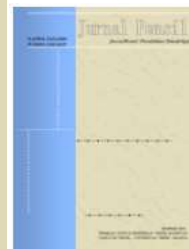


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## ANALYSIS OF THE EFFECT OF FOUNDATION DIMENSIONS ON THE BEARING CAPACITY AND SETTLEMENT OF PILE FOUNDATIONS FOR THE WTP SPAM KOBEMA BENGKULU BUILDING

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### Abstract

The Water Treatment Plant (WTP) in the Benteng Kobema Bengkulu Regional Drinking Water Supply System (SPAM), with a capacity of 380 Litres per Second, plays a crucial role in providing clean water to the community. This study aims to analyse the influence of dimensional variations on the bearing capacity and foundation settlement of the WTP building using the Poulos and Davis method, the Reese and Wright method, the Luciano Decourt method, and the finite element method. Based on the results of the Standard Penetration Test (SPT), the influence of variations in shape, namely square with dimensions of 300 mm, 400 mm, and 500 mm, as well as depths of 7m, 9m, 11m, and 13m, affects the bearing capacity and foundation settlement. This analysis compares the results of bearing capacity calculations and pile foundation settlement in WTP buildings using several different methods. The analysis results show that the bearing capacity, deflection magnitude, and smallest settlement are below the permitted settlement limit, i.e., less than 10% of the foundation dimensions. The comparison between static and numerical methods, or the Bearing Capacity Ratio (BCR) approaching 1, is more efficient and safer. In this analysis, the BCR value closest to 1 was obtained for a 500 mm foundation using the Reese and Wright method at a depth of 9 m, yielding a bearing capacity of 312.04 tonnes for a single pile and 207.69 tonnes for a pile group.

**Keywords:** Bearing Capacity, Settlement, Field Foundation

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## Introduction

The Water Treatment Plant (WTP) is one of the essential buildings in the Benteng Kobema Bengkulu Regional Water Supply System. This building treats raw water into clean water that is safe for use (Ashuri, 2022). In the planning of WTP construction, the foundation plays a vital role in supporting the building above it by distributing the load into the ground (Lestari et al., 2024; Maulana et al., 2023; Mochammad Nouval Diva Ramadhan et al., 2022). Basically, foundations serve as the base that supports buildings and distributes the building's load evenly to the ground. (M. Arpando Eko Wianto, 2024; Maulana et al., 2023; Muhammad Faris Aprizaldia, 2022; Prativi et al., 2022; Ridhayani et al., 2022; Yuslinda & Rani, 2025). In general, foundations fall into two major groups: deep foundations and shallow foundations. The selection of a particular foundation system is determined by structural requirements and the depth of the solid soil layer. (Azizi & Marhendi, 2023; Nanda Zulna Saputra, Vivi Bachtiar, 2025; Nurjanah, 2024; Rafidatul Hildayani et al., 2024).

This study primarily addresses the challenge of evaluating foundation stability and deformation characteristics to ensure the design meets both safety standards and efficiency requirements. Given the significant risks associated with the Mentawai Pagai Megathrust subduction zone, assessing the settlement and bearing capacity of structural foundations is a critical necessity (Fahrezi et al., 2025; Litman, 2021; Misliniyati et al., 2024; Nainitania & Darmawan, 2020). This study examines the extent to which variations in pile dimensions and embedment depth dictate the foundation's settlement behavior and ultimate load-bearing capacity (Yanita et al., 2025).

In the Benteng Kobema Regional SPAM project, the WTP foundation type is a pile foundation. Pile foundations are a type of foundation in which piles are installed until they reach a hard soil layer (Mardianti et al., 2022). The fundamental role of this foundation system is to redistribute structural loads to deeper, more competent soil layers that can provide adequate support (Khusnah et al., 2021). Deep pile foundations are implemented when the surface soil strata lack the requisite shear strength and bearing capacity to safely sustain the superstructure's loads (Nugroho et al., 2022).

Selecting methods for analyzing bearing capacity and pile foundation settlement depends heavily on the availability of soil data obtained from the research site, which can be in the form of Cone Penetration Test (CPT) or Standard Penetration Test (SPT) data. SPT is a dynamic penetration test that provides an overview of soil resistance to pile driving, while CPT provides more detailed quantitative data through resistance measurements at the cone tip (Yoshi Wiweka PP & Setyanto, 2024) (Rus et al., 2021). In this study, bearing capacity and foundation settlement analysis were performed using SPT data (Tham & Manh, 2021).

Bearing capacity and foundation settlement analyses were conducted using several methods, namely the Poulos and Davis (1980) method, the Reese and Wright (1977) method, the Luciano Decourt (1987) method, and the finite element method. These methods were selected based on available calculations and data and yielded accurate, conservative results for the soil and building conditions (Ningsih & Setiawan, 2023).

Ramadhan et al. (2022) conducted research comparing bearing capacity values obtained using static methods with those obtained using dynamic methods, namely the Pile Driving Analyzer (PDA), to determine whether the bearing capacity of several methods could approximate that of field-testing using PDA. In this study, bearing capacity values were compared using static and numerical methods to determine whether the static method could approximate the numerical method's bearing capacity (Prilia et al., 2021).

Analysis of bearing capacity with varying dimensions shows that the larger the pile's cross-sectional area, the greater the foundation's bearing capacity (Gazali et al., 2024). Foundations with a square cross-section have a greater bearing capacity than foundations with a circular cross-section (Ramadhan et al., 2022). A comparison of static and numerical methods was conducted to assess

the foundation's efficiency and safety. Other studies show that dynamic methods, such as the Pile Driving Analyzer (PDA), can approximate field test results (Sari et al., 2023). Hence, a combination of static, dynamic, and numerical methods is essential for the optimal and safe planning of pile foundations.

### Research Methods

This research was conducted at the Benteng Kobema Regional SPAM construction site located in Lubuk Puar Village, Merigi Sakti District, Central Bengkulu Regency, Bengkulu Province, as shown in Figure 1. At the time of the research, the Benteng Kobema Regional SPAM WTP building had been constructed with a planned square pile foundation, measuring 400 mm by 400 mm and 9 meters deep. There were four soil sampling points (SPT) at the research site.

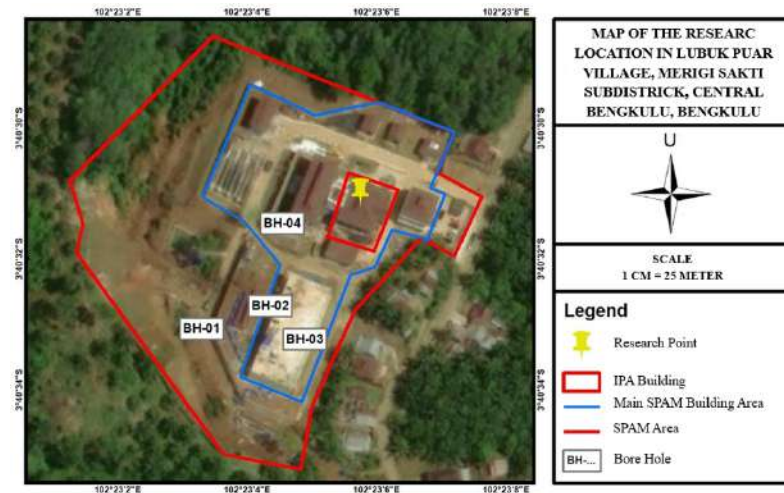


Figure 1. Map of Research Location

Pile foundations are structures that distribute a building's load evenly to a layer of hard soil at a specified depth. This structure is essential in heavy-load constructions, such as multi-story buildings or bridges, especially on soft or unstable ground. The WTP building was designed with pile foundations because SPT test results from the soil investigation indicated that a hard soil layer was at a depth of 9 meters.

Figure 2 shows the foundation plan of the WTP building, indicating that the foundation consists not only of a single pile but also of a group pile foundation. The choice between single piles and group piles depends heavily on several key factors, particularly structural load, soil conditions, type, efficiency, and design economics (Agustina, 2022).

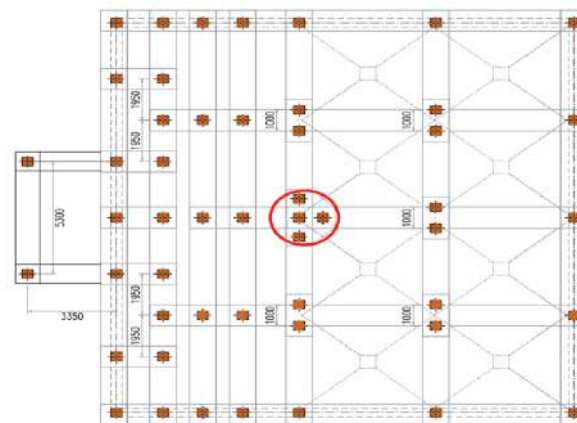


Figure 2. Foundation Plan and Foundation Points Receiving the Greatest Load

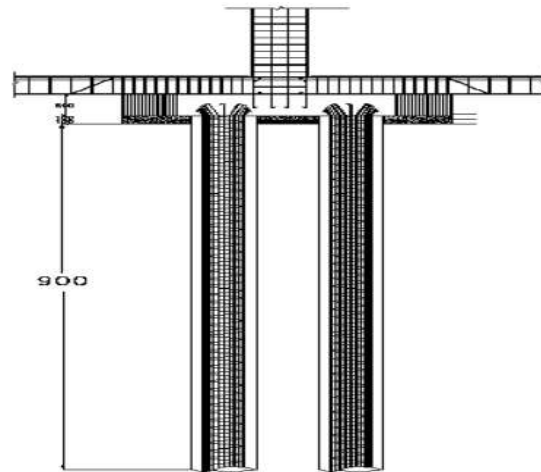


Figure 3. Pile Foundations Detail

The analysis investigated the correlation between foundation geometry and performance by varying the dimensions and depths of square footings. Figure 3 provides a detailed cross-sectional view of the 500 mm circular pile foundation group at a 9 m depth used in this assessment.

The soil data presented is essential information for bearing capacity and foundation settlement analysis, including soil classification, layer depth, N-SPT value, undrained shear strength (Cu), soil unit weight ( $\gamma$ ), and internal friction angle ( $\phi$ ) as shown in Table 1. In this study, BH-04 SPT data were used, as shown in Figure 1.

Table 1. Soil Classification Data Based on SPT

Depth (m)	Soil Type	N-SPT	Cu	$\gamma$	$\phi$
0-2	Silty	6	3.6	19.3	20°
2-4	Silty Clay	5	3.0	18.5	25°
4-6	Silt	16	9.6	19.7	25°
6-8	Silt	37	22.2	20.5	25°
8-10	Silt	49	29.4	20.7	25°
10-20	Silt clay	50	30.0	20.6	25°

At the Benteng Kobema Regional SPAM building, the WTP building structure was modeled in SAP 2000 (Figure 4). The structure model consists of columns, beams, shear walls, and steel roof trusses. After structural modeling was completed in SAP2000, the next step was to perform a load analysis using the defined load patterns and types (Yusmar et al., 2021).

Following the standards set by **SNI 1727:2020**, the load analysis for this facility accounts for dead, live, and earthquake loads. The calculated dead load includes the weight of the structural components as well as all permanent additional loads (Irawan et al., 2024) (Gumelar Syah, Dedi Rutama, 2023).

After all loads were entered, the maximum load values acting on a single foundation point of the WTP building are shown in Figure 4 as follows:

- P (Axial Load) : 2360.396 kN
- Vx (Shear Force) : 210.756 kN
- Vy (Shear Force) : 0.571 kN
- Mx (Moment) : -0.515 kNm
- My (Moment) : -439.967 kNm

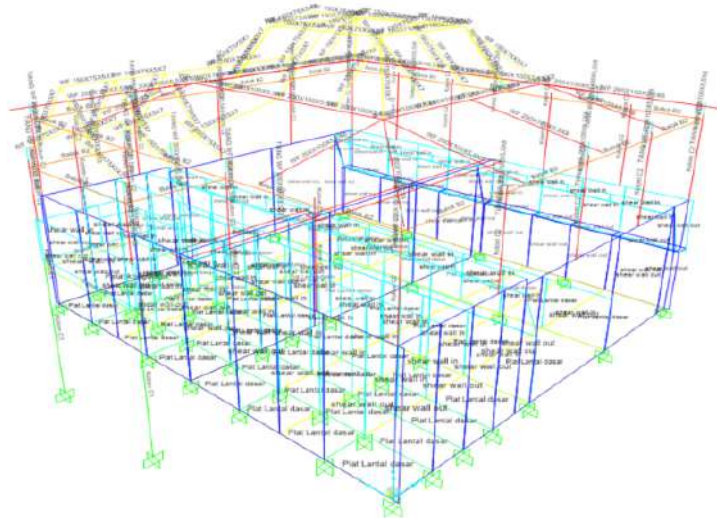


Figure 4. Building Structure Modelling of the WTP Building in SAP2000.

### Single Pile Bearing Capacity

Pile bearing capacity refers to the maximum load a pile foundation can support while ensuring that neither structural failure nor unacceptable settlement occurs (Mutia Suharlin Putri, Yayuk Apriyanti, 2018; Yelvi, Muchsin Farid Habibie, 2022).

SPT (Standard Penetration Test) data processing to obtain pile bearing capacity values can use the Equation from Poulos and Davis (1980) as follows:

$$Q_s = A_b \times P'_b \times N_q$$

$$Q_b = A_s \times P_o K_d \text{tg} \delta$$

$$Q_a = Q_b + Q_s$$

$$Q_a = Q_u / S.F$$

Where  $Q_b$  is the ultimate end resistance (tons),  $P_b'$  is the adequate vertical pressure at the base of the pile (tons/m<sup>2</sup>),  $N_q$  is the tip bearing capacity factor, depending on the angle of internal friction in the soil ( $\Phi$ ),  $Q_s$  is the ultimate wall friction resistance (tons), and SF is the safety factor (Azizi & Marhendi, 2023).

To determine the bearing capacity, this study adopts the Reese and Wright (1977) method, which correlates foundation strength with SPT results as shown below:

$$Q_p = 9 \times C_u \times A_p$$

$$Q_s = \alpha \times C_u \times P \times L$$

$$Q_u = Q_p + Q_s$$

Following the analytical framework established by Luciano Decourt (1987), the ultimate capacity of the single pile foundation was calculated using SPT-derived values and the equation below:

$$Q_u = [\alpha \times (\check{N}_p \times K)A_p] + \left(\frac{\check{N}_s}{3} + 1 \times A_s\right)$$

Where  $N_p$  is the average SPT value approximately 4D below the pile base and 4D above the pile base,  $A_s$  is the pile length from the surface base multiplied by the pile circumference ( $m^2$ ),  $N_s$  is the average N-SPT along the embedded pile,  $\alpha$  is the base coefficient, and  $\beta$  is the pile skin coefficient.

### **Group Pile Bearing Capacity**

To determine the total bearing capacity of a pile group, the individual capacity of a single pile must be integrated with the total number of piles and the group efficiency factor.

In accordance with the methodologies proposed by Poulos and Davis (1980), Reese and Wright (1977), and Luciano Decourt (1987), the total capacity for a group of piles is determined by the equation below:

$$Q_g = Q_a \times n \times E_g$$

$$Q_{ag} = Q_g / SF$$

Where  $Q_g$  is the group pile bearing capacity (tons),  $n$  is the number of piles, and  $E_g$  is the group pile efficiency.

### **Single Pile Settlement**

Following the evaluation of load-bearing limits, it is essential to quantify foundation settlement to guarantee that the structure remains within safe operational and stability thresholds.

Poulos and Davis (1980) provided the following estimates for the decline of the Tunggal pole:

$$S = \frac{Q \times I}{E_s \times D}$$

$$I = I_o \times R_k \times R_h \times R_\mu$$

Where  $Q$  is the working load (tons),  $E_s$  is the modulus of elasticity of the soil (tons/m<sup>2</sup>), and  $D$  is the diameter of the pile (m).

According to Reese and Wright (1977), the settlement of a pile foundation after receiving vertical loads will experience three types of settlement, as shown in the following equation:

$$S = S_s + S_p + S_{ps}$$

$$S_s = \frac{(Q_p + \alpha \times Q_s)L}{A_p \times E_p}$$

$$S_p = \frac{C_p \times Q_p}{D \times q_p}$$

Where  $S_s$  is the settlement due to axial deformation,  $S_p$  is the settlement due to the load at the end of the pile, and  $S_{ps}$  is the settlement of the soil layer along the foundation pile due to the load transferred through the pile.

Luciano Decourt (1987) calculated the group pile reduction using the following formula:

$$s = (K \times N - SPT \times A) / Q_u$$

Where  $K$  is the correction factor,  $A$  is the surface area, and  $Q_u$  is the ultimate bearing capacity.

### Group Pile Settlement

Pile foundation analysis often determines the allowable pile capacity based on settlement standards. Pile settlement is significantly influenced by the distribution of the applied load between the tip resistance and the shaft friction. If the pile's supported load is less than its end resistance, the settlement will likely be minimal (Mochammad Nouval Diva Ramadhan et al., 2022).

Poulos and Davis (1980) presented the following calculation for group pile Settlement:

$$S_g = \frac{q \times B_g \times I}{2 \times qc}$$

Where  $L_g$  and  $B_g$  are the width of the pile group, and  $qc$  is the end bearing capacity. Determining the group pole reduction proposed by Reese and Wright (1977) and Luciano Decourt (1987) is as follows:

$$S_g = S \times \sqrt{\frac{B}{D}} < 10\%D$$

Where  $S$  is the total settlement of a single pile foundation, which must be less than the allowable settlement (m), the permissible pile settlement is 10% times the pile diameter,  $B$  is the pile group width (m), and  $D$  is the pile diameter (m).

### Finite Element Method

Plaxis 8.6 is a finite element-based suite utilized for conducting 2D geotechnical simulations and slope stability assessments, as well as other geomechanical analyses in geotechnical engineering and rock mechanics. Through intuitive graphics for entering soil property data, it can produce complex finite element models and display detailed results. The entire calculation process in this program is carried out automatically, based on accurate number writing procedures.

The procedure for calculating the bearing capacity of pile foundations using the finite element method is carried out through the following stages: Describe the geometry of the foundation and soil layers based on N-SPT data using a 12-nodal axisymmetric model and Mohr-Coulomb soil modelling, and enter the pile and soil parameters (Suradi et al., 2024). Perform the calculation program in several stages, starting from the construction stage, through safety factor calculation, and concluding with settlement. The finite element method results provide bearing capacity and settlement values, which are presented in Figure 5.

The finite element method has advantages over manual calculation methods and simpler approaches, such as the bishop method, because it can produce more comprehensive results. This analysis not only provides safety factor values but also presents detailed information on soil deformation, effective stress distribution, pore water pressure, and soil response to loads. This enables a more comprehensive and realistic understanding of soil behaviour.

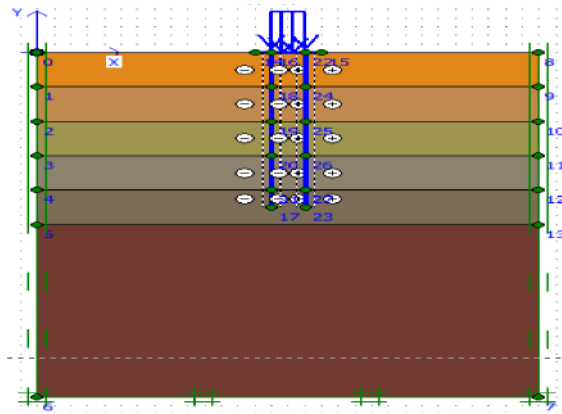


Figure 5. Foundation modelling using the finite element method.

The ultimate load capacity of the pile ( $Q_u$ ) is determined using finite element analysis calculated using the following formula:

$$Q_{all} = P_{all} = \frac{Q_u}{\Sigma - M_{sf}}$$

$$Q_u = P_{all} \times \Sigma - M_{sf}$$

Where  $Q_{all}=P_{all}$  is the bearing capacity of the pile (60 tons),  $Q_u$  is the ultimate bearing capacity (tons), and  $\Sigma - M_{sf}$  is the quotient of the actual strength parameter and the reduced strength parameter.

### Analysis of Deflection Due to Lateral Forces

In lateral force analysis, columns are distinguished by their connection to the column cover plate, namely, clamped-end columns and free-end columns. This connection model significantly affects the behavior of columns in resisting lateral loads (Liongono et al., 2023)(Kawengian et al., 2018).

Broms' method (1964) for piles in cohesive soil, pile deflection is related to the dimensionless factor  $\beta L$ , as follows:

$$\beta = \left( \frac{k_h d}{4 \cdot E_p \cdot I_p} \right)^{\frac{1}{4}}$$

Depending on the type of pile restraint, the deflection of the pile tip at the ground surface ( $Y_o$ ) is determined using the following formula:

$$Y_o = \frac{H_u \times \beta}{k_h \times d}$$

Where  $H_u$  is the horizontal shear force,  $\beta$  is the dimensionless deflection factor,  $k_h$  is the horizontal soil reaction modulus, and  $D$  is the foundation diameter. The condition is that the value of  $Y_o < 6$  mm(Situmorang et al., 2020).

### Bearing Capacity Ratio

The Bearing Capacity Ratio (BCR) represents the ratio of the static load capacity calculated from SPT data to that derived from numerical analysis. The latter is often considered a more

precise reflection of field conditions due to its ability to simulate complex structural geometries and nonlinear material behavior (Mase et al., 2022; Rumbayrso et al., 2022).

To determine the level of agreement between the static method and the finite element approach, the BCR value is utilized as a comparative index. The ideal BCR value is close to 1, consistent with the finite element results. By using BCR, planners can assess the reliability of the analytical approach and adjust it when significant deviations occur, resulting in a safer, more efficient foundation Design.

## Research Results and Discussion

### Comparison of Single Pile Foundation Bearing Capacity

The foundation’s bearing capacity analysis was conducted using a method that relies on predetermined safety factors. Based on the graph, the foundation’s bearing capacity is influenced by pile depth. The deeper the pile driving and the larger the foundation cross-section, the greater the bearing capacity produced (Yuslinda & Rani, 2025).

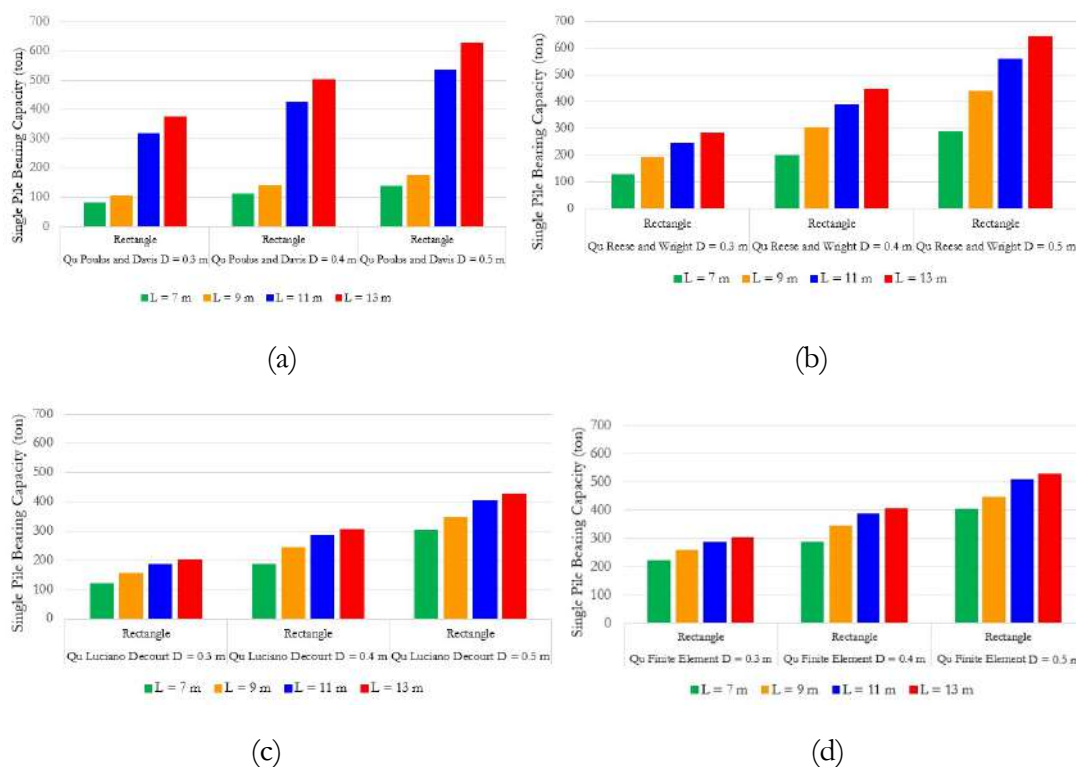


Figure 6. Load-bearing capacity of square and circular single pile : (a) Poulos and Davis Method, (b) Reese and Wright Method, (c) Luciano Decourt Method, (d) Finite Element Method.

Figure 6 illustrates a graph comparing the bearing capacity of pile foundations analyzed using the equations of Poulos and Davis (1980), Reese and Wright (1977), Luciano Decourt (1987), and Finite Elements. It was found that differences in calculated bearing capacity affect the foundation’s cross-sectional diameter and depth. Foundations with larger cross-sectional diameters and greater depths generally have greater bearing capacity. Still, many factors must be considered to ensure the Design does not pose risks and cause unnecessary cost overruns. A comprehensive evaluation of soil conditions, selection of appropriate dimensions, compliance with technical standards, and consideration of cost efficiency are critical in designing safe and optimal foundations.

Based on the analysis results, the Reese and Wright (1977) method provides load capacity estimates that tend to be greater than other conventional static methods, where the level of significance of the difference is influenced by input parameters. The data shows that the highest capacity value is obtained for a 500 mm square pile foundation with a depth of 13 m. However, the use of a depth of 9 m is considered more technically and economically optimal at this location, given that a hard soil layer has been found at this depth, ensuring the safety of the structure.

### Comparison of Group Pile Foundation Bearing Capacity

Single pile capacity and the total quantity of piles (n) serve as the basis for calculating the group bearing capacity (Qg). Because the spatial arrangement and number of piles significantly influence the foundation's overall performance, this study evaluates (Qg) using four distinct approaches: the Poulos and Davis (1980) method, the Reese and Wright (1977) method, the Luciano Decourt (1987) method, and Finite Element analysis, with the comparative results illustrated in the following figure.

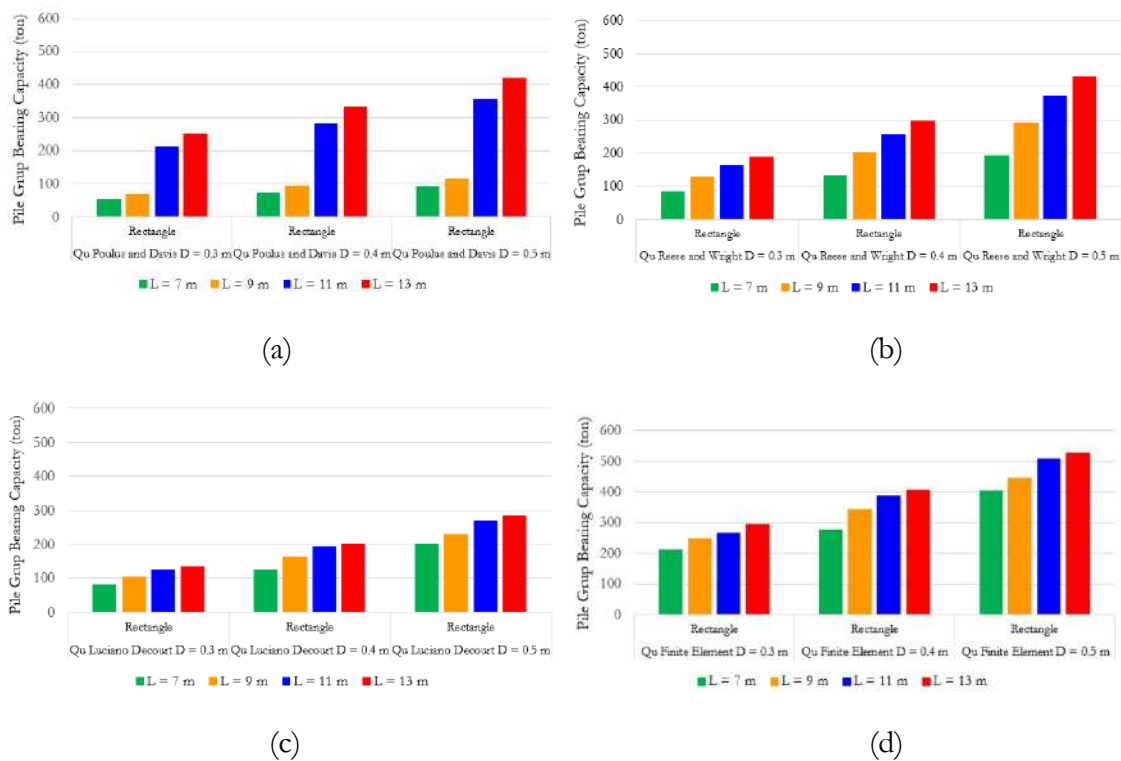


Figure 7. Load-bearing capacity of square and circular Group piles: (a) Poulos and Davis Method, (b) Reese and Wright Method, (c) Luciano Decourt Method, (d) Finite Element Method.

Figure 7 shows a graph comparing the bearing capacity of the analyzed foundation piles with the equations of Poulos and Davis (1980), Reese and Wright (1977), Luciano Decourt (1987), and Finite Elements. The analysis results show that foundations with larger diameters and greater depths generally have greater bearing capacity, but the Design selection must still consider soil conditions and cost efficiency. The Reese and Wright (1977) method produced the highest bearing capacity values, especially for square foundations with a diameter of 500 mm and a depth of 13 m. however, given that the soil layer below 10 m consisted of gravelly sand.

### Pile Settlement

Settlement of foundations is greatly influenced by the condition of the soil layers surrounding the foundation and the cross-sectional size of the piles. Piles with a larger cross-sectional diameter generally experience less settlement. This occurs because a larger cross-sectional area allows the load to be distributed more evenly across the ground, thereby reducing the pressure per unit area and minimizing settlement.

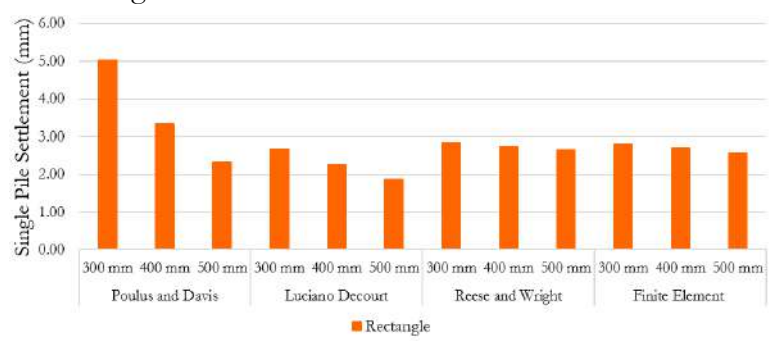


Figure 8. Foundation Settlement of Square

Figure 8 shows the results of settlement using several pile foundation analysis methods, as each method has a different level of accuracy. In addition, the pile’s cross-sectional diameter and shape also affect the bearing capacity obtained. The Luciano Decourt (1987) method produced the smallest settlement value.

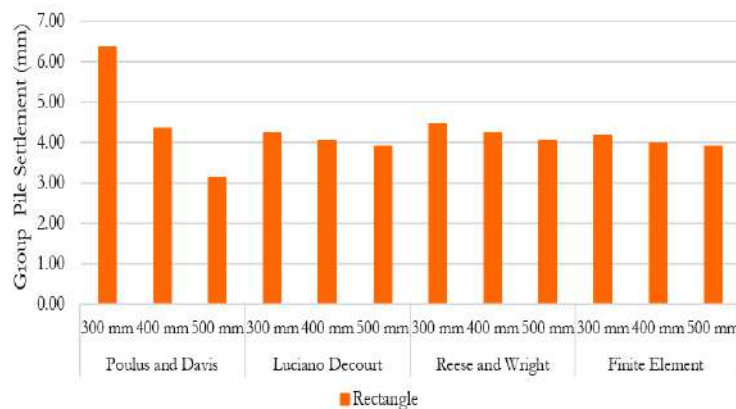


Figure 9. Foundation Settlement of Square

Figure 9 shows the results of settlement analyses using several group pile foundation analysis methods, each with a different level of accuracy. In addition, the pile’s cross-sectional diameter and shape also affect the bearing capacity obtained. The Luciano Decourt (1987) method produced the smallest settlement value.

### Deflection due to Lateral Force

The position of the clamping point is at a certain depth below the ground surface, and foundation clamping points that are completely buried in the ground do not significantly affect pile reinforcement. This is due to the relatively small moment, which also results in a horizontal pile deflection considered safe because its magnitude does not exceed the maximum deflection allowed for piles with pinned heads, which is 6 mm [9]. Based on Table 2, the pile deflection value ( $Y_0$ ) is influenced by variations in foundation cross-section size; the smaller the foundation cross-section, the smaller the deflection.

Table 2. Deflection Values of Pile Foundations for WTP Buildings

Shape	Diameter (mm)	$Y_0$ (mm)
Square	300	0.133
	400	0.150
	500	0.172

### Bearing Capacity Ratio

BCR values obtained from conventional approaches often differ from those obtained from finite element method analyses. Conventional approaches generally rely on analytical formulas and simple assumptions about soil and foundation behavior, thereby yielding more conservative bearing capacity estimates. Meanwhile, the finite element method can analyze soil-foundation interactions in greater detail, including stress distributions, strains, and deformations. Given the non-linear nature and variability of soil characteristics, this method yields more accurate and realistic bearing capacity estimates that reflect field conditions.

According to Table 3, the Bearing Capacity Ratio (BCR) for single columns calculated using the Reese and Wright (1977) method is approximately 1. This suggests a high level of accuracy, as the bearing capacity derived from this empirical method aligns almost perfectly with that from the finite element method. The BCR values for pile bearing capacity calculated using conventional methods generally show comparable results. The BCR value closest to 1 was obtained from the Reese and Wright method

Table 3. BCR Value Soil Bearing Capacity Single Pile Foundation and Group Piles Foundation

Method	Shape	Depth (m)	BCR Single Foundation	BCR Group Foundation
Qu Poulus and Davis (1980)	Square	7	1.92	2.03
		9	2.19	1.85
		11	0.81	0.68
		13	0.72	0.61
Qu Reese, and Wright (1977)	Square	7	1.02	1.09
		9	0.98	1.04
		11	0.86	0.99
		13	0.78	0.99
Qu Luciano Decourt (1987)	Square	7	1.03	1.08
		9	1.23	0.83
		11	1.17	0.73
		13	1.15	0.67

### Conclusion

Results from evaluating the bearing capacity of pile foundations using various SPT data variations indicate that the Reese and Wright (1977) method yields the highest value among conventional approaches. The accuracy level of this method is considered the highest because the

results show the smallest deviation from the finite element method analysis, thus better reflecting the actual bearing capacity in the field.

The dimensions of pile foundations affect foundation bearing capacity. Specifically, an increase in the cross-sectional area correlates directly with higher capacity, as a larger surface area facilitates a broader distribution of structural loads into the underlying soil. In piles with smaller cross-sections, although the bearing capacity tends to be lower, the deflection and settlement that occur also tend to be smaller. In the Luciano Decourt (1987) method, more miniature settlement figures are shown for both single pile foundations and pile groups.

Overall, among the analyzed variations, pile foundations with a 500 mm square cross-section and a depth of 9 meters proved to be the most efficient and safe solution. These dimensions can provide adequate support and produce deflections and settlements within permissible limits, thereby reducing the risk of structural damage.

The author suggests developing research by comparing pile bearing capacity calculation methods (such as the Vesic method) based on sounding data. Cost analysis is also recommended to determine the most economical foundation dimensions, supported by the creation of an efficient 3D structural model.

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