

Analysis of Steel Chip Fiber Reinforced Composite Dual Pile Under Lateral Load Conditions on Sloping Terrain

Aman Tiwari^{1,*}, Nitin Dindorkar², Suneet Kaur³

Abstract

Pile foundations, in addition to supporting vertical loads from superstructures, are subjected to lateral stresses arising from seismic activities, wind gusts, water currents, and traffic impacts etc. Failure to account for these lateral forces can pose significant risks if the structure is expected to encounter any form of lateral pressure. Previous research has investigated the behavior of individual composite piles under horizontal forces, considering different soil properties, to determine the deflection and maximum bending moment. The current study examines lateral load capacity of steel chip fiber reinforced concrete (SCFRC) composite piles consisting of two piles spaced 2.5 times the diameter (D) apart, treated as a single unit. A horizontal force is applied at the upper part of the pile pair, which is connected by a structural pile cap (connection plate). Strain gauges are installed along the outer edge of each pile to obtain experimental data on deflection. A finite element model (FEM) is developed and analyzed in PLAXIS 3D software to simulate the soil-pile interaction for the given arrangement. The results obtained from both experimental and numerical analyses demonstrate a strong correlation, indicating that an increase in the slope angle leads to a decrease in the lateral load capacity of the SCFRC composite pile assembly. There is a significant influence of pile location and angle of slope on the lateral load capacity of pile. The use of SCFRC dual pile can effectively reduce the impact on the existing pile, resulting in smaller lateral displacement and bending moment compared to an isolated pile.

Keywords: Lateral load, steel chip fiber reinforced concrete, composite pile, dual pile, FEM, PLAXIS.

INTRODUCTION

Pile foundations are an essential component of various structural systems, particularly when transferring loads to deep soil strata or when significant horizontal forces are anticipated to act on the structure. These lateral forces can arise from diverse sources, such as wind gusts, water waves, seismic ground motions, and impact loads from vessels or other objects [1]. Accurate evaluation of the soil-pile interaction is crucial when piles are subjected to lateral loading, as failure to account for these forces can compromise the structural integrity and safety. In the design of laterally loaded piles, two critical parameters are considered: the maximum bending moment experienced by the pile and the pile top displacement [2]. The behavior of laterally loaded piles on level ground has been extensively studied through computational simulations and experimental investigations. It has been observed that the pile response is highly dependent on the relative stiffness of both the pile and the surrounding soil [3]. For onshore structures, lateral

*Author for Correspondence

Aman Tiwari
E-mail: amantiwari1946@outlook.com

¹Research Scholar, Department of Civil Engineering, Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh, India

^{2,3}Professor, Department of Civil Engineering, Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh, India

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loads typically account for 10–15% of the vertical loads, while in offshore structures, they can contribute up to 25–30% of the vertical loads [4].

Piles are often constructed in groups to support structures, and the behavior of pile groups differs significantly from that of single piles. Experimental evidence has shown a substantial reduction in the ultimate soil resistance for pile groups compared to similarly cyclic-loaded single piles [5]. The p-y curve approach, which accounts for the nonlinear behavior of soil and provides flexibility and simplicity, is frequently employed in the design of laterally loaded piles [6]. In the past, researchers have conducted full-scale field experiments, 1-g model tests, and centrifuge model testing on laterally loaded piles and pile groups [7-9]. Various L/D ratios (length-to-diameter ratios) have been considered to investigate the influence of pile flexibility on the p-y curves [10]. However, due to the high costs and logistical complexities associated with evaluating large pile groups, no experimental research is currently available.

In previous studies on the group action of piles under lateral loading, a p-multiplier has been used to reduce the soil resistance, accounting for the decrease in lateral resistance due to the group effect [11, 12]. While this approach has been widely adopted, it may not accurately capture the complex soil-pile-pile interactions in pile groups, particularly when the pile spacing or group configuration is altered. In recent years, there has been an increasing interest in the use of composite polymer piles as an alternative to traditional materials like concrete and steel. Composite polymer piles offer several advantages, including high strength-to-weight ratio, corrosion resistance, and ease of installation [13, 14]. However, their lateral behavior, especially in pile group configurations, has not been extensively studied.

Steel Chip Fiber-reinforced concrete (SCFRC) piles exhibit several enhanced characteristics, such as increase strength. SCFRC possesses 20-50% greater compressive strength, 30-40% higher modulus of elasticity, and 50% higher water permeability compared to normal concrete [15,16]. Cracking resistance and impact load resistance are notable characteristics of SCFRC and enhanced durability exhibits greater tensile and bending strength, increased ductility, and more resistance to cracking. SCFRC has improved chemical stability, increased resistance to abrasion, and greater resistance to corrosion.

The present study aims to investigate the lateral behavior of steel chip fiber reinforced concrete composite dual piles, which are considered as a single unit rather than a traditional pile group. By examining a dual pile configuration with a spacing of 2.5D (where D is the pile diameter), this research aims to provide insights into the soil-pile-pile interactions and the resulting lateral load capacity.

Experimental investigations were conducted to collect data on the deflection and bending moment response of the dual composite pile assembly under lateral loading. Strain gauges were installed along the periphery of each pile to record the deflection data. The experimental setup involved applying a lateral load at the top of the dual pile, which was connected by a pile cap (connection plate). In parallel with the experimental efforts, a finite element model (FEM) of the same setup was created and analyzed using the PLAXIS 3D software. This numerical model incorporated the soil-pile interaction and aimed to simulate the behavior of the dual fiber reinforced composite pile assembly under lateral loading.

By investigating the lateral behavior of dual fiber reinforced composite piles, this study aims to contribute to the understanding of soil-pile-pile interactions in closely spaced pile configurations. The findings can have implications for the design and analysis of pile foundations for various structures, particularly those subjected to significant lateral loads, such as offshore platforms, wind turbines, and bridge structures. In previous studies on the group action of piles under lateral loading, a p-multiplier has been used to reduce the soil resistance, accounting for the decrease in lateral resistance due to the group effect. In the present study, two composite piles are considered as a dual pile instead of a pile group, and the results are presented in the form of p-y curves, which illustrate the soil resistance (p) and horizontal pile deflection (y), as well as bending moment curves. The experimental data are utilized to

construct and validate numerical models. The proposed p-y curve is then employed to conduct a parametric analysis on the lateral response of piles.

EXPERIMENTATION

Test Setup

Experimental investigations were conducted in a tank with three different slope conditions, characterized by slope ratios of 1V:1H (vertical: horizontal), 1V:2H, and 1V:5H. The dimensions of the test tank were 2000 mm × 1000 mm × 1000 mm, chosen to minimize the influence of boundary effects on the experimental outcomes. In the experimental model, lateral loads were applied using dead weights, and the resulting pile head deflections were measured using dial gauges.

The model dual pile system consisted of two SCFRC piles, each with an external diameter of 25 mm and a wall thickness of 1 mm. The two piles were connected at the top with a steel plate, forming a composite system. To mitigate potential friction arising from the interface between the soil and the tank's side walls, the test tank was lined with a film [17]. The spacing between the two piles was maintained at 2.5D (where D is the pile diameter).

The model dual pile was embedded 889 mm into the soil, with 111 mm protruding above the ground level, which was considered as the eccentric length of the pile for all ground slope cases. The dual pile system was instrumented with electrical resistance strain gauges, each having a gauge length of 5 mm and a resistance of 110 Ω. These strain gauges were positioned at intervals of 50 mm along the entire length of the pile.

The data acquisition system recorded the strain gauge measurements at a frequency of 50 Hz, enabling the collection of real-time data during the experimental process (Figure 1).

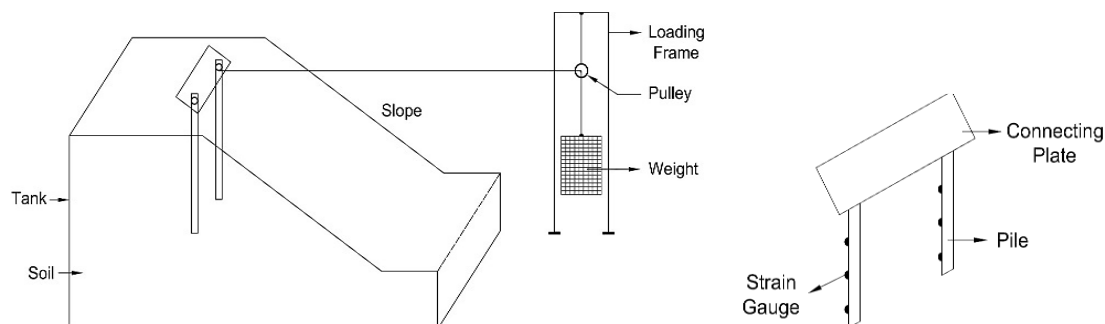


Figure 1. Schematic diagram of experimental setup.

Soil and Pile Preparation

The experimental investigations were conducted utilizing clay sourced from a local region, which exhibited a water content of 28.4% and an undrained shear strength (c_u) of 52.4 kPa. The undrained shear strength is a critical parameter in the characterization of cohesive soils, as it represents the soil's resistance to shear deformation under undrained conditions, where no volume change occurs.

The clay was compacted in layers using a plate hammer to achieve a uniform thickness of 250 mm for each layer. The compaction process aimed to achieve a dry unit weight of 18.3 kN/m³, which is a measure of the soil's density in its dry state. Maintaining a consistent dry unit weight throughout the soil profile was essential to ensure uniform soil properties and behavior.

The layering and compaction process was repeated multiple times until the desired slope height and slope angle were attained. During this process, particular attention was paid to the tamping procedure around the pile to ensure adequate soil-pile contact. Proper soil-pile contact is crucial for accurately capturing the soil-pile interaction mechanisms and the associated load transfer mechanisms.

To characterize the elastic properties of the clay, triaxial tests were performed on the same soil sample. These tests involved subjecting the soil specimen to confining pressures and measuring the resulting deformations. The triaxial test data provided the necessary information to determine the values of the modulus of elasticity (E) and Poisson's ratio (ν) for the clay.

The experimental pile was cast using steel chip fiber reinforced concrete (SCFRC), a composite material consisting of conventional concrete reinforced with discrete steel chip fibers. SCFRC offers enhanced mechanical properties and improved durability compared to plain concrete. The steel chip fibers, typically ranging from 25 to 60 mm in length and 0.4 to 1.0 mm in diameter, were uniformly dispersed throughout the concrete matrix at a dosage rate of 1% by volume of concrete.

The SCFRC mix design incorporated ordinary Portland cement, fine and coarse aggregates, water, and chemical admixtures to achieve a target compressive strength of 40 MPa at 28 days. The addition of steel chip fibers increases the tensile and flexural strengths of the concrete, as well as its toughness, impact resistance, and crack resistance. Typical properties of SCFRC with 1% steel chip fibers include a splitting tensile strength of 5-7 MPa, a flexural strength of 8-12 MPa, and a significant improvement in post-crack behavior and energy absorption capacity.

The methodology employed for preparing the experimental model closely resembled the approaches adopted in previous research studies [17,18]. This consistency in experimental procedures facilitates the comparison and validation of results across different investigations, contributing to the broader understanding of the phenomenon under investigation (Table 1).

Table 1. Properties of soil used.

Property	Value
Unit weight, γ_s (kN/m ³)	18.3
Undrained shear strength, c_u (kPa)	53.24
Modulus of elasticity, E (MPa)	30.12
Poisson's ratio, ν	0.35

Loading Arrangement and Measurement

During the lateral load tests, critical measurements were taken to characterize the response of the dual composite pile system. The deflections at the pile head, which represent the lateral displacements experienced by the top of the pile, were recorded. Additionally, axial strains along the pile length were measured, enabling the calculation of bending moments and the determination of the maximum bending moment location.

The lateral loads were applied in a static manner, with increments of 100 N. This incremental loading approach allowed for the observation of the pile's behavior under gradually increasing lateral forces. The loading process continued until the pile head displacement rate was less than 0.01 mm/min, indicating a quasi-static condition where the pile's deformation had stabilized under the applied load.

This loading sequence was repeated iteratively until a state of plastic failure was observed in the soil in front of the pile. Plastic failure is characterized by the formation of visible cracks in the soil, indicating that the soil has exceeded its elastic limit and undergone irreversible deformations. This failure mechanism is typically accompanied by a significant reduction in the soil's ability to provide lateral support to the pile, leading to a decrease in the overall lateral load capacity of the system.

The observation of plastic failure in the soil is a critical indicator of the ultimate lateral load capacity of the dual composite pile assembly. Beyond this point, further increases in lateral loading would result in excessive deformations and potential instability of the pile-soil system, posing a risk to the structural integrity of the foundation.

Experimental Results

Throughout the lateral loading process, meticulous measurements were taken for each load increment. Specifically, the applied lateral load and the corresponding lateral displacement at ground level were recorded, providing a comprehensive dataset for analyzing the response of the dual fiber reinforced composite pile system.

Figure 2 presents the relationship between the pile top (connecting plate) deflection and the applied lateral loading for varying slope ratios, ranging from gentle to steep inclinations. The graphs clearly illustrate that for a given lateral load, the pile head deflection increases as the slope angle becomes steeper. This behavior can be attributed to the reduced passive resistance offered by the soil in front of the pile and the lower initial confining pressure acting on the soil mass.

The observed disparity in the lateral resistance of the soils in front of the piles across the three slope conditions can be a key contributing factor to the observed deflection patterns. When the slope angle is steeper, the soil mass in front of the pile experiences lower confinement and is more susceptible to deformation, leading to a reduction in the passive resistance it can provide against the lateral pile movement.

It is important to note that in the present study case, the center-to-center distance between the two piles can also influence the soil resistance for a given lateral load. The interaction between the closely spaced piles and the surrounding soil can lead to alterations in the stress distribution and arching effects within the soil mass, potentially affecting the overall lateral resistance capacity of the dual pile system.

This phenomenon highlights the complex nature of soil-pile-pile interactions in closely spaced pile configurations and underscores the importance of considering the pile spacing as a critical parameter in the design and analysis of such systems. The experimental and numerical investigations conducted in this study aim to provide insights into these intricate interactions and their implications for the lateral load capacity of dual fiber reinforced composite pile foundations.

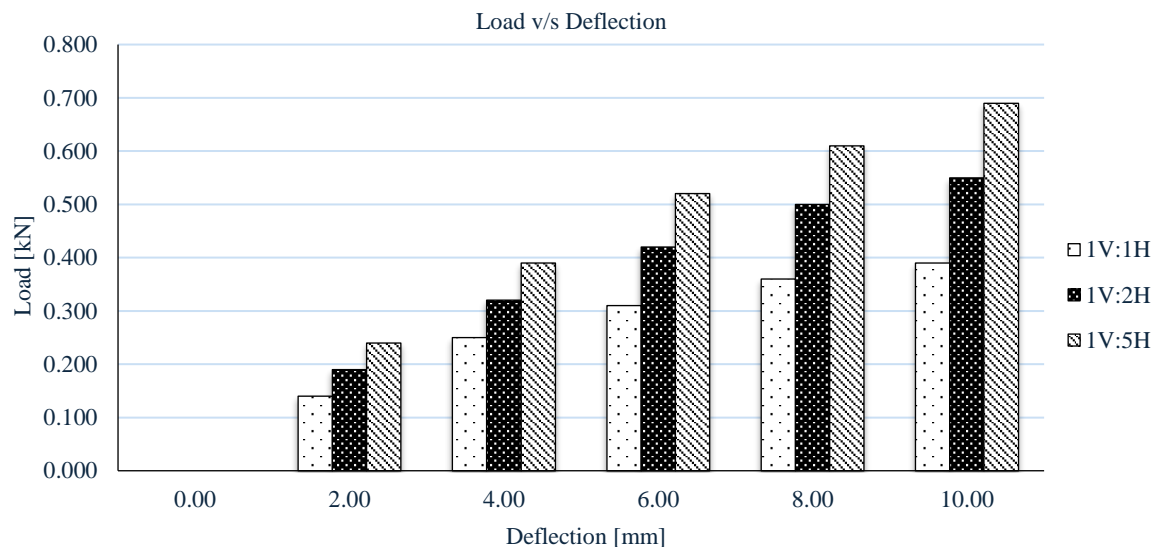


Figure 2. Load-Deflection curves for various slope ratios recorded experimentally

NUMERICAL ANALYSIS

Software Modelling

Finite element modeling (FEM) is a widely accepted and powerful computational tool for simulating and analyzing the behavior of the pile-soil interface. In recent times, several researchers [19,20] have employed 3D FEM analyses to investigate the lateral behavior of piles under various conditions.

Figures 3 and 4 illustrate a typical numerical model and 3D meshed view, respectively, used in the present study. The numerical model accurately represents the experimental setup, consisting of a soil profile with a sloping ground surface and a dual fiber reinforced composite pile assembly connected to a plate at the pile surface. This numerical representation enables a detailed examination of the soil-pile-pile interactions and the resulting load transfer mechanisms.

The selection of an appropriate constitutive model is crucial for accurately capturing the failure and deformation properties of soils. Many authors [21, 22] have proposed the Mohr-Coulomb model as a suitable choice for modeling the behavior of soils under various loading conditions. Consequently, this study utilizes the Mohr-Coulomb constitutive model to simulate the responses of the slope-built pile system.

The analysis of the dual fiber reinforced composite pile model was performed using the PLAXIS 3D software, a robust and widely used finite element analysis package for geotechnical applications. Within the software, the soil profile was modeled using the borehole property, which allows for the specification of soil layers with varying properties and thicknesses. The piles were modeled as embedded beams, enabling the accurate representation of the pile-soil interaction and the transfer of loads between the two domains.

The soil properties were assigned values consistent with those obtained from the experimental investigations, ensuring consistency between the numerical and experimental components of the study. For the composite piles, a density of 24 kN/m^3 was specified, reflecting the lightweight yet durable nature of these materials compared to conventional concrete.

At the interface between the soil and the pile, a standard interface stiffness was considered, with the value of R_{inter} set to 0.50. The interface stiffness parameter governs the relative movement and stress transfer between the soil and pile elements, playing a crucial role in capturing the pile-soil interaction mechanisms accurately.

After assigning the appropriate material properties and boundary conditions, the numerical model was prepared for analysis. A horizontal load was applied on the plate connecting the dual fiber reinforced composite piles, simulating the experimental loading conditions. Subsequently, the model was subjected to mesh generation processing, where the mesh element distribution was set to a medium density, ensuring a balance between computational efficiency and accuracy.

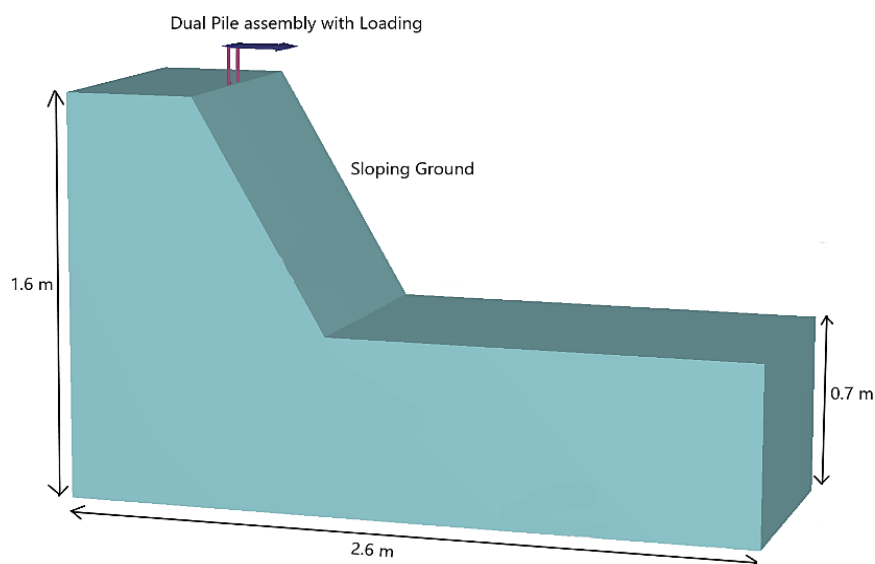


Figure 3. FEM model of Dual pile located at the crest.

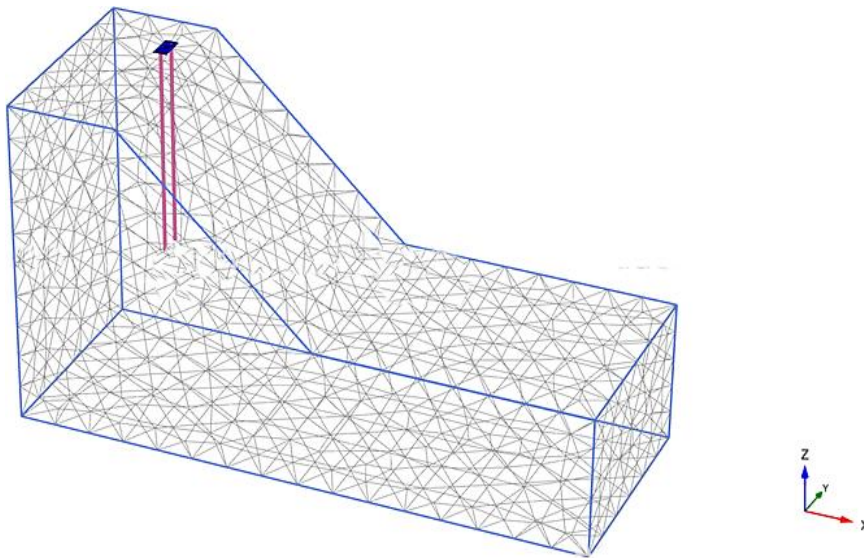


Figure 4. Meshed model of soil pile assembly

The final stage of the numerical analysis involved the calculation phase, where the finite element equations were solved iteratively to determine the deformations, stresses, and other relevant quantities throughout the model domain. The results obtained from these numerical simulations were then compared with the experimental data, enabling a comprehensive understanding of the lateral behavior of the dual fiber reinforced composite pile system under various slope conditions.

FEM results

The effect of the ground inclination on the side behavior of the dual fiber reinforced composite pile assembly is clearly shown by the typical results of the finite-element analyses, illustrated in Figure 5. This figure demonstrates the relation between the applied lateral load and the lateral pile head displacement, denoted as 'y,' for three different sloping situations.

It is evident from the Figure 5 that the slope inclination is directly proportional to the lateral load capacity of the dual composite pile assembly and as the slope inclination increases, the lateral load capacity of the dual composite pile assembly decreases. This change is due to the modified stress state and soil-pile interaction mechanisms that are created by the steeper slopes.

The slope becomes more inclined, and as a result, the pile head assembly deflection takes place at the lower values of the applied lateral load. This behavior is the result of the decreased lateral soil resistance and the small confining stresses acting on the soil mass in front of the pile. With the increase of the slope angle, the soil's potential to resist the pile movement is lower, which results in larger deformations under the lower load levels.

A quantitative analysis of the results reveals that the lateral load capacity of the dual composite pile assembly is reduced by approximately 80% when the slope condition is changed from a gentle 1V:5H (vertical to horizontal) inclination to a steep 1V:1H slope. This large decrease in the load capacity on the pile foundations shows how much the ground inclination can be the main factor of the lateral performance of the pile foundations, especially when the pile configurations are closely spaced.

The seen behavior is the result of the intricate soil-pile-pile interactions that are the main factors of the load transfer mechanisms in these systems. As the slope angle goes up, the stress distribution and soil arching aka the soil inside the soil mass change, and this leads to the lateral soil reaction to be different, thus the lateral load capacity of the dual composite pile assembly is reduced and it cannot sustain the excessive deformations or potential failure mechanisms.

These results highlight the significance of taking ground inclination into account as a key design parameter for pile foundations, particularly in places that are susceptible to sloping or inclined ground conditions. The numerical simulations that were carried out in this study give us a good understanding of the lateral behavior of dual fiber reinforced composite pile systems under different slope conditions, thus it can be used to design the pile system optimally and guarantee the safety of the foundation.

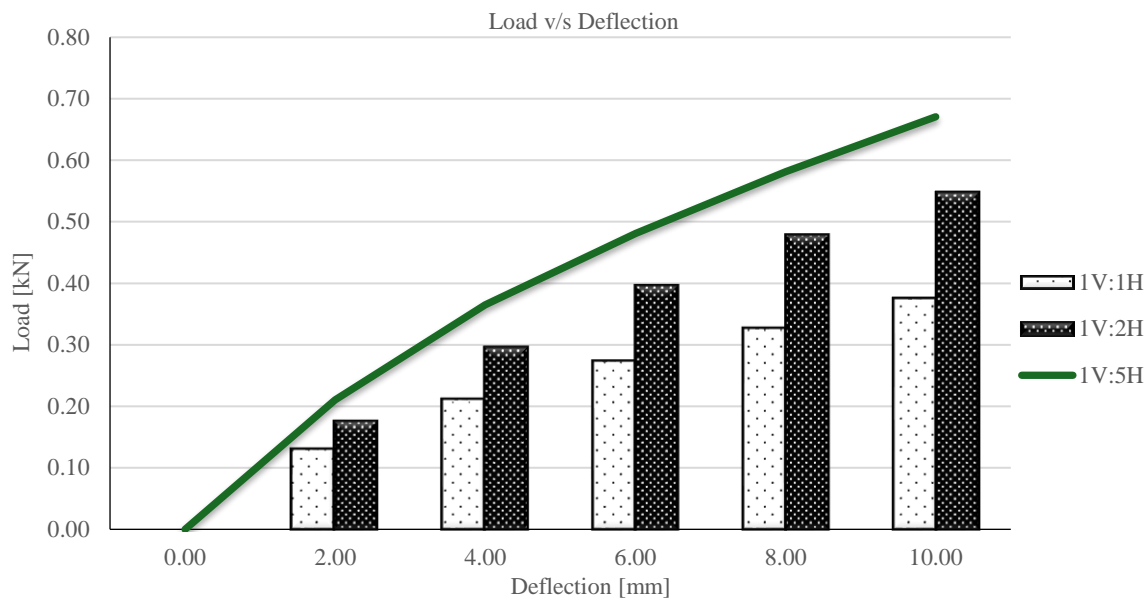


Figure 5. Load-Deflection curves for various slope ratios through FEA.

Comparison of Both the Results

Figure 6 presents a comparative analysis of the pile head deflections obtained from the finite element analyses (FEAs) and those derived from the experimental model test data. This comparison serves as a crucial step in validating the numerical simulations and ensuring their accuracy in predicting the lateral behavior of the dual fiber reinforced composite pile system.

In the validation process, a simplified approach was adopted, wherein a constant Young's modulus was assumed in both the horizontal and vertical directions. This assumption is consistent with the practices followed by many researchers [23,24] when comparing experimental and numerical calculations for piles embedded in sloping ground conditions.

The curves depicted in Figure 6 correspond to each set of slope conditions, and a remarkable agreement can be observed between the FEA results and the experimental data. This close correlation validates the effectiveness of the finite element analysis (FEA) technique in accurately predicting the response of laterally loaded piles, even in the case of complex soil-pile-pile interactions and varying ground inclinations. While there exist minor deviations in the deflection curves between the experimental and FEA results, ranging from 4mm to 8mm, the ultimate lateral load corresponding to a specified deflection coincides remarkably well across all slope conditions. This agreement in the ultimate lateral load capacity is of paramount importance, as it confirms the ability of the numerical simulations to capture the critical failure mechanisms and load-deformation behavior of the dual fiber reinforced composite pile system accurately.

The observed deviations in the deflection curves can be attributed to various factors, such as inherent variability in soil properties, simplifying assumptions made in the numerical model, and potential experimental uncertainties. However, the close agreement in the ultimate lateral load capacity demonstrates the robustness of the finite element modeling approach and its applicability in predicting the lateral behavior of pile foundations under varying ground conditions.

The successful validation of the numerical simulations against experimental data underscores the potential of FEA techniques as powerful tools for design and analysis purposes in geotechnical engineering applications. By incorporating advanced constitutive models, soil-structure interaction mechanisms, and site-specific conditions, these numerical simulations can provide valuable insights into the complex behavior of pile foundations, enabling optimized and efficient design solutions.

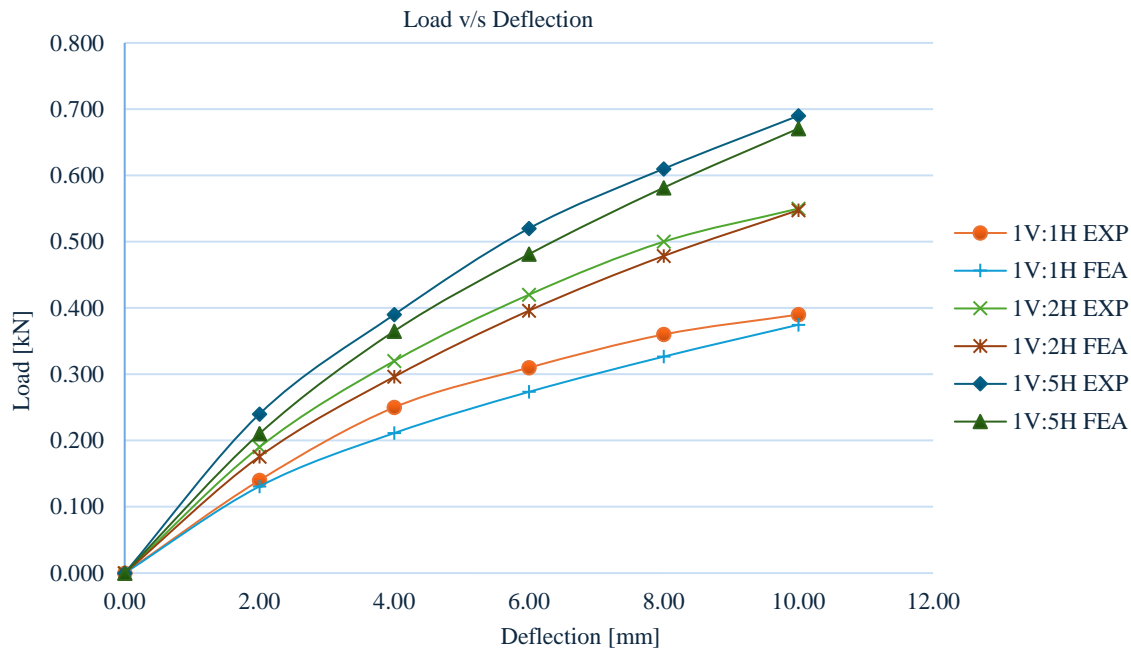


Figure 6. Load-Deflection curves for various slope ratios through FEA and Experiments.

CONCLUSIONS

This research provides a comprehensive investigation into the behavior of a steel fiber reinforced composite dual pile assembly under lateral loading conditions, with a particular focus on scenarios where the assembly is situated within the crest of steep clay slopes, commonly encountered in mountainous regions. To gain a holistic understanding of the system's response, a two-pronged approach encompassing both experimental and numerical analyses was employed. The findings from the experimental and numerical analyses have led to several significant conclusions:

There exists a strong correlation between the slope angle and the deflections observed in the pile heads. As the slope inclination increases, the pile head deflections exhibit a notable increase, indicating a reduced lateral capacity of the dual pile assembly.

- Quantitatively, the pile deflection is amplified by a factor of approximately 1.8 when the slope inclination changes from a gentle 1V:5H (vertical: horizontal) to a steep 1V:1H condition, highlighting the profound impact of slope angle on the deformation behavior of the pile assembly.
- The lateral load capacity of the SCFRC dual pile assembly decreases with an increase in the slope angle. This phenomenon can be attributed to the altered soil-pile-pile interactions, modified stress distributions, and diminished lateral soil reactions arising from steeper slope conditions.
- Compared to single pile configurations studied extensively in previous research, the dual pile assembly exhibits enhanced strength and rigidity, owing to the combined action of the two closely spaced piles and the interconnecting pile cap. This behavior underscores the potential advantages of dual pile assemblies in providing improved lateral load resistance and deformation control.

The findings of this study have significant implications for the design and analysis of pile foundations, particularly in regions prone to sloping or inclined ground conditions. By accurately capturing the complex soil-pile-pile interactions and the influence of ground inclination, the proposed

experimental and numerical approaches offer valuable insights for optimizing the design of dual **fiber reinforced** composite pile assemblies, ensuring their structural integrity and safety under lateral loading scenarios.

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