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RESEARCH ARTICLE **OPEN ACCESS**

EFFECT OF BATTERED PILES ON THE RESPONSE OF PILED RAFT AND PILE GROUP FOUNDATIONS: A NUMERICAL STUDY

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ABSTRACT

The piled raft (PR) foundation system combines a shallow raft with deep piles, mobilising both components through complex raft–pile–soil interactions. Due to its effectiveness under vertical and lateral loads, it is widely used to support tall, heavily loaded structures. However, the complexity of the system often leads to reliance on simplified design methods. This study uses numerical simulations in FLAC3D to investigate the effect of pile battering on the behaviour of PR and pile group (PG) foundations in drained sandy soils. Unlike previous research combining vertical and battered piles, only battered piles are adopted here to isolate their influence under combined loading. A batter angle of 10° is selected to avoid excessive bending moments. Results indicate that battered piles improve lateral resistance in PR foundations by up to 66%, though vertical capacity is slightly reduced (by 14%) due to axial–bending interaction. Under combined loading, vertical piles outperform battered ones in overall resistance gain (55.7% vs. 38.8%), mainly due to improved soil confinement. Batter piles also play a key role in reducing tilt and enhancing foundation stability. This study offers practical insights for designing foundations exposed to strong lateral forces, such as in offshore structures and wind turbines.

List of notations

PR	Piled raft foundation	Lp	Lateral load carried by the piles in PR
BPR	Battered PR	Lr	Lateral load carried by the raft in PR
PG	Pile Group Foundation	γ'	Unit weight of the soil
BPG	Battered PG	φ	Friction angle of the soil
PRp	Piles component in PR	ψ	Dilation angle of the soil
PRr	Raft component in PR	δ	Soil/Foundation interface friction angle
Br	Width of raft	D_{50}	Mean grain size
Tr	Thickness of raft	E	Young's modulus
Lp	Length of pile	ν	Poisson's ratio
D	Pile diameter	c'	Cohesion
ϴ	Pile inclination angle	Kn	Interface normal stiffness
Lpr	Lateral load carried by PR	Ks	Interface shear stiffness

I. INTRODUCTION

Piled raft foundations have gained significant attention in geotechnical engineering as an efficient solution that combines the advantages of both shallow and deep foundations. By integrating a raft with a group of piles, this system enhances load-bearing capacity while minimising differential settlement. Unlike conventional pile or raft foundations, the piled raft system utilises the combined contribution of both components—the raft provides additional bearing support, while the piles primarily control settlement—resulting in improved structural performance and cost-effectiveness [1]. The behaviour of a piled raft is governed by complex soil-structure interactions, including pile-soil, pile-pile, raft-soil, and pile-raft interactions [2-5]. Due to these interactions, accurately evaluating the bearing capacity of piled rafts is challenging and requires consideration of multiple design parameters and soil conditions. While numerous studies have focused on the performance of piled raft foundations under vertical loads [6-11]. Infrastructure such as high-rise buildings, bridges, wind turbines, and offshore platforms are also subjected to significant horizontal loads. Many researchers have stated that it is necessary to understand the response of piled rafts under lateral loading through both experimental investigations and numerical simulations to establish design criteria [12-15]. However, experimental studies on piled rafts subjected to combined vertical and horizontal loading remain limited.

Although recent research efforts have attempted to address this gap by analysing the combined effects of vertical and lateral loads on piled rafts [16], [17], a comprehensive design framework for such conditions has yet to be fully established. Recently, there has been growing interest in incorporating batter piles into piled raft foundations due to their promising potential in enhancing foundation stability. However, research on this topic remains scarce, with only a few experimental and numerical studies available. [18] conducted vertical and horizontal load tests on pile groups and piled rafts with and without batter piles in dry sand under 1g gravitational conditions. Their results demonstrated that batter piles improve resistance and reduce settlement compared to purely vertical piles. Finite element analyses corroborate these findings, offering more profound insight into the resistance mechanisms of these foundation systems. Similarly, [19] employed three-dimensional finite element models to investigate the seismic behaviour of pile groups with batter piles. Their study considered various pile configurations, including groups with a combination of vertical and inclined piles. Both hinged and fixed-headed pile conditions were analysed to assess the influence of pile-to-cap connections. Their results indicated that pile groups with batter piles exhibit greater horizontal stiffness than those composed solely of vertical piles. Other researchers have reached similar conclusions regarding the effectiveness of batter piles. [15], found that replacing vertical piles with batter piles reduces settlement and increases load-carrying capacity.

[20] experimentally investigated 3-pile and 6-pile batter pile foundations under vertical and lateral loads and found that batter piles enhance overall stiffness and reduce settlement. [21] analysed the effect of batter angles ranging from 10° to 30° under lateral loads, determining that an in-battered pile inclination of 15°–20° provides optimal resistance. [22] conducted dynamic load tests on 6-pile foundation models with and without batter piles, demonstrating that piled rafts incorporating batter piles are highly effective in minimising settlement and inclination under vertical dynamic loading. Although numerical simulations have proven to be a powerful tool for understanding foundation behaviour, relatively few numerical studies have explored the influence of batter piles. [23] developed a numerical analysis method to examine deformation and load distribution in piled raft foundations with batter piles. Their parametric studies confirmed that batter piles significantly enhance the deformation behaviour of piled rafts. Given this context, the present study aims to model and analyse the experimental work conducted by [24] while varying the batter pile for two foundation configurations: piled raft and pile group. The objective is to assess the impact of batter angle on vertical and lateral resistance, offering more details about their behaviour under combined loading. By considering the coupled action of vertical and horizontal loading, this study seeks to improve the understanding of failure mechanisms and key design parameters for piled raft foundations with batter piles. The analysis is performed using a three-dimensional numerical model, validated against Matsumoto's experimental study to ensure accuracy and reliability.

II. FINITE DIFFERENCE MODELING

II.1 DESCRIPTION OF THE ANALYSED FOUNDATION SYSTEM

This study investigates the influence of pile inclination on the behaviour of piled raft and pile group foundations subjected to vertical, lateral, and combined loading in sandy soil. The problem is addressed numerically using a three-dimensional finite-difference model, which explicitly captures the interaction between the raft, the inclined piles, and the surrounding soil continuum. Special emphasis is placed on how pile inclination modifies load transfer mechanisms, stiffness, and failure patterns compared with conventional systems supported only by vertical piles. To isolate the mechanical response of inclined piles under combined loading, the foundation system is idealised as consisting solely of inclined piles rather than a mixed arrangement of vertical and inclined elements. This simplification allows a clearer interpretation of the role of inclination angle on global response, raft displacements, and pile forces, without the additional complexity introduced by heterogeneous pile layouts. The numerical framework enables systematic variation of inclination angle and load combination, thereby providing a consistent basis for parametric analysis.

The influence of pile inclination on both vertical and lateral load-carrying capacities is examined using displacement-based failure criteria. For vertical capacity, ultimate bearing capacity is often defined at a settlement equal to 10% of the raft width Br; however, this criterion is not directly suitable for the reduced-scale geometry adopted here. In line with recommendations for small-scale modelling, a stricter settlement limit equal to 10% of the pile diameter d is adopted to define the ultimate vertical capacity, ensuring that the response remains within an appropriate deformation range for model-scale interpretation. For lateral capacity Lpr, a horizontal displacement criterion of 0.1d is employed, consistent with common practice in evaluating laterally loaded pile and piled-raft systems. Within this framework, the effects of inclination are quantified in terms of: (i) ultimate vertical and lateral capacities, (ii) load–displacement behaviour under pure and combined loading, and (iii) load sharing between raft and piles as the inclination angle and loading regime vary. The different external load components and the internal forces mobilised in the piled-raft system under combined vertical–lateral loading are schematically illustrated in Figure 1, providing a conceptual basis for the subsequent numerical analyses.

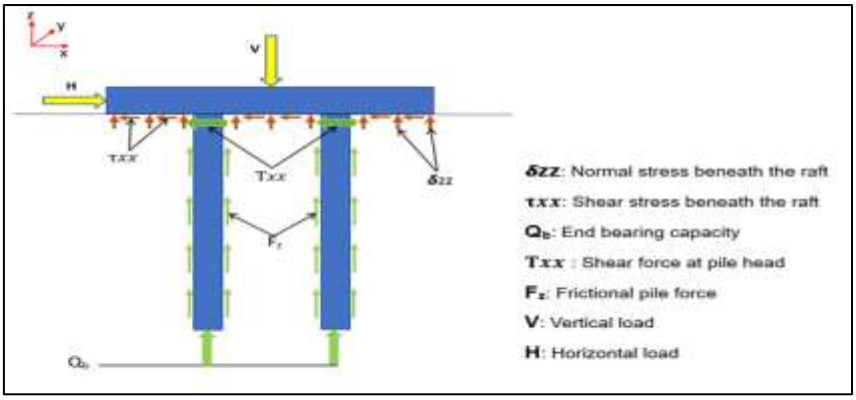

Figure 1: Forces Developed at the Soil-Piled Raft Interface.
Source: Authors, (2026).

The lateral load contribution of the raft (Lr) in the piled raft system is determined by integrating the shear stress at the interface between the soil and the raft. Figure 1 illustrates this, and it is expressed in Equation (1). In these equations, τiixx represents the shear stress at the interface between the soil and the raft for each element i, and dSi is the segment's cross-sectional area of element i.

$$Lr = \iint_{-Br/2}^{Br/2} \tau ixx \;\; dSi \tag{1}$$

Due to the complexity of directly calculating the lateral load contribution of piles, especially inclined piles, it is determined indirectly by deduction. The lateral load carried by the piles (Lp) is calculated as the total lateral load of the piled raft system (Lpr) minus the lateral contribution of the raft (Lr), as expressed in Equation (2):

$$Lp = Lpr - Lr \tag{2}$$

Two foundation configurations are considered: a piled raft foundation where the raft is in direct contact with the soil, and a pile group foundation where the raft is elevated above the ground by a distance equal to the raft thickness. This distinction allows for a clear comparison between configurations with and without raft–soil contact, emphasising the role of the raft in load sharing and settlement control. The effect of pile inclination is examined by comparing vertical (0°) and inclined (10°) pile arrangements. Four configurations were studied, as shown in **Figure 2**, to analyse the combined effect of pile inclination and foundation type on load distribution, settlement behaviour, and lateral resistance. By evaluating the performance of these foundation systems, this study aims to provide insights into the role of pile inclination in optimising foundation design, particularly in sandy soils where both vertical and lateral loads play a crucial role in structural stability.

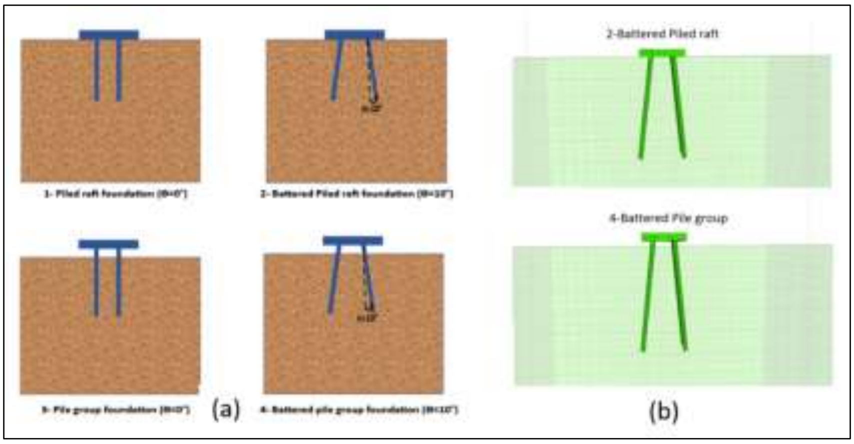

Figure 2: (a) Configurations studied in this paper, (b) battered confugurations modeled in FLAC 3D.
Source: Authors, (2026).

II.2 MODELING PROCEDURE

This paper conducts numerical simulations using the explicit finite difference code FLAC3D (Itasca Consulting Group Inc., 2013) to assess the behaviour of a battered piled raft under combined vertical and lateral loading in sandy soil. FLAC3D offers robust computational capabilities, making it particularly valuable for analysing foundation systems, where experimental testing, especially on inclined piles, is complex and resource-intensive. Additionally, 1g experimental tests are known to suffer from scale effects and limitations in reproducing real stress conditions, justifying the use of numerical modelling to achieve accurate and scalable results. The numerical model is based on the experimental work of [24] which involved 1g tests on composite piled raft foundations subjected to vertical and lateral loads. The experimental setup consisted of a 400 mm × 400 mm raft, 40 mm thick, supported by four piles of 600 mm length and 40 mm diameter, arranged with uniform spacing of 200 mm in both the x and y directions. The piles were embedded in a two-layer soil profile consisting of 1 metre of Toyoura sand overlying a 1-metre-thick compacted brick base.

While the primary goal is to simulate [24] experimental configuration for validation, the study also aims to contribute to the broader engineering objective of optimising foundation systems for high-rise buildings and structures subject to combined vertical and lateral loads—such as wind turbines and tall towers—by evaluating the effect of pile inclination on load capacity and load sharing. In the simulations, the piles are modelled using six-node cylindrical solid elements, while the raft is represented by a combination of 12-node radial cylindrical solid elements and eight-node brick elements. Although solid elements do not directly capture internal forces, they allow a realistic geometric representation of structural components under external loads. The overall soil domain dimensions are set to 3 m × 3 m × 2 m—twice the lateral extent of the experimental setup—to reduce the influence of boundary effects. Boundary conditions include fixed constraints at the base and lateral restrictions against displacement in the X and Y directions.

The soil is modelled using the Mohr–Coulomb failure criterion, selected for its simplicity and effectiveness in capturing the essential behaviour of sandy soils with minimal input parameters. Although more advanced constitutive models such as the Hardening Soil model exist, the Mohr–Coulomb model is adequate for this study's scope and offers a balance between computational efficiency and realistic approximation of soil strength. The parameters used to simulate Toyoura sand are Young's modulus E = 44 MPa, Poisson's ratio ν = 0.3, unit weight γ' = 15.9 kN/m3, friction angle ϕ' = 40°, dilation angle ψ = 10° and cohesion c' = 0 kPa. The parameters for the soil and foundation are summarised in Table 1.

Table 1: Material parameters used in [24] and this study.

Parameter	Toyoura sand	Base brick	Foundation
E (MPa)	44	$6x10^3$	$7x10^4$
ν	0,3	0,2	0.3
γ' (kN/m3)	15,90	22	27
c'(kPa)	0	/	/
φ' (°)	40	/	/
ψ (°)	10	/	/
D 50 (mm)	0,17	/	/

Source: [24].

The mesh was carefully refined beneath and around the raft and piles using a fine grid with an element size approaching the average particle diameter of Toyoura sand ($D_{50} = 0.17$ mm). A mesh convergence study was performed and showed that stable, mesh-independent results were obtained when the minimum element size was taken approximately equal to D_{50}, which was therefore adopted in the final model. Mesh refinement was continued until changes in key response quantities (such as raft displacement and pile head shear) between successive refinements fell within a small tolerance, ensuring that the numerical response was controlled by the physics rather than by the discretization. The mesh gradually becomes coarser with distance from the foundation to reduce computational cost while maintaining numerical accuracy. The raft and piles are assumed to be isotropic and perfectly elastic. Soil–structure interaction is simulated using interface elements that allow for realistic relative movement between soil and structural components. Interface properties were defined as follows: friction angle δ = 40°, cohesion c = 0 kPa, normal stiffness Kn = 10^9 Pa/m, and shear stiffness Ks = 10^9 Pa/m.

These interface stiffness values are selected to be sufficiently high to ensure force transfer without inducing unrealistic rigidity, and sensitivity checks confirmed that moderate variations in Kn and Ks had negligible influence on the global response. The loading process was divided into four main steps: (1) gravity loading to generate the initial geostatic stress field; (2) installation of the raft and piles by assigning structural material properties to the relevant zones; (3) application of a uniform vertical load on the raft to simulate a surcharge; and (4) application of a lateral force at the centre of the raft's vertical surface. Vertical and lateral loads were applied incrementally, with the vertical load kept constant during the lateral loading phase to represent combined loading and to capture the progressive development of nonlinearity in the soil response. The numerical model mesh and the foundation dimensions are illustrated in Figure 3.

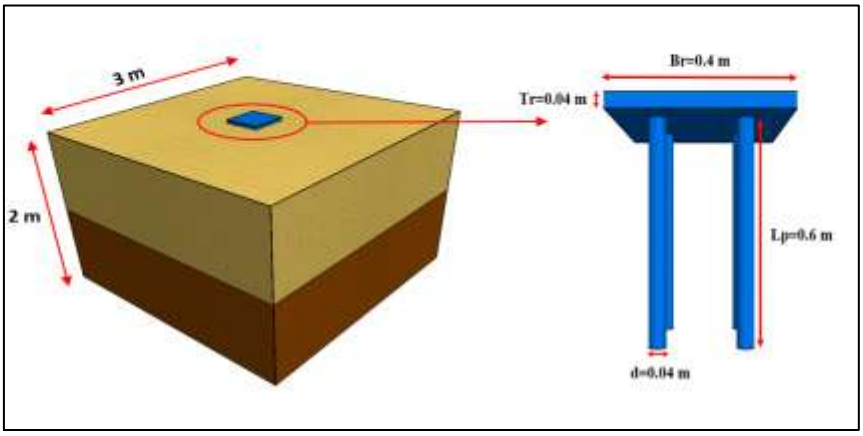

Figure 3: Mesh Pattern and Element Dimensions.
Source: Authors, (2026).

II.3 VALIDATION OF NUMERICAL MODELING

To validate the numerical modelling procedure used in this study, the results were compared with one case study from the seven experimental tests conducted by [24]. In this case, a rigid piled raft foundation was tested under static vertical and static horizontal loading. The loading process was divided into two stages: the vertical loading stage and the cyclic horizontal loading stage. In the vertical loading stage, a total vertical load of Vi =3.384 kN was applied to the model foundation. After completing the vertical stage, a cyclic horizontal loading stage was applied to the model raft. It is important to note that, although cyclic horizontal loading was performed on the model foundation, a monotonic horizontal loading test was also carried out. As illustrated in Figure 4, the numerical results closely align with the experimental data, demonstrating the accuracy of the simulations.

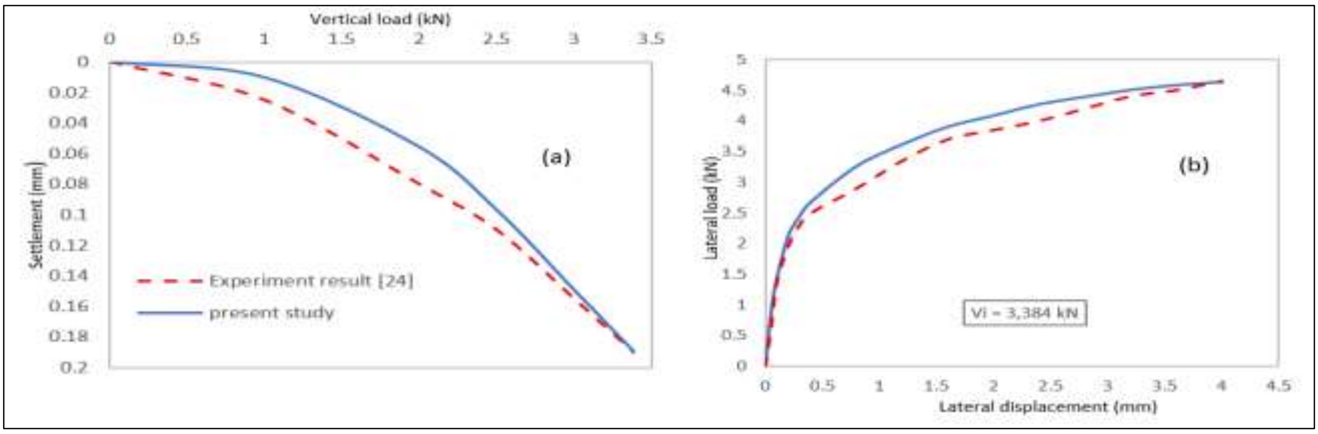

Figure 4: Comparison between the results of present study and previous experimental work [24],
(a) load-settlements and (b) lateral load-lateral displacement behaviors of piled raft.
Source: [24].

III. RESULTS AND DISCUSSIONS

III.1 PURE VERTICAL LOAD TEST

The influence of pile inclination on vertical resistance was first examined. As shown in Figure 5, increasing the inclination angle from 0° to 10° negatively impacts vertical resistance for both foundation types. Under a vertical load of 3 kN, settlement increases from 0.14 mm to 0.16 mm for the piled raft foundation and from 0.27 mm to 0.316 mm for the pile group foundation. This reduction in vertical resistance occurs because a portion of the applied vertical load is redirected into a horizontal component, reducing the effective axial capacity of the piles. As a result, settlement increases. In piled raft foundations, the decreased pile contribution transfers more load onto the raft, leading to greater deformation. In pile group foundations, inclined piles experience additional bending stresses, further diminishing their ability to resist vertical loads. Consequently, as the inclination angle increases, vertical resistance decreases.

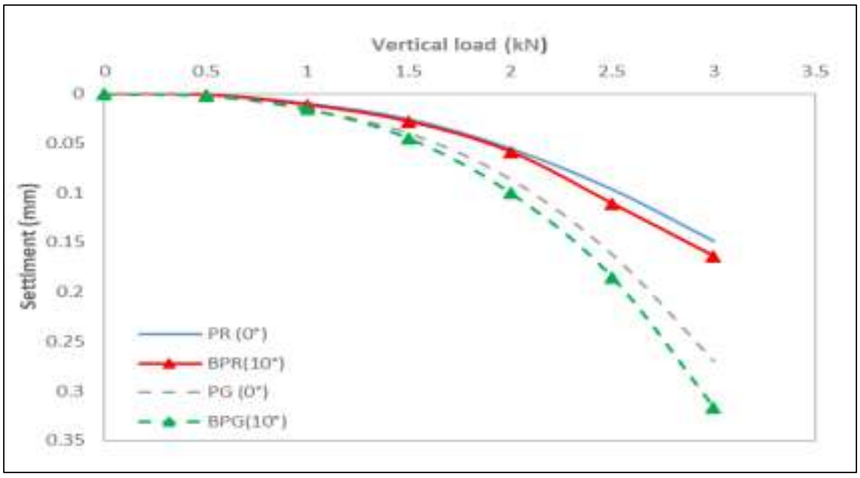

Figure 5: Vertical Load vs settlement curves of PR, BPR.PG and BPG.
Source: Authors, (2026).

III.2 PURE LATERAL LOAD TEST

In this study, the foundation was initially subjected only to the force of gravity due to its own weight, without any external loads applied. We then analysed the effect of pile inclination on lateral resistance by applying a pure lateral load until a lateral displacement equal to 10% of the pile's diameter was reached. This specific load, as corroborated by several studies, represents the lateral resistance of the foundation. As illustrated in Figure 6, under pure lateral loading, lateral resistance consistently increases with the inclination angle. For the piled raft foundation, increasing the inclination angle from 0° to 10° led to a significant 66% increase in lateral resistance, rising from 2.853 kN to 4.74 kN. In contrast, the increase for the pile group foundation was more modest, with lateral resistance increasing by

21%, from 2.864 kN to 3.478 kN. The increase in lateral resistance with pile inclination is due to the enhanced pile-raft-soil interaction. When piles are inclined, they interact differently with the surrounding soil compared to vertical piles. Instead of resisting the lateral load purely through bending, inclined piles transfer part of this load into axial compression or tension. This redistribution reduces bending stress and increases overall stability. Additionally, a portion of the lateral load is redistributed into axial compression or tension along the pile length, reducing bending effects and enhancing stiffness. This inclination also modifies the pile-soil contact, activating greater lateral resistance, particularly in sandy soil. In a piled raft foundation, the raft's contribution becomes more significant as the axial load component transferred from the inclined piles increases the raft-soil interaction. This combined effect of pile-raft-soil interaction and load redistribution explains the improved lateral resistance observed with inclined piles.

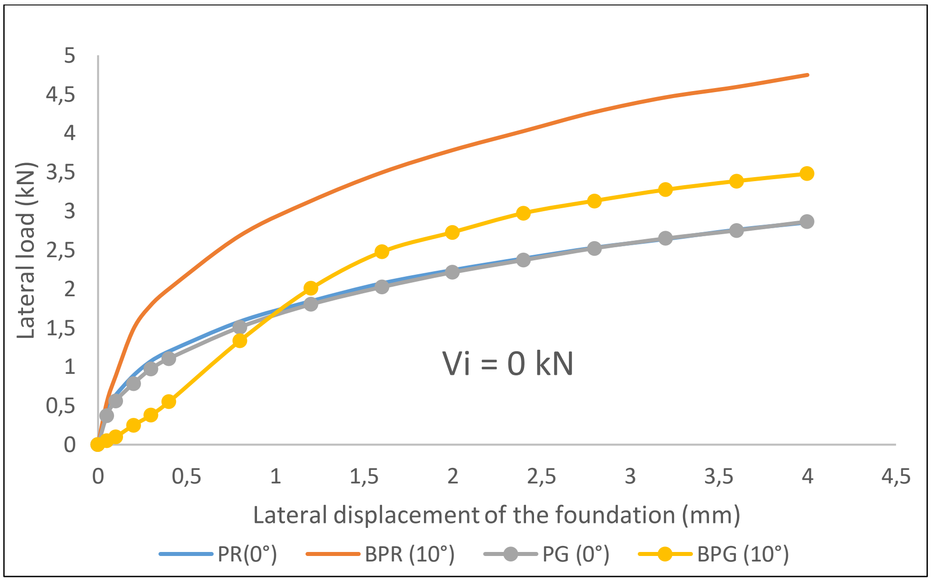

Figure 6: Lateral load vs lateral displacement under pure lateral load curves of PR, BPR.PG and BPG.
Source: Authors, (2026).

III.3 COMBINED VERTICAL AND LATERAL LOADS TEST

Finally, the behaviour of both foundation types was analysed under a combined loading. For the four configurations mentioned earlier, a vertical load of Vi= 3 kN was first applied until stabilisation, followed by a lateral load until a lateral displacement equal to 10% of the pile diameter was reached. As shown in Figure 6 and Figure 7, lateral resistance under combined loading is higher than under pure lateral loading. For vertical piles in the piled raft foundation, lateral resistance reaches 4.44 kN under combined loading, representing a 55.7% increase compared to pure lateral loading. For inclined piles, lateral resistance under combined loading reaches 6.59 kN, whereas it was 4.74 kN under pure lateral loading, indicating a 38.8% increase. Similarly, for the pile group foundation, lateral resistance increases by 16.23% and 27.4% when the inclination angle changes from 0° to 10°, respectively. This difference in percentage increase can be attributed to the role of vertical load in enhancing soil confinement and increasing normal stress along the pile shaft, which is more beneficial for vertical piles. Additionally, vertical piles rely primarily on passive soil resistance and shaft friction for lateral resistance, while inclined piles already experience higher lateral stiffness, making the effect of vertical load less pronounced.

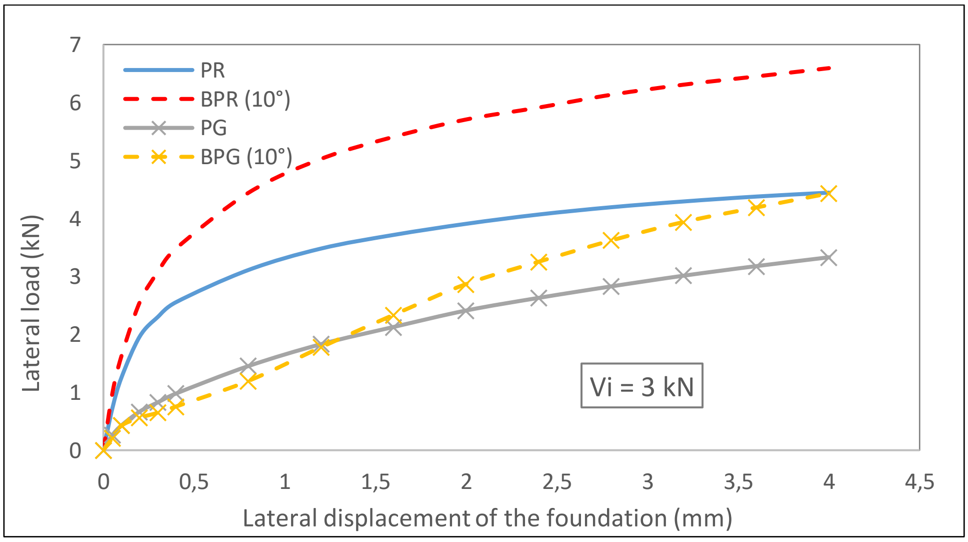

Figure 7: Lateral load vs lateral displacement under combined loads (Vi=3N) of PR, BPR.PG and BPG.
Source: Authors, (2026).

III.4 LOAD DISTRIBUTION AND LATERAL RESISTANCE UNDER PURE AND COMBINED LOADINGS

III.4.1 Under Pure Lateral Loading

Figure 8 shows that the load-sharing mechanism between the raft and piles under pure lateral load remains constant regardless of pile inclination; however, the contribution of each component varies. As pile inclination increases, both the raft and piles mobilize increased lateral resistance. The lateral resistance of the raft increases by 48% due to greater soil-raft interaction, with inclined piles transferring more load to the raft. Meanwhile, the 69% increase in pile resistance suggests that inclined piles engage a greater soil mass, thus improving their ability to resist lateral loads. It is important to highlight the complexity of the soil-raft interaction. Comparing piles in the PR system with piles in the PG system, when the piles in the PR system are vertical, they support 89% of the load carried by the piles in the PG system. However, at an inclination of 10°, this percentage reaches 123%. This increase results from the higher axial forces developed by inclined piles due to their orientation, which improves the efficiency of load transfer. Therefore, inclined piles not only improve lateral resistance, but also significantly change the overall load distribution within the foundation system.

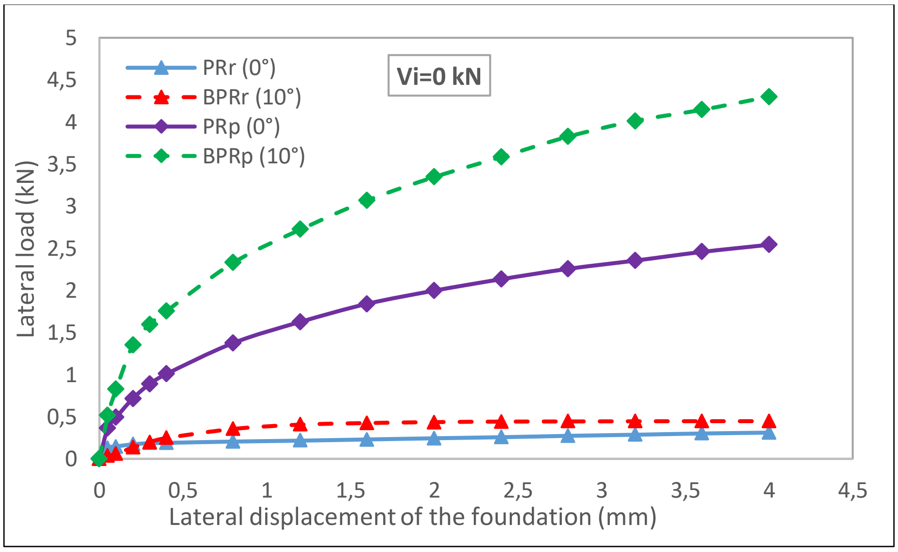

Figure 8: Distribution of Lateral load vs lateral displacement curves for PRr, BPRr, PRp and BPRp under pure lateral load.
Source: Authors, (2026).

III.4.2 Under Combined Vertical and Lateral Loads

Under combined loading, increasing pile inclination enhances lateral resistance for both foundation types. As shown in Figure 9, the lateral contribution of the raft increases slightly from 0.641 kN to 0.691 kN, while the pile contribution rises more significantly from 3.8 kN to 5.9 kN. While comparing the lateral resistance of vertical and inclined piles in PR against that of PG. For vertical piles, the lateral resistance in the PR is 3.8 kN, slightly higher than the 3.32 kN observed for PG. Similarly, for inclined piles, the piles in BPR exhibit greater lateral resistance 5.9 kN compared to BPG 4.4 kN. These results indicate that under vertical loading, both vertical and inclined piles in a PR exhibit improved lateral performance due to enhanced interaction with the surrounding soil.

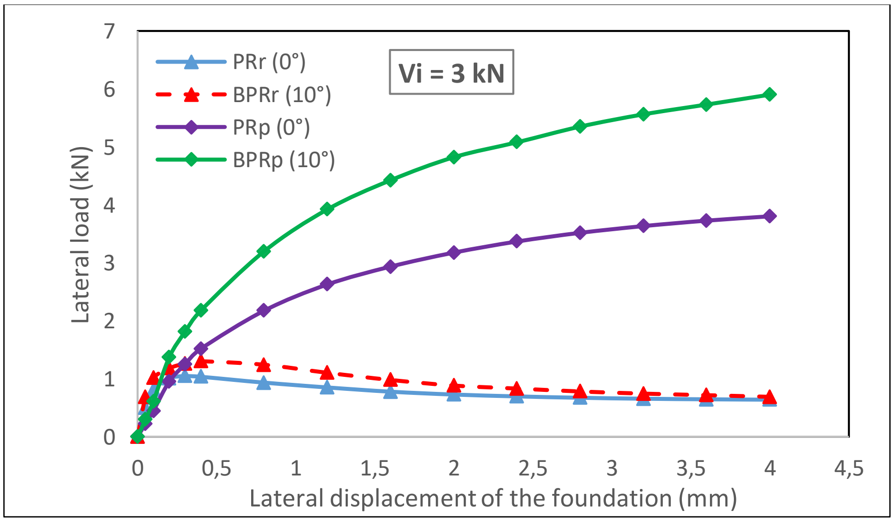

Figure 9: Distribution of Lateral load vs lateral displacement curves
under combined loads (Vi=3N) for PRr, BPRr, PRp and BPRp.
Source: Authors, (2026).

III.5 RAFT INCLINATION BEHAVIOR UNDER LATERAL AND COMBINED LOADS

As shown in Figure 10, when the foundation is subjected to pure lateral load, the raft in the piled raft system tilts slightly less than in the pile group, with inclinations of 7.824 × 10^{-3} radians and 8.099 × 10^{-3} radians, respectively. This suggests that the piled raft performs a bit better in controlling raft inclination under lateral forces. When inclined (or battered) piles are used, the raft inclination decreases even further. In the case of the battered piled raft, the inclination drops to 6.749 × 10^{-3} radians, and for the battered pile group, it goes down to 7.46 × 10^{-3} radians. This shows how effective inclined piles can be in improving the stability and stiffness of the foundation under lateral loading. When both vertical and lateral loads are applied (combined loading), the vertical load plays an important role in further reducing the raft's inclination. We can see this in all four foundation configurations: the piled raft shows an inclination of 7.274 × 10^{-3} radians, the battered piled raft 6.749 × 10^{-3} radians, the pile group 7.499 × 10^{-3} radians, and the battered pile group 6.824 × 10^{-3} radians. Overall, these results highlight how vertical load helps stabilise the foundation, and they confirm that the battered piled raft performs the best at minimising raft inclination under combined loading conditions.

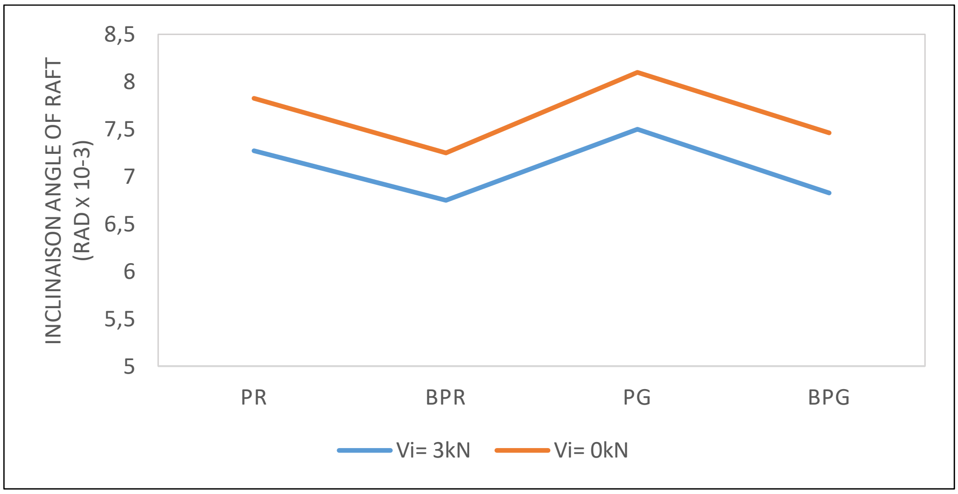

Figure 10: Inclination angles of raft under pure lateral and combined loads for PR, BPR, PG and BPG.
Source: Authors, (2026).

IV. CONCLUSIONS

This study concludes that pile inclination has a dual impact on piled raft and pile group foundations: it reduces vertical load capacity and increases settlements due to bending and axial load redistribution, especially under pure vertical loading, but markedly enhances lateral resistance under pure lateral and combined loading by mobilizing larger soil volumes and redistributing forces more effectively. The combined load scenario reveals that vertical piles benefit more from vertical load-induced soil confinement than inclined piles, though both configurations improve lateral stiffness. Load sharing shifts with inclination, where inclined piles significantly increase raft and pile resistance and carry a higher portion of total load. Raft inclination under lateral and combined loading decreases most with battered piles, highlighting their stabilizing effect. Overall, while inclined piles compromise vertical capacity, their significant lateral resistance gains make them critical for foundations subject to lateral or combined loads, affirming pile inclination as a key design parameter consistent with the research objectives and scientific considerations outlined in this work.

V. AUTHOR’S CONTRIBUTION

Conceptualization: Toudert Bougrires and Sadok Benmebarek.
Methodology: Toudert Bougrires and Sadok Benmebarek.
Investigation: Toudert Bougrires.
Discussion of results: Toudert Bougrires, Sadok Benmebarek, and Naïma Benmebarek.
Writing – Original Draft: Toudert Bougrires.
Writing – Review and Editing: Toudert Bougrires, Sadok Benmebarek and Naïma Benmebarek.
Resources: Toudert Bougrires, Sadok Benmebarek.
Supervision: Sadok Benmebarek and Naïma Benmebarek.
Approval of the final text: Toudert Bougrires, Sadok Benmebarek, and Naïma Benmebarek**.**

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