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Finite element analysis of bore pile foundation performance in silty soils of Gorontalo Indonesia

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ABSTRACT

The development of multi-story buildings on soft soils poses significant challenges in geotechnical design, particularly in tropical regions such as Gorontalo, Indonesia. This study investigates the behavior of bored pile foundations with varying diameters (0.60 m, 0.80 m, and 1.00 m) using the finite element method (FEM) via PLAXIS 2D. The simulation integrates in-situ soil investigation data, including SPT and laboratory tests, with a staged construction model to evaluate total deformation and stress distribution. The borehole profile revealed predominantly silty and silty sand layers with high compressibility and low bearing capacity, requiring precise analysis to mitigate settlement risks. Two loading stages were analyzed: (1) pile installation and (2) column load application with a maximum load of 3,363.3 kN per column. Results show that increasing pile diameter significantly reduces vertical displacement. During pile installation, the total deformation was 4.37 mm for the 0.6 m pile, 4.68 mm for the 0.8 m pile, and 4.19 mm for the 1.0 m pile. Under full column load, displacement reached 35.3 mm (0.6 m), 29.6 mm (0.8 m), and 29.4 mm (1.0 m), respectively. Total stress analyses revealed more concentrated stress beneath the smaller piles and more diffused stress in larger piles. The 1.0 m pile showed the best performance, but the 0.8 m pile offered a comparable result with better material efficiency. This study supports the use of FEM for foundation optimization and provides technical guidance for sustainable infrastructure in soft soil regions.

Keywords: bored pile; finite element method; PLAXIS 2D

1 Introduction

The design and performance evaluation of deep foundations remain central issues in geotechnical engineering, particularly for structures built on soft or variable soil conditions. Among various types of deep foundations, bored piles have gained significant importance due to their adaptability, load-bearing efficiency, and reduced environmental impact during construction [1], [2]. With rapid urbanization and the need for vertical infrastructure, the construction of multi-story buildings requires foundation systems capable of sustaining high axial and lateral loads while minimizing settlement.

Rock and soil engineering systems face escalating threats from climatic events and deep engineering complexities, necessitating a shift toward resilience-oriented frameworks [3]. In urban environments like Wuhan, external factors such as heavy rainstorms and internal factors like drainage disrepair have intensified flash flood risks for underground infrastructure [4]. Furthermore, soil behavior is often compromised by environmental cycles; for instance, freeze-thaw cycles and saline intrusion significantly affect the permeability and desiccation cracking of clay, which can induce geohazards [5]. Recent trends in biogeotechnics, such as microbially induced calcite precipitation (MICP), offer greener opportunities for soil stabilization, though large-scale application remains challenging [6].

Accurate prediction of foundation behavior depends on understanding the soil–structure interaction (SSI) and its complex stress–strain relationships. Numerical modeling, especially using the finite element method (FEM), offers a powerful tool for simulating soil–structure behavior and predicting pile responses under various loading conditions [7].

In Gorontalo, Indonesia, the construction of a six-story building poses specific geotechnical challenges due to the prevalence of silty and silty-sand deposits.

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These soil types are characterized by low shear strength, high compressibility, and elevated groundwater levels, which increase the risk of excessive settlement [8]. Traditional analytical approaches often oversimplify these conditions, neglecting nonlinear behavior and soil heterogeneity [9]. Therefore, the integration of FEM through PLAXIS 2D provides a means to simulate staged construction and evaluate stress redistribution accurately [10]. Although finite element analysis using PLAXIS 2D is a well-established tool in geotechnical engineering, its application to the site-specific behavior of bored pile foundations in Gorontalo's silty and silty-sand deposits remains limited. The local subsurface condition, which consists of loose to medium silty sand, intermediate silt layers, and shallow groundwater, presents distinct settlement-related challenges for multi-story building foundations. Therefore, this study contributes by integrating local SPT and laboratory test data into a staged FEM model to evaluate how bored pile diameter influences deformation and stress redistribution under construction and service loading conditions. This localized assessment provides practical design insight for optimizing bored pile foundations in tropical soft soil environments.

Moreover, FEM is not only useful in geotechnical analysis but has also proven effective in structural engineering contexts. For example, [11] applied the Concrete Damage Plasticity (CDP) model using FEM to evaluate the performance of wide beam-column joints under cyclic loading. Their study highlighted the sensitivity of simulation accuracy to parameters such as mesh size, dilation angle, and viscosity, which contributed to the realistic prediction of failure modes such as diagonal cracks, flexural failure, and torsional effects. This versatility reinforces FEM's value in integrated foundation-structure interaction studies. This study seeks to quantify the effects of pile diameter variations on foundation performance in silty soil conditions, providing design recommendations relevant to Indonesia's geotechnical context, especially for developing vertical infrastructure within educational campuses.

2 Data and Methods

This study was conducted at the building construction site in Kota Gorontalo. The study employed a quantitative methodology using a numerical approach based on the Finite Element Method (FEM) implemented through the PLAXIS 2D software. The primary objective was to analyze the behavior of bored-pile foundations under layered soil conditions at the study site, thereby developing a comprehensive understanding of bearing capacity, vertical deformation, and load-transfer mechanisms. The research framework was designed to integrate numerical simulation results with field-derived soil parameters, ensuring that the analysis was not only theoretically valid but also representative of in-situ conditions and applicable to real-world construction projects.

The research process began with the acquisition of secondary data from soil investigations, including the *Standard Penetration Test (SPT)* and laboratory testing. These data provided the physical and mechanical properties of the soil—such as unit weight, cohesion, internal friction angle, and elastic modulus—which were used as input parameters for the numerical model. These parameters are critical for defining soil behavior within the *Hardening Soil* model, which was selected for its ability to more accurately capture the nonlinear stress–strain response of both granular and cohesive soils. The use of advanced computational intelligence, such as integrating genetic algorithms into neural networks, has been shown to optimize structural performance predictions in tunneling contexts [12], reinforcing the value of robust numerical frameworks like the one used here.

A key focus of the study was the analysis of soil–pile interaction, modeled by representing the pile as an *embedded beam row (EBR)* element in *PLAXIS 2D*. This approach is important because the axial response of a pile is governed not only by end-bearing capacity but also by the mobilized shaft friction along its length. Therefore, variations in pile diameter (0.60 m, 0.80 m, and 1.00 m) were analyzed to evaluate differences in deformation behavior. Each model was assessed for safety using the *strength reduction method* to determine the factor of safety, and for serviceability by comparing the computed settlement against allowable limits.

The bored pile was modeled as an elastic material with a modulus of 24 GPa and Poisson's ratio of 0.3. The model domain was defined as 50 m wide and 35 m deep to minimize boundary effects. The staged construction procedure included two primary phases: (1) pile installation and (2) superstructure loading. The maximum design load per column was 3,363.3 kN, distributed at the pile head. Displacement contours and stress distributions were analyzed to assess deformation patterns and load transfer mechanisms.

3 Results and Discussion

3.1 Geological Condition

According to the *Geological Map of the Kotamobagu Sheet* [13], Gorontalo City lies within a low-lying plain predominantly composed of the Limboto Lake Deposits. This geomorphological unit exhibits a gently sloping terrain with gradients ranging from 0% to 5% and elevations between 10 and 12 meters above sea level, adjacent to the Tomini Bay coastline. Regionally, the stratigraphic sequence of the study area and its surroundings-arranged from the oldest to the youngest-comprises the Bone Diorite Formation (Tmb), the Pinogu Volcanic Rocks

Formation (TQpv), and the Limboto Lake Deposits (Qpl).

The Bone Diorite Formation (Tmb) consists of quartz diorite, granodiorite, and granite, representing the intrusive basement rocks that form the foundation of the region. Overlying this unit, the Pinogu Volcanic Rocks Formation (TQpv) is composed of tuff, lapilli tuff, breccia, and andesitic lava, signifying intense volcanic activity during the late Tertiary to Quaternary periods. The uppermost Limboto Lake Deposits (Qpl) comprise gray claystone interbedded with fine- to coarse-grained sandstone and local gravel layers, occasionally containing plant remnants and lignite. These lacustrine deposits are weakly consolidated, with an estimated thickness of about 94 meters.

Structurally, Gorontalo is traversed by a major southeast–northwest trending strike-slip fault, extending from the Modelomo coast in the south to Molosipat in the north. This tectonic feature plays a critical role in shaping the regional geomorphology and subsurface conditions, influencing both groundwater flow and the geotechnical characteristics of the lowland deposits.

3.2 Soil Characterization

The borehole log indicated stratified deposits dominated by sandy silt (sML) and silty sand (SM) extending to 30 m depth. The groundwater table was identified at a depth of 3.5 m. The increasing friction angle with depth suggests progressive densification. However, the presence of loose silty sand near water bodies can lead to liquefaction hazards during seismic events, where pore water pressure rises and effective shear strength is lost [14]. Evaluating the factor of safety through SPT N-values is critical in such transition zones [14].

Soil properties used in the FEM model are summarized in **Table 1**. The soil profile revealed silty deposits with varying density and friction angle, indicating moderate to weak bearing capacity. The increasing friction angle with depth (from 28° to 33°) suggests progressive densification and a stiffer response at deeper layers. High water content in the upper silt layer contributes to lower effective stress and higher potential settlement [15]. These findings align with previous regional studies, which reported similar geotechnical conditions in lacustrine silts across northern Sulawesi.

Table 1. Soil Properties

Description	Symbol	Depth (m)			
		0 – 10	**10 - 15**	**15 - 22**	**22 - 30**
		Silty Sand (loose)	**Silty Sand (Medium)**	**Silt (Medium)**	**Silty Sand (Medium)**
Material Model	-	Hardening Soil	Hardening Soil	Hardening	Hardening Soil
Drainage Type	-	Drained	Drained	Undrained B	Drained
N-SPT$_{average}$	$N_{60'}$	6.80	10.70	16.00	24.50
Unit Weight, kN/m^3	γ_{sat}	17.05	15.58	13.44	18.70
	γ_{unsat}	14.63	13.05	11.42	17.15
Cohesion, kN/m^2	c_u	22.41	23.39	27.11	21.70
	c_u'	14.94	15.59	18.07	14.47
Angle of Internal Friction, ^{o}	φ	28.39	29.64	-	33.01
	φ'	18.93	19.76	-	22.01
Modulus Young, kN/m^2	E	25,000.00	30,000.00	25,000.00	50,000.00
	E_{50}	16,667.00	20,000,00	16,667.00	33,333.00
Poisson Ratio	υ	0.20	0.20	0.20	0.20

3.3 Finite Element Simulation Results

Simulation using PLAXIS 2D software, based on the finite element method, aims to model the response of bored pile foundations under vertical and lateral loads. The modeling includes input of soil parameters from borehole investigation data, geometric modeling of the pile, loading scenarios, and the analysis of resulting deformation and stress distribution. Simulation using PLAXIS 2D software, based on the finite element method, aims to model the response of bored pile foundations under vertical and lateral loads. The modeling includes input of soil parameters from borehole investigation data, geometric modeling of the pile, loading scenarios, and the analysis of resulting deformation and total stress.The simulation was divided into two main stages:

1. Foundation construction (pile installation)
2. Superstructure (column) load application

Vertical and horizontal deformation values were obtained from PLAXIS 2D with pile diameter as the primary variable. The resulting total deformation represents cumulative changes throughout the construction sequence. The maximum column load applied in the simulation was 3,363.3 kN. **Table 2** presents the detailed deformation results for each pile diameter variation.

Table 2. Deformation of bored pile foundation

Pile Diameter (m)	Construction Stage	Displacement (m)			
		Vertical	Horizontal		Total
			Min.	Max.	
0.60	Foundation Construction	-4.369E-03	-7.512E-04	7.167E-04	4.37E-03
	Column Load Application	-3.527E-02	-6.978E-03	7.550E-03	3.53E-02
0.80	Foundation Construction	-4.674E-03	-7.462E-04	7.312E-04	4.68E-03
	Column Load Application	-2.962E-02	-4.836E-03	5311E-03	2.96E-02
1.00	Foundation Construction	-4.187E-03	-5.841E-04	5.506E-04	4.19E-03
	Column Load Application	-2.943E-02	-3.998E-03	4.373E-03	2.94E-02

1. Foundation Behavior During Installation

During the foundation construction stage, the simulation represents the phase of bored pile insertion into the soil before any vertical load is applied. The deformation pattern appears concentrated near the pile head and propagates radially downward, forming a basin-like displacement profile.

a. For a 0.6 m diameter pile, the total deformation reached 4.37 mm.
b. The 0.8 m diameter pile experienced slightly more deformation at 4.68 mm.
c. However, the 1.0 m diameter pile showed a reduction to 4.19 mm.

These results indicate that deformation does not increase linearly with pile diameter. The 0.8 m pile may have induced more localized stress during insertion, while the 1.0 m pile distributed the load more evenly due to its larger surface area.

2. Behavior Under Column Load

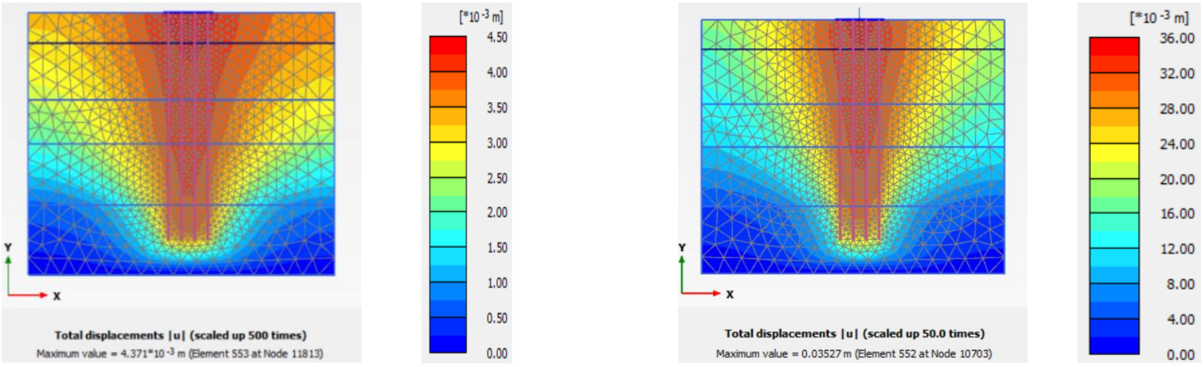
After pile installation, the column load is applied. This stage is crucial in evaluating the foundation's ability to withstand service loads.

a. The 0.6 m pile experienced the greatest displacement of 35.3 mm, indicating potential settlement concerns.
b. The 0.8 m pile reduced the displacement to 29.6 mm, showing improved interaction with the surrounding soil.
c. The 1.0 m pile resulted in the lowest total displacement of 29.4 mm, demonstrating the best performance in limiting settlement.

These deformation patterns align with the load transfer theory which suggests that larger diameters improve load dispersion [16]. This behavior is further influenced by interparticle behavior and mineralogy; for example, rounded particles with strong mineralogy are more likely to produce an arching effect compared to angular particles with weaker minerals [17]. Such soil-structure interaction nuances are vital for assessing stability in complex hydrological conditions, as seen in field studies of bridge pier scour where pier dimensions correlate strongly with scour hole characteristics [18].

Overall, increasing pile diameter leads to better load transfer efficiency and reduced vertical displacement. This affirms the effectiveness of using larger bored piles in soft to medium soils as found in the Gorontalo region.

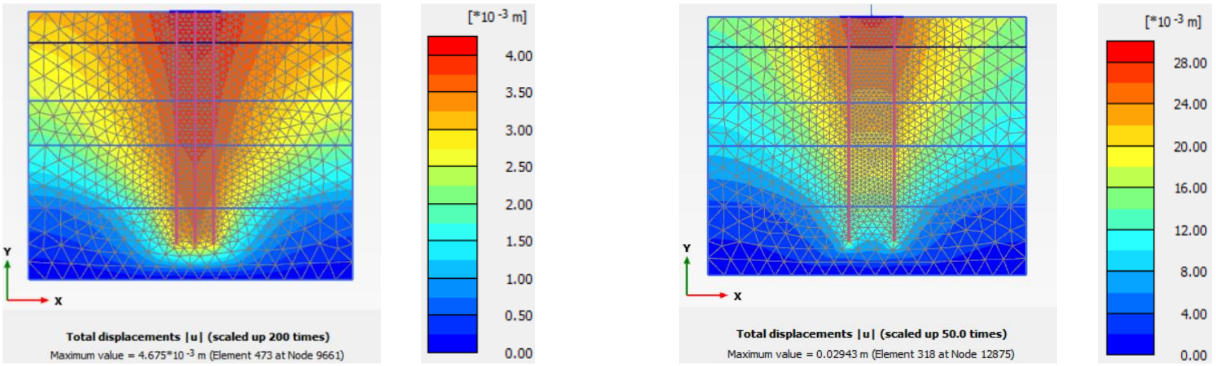
The FEM simulations illustrated distinct deformation patterns around the pile shaft and toe under both construction and service loading stages, as **Figure 1-3**.



a. Foundation Installation Phase

b. Column Load Application Phase

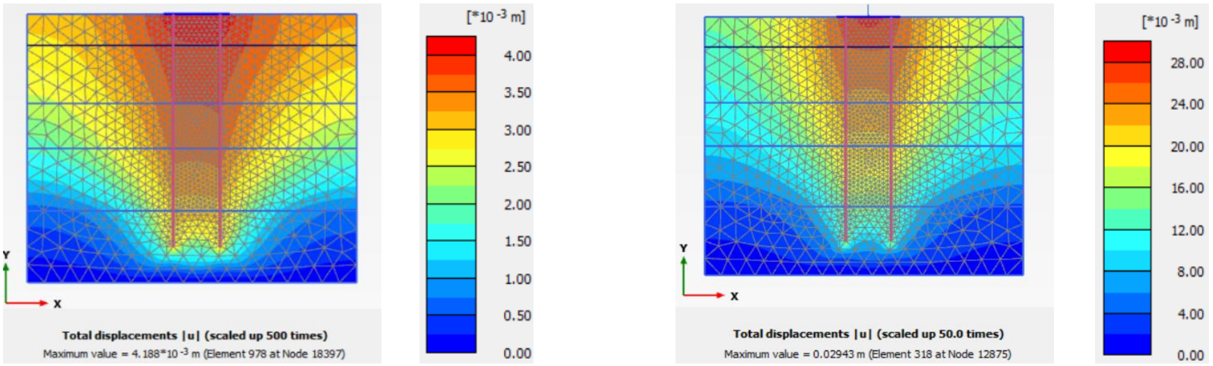
Figure 1. Behavior of Pile Foundation with Diameter 0.6 m



a. Foundation Installation Phase

b. Column Load Application Phase

Figure 2. Behavior of Pile Foundation with Diameter 0.8 m



a. Foundation Installation Phase

b. Column Load Application Phase

Figure 3. Behavior of Pile Foundation with Diameter 1.0 m

1. Total Deformation of Bored Pile with 0.6 m Diameter
   a. Foundation Installation Phase

      During the initial stage of pile installation, the simulation results indicate that total deformation is concentrated near the pile head and gradually propagates downward. The displacement pattern resembles an inverted basin, suggesting stress redistribution into the soft surrounding soil. The maximum vertical deformation reached approximately 4.37 mm, indicating significant interaction between the pile and the underlying silty clay layers.

   b. Column Load Application Phase

      Upon the application of vertical loads from the column, deformation increases substantially. The pile tip experiences deeper settlement while the upper section shows lateral movement, demonstrating combined axial and bending responses. The maximum total deformation recorded in this stage is 35.3 mm.

2. Total Deformation of Bored Pile with 0.8 m Diameter
   a. Foundation Installation Phase

      The 0.8 m pile shows a slightly larger deformation than the 0.6 m during the foundation installation phase, reaching 4.68 mm. This increase is attributed to greater soil displacement during drilling, though the pile's larger area provides more resistance at depth. The stress contours reveal better distribution compared to the smaller pile.

   b. Column Load Application Phase

      When subjected to column loads, the 0.8 m pile exhibits improved performance compared to the 0.6 m pile, with total deformation reduced to 29.6 mm. The deformation is more uniformly distributed along the shaft, indicating better mobilization of shaft resistance and interaction with stiffer soil layers at depth.

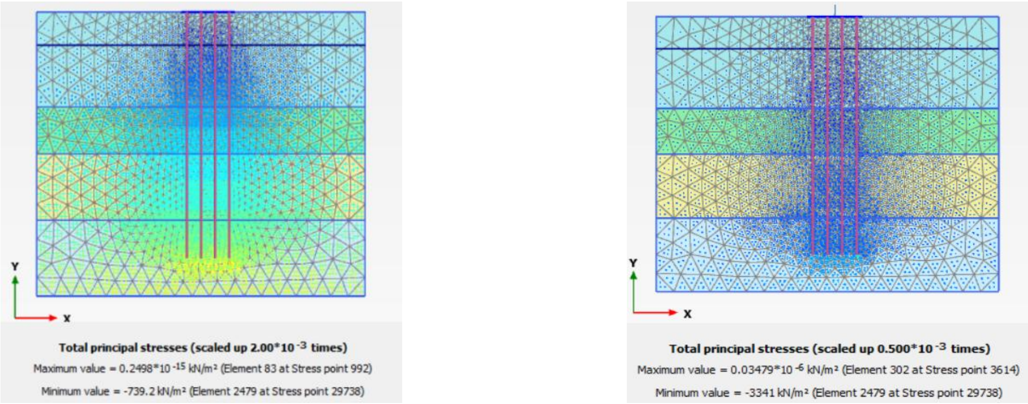
3. Total Deformation of Bored Pile with 1.0 m Diameter
   a. Foundation Installation Phase

      The largest pile diameter shows the least deformation during the foundation phase, with a total of 4.19 mm. This demonstrates the benefit of increased stiffness and load transfer capability. The stress contours and displacement vectors suggest that the soil reacts more passively, spreading the load over a wider area.

   b. Column Load Application Phase

Under full structural load, the 1.0 m pile records the smallest deformation among the three variants—only 29.4 mm. This indicates superior structural stability and confirms the efficiency of larger-diameter bored piles in mitigating settlement in silty soil conditions.

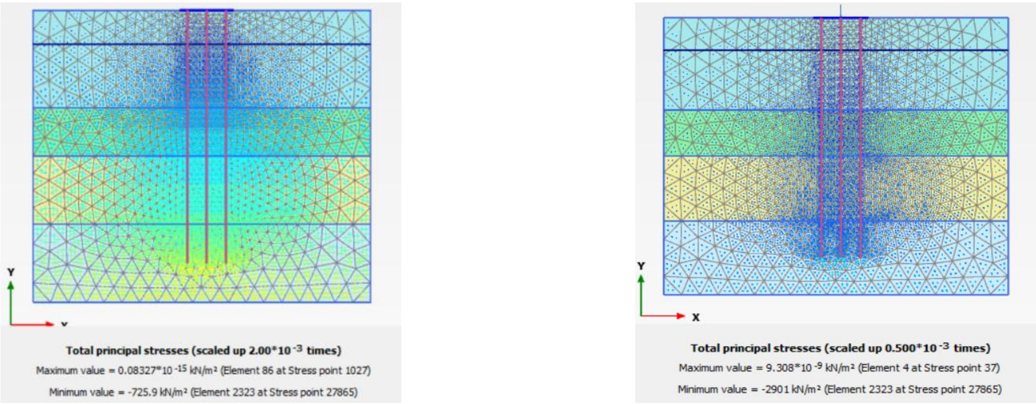
Figures 4 through 6 illustrate the total stress distribution occurring in group pile foundations with varying diameters of 0.6 m, 0.8 m, and 1.0 m during two construction stages: the foundation installation and the application of vertical loads from the column.



a. Foundation Installation Phase

b. Column Load Application Phase

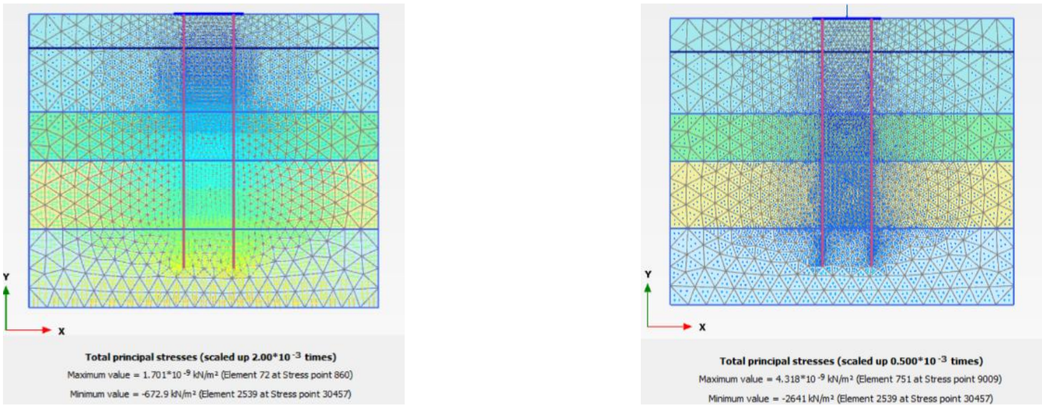
Figure 4. Total Stress Analysis of Group Pile with Diameter 0.6 m



a. Foundation Installation Phase

b. Column Load Application Phase

Figure 5. Total Stress Analysis of Group Pile with Diameter 0.6 m



a. Foundation Installation Phase

b. Column Load Application Phase

Figure 6. Total Stress Analysis of Group Pile with Diameter 0.6 m

1. Total Stress in 0.6 m Diameter Pile
    a. Foundation Installation Phase

    In the smallest diameter pile, the stress concentration is observed to be high around the pile shaft and tip. The vertical stress is focused mainly beneath the pile base, extending in a narrow and deep profile into the lower strata, which indicates a greater reliance on end bearing behavior due to the limited shaft area.

    b. Column Load Application Phase

    Once the structural load is applied, the stress increases significantly and extends more laterally, though still remaining relatively concentrated. The smaller diameter contributes to higher stress intensity within a confined zone, increasing the potential for local failure if the soil is weak.
2. Total Stress in 0.8 m Diameter Pile
    a. Foundation Installation Phase

    The stress contours show more uniform distribution along the shaft compared to the 0.6 m pile. There is a wider spread of stress beneath the base, indicating a better combination of shaft and end bearing resistance.

    b. Column Load Application Phase

    With the applied column load, the stress is distributed both downward and radially outward, forming a balanced transition zone. This suggests improved soil-pile interaction, reducing the possibility of overstressing the soil at a singular point.
3. Total Stress in 1.0 m Diameter Pile
    a. Foundation Installation Phase

    The largest pile exhibits the most favorable stress distribution, where the stress is diffused over a larger area both along the shaft and at the tip. The contour lines are broader and less steep, signifying lower stress gradients in the surrounding soil.

    b. Column Load Application Phase

    Under maximum loading, the stress propagates deeper and wider compared to the smaller piles, but with lower intensity. This indicates efficient load transfer with minimal risk of bearing failure or excessive settlement. The results confirm the structural advantage of larger diameter piles in spreading the load more effectively and uniformly.

The deformation contour maps revealed that displacement was concentrated near the pile head and gradually dissipated radially outward. This pattern aligns with the *load transfer theory* of Poulos [16], which suggests that larger diameters improve load dispersion and reduce stress concentration at the pile tip. Similar findings were noted by [19], who emphasized that the interaction between pile stiffness and surrounding soil modulus governs the settlement behavior of deep foundations. The results further support the elastic–plastic deformation theory proposed by Randolph and Wroth, which predicts that increasing pile diameter reduces mobilized shaft friction while improving end-bearing efficiency in cohesive soils [20].

Stress contours indicated higher concentration at the pile base, especially in the smaller-diameter pile. As diameter increased, stress diffused over a wider area, reducing localized strain. This observation is consistent with [21], who demonstrated through FEM simulations that larger-diameter piles experience lower bending moments and more uniform axial stress profiles. Similarly, a study by [22] confirmed that in silty soil conditions, pile diameter optimization can improve load-sharing ratios between shaft and toe resistance, mitigating long-term settlement.

3.4 Comparative Analysis and Theoretical Correlation

Comparing simulation outcomes across diameters reveals a clear trade-off between structural performance and material efficiency. Although the 1.0 m pile exhibited the smallest settlement, the difference compared with the 0.8 m pile was marginal, less than 0.5 mm. Therefore, the 0.8 m diameter pile can be considered a more efficient option because it provides comparable deformation performance with lower material demand. The comparison also indicates a non-linear relationship between pile diameter and displacement. Increasing the pile diameter from 0.6 m to 0.8 m resulted in a more substantial reduction in displacement, whereas the increase from 0.8 m to 1.0 m produced only a slight additional improvement. This pattern suggests a diminishing return effect rather than a specific logarithmic correlation. This interpretation is broadly consistent with the theoretical understanding of pile behavior proposed by Poulos and Davis [23], in which pile geometry affects load transfer and settlement response.

The disturbance caused by pile installation can affect soil sensitivity. Studies on clay formations suggest that strength recovery models (thixotropy) are essential for predicting the stability of surrounding soil after construction disturbance [24]. The higher the sensitivity and density, the stronger the thixotropy, whereas higher moisture content tends to weaken this effect [24]. Moreover, the staged-construction model effectively captured the influence of sequential loading and soil stress redistribution, improving predictive accuracy over static loading analyses [25].

The findings of this study are also consistent with recent works emphasizing the importance of site-specific calibration. [26] and [27] highlighted the necessity of integrating laboratory test data into FEM calibration to achieve realistic deformation predictions. Recent advancements by [28] and [29] further demonstrated that incorporating nonlinear stiffness degradation improves model reliability, particularly in silty soils with varying moisture content. Therefore, the present model's ability to simulate both immediate and long-term deformations provides a robust analytical framework for tropical geotechnical conditions.

4 Conclusion

The finite element simulation demonstrated that pile diameter has a significant influence on the performance of bored pile foundations in silty and silty-sand soil conditions in Gorontalo, Indonesia. During the foundation construction stage, the total deformation values were 4.37 mm, 4.68 mm, and 4.19 mm for pile diameters of 0.60 m, 0.80 m, and 1.00 m, respectively. Under the column load application stage, the total displacement decreased from 35.3 mm for the 0.60 m pile to 29.6 mm for the 0.80 m pile and 29.4 mm for the 1.00 m pile. These results indicate that increasing pile diameter can reduce settlement and improve stress distribution; however, the improvement from 0.80 m to 1.00 m was relatively small.

The 1.00 m diameter pile produced the lowest displacement and the most favorable stress distribution, confirming its superior structural performance. Nevertheless, the 0.80 m diameter pile provided comparable performance, with only about 0.2 mm greater displacement than the 1.00 m pile under column loading, while potentially requiring less material. Therefore, the 0.80 m pile may be considered an efficient alternative for balancing foundation performance and material use. The staged construction analysis also showed that FEM-based modeling using PLAXIS 2D can effectively represent deformation patterns and stress redistribution during pile installation and service loading. These findings provide practical guidance for bored pile diameter selection in multi-story building foundations constructed on silty soil deposits in Gorontalo and similar tropical soft soil regions.

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