Science, Engineering and Technology Vol. 7, No. 1, pp. 52-60
www.setjournal.com https://doi.org/10.54327/set2027/v7.i1.409

An Experimental Study on the Response of Passive Piles in Soft Clay

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Abstract

This paper experimentally evaluates the behavior of model piles in a clayey soil exposed to horizontal ground movement. A custom-designed laboratory apparatus, split into upper and lower components, was developed to simulate pile response under a uniform lateral soil movement profile. The device was designed to permit the upper box to slide over the lower box when a horizontal force is applied. Thus, the soil is divided into two separate zones: a moving upper layer and a stable lower stratum. Several tests were performed using square aluminum tubes of varying dimensions embedded in soft clay. Several parameters were investigated in this study, including the thickness of the moving layer (Lm), pile embedded depth in the stable layer (Ls), and pile width (B). The results showed that the (Lm/Ls) ratio significantly influenced both the value and distribution of the bending moments (BM) along the pile. At a constant Ls, a reduction in Lm from 350 mm to 150 mm resulted in an 88% decrease in maximum bending moment. Reducing Ls from 350 mm to 100 mm, while maintaining a constant Lm, decreased maximum bending moment by 95%**.** Results further indicated a positive association between maximum moment and pile width B, with BM increasing by 317% as B increased from 30 mm to 50 mm. This increment was driven by the combined effects of increases in both pile width and bending stiffness. The findings provide valuable insights for improving the geotechnical engineering of piles under passive lateral loading.

Keywords*:* Passive Pile, Soft Clay, Horizontal Soil Movement, Bending Moment, Deflection

1. Introduction

Most pile foundations are designed to withstand axial and lateral forces transmitted directly to the pile head from the superstructure. Nevertheless, piles are frequently exposed to passive loadings caused by nearby construction. The horizontal soil displacements (Ws) generated by adjacent excavations, application of surcharge loads, nearby pile installation, tunneling, slope instability, and embankment construction are typical examples of passive loadings [1]. The fundamental problem is piles affected by adjacent ground displacement, where the surrounding ground consists of moving and fixed layers. The pile's upper part is located within the unstable zone, subjecting it to horizontal displacement. In comparison, the lower part is anchored in the stable stratum, providing passive resistance to horizontal pressure generated from the upper part [2], [3], [4]. The horizontal soil displacement generates horizontal pressure within the pile-soil system [5], [6]. In critical situations, the internal forces resulting from this pressure can generate bending moments (BM) and deflections that may cause the pile to fail [7]. A prominent case of pile foundation failure due to horizontal ground displacement occurred in the 2009 Lotus Riverside Complex collapse in China. The building collapsed due to pile failure caused by massive pressure, which resulted from deep

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Received: 1 July 2026; Revised: 16 October 2026; Accepted: 26 October 2026; Published: 19 November 2026
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excavations on one side and the accumulation of debris on the other [8]. This research aims to experimentally investigate the behavior of model piles in soft clay subjected to horizontal ground movement by developing a custom-designed laboratory split apparatus.

To investigate the behavior of passive piles subjected to horizontal ground movement, several researchers have developed theoretical and numerical models and conducted experimental laboratory tests. Theoretical and analytical investigations [9], [10], [11] analyzed the response of passive piles in cohesive soil. These studies demonstrated that horizontal ground movements produced both bending moments and alterations in the lateral resistance of the nearby piles. Experimental data on passive piles in clay provide the necessary basis for verifying the reliability of theoretical predictions. The field tests conducted by [12] and [13] on passive piles in soft clay indicated that theoretical approaches overestimate bending moments and lateral resistance. Stewart et al. [14] and Zhou et al. [15], through performing centrifuge tests on piled bridge abutments in soft clay, revealed that induced pile bending moments increase with higher embankment loading.

The fundamental approach for exploring soil-structure interaction for pile performance across different loading conditions is the small-scale 1g physical modeling [16]. Pan et al. [17] investigated the response of steel piles (295 mm long, 20 mm wide, and 6 mm thick) embedded in soft clay within a 1000 mm × 1000 mm × 800 mm box soil subjected to lateral soil movements. The results demonstrated that the movements induced bending moments and lateral soil pressures. Using a laminar shear box with internal dimensions of 500 mm × 500 mm × 800 mm, [18] studied the behavior of aluminum piles in soft clay under lateral soil movement. It was found that both bending moments and pile deflections increase progressively with horizontal soil movement. Bauer and Reul [19] used a laboratory model test box with dimensions of 1000 mm × 450 mm and a 300 mm depth filled with soft clay to study the response of passive piles with diameters of 20, 30, and 40 mm. It was observed that the bending moment increased with the pile diameter.

Most previous laboratory 1g model investigations into the behavior of piles subjected to horizontal ground movement have focused more on sandy soil than clay. The laboratory tests in sand demonstrated that the response of passive piles is significantly influenced by several parameters including the lengths of the unstable and stable zones, pile geometry, relative sand density, and pile head conditions [20], [21], [22], [23], [24]. Although the deformation of piles differs fundamentally between cohesionless and cohesive soils, laboratory model investigations addressing these specific variables in clay remain limited. Therefore, this study aims to bridge this knowledge gap, offering significant insights for the field of geotechnical engineering. The present work provides a comprehensive experimental study for exploring the impact of the thickness of the moving layer (Lm) and the pile embedded depth in the stable layer (Ls) on the response of passive piles in soft clay subjected to lateral soil movements. The research also included a study of the width of the piles, due to its direct impact on soil pressure, the generated bending moments, and pile deflections.

2. Materials and Methods

This section outlines the specific materials utilized and the experimental model developed to evaluate the behavior of passive piles subjected to lateral soil movement in cohesive soil.

2.1. Soil

This research used commercial kaolin clay brought from the northern Hussainiyat area in the Iraqi Anbar Governorate as a model soil. Based on the Atterberg limits tests, the plastic and liquid limits were 20% and 46%, respectively, yielding a plasticity index of 26 %. According to the Unified Soil Classification System (USCS), this soil was categorized as low plasticity clay (CL). The value of the undrained strength (Cu) was about 15 kPa, corresponding to a consistency index (Ic) of 0.42.

2.2. Model pile

Four square hollow aluminum tubes with varying dimensions (20, 30, 40, and 50 mm), wall thicknesses (1.2, 1.5, 2, and 3 mm) and different values of bending stiffness (E_p I_p) were utilized as model piles, as listed in Table 1.

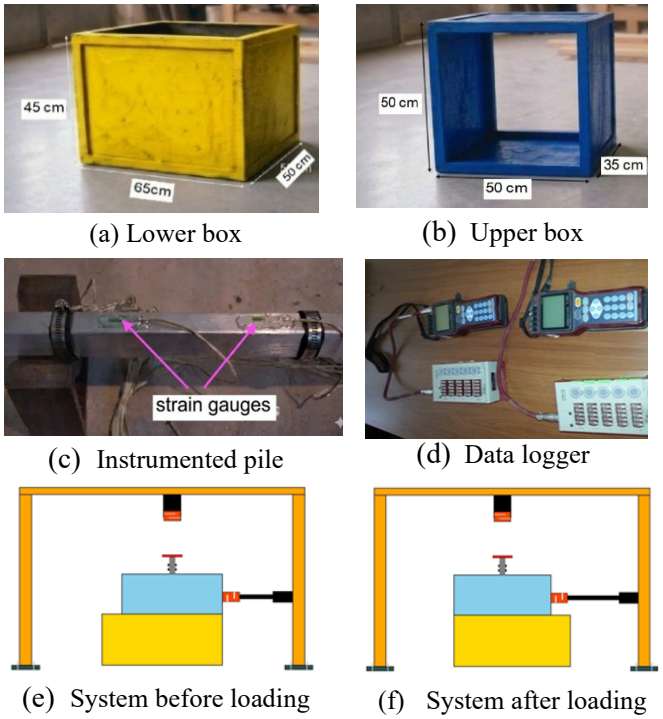
Table 1. Cross-sectional and structural properties of piles.

Pile	Outer width (mm)	Thickness (mm)	Bending stiffness $E_p I_p$ (kN·mm^2)	Yield bending moment (kN·mm)
1	20	1.2	368000	122
2	30	1.5	1600000	345
3	40	2	5060000	785
4	50	3	14370000	1156

Ten pairs of strain gauges were attached to each pile to measure the moment at those specific points. These pairs were distributed at equal distances, with two pairs above the ground surface and eight within the embedded pile depth. The strain gauges were coated with an epoxy resin to protect them from moisture in the clay environment and ensure a complete seal.

2.3. Test set-up

A specialized physical model was constructed to explore the pile's response to horizontal soil displacement. It consists of four primary components: a shear box, a loading assembly, the tested pile, and a data logger, as shown in Figure 1.



(a) Lower box (b) Upper box

(c) Instrumented pile (d) Data logger

(e) System before loading (f) System after loading

Figure 1. Details of the test setup.

The shear box, which comprises two different pieces made of thick steel plates, was utilized to impose a uniform profile of horizontal soil displacements. The dimensions (Width × Length × Height) of the upper and lower boxes were 50 cm × 50 cm × 35 cm and 50 cm × 65 cm × 45 cm, respectively. Consistent with previous studies, these dimensions were adopted to minimize boundary influences and facilitate the investigation of various substrate lengths undergoing uniform lateral soil movement. The boundary distance from the pile face to the inside wall of the box must be greater than 4D, where (D) represents the pile diameter [18]. In the present study, these distances were 240, 235, 230, and 225 mm for widths of 20, 30, 40, and 50 mm, respectively (all exceeding four times the equivalent diameter).

The device was designed to permit the upper box to slide over the lower box when a horizontal force is applied. Thus, the soil is divided into two separate zones: a moving upper layer and a stable lower stratum. Two hydraulic jacks (5-ton capacity) were employed: a vertical one for installing the pile into the clay, and a horizontal jack for exerting a lateral force on the upper part of the shear box. A data logger was used for recording strain gauge readings along the pile shaft during each increment of horizontal soil displacement.

2.4. Calibration and analytical methodology

Prior to testing, all instrumented piles were calibrated by setting up each pile in a simply supported beam configuration resting on knife-edge supports, following the methodology described by Qin and Guo (2013) [25]. The purpose of this calibration was to establish an accurate relationship between the strain gauge readings and the bending moment, as shown in Figure 2.

The bending moment calculated from this method closely aligned with that predicted theoretically from Euler-Bernoulli beam theory, expressed in Eq. (1):

$$BM = \frac{\varepsilon E I}{y} \quad (1)$$

Where BM is the bending moment, ε is the strain, E is the modulus of elasticity, I is the moment of inertia, and y is the distance from the neutral axis.

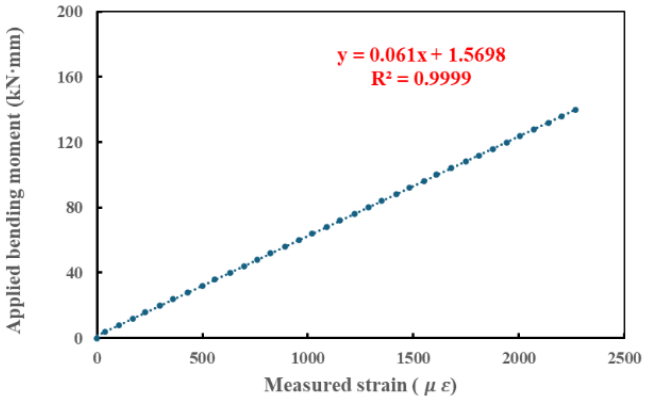


Figure 2. Calibration curve for the strain gauges (for 30 mm pile width).

Based on beam theory and numerical integration, the pile deflection was derived from the measured bending moment data. This specific method provides better accuracy for analyzing free-headed piles, as demonstrated by Qin (2010) [26]. In the present study, two dial gauges were attached to the exposed section of the pile at points a and b, corresponding to elevations h_a and h_b above the ground surface, close to the two strain gauges to measure the deflection at these points. The pile in this section was assumed to experience rigid displacement, as no lateral support is provided. Consequently, this assumption permits determining the pile deflection at the soil surface. The two integration constants of the double integration of bending moment correspond physically to the rotation (S_0) and lateral deflection (y_0) of the pile at the ground surface (z = 0), and can be found from Eq. (2) and Eq. (3), respectively.

$$S_0 = \frac{y_b - y_a}{h_b - h_a} \quad (2)$$

$$y_0 = y_a - S_0\, h_a \quad (3)$$

The boundary conditions for piles were assumed to have free ends, resulting in zero bending moments (M_0 and M_L =0). The trapezoidal rule was employed for the double numerical integration of the bending moment profile, thereby allowing for the determination of the pile deflection profile. The pile rotation and deflection at a specific point below the ground surface can be calculated using Eq. (4) and Eq. (5), respectively.

$$S_i = S_0 - \frac{1}{E_p\, I_p} \sum_{k=1}^{i} \frac{BM_k + BM_{k-1}}{2}\, \Delta z \quad (4)$$

$$y_i = y_0 + \sum_{k=1}^{i} \frac{S_k + S_{k-1}}{2} \Delta z \quad (5)$$

Where S_i is the pile rotation at node i, Δz is the spacing between strain gauges, n is the number of nodes, and y_i is the pile deflection at node i.

2.5. Experimental program and procedures

The clay and water were mixed mechanically inside a large steel mixing tank before being placed in the test box to ensure a uniform water content of 35% for all experiments. The lower fixed box was filled with clay, while the upper movable box was filled to varying heights depending on the value of Lm. The clay was placed and compacted in successive layers of 50 mm thickness each to ensure a uniform soil unit weight of 15.7 kN/m^3, featuring an undrained shear strength of 15 kPa across both the upper and lower boxes. Several laboratory vane shear tests were performed to determine the undrained shear strength for both boxes at various depths to confirm the adopted value. To verify the achieved soil density and moisture content of the clay, standard cylindrical molds (50 mm in diameter and 100 mm in height) were used to extract core samples from different locations in both boxes.

Once the instrumented pile was correctly aligned, the vertical jack was engaged to install the pile in the clay until the target depth was reached. Following the installation of the instrumented pile, two mechanical dial gauges were mounted at distinct locations above the clay surface to monitor pile head deflection. Each pair of wires was connected to a switching box and a data logger using a half-bridge configuration. The test was initiated by applying a horizontal force to the movable upper section of the apparatus using a jack, maintaining a constant horizontal soil displacement rate. A rate of 1 mm/min was employed in this study, which is consistent with those used in previous model tests [18], [19]. The strain gauge, data logger, and dial gauge readings were recorded at every 0.5B increment of horizontal soil displacement. Thirteen tests were performed on free-headed piles exposed to a uniform profile of horizontal soil displacement in clay. The tests were conducted to study the influence of Lm, Ls, and B on the pile response. Each

test was repeated at least twice independently to ensure reproducibility and validate the results. Data points with a mutual variance greater than 5% were discounted from the calculated average. Experimental data for piles exposed to a horizontal soil displacement pattern are summarized in Table 2.

Table 2. Details of the tested model piles.

Test	Pile width (B) (mm)	Lm (mm)	Ls (mm)	Embedded length (mm)	Notes
1	30	350	350	700	Reference test
2	30	300	350	650	
3	30	250	350	600	
4	30	200	350	550	Effect of moving layer depth (Lm)
5	30	150	350	500	
6	30	350	300	650	
7	30	350	250	600	
8	30	350	200	550	Effect of Stable layer depth (Ls)
9	30	350	150	500	
10	30	350	100	450	
11	20	350	350	700	
12	40	350	350	700	Effect of Pile width
13	50	350	350	700	

3. Results and Discussion

The results of the current experimental tests on passive piles in soft clay are presented and discussed below.

3.1. Reference test

In this test, both boxes were filled with soil, after which a 30 mm wide pile was inserted to a penetration depth of 700 mm in the clay. The penetration depth of the pile was divided into two sections: Lm of 350 mm in the upper movable layer and Ls of 350 mm in the lower stable layer. The profiles of bending moments along the pile's embedded depth corresponding to various levels of lateral soil displacement are depicted in Figure 3. It is observed that the measured bending moments increased alongside lateral soil displacement; however, the incremental gain attenuated, particularly when the displacement surpassed 3B, which corresponds to 90 mm. Since the maximum recorded moments of 15.6 kN·mm were less than the yield moment of 345 kN·mm, the observed nonlinearities are attributed to the plastic response of the surrounding soil (i.e., the plastic flow of soil around pile), as demonstrated in [19]. The peak bending moment occurred slightly below the interface of the two soil strata. The difference between the free upper part and the constrained lower part generated the peak moment near the shear plane. These results agree with and validate the numerical and image analysis findings of [19].

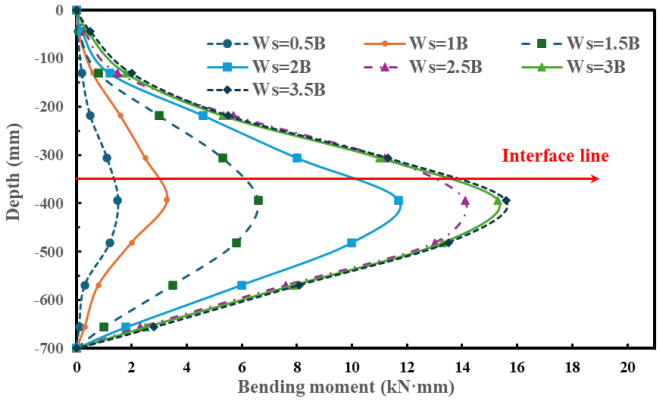


Figure 3. Bending moment profile for different lateral soil movement (Reference test, Lm =350 mm and Ls =350 mm).

Figure 4 presents the deflection profiles for the reference test with B =30 mm, Lm =350 mm, and Ls =350 mm at successive stages of horizontal soil displacement. In accordance with theoretical estimates, the peak deflection of the free-headed pile is observed at its top. The upper layer soil acts as the main driver of pile deflection because of its active pressure on the pile body. As soil displacement increases from 0.5B to 3.5B, the pile moves in line with the direction of ground displacement, resulting in a continuous increase in lateral deflection values.

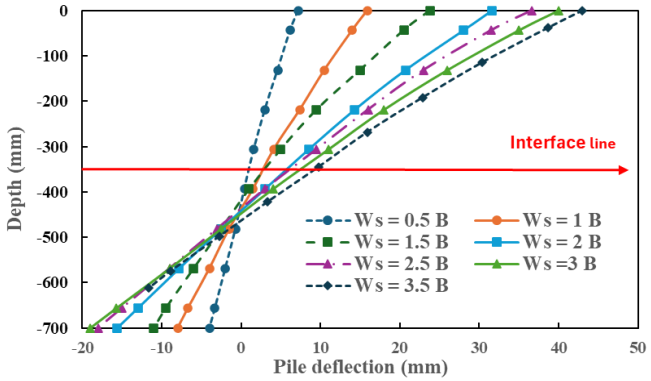


Figure 4. Pile deflection profile for different lateral soil movement (Reference test, Lm =350 mm and Ls =350 mm).

The deflection diagrams show that the pile rotation occurs about a fixed point situated at an approximate depth of 450 mm. Due to its structural rigidity and stabilization in the stable layer, the pile acts as a stiff element that resists the moving soil mass. The relationship between the pile head deflection and lateral soil movement is presented in Figure 5. Even as soil displacement continues significantly, the pile is subjected to a constant 'limiting' pressure, causing the deflection rate to stabilize; this is explained in [19].

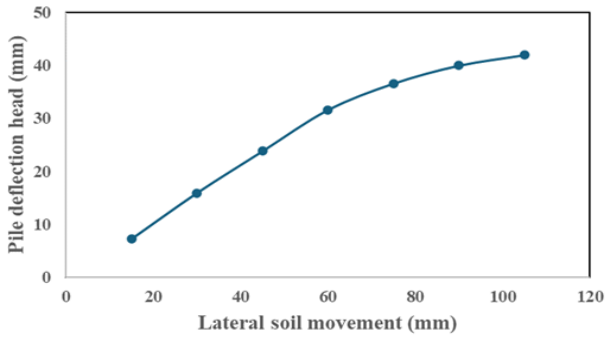


Figure 5. Pile head deflection for different lateral soil movement (Reference test).

determined the bending moment directly using strain gauges, offering a more comprehensive and detailed analysis. When Lm is significantly smaller than Ls, the high base fixity provided by the stable layer prevents the pile from tilting; consequently, the soil reaches its ultimate lateral capacity and bypasses the stationary pile in a 'flow' failure mode. This phenomenon was thoroughly analyzed in [27].

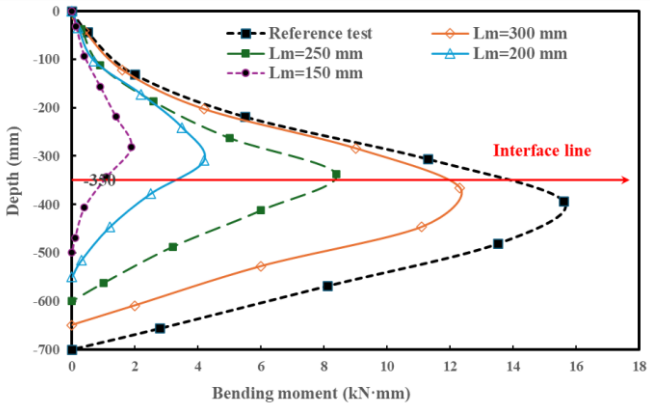


Figure 6. Bending moment profile for Ls =350 mm and different Lm values.

3.2. Effect of moving layer thickness (Lm)

In this test group, the thickness of the soil in the upper box was varied from 350 mm down to 150 mm in 50 mm increments, while the value of Ls was kept constant at 350 mm. It was found that decreasing the thickness of the moving layer resulted in a concurrent reduction in the lateral soil displacement needed to reach the maximum bending moment. A thin moving layer creates a "knife-edge" effect that concentrates the applied forces and lacks the sufficient confining pressure necessary to attenuate displacement, resulting in a completely plastic state in the clay almost immediately after movement begins [17]. The bending moment variations exhibit a consistent profile across the test series; however, their magnitudes differ significantly from those recorded in the reference test. The maximum moment decreases with a reduction in the depth of the moving layer; see Figure 6. Decreasing Lm from 350 mm to 300, 250, 200, and 150 mm led to a proportional reduction in BM by 21%, 46 %, 73%, and 88%, respectively. These findings align with those estimated by Pan et al. [17], who calculated the bending moment indirectly based on measured pressure using a mathematical relationship. However, the present study

3.3. Effect of stable depth (Ls)

In this test series, the magnitude of Lm was maintained at 350 mm, while the values of Ls were 300, 250, 200, 150, and 100 mm. Unlike the previous results, the lateral soil displacement required to induce the peak moment increased as the value of Ls decreased. Figure 7 illustrates the moment profiles at specific lateral ground displacement levels for varying stable layer depths.

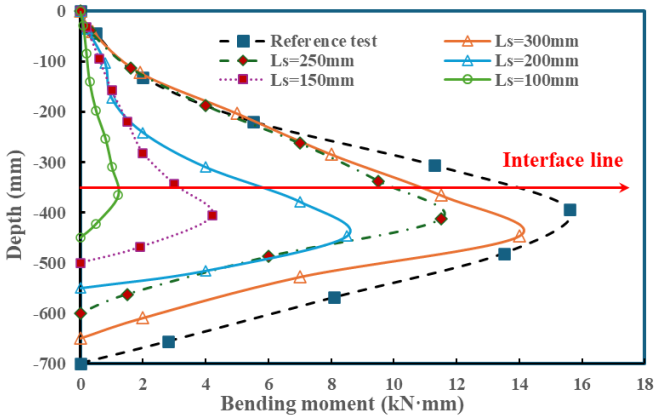


Figure 7. Bending moment profile for Lm =350 mm and different Ls values.

Both the magnitude and the corresponding depth of the peak moment decrease as the embedment length in stable soil reduces. Reducing Ls from 350 mm down to the range of 300–100 mm resulted in a BM drop between 26% and 95%. When the stable layer depth Ls is significantly smaller than Lm, the pile tends to move in unison with the sliding soil mass. This interaction characterizes a 'short-pile' response mode, where minimal bending moments are induced due to the lack of base fixity. A similar conclusion was observed by [20], [21] when studying the response of passive piles in sand.

3.4. Effect of pile width

To explore how pile width impacts structural response, tests were carried out on piles with widths of 20, 40, and 50 mm, maintained under identical experimental conditions as the reference tests. As shown in Figure 8, the moment profiles are similar in shape, but the magnitude increases as the pile width expands. Increasing B from 30 mm to 50 mm led to a proportional 317% increase in BM. This increment was driven by the combined effects of increases in both pile width and bending stiffness. The increase in bending moment results from higher pile stiffness and a larger contact area with the soil, which in turn increases the soil's reaction force on the pile. Due to the inability to hold the pile stiffness constant while varying the width in this study, the increase in bending moments reflects a simultaneous increase in both the pile width and its structural stiffness. This finding was also determined by [18] when using pile diameters of 25 and 32 mm.

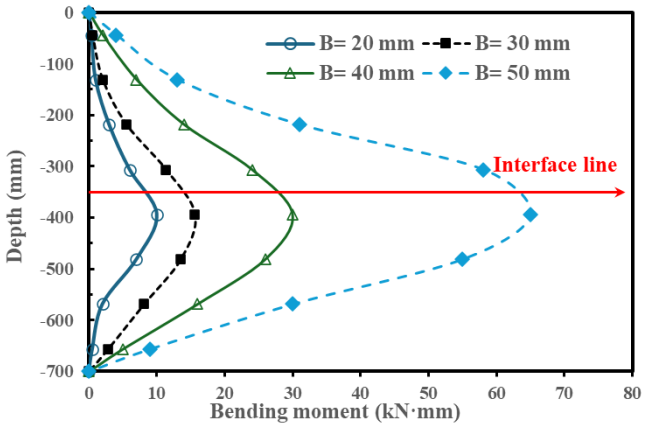


Figure 8. Bending moment profiles for different widths of pile.

3.5. Summary of results

Table 3 summarizes the results of the maximum bending moments and their corresponding soil displacements for all experiments conducted in this study.

Table 3. Summary of experimental results.

Test	(B) (mm)	Lm (mm)	Ls (mm)	Max. Ws (mm)	Max. BM (kN·mm)
1	30	350	350	105	15.6
2	30	300	350	105	12.3
3	30	250	350	90	8.4
4	30	200	350	75	4.2
5	30	150	350	45	1.9
6	30	350	300	105	11.5
7	30	350	250	120	9.5
8	30	350	200	120	4
9	30	350	150	135	2
10	30	350	100	150	0.8
11	20	350	350	60	10
12	40	350	350	140	30
13	50	350	350	175	65

4. Conclusions

The research experimentally evaluated the behavior of model piles in a clayey soil exposed to horizontal ground movement.

The bending moments increased with the increase in horizontal soil displacement; however, the rate of increase gradually diminished as the soil approached a plastic state. The results demonstrate that increasing the horizontal soil displacement from 0.5 B to 3.5 B yields a 940% increase in BM, from 1.5 kN·mm at 0.5B to 15.6 kN·mm at 3.5B under constant values of Lm, Ls, and B.

Decreasing Lm resulted in a corresponding reduction in the lateral soil displacement needed to reach BM. With Ls held constant, a reduction in Lm from 350 mm to 150 mm resulted in an 88% decrease in BM. When Lm was greater than Ls, the pile tended to move in unison with the sliding soil mass, resulting in minimal induced bending

moments. Both the magnitude and the corresponding depth of the maximum bending moment decreased as Ls reduced. Reducing Ls from 350 mm to 100 mm, while maintaining a constant Lm, decreased BM by 95%.

The lateral soil displacement required to induce the maximum bending moment increased as Ls decreased. When Ls significantly exceeded Lm, high base restraint prevented pile rotation, forcing moving soil to circumvent the stationary structure via a flow failure mechanism. The maximum bending moment reached its highest magnitude when Lm and Ls were similar in length. The maximum bending moment increased by 317% as B enlarged from 30 mm to 50 mm. This increment was driven by the combined effects of increases in both pile width and bending stiffness.

Finally, in laboratory 1g tests on clay, the full-scale undrained shear strength and stress-dependent stiffness cannot be replicated under low confining pressures. Future research could expand these quantitative data through in-situ field testing or numerical modeling to overcome these experimental limitations.

Author Contribution Roles

The study was implemented by the joint efforts of the authors, whose contributions are shown as follows:

- Mohammed Khachi Hatem: Conceptualization, Methodology, Formal analysis.
- Mohammed Hussein Al-Dahlaki: Investigation, Data curation, Formal analysis.
- Shaimaa Hasan Fadhil: Methodology, Formal analysis, Writing original draft.
- Ahmed Mancy Mosa: Validation, Writing final form, review and editing.

All authors reviewed the results and approved the final version of the manuscript.

Competing Interests Statement

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

The data will be made available by the authors on request.

Funding Statement

This research received no external funding.

Acknowledgment

The authors would like to express their gratitude to Mustansiriyah University, College of Engineering, for their assistance and support in completing this project.

References

[1] J. Boompandi, K. Muthukkumaran, and R. Manjula, "Lateral response of pile under passive loading conditions in horizontal and sloped grounds," *Indian Geotech. J.*, vol. 54, no. 1, pp. 134–153, Feb. 2024, doi: 10.1007/s40098-023-00833-1.

[2] W. D. Guo, "Response and stability of piles subjected to excavation loading," *Int. J. Geomech.*, vol. 21, no. 1, Art. no. 04020238, Jan. 2021, doi: 10.1061/(ASCE)GM.1943-5622.0001866.

[3] Y. Zhang, Y. Guo, and Q. Zhang, "Experimental study on the horizontal bearing performance of pile–soil composite foundation under coupled action of active and passive loads," *Buildings*, vol. 15, no. 17, Art. no. 3184, 2025, doi: 10.3390/buildings15173184.

[4] S. Li, M. Gong, L. Wei, Y. Zhang, Z. Deng, B. Wu, and F. He, "Passive loads on piles considering soft soil bypass flow based on a Coupled Eulerian-Lagrangian model," *KSCE J. Civ. Eng.*, vol. 29, no. 4, Art. no. 100107, 2025, doi: 10.1016/j.kscej.2024.100107.

[5] H. G. Poulos and L. T. Chen, "Pile response due to excavation-induced lateral soil movement," *J. Geotech. Geoenviron. Eng.*, vol. 123, no. 2, pp. 94–99, Feb. 1997, doi: 10.1061/(ASCE)1090-0241(1997)123:2(94).

[6] F. Huang, Z. Chen, H. Deng, and W. Zhu, "Lateral deformation mechanisms of piles in coastal regions under seawall surcharge loading and mitigation using Deep Cement Mixing (DCM) piles," *Buildings*, vol. 15, no. 11, Art. no. 1936, Jun. 2025, doi: 10.3390/buildings15111936.

[7] T. D. Bounds, K. K. Muraleetharan, and G. A. Miller, "Lateral movements of bridge embankments on soft soils: A case study inspired investigation," *Geotech.*

Geol. Eng., vol. 42, no. 1, pp. 121–139, Feb. 2024, doi: 10.1007/s10706-023-02559-6.

[8] W. D. Wang, Q. Li, Y. Hu, J. W. Shi, and C. W. W. Ng, "Field investigation of collapse of a 13-story high-rise residential building in Shanghai," *J. Perform. Constr. Facil.*, vol. 31, no. 4, Art. no. 04017012, Aug. 2017, doi: 10.1061/(ASCE)CF.1943-5509.0001005.

[9] W. Gu, L. Tong, H. Li, and K. Wu, "A numerical study on the lateral pile–soil interaction during the tunneling process in clay," *Iranian J. Sci. Technol., Trans. Civ. Eng.*, vol. 47, no. 6, pp. 3825–3838, Dec. 2023, doi: 10.1007/s40996-023-01161-3.

[10] I. Bellezza and E. Fratalocchi, "Analytical solutions for piles subjected to a passive load," *Géotechnique Lett.*, vol. 15, no. 3, pp. 172–178, Sep. 2025, doi: 10.1680/jgele.24.00148.

[11] P. N. Quang, P. N. Vinh, and H. P. Hoa, "Analysis of single pile ultimate lateral resistance in clayey soil under horizontal ground movement using RPFEM," *Tạp chí Khoa học và Công nghệ - Đại học Đà Nẵng*, vol. 23, no. 6A, pp. 23–28, Jun. 2025, doi: 10.31130/ud-jst.2025.23(6A).036E.

[12] M. A. Nunez, L. Briançon, and D. C. F. S. Dias, "Analyses of a pile-supported embankment over soft clay: Full-scale experiment, analytical and numerical approaches," *Eng. Geol.*, vol. 153, pp. 53–67, Feb. 2013, doi: 10.1016/j.enggeo.2012.11.006.

[13] H. Q. Li, L. M. Wei, S. Y. Feng, and Z. Chen, "Behavior of Piles Subjected to Surcharge Loading in Deep Soft Soils: Field Tests," *Geotech. Geol. Eng.*, vol. 37, no. 5, pp. 4019–4029, Oct. 2019, doi: 10.1007/s10706-019-00890-5.

[14] D. P. Stewart, R. J. Jewell, and M. F. Randolph, "Centrifuge modeling of piled bridge abutments on soft ground," *Soils Foundations*, vol. 34, no. 1, pp. 41–51, Mar. 1994, doi: 10.3208/sandf1972.34.41.

[15] S. Zhou, Z. Feng, J. Liu, C. Zhang, J. Zhang, and J. Wang, "Centrifugal model test study on the influence of subgrade filling on adjacent bridge pile foundations," *Buildings*, vol. 15, no. 22, Art. no. 4162, Nov. 2025, doi: 10.3390/buildings15224162.

[16] Q. Jiang, Q. Liu, W. Wu, F. Gong, and X. Lu, "A review of similar physical simulation in geotechnical engineering: Advances in the past 25 years," *J. Rock Mech. Geotech. Eng.*, 2026, doi: 10.1016/j.jrmge.2025.10.020.

[17] J. L. Pan, A. T. Goh, K. S. Wong, and C. I. Teh, "Model tests on single piles in soft clay," *Can. Geotech. J.*, vol. 37, no. 4, pp. 890–897, Aug. 2000, doi: 10.1139/t00-001.

[18] E. H. Ghee, "The behavior of axially loaded piles subjected to lateral soil movements," Ph.D. dissertation, School of Eng., Griffith Univ., Gold Coast, QLD, Australia, 2010.

[19] J. Bauer and O. Reul, "Lateral pressure on pile foundations in cohesive soils due to horizontal soil movements," *Acta Geotechnica*, vol. 19, no. 9, pp. 6375–6390, Sep. 2024, doi: 10.1007/s11440-024-02319-7.

[20] H. G. Poulos, L. T. Chen, and T. S. Hull, "Model tests on single piles subjected to lateral soil movement," *Soils Found.*, vol. 35, no. 4, pp. 85–92, Dec. 1995, doi: 10.3208/sandf.35.4_85.

[21] H. Qin and W. D. Guo, "Response of piles subjected to progressive soil movement," *Geotech. Test. J.*, vol. 39, no. 1, pp. 106–125, Jan. 2016, doi: 10.1520/GTJ20140148.

[22] W. D. Guo, H. Y. Qin, and E. H. Ghee, "Modeling single piles subjected to evolving soil movement," *Int. J. Geomech.*, vol. 17, no. 4, Art. no. 04016111, Apr. 2017, doi: 10.1061/(ASCE)GM.1943-5622.0000803.

[23] M. Khorashadizadeh, M. A. Hosseini, and A. S. Azizkandi, "Comparison between free-and fixed-head pile group responses under lateral spreading in the presence of protection piles using shake table tests," *Int. J. Geomech.*, vol. 24, no. 5, Art. no. 04024059, May 2024, doi: 10.1061/IJGNAI.GMENG-9223.

[24] J. Boompandi, K. Muthukkumaran, and M. R, "Experimental study on lateral behaviour of piles on sloping ground subjected to combined active and passive loads," *Int. J. Geotech. Eng.*, vol. 20, no. 1, pp. 31–45, 2026, doi: 10.1080/19386362.2025.2589177.

[25] H. Qin and W. D. Guo, "Group effects of piles due to lateral soil movement," *Int. J. Geomate*, vol. 4, no. 7, pp. 450–455, Mar. 2013, doi: 10.21660/2013.7.1857.

[26] H. Qin, "Response of pile foundations due to lateral force and soil movements," Ph.D. dissertation, School of Eng., Griffith Univ., Gold Coast, QLD, Australia, 2010.

[27] T. Ito and T. Matsui, "Methods to estimate lateral force acting on stabilizing piles," *Soils Found.,* vol. 15, no. 4, pp. 43–59, Dec. 1975, doi: 10.3208/sandf1972.15.4_43.