour of the pile driven into the soil, specific boundary conditions are applied. The ground surface was free to move in any direction, the bottom boundary (the x–z bottom plane) was fixed against movements in all directions (x, y, and z). Each node at the end of the x-y and y-z planes, or the vertical bounds of the model, was constrained in the z and x directions, respectively. The pile is treated as the contact body, while the soil surface in contact with the pile is designated as the target body. This approach allows for the analysis of the interaction between the pile and the surrounding soil, considering factors such as friction and contact pressure.

2.6. Loading Pattern

The load is applied at the edge of the pile head, representing the location where external forces or moments are expected to act on the pile structure. This point is chosen strategically to simulate realistic loading conditions and accurately capture the response of the pile to lateral forces. The magnitude and direction of the load are specified based on the design requirements or expected environmental conditions. This could involve applying a lateral force, such as wind or wave loading, or a moment, such as due to uneven soil settlement or seismic activity. The load magnitude and direction are chosen to represent the anticipated loading scenarios accurately. In general, the loading process involves applying loads to the pile head gradually over a number of load steps or time increments. By using a gradual loading approach, stability and convergence of the solution are ensured and the analysis is able to capture the progressive reaction of the pile and the surrounding soil.

Three types of loading patterns were utilized to analyze the lateral and axial load capacities of the pile. For static loading, the pile head is progressively shifted laterally from 0 to 10mm in 2mm increments per second as shown in Figure 6. The cyclic lateral loading test involved repetitive displacement, starting at 0mm to 2mm, then back to 0mm, followed by displacement to -2mm and back to 0mm, making one cycle which is 1Hz. This pattern was repeated with 2mm increments per cycle until reaching 10mm as depicted in Figure 7. In the axial loading test, the pile was displaced downward from its initial position 0mm to 10mm at a rate of 2mm per second as same as static loading but till 10mm which is shown in Figure 5. These loading patterns helped evaluate the pile's behaviour under different conditions.

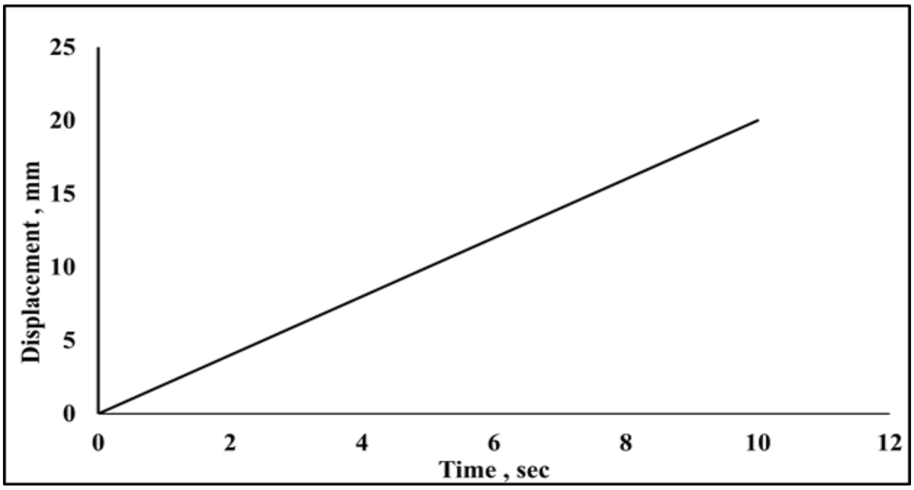


Figure 6. Static and axial loading

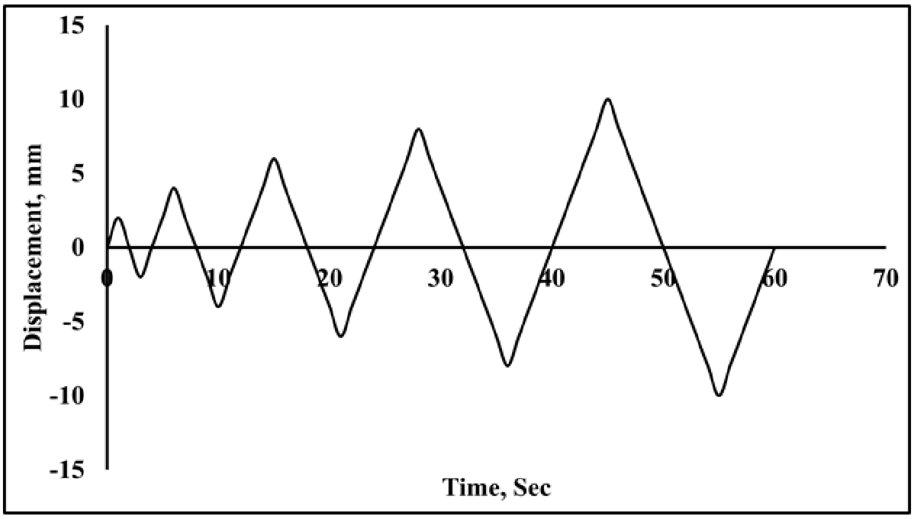


Figure 7. Cyclic loading pattern

3. Results and Discussion

The behaviour of rectangular winged piles with toothing systems in extremely porous soil was investigated using a series of finite element analyses by comparing it with conventional monopile. The loading conditions included axial, cyclic, and static loads applied at the pile head. The results are shown as load-deflection curves. The load–deflection relationship at pile head is a key need for all piles tested under a lateral load. Therefore, the design of lateral force is governed by the lateral deflection at working load and the ultimate strength of pile.

3.1. Rectangular Winged Pile with Toothing System under Static Load

The response of offshore structures, like monopiles supporting wind turbines, lateral loads is realistically simulated by means of static loading testing. The simulation can replicate the gradual and constant pressures that wind, waves, and currents deliver to the structure by progressively increasing the lateral forces. Static loading tests help identify potential failure points in the monopile structure under lateral loading conditions. In the static load analysis of the pile, a displacement of up to 20 mm was observed at the pile head. To evaluate their performance, a monopile and a rectangular winged pile with a toothing mechanism were compared. The monopile encountered a maximum load of 298 N to achieve a 20 mm displacement when a lateral force was applied to the pile head, with the largest stress localized at the pile head. On the other hand, a maximum load of 403 N was observed for the rectangular pile with a toothing mechanism to produce the same 20 mm displacement.

Due to its improved structural features and load-distribution mechanism, the toothing system took on more load than the monopile. The purpose of the toothing system is to increase the surface area in contact with the soil by placing projecting components, or teeth, along the surface of the pile. Because of the higher surface area, the weight is transferred from the pile to the surrounding soil more effectively, thereby dispersing the applied load across a greater region. Further improving the pile's resistance to lateral loads is the added frictional resistance that the teething system's teeth provide between the soil and the pile. The pile is stabilized and excessive movement under load is prevented by the greater frictional resistance. Higher relative densities are linked to increased lateral load capacities because increasing densities cause sand to have higher shear strengths, which results in a larger load-bearing capacity compared to the monopile [24-25]. The load displacement behaviour is shown in Figure 8.

3.2. Rectangular Winged Pile with Toothing System under Cyclic Load

Lateral cyclic loading tests help assess the structural integrity and performance of monopiles subjected to dynamic lateral forces, such as those induced by waves, wind, or seismic events. Cyclic load test is done to identify potential failure modes, such as fatigue cracking or excessive deformation, and evaluate the pile's ability to withstand repeated loading cycles over its design life. A rectangular winged pile with a toothing system performed better than a monopile in the pile's cyclic load analysis, which showed a maximum displacement of 10 mm at the pile head. The monopile demonstrated a maximum load of 296 N in the positive direction and 319 N in the negative direction to achieve a 10 mm displacement when subjected to lateral stresses applied at the pile head. The toothing system-equipped rectangular pile saw significantly greater loads; for a given displacement, the maximum load in the positive direction was 508 N, while the maximum load in the reverse direction was 557 N. Due to a number of important variables, the toothing system notably faced larger loads than the monopile, especially in the negative direction. Load displacement curves are shown in Figure 9 and Figure 10.

The presence of teeth in the toothing system introduces additional frictional resistance between the pile and the soil. This higher frictional resistance might cause a greater resistance to movement in the negative direction than in the positive direction when subjected to cyclic loading. In this case, the presence of teeth in the toothing system increases frictional resistance between the pile and the soil, which helps to stabilize the pile and resist movement, particularly under cyclic loading conditions. The toothing system helps to distribute applied loads more evenly along the length of the pile by increasing the surface area in contact with the soil. This improves the pile's ability to withstand lateral stresses and enhances its load-bearing capacity. Changes in soil behaviour, such as compaction and displacement, can affect the structural response of the pile. The toothing system interacts with the surrounding soil during cyclic loading, influencing its behaviour and contributing to the overall performance of the pile. Cyclic loading may cause fatigue and deformation in the pile and the toothing system, altering their mechanical characteristics and potentially affecting their load-carrying capabilities. Mechanical fatigue occurs when a material undergoes repeated loading and unloading cycles, leading to degradation and potential failure over time.

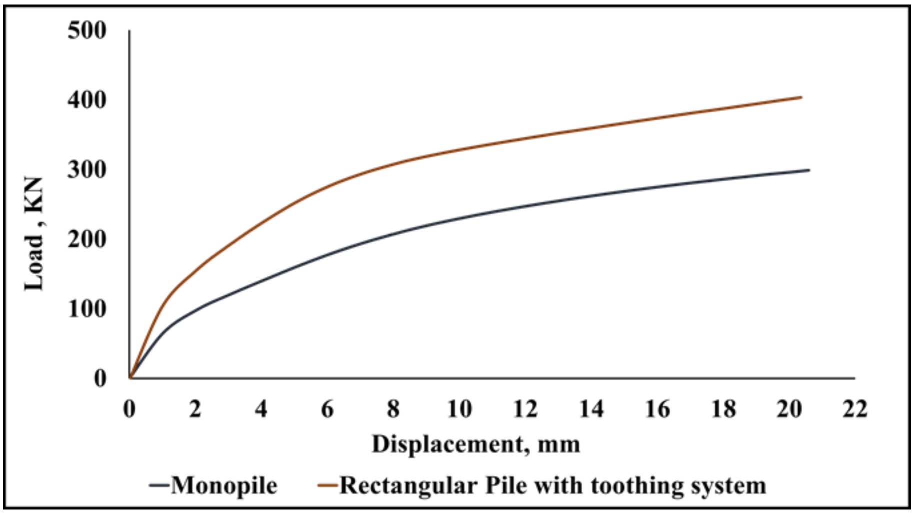


Figure 8. Response of piles under static loading

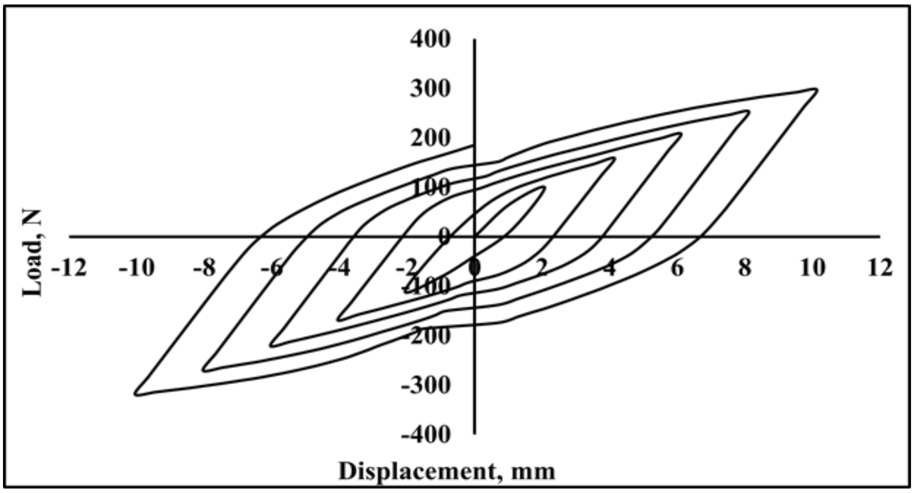


Figure 9. Response of monopile under lateral cyclic loading

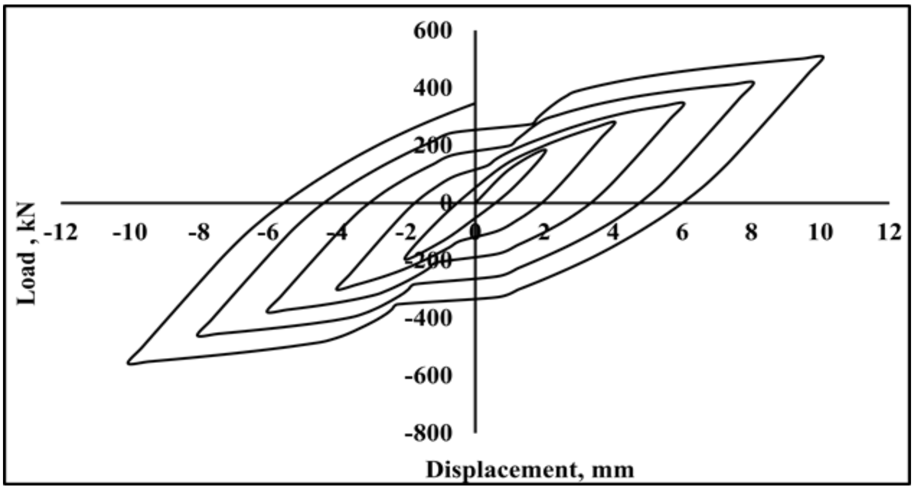


Figure 10. Response of rectangular winged pile with toothing system under cyclic loading

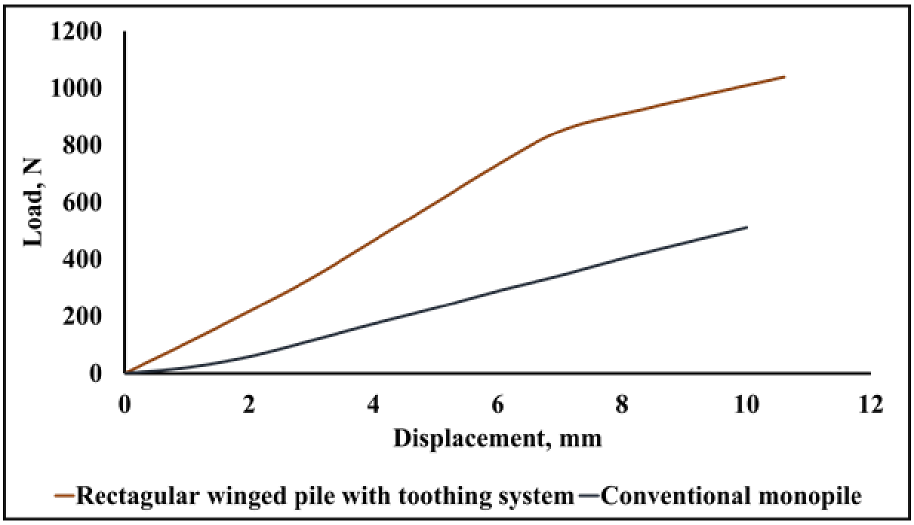


Figure 11. Response of rectangular winged pile with toothing system under axial loading

3.3. Rectangular Winged Pile with Toothing System under Axial Load

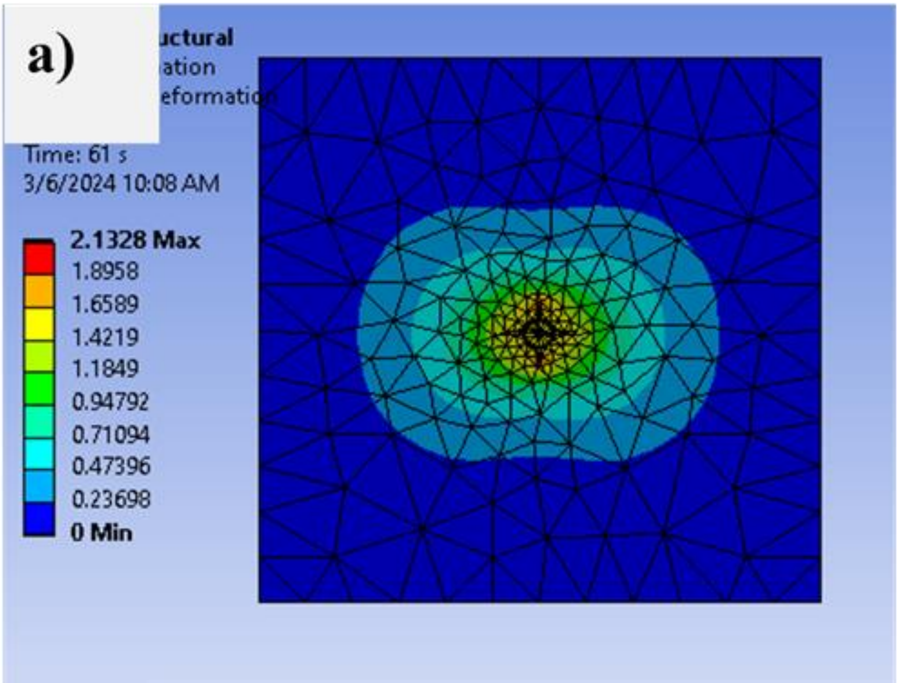
The axial load test helps evaluate the stability and performance of the monopile as a foundation element. It assesses how well the monopile resists settlement, uplift, or lateral movement under vertical loads, which is crucial for maintaining the stability of offshore structures. The monopile showed a linear response, needing a force of 510 N to create a 10 mm displacement, according to the load-displacement graph. The smooth surface of the monopile, which causes little contact with the surrounding soil, is responsible for this linear behaviour. In contrast, a far larger load of 1038 N was required for the winged pile with a toothing mechanism to achieve the same 10 mm displacement. The existence of the toothing system and soil modification are the two main causes of this significant increase in load.

In the analysis of axial load, the responses were observed between the monopile and the winged pile with a toothing mechanism. The monopile exhibited a linear relationship between the applied axial load and the resulting displacement. This linear behaviour can be attributed to the smooth surface of the monopile, which limits its contact with the surrounding soil. Conversely, the winged pile with a toothing mechanism displayed a nonlinear response to axial load. The presence of the toothing system increased surface contact with the soil, leading to compaction and modification of the surrounding soil. As a result, higher loads were required to produce displacement compared to the monopile. The toothing system also introduced additional frictional resistance between the pile and the soil, enhancing the pile's ability to support weight. This improved load distribution mechanism allowed the winged pile to efficiently distribute the applied weight more evenly along its length, thereby increasing its total load-carrying capability.

Overall, the analysis of axial load highlighted the influence of surface contact, soil modification, and load distribution on the load-displacement behaviour of piles, underscoring the significance of these factors in pile design and performance evaluation. Consequently, as comparison to a monopile, the toothing system efficiently distributed the applied weight more evenly down the length of the pile, increasing its total load-carrying capability. The load displacement curves are shown in Figure 11.

4. Pile-Soil Deformation

The investigation found that there was a considerable amount of soil disturbance surrounding the pile's front, with the greatest lateral displacement happening right behind the pile. The precise timing of the soil's movement matched the pile's own displacement. This link is demonstrated by the pile-soil deformation in Figure 12, which also shows the amount of soil movement in response to the activity of the pile. These results highlight the complex relationship between structural components and the soil environment around them.



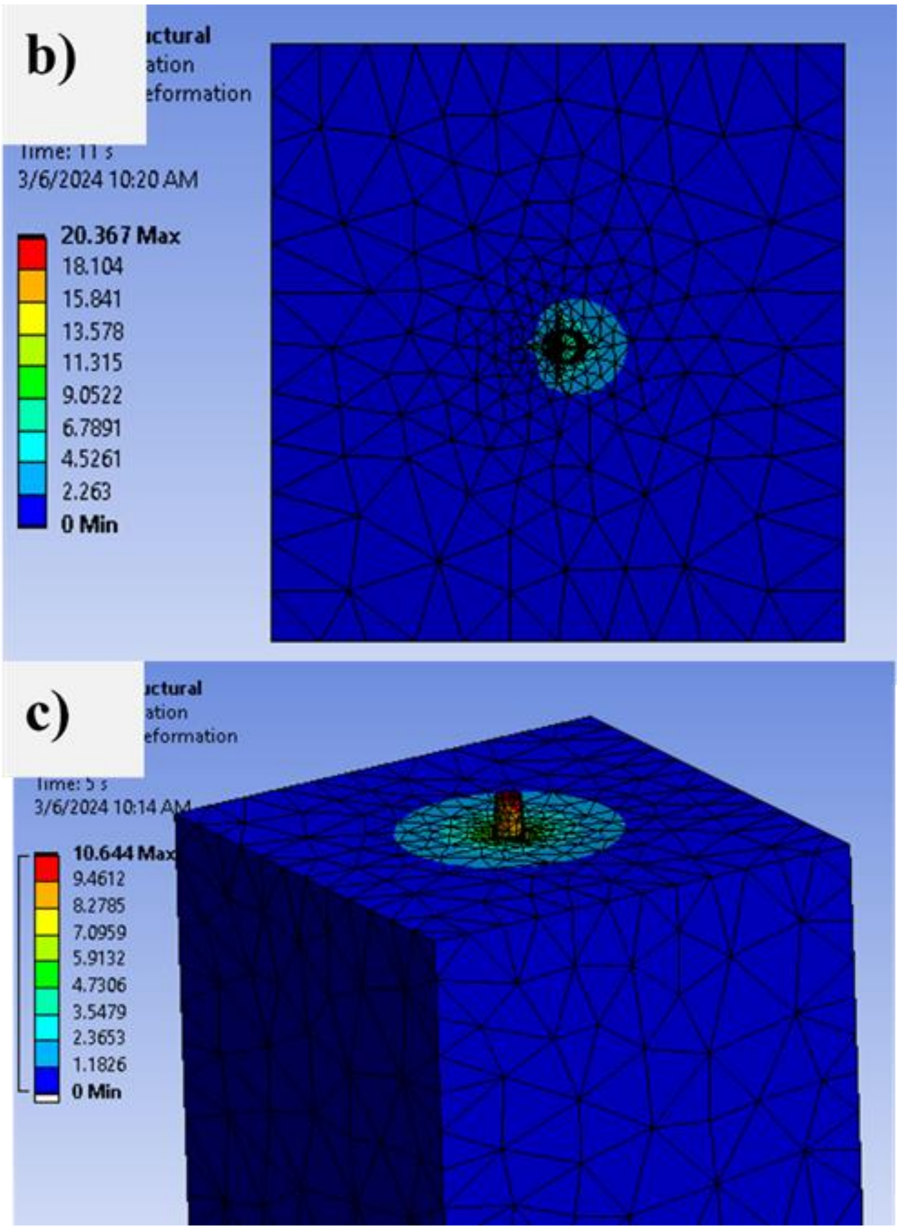


Figure 12. Pile-Soil deformation at total displacement under a) Cyclic load, b) Static load c) Axial load

5. Experimental Validation

As part of an experimental validation procedure, an axial load test was carried out to validate numerical results. In order to conduct the experimental test, a toothing system-equipped rectangular pile made of structural steel that was built to the same dimensions as the ones used in numerical simulations was immersed in dry, loose sand inside a cylindrical container which is 140 mm in diameter and 250 mm deep. The pile was anchored in the middle of the container at a depth of 210 mm, precisely reaching the top of the wing as shown in Figure 12. Axial load test was carried out in the universal testing machine. The pile is marked at 5mm and 10 mm above the wing in order to measure the load at each displacement. The experimental setup is depicted in Figure 13. Load readings were obtained at 5 mm and 10 mm displacements during the axial load test.

At 5 mm displacement, the observed load was 508 N; at 10 mm displacement, the load was 1027 N. whereas for numerical simulation maximum load of 1038N was observed when the pile is displaced by 10mm. A close alignment of the axial load test results from both numerical simulation and experimental testing gives validity to the entire analysis process. This congruence indicates the behaviour of the monopile under axial loading conditions is accurately represented by the simulation model. Consequently, there is a high possibility that the results of further investigations, including static and cyclic loading tests, will show similar correlations between experimental observations and numerical predictions. This validation strengthens the validity of the entire analysis approach and the simulation model's reliability, laying a strong basis for next design improvements. The response of monopile is depicted in Figure 14. The comparison of experimental and numerical investigation is validated in Figure 15.

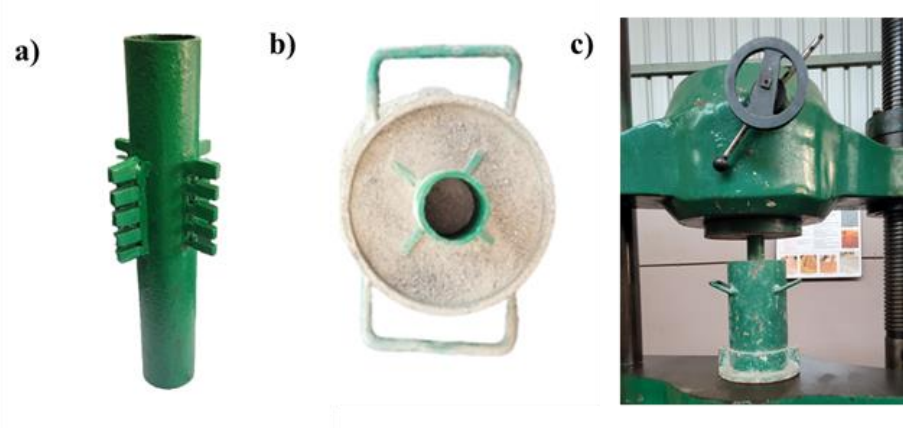


Figure 13. a) Rectangular winged pile with toothing system b) Monopile driven into soil c) Experimental setup

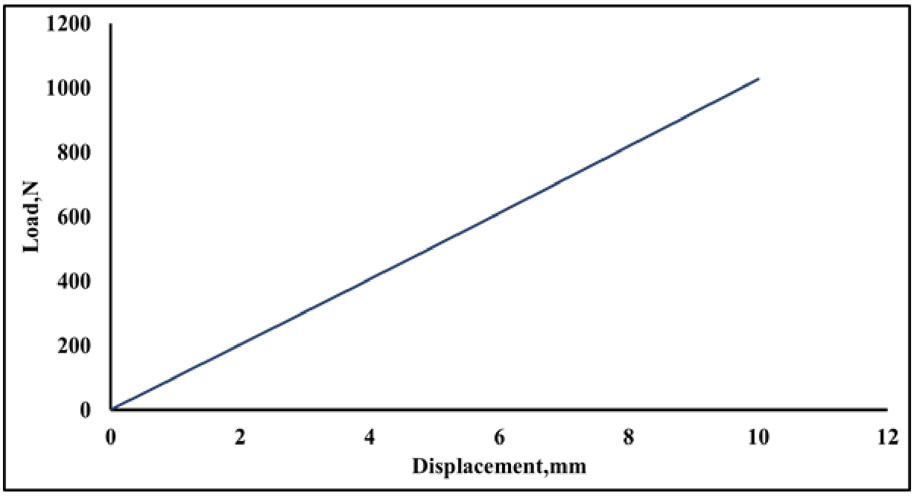


Figure 14. Response of Rectangular winged pile with toothing system under axial load-Experimental Validation

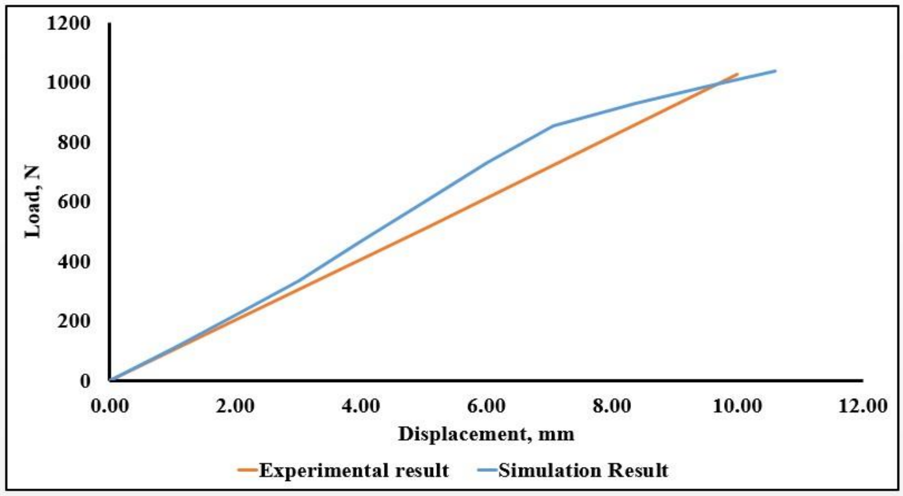


Figure 15. Comparison Graph of Experimental and Simulation Results for Rectangular Winged Pile with Toothing System Under Axial Load

6. Conclusions

In conclusion, the toothing-equipped rectangular piles are compared to conventional monopiles, and the results show a steady increase in load-bearing capability under all loading conditions.

- The toothing system showed an incredible 35.24% increase in load over the monopile in the static load analysis. Similarly, both positive and negative loads saw significant increases under cyclic loading conditions, rising by 71.62% and 74.29%, respectively.
- The axial load analysis, which demonstrated an astounding 103.53% increase in load, further demonstrated the toothing system's superiority. The close alignment between the axial load test results obtained from numerical simulation and experimental testing provides strong validation for the analysis process. This congruence suggests that the behavior of the monopile under axial loading conditions is accurately represented by the simulation model.
- As a result, there is a high likelihood that further investigations, including static and cyclic loading tests, will also demonstrate similar correlations between experimental observations and numerical predictions. These significant improvements can be attributed to a number of key elements within the toothing system.
- The presence of teeth along the pile's surface increases the surface area in contact with the soil, allowing for better load distribution. In addition, the teeth increase the pile's frictional resistance, increasing its ability to withstand both lateral and axial loads.
- Furthermore, the interaction between the toothing system and the adjacent soil causes soil change and compaction, which strengthens the pile's stability and load-bearing capacity. Consequently, the toothing system excels across static, cyclic, and axial loading scenarios, making it a valuable improvement for pile designs, particularly in difficult soil conditions. Finally, the inclusion of a toothing system into rectangular piles is a significant step positive in offshore structures.
- Future work: Comprehensive experimental validation of cyclic and static loading tests to ensure the robustness of numerical simulations. Extensive parametric studies are needed to explore the effects of varying key parameters such as pile diameter, wing dimensions, tooth spacing, and soil properties and fatigue analysis can be conducted to assess the long-term durability under cyclic loading, while investigations into dynamic loading conditions, such as wave, wind, and seismic loads, are essential to simulate real offshore environments.

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