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Research Article

Influence of pile spacing on lateral bearing capacity of group foundations in soft soil

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Abstract

Pile foundations supporting tall structures must withstand axial and lateral forces, necessitating designs for various horizontal loads such as wind, lateral earth pressure, seismic activity, water waves, ship impacts (at docks), eccentric column loads, cable forces on transmission towers, and more. Consequently, studying the lateral bearing capacity of group pile foundations is crucial. This study investigates pile group lateral bearing capacity behavior utilizing a triangular configuration. Variations in pile spacing within the group foundation include distances of 2.5D and 3D, where wooden piles measuring 400 cm in length and 6 cm in diameter are used, with a pile cap composed of an L-shaped iron profile 45 x 45 x 2 mm affixed atop the group foundation. The soil at the study site, classified as OH according to the Unified Soil Classification System (USCS), consists of organic clay with moderate to high plasticity and an average cone penetration pressure ranging from 5.97 to 6.90 kg/cm^2, characterizing it as soft consistency soil. Results from the pile group loading tests indicate an increasing efficiency trend from a spacing distance of 2.5D to 3D. The findings suggest that pile spacing variations significantly impact the lateral bearing capacity of group foundations in soft soil, with implications for the design and construction of tall structures in similar geological conditions.

1. Introduction

Pile foundations play a vital role in transferring loads from tall and heavy structures to deeper and more stable soil or rock layers [1,2]. These foundations are essential for ensuring the stability and integrity of buildings, bridges, and other large-scale infrastructures [3]. They are designed to resist not only vertical or axial forces but also horizontal or lateral forces, which are equally critical for structural performance. Axial forces act vertically and are primarily generated by the weight of the structure, along with additional loads such as occupants, furnishings, and equipment[4]. The pile shaft distributes these forces into the underlying soil or rock. Without sufficient axial resistance, pile foundations may experience settlement, tilting, or even structural failure, thereby compromising the stability and safety of the supported structure [5,6]. In addition to axial loads, pile foundations must also withstand lateral forces that act horizontally at the foundation level. These forces originate from multiple sources, including wind, seismic activity, hydrodynamic effects of water waves, lateral soil pressure, and eccentric loading [7,8]. Unlike axial loads, lateral loads require the foundation to have adequate stiffness and resistance to prevent excessive

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deflection or rotation[9]. Insufficient lateral resistance may result in displacement or collapse, particularly in tall structures or infrastructure exposed to strong environmental forces[10].

The lateral forces acting on pile foundations present diverse engineering challenges. Wind loads impose lateral pressures on tall buildings and bridges, varying with building height, shape, and exposure conditions[11,12]. Seismic loads, arising during earthquakes, generate dynamic lateral stresses and may be exacerbated by soil liquefaction or lateral spreading[13]. Hydrodynamic forces from waves and currents affect pile-supported marine structures, such as bridges, docks, and waterfront buildings [14]. Additionally, soil exerts lateral pressures, particularly in soft clay or under fluctuating groundwater levels, while eccentric loading generates unbalanced lateral forces that can cause tilting if not adequately resisted [15,1617].

In Pontianak, West Kalimantan, the problem of lateral resistance is especially significant due to its geological conditions. The city's subsurface is dominated by soft to very soft organic soils [18], which have low to moderate bearing capacity and present considerable challenges for construction [19,20]. Pile foundations in such soils often face reduced axial capacity, with friction piles showing limited effectiveness and end-bearing piles requiring depths of up to 30 meters to reach competent layers[21]. However, beyond axial performance, inadequate lateral load resistance frequently leads to structural issues[22]. Failures in pile-supported docks in the region illustrate how lateral forces can cause deformations, tilting, and settlement, thereby reducing safety and durability [23,24,25].

Given these geotechnical challenges, a comprehensive investigation of lateral pile performance in Pontianak's soft soils is needed. This study focuses on the behavior of triangular group pile foundations with varied pile spacing, aiming to evaluate their lateral load-bearing performance under controlled experimental conditions. The specific objectives are to determine the lateral bearing capacity of both single piles and triangular group piles, and to compare analytical predictions with field test results. The experimental program employed wooden piles with a diameter of 6 cm and a length of 400 cm, installed in triangular group arrangements with pile spacing of 2.5D and 3D. Static horizontal load tests were conducted according to ASTM D-3966-90 standards. Test results were interpreted using several established methods, including those of Sharma, Elasto-Plastic, and Mazuerkiwicz, while analytical comparisons were made with the Broms method. This research addresses a critical gap in experimental studies on triangular pile group configurations, particularly in soft tropical soils with high moisture content. While much prior work has concentrated on single piles or group piles in linear and square arrangements, triangular configurations remain underexplored. By investigating the effect of pile spacing on lateral group efficiency, this study provides valuable insights for optimizing foundation design in challenging geotechnical conditions and enhancing the resilience of structures in soft-soil regions.

2. Literature Review

2.1. Piles Under Lateral Loads

Pile foundations are critical components in structural engineering due to their ability to resist lateral loads—horizontal forces acting perpendicular to the pile axis [26]. These loads pose significant challenges across various applications, making pile foundations indispensable in geotechnical and structural design [27]. Pile foundations have been widely used in engineering construction owing to their high bearing capacity, small settlement, and good durability [28].

One prominent application of pile foundations is in constructing retaining walls, which are pivotal in providing stability against lateral earth pressure. When soil exerts horizontal pressure on a retaining wall, pile foundations effectively counteract these forces, thereby preventing potential failure or deformation of the wall. This function becomes particularly crucial in scenarios where the structure is intended to retain soil or prevent slope erosion, highlighting the indispensable role of pile foundations in geotechnical engineering [29,30].

In addition to retaining walls, pile foundations are instrumental in supporting high-rise structures such as steel-framed buildings or skyscrapers [8,31]. These towering structures are subject to wind loads that exert lateral forces capable of causing instability. However, owing to their deep penetration into the ground, pile foundations offer robust stability against these wind-induced lateral forces [32]. The unique ability of pile foundations to resist both tensile and compressive forces is instrumental in ensuring the structural integrity and safety of such tall buildings, underscoring their indispensability in the construction of vertical structures in urban environments.

Moreover, pile foundations also play a vital role in supporting retaining walls facing external environmental forces in offshore constructions [33]. In these challenging environments, lateral loads can arise from various sources, including the impact of ocean waves, strong winds, and collisions with ships [34]. Pile foundations provide essential support and stability to ensure retaining walls can withstand these dynamic lateral forces without compromising the structure's integrity [35]. This application highlights the adaptability of pile foundations in marine engineering and offshore constructions, where resilience against environmental impacts is paramount for long-term structural integrity. Overall, pile foundations play a multifaceted role in resisting lateral loads. By ensuring stability against earth pressures, wind forces, and environmental impacts, they remain indispensable elements in both onshore and offshore construction.

2.2. Influence of Pile Configuration on Lateral Load Resistance

The configuration of piles within a foundation plays a crucial role in determining their ability to resist lateral loads effectively. Various pile configurations, including single piles, group piles, and batter piles, offer different levels of lateral load resistance influenced by factors such as spacing, alignment, and embedment depth [36,37]. Understanding these configurations and their impact is essential for optimizing the performance and stability of pile foundations under lateral loading conditions.

Single piles, commonly used in foundation systems, inherently possess a certain degree of lateral load resistance determined by their diameter, length, and the characteristics of the surrounding soil [1, 39, 40]. However, the effectiveness of single piles in resisting lateral loads can be further enhanced through specific configurations, such as batter piles. Batter piles are inclined at an angle to the vertical axis [36, 38, 41], allowing them to distribute lateral loads more efficiently by utilizing axial and lateral resistance mechanisms. This configuration improves the overall stability of the foundation against lateral forces by reducing pile deflections and enhancing load-bearing capacity.

Group piles, including clustered and triangular configurations, further enhance lateral resistance by distributing loads among multiple piles [42]. Pile spacing and arrangement are critical: triangular layouts, for instance, optimize load sharing, reduce deflections, and improve stability compared to other patterns. Another critical factor is embedment depth, as deeper piles engage stronger soil layers, improving lateral performance [43]. However, the optimal depth depends on soil conditions, pile geometry, and structural requirements. Careful consideration of these factors is essential to achieve both efficiency and stability [44]. In summary, pile configuration—through battering, grouping, and embedment depth—plays a decisive role in improving lateral load resistance and ensuring foundation stability under diverse geotechnical conditions.

2.3. Methods for Evaluating Lateral Load Resistance

Several methods are employed to evaluate the lateral load resistance of pile foundations, encompassing analytical methods, numerical modeling, and field testing. Each method offers unique insights into the complex behavior of pile foundations under lateral loads, contributing to a comprehensive understanding of their performance and structural integrity [45,46].

Analytical approaches, such as the Broms method, p-y curves, and beam-on-elastic-foundation models, estimate pile deflections and soil-pile responses using simplified assumptions and empirical relationships [12,48,49]. Although approximate, they are valuable for preliminary design by incorporating soil properties, pile geometry, and loading conditions.

Numerical methods, including finite element analysis (FEA) and finite difference methods (FDM), allow detailed simulations of soil–structure interaction, predicting deflections, stresses, and load distribution [50]. By capturing complex geometries and material behaviors, numerical modeling supports design optimization and identification of potential failure mechanisms. Field testing, such as static load tests and dynamic methods like pile driving analyzer (PDA), directly measures pile deflections and soil reactions under applied loads [51]. These tests provide essential validation for analytical and numerical models, ensuring design Reliability in real conditions. In practice, engineers often integrate analytical, numerical, and field methods to achieve a comprehensive assessment of lateral pile behavior, optimizing design and ensuring safety across varied geotechnical environments.

2.4. Soil Failure Mechanisms and Bending Moments in Long Pile Foundations

The depiction of soil failure mechanisms and the distribution of soil resistance and bending moments for long pile foundations with free head conditions are presented in Figure 1. Figure 1 provides valuable insights into the behavior of long pile foundations with free head conditions under lateral loads on cohesive soil, a crucial aspect in geotechnical engineering.

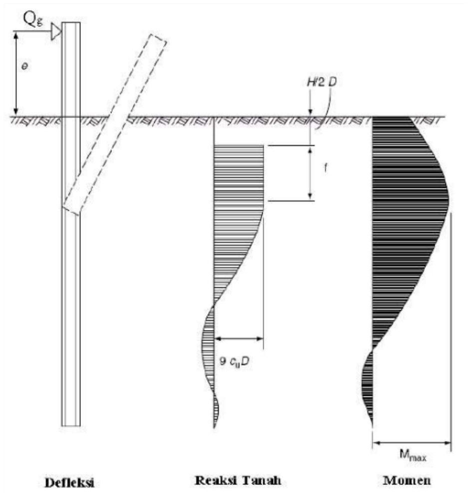

Fig. 1. Deflection and failure mechanism for long pile foundations with free head conditions under lateral loads on cohesive soil [25]

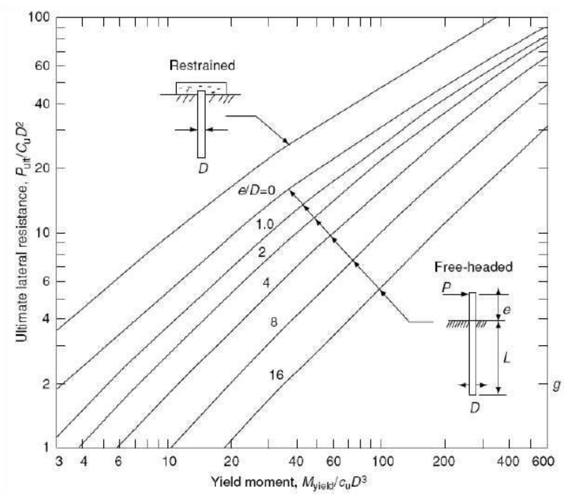

Fig. 2. The lateral load capacity for long pile foundations in cohesive soil [25]

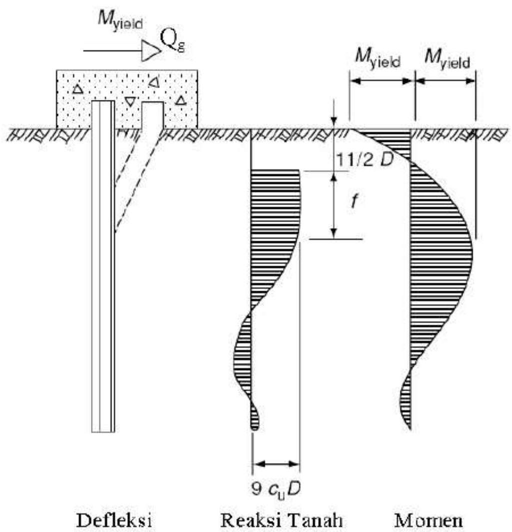

Fig. 3. Deflection Due to Lateral Loads for Long Pile Foundations with Fixed Head Conditions on Cohesive Soil [25]

The depicted deflection and failure mechanism reveal important considerations for designing and analyzing pile foundations in real-world scenarios. The observed pile deflection near the soil surface emphasizes the significance of soil-structure interaction in determining the overall response of the foundation system.

Figure 2 illustrates a graph representing the lateral load capacity for long pile foundations constructed on cohesive soil. Furthermore, Figure 3 provides detailed information on the failure mechanisms, distribution of ultimate soil resistance, and bending moments along the pile under fixed head conditions on cohesive soil. The static load test data analysis using methods such as Sharma, Elasto-Plastic, and Mazurkiewich allows for a deeper understanding of the behavior of pile foundations subjected to lateral loads. This holistic approach, which integrates analysis, experimentation, and interpretation, enhances our understanding of pile foundation performance and contributes to the effective design and construction of civil engineering structures.

2.5. Static Load Testing

Static load testing is crucial in understanding how soil behaves under planned loads in real-world conditions. By subjecting the soil to known loads, engineers can accurately assess its response and behavior, providing valuable foundation design and construction insights [52]. The static load testing method choice depends on various factors, such as project requirements and available resources. This study selects the Quick Maintained Load Test (QM Test), indicating a preference for a specific approach tailored to the project's needs. Lateral load tests were performed as static horizontal load tests following ASTM D-3966-90. Loads were applied gradually at the pile head using a reaction frame and hydraulic jack, simulating real-world lateral forces. Each loading step was maintained until displacement stabilized, with testing durations typically extending several hours per pile group. Deflections were recorded at incremental load levels until reaching ultimate resistance or significant displacement criteria.

During static load testing, lateral loads are applied to one side of the pile head to simulate real-world conditions. The resulting vertical deformation over time is carefully monitored and recorded. This deformation comprises two main types: elastic and plastic. Elastic deformation occurs due to the lateral displacement of the pile, while plastic deformation arises from the collapse of supporting soil near the pile's end or around it. By observing and analyzing these deformations, engineers gain valuable insights into the soil-pile interaction and the overall behavior of the foundation system.

Table 1. Drill pipe dimensions and properties [4]

#	Material	Dimensions		Thickness (mm)	Area (cm2)	Weight/ length ratio (kg/m)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elong %
		O.D. (mm)	I.D. (mm)						
110	S-135	5" (127)	108.61	9.195	34.03	29.02	1014.22	1099.71	23.1
135	S-135	5.5" (139.7)	121.30	9.169	37.60	32.59	1052.83	1101.78	20.0

Once the static load testing is completed, the obtained data undergoes interpretation using various methods. Sharma, elasto-plastic, and Mazurkiewich methods are commonly used for interpreting static load test data [1]. These methods give engineers a deeper understanding of the soil's response to applied loads, including its stiffness, strength, and deformation characteristics. By analyzing the test data through these methods, engineers can make informed decisions regarding foundation design, ensuring the structural integrity and stability of the entire system. Overall, static load testing plays a critical role in the design and construction of pile foundations by providing valuable data on soil behavior under load. Integrating advanced testing methods and rigorous data interpretation techniques enhances engineers' ability to accurately assess foundation performance, leading to more reliable and resilient civil engineering structures.

3. Methodology

The research methodology employed in this study involved a meticulous approach to evaluating the performance of a pile group foundation through rigorous load testing [53], [54]. The foundation was intricately designed with a triangular layout, comprising eight piles within each group strategically positioned at varying distances from one another, ranging between 2.5D and 3D. In this study, D refers to the pile diameter (6 cm). Thus, pile spacing of 2.5D and 3D corresponds to center-to-center distances of 15 cm and 18 cm, respectively.[55]. To ensure the structural integrity and cohesion of the foundation, the ends of each pile were rigidly tied at the top using 45 × 45 × 2 mm L-profile steel connectors. These connectors functioned as a pile cap, maintaining equal spacing and ensuring that the group acted as a unified structural system. By preventing relative displacement among piles, the L-profiles enhanced rigidity and improved the accuracy of lateral load transfer simulation.

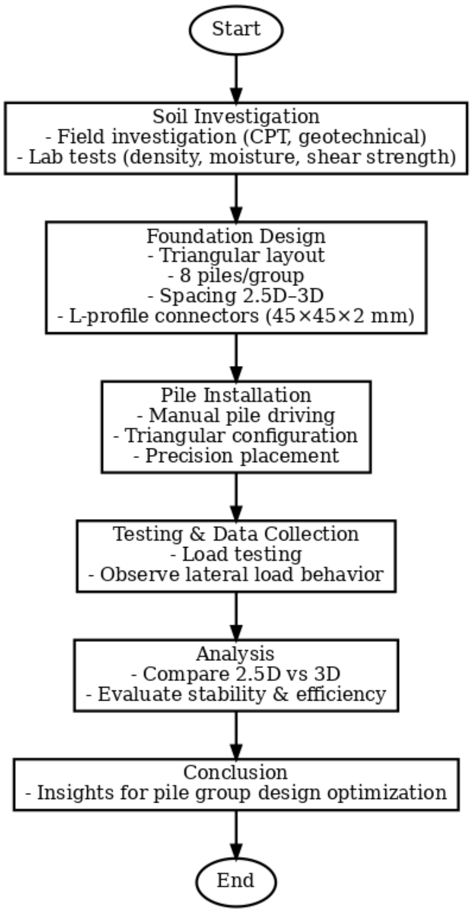

Fig. 4. Research methodology flowchart

Before initiating the installation process, an exhaustive soil investigation was conducted, employing a comprehensive blend of field and laboratory techniques. Field investigations encompassed cone penetration testing and various geotechnical methods aimed at precisely mapping out soil layers and delineating their physical and mechanical attributes. These field assessments provided crucial initial soil composition and behavior data. Cone penetration tests (CPT) were conducted to depths of 10 m, capturing the profile of soft organic clay layers. Soil sampling for laboratory testing was carried out at 3.5–4 m depth, corresponding to the layer where piles were embedded and lateral resistance was mobilized.

Following the field investigations, meticulous laboratory tests were conducted on soil samples collected, supplementing the data obtained from the field and offering a more detailed and comprehensive analysis of the soil's characteristics. These laboratory tests included assessments of soil density, moisture content, shear strength, and other pertinent parameters, ensuring a thorough understanding of the site's soil conditions. This comprehensive approach to soil investigation ensured that the foundation's design and installation process was tailored to suit the project site's specific soil properties and engineering requirements, thereby enhancing the overall reliability and performance of the pile group foundation.

The installation of the group pile foundation involved manual pile driving, leveraging human labor for precision and control. Eight piles were driven into the ground in a triangular configuration at each designated testing point. The triangular configuration with eight piles was selected because it provides balanced load distribution, minimizes pile interaction, and represents an efficient group arrangement compared to linear or square layouts. The distances between the piles were deliberately varied at each testing point, starting at 2.5D at the initial testing point and gradually extending to 3D at subsequent points. This deliberate variation in pile spacing was a critical aspect of the experimental setup, allowing for the systematic assessment of the foundation's response under various geometric configurations and loading conditions.

Manual pile driving was performed with controlled hammering to maintain consistent penetration depth and vertical alignment. Repeated measurements and markings ensured that all piles reached the same final length (4.0 m) and were aligned within the triangular layout, minimizing installation variability. The manual pile driving process ensured meticulous control over the installation, enabling precise placement and alignment of the piles within the designated triangular configuration. This meticulous approach was essential for maintaining the integrity and cohesion of the foundation, ensuring that it would function effectively as a unified structural element.

Overall, the intentional variation in pile spacing and manual pile driving facilitated a thorough evaluation of the foundation's response to different loading conditions, providing valuable data and insights into its structural behavior and stability. This comprehensive experimental setup informed future design considerations and enhanced the overall reliability of pile group foundations in similar real-world applications. The analysis employed Broms' analytical method for baseline capacity estimation, while lateral load test results were interpreted using Sharma, Elasto-Plastic, and Mazuerkiwicz methods**.** Broms' method was adopted as a baseline because it is a well-established analytical approach for estimating lateral pile capacity in cohesive soils, providing conservative estimates suitable for design. For interpreting lateral load test results, three methods—Sharma, Elasto-Plastic, and Mazuerkiwicz—were selected because they represent different assumptions regarding soil–pile interaction and displacement criteria, thus enabling a broader evaluation of the experimental results. Numerical methods such as finite element analysis was not applied, considering the study's focus on correlating experimental field data with simple but robust analytical models.

4. Results and Discussion

4.1 Testing of the Original Soil's Physical and Mechanical Properties

Laboratory testing was conducted on soil samples obtained from two points at a depth of 3.5 – 4 m at the site. This depth was chosen because it represents the soft organic clay layer directly influencing pile-soil interaction under lateral loading. Testing soil from this critical layer ensured a realistic assessment of the pile foundation's lateral performance. Table 2 below presents the data on the soil's physical and mechanical properties obtained from laboratory testing. From this table, the average values of cohesion (c), unit weight (γ), and soil shear angle (ϕ) were determined to be 0.0583 kg/cm^2, 1.52 gr/cm^3, and 9.95°, respectively. The soil type was identified as organic clay with moderate to high plasticity. Laboratory direct shear tests were performed on undisturbed soil samples to determine cohesion (c) and friction angle (ϕ). These parameters were essential for both analytical calculations and interpreting field performance.

Table 2 presents a comprehensive overview of these properties, offering valuable data for analysis and interpretation. From the table, several key parameters can be derived. Firstly, the soil samples' moisture content (W), ranging from 78.977% to 86.187%, with an average of 82.58%. The soil exhibited a high average moisture content of 82.58%**,** which significantly reduced its shear strength. This condition increased the potential for large lateral displacements and highlighted the importance of testing pile groups in such challenging tropical soil environments.

The soil samples' unit weight (γ), with values of 1.509 gr/cm^3 and 1.532 gr/cm^3 for Sample I and Sample II, respectively, resulted in an average unit weight of 1.52 gr/cm^3. This parameter is essential for understanding the density and compactness of the soil, providing insights into its load-bearing capacity and stability. The specific gravity (Gs) of the soil, determined to be 2.490 for Sample I and 2.452 for Sample II, with an average value of 2.47, offers further insights into the density and composition of the soil particles. This parameter is crucial for evaluating soil composition and identifying any variations in particle characteristics.

Table 2. Laboratory test results of soil's physical and mechanical properties

Soil Parameter	Sample I	Sample II	Average
Moisture Content (W)	86.187%	78.977%	82.58%
Unit Weight (γ)	1.509 gr/cm^3	1.532 gr/cm^3	1.52 gr/cm^3
Specific Gravity (Gs)	2.490	2.452	2.47
Liquid Limit (LL)	55.012%	55.012%	
Plastic Limit (PL)	34.641%	31.139%	
Plasticity Index (IP)	20.371%	23.873%	
Cohesion (c)	0.0654 kg/cm^2	0.0512 kg/cm^2	0.0583 kg/cm^2
Shear Angle (ϕ)	9.890°	10.000°	9.945°

The plasticity index (IP), calculated as the difference between the liquid limit (LL) and the plastic limit (PL), provides information on the soil's plasticity and its ability to undergo deformation without cracking. With values of 20.371% for Sample I and 23.873% for Sample II, the average plasticity index indicates moderate to high plasticity in the soil, suggesting its potential for deformation under load. The soil samples' cohesion (c), determined to be 0.0654 kg/cm^2 for Sample I and 0.0512 kg/cm^2 for Sample II, resulted in an average cohesion of 0.0583 kg/cm^2. This parameter represents the soil's ability to resist shear stress and is crucial in determining its stability and bearing capacity. The soil's shear angle (ϕ), with values of 9.890° for Sample I and 10.000° for Sample II, resulting in an average shear angle of 9.945°, provides insights into the soil's strength and resistance to shear deformation. This parameter is essential for assessing the soil's stability and behavior under different loading conditions.

Based on the cone penetration data, the average cone pressure ranged from 5.97 to 6.90 kg/cm^2, categorizing the consistency of the soil as soft. This characterization is crucial for understanding the soil's response to external loads and its overall suitability for construction purposes. Overall, the comprehensive analysis of the soil's physical and mechanical properties provides valuable insights into its behavior and stability, informing further engineering considerations and ensuring the successful design and implementation of construction projects.

4.2 Comparison of Lateral Bearing Capacity

The lateral bearing capacity of the pile group foundation with a triangular configuration obtained analytically using the Broms Method is compared with the lateral bearing capacity obtained from the interpretation of field lateral load testing data, as shown in Table 3 below. It is observed that the lateral bearing capacity of the pile group foundation, interpreted from the field lateral load testing data, varies across the three interpretation methods, ranging from lower to near, and even exceeding, the analytical lateral bearing capacity obtained using the Broms Method for both pile groups with 2.5D and 3D spacing. Analytical group pile capacity was estimated by multiplying single pile capacity by *n* (number of piles). However, field results demonstrated efficiency factors below and above 100%, indicating that pile interaction and spacing strongly influenced load sharing, rather than equal distribution among piles. Consequently, it can be concluded that the pile group foundation with a 3D spacing between piles exhibits a higher lateral bearing capacity compared to the 2.5D spacing.

Table 3. Comparison of Lateral Bearing Capacity in Pile Groups

No	Pile Spacing	Broms (Kg)	Dimensions			Average Interpretation (Kg)
			Sharma (Kg)	Elasto-Plastic (Kg)	Mazuerkiwicz (Kg)	
1	2.5 D	135.667	120	128	202	150
2	3 D	244.201	145	260	262	222.33

The results presented in Table 3 demonstrate significant differences in the lateral bearing capacity values derived from various interpretation methods, including those proposed by Sharma, the Elasto-Plastic approach, and Mazuerkiwicz, in comparison with the analytical solution of Broms. It is evident that for both piles spacing conditions (2.5D and 3D), the field-based interpretations consistently yield a wide range of values, some of which are lower than Brom's analytical prediction, while others exceed it. For instance, at a spacing of 2.5D, the capacity derived from Sharma's interpretation (120 kg) falls below Brom's value (135.667 kg), whereas the Mazuerkiwicz method predicts a substantially higher capacity (202 kg). Conversely, for the 3D spacing, the field interpretations, particularly the Elasto-Plastic (260 kg) and Mazuerkiwicz (262 kg) methods, provide values that exceed Brom's analytical calculation (244.201 kg), thereby suggesting enhanced performance with wider pile spacing.

These variations highlight two critical aspects. First, they emphasize the sensitivity of lateral capacity predictions to the interpretation method employed, given that each method is based on different assumptions about pile-soil interaction and the definition of ultimate failure. For example, the Elasto-Plastic and Mazuerkiwicz methods tend to account for larger displacement tolerances before declaring ultimate capacity, resulting in higher values. Second, the results clearly illustrate the role of pile spacing in improving group efficiency. The transition from 2.5D to 3D spacing consistently increases the average interpreted lateral bearing capacity from 150 kg to 222.33 kg, reflecting the reduction of pile-to-pile interaction effects at larger spacings.

From a practical design perspective, this comparative analysis underscores the necessity of integrating both analytical approaches and field test interpretations when evaluating the lateral performance of pile group foundations. While Broms' method provides a reliable baseline for conservative estimates, field-based interpretations capture the actual soil response under load and can better represent real-world conditions. The observed improvement in capacity with increased pile spacing further suggests that spacing optimization is a key factor in enhancing the lateral resistance of pile groups, which can be particularly beneficial in structures subjected to significant lateral forces, such as offshore platforms, high-rise buildings, or bridge foundations.

Table 4. Percentage of the load-bearing capacity of each pile within the group due to spacing variation

Pile	Single Pile (Kg)	Single Pile Capacity x n (Kg)	Group Pile Capacity (Kg)	Percentage (Kg)
2.5 D	26.8	214.4	150	69.96%
3 D	26.8	214.4	222.33	103.70%

Table 4 shows how pile spacing affects the efficiency of lateral load-bearing capacity in a pile group. At a spacing of 2.5D, the group capacity is 150 kg, which is only 69.96% of the theoretical single-pile total (214.4 kg). This means that when piles are placed too close together, the soil stress zones overlap, and the group cannot reach its full potential. At a spacing of 3D, the group capacity increases to 222.33 kg, reaching 103.70% of the theoretical capacity. This indicates that with wider spacing, the piles work more efficiently because soil interaction is reduced, and in some cases, the group can even resist more load than the sum of individual piles. In short, closer spacing reduces efficiency, while wider spacing improves the performance of the pile group under lateral

4.3 Soil Properties and Lateral Bearing Capacity Analysis

The laboratory testing conducted on soil samples obtained from two points at a depth of 3.5 – 4 m provided valuable insights into the physical and mechanical properties of the soil, revealing key parameters such as moisture content, unit weight, specific gravity, plasticity index, cohesion, and shear angle crucial for understanding its behavior and suitability for construction purposes [55], [56]. The significant moisture content averaging 82.58% indicated the presence of a considerable amount of water within the soil structure, influencing its various properties and behaviors. The unit weight and specific gravity values offered insights into the soil's density and composition, crucial for evaluating its load-bearing capacity and stability. At the same time, the plasticity index indicated moderate to high plasticity, suggesting its potential for deformation under load [57], [58].

Analyzing soil's physical and mechanical properties provided a robust foundation for further engineering considerations, ensuring successful design and implementation of construction projects [39], [59]. The comparison of the lateral bearing capacity of the pile group foundation obtained analytically using the Broms Method with that obtained from field lateral load testing data interpretation revealed significant variations, with lateral bearing capacity interpreted from the field data varying across different methods and pile spacing configurations [60]. These variations underscored the importance of considering real-world field conditions and testing data interpretations in evaluating the foundation's actual behavior under lateral loads, emphasizing the need to optimize pile group configurations for enhanced structural performance and stability.

The diverse results in lateral load-bearing capacity were attributed to different approaches used in each method to determine pile failure under lateral loads, further illustrated by the percentage load-bearing capacities for each pile within the group, with the 3D spacing configuration exhibiting the highest percentage increase. The analysis of the lateral bearing capacity data revealed that the 3D spacing configuration exhibited a higher lateral bearing capacity than the 2.5D spacing, indicating the importance of pile spacing in optimizing the foundation's performance. Overall, the comparison highlighted the importance of integrating analytical methods and field testing data interpretations to assess the foundation's behavior and optimize its design for improved performance and stability in real-world applications.

The results of this study show that pile spacing has a significant influence on the lateral bearing capacity of pile groups in soft soil. Similar to research by [61], who highlighted the significance of pile–cap connection flexibility, and [62], who proposed weakened section detailing for resilient behavior, the present results indicate that spacing and interaction effects largely govern the lateral response of pile groups in soft soil. Furthermore, the importance of integrated composite foundation systems as reviewed by [63] reinforces the need for combined analytical and experimental approaches.

5. Conclusions

After conducting in-depth analysis and calculations regarding the lateral bearing capacity of single-pile and group pile foundations with a triangular configuration and considering variations in pile spacing of 2.5D and 3D, several significant conclusions and recommendations have been drawn.

Firstly, the soil classification at the study site, according to the Unified Soil Classification System (USCS), belongs to the OH group, indicative of organic clay with moderate to high plasticity, underscoring the importance of understanding the soil's characteristics for foundation design. Moreover, identifying the average cone penetration pressure ranging from 5.97 to 6.90 kg/cm^2 highlights the soil's soft consistency, which must be considered in load-bearing capacity assessments.

Secondly, the results obtained from the loading tests on pile groups demonstrate a notable increase in efficiency when comparing pile groups with 2.5D and 3D spacing configurations. This finding emphasizes the significance of pile spacing in optimizing the efficiency and performance of group pile foundations. Thirdly, the study reveals that the spacing between piles within the group significantly influences the group's efficiency, with larger spacing resulting in higher bearing capacity. This underscores the importance of considering pile spacing as a crucial factor in building pile foundations. Sensitivity to pile spacing was evident: a shift from 2.5D to 3D spacing improved efficiency from 69.96% to 103.70%, underscoring spacing as a critical design parameter for pile groups under lateral loads.

While the experiments used scaled wooden piles, the observed trends—particularly the influence of spacing on group efficiency—are transferable to full-scale systems. However, scaling effects, material differences, and site-specific soil variability must be considered when applying these findings to large civil engineering projects. This study was limited to soft organic clay soils in Pontianak, wooden piles of 6 cm diameter, and triangular configurations with only two spacing variations. No numerical simulations were conducted. It is essential to acknowledge these limitations, particularly the focus on a specific soil type and limited variations in pile spacing configurations. Therefore, further research is recommended to explore a wider range of configuration variations to provide more comprehensive insights into optimizing the design and performance of pile group foundations, particularly in soft soil conditions. By considering soil characteristics and pile spacing in the design process, engineers can ensure the stability and effectiveness of pile foundations in real-world applications, ultimately contributing to safer and more reliable infrastructure development.

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