Bilad Alrafidain Journal for Engineering Science and Technology
https://dx.doi.org/10.56990/bajest/2026.050102

ISSN: 2073-9524
Pages:15-23

The Experimental Seismic Performance of Positive and Negative Batter in a 2 x 2 Piles Group in Loose Sand

Qassim I. Hussain [1*], Mohammed A. Al-Neami [2], Falah H. Rahil [3]
[1,2,3] Materials Engineering Dept, University of Technology-Iraq, Alsinaa street, 10066, Baghdad, Iraq.
Koz2019@yahoo.com[1], 40008@uotechnology.edu.iq[2], c4029@uotechnology.edu.iq[3]

Abstract

In the event of an earthquake, pile foundations help to keep a structure stable. Batter piles, which are a sort of angled foundation, can resist both vertical and horizontal loads better than a typical vertical pile. The primary objective of this research is to address the seismic response of negatively battered piles in 2 × 2 pile groups embedded in loose sand through an experimental approach. The experimental study used 2 × 2 pile groups embedded in a loose sandy soil with 31.2% relative density, and seismic loading was replicated using a shaking table. Ground motion in the El Centro and Kobe earthquakes was applied to piles with batter angles of -5°, 0°, and +5°. The purpose was to assess and contrast the case of a negatively battered pile with vertical and positively battered piles, about the lateral and vertical displacements, and the acceleration. Experimental findings demonstrated that negative battering notably amplifies pile group displacements under seismic excitation. Specifically, for the El Centro earthquake, changing the batter angle from 0° to 5° increased the maximum lateral displacement by 24.287%, while adjusting it from 0° to +5° reduced it by 3.877%. Similarly, vertical displacement rose by 19.923% for the negatively battered piles, whereas positive battering resulted in a 7.511% reduction in lateral displacement for the same event.

Keywords: El–Centro earthquake; Loose sand; Negative batter; Seismic performance; Deep foundations and shaking table.

Article history: **Received:** 7 Oct 2025**, Accepted:** 7 Dec 2025**, Published:** 15 Mar 2026**.**

1. Introduction

Pile foundations are the fundamental components of civil infrastructure, responsible for transferring structural loads to deeper, more competent soil layers. These loads comprise a wide spectrum of types, including static and dynamic loads such as seismic, cyclic, and even machine loads [1]. Among the different pile configurations, batter piles, also known as inclined piles, offer improved resistance to lateral loads and are widely used in bridge abutments, marine structures, and seismic regions. The performance of batter piles is significantly impacted by their installation angle, which is an inclination to the vertical axis, in contrast to vertical piles. A pile is referred to as a "positive batter pile" when it is inclined in the direction of the applied horizontal load, and a "negative batter pile" when it is inclined away from the direction of the load. The intricacy of soil-structure interactions, particularly when embedded in loose sandy soils, affects the seismic performance of such piles in addition to their geometry and batter angle.

In seismic regions, understanding the behavior of pile foundations is critical, as ground shaking generates significant lateral forces that induce stresses and displacements in the pile–soil system. While considerable research has been devoted to understanding the seismic response of vertical piles, studies on battered piles, especially in group configurations, remain relatively limited. Depending on variables such as batter angle, soil type, pile spacing, and excitation frequency, earthquake-induced dynamic loading affects pile performance. These effects are even more complex when taking

* Corresponding Author: Koz2019@yahoo.com

group behavior into consideration (pile–soil–pile interaction, shadowing), which comes with the need for experimental and numerical work to fully understand such phenomena, and valuable clues have been found in basic studies of this pursuit. In their study on the response of single piles under lateral loading in unsaturated soils [2].

Highlighted the influence of excitation frequency and moisture content on pile response, in a similar vein [3]. Determined that pile geometry is a critical component in seismic design after examining the effect of the slenderness ratio on the ultimate lateral resistance of piles in sandy soils. The pullout capacity of batter pile groups was numerically assessed [4], which confirmed that the batter angle significantly influences pile resistance in sandy soils. Together, these studies highlight the significance of pile geometry and inclination in seismic analysis, but they also highlight a glaring knowledge gap regarding the seismic behavior of (negative batter piles), especially in group configurations.

The seismic performance of batter piles under multidirectional earthquake loading has received renewed attention due to recent developments in geotechnical research. To evaluate their behavior, several researchers have used centrifuge modeling, finite element analysis, and experimental setups. To investigate the effects of positive and negative batter angles on pile groups during seismic excitation [5]. The authors used dynamic centrifuge tests. They found that negative batter piles undergo greater lateral displacements, particularly in loose sands. Similarly [6].

Used three-dimensional finite element modeling to investigate bidirectional seismic loading on pile groups and discovered that under shaking, negative batter piles show complex moment redistribution. Shaking table experiments on pile groups with varying batter angles were done on saturated sand by [7], which found that front-row piles with negative batter exhibited more bending moments and greater displacements than their vertical and positive counterparts. Liu and Chen [8] revealed the seismic weakness of negative batter piles on low-density sands [9]. For inclined piles, assessment of reinforcement methods discovered in the negative batter piles that predicted seismic performance improvement [10]. The mitigation of opening displacement along the vertical direction by the positive batter pile configurations also improved the energy dissipation [11]. Seismic retrofitting of bridge pier in batter piles [12]. The increase in the seismic response of bridge pier batter piles [13]. Negative batter piles buckled more easily, exhibiting more kinematic earth forces. The analyzed piles [14].

The studies summarized in the mentioned papers during ground shaking and negative batter angles exhibit greater failure potential. In Relation to the above paragraph, there is an absence of other published work that provides detailed examinations of experimental and numerical techniques to assess the seismic performance of a pile group consisting of 2x2 pile arrangements in loose sandy soils with different batter configurations. Most of the previously published works have concentrated on single piles or small arrangements of piles, although the loading and boundary conditions may be simplified. The mechanisms of interactions, the redistribution of the stresses, and the movement of the displacement in larger arrangements of piles have yet to be properly defined, including the movement formed during real earthquakes such as those in El Centro and Kobe.

In addition to the above, there has been an over focus on the vertical or positive batter piles and the different unique behavior of negatively battered arrangements, which may have a more unstable behavior, has been overlooked. The current experiment attempts to address this issue by incorporating experimental shaking table tests in order to assess the seismic performance of 2x2 pile group configurations with positive and negative batter angles in loose sandy soils. The specific areas of focus will be on the lateral and vertical movement, and the response to acceleration during specific earthquakes will be recorded. Focus will be placed on the negative batter angles, which marked the behaviors of the previously mentioned studies as more complex and lesser known.

ISSN: 2073-9524
Pages:15-23

2. Materials and Methods

2.1 Materials of the study

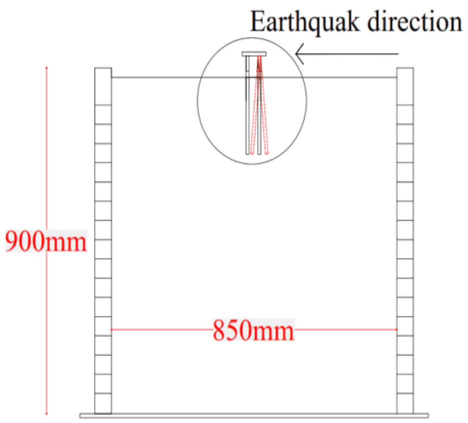
Table 1 presents the key basic properties of the sandy soil sample utilized in the current experimental study

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

A state-of-the-art tool used in geotechnical experimental research as a workable substitute for extensive field testing is the laminar soil box. There are big advantages to it, including cheaper building and faster assembly. It also allows one to easily change soil types and apply different loading conditions. These properties contribute to a degree of confidence, consistency, and accuracy in the experimental results created [12–14]. The laminar box is specifically designed to simulate the controlled simulation of shear stresses and ground motion during seismic events by simulating horizontal shear wave transmission through soil layers. In the present study, the laminar box is composed of aluminum laminate, each 50 mm in height, with total dimensions of 85 × 85 × 90 mm³. The structural design of the box is depicted in Fig.1.



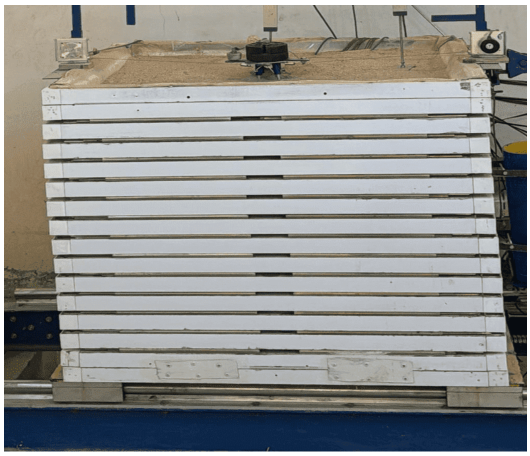


Fig. 1 Schematic and photographic views of the soil laminar box.

2.3 Pile group

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

 ISSN: 2073-9524
Pages:15-23

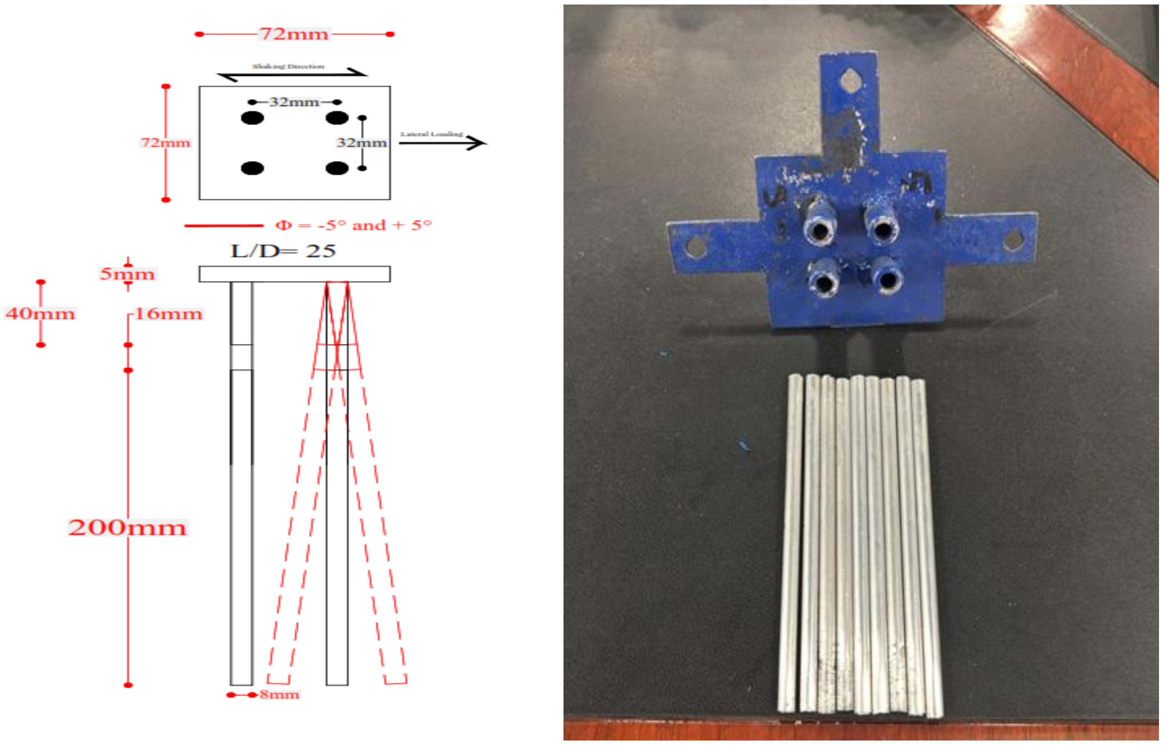


Fig. 2 Schematic and photograph of the model pile group and pile appearance.

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.

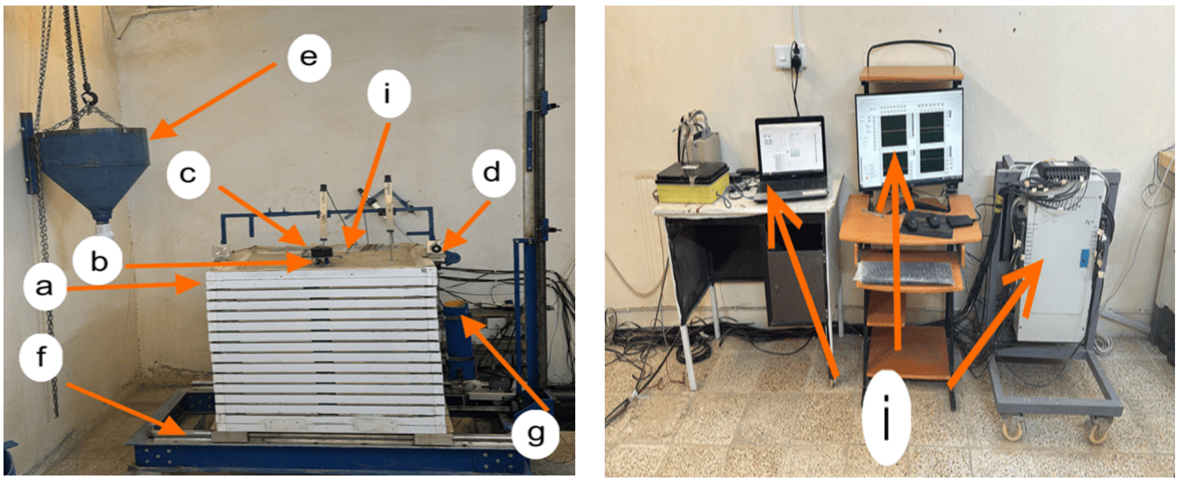


Fig. 3 Details of the testing apparatus.

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 was adopted, as supported by recent research [14] and [15]. As shown in Fig. 4, sand was dropped from a height of 115 cm and fell freely for 100 mm above the developing soil surface until the desired fill height was reached.

We applied an axial gravitational load that was equal to the maximum load that each configuration could hold. We used a shaking table setup to simulate seismic excitation. It had a steel frame, a supporting platform, a screw-ball drive mechanism, and a bunch of sensors for monitoring and measuring. Fig. 5 shows how the pile group reacted to input ground motions from the El Centro and Kobe earthquake records. To achieve a uniform relative density of 31.2%, the sand was deposited in layers throughout the model preparation.

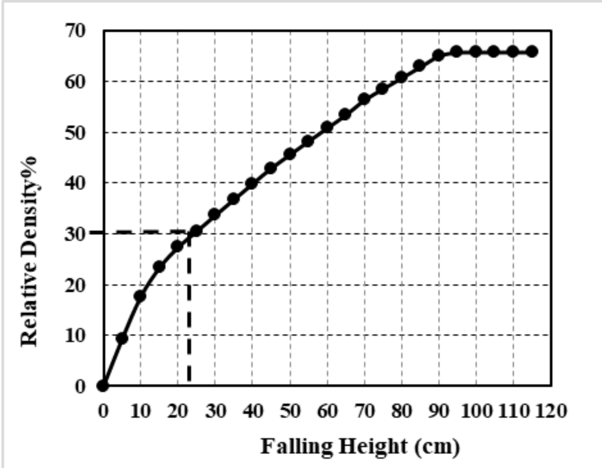
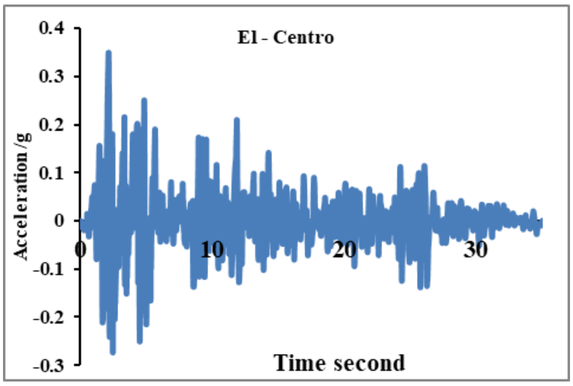
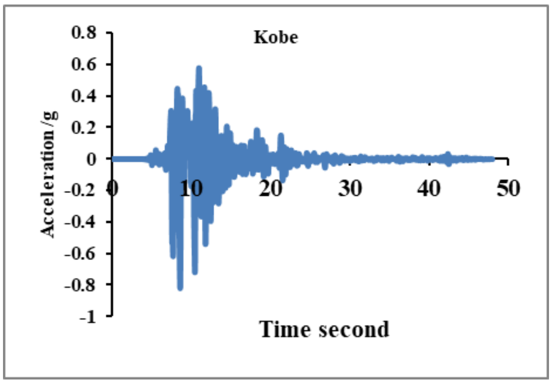


Fig. 4 Raining technique curve.



A) El–Centro



B) Kobe

Fig. 5 Earthquakes of the study: (A) El–Centro. (B) Kobe.

3. Experimental results

3.1 Lateral Displacement

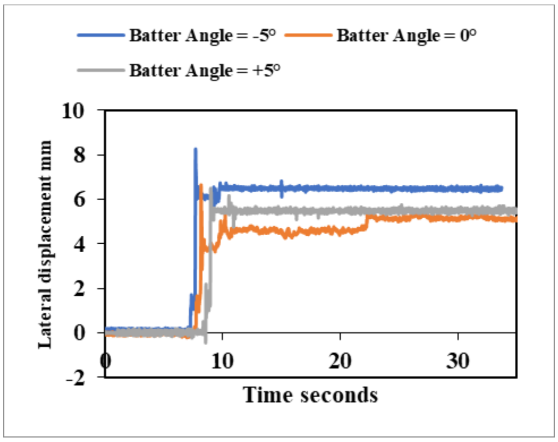
Table 2 and Fig. 6 show how the type of batter affects how the 3 × 3 pile group moves sideways. The figure shows that for the El Centro earthquake; the lateral displacement peaks are pretty much the same for both positive and negative batter configurations. The highest values happen between the 5th and 7th seconds after motion starts. After these peaks, the shaking of the ground causes the sand to become denser, which makes the readings of displacement more stable. In contrast, the lateral displacement response during the Kobe earthquake had negative values, which was a big difference.

The maximum lateral displacement of the pile group increased by 24.287% in the El Centro case when a negative batter angle (-5°) was applied. This number varied by -2.353%, which may be obtained with a positive batter angle (+5°). A trend is obtained under the Kobe earthquake loading, also, and we observe an increase of 22.004% with negative batter angle but a decrease of 3.877% with positive batter angle in lateral response. These results reveal that negative batter angles can greatly reduce the seismic response of pile groups, while positive batter angles may protect pile groups against such a threat. 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.

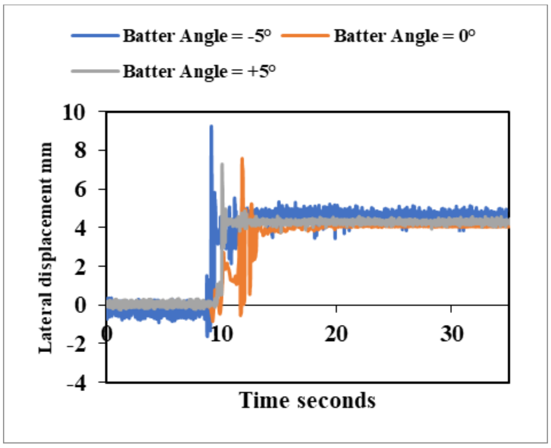
This alignment improves the mobilization of soil resistance, thereby limiting lateral displacement. On the other hand, negative batter piles are inclined away from the direction of loading, which restricts their capacity to engage the surrounding soil effectively, making them more vulnerable to lateral movement.

Table 2: 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)	8.267	9.256	6.652	7.587	6.495	7.293
Difference from 0º reading %	24.287	22.004	/	/	-2.353	-3.877



B) El Centro



B) Kobe

Fig. 6 The propagation of lateral displacement: (A) El–Centro (B) Kobe

3.2 Vertical Displacement

Table 3 and Fig. 7 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 [13].

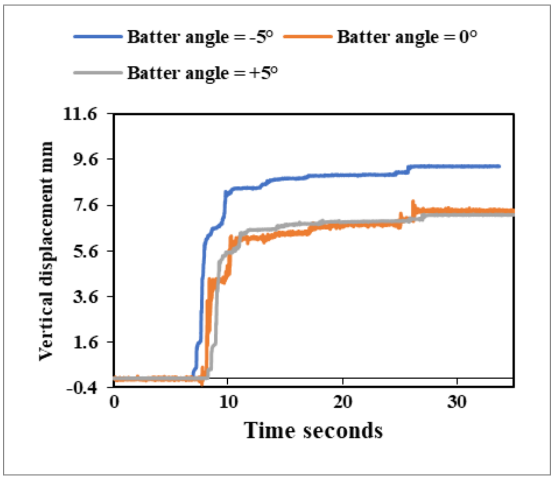
For the El Centro ground motion, the application of a negative batter angle (-5°) led to a 19.923% increase in the maximum vertical displacement. In contrast, a positive batter angle (+5°) reduced the maximum value by 7.511%. Similarly, under the Kobe earthquake, the negative batter configuration resulted in a 23.247% increase, while the positive batter reduced the displacement by 2.816%. 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

Bilad Alrafidain Journal for Engineering Science and Technology
https://dx.doi.org/10.56990/bajest/2026.050102
ISSN: 2073-9524
Pages:15-23

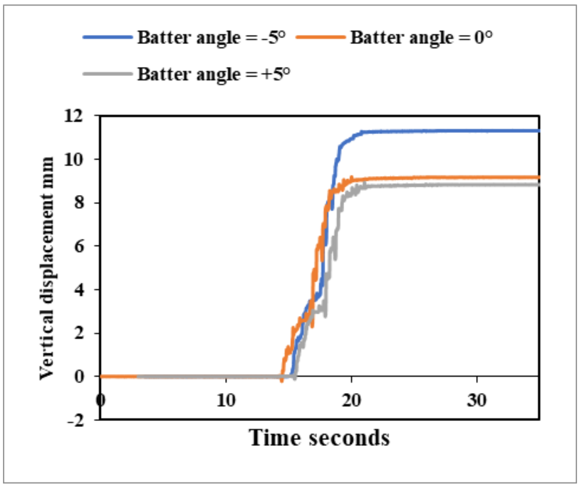
compression, a condition that improves pile stability and reduces the likelihood of structural failure.

Table 3: 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)	9.337	11.329	7.786	9.192	7.201	8.934
Difference from 0º reading %	19.923	23.247	/	/	-7.511	-2.816



A) El Centro.



B) Kobe.

Fig. 7 The propagation of vertical displacement: (A) El–Centro (A) Kobe

3.3 Peak Ground Acceleration Response

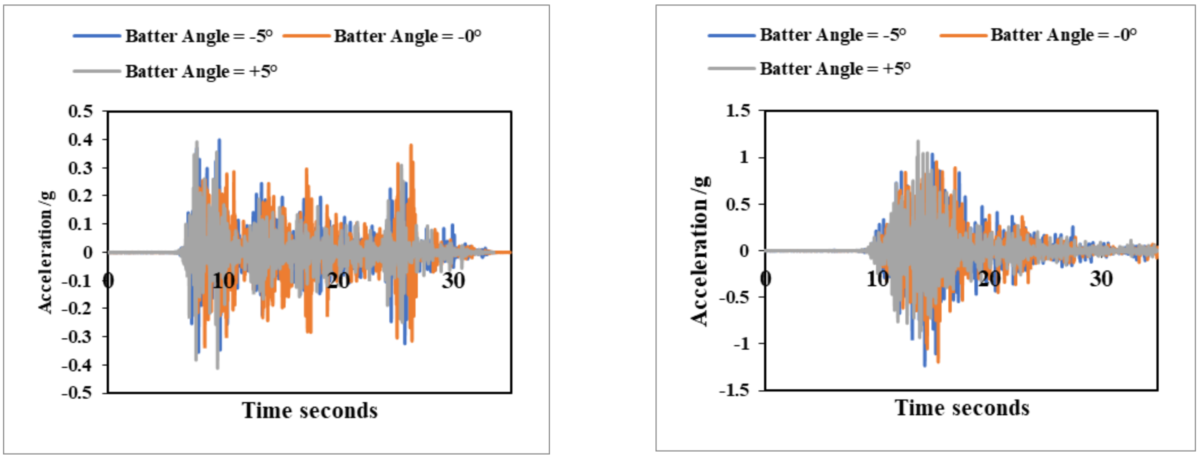
Table 4 and Fig. 8 display the effect of batter angle on the peak acceleration response of the 3 × 3 pile group. In the case of the El Centro earthquake, the negative batter angle (-5°) led to a 3.937% increase in the maximum acceleration. In comparison, the positive batter angle (+5°) resulted in a larger increase of 7.087%. For the Kobe earthquake, the negative batter angle increased the maximum PGA by 3.976%, whereas the positive batter angle caused only a slight increase of -0.677%.

These results indicate that there is no consistent or clear trend in PGA response associated with the different batter angles tested. The accelerometer's placement in the middle of the pile group cap may be the cause of this discrepancy. More research is advised to better understand the relationship between the forces causing vertical and lateral displacements and peak ground acceleration.

Bilad Alrafidain Journal for Engineering Science and Technology
https://dx.doi.org/10.56990/bajest/2026.050102
ISSN: 2073-9524
Pages:15-23

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 Acceleration	0.396	1.229	0.381	1.182	0.408	1.174
Difference from 0o reading %	3.937	3.976	/	/	7.087	-0.677



A) El–Centro B) Kobe

Fig. 8 The propagation of lateral displacement: (A) El–Centro. (B) Kobe

4. Conclusions

This study advances geotechnical engineering by offering significant experimental insights into the seismic behavior of negative battered piles, a relatively unexplored aspect. The findings demonstrate that negative battered piles perform worse under seismic loading than both positive battered and vertical piles. These findings provide a vital foundation for enhancing pile foundation design methods in seismically active areas, ultimately boosting structural resilience and safety. The main conclusions of the study are as follows:

1. Due to the densification of the sandy soil brought on by seismic vibrations, the load-displacement curves tended to stabilize after the initial load peaks. Once the peak displacement was reached, this densification produced a consistent deformation pattern.
2. The significance of batter angle in determining horizontal response is highlighted by the fact that the performance difference between positive and negative battered piles was more pronounced in lateral displacement than in vertical displacement.
3. Negative battered piles performed worse seismically than positive battered piles because tensile stresses developed along their inclined axes, weakening the load transfer mechanism.
4. A 2x2 pile group with a negative batter angle of -5° had a maximum lateral displacement that was about 22–25% larger than that of vertical piles. The maximum vertical displacement of 5° negative battered piles in a 2x2 pile group increased by 20–24% under seismic excitation.
5. Negative battered piles should be placed in less critical areas of pile groups where seismic forces are generally lower. Furthermore, thorough pre-design analyses are essential to preserving pile foundations' structural efficacy and stability under seismic loads.
6. The maximum vertical displacement of 5° negative battered piles in a 2x2 pile group increased by 20–24% during seismic excitation. The use of +5° positive battered piles also led to about a 3 to 8% decrease in maximum vertical

ISSN: 2073-9524
Pages:15-23

displacement, reflecting better horizontal load distribution.

7. During earthquakes, positive battered piles with a +5° inclination demonstrated improved lateral stability, resulting in a 3–4% reduction in lateral displacement.
8. The seismic performance of negative batter in soft clay soils should be covered in future research.
9. The impact of earthquake intensity on the pertinent seismic behavior of batter piles requires more research.

Conflict of interest

The authors declare that there is no conflict of interest.

Acknowledgement

The authors thank every person/foundation that helped them in doing this research.

Reference

[1] Hadi, G. H., & Abbas, J. M. (2024). Experimental model for machine foundation response under earthquake loading in sandy soil. The International Scientific Conference of Engineering Sciences and Advanced Technologies, 3229, 060002. AIP Publishing. https://doi.org/10.1063/5.0236930.

[2] Abood, M., Mahmood, M., & Salim, N. (2021). Effect of dynamic earth vibration on the behavior of laterally loaded single pile embedded within unsaturated soil. Engineering and Technology Journal, 39, 1748–1752. https://doi.org/10.30684/etj.v39i12.508.

[3] Ali, I., Abbas, S., & Ibrahim, K. (2021). Effect of the slenderness ratio of piles on ultimate lateral resistance in sandy soil. Engineering and Technology Journal, 39, 1740–1747. https://doi.org/10.30684/etj.v39i12.105.

[4] Al-Tememy, M., Al-Neami, M., & Asswad, M. (2022). A numerical analysis on the pullout capacity of batter pile groups in sandy soil. Engineering and Technology Journal, 40, 1352–1357. https://doi.org/10.30684/etj.2021.131818.1062.

[5] Ghasemi, A., & Morteza, F. (2023). Dynamic performance of batter pile foundations in liquefiable soils: A 3D numerical study. Soil Dynamics and Earthquake Engineering, 170, 107114. https://doi.org/10.1016/j.soildyn.2023.107114.

[6] Han, Y., Zhang, Q., & Xu, M. (2023). Numerical investigation on the seismic behavior of negative batter piles in loose sands. Geotechnical Research, 12(2), 135–148.

[7] Lin, F., & Zhao, J. (2024). Finite element analysis of inclined pile groups under multidirectional seismic loading. Earthquake Engineering and Engineering Vibration, 23(1), 88–101.

[8] Liu, P., & Chen, T. (2025). Seismic resilience of reinforced batter piles in soft soils. Computers and Geotechnics, 168, 105341.

[9] Othman, R., Khalaf, H., & Al-Azzawi, M. (2024). Retrofit strategies for bridge foundations with batter piles in seismic zones. Structural Engineering International, 31(3), 221–229.

[10] Wang, D., Li, C., & Sun, J. (2023). Dynamic centrifuge modeling of batter pile groups in sandy soil. Journal of Earthquake Engineering, 29(5), 673–692.

[11] Zhou, Y., Wang, X., & Liao, H. (2024). Experimental study on seismic performance of pile groups with different batter angles in saturated sands. Engineering Geology, 325, 107121.

[12] Mohammed, A. A. (2018). Investigation of sampling error on soil testing results. International Journal of Civil Engineering and Technology, 9, 579–589.

[13] Al-Neami, M. A., Rahil, F. H., & Al-Bayati, K. S. (2020). Behavior of batter pile group models embedded in sandy soil under monotonic loading. IOP Conference Series: Materials Science and Engineering, 737, 012088. https://doi.org/10.1088/1757-899X/737/1/012088.

[14] Daher, R., & Abbas, M. (2021). The behavior of a pile group under inclined static load with different angles of inclination in sandy soil. Diyala Journal of Engineering Sciences, 14, 52–61.https://doi.org/10.24237/djes.2021.14205