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Analysis Of The Axial Bearing Capacity And Settlement Of Bored Pile Foundations Using The Finite Element Method (Case Study: Construction Of The Sumatera Main Stadium)

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Abstract
Foundation is the lowest part of a structure that functions to support the entire load of the building. Bored pile foundation is one type of deep foundation used to carry axial loads in building construction. The axial bearing capacity of a bored pile can be determined through a Static Loading Test (SLT). This study aims to analyze a bored pile foundation with a diameter of 80 cm at the Main Stadium of North Sumatra Project, located in Batang Kuis District, Deli Serdang Regency, North Sumatra Province, including the ultimate bearing capacity of a single bored pile and the settlement of the foundation. Analytical methods using SPT data were calculated using Reese & Wright equations, while loading test data were analyzed using curve interpretation methods including the Davisson Method, Chin Method, and Mazurkiewicz Method. Meanwhile, Finite Element Method (FEM) analysis was carried out using the FEM program (PLAXIS). The analysis results show that the ultimate axial bearing capacity of a single bored pile (Qu) obtained from the analytical method is 600 tons, the Chin Method based on Static Loading Test data is 617.895 tons, and the Mazurkiewicz Method based on Static Loading Test data is 590.65 tons. The Finite Element Method (FEM) produced an ultimate bearing capacity (Qu) of 597.8 tons with a tendency for upward settlement. The settlement of a single bored pile foundation from the Static Loading Test curve was 65 mm, while the Mazurkiewicz Method indicated a settlement of 60 mm.

Keywords: *Bearing Capacity, Settlement, Bored Pile, Finite Element Method*

Abstrak
Pondasi merupakan bagian terbawah dari suatu struktur bangunan yang berfungsi untuk menahan seluruh beban bangunan. Pondasi bored pile adalah salah satu jenis pondasi dalam yang digunakan untuk memikul beban aksial pada konstruksi bangunan. Kapasitas daya dukung aksial pondasi bored pile dapat ditentukan melalui Uji Pembebanan Statik (Static Loading Test/SLT). Penelitian ini bertujuan untuk menganalisis pondasi bored pile dengan diameter 80 cm pada Proyek Stadion Utama Sumatera Utara yang terletak di Kecamatan Batang Kuis, Kabupaten Deli Serdang, Provinsi Sumatera Utara, meliputi kapasitas daya dukung ultimit bored pile tunggal dan penurunan pondasi. Metode analisis menggunakan data SPT dihitung dengan persamaan Reese & Wright, sedangkan data uji pembebanan dianalisis menggunakan metode interpretasi kurva yang meliputi Metode Davisson, Metode Chin, dan Metode Mazurkiewicz. Sementara itu, analisis Metode Elemen Hingga (Finite Element Method/FEM) dilakukan menggunakan program FEM (PLAXIS). Hasil analisis menunjukkan bahwa kapasitas daya dukung aksial ultimit bored pile tunggal (Qu) yang diperoleh dari metode analitis adalah 600 ton, Metode Chin berdasarkan data Uji Pembebanan Statik adalah 617,895 ton, dan Metode Mazurkiewicz berdasarkan data Uji Pembebanan Statik adalah 590,65 ton. Metode Elemen Hingga (FEM) menghasilkan kapasitas daya dukung ultimit (Qu) sebesar 597,8 ton dengan kecenderungan penurunan ke atas. Penurunan

pondasi bored pile tunggal dari kurva Uji Pembebanan Statik adalah 25,66 mm, sedangkan Metode Mazurkiewicz menunjukkan penurunan sebesar 24 mm.
Kata kunci: *Daya Dukung, Penurunan, Bored Pile, Metode Elemen Hingga*

INTRODUCTION

Large-scale infrastructure projects, such as stadiums, require structural and foundation systems capable of safely and reliably supporting significant loads. As wide-span structures with large capacities, stadiums are subjected to various types of loads, including dead loads, live loads, and other loads acting on the superstructure, which must be effectively transferred to the soil through the foundation system (Truty, 2024). Foundations serve as the lower structural elements that transfer all loads from the superstructure to the ground, which possesses adequate bearing capacity, thereby ensuring the building's stability. Consequently, foundation design is a critical factor in ensuring safety, structural performance, and the long-term functionality of the building (Satria & Rasidi, 2021).

The North Sumatra Main Stadium, located in the North Sumatra Sport Center area, Deli Serdang Regency, is planned to serve as the main stadium for the 21st National Sports Week (PON). In this project, a deep foundation system in the form of bored piles with a diameter of approximately 80 cm is used to support the load of the superstructure. The selection of bored piles as the foundation type is based on surface soil conditions that have relatively low bearing capacity or consist of unstable soil layers, so that the structural load needs to be transferred to deeper soil layers with better mechanical characteristics (Das & Sobhan, 2014).

Bored pile foundations bear axial loads through a combination of end bearing and skin friction. In the design of pile foundations, not only must the bearing capacity be considered (Siemaszko, 2024), but also soil deformation, as indicated by the amount of settlement. The settlement value is influenced by various factors such as soil mechanical properties, soil–structure interaction, pile configuration, and construction methods (Chen & Chen, 2024). Excessive foundation settlement or differential settlement can cause structural damage and reduce building performance, making settlement analysis a critical aspect of deep foundation design (Gendy, 2025).

Analysis of large-diameter bored pile foundations increasingly employs numerical approaches based on the Finite Element Method (FEM). This method can model soil–foundation interaction more realistically than conventional analytical methods (Brinkgreve et al., 2018). Other studies indicate that the finite element method can better describe the load–settlement relationship of bored pile foundations because it accounts for nonlinear soil behavior and soil–structure interaction (Pham et al., 2024). Furthermore, studies on bored pile foundation analysis indicate that the FEM is widely used for large-diameter pile foundations because it can simulate field conditions more closely to actual conditions (kaisar, 2025). In addition, studies on the analysis of bored pile foundations indicate that the FEM is widely used for large-diameter pile foundations because it can simulate field conditions more closely to actual conditions (Mungkur et al, 2025).

Based on this literature review, the scientific novelty (state of the art) of this study lies in the application of the finite element method with a Hardening Soil model to analyze the axial bearing capacity and settlement of bored pile foundations for the North Sumatra Main Stadium project in an integrated manner, as well as directly comparing these results with those from static loading tests conducted in the field. Similar studies are still limited to locations with different geotechnical conditions, so validation of the actual foundation behavior at the study site is necessary. It is hoped that this novel contribution can provide a reference for the design of bored pile foundations in projects with relatively unstable soil conditions in the North Sumatra region.

The research questions in this study are: (1) what are the differences in the axial bearing capacity of bored pile foundations between the results of static loading tests and the results of numerical analysis using FEM?; (2) how do the axial settlement values of bored pile foundations compare between field test results and numerical analysis results?; (3) To what extent can the soil parameters used in numerical modeling represent the actual behavior of bored pile foundations in the field?

This study has the following scope limitations: (1) the project data used in this study was collected from the construction of the North Sumatra Main Stadium Sports Center, located in Sena Village, Batang Kuis Subdistrict, Deli Serdang Regency; (2) the data used consists of results from static loading tests conducted by the contractor, as well as some data from the correlation of bore logs and SPT (Standard Penetration Test) results; (3) the analysis focuses solely on calculating the axial bearing capacity of single bored piles and the elastic settlement of bored pile foundations; (4) the analysis uses the finite element method (FEM) with a Hardening Soil model; (5) the analysis results cover only the axial bearing capacity of the bored pile and the elastic settlement of the bored pile; (6) this study does not discuss the lateral behavior of the foundation, does not analyze the effects of seismic loads, and does not include pile group analysis.

The objectives of this study are: (1) to analyze and compare the axial bearing capacity of bored pile foundations between the results of static loading tests and the results of numerical analysis using FEM;

$$Q_u = Q_p + Q_s$$

(2) to evaluate the comparison of axial settlement values of bored pile foundations between field test results and numerical analysis results; (3) to assess the representativeness of soil parameters used in numerical modeling regarding the actual behavior of bored piles in the field.

Basic Concepts of Bored Pile Foundations

A bored pile foundation is a foundation shaped like a long tube (Hutapea & Roesyanto, 2021), created by first drilling into the ground using a drilling rig, then filling the drilled hole with steel reinforcement and concrete (Waheed & Asmael, 2023). Bored pile foundations are classified as deep foundations designed to support heavy building structures. Loads acting on a building are borne by the building structure and transmitted to the foundation to be transferred to the ground. (Banta, 2025; Yuliawan &Rahayu, 2018).

Axial Bearing Capacity of Piles

The test load applied is 200% of the design load, with incremental increases of 25% of the design load. However, if failure occurs before reaching the maximum load, the testing process is stopped. Further loading is performed only if the settlement rate does not exceed 0.25 mm per hour (or 0.01 inch per hour), and each stage does not exceed two hours in duration. If failure occurs, the maximum load applied may be unloaded after a 12-hour rest period, provided that the settlement during the last hour does not exceed 0.25 mm (0.01 inch). If the settlement is still greater than 0.25 mm, the load must be maintained for 24 hours. ASTM (2013). Standard Test Methods for Deep Foundations Under Static Axial Compressive Load (ASTM D1143/D1143M-07). ASTM International, West Conshohocken, PA.

Table 1 Cyclic Loading: Loading-Unloading Procedure

Cyclic 1	0 %	25%	50%	25%	0%					
Cyclic 2	0%	50%	75%	100%	75%	50%	0%			
Cyclic 3	0%	50%	100%	125%	150%	125%	100%	50%	0%	
Cyclic 4	0%	50%	100%	150%	175%	200%	150%	100%	50%	0%

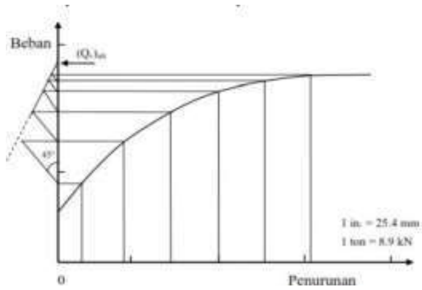
Sumber : (ASTM D1143)

Intepretasi Loading Test

The ultimate bearing capacity (Qu) of bored pile foundations can be determined based on Static Loading Test (SLT) data using the Chin and Mazurkiewicz methods. The Chin method uses a linear relationship between the settlement-to-load ratio (s/Q) and settlement (s), expressed as:

$$s/Q = C_1 s + C_2$$

A graph is plotted of s/Q versus s, and the Qu value is obtained from the inverse of the slope of the line (1/slope). This method tends to yield higher (more optimistic) values. The Mazurkiewicz method uses a direct relationship between load (Q) and settlement (s) in graphical form. The Qu value is determined from the point where the interpretation line intersects the load–settlement curve. This method is graphical and generally yields more conservative results. Using both methods together can provide more accurate results in determining the ultimate bearing capacity of the foundation.



Gambar 1. Graph showing the relationship with the Mazurkiewicz method's decline

Intepretasi Loading Test

In geotechnical analysis using the finite element method, soil models are used to represent the mechanical behavior of soil under loading. The Mohr-Coulomb (MC) model is a simple elastic-plastic model based on shear failure criteria, with the primary parameters being cohesion (c) and internal friction angle (φ). This model assumes a linear stress–strain relationship up to the yield point, making it widely used for preliminary analyses due to its simplicity. However, it has limitations in describing nonlinear soil behavior and changes in stiffness due to strain level (Das & Sobhan, 2014).

The Hardening Soil (HS) model is a more advanced elastoplastic model capable of describing soil behavior nonlinearly by considering the influence of stress level on soil stiffness. This model uses stiffness parameters such as the secant modulus (E_{50}), oedometer modulus (Eoed), and reloading modulus (Eur). Additionally, this model can represent the phenomenon of strain hardening as well as the difference in response between initial loading and reloading, thereby providing more realistic results in deformation analysis and soil–structure interaction (Schanz,Vermeer & Bonnier, 1999).

Thus, the Mohr-Coulomb model is simpler and suitable for preliminary analysis, while the Hardening Soil model is more accurate for deformation analysis and complex soil conditions.

METHOD

Research Location

This study was conducted as part of the construction project for the North Sumatra Main Stadium, located in Sena Village, Batang Kuis Subdistrict, Deli Serdang Regency, North Sumatra, and included:

1. Static Load Test on 80 cm diameter bored pile foundations
2. Collection of SPT data from soil investigation results (borehole log BH-3).
3. Numerical simulation using PLAXIS 3D.

Soil Parameters

Lapisan	Kedalaman (m)	Tipe Tanah	N-SPT	γsat (kN/m³)	c' (kPa)	Φ' (°)	E50 (kPa)	Eoed (kPa)
1	+2.9 – 0	Timbunan	-	17.55	0	23.1	15000	15000
2	0 – 7	Silty Clay (Lunak)	6	16.40	16.5	23.4	1996	1996
3	7 – 14	Silty Sand (Lepas)	8	18.15	14.4	24.0	3324	3324
4	14 – 20	Silty Sand (Sedang)	25	17.35	0	23.1	3854	3854
5	20 – 36	Silty Sand (Padat)	55	17.33	0	23.1	6993	6993
6	36 – 40	Silty Clay (Kaku)	20	18.13	15.6	23.6	3865	3865
7	40 – 50	Aluvium	70	18.48	15.6	23.6	4679	4679

Research Diagram

This study followed the following systematic steps:

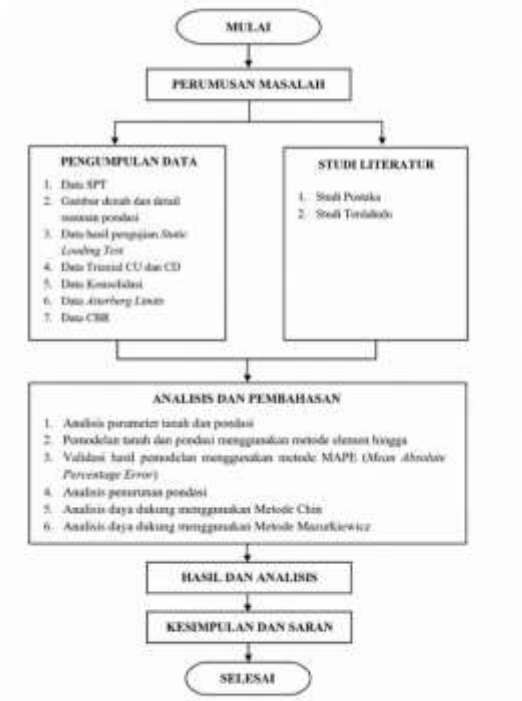


Figure 2 Research Flowchart

RESULTS AND DISCUSSION

Interpretation of Load Test Results

The load-settlement curve from the static load test (200% of design load / 400 tons) yielded three estimates of ultimate capacity:

Chin Method : 617.895 tons
Mazurkiewicz Method : 590.65

The Mazurkiewicz value is considered sufficiently representative because it lies between the conservative and optimistic values.

Numerical Simulation with PLAXIS 3D

Finite element modeling provides results consistent with field data (Table 1):

Table 2 Comparison of Simulation Results :

Parameter	**Chin**	**Mazurkiewich**	**FEM**
Qu (ton)	617.895 ton	590.65 ton	600 ton
Penurunan (mm)	75 mm	60 mm	65 mm

The results of numerical simulations using the finite element method (FEM) indicate an ultimate bearing capacity (Qu) of 600 tons, which falls between the results of the Chin method (617.895 tons) and the Mazurkiewicz method (590.65 tons). This indicates that the simulation results show a fairly consistent trend with field interpretation data, particularly falling within the range of conservative and optimistic values. In terms of settlement, the Chin and Mazurkiewicz methods provide relatively consistent values, namely 75 mm and 60 mm, respectively. Meanwhile, the FEM simulation results show a significantly larger settlement value of 65 mm. This difference indicates that numerical models tend to provide deformation predictions that are more sensitive to the soil parameters and boundary conditions used in the modeling. Overall, the Mazurkiewicz method can be considered more representative in describing actual field conditions because it produces more conservative values. On the other hand, the FEM simulation results show a trend that approaches the average value of the two interpretation methods, so they can be used as an additional verification tool in foundation bearing capacity analysis.

CONCLUSION

1. Based on the validation results using the MAPE (Mean Absolute Percentage Error) method, it was found that the FEM modeling results showed a fairly good level of agreement with the Static Loading Test data during the loading phase, with MAPE values of 13.42% in Loading Cycle II, 12.55% in Loading Cycle III, and 5.04% in Loading Cycle IV. These values indicate that the soil model used is sufficiently representative in describing the behavior of bored pile foundations. However, during the reloading and unloading phases, relatively high MAPE values were still obtained, indicating a discrepancy in response between the simulation results and actual field conditions.
2. Analysis results show differences in ultimate bearing capacity (Qu) and foundation settlement values among the FEM, Chin, and Mazurkiewicz methods due to differing approaches in interpreting the relationship between load and foundation settlement.
3. The FEM method yields an ultimate bearing capacity of 600 tons with a settlement of 65 mm; the Chin method yields the highest Qu value of 617 tons with a settlement of 75 mm; while the Mazurkiewicz method yields a Qu value of 590.65 tons with a settlement of 60 mm.
4. The Mazurkiewicz method can be considered sufficiently representative as it falls between the conservative and optimistic results, while the Chin method can serve as an upper bound; therefore, the use of more than one analysis method is highly recommended to obtain more accurate and reliable results.

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