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Experimental assessment of battered pile configurations under seismic loading: focus on negative inclinations

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HIGHLIGHTS

- A shaking table was fabricated to simulate seismic load excitation on pile foundations.
- The role of positive and negative batter piles under seismic loads was analyzed.
- Negative batter piles performed worse than positive batter piles under seismic excitation.
- Earthquake intensity affected both positive and negative batter piles noticeably.

Keywords:

Sandy soil
Deep foundations
El–Centro earthquake
Kobe earthquake
Seismic performance
Negative batter and Shaking table test

ABSTRACT

Pile foundations play a crucial role in maintaining structural stability during earthquakes. This study addresses the underexplored behavior of negative battered piles under seismic loading. An experimental investigation was conducted on 2×2 pile groups embedded in sandy soil with a relative density of 30%, using a shaking table to simulate seismic events. The study evaluated the seismic response of front-row piles battered at -5°, 0°, and +5°, under input motions from the El Centro and Kobe earthquakes. The aim was to assess the comparative performance of negative battered piles relative to vertical and positively battered piles in terms of lateral and vertical displacement. The physical model tests revealed that negative battering significantly increases pile displacements under seismic loading. Specifically, shifting the batter angle from 0° to -5° caused a 315.93% increase in maximum lateral displacement, whereas a change from 0° to +5° resulted in only a 3.37% increase. Similarly, the maximum vertical displacement increased by 43.11% with negative battering, while positive battering led to a 2.33% reduction in lateral displacement. These findings demonstrate the adverse effects of negative battering on seismic performance and highlight the importance of considering batter angle orientation in pile group design for earthquake resistance. Overall, this research provides new experimental insight into the behavior of negatively battered piles, emphasizing their vulnerability under seismic loading and contributing valuable data to guide geotechnical and structural design in sandy soils.

1. Introduction

The most significant investigation within the work of the designers and researchers is to establish the safety and stability of the pile-soil system. During seismic events, the pile systems endure a combination of eccentric stress due to the stress nature, which includes compressive axial loads, transverse forces, and seismic actions. These forces operate collectively and cause large variations in stress that influence the efficiency of the pile group [1].

In understanding the principles of pile groups that are subjected to seismic forces, there are some governing factors. These include the type of soil in the vicinity of the piles, the soil surrounding the pile caps, the geometry of the loaded pile, and the loading pattern. These factors are essential determinants of the capacity of a pile group to resist forces, including those required when an earthquake strikes [2,3]. A battered pile is a structural element that is more efficient in carrying lateral forces because it is driven into the ground at a sloping angle. This design option can achieve great stability against horizontal forces such as wind or seismic forces. Such a form of construction is widely utilized in foundation engineering, where battered piles tend to increase the load-resisting tendencies to lateral stresses of a structure, hence increasing the overall stability of the structure [2,3]. Battered piles are classified into two types: positive battered piles, which are sloped away from the structure, and negative battered piles, which are internally sloped to the structure. Its selection is in accordance with the design requirements and the loads to be borne by the foundation [4]. The decision between positive and negative batter is based on the specific structural and geotechnical factors of the project, such as the soil type, the amount of lateral loads, and the overall design specifications [5,6].

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Usually, batter piles are constructed in a similar way to traditional piles; they can be steel or reinforced concrete piles. Consequently, the type of construction material also needed to be established in addition to other circumstances when batter piles needed to be located in an active seismic area [7,8]. The performance of battered piles under lateral loads during an earthquake has been a concern in most recent studies focusing on the seismic performance of structures. It has been conclusively shown that the positive use of battered piles can reduce the risk of a building being affected by horizontal stresses due to ground shaking during an earthquake. The effects of negative batter in pile groups and their consequences are significantly underrepresented in the existing literature.

Gerolymos et al. [9], conducted a three-dimensional finite element analysis to investigate the seismic behavior of positive piles. The findings of the study showed that the slenderness ratio of the whole building, as well as the connection between piles and their caps, can seriously affect the seismic behavior of the positive piles. I=-ODFIn addition, some literature efforts showed that the positive piles can illustrate a negative impact under severe seismic conditions, (Giannakou et al.) [10]. The experimental research programs using centrifuge modeling showed that positive batter can give a potential benefit against earthquakes, depending upon the earthquake event and the nature of the supported structure, (Li et al.) [11]. Bharathi et al. [12], investigated the behavior of positive battered bored piles against machine load experimentally and numerically.

The notable findings made through this research highlight that there is a variable nature of the effect caused by inclined piles since their impact can be sometimes beneficial and sometimes detrimental. The variation of this factor depends on the slenderness of the superstructure, which is defined as that part of a building above its foundations. It also depends on the type of connection between the inclined piles and the structural cap (the footing) resting on top of them; however, this has been attributed to one more risk factor impacting the total system's response to seismic loadings. Table 1 provides a comparative study with previous studies.

Table 1: Comparative summary of previous studies on battered piles under seismic and lateral loading

Pile Type	Method	Soil type	Focus	Key findings	How the current study differs	Study
Positive battered piles	3D Finite Element Analysis	Not specified	Seismic response of piles and pile cap connection	Pile-cap connection and slenderness ratio significantly influence behavior	The study uses experimental shaking table tests, focusing on negative batter	[9]
Positive battered piles	Numerical modeling	Not specified	Behavior under severe seismic events	Positive batter can be detrimental under strong earthquakes	They provide experimental validation and test negative battered piles	[10]
Positive battered piles	Centrifuge modeling	Sandy soil	Lateral resistance during earthquakes	Positive batter can be beneficial depending on the earthquake and the structure type	The study simulates two specific earthquakes (El Centro & Kobe) in 1g shaking tests	[11]
Positive battered piles	Experimental & Numerical	Clayey soil	Machine load behavior	Positive batter increased lateral resistance under machine loads	The study deals with dynamic seismic loads, not machine loading	[12]
Negative battered piles	Shaking table (1g) tests	Sandy soil	Seismic response of 2×2 pile groups with negative batter	Negative batter significantly increases both lateral and vertical displacement	First to experimentally compare negative vs. positive/vertical battering in sand	Current study (2025)

Although past investigations concentrated largely on positive and vertical batter piles, little information is available on the seismic response of negatively battered configurations, particularly for sandy soils. This article intends to address that gap by analyzing the impact of negative inclination on the dynamics of the interactions between piles and the surrounding soil. The findings of this study can help refine the seismic design provisions for pile-supported structures by enhancing the optimization methods used in foundation performance design in seismic zones.

However, while previous studies found that positive battered piles improve seismic performance by effectively combining axial and lateral resistance, this study shows that negatively battered piles perform poorly. The inward inclination of negative batter piles increases bending and shear stresses during seismic loading, leading to greater displacements, especially in sandy soils, which provide less confinement. These results highlight that the direction of battering is critical, and negative battering may be detrimental in earthquake-prone areas.

2. Experimental work

2.1 Materials

Table 2 lists the most preliminary properties of the sandy soil sample used in the current experimental program. This soil was obtained from the Karbala Governorate (about 100 km southwest of Baghdad).

2.2 Laminar container

The laminar soil box is an innovative tool used in geotechnical experimental research as an alternative to full-scale field models. It offers several advantages, including lower construction costs and faster setup, making it easier to change soil types and apply various loading conditions efficiently. This results in accurate, repeatable, and reliable experimental outcomes [13-15].

Designed to simulate horizontal shear wave propagation through a soil layer during seismic events, the laminar box enables controlled application of shear stresses and ground motion. In this study, the laminar box is constructed from aluminum laminae, each measuring 50 mm in height, with overall dimensions of 85 × 85 × 90 mm^3. The box's structural configuration is illustrated in Figure 1.

Table 2: 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

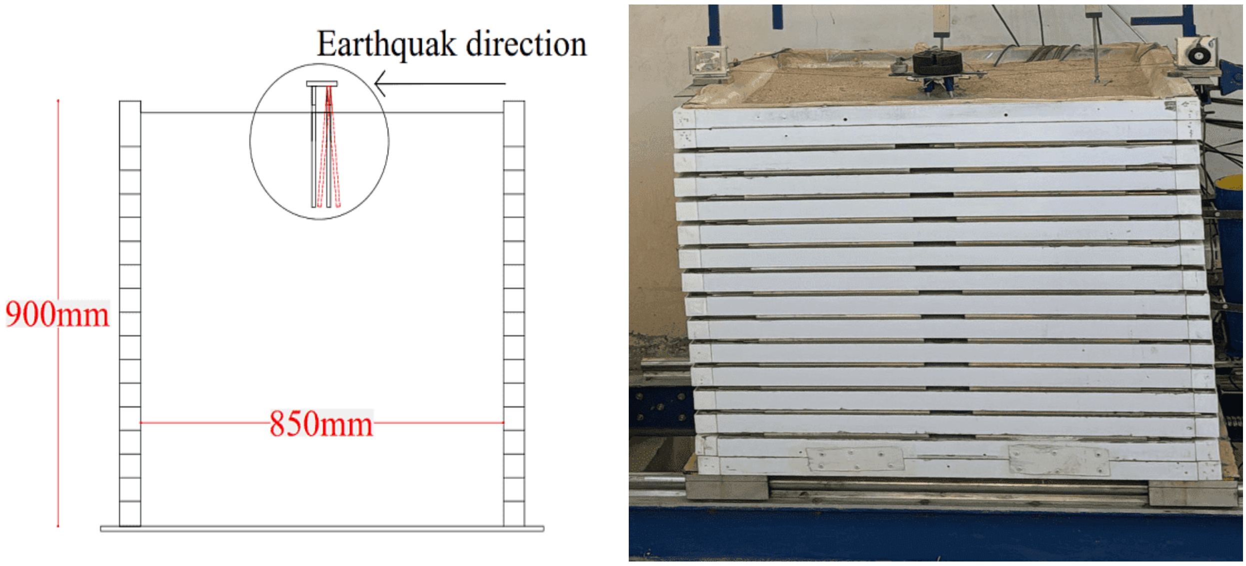


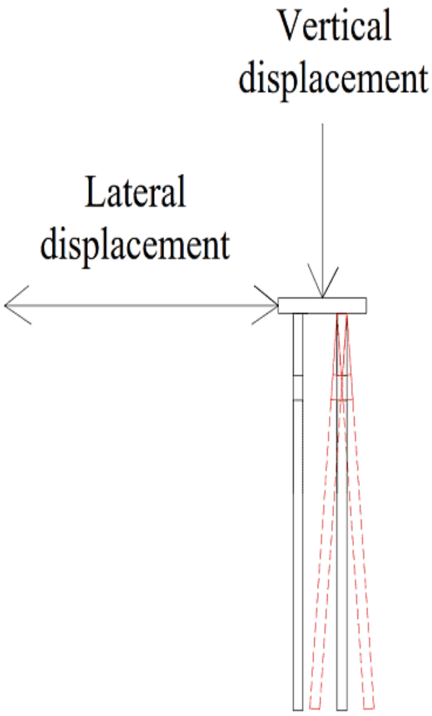
Figure 1: Schematic and photographic views of the soil laminar box

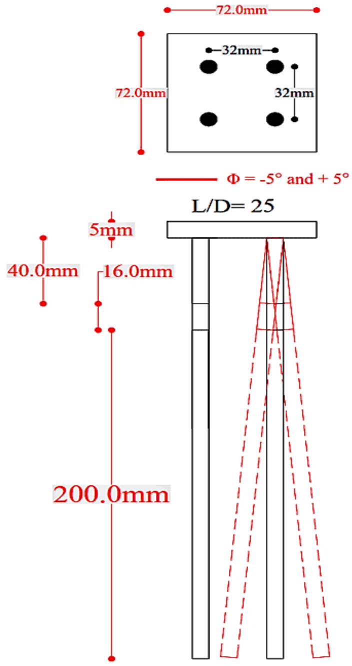
2.3 Pile group

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 Figure 2. The pile was configured in a 2 x 2 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 (a and b) shows the schematic view of the piles model while Figure 3c shows the photographic view.

2.4 Loading frame

The Loading frame used in this study for the required testing consists of the following components: (a) the soil container, (b) the 2 × 2 pile group, (c) the vertical displacement measurement device, known as Linear Variable Differential Transformers (LVDT), (d) additional LVDT devices for measuring lateral displacement, (e) the hopper for the raining technique, (f) the shaking table, (g) the lateral load application system, (h) an accelerometer, and (i) the data acquisition system. The basic hardware components are shown in Figure 3a while the data acquisition system is shown in Figure 3b.





(a) **(b)**

(c)

Figure 2: Schematic and photograph of the model pile group and pile appearance: (a,b) Schematic view, and c) Photographic view

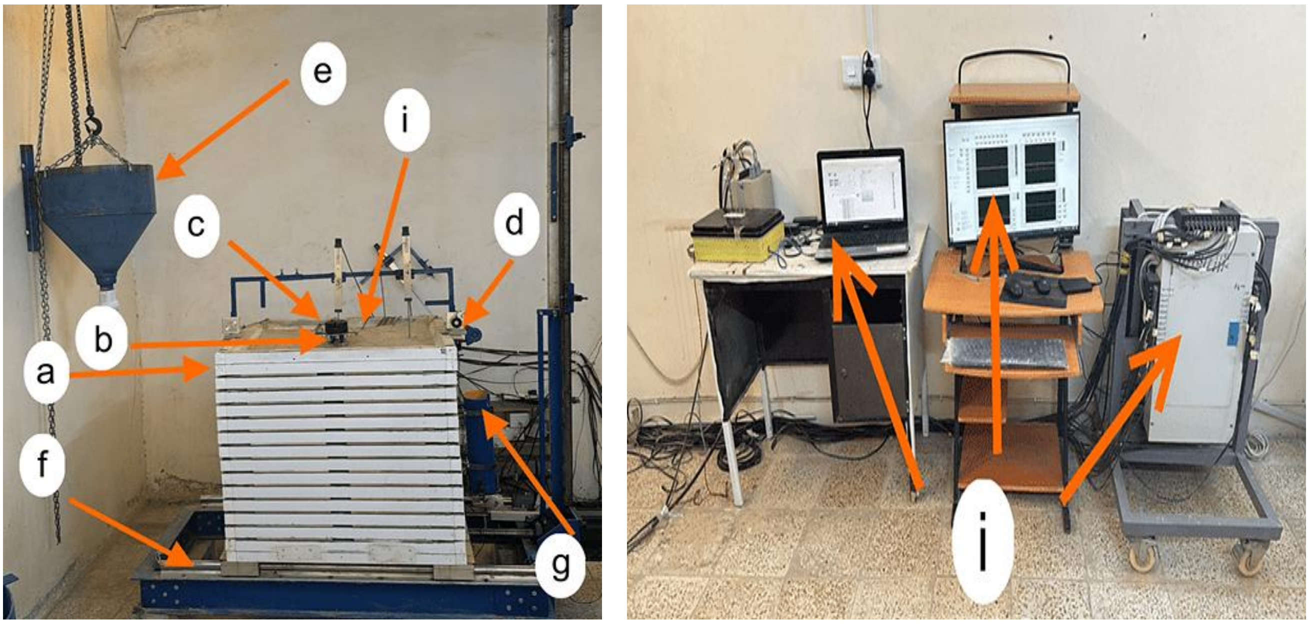


Figure 3: The details of the pile model apparatus: (a) Harware components of system. (b) data acquisition system

2.5 Testing sequence

In this study, a box with dimensions 85 × 85 × 90 mm^3 was used, with its inner walls lined with 5 cm-thick cork to minimize vibrations during seismic loading. The box was firmly clamped to the shaking table to prevent any movement during testing. The sand-raining hopper method, recommended by Rad and Tumay [16], and Vaid and Negussey [17], was employed for sand placement. Sand was poured from a height of 115 cm, maintaining a vertical drop of 100 mm above the soil surface, until the target height was achieved, as illustrated in Figure 4.

Lateral loading, equivalent to 20% of the axial force, was applied to all pile models. A gravitational axial load of 2 kg was used, corresponding to twice the lateral load, which was set at 1 kg. The shaking table apparatus, comprising a steel frame, supporting platform, screw-ball drive mechanism, and measurement sensors, was utilized to simulate seismic activity and assess the dynamic response of the pile group. Figure 5a illustrates the El Centro earthquake acceleration time history, showing fluctuating ground motion with peak accelerations reaching approximately ±0.35g over a 35-second duration. In addition, Figure 5b presents the Kobe earthquake acceleration time history, characterized by intense ground motion between 10 and 20 seconds, with peak acceleration values reaching approximately ±0.7g. The sand was deposited in layers to maintain a relative density of 65% (Dr = 30%) throughout the model.

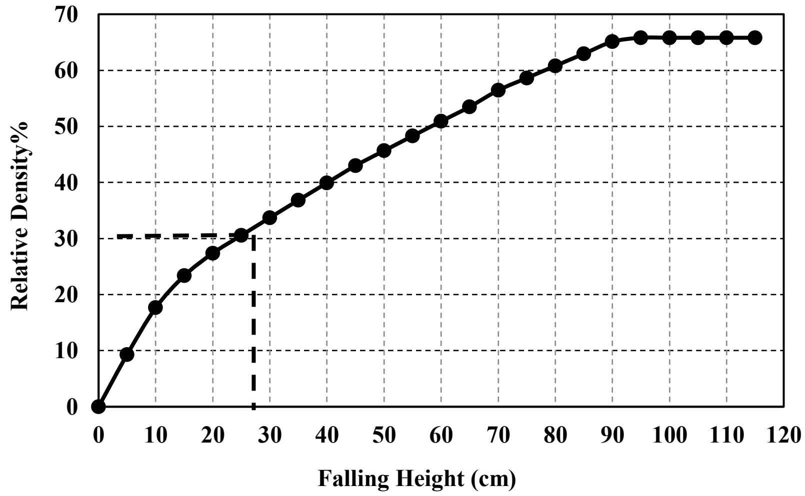
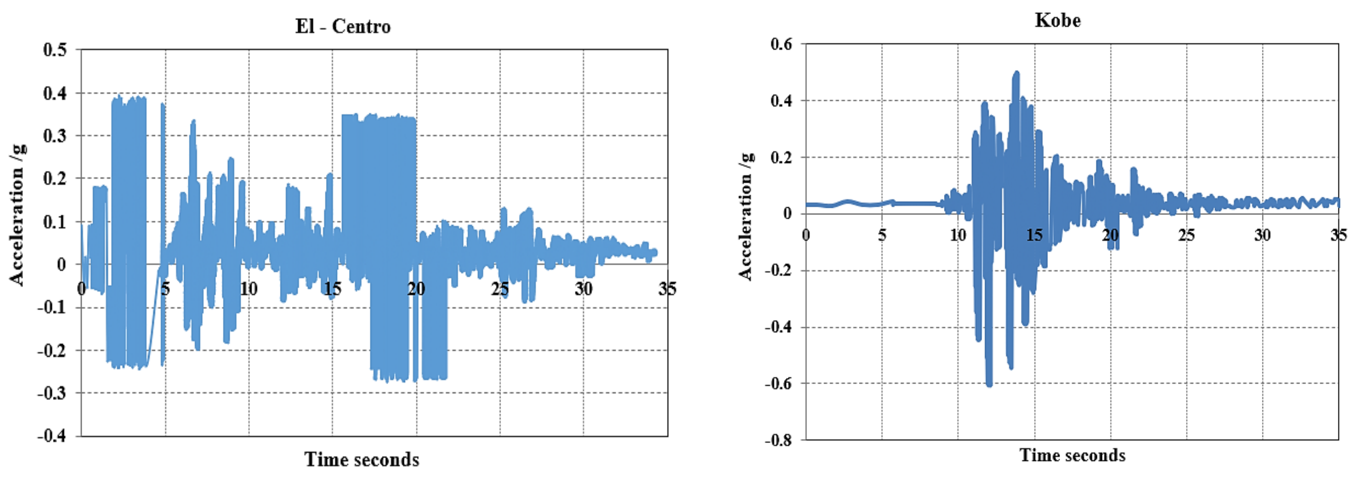


Figure 4: Rainfall technique density curve



(a) (b)

Figure 5: Earthquakes of the study: a) El – Centro, and b) Kobe

2.6 Testing program

The flowchart of the experimental program is presented in Figure 6. The experimental procedure began with the placement and securing of the piles. Following this, the sand-raining technique was used to fill the laminar soil box. The computer system was then prepared to apply seismic loads and record the responses. The behavior of the system was characterized by lateral displacement, vertical displacement, and acceleration response.

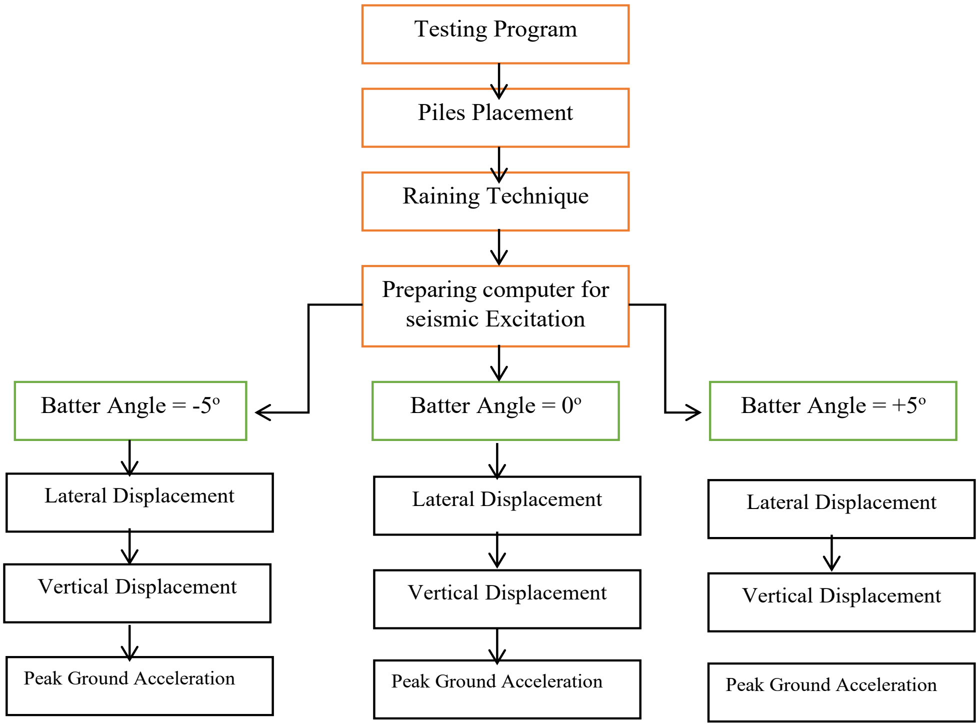


Figure 6: Flow chart of the current research methodology

3. Results and discussion

Table 3 and Figure 7 (a and b) show the impact of batter type on the lateral displacement response in the 2 × 2 pile group. The figure shows that for El-Centro, the peaks are rather identical in positive and negative batter while the peaks appeared between the 5th and the 7th seconds after response beginning. After such peaks, the shaking induced by the applied seismic load causes the sand to transition from a medium to a dense state, resulting in more stable readings. In the case of the Kobe earthquake, the primary difference in the lateral displacement path is the negative readings, which arise because the lateral load is insufficient to adequately confine the pile system, unlike the El Centro earthquake. This difference is attributed to the varying intensity levels of the two events.

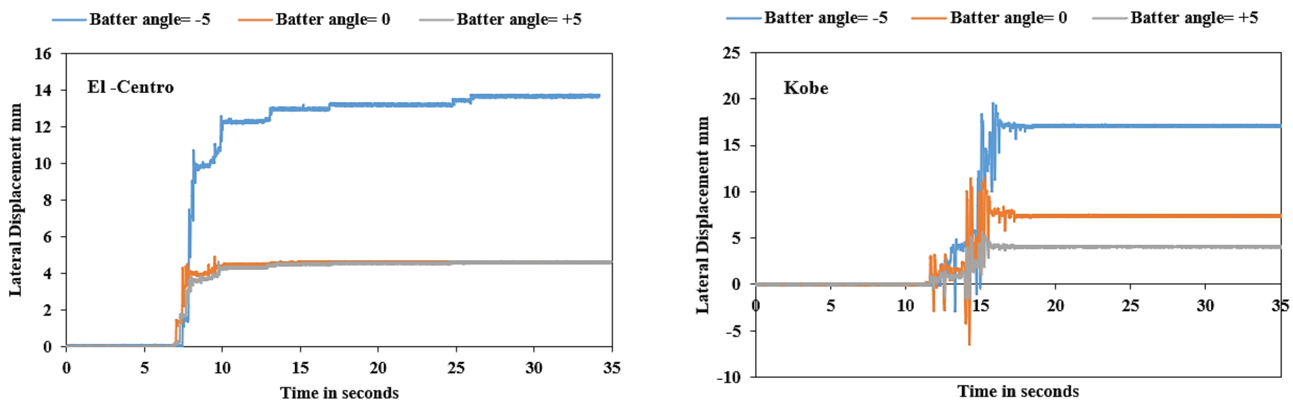
As in the El-Centro case, the negative batter angle (-5°) increased the maximum lateral response of the pile group by 179.687%. Conversely, the positive batter angle (+5°) reduced this value by 5.769%. It can also be shown that the negative batter angle (-5°) led to a 200.860% increase in the maximum lateral response, while the positive batter angle (+5°) decreased this value by 12.831%. These results highlight that the negative batter angle can significantly reduce the overall performance of the pile group, whereas the positive batter angle yields better performance. The orientation of the batter piles can explain this discrepancy. Positive batter piles are aligned in the direction of the lateral load, improving their effectiveness in resisting bending moments and shear forces. This inclination enhances soil resistance mobilization, reducing lateral displacement. In contrast, negative batter piles are oriented opposite to the load, which limits their ability to mobilize soil resistance effectively, making them more susceptible to lateral displacement.

It can be concluded that generally, the seismic performance of the tested piles that have negative batter (piles inclined toward the structure) is low compared to positive piles that may experience tensile stress. This can be attributed to the inherent decrease in confinement and the limitation of the mobilization of frictional resistance.

Finally, the difference in earthquake intensity between the El Centro and Kobe earthquakes is evident, particularly in the maximum lateral displacement values observed.

Table 3: Lateral displacement response (maximum values)

Batter Angle (degrees)	**-5°**		**0°**		**5°**	
Earthquake	**El- Centro**	**Kobe**	**El- Centro**	**Kobe**	**El- Centro**	**Kobe**
Maximum Lateral Displacement (mm)	13.769	19.566	4.923	6.503	4.639	5.669
Difference from 0° reading %	179.687	200.860	/	/	-5.769	12.831



(a) (b)

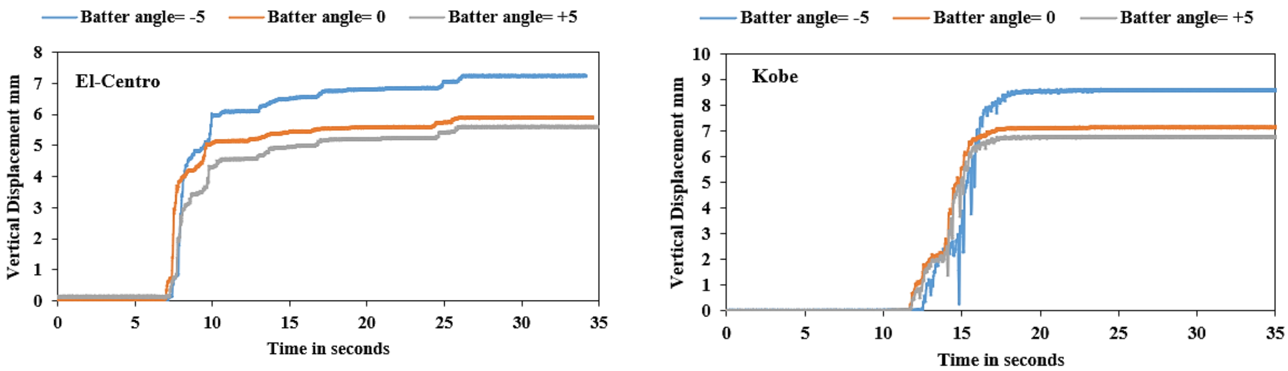
Figure 7: The propagation of lateral displacement: a) El – Centro, and b) Kobe

3.1 Vertical displacement

Table 4 and Figure 8 a illustrate the impact of batter type on the vertical displacement response of the 2x2 pile group for El Centro earthquake while Figure 8b shows such impact to Kobe earthquake. The vertical displacement response shows that the negative batter configuration resulted in lower performance compared to both vertical piles and positive batter piles. This pattern mirrors the lateral displacement response in terms of overall behavior. Additionally, the difference in vertical displacement between negative batter piles and vertical or positive piles is less pronounced than in the lateral response for both the El Centro and Kobe earthquakes. This is because the tilt starts from a vertical position, as previously described by Al-Neami et al., [14].

For the El Centro earthquake, the negative batter (-5°) increased the maximum vertical displacement of the group by 22.784%. In contrast, the positive batter (+5°) reduced the maximum displacement by 5.007%. For the Kobe earthquake, the negative batter (-5°) increased the maximum vertical displacement by 20.855%, while the positive batter (+5°) decreased this value by 4.928%.

However, the positive batter consistently performs better than the negative batter. This is because positive batter piles resist lateral loads while working in compression, which generally enhances the stability of the piles and makes them less prone to failure.



(a) (b)

Figure 8: The propagation of vertical displacement: a) El –Centro, and b) Kobe

Table 4: Vertical displacement response (maximum values)

Batter Angle (degrees)	**-5°**		**0°**		**5°**	
Earthquake	**El- Centro**	**Kobe**	**El- Centro**	**Kobe**	**El- Centro**	**Kobe**
Maximum Lateral Displacement (mm)	7.259	8.638	5.912	7.148	5.616	6.795
Difference from 0° reading %	22.784	20.855	/	/	-5.007	-4.928

3.2 Peak ground acceleration

Table 5 and Figure 9 illustrate the impact of better type on the peak ground acceleration (PGA) response in the 2x2 pile group. For the El Centro earthquake, the negative batter (-5°) increased the maximum PGA response of the group by 2.215%, while the positive batter (+5°) decreased it by 1.582%. For the Kobe earthquake, the negative batter (-5°) increased the maximum PGA response by 3.104%, while the positive batter (+5°) slightly increased the acceleration by 0.129%.

It is evident that there is no clear trend in the peak ground acceleration response with respect to the batter angles tested. This lack of discernible pattern may result from the placement of the accelerometer, which is centrally located at the center of the pile group cap. Further studies are needed to better understand the relationship between peak ground acceleration and the forces corresponding to vertical and lateral displacements.

Table 5: Ground acceleration response.

Batter Angle (degrees)	-5°		0°		5°	
Earthquake	**El- Centro**	**Kobe**	**El- Centro**	**Kobe**	**El- Centro**	**Kobe**
Maximum Lateral Displacement (mm)	0.323	0.375	0.316	0.363	0.311	0.364
Difference from 0° reading %	2.215	3.104	/	/	-1.582	0.129

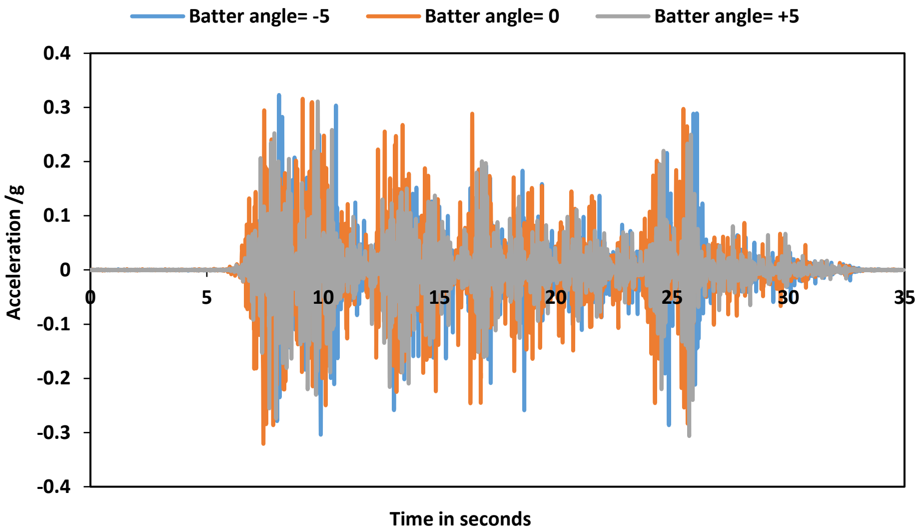


Figure 9: The propagation of vertical displacement

4. Conclusion

This study contributes to the advancement of geotechnical engineering by experimentally investigating the seismic behavior of negative battered piles, which have been relatively underexplored in this field. The findings suggest that negative battered piles perform worse under seismic conditions compared to positive battered and vertical piles. This knowledge is crucial for enhancing the design of pile groups in seismic regions, ultimately improving the safety of foundation engineering. The main conclusions of this study are as follows:

1) After the initial peaks, the load-displacement curve stabilized due to densification of the sandy soil induced by seismic loading, resulting in a consistent response path once the maximum displacement was reached.
2) Negative batter piles exhibit low performance during earthquakes compared to positive batter piles, primarily due to the induced tensile stresses arising from their inclination. This leads to a degradation in the efficiency of the load transfer mechanism.
3) The performance disparity between positive and negative batter piles is more pronounced in lateral displacement than in vertical displacement, highlighting the influence of batter angle on horizontal behavior.
4) In conclusion, negative batter piles should be positioned within pile groups in areas less susceptible to immediate earthquake impacts. Furthermore, prior to design adjustments, a comprehensive analysis should be conducted to ensure optimal structural performance under seismic loading.
5) The installation of -5° negative batter piles in a 2×2 pile group can result in a 180% to 200% increase in maximum lateral displacement compared to vertical piles.
6) Negative batter piles at -5° in a 2×2 pile group lead to a 20% to 23% increase in maximum vertical displacement under seismic loading.
7) Positive batter piles (+5°) can reduce maximum lateral displacement by 5% to 13%, indicating an improvement in horizontal stability under seismic forces.
8) The use of positive batter piles (+5°) results in a decrease in maximum lateral displacement by approximately 5%, enhancing lateral load distribution.
9) The influence of earthquake intensity on pile group response is evident in the results of this experimental study, with noticeable variations in performance as a function of seismic event characteristics.

Author contributions

Conceptualization, **Q. Hussain, M. Al-Neami,** and **F. Rahil**; data curation, **Q. Hussain**; formal analysis, **Q. Hussain**; investigation, **Q. Hussain**; methodology, **Q. Hussain**; project administration, **M. Al-Neami**; resources, **F. Rahil**; software, **Q. Hussain**; supervision, **Al-Neami**; validation, **M. Al-Neami** and **Q. Hussain**; visualization, **Q. Hussain**; writing—original draft preparation, **Q. Hussain**; writing—review and editing, **Q. Hussain**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] M. Abood, M. Mahmood, and N. Salim, Effect of Dynamic Earth Vibration on the Behavior of Laterally Loaded Single Pile Embedded within Unsaturated Soil, Eng. Technol. J., 39 (2021) 1748–1752. http://doi.org/10.30684/etj.v39i12.508

[2] M. Al-Tememy, M. l-Neami, and M. Asswad, A Numerical Analysis on Pullout Capacity of Batter Pile Groups in Sandy Soil, Eng. Technol. J., 40 (2022) 1352–1357 https://doi: 10.30684/etj.2021.131818.1062

[3] H. Ghasemzadeh, M. Tarzaban and MM. Hajitaheriha, Numerical Analysis of Pile–Soil–Pile Interaction in Pile Groups with Batter Piles, Geotech. Geol. Eng., 36 (2018) 2189–2215. http://dx.doi.org/10.1007/s10706-018-0456-4

[4] M. Al-Tememy, M. A. Al-Neami, M. F. Asswad, Finite Element Analysis on Behavior of Single Battered Pile in Sandy Soil Under Pullout Loading, Int. J. Eng. Trans. B., 35 (2022), 1127-1134. https://doi.org/ije.2022.35.06c.04

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

[6] F. I. Shalabi and M. U. Saleem, 3D Finite Element Analysis of Bored Pile-Cap Interaction in Sandy Soils under Lateral Loading, World Congress on Sustainable Technologies (WCST-2023) 121–125. https://doi.org/10.20533/wcst.2023.0008

[7] M. Al-Neami and M. Wasmi, Influence of cyclic loading on performance of steel piles in sandy soil, MATEC Web of Conferences, 162 (2018) 01012. https://doi.org/10.1051/matecconf/201816201012

[8] C. Rudolph, J. Grabe & B. Bienen, Drift of Piles Subjected to Cyclic Lateral Loading From a Varying Direction: System vs, Soil Element Behavior, Int. Conf. Ocean, Offshore, and Arctic Eng., 3 (2014) https://doi.org/10.1115/omae2014-23212

[9] N. Gerolymos, A. Giannakou, I. Anastasopoulos and G. Gazetas, Evidence of beneficial role of inclined piles observations and summary of numerical analyses, Bull. Earthquake Eng., 6 (2008) 705–722. https://doi.org/10.1007/s10518-008-9085-2

[10] A. Giannakou, N. Gerolymos, G. Gazetas, T. Tazoh and I. Anastasopoulos, Seismic Behavior of Batter Piles Elastic Response, J. Geotech. Geoenviron. Eng., 9 (2010) 1187–1199. http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0000337

[11] Z. Lie, S. Escoffier and P. Kotronis, Centrifuge modeling of batter pile foundations under earthquake excitation, Soil Dyn. Earthquake Eng., 88 (2016) 176–190. https://doi.org/10.1016/j.soildyn.2016.05.013

[12] M. Bharathi, R.N. Dubey and S.K. Shukla, Behaviour of Batter Piles Under Machine Induced Vibrations, Springer Tracts in Civil Engineering, (2023) 149–174. https://doi.org/10.1007/978-981-99-0081-7_8

[13] A. A. Mohammed, Investigation of Sampling Error on Soil Testing Results, Int. J. Civ. Eng. Technol., 9 (2018) 579-589.

[14] M. A. Al-Neami, F. H. Rahil, and K. S. Al-Bayati, Behavior of batter pile group models embedded in sandy soil under monotonic loading, IOP Conf. Ser.: Mater. Sci. Eng., 737 (2020) 012088. https://doi.org/10.1088/1757-899X/737/1/012088

[15] R. Daher and M. Abbas, The Behavior of Pile Group Under Inclined Static Load With Different Angle of Inclination in Sandy Soil, Diyala J. Eng. Sci., 14 (2021) 52–61. https://doi.org/10.24237/djes.2021.14205

[16] N. S. Rad and M. T. Tumay, Factors affecting sand specimen preparation by raining, Geotech. Test. J., 10 (1987) 31–37.

[17] Y. P. Vaid, and D. Negussey, Relative density of pluviated sand samples, Soils and Foundations 24 (1984) 101–105.