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Experimental and Numerical Study on Seismic Performance of Batter Pile Groups in Loose Sand

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Abstract

Pile foundations are critical for maintaining structural integrity under seismic loading, and batter piles, being inclined elements, offer enhanced resistance to combined vertical and lateral forces compared to conventional vertical piles. The objective of this study is to investigate the seismic performance of negative and positive batter pile groups in loose sand. The research employed experimental and numerical approaches: shaking table tests were conducted on 3×3 pile groups embedded in sand with a relative density of 31.2%, subjected to the El Centro and Kobe earthquakes, while finite element modeling was performed to validate the experimental outcomes. The analysis compared the responses of piles with batter angles of -5°, 0°, and +5° in terms of lateral displacement, vertical displacement, and acceleration. Findings revealed that negative battering substantially amplifies pile group displacements, as demonstrated by a 22.085% increase in maximum lateral displacement and a 23.061% rise in vertical displacement for the El Centro motion when the batter angle shifted from 0° to -5°. Conversely, positive battering reduced displacements by up to 4.765%. The novelty of this work lies in experimentally and numerically quantifying the seismic drawbacks of negative battered piles, thereby providing new insights for optimizing pile group design in seismic regions.

Keywords: Loose Sand; El–Centro Earthquake; Seismic Performance; Negative Batter; Deep Foundations; Shaking Table.

1. Introduction

Pile foundations play a pivotal role in civil infrastructure by transferring superstructure loads to deeper, more competent soil strata, thereby ensuring safety and serviceability under static and dynamic loading conditions. In earthquake-prone regions, the demand on pile foundations becomes even more critical because ground shaking can induce large lateral forces, vertical displacements, and bending moments within the soil–pile–structure system. Among the various pile configurations, batter piles—also known as inclined piles—have attracted significant attention due to their ability to resist combined vertical and horizontal forces more effectively than conventional vertical piles. Their geometry allows them to provide enhanced lateral resistance, making them particularly useful in bridge abutments, waterfront facilities, and marine and offshore structures. The inclination of batter piles, commonly expressed as the batter angle, strongly influences their load transfer mechanisms. Piles inclined toward the applied horizontal load are categorized as positive batter piles, while those inclined away are termed negative batter piles. This distinction is important because pile inclination alters the stress distribution, soil reaction, and overall seismic response of pile groups.

Understanding the seismic performance of batter piles is challenging due to the complexity of soil–structure interaction. Loose sandy soils, in particular, present a highly nonlinear and strain-dependent behavior under dynamic loading. During earthquakes, phenomena such as densification, excess pore pressure buildup, and cyclic mobility can

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significantly affect pile performance. The seismic response is further complicated when piles are arranged in groups, where pile–soil–pile interactions, group shadowing effects, and stress redistribution alter the behavior compared to single piles. Despite the widespread application of batter piles in practice, research on their performance under earthquake loading, especially for negative batter configurations, remains limited. This lack of understanding poses potential risks for design in seismic regions.

A substantial body of research has addressed the seismic response of vertical piles. Early studies primarily focused on single piles under lateral loading and explored the influence of soil type, pile slenderness ratio, and excitation frequency. For example, Abood et al. [1] examined single piles embedded in unsaturated soils under dynamic lateral loading, emphasizing the role of soil moisture and frequency effects. Ali et al. [2] investigated the slenderness ratio and highlighted its critical role in lateral resistance. These studies advanced knowledge of single pile behavior but did not sufficiently address batter piles or group effects under seismic excitation. Al-Tememy et al. [3] numerically studied the pullout capacity of batter pile groups and showed that batter angle significantly influences pile resistance in sandy soils, but their analysis did not extend to seismic conditions or dynamic loading.

More recently, researchers have begun to examine the dynamic behavior of batter piles, with particular attention to their seismic performance. Li et al. [4], using dynamic centrifuge modeling, investigated both positive and negative batter pile groups subjected to earthquake excitations and found that negative batter piles exhibited excessive lateral displacements in loose sand. Similarly, Zhang et al. [5] performed three-dimensional finite element simulations to explore pile group behavior under bidirectional seismic loading and demonstrated complex moment redistribution in negatively battered piles. Huang et al. [6] conducted shaking table tests on pile groups in saturated sand and reported that negative batter front-row piles suffered larger bending moments and displacements than their vertical or positive counterparts. Numerical investigations by Zhao et al. [7] further revealed that soil nonlinearity amplifies the seismic vulnerability of negative batter piles, particularly in low-density sandy soils. Giannakou et al. [8] examined reinforcement strategies to improve the resilience of inclined piles and concluded that pile cap stiffness and pile spacing are critical factors in mitigating adverse seismic effects.

In addition to academic studies, practical applications and case studies have highlighted the relevance of batter pile configurations in seismic design. Su et al. [9] investigated seismic retrofitting of bridge piers supported by batter piles and observed that positive batter arrangements improved displacement control and energy dissipation capacity. Likewise, Bharathi et al. [10] analyzed pile groups in liquefiable soils and showed that negative batter piles intensified buckling tendencies due to increased kinematic loads during ground shaking. Collectively, these findings emphasize that while positive batter piles may enhance seismic resilience, negative batter piles often lead to adverse effects, particularly in loose or liquefiable soils.

Recent research has further expanded our understanding of pile group behavior under seismic and dynamic loading conditions. Hökelekli et al. [11] studied seismic failure mechanisms of concrete pile groups in layered soft soil profiles, highlighting complex group responses in stratified media. Research by Jassim & Albusoda [12] provided experimental insights into batter pile performance under seismic activity, enhancing empirical knowledge on inclined pile behavior. Soomro et al. [13] employed advanced three-dimensional numerical modeling to investigate deformation and failure mechanisms of batter pile groups subjected to fault ruptures, revealing significant tilting and damage mechanisms. Pan et al. [14] conducted numerical modeling of batter and vertical pile groups under liquefaction-induced lateral spreading, showing that batter piles can reduce lateral displacements by up to 20% and mitigate tilting. Finally, Alsultani et al. [15] offered an experimental–numerical evaluation of pile spacing effects on dynamic performance of coastal pile foundations under combined current-wave-earthquake loading, underlining the importance of spacing design for seismic resilience.

Despite these advances, significant gaps remain. First, most existing studies have concentrated on single piles or very small groups, overlooking the interaction effects in larger pile groups that are more representative of real foundations. Second, while centrifuge and numerical studies have provided useful insights, integrated experimental and numerical investigations remain scarce. Few studies have validated numerical predictions with physical testing under realistic earthquake motions. Third, the majority of available work has emphasized positive batter piles or vertical piles, with limited systematic exploration of negative batter piles, which may behave fundamentally differently under seismic conditions. Finally, studies that combine realistic earthquake ground motions—such as the well-documented El Centro or Kobe records—with loose sandy soil conditions are particularly rare.

To address these knowledge gaps, the present study undertakes a comprehensive investigation into the seismic performance of 3×3 pile groups with batter angles of -5°, 0°, and +5° embedded in loose sandy soil with a relative density of 31.2%. The research employs a twofold approach: (i) shaking table experiments subjecting pile groups to scaled El Centro and Kobe earthquake excitations, and (ii) finite element simulations using PLAXIS 3D to validate experimental findings and provide further insights into soil–structure interaction mechanisms. The analysis focuses on lateral and vertical displacements and acceleration response to evaluate and compare the seismic performance of negative, vertical, and positive batter piles.

The novelty of this work lies in its integrated experimental–numerical framework, its focus on negative batter piles within realistic 3×3 pile groups, and its application to loose sandy soils under strong ground motions. By quantifying the detrimental effects of negative batter angles and comparing them to vertical and positive counterparts, the study provides new knowledge for advancing seismic design practices. The outcomes are expected to inform engineers and researchers on the risks associated with negative batter configurations and contribute to developing safer foundation strategies for critical structures in seismic regions.

The remainder of this paper is organized as follows. Section 2 describes the materials, experimental setup, and testing procedures, including details of the laminar container, pile group configuration, and loading system. Section 3 presents the experimental results, focusing on lateral displacement, vertical displacement, and acceleration response under seismic excitations. Section 4 discusses the numerical modeling using PLAXIS 3D and compares the numerical outcomes with the experimental findings. Section 5 provides a comprehensive discussion of the results, highlighting the influence of batter angle on seismic performance. Finally, Section 6 summarizes the key conclusions and practical implications of the study.

2. Materials and Methods

2.1. Materials of the Study

Table 1 presents the key basic properties of the sandy soil sample utilized in the current experimental study.

Table 1. The used sandy soil preliminary properties

Soil property	Testing results	Specification
Specific gravity	2.66	ASTM D854
Angle of internal friction (ϕ)	36°	ASTM D3080 / D3080M
Minimum dry density (kN /m^3)	14.87	ASTM D4254
Maximum dry density (kN /m^3)	17.65	ASTM D4253
Minimum void ratio	0.504	ASTM D4253
Maximum void ratio	0.81	ASTM D4254
Coefficient of curvature	1.13	ASTM D6913 / D6913M
Coefficient of uniformity	2.61	ASTM D6913 / D6913M
Classification according to the unified classification system	SP	ASTM D2487

2.2. Laminar Container

The laminar soil box is a cutting-edge apparatus employed in geotechnical experimental research as a practical alternative to full-scale field testing. It provides notable benefits such as reduced construction costs and quicker assembly, while also allowing for easy modification of soil types and application of different loading scenarios. These features contribute to producing accurate, consistent, and dependable experimental results [16–18]. Specifically engineered to replicate horizontal shear wave transmission through soil layers during seismic events, the laminar box facilitates the controlled simulation of shear stresses and ground motion. In the present study, the laminar box is composed of aluminium laminate, each 50 mm in height, with total dimensions of 85 × 85 × 90 mm³. The structural design of the box is depicted in Figure 1.

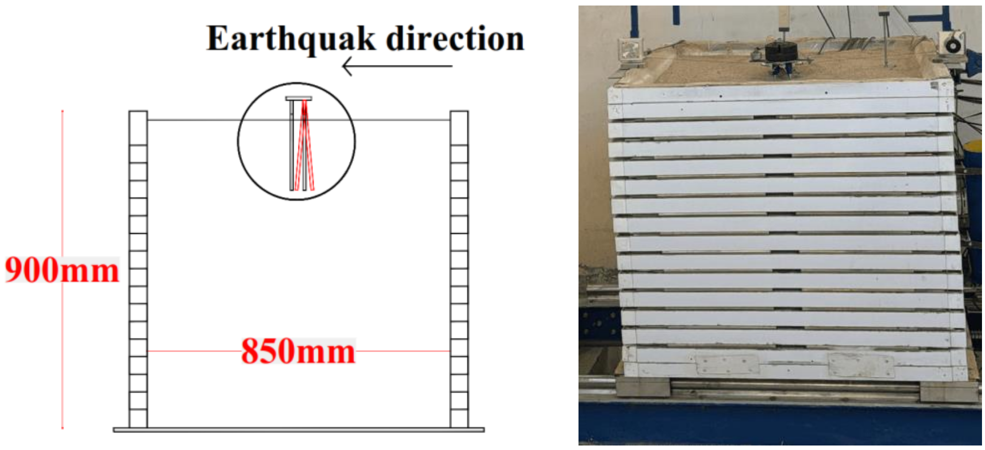


Figure 1. Schematic and photographic views of the soil laminar box

2.3. Pile Group

The model piles used in this study were circular aluminium tubes with a diameter of 8 mm and a length of 200 mm, resulting in a L/D = 25, as depicted in Figure 2. The pile was configured in a 3 × 3 grid, supported by a plate measuring 72 × 72 × 5 mm^3. The pile row subjected to seismic loading was installed at angles of -5°, 0°, and +5°.

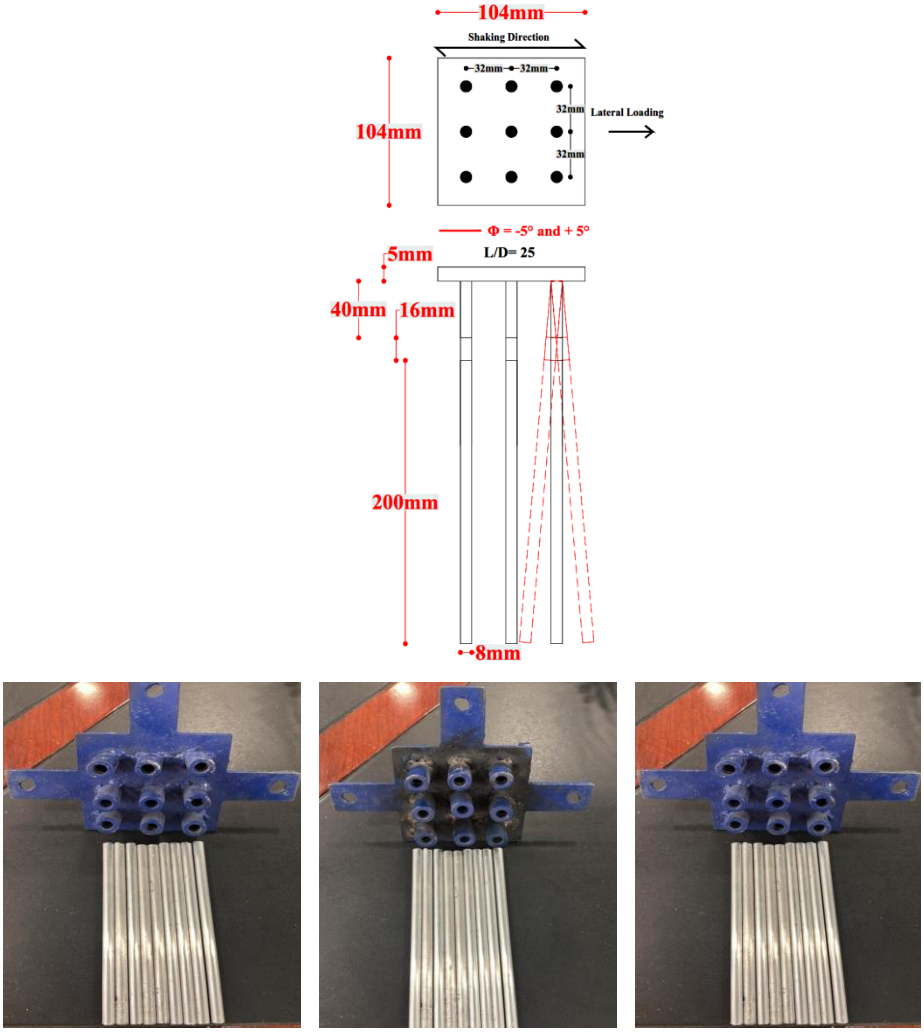


Figure 2. Schematic and photograph of the model pile group and pile appearance

2.4. The Loading Frame

The loading frame utilized in this study comprises several key components necessary for the experimental testing: (a) the soil container, (b) the 3 × 3 pile group setup, (c) a vertical displacement measuring device known as a Linear Variable Differential Transformer (LVDT), (d) additional LVDTs to record lateral displacements, (e) a sand hopper used for the raining deposition method, (f) the shaking table, (g) the system for applying lateral loads, (h) an accelerometer, and (i) the data acquisition system.

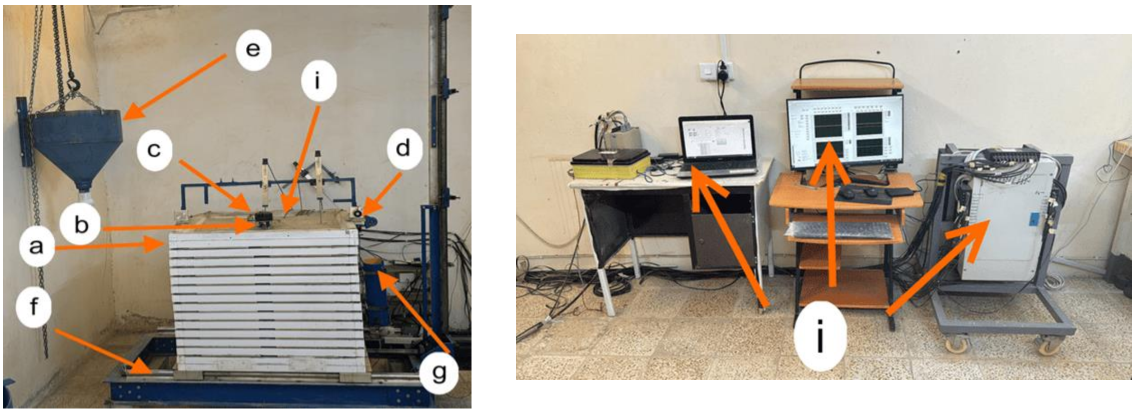


Figure 3. Details of the testing apparatus

2.5. Testing Sequence

In this study, a box measuring 85 × 85 × 90 mm³ was employed, with its inner surfaces lined with 5 cm-thick cork to help dampen vibrations during seismic loading. The box was securely fastened to the shaking table to ensure stability and eliminate any unintended movement during testing. For soil placement, the sand-raining hopper method—endorsed by recent research [19, 20] was adopted. Sand was dropped from a height of 115 cm, maintaining a consistent free-fall distance of 100 mm above the developing soil surface, until the desired fill height was reached, as depicted in Figure 4.

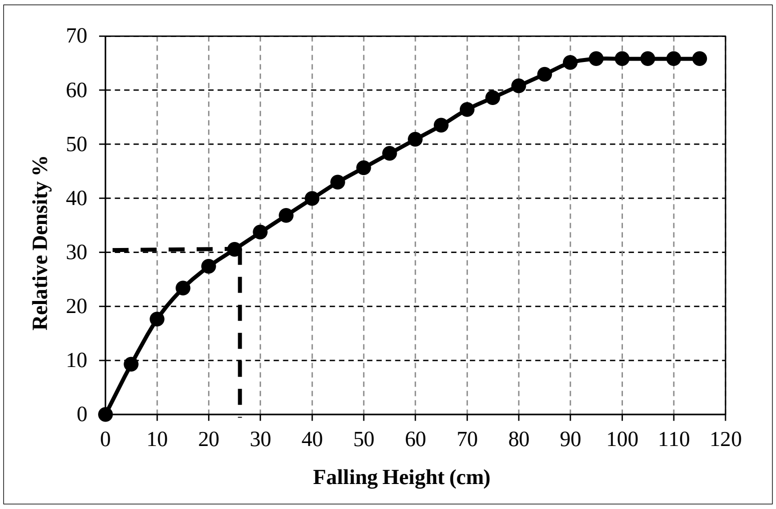


Figure 4. Raining technique curve

An axial gravitational load equals to its allowable bearing capacity for each configuration was applied. To replicate seismic excitation, a shaking table setup was used, consisting of a steel frame, a supporting platform, a screw-ball drive mechanism, and an array of sensors for monitoring and measurement. The dynamic response of the pile group was evaluated under input ground motions derived from the El Centro and Kobe earthquake records, as shown in Figure 5. To achieve a uniform relative density of 31.2%, the sand was deposited in layers throughout the model preparation.

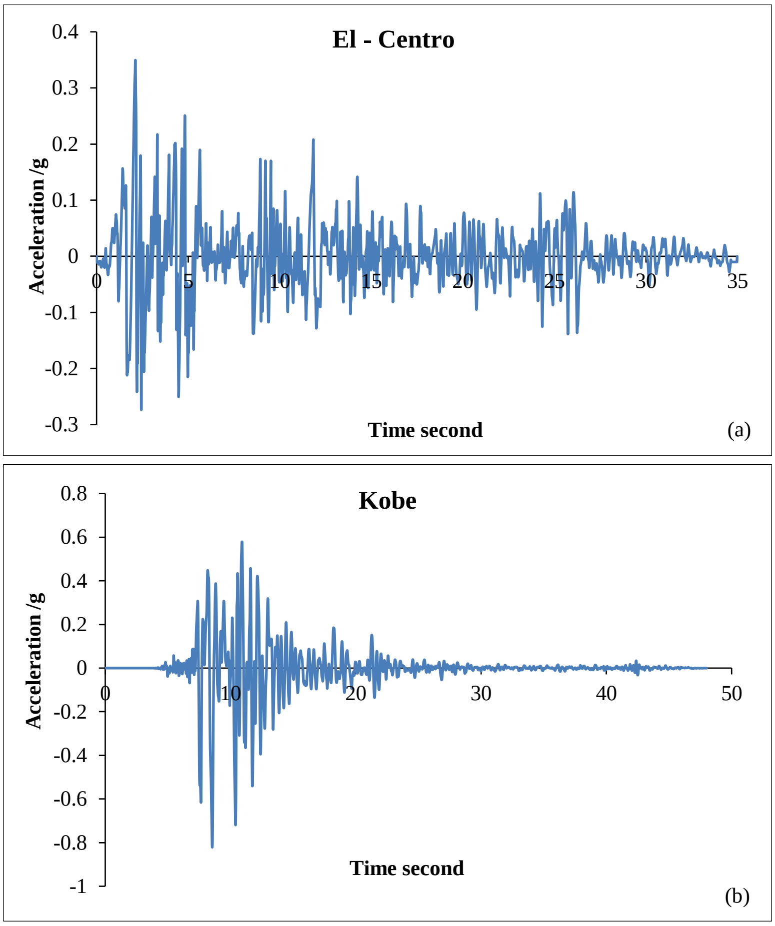


Figure 5. Earthquakes of the study: (a) El – Centro; (b) Kobe [21]

2.6. Numerical Modelling of Experimental Setup

To verify the accuracy of the experimental results obtained from laboratory testing, numerical simulations were conducted using the finite element method implemented in PLAXIS 3D 2020. The numerical models were subjected to the same loading and boundary conditions as those applied in the physical experiments, ensuring a consistent basis for comparison. The soil domain was modeled using 10-node tetrahedral elements governed by the Mohr-Coulomb constitutive model. The structural system comprises a circular pile represented by a plate element. Interface elements were incorporated along the inner and outer surfaces of the pile to capture soil–pile interaction effects. The raft foundation was also modeled using a plate element, assuming linear elastic behavior.

PLAXIS 3D applies two types of boundary conditions, corresponding to the nature of the analysis. Roller supports were assigned to the lateral boundaries for the elastic-plastic analysis, while the bottom boundary was treated as fully fixed. In the dynamic analysis, free-field boundary conditions were applied in the direction of seismic shaking to absorb outgoing waves, while the perpendicular boundaries were treated as non-viscous. The model base was defined as a compliant base to accommodate vertical and horizontal movement under seismic loading. A vertical point load was directed at the cap to simulate static loadings, while dynamic excitation was introduced through a prescribed displacement-time input derived from the El Centro earthquake acceleration record. To ensure a balance between accuracy and computational efficiency, a medium global mesh was used, with double local refinement applied in the vicinity of the structural elements.

The numerical simulations in PLAXIS 3D were conducted in multiple phases using the Staged Construction mode. Only the geostatic stress field was generated in the initial phase based on the Ko procedure, without activating any structural components. In the first phase, both the pile and the pile cap were activated. In the second phase, the static point load was applied to the top of the pile cap. Finally, in the third phase, the effect of dynamic loading (seismic shaking) was introduced by applying a prescribed displacement time-history, scaled by the displacement multiplier corresponding to the El Centro earthquake record.

This research focuses on the principles of soil-structure interaction concerning seismic loading. The sandy soil was modeled using the Mohr–Coulomb constitutive law, which describes shear strength parameters of soils like friction angle, dilatancy, and even some cohesion, and is well-known for its effectiveness in dynamic geotechnical analyses because of its simplicity and reliability. Piles and pile caps were modeled as linear elastic elements, and soil–pile interaction was modeled with interface elements with slip and gapping. The boundary conditions were carefully selected to mimic realistic field behavior: roller boundaries on the lateral sides permitted out-of-plane motion, and free-field boundaries in the shaking direction contained wave reflections. The compliant base boundary condition permitted vertical and horizontal propagation of seismic waves, which is more accurate for dynamic simulations. In shaking table tests, similitude laws were applied to the model to maintain geometric, kinematic, and dynamic similarity alongside the model's displacement and acceleration response scaling. The integration of theoretical and experimental works allows the study to create a reliable framework for the comparison of different pile group configurations.

Figure 6 presents the various configurations of simulated battered pile groups used in this study, while Table 2. summarizes the input keys of soil, pile, and cap utilized in the numerical model.

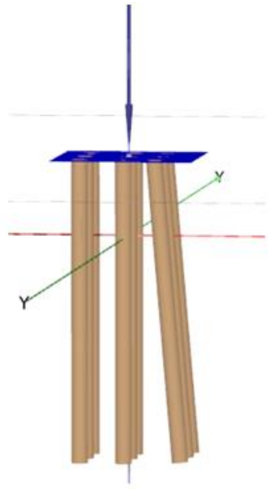


Figure 6. The configuration of simulated battered piles in PLAXIS 3D

Table 2. Input parameters of soil, pile, and pile-cup

	Parameter	Sand
Input parameters of sandy soil	Constitutive model	Mohr-Coulomb
	Unit Weight (kN/m³)	16
	Young's Modulus (kPa)	32×10^3
	Poisson's Ratio (ν)	0.275
	Cohesion (c) (kPa)	0
	Friction Angle (ϕ) (degree)	36
	Dilatancy Angle, Ψ (degree)	6
	R_{inter}	0.7
	Parameter	**Piles**
Input parameters of the pile and pile-cup	Constitutive model	Linear elastic
	Unit Weight (kN/m³)	78.5
	Young's Modulus (kPa)	200×10^6
	Poisson's Ratio (ν)	0.26

2.7. Flow Chart

The experimental program is outlined in the flowchart shown in Figure 7. The procedure commenced with positioning and firmly fixing the piles in place. Subsequently, the laminar soil box was filled using the sand-raining method. Once the soil preparation was complete, the computer system was configured to apply seismic excitations and capture the resulting data. The system's response was evaluated based on lateral displacement, vertical displacement, and acceleration measurements. After getting results of the experimental work, the numerical modeling was conducted and compared with such results.

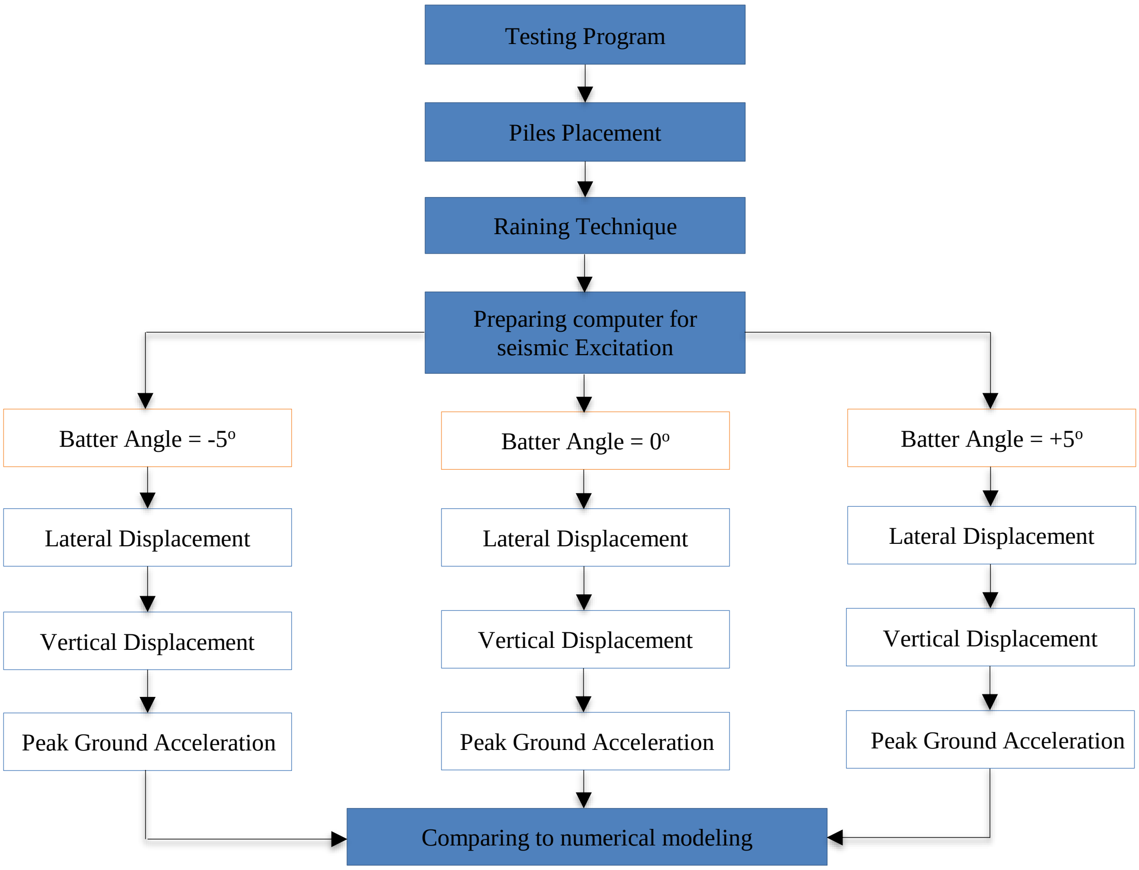


Figure 7. Flow chart of the current research methodology

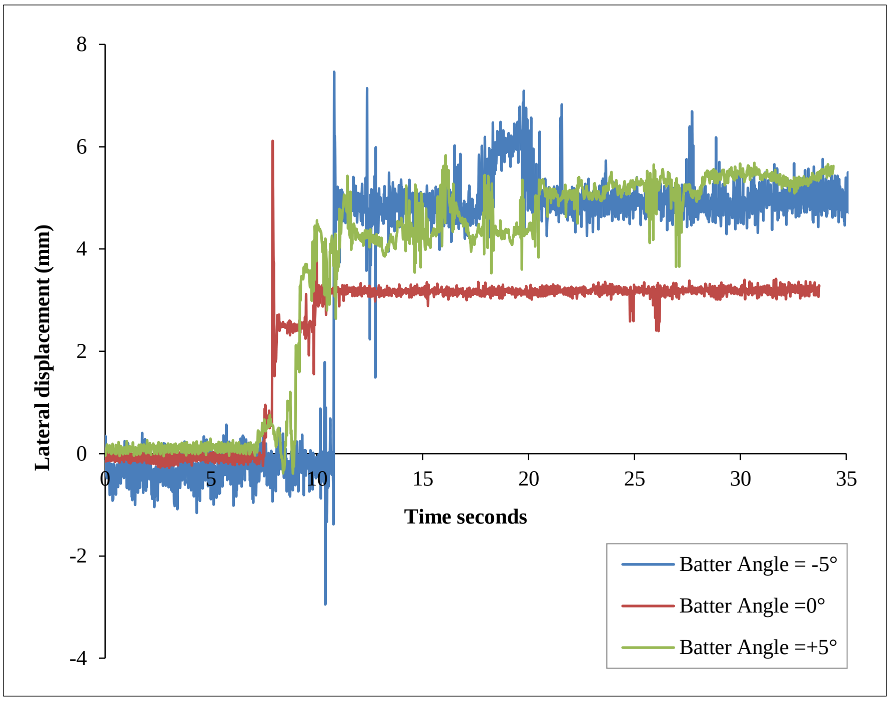
3. Experimental Results

3.1. Lateral Displacement

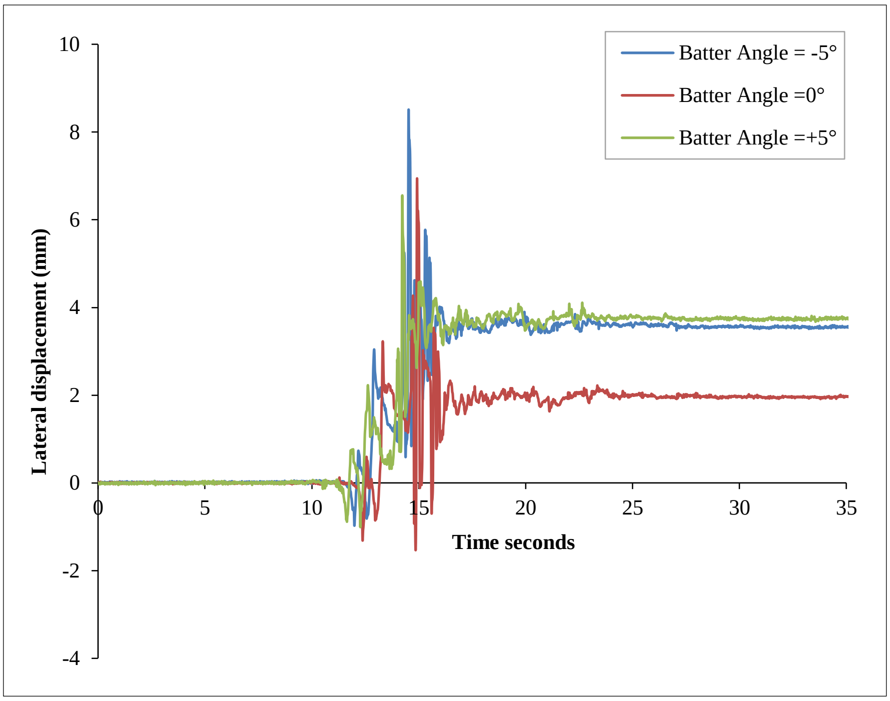
Table 3 and Figure 8 illustrate the effect of batter type on the lateral displacement response of the 3 × 3 pile group. As shown in the figure, for the El Centro earthquake, the lateral displacement peaks are relatively similar for both positive and negative batter configurations, with peak values occurring between the 5th and 7th seconds after the onset of motion. Following these peaks, the seismic shaking causes densification of the sand, transitioning it from a loose to a denser state, which leads to more stable displacement readings. In contrast, during the Kobe earthquake, a key distinction in the lateral displacement response is the presence of negative values.

Table 3. Lateral displacement response (maximum values *in mm*)

Batter Angle	-5º		0º		5º	
Earthquake	El- Centro	Kobe	El- Centro	Kobe	El- Centro	Kobe
Maximum Lateral Displacement (mm)	7.463	8.513	6.113	6.944	5.831	6.556
Difference from 0º reading %	22.085	22.597	-	-	-4.620	-5.583



(a)



(b)

Figure 8. The propagation of lateral displacement: (a) El – Centro. (b) Kobe

For El Centro case, the application of a negative batter angle (-5°) resulted in a 22.085% increase in the maximum lateral displacement of the pile group. In contrast, using a positive batter angle (+5°) led to a 4.620% reduction in this value. A comparable trend was observed under the Kobe earthquake loading, where the negative batter angle caused a 22.597% increase in lateral response, while the positive batter angle reduced it by 5.583%. These findings indicate that negative batter angles can considerably degrade the seismic performance of pile groups, whereas positive batter angles tend to enhance it. This variation in behavior is primarily due to the orientation of the piles. Positive batter piles are inclined in the direction of the lateral load, enabling them to better resist bending moments and shear forces. This alignment improves the mobilization of soil resistance, thereby limiting lateral displacement. On the other hand, negative batter piles are inclined away from the direction of loading, which restricts their capacity to engage the surrounding soil effectively, making them more vulnerable to lateral movement.

The influence of earthquake characteristics is also evident. While both El Centro and Kobe motions produced similar trends, the magnitude of displacement was higher under the Kobe record due to its higher peak ground acceleration and frequency content, which amplified soil–pile interaction effects. These findings are consistent with Li et al. [4], who observed excessive lateral movements in negative batter piles under dynamic centrifuge testing, and Huang et al. [6], who reported increased bending moments for negatively battered front-row piles in shaking table experiments.

3.2. Vertical Displacement

Table 4 and Figure 9 present the influence of batter type on the vertical displacement response of the 3 × 3 pile group. The results indicate that negative batter piles exhibited poorer performance in terms of vertical displacement compared to both vertical and positive batter piles, following a similar trend to that observed in lateral displacement behavior. However, the differences in vertical displacement among the various batter configurations are less significant than those seen in the lateral response for both the El Centro and Kobe earthquakes. This reduced disparity is attributed to the fact that the inclination originates from a vertical alignment, as previously explained by Jassim & Albusoda [12].

For the El Centro ground motion, the application of a negative batter angle (-5°) led to a 23.061% increase in the maximum vertical displacement, whereas a positive batter angle (+5°) reduced the maximum value by 4.765%. Similarly, under the Kobe earthquake, the negative batter configuration resulted in a 20.619% increase, while the positive batter reduced the displacement by 5.138%. Although vertical displacements were generally smaller than lateral displacements, they remain critical because they contribute to pile group instability during strong shaking. Moreover, the effect of earthquake type was again evident: the Kobe motion produced larger settlements than the El Centro motion, which can be linked to its higher acceleration pulses and longer-duration shaking. The observed settlement patterns align with Zhao et al. [7], who found that nonlinear soil response amplifies vertical displacement in negative batter piles, especially in loose sandy soils.

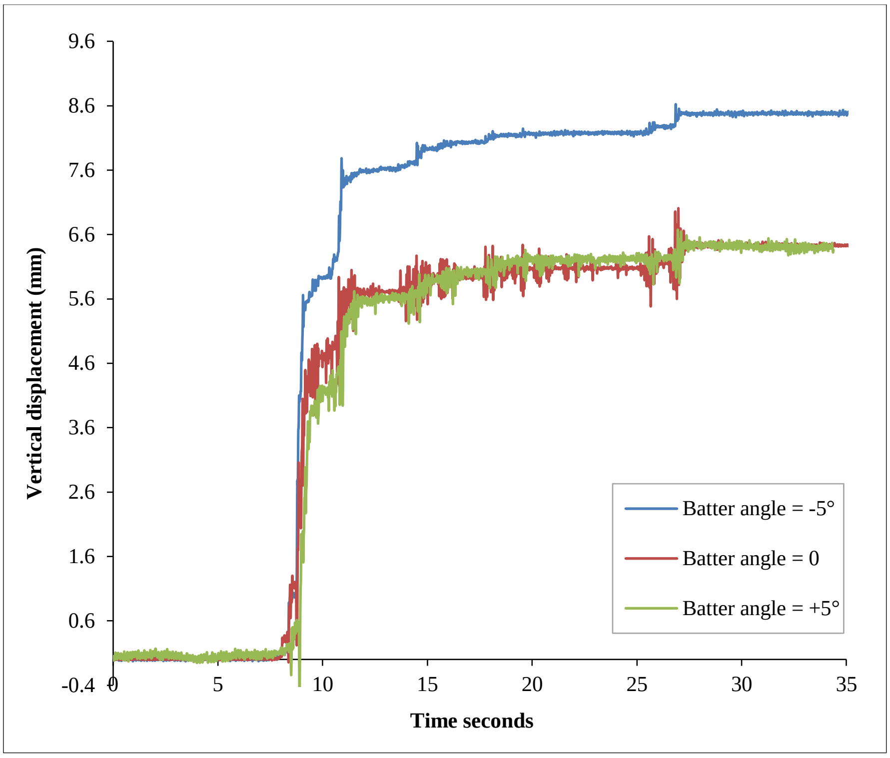
Overall, positive batter piles consistently demonstrated superior performance compared to their negatively battered counterparts. This is primarily because positive batter piles resist lateral forces while simultaneously engaging in compression, a condition that improves pile stability and reduces the likelihood of structural failure.

Table 4. Vertical displacement response (maximum values in mm)

Batter Angle	**-5º**		**0º**		**5º**	
Earthquake	El- Centro	Kobe	El- Centro	Kobe	El-Centro	Kobe
Maximum Vertical Displacement (mm)	8.624	10.244	7.008	8.493	6.674	8.056
Difference from 0º reading %	23.061	20.619	-	-	-4.765	-5.138

3.3. Peak Ground Acceleration Response

Table 5 and Figure 10 display the effect of batter angle on the peak acceleration response of the 3 × 3 pile group. In the case of the El Centro earthquake, the negative batter angle (-5°) led to a 3.857% increase in the maximum acceleration, while the positive batter angle (+5°) resulted in a larger increase of 7.163%. For the Kobe earthquake, the negative batter angle increased the maximum PGA by 4.313%, whereas the positive batter angle caused only a slight increase of 0.629%.



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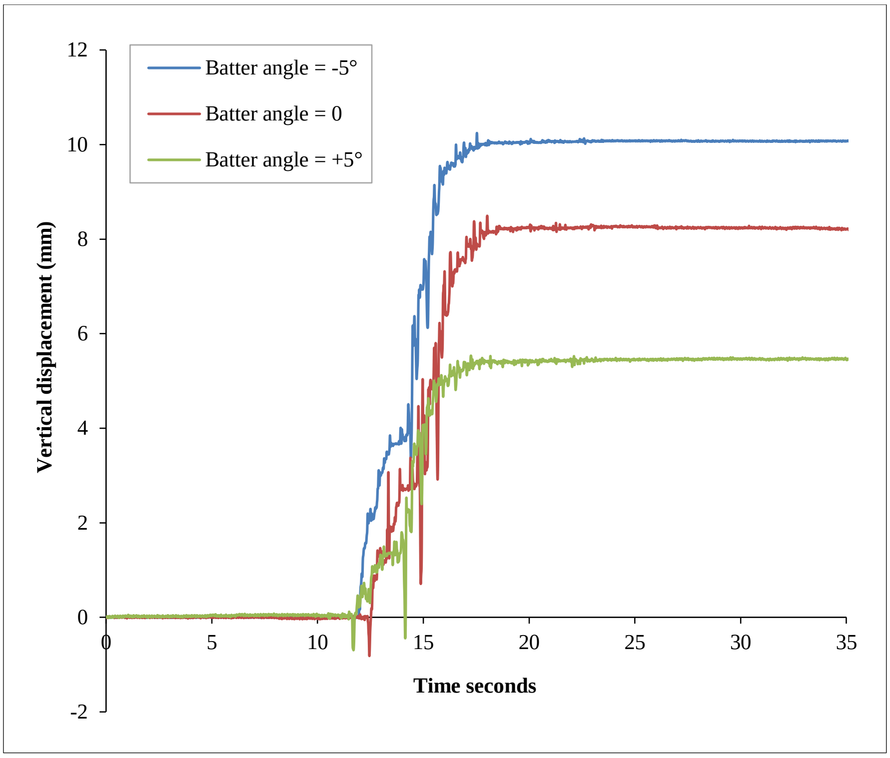
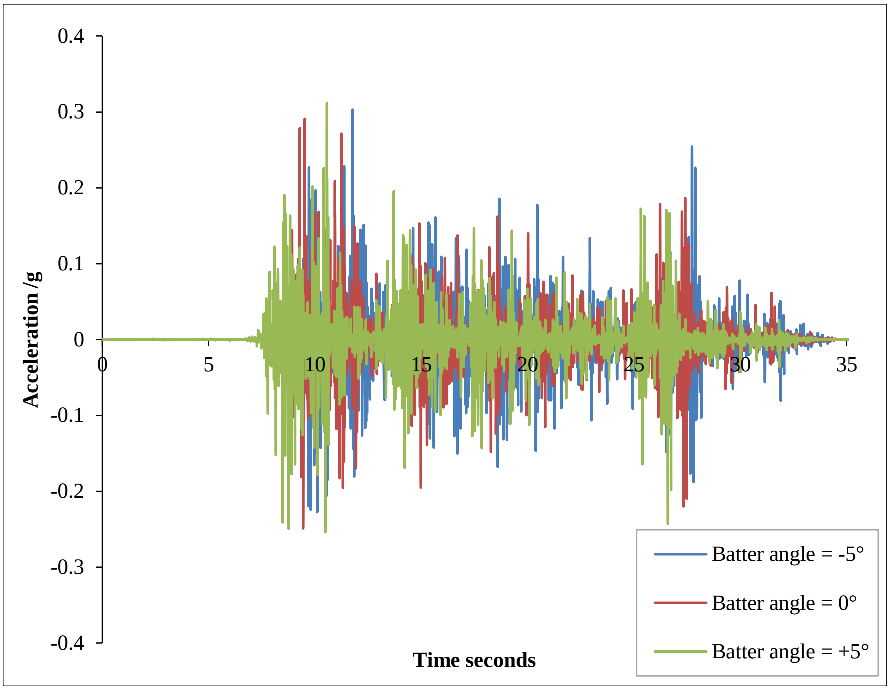


(b)

Figure 9. The propagation of vertical displacement: (a) El – Centro. (b) Kobe

Table 5. Acceleration response (maximum values)

Batter Angle	-5º		0º		5º	
Earthquake	**El- Centro**	**Kobe**	**El- Centro**	**Kobe**	**El- Centro**	**Kobe**
Maximum Acceleration (1/g)	0.377	1.161	0.363	1.113	0.389	1.106
Difference from 0º reading %	3.857	4.313	-	-	7.163	-0.629



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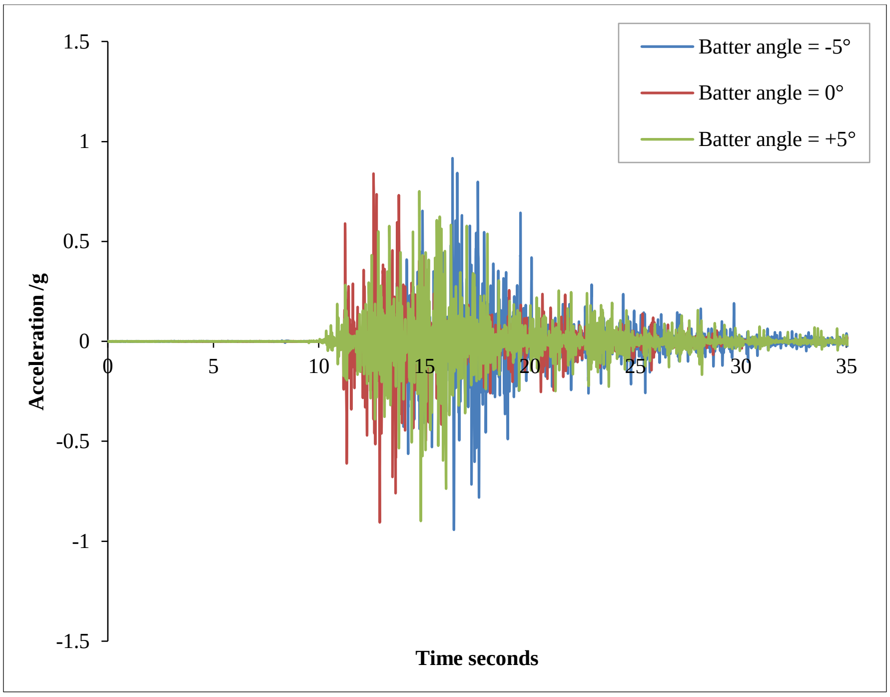


(b)

Figure 10. The propagation of acceleration displacement: (a) El – Centro. (b) Kobe

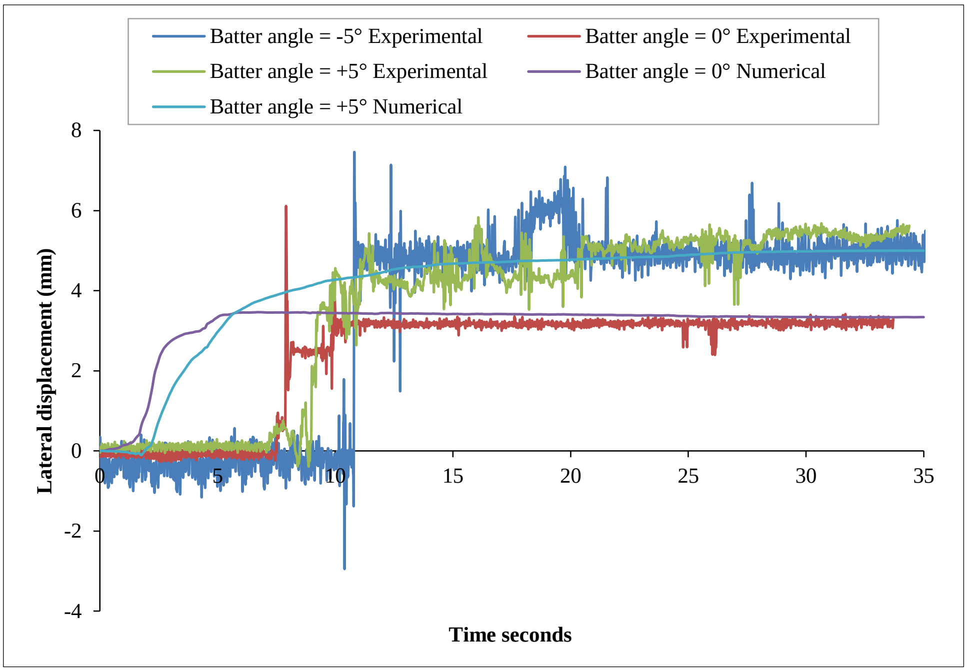
The acceleration response of pile groups did not show a fully consistent trend with batter angle. In some cases, negative batter piles showed amplification of peak ground acceleration (PGA) at the pile cap, while in others the difference was marginal. This irregularity suggests that pile acceleration is influenced by multiple factors, including soil densification, pile inclination, and dynamic wave propagation through the soil mass. Unlike displacement responses, which are dominated by geometric orientation and soil–pile interaction, acceleration responses are strongly dependent on the frequency content of the input motion and local resonance effects.

For instance, in the El Centro motion, negative batter piles amplified PGA due to unfavorable alignment with inertial loads, while positive batter piles tended to dissipate seismic energy more effectively. However, under the Kobe motion, soil densification during shaking reduced acceleration amplification. This highlights that displacement-based parameters are more reliable indicators of seismic pile performance than PGA alone. Similar conclusions were reached by Giannakou et al. [8], who emphasized the importance of considering displacement and settlement metrics rather than acceleration alone when evaluating inclined pile performance.

4. Results of Numerical Model

The Mohr–Coulomb model was adopted for sand due to its simplicity, efficiency, and established use in seismic soil–structure interaction studies. However, it is recognized that this model cannot fully capture nonlinear hysteretic soil behavior, cyclic stiffness degradation, or pore pressure accumulation under strong seismic loading. Consequently, while the model is suitable for capturing the general displacement and acceleration trends observed in the experiments, the absolute values of response may be affected by this simplification. Advanced constitutive models, such as the Hardening Soil (HS) model with small-strain stiffness (HS-Small), bounding surface plasticity, or PM4Sand, may provide more realistic simulation of cyclic soil response. Incorporating such models in future studies would strengthen the predictive capacity of numerical analyses.

Verification of the numerical model was conducted by comparing the simulation results with experimental measurements obtained from laboratory tests. The vertical displacements were numerically computed using PLAXIS 3D, with representative results illustrated in Figure 11. This figure, displays the settlement distribution through contour line outputs. The Figure presents a direct comparison between the vertical displacements measured in the laboratory and those obtained from the numerical simulations, highlighting the consistency and accuracy of the finite element model in replicating the observed experimental behavior.



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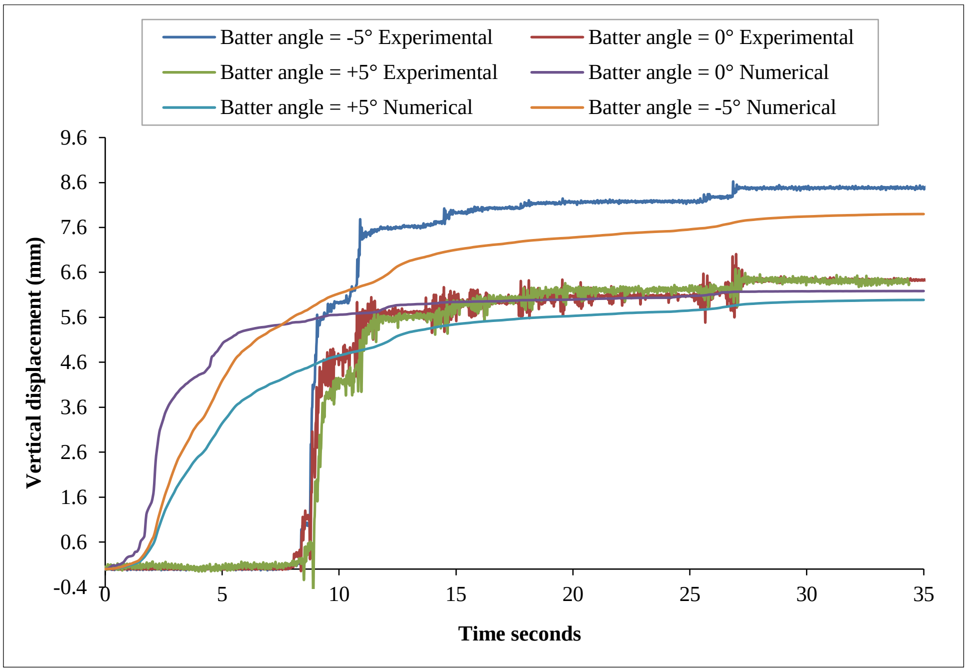

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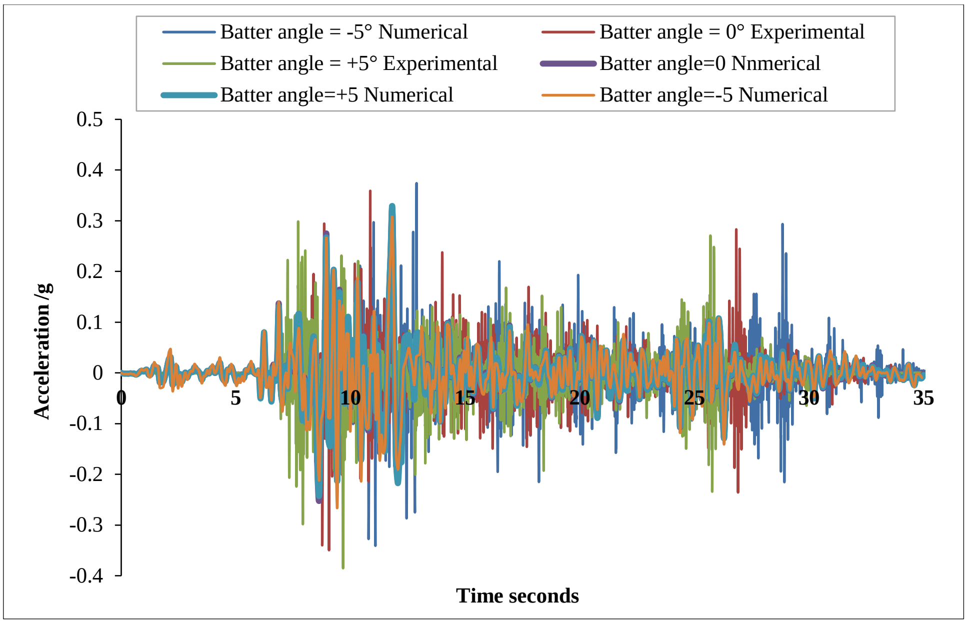

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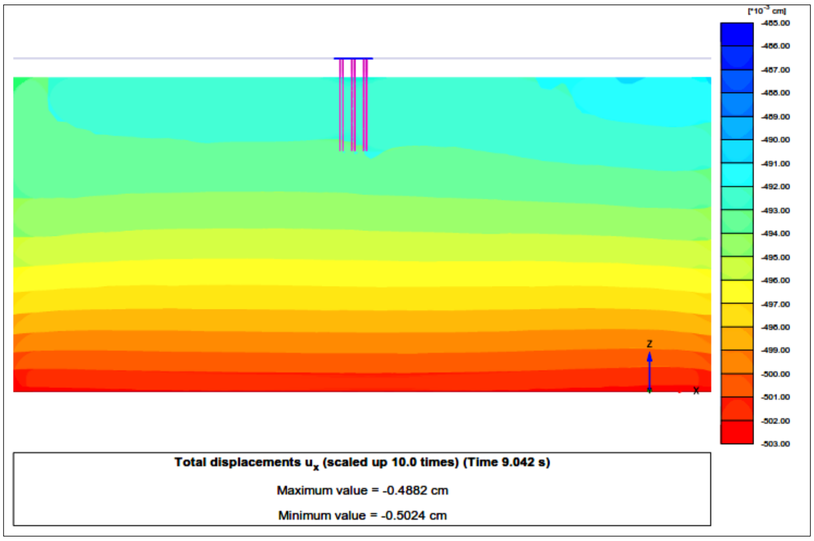

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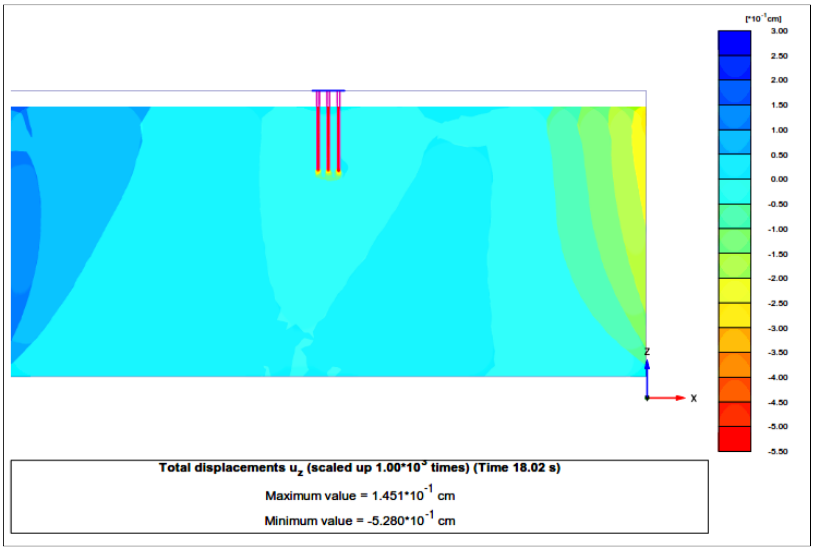

(e)

Figure 11. Numerical verification: (a) Lateral displacement response. (b) Vertical displacement response. (c) Acceleration response. (d) Contour diagram for lateral displacement response at specific time (9.042 s) for vertical piles. (d) Contour diagram for vertical displacement response at specific time (18.02 s) for vertical piles.

The comparison reveals that the settlement results obtained from the finite element analysis closely align with those observed in the experimental tests under seismic loading conditions. The minor discrepancies between the two sets of results can be attributed to several factors. Notably, PLAXIS 3D assumes a constant soil density throughout the model domain, whereas the experimental study used an average soil density. In reality, soil density may vary with depth due to changes in geostatic stress, typically decreasing toward the surface. This variation introduces a more realistic representation of soil behavior in the physical model.

Additionally, PLAXIS 3D models the soil as an ideal homogeneous and isotropic material, while in practice, natural soils are neither perfectly homogeneous nor isotropic. Such simplifications may contribute to the observed differences between the numerical and experimental outcomes. Regarding lateral displacement, the finite element analysis demonstrates strong consistency with the experimental results. By thoroughly comparing the outcomes of both numerical and physical models across a range of influencing parameters, the feasibility of using finite element method to simulate dynamic soil–pile–structure interaction is confirmed. The lateral displacement results are presented in Figure 11, further validating the reliability of the numerical model. In the experimental tests, peak ground acceleration is identified as the maximum amplitude observed in each test case's acceleration-time–time history. In the numerical simulations, PLAXIS 3D provides spatial acceleration outputs that allow for a detailed assessment of both the magnitude and direction of acceleration at various points within the model. This capability supports a more comprehensive understanding of the dynamic response of the soil–pile–structure system and enhances the ability to compare numerical results with experimental measurements.

5. Conclusions

This research advances the field of geotechnical engineering by providing experimental insight into the seismic performance of negative battered piles—an area that has received limited attention to date. The results indicate that negative battered piles exhibit inferior behavior under seismic loading when compared to both positive battered and vertical piles. These findings are significant for improving the design strategies of pile foundations in earthquake-prone regions, thereby enhancing overall structural safety. The key conclusions drawn from the study are:

- Following the reported initial loading peaks, the load–displacement curves demonstrated stabilization due to the densification of the sandy soil, triggered by seismic shaking. This densification resulted in a consistent deformation path once the peak displacement was attained.
- Negative battered piles showed diminished seismic performance relative to positive battered piles, primarily due to the generation of tensile stresses along their inclined axes, which compromise the effectiveness of the load transfer system.
- The disparity in performance between positive and negative battered piles was more significant in lateral displacement than in vertical displacement, underscoring the batter angle’s impact on horizontal response characteristics.
- It is recommended that negative battered piles be placed in less critical zones of pile groups where seismic forces are less intense. Additionally, thorough pre-design analyses are essential to ensure the structural integrity and efficiency of pile foundations under seismic loads.
- A negative batter angle of -5° in a 3×3 pile group configuration resulted in an increase in maximum lateral displacement by about 23% when compared to vertical piles.
- Under seismic conditions, the installation of -5° negative battered piles in a 3×3 pile group led to a 20% to 23% rise in maximum vertical displacement.
- Positive battered piles inclined at +5° contributed to a reduction in lateral displacement by approximately 4% to 6%, indicating enhanced lateral stability during seismic events.
- The incorporation of +5° positive batter piles was also associated with a roughly 5% reduction in maximum vertical displacement, supporting improved horizontal load distribution.
- The experimental findings underscore the significant influence of earthquake intensity on the behavior of pile groups, with observable differences in performance depending on the characteristics of the seismic excitation.
- The numerical modeling showed a good agreement between the experimental and numerical results.

6. Declarations

6.1. Author Contributions

Conceptualization, L.A. and B.G.; methodology, B.G.; software, L.A.; validation, D.M. and G.B.; formal analysis, D.M.; investigation, L.A.; resources, B.G.; data curation, B.G.; writing—original draft preparation, L.A.; writing—review and editing, D.M.; visualization, L.A.; supervision, G.B.; project administration, D.M.; funding acquisition, D.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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