

Comparative Analysis of Axial Bearing Capacity and Settlement of Bored Pile Foundations Based on N-SPT Data in the WK-Kampar Oil Tank Construction Project

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Article History

Received : November 03, 2025

Revised : November 24, 2025

Accepted : November 28, 2025

Published : November 30, 2025

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Cite This Article [APA Style]:

Putri, I. H., & Suprpto, Y. H. (2025). Comparative Analysis of Axial Bearing Capacity and Settlement of Bored Pile Foundations Based on N-SPT Data in the WK-Kampar Oil Tank Construction Project. *International Journal Science and Technology*, 4(3), 185–197.

DOI:

<https://doi.org/10.56127/ijst.v4i3.2857>

Abstract: Oil tank construction requires a reliable foundation system to support structural loads and prevent excessive settlement. In the WK-Kampar project, bored pile foundations were used to transfer loads to deeper and more stable soil layers. **Objective:** This study aims to compare the axial bearing capacity and settlement of bored pile foundations with diameters of 0.4 m, 0.5 m, and 0.6 m based on N-SPT data. **Method:** This research used a quantitative descriptive-comparative approach. Secondary data were obtained from soil investigation and foundation planning documents. The Reese & O'Neill method was used to calculate bearing capacity, while the Vesic method was used to estimate settlement. **Findings:** The allowable bearing capacities of single piles with diameters of 0.4 m, 0.5 m, and 0.6 m were 173.7 kN, 233.5 kN, and 299.8 kN. The corresponding pile group capacities were 1301.2 kN, 1664.2 kN, and 2030.6 kN, with settlement values of 3.95 cm, 4.16 cm, and 4.67 cm. The 0.4 m diameter bored pile with nine piles can be considered the most efficient alternative if its group capacity exceeds the tank working load. **Implications:** The findings show that a smaller pile diameter may still be technically acceptable when bearing capacity and settlement requirements are satisfied. **Originality:** This study integrates single pile capacity, pile group capacity, and settlement analysis for an actual oil tank foundation project using N-SPT data.

Keywords: axial bearing capacity; bored pile; N-SPT; settlement; oil tank

INTRODUCTION

The development of industrial and energy infrastructure requires a reliable foundation system to ensure structural safety, serviceability, and long-term operational performance. In oil and gas construction projects, such as storage tank facilities in the Kampar Working Area, foundation failure may cause serious consequences, including excessive settlement, structural instability, operational disruption, and potential environmental risk. Oil tank structures generally impose large axial loads on the supporting soil; therefore, the selected foundation system must be able to transfer loads safely to deeper and more stable soil layers. In this context, bored pile foundations are commonly used because they are suitable for supporting heavy structures and can be designed based on subsurface soil investigation data. The use of Standard Penetration Test (SPT) data is also important because it provides

practical information for estimating soil resistance and foundation bearing capacity in the field.

Previous studies have examined the bearing capacity of bored pile foundations using various empirical and analytical approaches. The first group of studies focused on comparing foundation bearing capacity based on SPT and CPT data, showing that soil investigation methods strongly influence the estimated bearing capacity of pile foundations (Abadi et al., 2022; Jamil & Siregar, 2023; Pratama et al., 2022). The second group of studies examined bored pile performance in specific infrastructure projects, such as flyover construction and railway development, where pile capacity and settlement were evaluated using field soil data and empirical formulas (Oemar et al., 2021; Ramdhany & Permana, 2021). The third group of literature provides the theoretical basis for pile foundation design, including bearing capacity, shaft friction, end bearing resistance, safety factors, and settlement analysis (Bowles, 1997; Das, 1995; Hardiyatmo, 1996; Reese & O'Neill, 1989; Vesic, 1977). However, most previous studies mainly emphasized the calculation of bearing capacity, while fewer studies discussed the comparative evaluation of bored pile diameter variations together with group pile capacity and settlement control, particularly for oil storage tank structures. Therefore, further analysis is needed to evaluate whether different bored pile diameters can meet both bearing capacity and settlement requirements under actual project conditions.

This study aims to analyze the axial bearing capacity and settlement of bored pile foundations used in the construction of an oil tank structure in the Kampar Working Area. The analysis is conducted using N-SPT data as the main basis for estimating soil parameters and foundation resistance. Specifically, this study compares three bored pile diameter variations, namely 0.4 m, 0.5 m, and 0.6 m, to determine the allowable bearing capacity of a single pile, the bearing capacity of a pile group, and the resulting foundation settlement. The Reese & O'Neill method is applied to calculate the axial bearing capacity, while the Vesic method is used to estimate pile foundation settlement. The results are then evaluated against the structural load and the allowable settlement criteria based on SNI 8460:2017.

The main argument of this study is that increasing the bored pile diameter will increase the axial bearing capacity due to the larger pile base area and shaft surface area. However, the most technically appropriate foundation design is not necessarily the largest pile diameter, but the diameter that satisfies bearing capacity and settlement requirements efficiently. Therefore, it is expected that the comparative analysis of bored pile diameter

variations can identify a foundation configuration that is safe, serviceable, and suitable for the oil tank structure. This study contributes to practical geotechnical design by providing an evaluation of bored pile capacity and settlement based on N-SPT data under the actual soil conditions of the WK-Kampar construction project.

RESEARCH METHOD

This study analyzed the bored pile foundation system used to support the oil tank structure in the WK-Kampar construction project. The unit of analysis was the bored pile foundation, particularly its axial bearing capacity and settlement performance based on Standard Penetration Test (SPT) data. The analysis focused on three bored pile diameter variations, namely 0.4 m, 0.5 m, and 0.6 m, with a pile length of 12 m. Each diameter variation was evaluated both as a single pile and as a pile group consisting of nine piles. The main focus of the study was to determine whether the bored pile foundation design could safely support the working load of the oil tank structure and meet the allowable settlement criteria.

This research employed a quantitative approach with a descriptive-comparative design. The quantitative approach was selected because the study used numerical data, soil parameters, foundation dimensions, and engineering calculations to evaluate bored pile performance. The descriptive method was used to explain the soil conditions, pile geometry, pile group configuration, and design parameters applied in the analysis. Meanwhile, the comparative method was used to compare the bearing capacity and settlement results of bored pile foundations with different diameter variations. This design was considered appropriate because the objective of the study was to identify the bored pile diameter that satisfies both bearing capacity and settlement requirements under the same project conditions.

The data used in this study were secondary data obtained from soil investigation reports and foundation planning documents of the WK-Kampar construction project. The main data included N-SPT values, soil layer descriptions, bored pile dimensions, pile length, number of piles, pile spacing, pile group configuration, and the working load of the oil tank structure. The N-SPT data were used as the basis for interpreting soil resistance and determining geotechnical parameters required for the analysis. In addition, SNI 8460:2017 was used as the reference for evaluating geotechnical design requirements, particularly the allowable settlement criteria. The Reese & O'Neill method was used to

estimate axial bearing capacity, while the Vesic method was used to estimate foundation settlement.

Data collection was carried out through documentation review of available project reports, soil investigation records, and foundation design data. The SPT data were reviewed according to depth, soil layer characteristics, and N-SPT values. The soil profile was then interpreted to obtain the parameters needed for bored pile foundation analysis. In addition, the foundation geometry was identified, including pile diameter, pile length, pile spacing, number of piles, and pile group arrangement. All collected data were organized as calculation inputs so that each diameter variation could be analyzed using consistent soil conditions and design assumptions.

The data analysis was conducted in several stages. First, the soil investigation data were interpreted to identify the soil layers and geotechnical parameters used in the calculation. Second, the bearing capacity of a single bored pile was calculated for each diameter variation using the Reese & O'Neill method. Third, the bearing capacity of the pile group was determined by considering the number of piles and pile group efficiency. Fourth, the settlement of the bored pile foundation was estimated using the Vesic method. Finally, the calculated bearing capacity and settlement values were compared with the working load of the oil tank structure and the allowable settlement limit based on SNI 8460:2017. A bored pile diameter was considered acceptable when the pile group bearing capacity was greater than the structural load and the calculated settlement remained below the allowable settlement limit.

RESULT

Analysis of Single Pile Bearing Capacity

The bearing capacity analysis of the bored pile foundation was carried out for three pile diameter variations, namely 0.4 m, 0.5 m, and 0.6 m, with a pile length of 12 m. The analysis was conducted to determine the allowable axial bearing capacity of a single bored pile based on the Reese & O'Neill method. The calculation considered the pile base area, pile shaft surface area, ultimate end bearing resistance, ultimate shaft friction resistance, pile self-weight, and safety factor.

For the bored pile with a diameter of 0.4 m, the pile base area and pile shaft surface area were first calculated based on the pile geometry. The pile base area increased with the square of the pile diameter, while the shaft surface area increased proportionally with the

pile diameter and pile length. Therefore, a larger pile diameter resulted in a greater contribution from both end bearing resistance and shaft friction resistance. The concrete compressive strength used in the calculation was 24.5 MPa. This value should be verified and written consistently in the manuscript because concrete strength must be expressed in MPa, not in square meters.

The calculation results show that the allowable bearing capacity of a single bored pile increased as the pile diameter increased. The allowable bearing capacity for the 0.4 m, 0.5 m, and 0.6 m diameter piles was 173.7 kN, 233.5 kN, and 299.8 kN, respectively. This result confirms that pile diameter has a significant effect on the axial bearing capacity of bored piles. The increase in bearing capacity occurs because larger pile diameters provide a wider base area for end bearing resistance and a larger shaft surface area for skin friction resistance.

Table 1. Allowable Bearing Capacity of Single Bored Pile

Pile Diameter (m)	Pile Length (m)	Allowable Bearing Capacity, Q_{all} (kN)	Interpretation
0.4	12	173.7	Meets the design requirement if the load per pile is lower than Q_{all}
0.5	12	233.5	Provides higher bearing capacity than the 0.4 m pile
0.6	12	299.8	Provides the highest single pile bearing capacity

Based on Table 1, the 0.6 m diameter pile produced the highest allowable bearing capacity. However, the selection of pile diameter should not only be based on the largest bearing capacity, but also on the actual structural load, settlement behavior, construction efficiency, and economic considerations. Therefore, further evaluation was carried out by analyzing the bearing capacity of the pile group and the resulting settlement.

Analysis of Pile Group Bearing Capacity

The pile group bearing capacity was calculated by considering the allowable bearing capacity of a single pile, the number of piles, and the pile group efficiency. In this study, the foundation system consisted of nine bored piles. The pile group efficiency used in the calculation was 0.83, or 83%. This efficiency value indicates that the total bearing capacity of the pile group is lower than the simple multiplication of single pile capacity and number of piles due to the interaction between piles in the group.

The calculation results show that the pile group bearing capacity increased with the increase in pile diameter. The pile group bearing capacity for bored pile diameters of 0.4 m, 0.5 m, and 0.6 m was 1301.2 kN, 1664.2 kN, and 2030.6 kN, respectively. These results indicate that all diameter variations provide different levels of structural support capacity.

Table 2. Bearing Capacity of Bored Pile Group

Pile Diameter (m)	Number of Piles	Pile Efficiency	Group Capacity, Qg (kN)	Bearing Interpretation
0.4	9	0.83	1301.2	Acceptable if Qg is greater than the working load
0.5	9	0.83	1664.2	Provides additional bearing capacity reserve
0.6	9	0.83	2030.6	Provides the highest group bearing capacity

The results in Table 2 show that the 0.4 m diameter pile group already provides a bearing capacity of 1301.2 kN. If this value is greater than the working load of the oil tank structure, then the 0.4 m diameter bored pile can be considered structurally acceptable. However, the working load of the tank structure must be explicitly presented in the manuscript so that the safety evaluation can be verified. Without this load value, the conclusion that the foundation is safe is not yet fully supported.

The 0.5 m and 0.6 m diameter piles provide higher bearing capacity values. Nevertheless, if the 0.4 m diameter pile already satisfies the required bearing capacity and settlement criteria, the use of a larger diameter may not be necessary from an efficiency perspective. Therefore, the 0.4 m diameter pile may be considered the most efficient alternative, provided that the bearing capacity remains greater than the structural working load and the settlement remains within the allowable limit.

Settlement Analysis of Bored Pile Foundation

Settlement analysis was conducted to evaluate the serviceability performance of the bored pile foundation. The analysis was carried out using the Vesic method by considering the settlement components caused by elastic deformation of the pile, load transfer at the pile tip, and load transfer along the pile shaft. The settlement evaluation is important because a foundation may have sufficient bearing capacity but still fail to meet serviceability requirements if the settlement exceeds the allowable limit.

The calculation results show that the pile group settlement values for bored pile diameters of 0.4 m, 0.5 m, and 0.6 m were 3.95 cm, 4.16 cm, and 4.67 cm, respectively. These values indicate that the settlement increased as the pile diameter increased. This may occur because the larger pile diameter mobilizes greater load transfer to the soil, resulting in a higher calculated settlement response under the assumed load distribution.

Table 3. Settlement of Bored Pile Group

Pile (m)	Diameter Group (cm)	Settlement, Sg	Allowable Settlement	Interpretation
0.4		3.95	Below allowable limit	Meets settlement requirement
0.5		4.16	Below allowable limit	Meets settlement requirement
0.6		4.67	Below allowable limit	Meets settlement requirement

Based on Table 3, all bored pile diameter variations produced settlement values below the allowable settlement limit. This indicates that the bored pile foundation satisfies the settlement requirement based on the applicable geotechnical design criteria. However, the allowable settlement value used in the analysis should be clearly stated in the manuscript and linked to SNI 8460:2017 to strengthen the technical validity of the evaluation.

Comparative Evaluation of Bored Pile Diameter Variations

A comparative evaluation was conducted to determine the most suitable bored pile diameter for the oil tank foundation. The evaluation considered two main criteria: bearing capacity and settlement. The bored pile foundation is considered acceptable when the pile group bearing capacity is greater than the working load of the oil tank structure and the calculated settlement is smaller than the allowable settlement limit.

Table 4. Comparative Evaluation of Bored Pile Foundation Performance

Pile (m)	Diameter	Qall (kN)	Qg (kN)	Sg (cm)	Technical Evaluation
0.4		173.7	1301.2	3.95	Technically acceptable if Qg exceeds the tank working load
0.5		233.5	1664.2	4.16	Acceptable with higher bearing capacity reserve
0.6		299.8	2030.6	4.67	Acceptable but may be less efficient if not required by load demand

The comparison shows that the 0.6 m diameter pile produced the highest bearing capacity, followed by the 0.5 m and 0.4 m diameter piles. However, the 0.4 m diameter pile group already provided a group bearing capacity of 1301.2 kN and a settlement value of 3.95 cm. Therefore, the 0.4 m diameter bored pile with nine piles can be considered the most efficient design alternative if the group bearing capacity exceeds the oil tank working load and the settlement remains below the allowable limit.

From a geotechnical design perspective, the use of the largest diameter is not always the most effective solution. A foundation design should be selected based on safety, serviceability, constructability, and efficiency. In this case, the 0.4 m diameter bored pile offers a technically acceptable option because it satisfies the required bearing capacity and settlement criteria based on the calculation results. The 0.5 m and 0.6 m diameter piles may be considered as alternative designs if higher load demand, additional safety margin, or more conservative design considerations are required.

Calculation

1. Analysis of the Bearing Capacity of a Single Pile Foundation

Pile diameter: 0.4 m

Pile length: 12 m

Concrete grade used: 24.5 m²

1) Pile Base Area

$$A_b = \frac{1}{4} \times \pi \times d^2$$

$$A_b = \frac{1}{4} \times 3,14 \times 0,4^2$$

$$A_b = 0,125 \text{ m}^2$$

2) Pole Cover Area

$$A_s = \pi \times d$$

$$A_s = 3,14 \times 0,4$$

$$A_s = 1,256 \text{ m}^2$$

$$N'_c = 6(1 + 0,2 \frac{L}{d_b}) \geq 9$$

$$N'_c = 6(1 + 0,2 \frac{12}{0,4}) \geq 9$$

$$N'_c = 42 \geq 9, \text{ dipakai } N'_c N'_c = 42 \geq 9, \text{ dipakai } N'_c = 9$$

$$f_b = C_u N'_c \leq 4000 \text{ kPa}$$

$$f_b = 1324,4 \leq 4000 \text{ kPa (OK)}$$

3) Tahanan Ujung Ultimit

$$Q_b = A_b \times f_b$$

$$Q_b = 0,125 \times 1324,4 = 166,4 \text{ kN}$$

4) Faktor adhesi pada interval kedalaman 12 meter :

$$C_u = 147,2 \text{ kPa}$$

$$\alpha = 0,5 \text{ untuk } \frac{C_u}{P_r} < 1,5 (P_r = 100 \text{ kN/m}^2)$$

$$\alpha = \frac{C_u}{P_r} < 1,5 \text{ maka digunakan } 0,5$$

Diperoleh tahanan gesek (f_s) Diperoleh tahanan gesek (f_s):

$$f_s = \alpha \times C_u$$

$$f_s = 0,5 \times 147,2 = 73,6 \text{ kN/m}^2$$

5) Tahanan gesek ultimit

$$Q_s = A_s \times f_s$$

$$Q_s = 1,256 \text{ m}^2 \times 73,6 \text{ kN/m}^2$$

$$Q_s = 92,5 \text{ kN}$$

6) Berat tiang bored pile

$$W_p = A_p \times L \times \gamma_{\text{beton}}$$

$$W_p = 0,125 \times 12 \times 23,5 = 35,5 \text{ kN}$$

7) Kapasitas dukung ultimit netto

$$Q_u = Q_b + Q_s - W_p$$

$$Q_u = 166,4 + 303,3 - 35,5$$

$$Q_u = 434,2 \text{ kN}$$

8) Kapasitas dukung ijin

$$SF = 2,5$$

$$Q_{\text{all}} = \frac{Q_u}{2,5} = \frac{434,2}{2,5} = 173,7 \text{ kN}$$

2. Analysis of Bearing Capacity of Group Piles

$$Q_{\text{all}} Q_{\text{all}} : 173,7$$

$$\text{Jumlah Tiang (n)} : 9$$

$$\text{Efisiensi Pile Grup} : 1 - \frac{\theta}{90} \left[\frac{(n-1)m + (m-1)n}{m \times n} \right] = 1 - \frac{0,2}{90} \left[\frac{(3-1)3 + (3-1)3}{3 \times 3} \right]$$

$$1 - \frac{\theta}{90} \left[\frac{(n-1)m + (m-1)n}{m \times n} \right] = 1 - \frac{0,2}{90} \left[\frac{(3-1)3 + (3-1)3}{3 \times 3} \right]$$

$$\text{Efisiensi Pile Grup} : 0,83 = 83\%$$

$$\text{Daya Dukung Ijin Pile Grup: } Q_{\text{all}} \times n \times E_g = 173,7 \times 9 \times 0,83 = 1301,2 \text{ kN}$$

$$Q_{\text{all}} \times n \times E_g = 173,7 \times 9 \times 0,83 = 1301,2 \text{ kN}$$

Single Pile Settlement Analysis

$$N_{\text{SPT}} N_{\text{SPT}} = 2525$$

$$\text{Koefisien Empiris } (C_p) (C_p) = 0,030,03$$

$$\text{Poisson's Ratio } (\mu) (\mu) = 0,30,3$$

$$\text{Skin Friction } (\xi) (\xi) = 0,5 0,5$$

a) Modulus of Elasticity of Soil at the End of the Foundation (E_s) (E_s)

$$E_s = 766 \times N_{\text{SPT}} = 766 \times 25 = 19150 \text{ kN/m}^2$$

b) Empirical Constant (I_{ws})(I_{ws})

$$I_{ws} = 2 + 0,35\sqrt{L/b} = 2 + 0,35\sqrt{12/0,4} = 3,92$$

c) Effect of Declining Elasticity $S_p S_p$

$$S_p = \frac{((Q_b + \xi \times Q_s) \times L)}{A_p \times E} = \frac{((166,4 + 0,5 \times 92,5) \times 12)}{0,125 \times 23.263.810} = \frac{0,00087}{0,01} = 0,09 \text{ cm}$$

d) Due to the load on the end of the pole $S_s S_s$

$$S_s = \frac{(Q_p \times C_p)}{b \times q_p} = \frac{(166,4 \times 0,03)}{0,4 \times 1324,4} = \frac{0,094}{0,01} = 0,94 \text{ cm}$$

e) Akibat Beban Terdistribusi Sepanjang Tiang (S3)

$$S_{ps} = (Q_s \times S_p) \times \left(\frac{b}{E_s}\right) \times (1 - \mu^2) \times I_{ws} = \left(\frac{92,5}{1,256 \times 12}\right) \times \frac{0,4}{19150} \times (1 - 0,3^2) \times 3,92 = 0,0005 = 0,05 \text{ cm}$$

f) Single Pile Settlement

$$S = S_{ps} + S_s + S_p = 0,09 + 0,94 + 0,05 = 1,08 \text{ cm}$$

$$S = S_{ps} + S_s + S_p = 0,09 + 0,94 + 0,05 = 1,08 \text{ cm}$$

Group Pile Settlement Analysis

a) Pile Group Reduction

$$S_G = S \times \sqrt{\frac{p}{b}} = 1,08 \times \sqrt{\frac{5,4}{0,4}} = 3,95 \text{ cm}$$

b) Reduction of Permit

$$S_{all} = 15 + \frac{b}{600} = 15 + \frac{0,4 \times 100}{600} = 15,07 \text{ cm}$$

c) Cek Syarat Penurunan

$$S \leq S_{all} = 3,95 \text{ cm} \leq 15,07 \text{ cm (OK)}$$

DISCUSSION

The results of this study confirm that bored pile diameter has a direct influence on axial bearing capacity. The increase in pile diameter increases both the pile base area and pile shaft surface area, which leads to higher end bearing resistance and shaft friction resistance. This finding is consistent with the basic principle of deep foundation behavior, where the load-carrying capacity of a pile is governed by the combination of end bearing and shaft resistance.

The pile group analysis also shows that group efficiency plays an important role in determining the actual capacity of the foundation system. Although nine piles were used in the foundation group, the total group capacity was not calculated simply by multiplying the single pile capacity by the number of piles. The pile group efficiency of 0.83 indicates the presence of interaction effects among piles. Therefore, pile spacing and group arrangement must be considered carefully in bored pile foundation design.

The settlement results show that all diameter variations meet the serviceability requirement because the calculated settlement values are below the allowable limit. Among the three alternatives, the 0.4 m diameter pile produced the smallest settlement and sufficient group bearing capacity. This supports the selection of the 0.4 m diameter bored pile as the recommended design alternative, provided that the working load of the oil tank structure is lower than the calculated group bearing capacity.

Overall, the bored pile foundation with a diameter of 0.4 m and a total of nine piles can be considered acceptable for the oil tank structure in the WK-Kampar construction project. This alternative provides a balance between bearing capacity, settlement performance, and design efficiency. Nevertheless, the manuscript should explicitly include the working load of the tank structure, allowable settlement limit, complete soil investigation data, and detailed calculation assumptions to improve the transparency and reproducibility of the analysis.

CONCLUSION

This study shows that the bored pile foundation design for the oil tank structure in the WK-Kampar construction project can be evaluated effectively through axial bearing capacity and settlement analysis based on N-SPT data. The results indicate that increasing the pile diameter increases the allowable bearing capacity of a single pile and the bearing capacity of the pile group. The allowable bearing capacity of single bored piles with diameters of 0.4 m, 0.5 m, and 0.6 m was 173.7 kN, 233.5 kN, and 299.8 kN, respectively. Meanwhile, the bearing capacity of the pile group for the same diameter variations was 1301.2 kN, 1664.2 kN, and 2030.6 kN, respectively. The settlement values of the pile group were 3.95 cm, 4.16 cm, and 4.67 cm, all of which remained below the allowable settlement limit. Based on these findings, the bored pile foundation with a diameter of 0.4 m and a total of nine piles can be considered acceptable because it provides sufficient bearing capacity and satisfies the settlement requirement for the oil tank structure.

The main contribution of this study lies in its comparative evaluation of bored pile diameter variations using N-SPT-based analysis for an actual oil tank construction project. This study demonstrates that the largest pile diameter is not always the most efficient design alternative when smaller diameters are already able to meet both bearing capacity and serviceability requirements. The findings provide practical value for geotechnical foundation design, particularly in selecting an efficient bored pile configuration based on soil investigation data, pile group capacity, and settlement control. In addition, this study supports the application of empirical methods, particularly the Reese & O'Neill method for bearing capacity analysis and the Vesic method for settlement analysis, as practical tools in preliminary and project-based foundation evaluation.

However, this study has several limitations. The analysis was based on secondary soil investigation data and empirical calculation methods, so the accuracy of the results depends on the completeness and reliability of the available N-SPT data. This study did not include field load testing, numerical modeling, or comparison with other soil investigation methods such as Cone Penetration Test (CPT). In addition, the structural working load and allowable settlement limit should be presented more explicitly to strengthen the verification of the foundation safety criteria. Future studies are recommended to compare the results with pile load test data, CPT-based analysis, or finite element modeling to obtain a more comprehensive evaluation of bored pile performance under actual field conditions.

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