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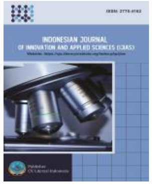

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The influence of soil elastic modulus on lateral deflection behavior and fixity point of piles under lateral loading

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ABSTRACT

This research investigates the effect of soil elastic modulus variation on the lateral behavior of pile foundations, particularly focusing on the deflection profile and the depth of the fixity point, which are critical parameters in assessing the lateral capacity of deep foundations. Pile foundations, as structural elements embedded into the ground, must effectively transfer axial and lateral loads to the supporting soil layers while maintaining deformation within allowable limits. In geotechnical engineering, the elastic modulus of soil represents its stiffness and directly influences the bending moment distribution and lateral deflection behavior of embedded piles. The research was conducted through a controlled laboratory experiment using scaled physical modeling based on the principles of scaling laws. The soil used was lateritic clay from the Gunung Kupang area, characterized by fine grains and high plasticity. Variations in soil type and pile dimensions were applied to evaluate the structural response under lateral loading. Matlab software was employed for deflection visualization and fixity point estimation, leveraging its matrix-based computational environment and dynamic system modeling capabilities. The results indicate that the depth of the fixity point for test piles with diameters of 6 mm and 8 mm is significantly influenced by the soil's modulus of elasticity. In soft soil, the fixity point ranges from 13.1D - 14.2D with deflections between 0.26D - 0.44D. In medium-stiff soil, the values range from 11.3D to 12.5D with deflections of 0.25D to 0.37D, while in hard soil, the fixity point occurs at 7.5D to 9.0D with deflections of 0.21D to 0.30D. A higher modulus of elasticity significantly reduces lateral deformation and results in a shallower fixity depth, reflecting an improvement in the lateral performance of the foundation system.

INTRODUCTION

The foundation is a part of a structure responsible for transferring loads from the superstructure to supporting soil that is sufficiently strong, thereby playing a key role in maintaining the stability of the entire building (Bowles, 1997). Loads acting on piles can be vertical or lateral, each producing different response characteristics in the soil-structure system (Tomlinson & Woodward, 2008). Vertical loads act along the pile axis, whereas lateral loads act perpendicular to the pile axis and can induce significant lateral displacement and bending moments in the pile (Das, 2011). In structures such as bridges, wharves, and buildings in seismic- and wind-prone areas, the effects of lateral loads often become a primary design consideration for foundations (Sompie, 2020). Experimental studies on pile foundations in soft soils have shown that pile behavior under loading is strongly influenced by soil properties and structural configuration (Effendi et al., 2024). Studies on laterally loaded piles indicate that soil stiffness and loading conditions significantly influence pile capacity and deformation behavior, particularly in offshore and soft soil environments (Hazzar et al., 2017).

In designing pile foundations for lateral loads, safety considerations are based not only on maximum capacity but also on permissible deformation limits according to the serviceability limit state concept (Moayedi et al., 2018). Conventional soil mechanics approaches emphasize that soil deformation plays a crucial role in determining foundation system stability (Gerolymos et al., 2020). Lateral pile response is strongly influenced by nonlinear soil-structure interaction (Chen et al., 2016). The p-y curve approach demonstrates that the relationship between soil pressure and deflection is nonlinear and highly dependent on soil characteristics (Houda et al., 2021). This nonlinear behavior has been validated through advanced analytical and numerical models (Yuan et al., 2022), which demonstrate that soil resistance and pile response are strongly interdependent under lateral loading conditions (Gupta & Basu, 2020). Therefore, soil mechanics parameters must be determined through testing to ensure analyses more accurately reflect field conditions (Sosrodarsono & Nakazawa, 2000).

One of the main parameters in lateral analysis is the soil modulus of elasticity (Es), which represents the soil's stiffness in response to deformation (Tang & Yang, 2020). A higher modulus of elasticity corresponds to smaller deformations under the same load condition. In practice, Es is often estimated through correlations with the undrained shear strength (Su) of cohesive soils (Jayasree et al., 2018). The Vane Shear Test is commonly used to determine Su in soft to medium soils due to its practicality and representativeness of field conditions (Perumalsamy & Ranganathan, 2022). Variations in the modulus of elasticity have been shown to influence soil stability and deformation in numerous geotechnical studies (Allowenda, 2018). Recent studies indicate that the soil elastic modulus directly controls load transfer mechanisms and significantly affects lateral deflection profiles along the pile (Liu et al., 2021; Wan et al., 2021).

Besides soil stiffness parameters, the depth of the fixity point is a crucial factor in lateral pile analysis (Sari, 2015). The fixity point is defined as the effective depth at which pile rotation approaches zero due to soil resistance along the pile shaft (Ramadhan, Solin & Astawa, 2022). Similar experimental approaches have been widely used to investigate lateral pile response and soil deformation characteristics (Subramanian & Boominathan, 2016; Yuan et al., 2017a). Changes in soil characteristics can significantly shift the fixity point location(Subramanian & Boominathan, 2016). Incorrect assumptions regarding fixity depth may result in inaccurate estimates of maximum bending moments (Sari, Effendi & Rusliansyah, 2015). Furthermore, pile head behavior affects deflection and bending moment distribution along the shaft. In free-head conditions, pile head rotation is more unconstrained, leading to larger deflections compared to fixed-head conditions (Wartono, 2004; Wijaya, 2019). Experimental observations also show that pile head conditions significantly influence deflection patterns and bending strain distribution along the pile length (Subramanian & Boominathan, 2016; Yuan et al., 2016). Therefore, load configuration and system boundary conditions must be explicitly considered in structural analysis (Kavitha et al., 2016).

This study uses lateritic soil from the Gunung Kupang area, Cempaka, Banjarbaru. Lateritic soil generally consists of fine grains with relatively high plasticity and exhibits cohesive behavior when water content increases (Gu et al., 2016). Such soil characteristics result in deformation responses sensitive to changes in density and water content, making laboratory testing necessary to obtain measurable mechanical parameters (Basack & Nimbalkar, 2018). An experimental approach via physical modeling was chosen to directly observe deflection patterns due to lateral loads (Anoyatis & Lemnitzer, 2017).

To improve the precision of deflection measurements, this study employs image analysis based on MATLAB. Numerical computation allows for precise and systematic extraction of deformation coordinates (Basack & Nimbalkar, 2018). The MATLAB numerical process is supported by efficient matrix and array computation methods for engineering data processing (Y. Zhang et al., 2016). Digital image analysis has been widely applied in geotechnical research to quantitatively monitor physical model deformation (Sazzad et al., 20222). Particle Image Velocimetry (PIV) techniques have been proven to enhance the measurement accuracy of soil deformation compared to conventional observation methods (Ors et al., 2022). Image-based measurement techniques have also been successfully used to capture soil deformation and pile deflection behavior under lateral loading conditions (Yuan et al., 2017).

Based on this background, the study aims to analyze the influence of soil density on the modulus of elasticity, examine the effect of the modulus of elasticity on the fixity point depth, and evaluate pile deflection profiles through integration of laboratory-scale physical modeling and digital image analysis. The results are expected to contribute to the development of methods for evaluating lateral pile behavior in cohesive soils, particularly lateritic soils, and serve as a reference for determining more rational and experimentally-based design parameters. This study extends previous findings on soil–pile interaction by integrating stiffness-based analysis and experimental observation of deformation behavior under lateral loading (Wan et al., 2021; Xu et al., 2023; Yuan et al., 2022).

METHODS

This study employed an experimental approach through laboratory-scale physical modeling to analyze pile deflection behavior under lateral loads on lateritic soil. The experimental method was chosen because it allows direct observation of soil–structure interaction and controlled monitoring of deflection distribution along the pile shaft (Broms, 1964; Reese & Matlock, 1970).

The soil used in this study was lateritic soil obtained from the Gunung Kupang area, Cempaka District, Banjarbaru City. This location was selected due to the dominance of lateritic soils formed by intensive weathering of parent rock in tropical regions with high rainfall. Geotechnically, lateritic soil is known for a significant fine fraction, relatively high plasticity, and sensitivity to changes in water content, which can influence shear strength and soil stiffness parameters. These characteristics make lateritic soil suitable for studying deformation behavior under lateral loading, particularly in pile foundation systems. Previous studies have shown that soil type and composition significantly influence lateral pile behavior and deformation response, particularly in layered soils and soil–rock mixtures (Kaur et al., 2021; Yu et al., 2018).

Soil samples were collected at representative depths to ensure that the material reflects the upper soil layers, which generally support shallow to medium foundations. The soil investigation location is shown in Figure 1.

Figure 1. Soil Investigation Location

Based on regional geological conditions, lateritic soil in this area developed through laterization, resulting in soil structures with particle bonding influenced by iron and aluminum oxide content. Similar experimental approaches on pile foundations in soft soils have been conducted to evaluate structural response under loading conditions (Effendi et al., 2024). This property directly affects soil deformation response to changes in water content and compaction. Therefore, selecting soil from this location provides a representative basis for analyzing the relationship between density, modulus of elasticity, and lateral pile deflection behavior at the laboratory scale.

To analyze the effect of density on soil modulus of elasticity, lateritic soil samples were compacted to several density levels representing soft, medium-stiff, and stiff conditions. Compaction was performed incrementally, controlling water content and compaction energy to ensure measurable and consistent conditions for each variation. This approach simulates changes in field soil conditions due to natural density variations or soil improvement processes. Similar approaches have been applied to evaluate the influence of soil stiffness variation on pile–soil interaction under lateral loading (Wan et al., 2021; Yuan et al., 2022).

Each density variation was tested using the Vane Shear Test to determine the undrained shear strength (Su). Testing was performed under undrained conditions to represent the response of cohesive soils under rapid lateral loading. The obtained Su values increased with soil density, indicating higher internal shear resistance between soil particles.

The Su values were then used to estimate the soil modulus of elasticity (Es) using empirical correlations commonly applied to cohesive soils. The correlation assumes that soil stiffness is proportional to undrained shear strength; thus, higher density produces a larger Es. Theoretically, higher-density soils have a more compact particle structure and stronger interparticle contact, resulting in smaller deformations under the same stress (Das, 2011). This relationship between soil stiffness and deformation behavior has been widely observed in laterally loaded pile studies, where higher stiffness leads to reduced deflection and improved load transfer (Hazzar et al., 2017; Liu et al., 2021).

This approach ensures that variations in soil density not only generate differences in shear strength but also in stiffness, which are subsequently analyzed in relation to lateral deflection and fixity depth in the pile model. The experimental approach allows a comprehensive evaluation of the relationships among density, shear strength, and modulus of elasticity in the soil–structure interaction system.

Pile models were fabricated at a small scale with homogeneous material and uniform dimensions for each test. The piles were embedded in soil within transparent containers to facilitate visual observation of deformation. Physical modeling has been proven effective in capturing pile–soil interaction mechanisms and validating analytical predictions of lateral pile behavior (Subramanian & Boominathan, 2016).

Lateral loads were applied incrementally at the pile head under free-head conditions. The free-head condition was chosen because deflections are more pronounced, revealing clearer deformation responses than fixed-head conditions (Deendayal et al., 2020). This condition allows clearer observation of maximum deflection and bending behavior, which is consistent with previous experimental findings on laterally loaded piles (Yuan et al., 2017). At each loading stage, the applied load and horizontal displacement were recorded.

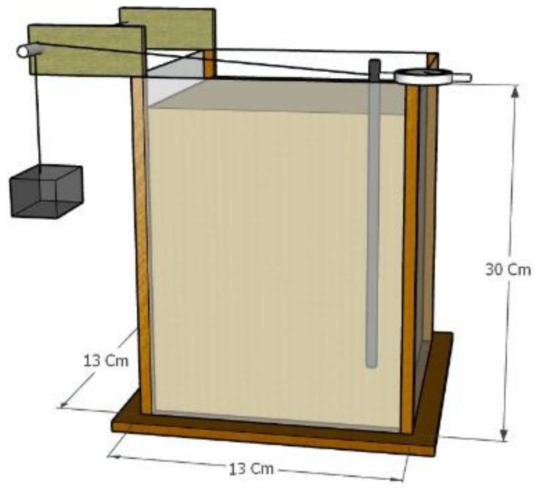

Figure 2. Pile Modeling Scheme

Deflection profiles along the pile were analyzed based on visual observation and horizontal displacement records. The fixity point depth was determined from the deflection curve, specifically at the depth where rotation approaches zero. Determining the fixity point is critical because it relates to the maximum bending moment distribution along the pile shaft. Several studies have emphasized that accurate determination of the fixity point is essential for predicting pile response and moment distribution under lateral loads (Abdelaziz et al., 2021; X. Ling Zhang et al., 2021). Incorrect estimation of the fixity point can lead to inaccurate lateral capacity calculations (Taghavi & Muraleetharan, 2017).

To improve the accuracy of deflection readings, a MATLAB-based image analysis method was employed. The analysis procedure included:

1. Capturing images at each loading stage
2. Scaling calibration relative to actual dimensions
3. Extracting coordinates of pile position changes
4. Generating deflection curves

This method enables quantitative deflection measurement while minimizing subjective errors in manual observations. Image-based deformation analysis techniques have been widely used in geotechnical studies to improve measurement accuracy and capture soil displacement patterns (Yuan et al., 2017). The visual-digital approach strengthens the validity of experimental data.

Model testing was conducted to evaluate pile behavior under specified loads using laboratory experimental methods. The testing included all stages from model preparation to data analysis and conclusions, following these procedures:

1. Model and Sample Preparation

Soil samples were prepared according to research specifications. Pile models were fabricated and placed into acrylic boxes filled with soil. Pile variations included:

   a. Diameter: 6 mm and 8 mm
   b. Length: 250 mm

2. Pile Installation and Loading

Piles were installed in the soil-filled acrylic boxes. Loads were applied incrementally to each pile variation to obtain representative data.

3. Measurement and Monitoring

Pile deflection was measured using installed dial gauges. Fixity points and pile deflection were observed and analyzed using MATLAB. Fixity depth was measured from the soil surface. This procedure was repeated for each pile variation to ensure consistency and comprehensive analysis.

4. Data Collection and Analysis

Data collected included deflection profiles and fixity locations. Analyses evaluated the influence of pile diameter on deflection and fixity.

5. Conclusions and Recommendations

Conclusions were drawn according to research objectives. Any issues outside the research scope were provided as recommendations for future studies. Model testing aimed to provide a comprehensive understanding of pile behavior under lateral loads, serving as a reference for further modeling development.

RESULTS AND DISCUSSION

Laboratory testing of lateritic soil from Gunung Kupang showed dominance of silt and clay (56.52%), with fine clay (<0.002 mm) at 18.05%. Other grain fractions included gravel 7.67%, coarse sand 5.55%, medium sand 5.69%, and fine sand 6.52%. Atterberg limits were LL = 57.34%, PL = 27.76%, resulting in a plasticity index PI = 29.58%, classified as CH. Compaction tests yielded maximum dry density γ_d = 1.44 g/cm³ at optimum moisture content 25.63%, indicating medium-to-high plasticity. Table 1 summarizes the physical properties of the soil:

Table 1. Properties of Lateritic Soil from Gunung Kupang

Grain Size Distribution	Gravel (>2mm)	%	7.67
	Coarse Sand (0.6-2.00mm)	%	5.55
	Medium Sand (0.2-0.6mm)	%	5.69
	Fine Sand (0.05-0.2mm)	%	6.52
	Silt and Clay (0.002-0.05mm)	%	56.52
	Clay (<0.002mm)	%	18.05
	No. 10 (2.00mm)	%	92.33
	No. 40 (0.425mm)	%	85.39
	No. 200 (0.0075mm)	%	78.49
Atterberg Limits	Liquid Limit (LL)	%	57.34
	Plastic Limit (PL)	%	27.76
	Plasticity Index (PI)	%	29.58
	Soil Classification		CH
Compaction Characteristics	Dry Unit Weight	gr/cm³	1.44
	Optimum Moisture Content	%	25.63

Table 1 shows that the lateritic soil has medium-to-high plasticity, influencing pile deformation. High fine clay content and PI > 25% indicate potential for significant deformation under vertical and lateral loading. In the calculation of the pile elastic modulus, steel was used as the pile material with an elastic modulus of E = 200 GPa, representing a material with high stiffness. The results indicate that the L/R ratio is greater than or equal to 3.5, which classifies all piles as long piles based on the Broms method.

Figure 3. Pile Modeling tests

The results of the pile model tests conducted in different soil conditions (soft, medium-stiff, and stiff soils) indicate variations in lateral deflection. The experiments were performed using model piles with diameters of 6 mm and 8 mm and a length of 250 mm.

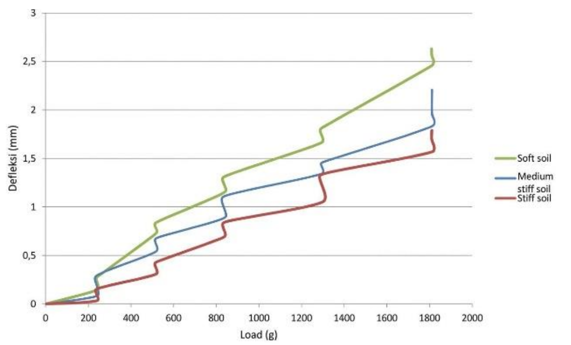

Figure 4. Load–Deflection Relationship of a 6 mm Diameter Pile

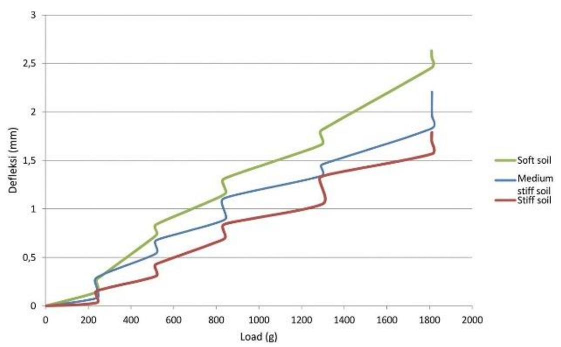

Figure 5. Time–Deflection Response of a 6 mm Diameter Pile

Figures 4 and 5 illustrate the relationship between deflection and applied load and between deflection and time, respectively. Based on the average analysis of the pile model tests with a 6 mm diameter, the deflection values obtained in soft soil, medium-stiff soil, and stiff soil were 2.63 mm, 2.21 mm, and 1.79 mm, respectively. For all variations of the soil elastic modulus, the ratio of deflection to pile diameter (D) for the 6 mm diameter pile ranged from 0.30D to 0.44D.

For the 8 mm diameter pile, the measured deflection values were 2.11 mm in soft soil, 2.01 mm in medium-stiff soil, and 1.66 mm in stiff soil. For all variations of the soil elastic modulus, the ratio of deflection to pile diameter (D) for the 8 mm diameter pile ranged from 0.21D to 0.26D. Results of Pile Modeling Analysis Using MATLAB.

Table 2. Coordinate Data of 6 mm Diameter Pile in Soft Soil (in pixels).

No	Start (pixels)		End (pixels)	
	x	y	x	y
1	2466.9	1781	2436.2	1781
2	2466.9	1914.2	2441.5	1925.7
3	2466.9	2284.6	2453.2	2267.2
4	2466.9	2631.8	2461.1	2631.8
5	2466.9	2967.5	2465.9	2973.3
6	2466.9	3303.1	2466.9	3303.1
7	2466.9	3650.4	2466.9	3633
8	2466.9	3968.7	2466.9	3974.5
9	2466.9	4292	2466.9	4292.8
10	2466.9	4617.1	2466.9	4622.7

Table 3. Coordinate Points of 6 mm Pile in Soft Soil

No	Start (mm)		End (mm)	
	x	y	X	y
1	0.00	0.00	-2.71	0.00
2	0.00	11.76	-2.24	11.76
3	0.00	44.45	-1.21	44.45
4	0.00	75.09	-0.51	75.09
5	0.00	104.72	-0.09	104.72
6	0.00	134.34	0.00	134.34
7	0.00	165.00	0.00	165.00
8	0.00	193.09	0.00	193.09
9	0.00	221.62	0.00	221.62
10	0.00	250.32	0.00	250.32

From Tables 2 and 3, the location of the fixity point for a 6 mm diameter pile with a length of 250 mm, tested in Soft Soil, was found to be at a depth of 85 cm from the soil surface, with a pile deflection of 2.71 mm. Based on these data, the pile deflection profile can be constructed as shown in the following figure.

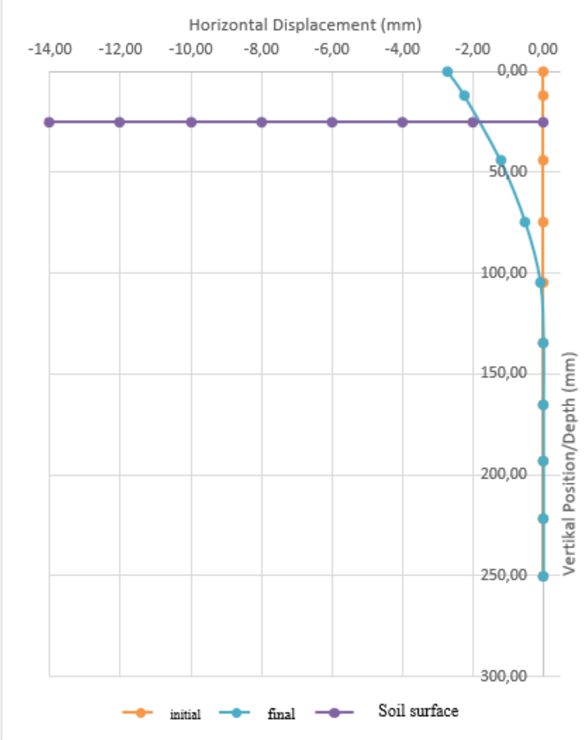

Figure 6. Pile Deflection Profile in Soft Soil

The fixity point for the 8 mm diameter pile is located 105 mm below the soil surface, which is deeper than the fixity point of the 6 mm diameter pile, located 85 mm below the soil surface. The 8 mm diameter pile has a higher flexural stiffness (EI), allowing it to transfer loads deeper into the soil because it resists bending more effectively, resulting in a deeper fixity point. In contrast, a pile with lower EI bends more readily near the soil surface, causing the fixity point to form at a shallower depth. The 6 mm diameter test pile exhibits greater deflection compared to the 8 mm diameter pile. In very soft soils, the lateral resistance provided by the shallow layers is insufficient, so the pile experiences significant deflection and rotation until reaching greater depths where the passive soil pressure becomes effective in restraining movement. For the soft soil variation, the ratio of the fixity point depth to pile diameter (D) for both 6 mm and 8 mm piles ranges from 13.1D to 14.2D.

Table 4. Coordinate Data of 6 mm Diameter Pile in medium-stiff soil (in pixels).

No	Start (pixels)		End (pixels)	
	x	y	x	y
1	2478	1290.1	2446.6	1647.5
2	2478	1404.8	2452	2043.1
3	2478	1806.5	2466	2457.5
4	2478	2243.9	2474	2840.6
5	2478	2652.7	2478	3229.9
6	2478	3090.2	2478	3631.8
7	2478	3520.5	2478	4008.5
8	2478	3929.3	2478	4397.8
9	2478	4338	2478	4762
10	2478	4795.3	2478	4791.1

Table 5. Coordinate Points of 6 mm Pile in medium-stiff soil

No	Start (mm)		End (mm)	
	x	y	x	y
1	0.00	0.00	-2.24	0.00
2	0.00	8.19	-1.86	8.19
3	0.00	36.86	-0.86	36.86
4	0.00	68.08	-0.29	68.08
5	0.00	97.26	0.00	97.26
6	0.00	128.49	0.00	128.49
7	0.00	159.20	0.00	159.20
8	0.00	188.38	0.00	188.38
9	0.00	217.55	0.00	217.55
10	0.00	250.19	0.00	250.19

From Table 5, the fixity point of a 6 mm diameter pile with a length of 250 mm, tested in medium-stiff soil, was found at a depth of 75 cm from the soil surface, with a pile deflection of 2.24 mm. Based on these data, the pile deflection profile can be constructed as shown in the following figure.

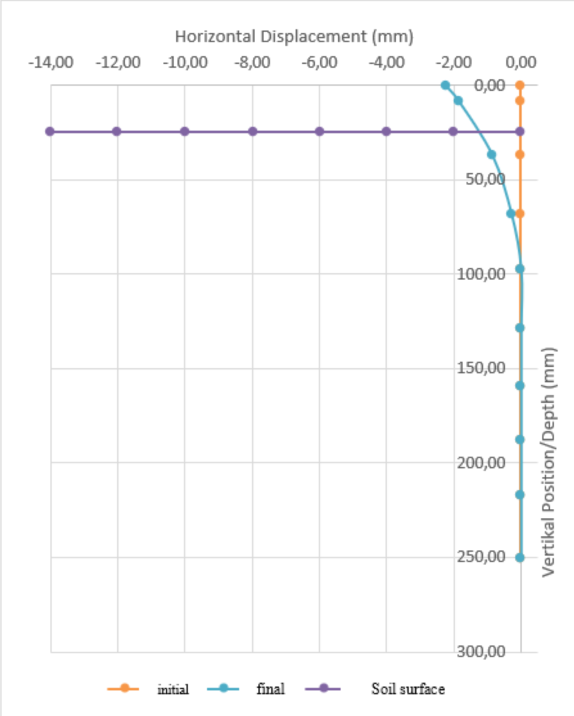

Figure 6. Pile Deflection Profile in medium-stiff soil

The fixity point for the 8 mm diameter pile is located 90 mm below the soil surface, which is deeper than the fixity point of the 6 mm diameter pile, located 75 mm below the soil surface. The 6 mm diameter test pile exhibits greater deflection compared to the 8 mm diameter pile. The medium-stiff soil provides sufficient stiffness to offer adequate lateral resistance at reasonable depths. For this soil variation, the ratio of fixity point depth to pile diameter (D) for both 6 mm and 8 mm piles ranges from 11.3D to 12.5D.

Table 6. Coordinate Data of 6 mm Diameter Pile in stiff soil (in pixels).

No	Start (pixels)		End (pixel)	
	x	y	x	y
1	2674	1760.9	2656	1760.9
2	2674	1964.7	2663	1964.7
3	2674	2178.7	2669	2178.7
4	2674	2484.4	2674	2479.3
5	2674	2790.2	2674	2785.1
6	2674	3106.1	2674	3090.8
7	2674	3401.7	2674	3406.7
8	2674	3707.4	2674	3712.5
9	2674	4018.2	2674	4023.3
10	2674	4274.4	2674	4269.3

Table 7. Coordinate Points of 6 mm Pile in stiff soil

No	Start (mm)		End (mm)	
	x	y	x	y
1	0.00	0.00	-1.81	0.00
2	0.00	20.30	-1.10	20.30
3	0.00	41.61	-0.50	41.61
4	0.00	72.06	0.00	72.06
5	0.00	102.52	0.00	102.52
6	0.00	133.98	0.00	133.98
7	0.00	163.43	0.00	163.43
8	0.00	193.87	0.00	193.87
9	0.00	224.83	0.00	224.83
10	0.00	250.35	0.00	250.35

From Table 7, the fixity point of a 6 mm diameter pile with a length of 250 mm, tested in stiff soil, was found at a depth of 45 mm from the soil surface, with a pile deflection of 1.81 mm at the pile tip. Based on these data, the pile deflection profile can be constructed as shown in the following figure.

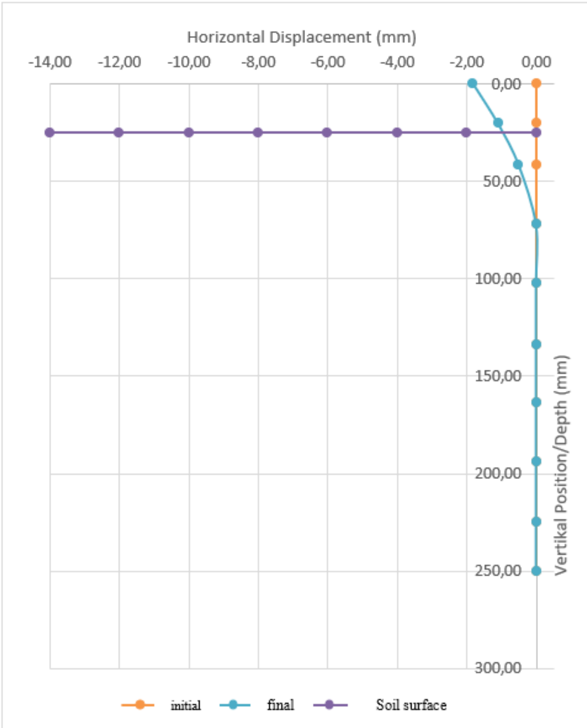

Figure 7. Pile Deflection Profile in stiff soil

The fixity point for the 8 mm diameter pile is located 90 mm below the soil surface, which is deeper than the fixity point of the 6 mm diameter pile, located 75 mm below the soil surface. The 6 mm diameter test pile exhibits greater deflection compared to the 8 mm diameter pile.

Stiff soil provides high lateral resistance, resulting in only minor deflection or rotation at shallow depths. Consequently, the effective fixity point occurs at a relatively shallow depth, as the soil already offers a rigid support beneath the surface. For this soil variation, the ratio of fixity point depth to pile diameter (D) for both 6 mm and 8 mm piles ranges from 7.5D to 9D.

The location of the fixity point is strongly influenced by the applied load, pile flexural stiffness (EI), and soil elastic modulus (E). The higher the soil elastic modulus (i.e., the stiffer the soil), the shallower the pile fixity point, and vice versa. In stiffer soils (high E), the fixity point is located closer to the surface, providing greater resistance to lateral pile movement. As a result, the pile is effectively restrained at a shallower depth, and the cantilever portion (the bending section) becomes shorter, resulting in smaller lateral deflection and bending moments.

In contrast, in softer soils (low E), the fixity point occurs at a greater depth, and the soil is less effective in resisting lateral pile movement, leading to larger deflection and bending over a longer pile length.

CONCLUSION

Based on the results of this study, the following conclusions can be drawn:

1. Soil density exhibits a directly proportional relationship with the soil elastic modulus, indicating that an increase in soil density leads to a corresponding increase in the value of the soil elastic modulus.
2. The modeling test results indicate that the location of the pile fixity point in soft soil ranges from 13.1D–14.2D, in medium-stiff soil from 11.3D–12.5D, and in stiff soil from 7.5D–9D. These results suggest that an increase in soil stiffness causes the fixity point to occur at a relatively shallower depth.
3. The deflection values obtained from dial gauge measurements show a consistent trend. In soft soil, the deflection ranges from 0.26D–0.44D; in medium-stiff soil, from 0.25D–0.37D; and in stiff soil, from 0.21D–0.30D. This trend indicates that stiffer soil conditions result in smaller lateral deflections.
4. Image analysis results using MATLAB for evaluating deflection and determining the fixity point indicate that pile lateral deflection is inversely proportional to the pile flexural stiffness (EI) and the soil elastic modulus (E). Consequently, piles with higher stiffness embedded in denser soil tend to experience smaller lateral deflections and exhibit a relatively deeper mechanical fixity point.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

REFERENCES

Abdelaziz, A. Y., El Naggar, M. H., & Ouda, M. (2021). Determination of depth-of-fixity point for laterally loaded vertical offshore piles: A new approach. *Ocean Engineering*, *232*(December 2020), 109113.

Anoyatis, G., & Lemnitzer, A. (2017). Kinematic Winkler modulus for laterally-loaded piles. *Soils and Foundations*, *57*(3), 453–471.

Basack, S., & Nimbalkar, S. (2018). Measured and Predicted Response of Pile Groups in Soft Clay Subjected to Cyclic Lateral Loading. *International Journal of Geomechanics*, *18*(7), 1–20.

Chen, S. L., Kong, L. G., & Zhang, L. M. (2016). Analysis of pile groups subjected to torsional loading. *Computers and Geotechnics*, *71*, 115–123.

Das, B. (2011). *Principles of Foundation Engineering 7th Edition*. Cengage Learning.

Deendayal, R., Muthukkumaran, K., & Sitharam, T. G. (2020). Analysis of laterally loaded group of piles located on sloping ground. *International Journal of Geotechnical Engineering*, *14*(5), 580–588.

Effendi, R., Pratiwi, A. Y., Chairunnisa, N., Alpindi, N. M., Nurwidayati, R., & Krasna, W. A. (2024). An Experimental Study on Industrial Concete Pile Foundation in Soft Soil: Comparison of Monolithic and Pile with Welded Joints. *Engineering, Technology and Applied Science Research*, *14*(6), 18608–18615.

Gerolymos, N., Giannakos, S., & Drosos, V. (2020). Generalised failure envelope for laterally loaded piles: Analytical formulation, numerical verification and experimental validation. *Geotechnique*, *70*(3), 248–267.

Gu, Q., Yang, Z., & Peng, Y. (2016). Parameters affecting laterally loaded piles in frozen soils by an efficient sensitivity analysis method. *Cold Regions Science and Technology*, *121*, 42–51.

Gupta, B. K., & Basu, D. (2020). *Nonlinear Solutions for Laterally Loaded Piles*. 1–36.

Hazzar, L., Hussien, M. N., & Karray, M. (2017). Influence of vertical loads on lateral response of pile foundations in sands and clays. *Journal of Rock Mechanics and Geotechnical Engineering*, *9*(2), 291–304.

Houda, M., Jenck, O., & Emeriault, F. (2021). Soft soil improvement by rigid inclusions under vertical cyclic loading: numerical back analysis. *European Journal of Environmental and Civil Engineering*, *25*(3), 409–428.

Jayasree, P. K., Arun, K. V., Oormila, R., & Sreelakshmi, H. (2018). Lateral Load Capacity of Piles: A Comparative Study Between Indian Standards and Theoretical Approach. *Journal of The Institution of Engineers (India): Series A*, *99*(3), 587–593.

Kaur, A., Singh, H., & Jha, J. N. (2021). Numerical study of laterally loaded piles in soft clay overlying dense sand. *Civil Engineering Journal (Iran)*, *7*(4), 730–746.

Kavitha, P. E., Beena, K. S., & Narayanan, K. P. (2016). A review on soil–structure interaction analysis of laterally loaded piles. *Innovative Infrastructure Solutions*, *1*(1), 1–15.

Liu, P., Chen, L., Huawei, C., & Jiang, C. (2021). A method for predicting lateral deflection of large-diameter monopile near clay slope based on soil-pile interaction. *Computers and Geotechnics*, *135*(October 2020), 104180.

Moayedi, H., Nazir, R., Mosallanezhad, M., Noor, R. B. M., & Khalilpour, M. (2018). Lateral deflection of piles in a multilayer soil medium. Case study: The Terengganu seaside platform. *Measurement: Journal of the International Measurement Confederation*, *123*(September 2016), 185–192.

Ors, D. M., Ebid, A. M., & Mahdi, H. A. (2022). Evaluating the lateral subgrade reaction of soil using horizontal pile load test results. *Ain Shams Engineering Journal*, *13*(5), 101734.

Perumalsamy, K., & Ranganathan, S. (2022). Single pile in cohesionless soil in sloping ground under lateral loading. *International Journal of Geo-Engineering*, *13*(1).

Sazzad, Md. M., Medha, R. A., & Fahim, F. Al. (20222). *Small-scale Model Study on the Load-Deflection Characteristics of Single Piles Under Static Lateral Load*.

Sompie. (2020). Perilaku Struktur terhadap Beban Lateral pada Tanah Lunak. *Jurnal Teknik Sipil Universitas Sam Ratulangi*, *6*(1), 22–30.

Subramanian, R. M., & Boominathan, A. (2016). Dynamic experimental studies on lateral behaviour of batter piles in soft clay. *International Journal of Geotechnical Engineering*, *10*(4), 317–327.

Taghavi, A., & Muraleetharan, K. K. (2017). Analysis of Laterally Loaded Pile Groups in Improved Soft Clay. *International Journal of Geomechanics*, *17*(4).

Tang, X., & Yang, M. (2020). Analysis of laterally-loaded piles in weathered rock slopes based on p-y curve method. *International Journal of Geotechnical Engineering*, *14*(7), 809–819.

Wan, X., Doherty, J. P., & Randolph, M. F. (2021). Relationships between lateral and rotational load transfer stiffnesses and soil modulus for the elastic response of monopiles. *Computers and Geotechnics*, *137*(June), 104256.

Xu, H., Zhang, S., Li, W., Cao, Z., & Jiang, K. (2023). Behaviors and group effects of pile composite foundation under lateral load. *Results in Engineering*, *17*(January), 100899.

Yu, Y., Sun, H., & Juang, C. H. (2018). A new model for response of laterally loaded piles in soil-rock mixtures. *Computers and Geotechnics*, *104*(August), 237–246.

Yuan, B., Chen, M., Chen, W., Luo, Q., & Li, H. (2022). Effect of Pile-Soil Relative Stiffness on Deformation Characteristics of the Laterally Loaded Pile. *Advances in Materials Science and Engineering*, *2022*.

Yuan, B., Xu, K., Wang, Y., Chen, R., & Luo, Q. (2017). Investigation of Deflection of a Laterally Loaded Pile and Soil Deformation Using the PIV Technique. *International Journal of Geomechanics*, *17*(6), 1–9.

Zhang, X. ling, Jun-yuan, X., Cheng-shun, X., & Kai-yuan, L. (2021). An analysis method for lateral capacity of pile foundation under existing vertical loads. *Soil Dynamics and Earthquake Engineering*, *142*(September 2020), 106547.

Zhang, Y., Andersen, K. H., & Tedesco, G. (2016). Ultimate bearing capacity of laterally loaded piles in clay – Some practical considerations. *Marine Structures*, *50*, 260–275.