

Comparative Analysis of Driven Pile Bearing Capacity Based on Pile Driving Analyzer Test Results and Settlement Evaluation of the Berawa Hotel Project

Ratna Santika ¹, I Wayan Ariyana Basoka ^{2✉}, Ida Ayu Cri Vinantya Laksmi ³
(1,2,3) Department of Civil Engineering, Warmadewa University, Bali, Indonesia

Abstract: Bearing capacity and settlement are fundamental parameters in foundation design, as inaccurate estimations can trigger excessive or differential settlement. Although Standard Penetration Test (SPT) empirical methods are widely used in practice, their predictive accuracy varies depending on site-specific ground conditions. This study evaluated the applicability of five SPT-based empirical methods (Meyerhof, Poulos and Davis, U.S. Army Corps, Coyle and Castello, and Kulhawy) for driven pile foundations in sandy gravel soil at the Berawa Hotel project site. Empirical predictions were compared against Pile Driving Analyzer (PDA) test results and finite element analysis using PLAXIS 3D. The Coyle and Castello method provided the closest empirical agreement to the field PDA test ($Q_{ult} = 173.00$ tons), predicting an ultimate bearing capacity of 213.74 tons (23.55% relative difference). PLAXIS 3D further refined this estimate to 199.76 tons (15.47% relative difference). For total settlement (13.15 mm measured via PDA), predictions were 6.94 mm for Coyle and Castello and 4.28 mm for PLAXIS 3D. Among the empirical approaches evaluated, Coyle and Castello is the most reliable for bearing capacity estimation in this soil profile, while PLAXIS 3D serves as a robust numerical tool for verifying overall foundation performance.

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INTRODUCTION

The rapid growth of the tourism industry in Bali, particularly in the Berawa area, has stimulated the development of various infrastructure projects, including hotels and other commercial buildings. The construction of multistory buildings requires foundation systems capable of safely transferring structural loads to competent bearing strata. Structures subjected to substantial loads generally require deep foundations to transfer loads to stronger soil layers located at greater depths below the ground surface (Kushartomo & Kevin, 2021). Among the various deep foundation systems used in multistory construction, driven pile foundations are one of the most widely adopted solutions.

In foundation engineering, bearing capacity and settlement are the primary design parameters that must be carefully evaluated to ensure structural safety and serviceability. Inaccurate estimation of these parameters may result in excessive settlement, differential settlement, and, in severe cases, structural failure. Therefore, foundation systems must be designed to adequately support applied loads while minimizing deformations that could compromise the structural integrity and performance of the structure (Basoka, 2020).

Furthermore, the performance evaluation of driven pile foundations is highly dependent on the accuracy of estimating ultimate bearing capacity and skin friction, which must be tailored to local soil stratifications. Uncertainties in determining shear parameters for coarse-grained soil layers often lead

to significant discrepancies between empirical analytical results and actual field conditions. Therefore, a comparative approach combining dynamic testing data, such as the Pile Driving Analyzer (PDA), with three-dimensional finite element numerical modeling is essential to verify the bearing capacity and the settlement behavior of the structure (Raharjo & Pratama, 2023).

The determination of pile foundation bearing capacity is generally performed using empirical approaches based on Standard Penetration Test (SPT) data. Nevertheless, the accuracy of each empirical method varies depending on field soil conditions. Consequently, direct testing methods, such as the Pile Driving Analyzer (PDA) test, are often employed to evaluate and validate analytical predictions. Soil conditions in coastal areas are typically characterized by a high degree of heterogeneity, resulting in significant variations in soil parameters that influence bearing capacity analysis. These variations are affected by depositional processes, groundwater conditions, and other environmental factors, making accurate geotechnical parameter evaluation essential for foundation design (Basoka, 2025).

Despite extensive research on driven pile bearing capacity in standard granular soils, predicting foundation performance in highly heterogeneous sandy gravel deposits, such as those found in the coastal regions of Bali, remains a critical engineering challenge. Existing empirical methodologies frequently over- or underestimate bearing capacity due to generalized stress assumptions that fail to capture the severe grain crushing, localized density variations, and dynamic degradation unique to coarse gravelly strata. Furthermore, while previous studies often evaluate empirical formulations or three-dimensional finite element numerical modeling in isolation, a comprehensive cross-validation that simultaneously integrates multiple empirical methods, field Pile Driving Analyzer dynamic test results, and three-dimensional finite element continuum settlement analysis under actual project conditions is still scarce in current literature. To address this research gap, this study offers key scientific novelties by providing a systematic accuracy benchmark of five widely used Standard Penetration Test empirical methods against high-strain dynamic field test data specifically calibrated for sandy gravel ground conditions. Additionally, this work elucidates the physical mechanisms governing the discrepancy between measured field settlement and numerical predictions, demonstrating how dynamic pile installation disturbance and grain crushing affect serviceability limits compared to linear-elastic constitutive models. Ultimately, this research establishes an empirical-numerical validation framework that identifies the Coyle and Castello method as the most reliable empirical tool and PLAXIS 3D as a safe lower-bound verification tool for high-rise building foundations in coastal gravelly soils, directly reducing geotechnical design uncertainty for regional infrastructure projects.

This study was conducted to compare the bearing capacities of driven pile foundations estimated using several empirical methods with those obtained from PDA test results, as well as to compare pile settlement values derived from empirical calculations and numerical modeling using PLAXIS 3D. Based on this background, the study addresses two main issues: (1) the comparison of pile bearing capacities predicted by various empirical methods and PLAXIS 3D analysis with those obtained from PDA testing; and (2) the comparison of pile settlement values derived from empirical calculations, PDA measurements, and PLAXIS 3D numerical analysis. The findings of this study are expected to provide a more reliable basis for selecting appropriate methods to evaluate the performance of driven pile foundations in sandy gravel soil conditions similar to those encountered at the Berawa Hotel project.

RESEARCH METHOD

Project Description

The case study for this research was conducted at the Berawa Hotel development project. The project is located in Tibubeneng Village, North Kuta District, Badung Regency, Bali Province, Indonesia. The site is situated within a rapidly developing area characterized by tourism facilities, accommodations, villas, and commercial establishments. The surrounding environment exhibits a high level of development activity, necessitating a foundation system capable of ensuring the structural stability and serviceability of the building.

Based on the site investigation, the subsurface conditions are predominantly composed of sandy gravel and hard soil layers (gravelly sandstone), which significantly influence the bearing capacity of the pile foundation used in the project. The foundation system consists of single driven piles (single-pile foundations). The piles were designed with a cross-sectional dimension of 40 × 40 cm and an embedded depth of 6.8 m. The pile caps are constructed of reinforced concrete with a compressive strength of K-500 and are designed in a square configuration (Carista, 2024).

Soil Investigation and PDA Test

Soil investigation was conducted to obtain information regarding subsurface stratification and geotechnical parameters required for foundation design (H. T. Santoso & Hartono, 2020). The Standard Penetration Test (SPT) is a widely used field investigation method for evaluating soil characteristics based on N-SPT blow counts (Pratama et al., 2022).

Table 1. Standard Penetration Test (SPT) Results

Depth (m)	Soil Description	SPT Value	Corrected N-SPT
1	Soft silty clay	2	1.74
3	Fine- to medium-grained dark gray sand	10	8.71
5	Yellowish-brown sandy gravel	18	15.68
8	Yellowish-brown sandy gravel	25	21.77
>9.0	Dark gray coarse sandy gravel	60	52.25

To evaluate the performance of the pile foundation at the Berawa Hotel Project, Pile Driving Analyzer (PDA) testing was conducted. PDA testing is widely used to rapidly and efficiently verify the actual bearing capacity of pile foundations compared with conventional static load testing (Kusuma et al., 2022). In this study, PDA testing was performed at five pile locations, namely TP 98, TP 383, TP 469, TP 629, and TP 646. The tested piles consisted of precast reinforced concrete piles with cross-sectional dimensions of 40 × 40 cm and an embedded length of 6.8 m. A summary of the bearing capacity and settlement results obtained from the PDA tests is presented in Table 2. The pile tested via PDA at TP383, which represents the location subjected to the highest structural loads, exhibited

the maximum bearing capacity and was selected as the reference pile for comparison with empirical methods and numerical modeling.

Table 2. PDA Test Results

Pile Name/ Pile Test	PDA		CAP WAP			
	Bearing Capacity	Bearing Capacity	Skin Friction	End Bearing	Elastic Displacement	Displacement Maksimum
	(RMX/RSU) [ton]	(Ru) [ton]	(SF) [ton]	(EB) [ton]	(Dy) [mm]	(Dx) [mm]
TP 98	131	137	31	106	8,55	9.73
TP 383	173	173	37	136	8,14	13,13
TP 469	150	151	82	68	7,65	11,04
TP 629	98	100	61	39	13,15	21.34
TP 646	135	144	73	72	8,02	9,01

Driven Pile Bearing Capacity Analysis

The bearing capacity analysis of driven piles was conducted to determine the ability of the pile foundation to safely support and transfer structural loads to the surrounding soil through both end-bearing resistance and shaft resistance (Mulyono & Agustina, 2022) In this study, several empirical methods were employed, including:

a. Meyerhof Method

The calculation of pile end-bearing capacity (Q_b) was performed using the Meyerhof method, which considers the soil characteristics at the pile tip level. The equation used to determine the end-bearing capacity is presented as follows:

$$Q_b = A_b (38 \bar{N}) \left(\frac{L_b}{d} \right) \leq 380 \bar{N} A_b \quad (1)$$

The pile shaft resistance (Q_s) was determined using the Meyerhof method by considering the soil parameters along the interface between the pile shaft and the surrounding soil. The governing equations used in the calculation are presented as follows:

$$Q_s = A_s f_s \quad (2)$$

$$f_s = \frac{1}{50} \sigma_r N_{60} \quad (3)$$

where Q_b is the pile end-bearing capacity (kN), A_b is the pile base area (m^2), N is the average SPT value around the pile tip, $\frac{L_b}{d}$ is the embedment ratio of the bearing layer, Q_s is the pile shaft resistance (kN), A_s is the pile shaft surface area (m^2), f_s is the unit shaft resistance (kN/m^2), σ_r is the reference stress, and N_{60} is the corrected SPT value corresponding to a hammer energy efficiency of 60%.

b. Poulos & Davis Method

The calculation of pile end-bearing capacity (Q_b) was performed using the Poulos and Davis method, which considers the soil characteristics at the pile tip level. The equation used to determine the end-bearing capacity is presented as follows:

$$Q_b = A_b f_b \quad (4)$$

$$f_b = p'_b N_q \quad (5)$$

where Q_b is the pile end-bearing capacity (kN), A_b is the cross-sectional area of the pile tip (m^2), f_b is the unit end-bearing resistance (kN/m^2), p'_b is the effective vertical stress acting at the pile tip (kN/m^2), and N_q is the bearing capacity factor associated with end-bearing resistance.

The effective friction angle (ϕ') was estimated from the SPT N-value using the empirical correlation proposed by (Peck et al., 1974). The bearing capacity factor (N_q) was subsequently determined using the relationship between N_q and ϕ' developed by (Berezantzev, 1961). The critical depth ratio (z_c/d) and the coefficients K_d and δ were obtained from the correlations proposed by (Poulos & Davis, 1980).

The pile shaft resistance (Q_s) was determined using the Poulos and Davis method by considering the soil parameters along the interface between the pile shaft and the surrounding soil. The governing equations used in the calculation are presented as follows.

$$Q_s = A_s f_s \quad (6)$$

$$f_s = K_d p'_o \tan \delta \quad (7)$$

where Q_s is the pile shaft resistance (kN), A_s is the surface area of the pile shaft (m^2), f_s is the unit shaft resistance (kN/m^2), K_d is the coefficient of lateral earth pressure, p'_o is the average effective vertical stress acting along the pile shaft (kN/m^2), and δ is the pile-soil interface friction angle, where $\tan \delta$ represents its tangent value.

The values of K_d and $\tan \delta$ were estimated from the effective friction angle (ϕ') using the empirical relationships proposed by (Poulos & Davis, 1980).

The ultimate pile bearing capacity (Q_{ult}) and allowable pile bearing capacity (Q_{all}) were determined based on the combined contributions of pile end-bearing capacity and shaft resistance. The equations used in the calculations are presented as follows.

$$Q_{ult} = Q_b + Q_s - W_p \quad (8)$$

$$Q_{all} = \frac{Q_{ult}}{SF} \quad (9)$$

where W_p is the self-weight of the pile (kN), Q_{all} is the allowable pile bearing capacity (kN), and SF is the safety factor.

c. U.S Army Corps Method

The calculation of pile end-bearing capacity (Q_b) was performed using the U.S. Army Corps method, which considers the soil characteristics at the pile tip level. The equation used to determine the end-bearing capacity is presented as follows.

$$Q_b = A_b f_b \quad (10)$$

$$f_b = p'_b N_q \quad (11)$$

where the symbols have the same definitions as those presented in Equations (2) and (3).

The bearing capacity factor (N_q) was determined from its relationship with the effective friction angle (ϕ'), as proposed by (Reese et al., 2006).

The pile shaft resistance (Q_s) was determined using the U.S. Army Corps method by considering the soil parameters along the interface between the pile shaft and the surrounding soil. The governing equation used in the calculation is presented as follows.

$$Q_s = A_s f_s \quad (12)$$

$$f_s = K_d p'_o \tan \delta \quad (13)$$

where the symbols have the same definitions as those presented in Equations (4) and (5).

The ultimate pile bearing capacity (Q_{ult}) and allowable pile bearing capacity (Q_{all}) were determined based on the combined contributions of pile end-bearing capacity and shaft resistance. The equations used in the calculations are presented as follows.

$$Q_{ult} = Q_b + Q_s - W_p \quad (14)$$

$$Q_{all} = \frac{Q_{ult}}{SF} \quad (15)$$

where the symbols have the same definitions as those presented in Equations (6) and (7).

d. Coyle & Castello Method

In predicting pile bearing capacity within non-cohesive or granular soils, the empirical method of Coyle & Castello is frequently referenced because it comprehensively considers the pile embedment depth and the soil's internal friction angle. Compared to other conventional methods, this empirical correlation effectively minimizes deviations from field dynamic load test results. Furthermore, modeling using the Mohr-Coulomb constitutive model in finite element-based software provides an accurate visual representation of stress distribution and plastic deformation around the pile shaft (Wijaya & Kusuma, 2024).

The calculation of pile end-bearing capacity (Q_b) was performed using the Coyle and Castello method, which considers the soil characteristics at the pile tip level. The equation used to determine the end-bearing capacity is presented as follows.

$$Q_b = A_b f_b \quad (16)$$

where the symbols have the same definitions as previously described.

The net unit end-bearing resistance (f_b) of piles in sandy soils was determined using the correlation proposed by (Coyle & Castello, 1981).

The pile shaft resistance (Q_s) was determined using the Coyle and Castello method by considering the soil parameters along the interface between the pile shaft and the surrounding soil. The governing equation used in the calculation is presented as follows.

$$Q_s = A_s f_s \quad (17)$$

where the symbols have the same definitions as previously described.

The unit shaft resistance (f_s) in granular soils was determined using the correlation proposed by (Coyle & Castello, 1981).

The ultimate pile bearing capacity (Q_{ult}) and allowable pile bearing capacity (Q_{all}) were determined based on the combined contributions of pile end-bearing capacity and shaft resistance. The equations used in the calculations are presented as follows.

$$Q_{ult} = Q_b + Q_s - W_p \quad (18)$$

$$Q_{all} = \frac{Q_{ult}}{SF} \quad (19)$$

where the symbols have the same definitions as those presented in Equations (6) and (7).

e. Kulhawy Method

The calculation of pile end-bearing capacity (Q_b) was performed using the Kulhawy method, which considers the soil characteristics at the pile tip level. The equation used to determine the end-bearing capacity is presented as follows.

$$Q_b = A_b f_b \quad (20)$$

where the symbols have the same definitions as previously described.

The pile shaft resistance (Q_s) was determined using the Kulhawy method by considering the soil parameters along the interface between the pile shaft and the surrounding soil. The governing equation used in the calculation is presented as follows.

$$Q_s = A_s f_s \quad (21)$$

where the symbols have the same definitions as previously described.

The bearing capacity factor (N_q) was determined using the correlation proposed by (Kulhawy, 1983).

The ultimate pile bearing capacity (Q_{ult}) and allowable pile bearing capacity (Q_{all}) were determined based on the combined contributions of pile end-bearing capacity and shaft resistance. The equations used in the calculations are presented as follows.

$$Q_{ult} = Q_b + Q_s - W_p \quad (22)$$

$$Q_{all} = \frac{Q_{ult}}{SF} \quad (23)$$

where the symbols have the same definitions as those presented in Equations (6) and (7).

f. Plaxis 3D Bearing Capacity Analysis

The bearing capacity obtained from the PLAXIS 3D analysis was calculated using the following equation:

$$Q = \sum M_{stage} \times P \quad (24)$$

where Q is the foundation bearing capacity, $\sum M_{stage}$ represents the cumulative loading multiplier obtained from PLAXIS 3D, and P is the maximum structural load applied to the foundation.

Driven Pile Settlement Analysis

Driven pile settlement analysis is performed to determine the magnitude of vertical deformation experienced by a foundation as a result of structural loads acting on the supporting soil layers (Azizi et al., 2020).

$$S = \frac{D}{100} + \frac{QL}{A_p E_p} \quad (25)$$

where S is the total settlement at the pile head (m), D is the pile diameter (m), Q is the applied axial load (ton), A_p is the cross-sectional area of the pile (m^2), L is the pile length (m), and E_p is the modulus of elasticity of the pile material (ton/m^2).

Settlement analysis of single-driven pile foundations requires verification between theoretical elastic calculations, dynamic sensor readings, and three-dimensional numerical simulations. The actual settlement recorded through PDA testing provides a realistic overview of the pile's elastic response under working loads. Although numerical modeling results may sometimes produce smaller deformation estimates due to assumptions of soil media homogeneity, this combination of approaches ensures that the foundation design remains within the safe tolerance limits required by geotechnical engineering standards (Prasetyo & Wibowo, 2022).

Analysis Plaxis 3D

A three-dimensional finite element analysis was conducted using PLAXIS 3D to evaluate the axial load–settlement behavior of a single square driven pile with a cross-sectional dimension of 40×40 cm (Pile D40). The subsurface profile was modeled based on the BH-1 borehole investigation, consisting of two distinct soil layers: Sandy Gravel 1 at depths of 3.2 – 8.0 m (average SPT N-value = 21.77) and Sandy Gravel 2 at depths of 9.0 – 20.0 m (average SPT N-value = 52.25).

Due to limited laboratory test results, the geotechnical properties were estimated using empirical correlations derived from Standard Penetration Test (SPT-N) data shown in Table 3. The soil layers were modeled using the Mohr–Coulomb (MC) constitutive model under drained conditions. The concrete pile (D40) was represented as a non-porous linear-elastic structural material with a unit weight of 24 kN/m^3 , an elastic modulus (E) of $3.03 \times 10^7 \text{ kN/m}^2$ ($30,277,632.01 \text{ kN/m}^2$), and a Poisson's ratio (ν) of 0.20. The input soil parameters included unit weight ($\gamma = 18 \text{ kN/m}^3$ and 21 kN/m^3), saturated unit weight ($\gamma_{\text{sat}} = 20.5 \text{ kN/m}^3$ and 22.5 kN/m^3), elastic modulus ($E' = 1,372,931 \text{ kN/m}^2$), Poisson's ratio ($\nu' = 0.38$ and 0.40), cohesion ($c' = 5 \text{ kN/m}^2$), and internal friction angle ($\phi' = 38^\circ$ and 40°), as summarized in Table 3.

To ensure numerical stability and minimize boundary effects, the model domain was extended laterally to $10 \times D$ (where $D = 0.40$ m) from the pile center and vertically down to $1.5 \times L$ (where L is the embedded pile length) below the pile tip. Standard displacement boundary conditions were assigned: full fixity ($u_x = u_y = u_z = 0$) at the bottom boundary, lateral fixity with vertical movement allowed ($u_x = u_y = 0, u_z \neq 0$) along the model perimeter, and a free surface at the top elevation.

The soil–structure interaction was modeled using interface elements placed along the pile shaft and base with a strength reduction factor ($R_{\text{inter}} = 0.70$). Finite element discretization was performed using a 10-node tetrahedral mesh geometry. Local mesh refinement with an element size factor of 0.25 was applied around the pile perimeter and tip to accurately capture high stress concentrations. The numerical execution was carried out in three sequential calculation stages:

- Initial Phase: Generation of initial in-situ effective stress states via the K_0 -procedure using effective unit weights and earth pressure coefficients.
- Pile Installation Phase: Activation of the pile structural element and interaction interfaces, followed by resetting displacement fields to zero to isolate load-induced deformations.
- Loading Phase: Application of incremental vertical point loading at the pile head corresponding to the actual field loading procedure to derive the load–settlement curve.

Table 3. Input Parameters Used in PLAXIS 3D

Parameter	Sandy Gravel 1	Sandy Gravel 2	Pile D40	Unit
	(3.2 – 8)m	(9-20)m		
Material Model	MC	MC		
SPT N-Value	21.77	52.25		
Material Behavior	Drained	Drained	Non-porous	
Unit Weight	18	21	24	kN/m ³
Saturated Unit Weight	20.5	22.5		kN/m ³
Elastic Modulus	1372931	1372931	30277632.01	kN/m ²
Poisson's Ratio	0.38	0.4	0.2	
Cohesion	5	5		kN/m ²
Internal Friction Angle	38	40		

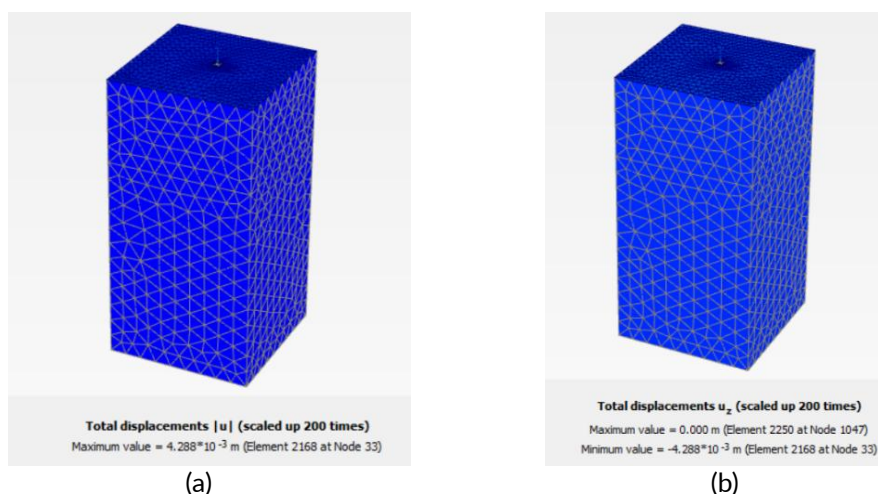


Figure 1. Total displacement contours: (a) maximum total displacement; (b) minimum total displacement

Figures 1(a) and 1(b) show the maximum and minimum total displacement contours of the pile foundation system obtained from the PLAXIS 3D analysis. A maximum displacement of 4.288 mm and a minimum displacement of -4.288 mm were recorded, with the negative value indicating downward settlement caused by axial loading. As the calculated maximum settlement is well below the allowable limit of 15.67 mm, the foundation system satisfies the serviceability criteria. These results confirm that the pile foundation exhibits sufficient stiffness and stability to support the applied load while maintaining acceptable deformation levels.

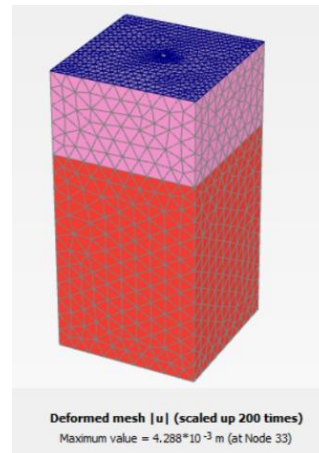


Figure 2. Deformed mesh obtained from the PLAXIS 3D analysis at the final loading stage

Figure 2 illustrates the deformed mesh obtained from the PLAXIS 3D analysis at the final loading stage under the maximum axial load derived from the ETABS structural analysis. The applied load was uniformly distributed to each single pile, with a load magnitude of 833 kN. The simulation results indicate that the applied loading produced a maximum settlement of 4.28 mm at the pile head. This settlement value remained well below the allowable limit, indicating that the pile foundation system satisfied the serviceability requirements and maintained stable performance under the design loading condition.

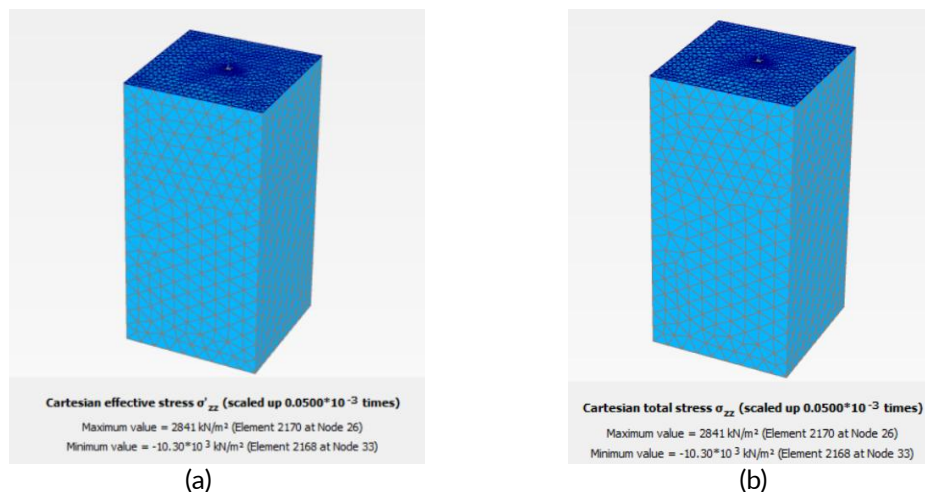


Figure 3. Vertical stress distribution: (a) vertical effective stress (σ'_{zz}); (b) vertical total stress (σ_{zz})

Figures 3(a) and 3(b) present the distributions of vertical effective stress (σ'_{zz}) and vertical total stress (σ_{zz}), respectively, obtained from the PLAXIS 3D analysis. Both stress contours exhibit similar distribution patterns, with a maximum stress of 2,841 kN/m² concentrated near the loaded area and gradually decreasing with increasing distance from the foundation. The effective stress distribution indicates the portion of the applied load carried by the soil skeleton, whereas the total stress distribution represents the overall stress state within the soil mass. The observed stress patterns demonstrate that the applied load was effectively transferred and distributed through the surrounding soil, indicating satisfactory load-transfer behavior and stable performance of the pile foundation system under the applied axial loading.

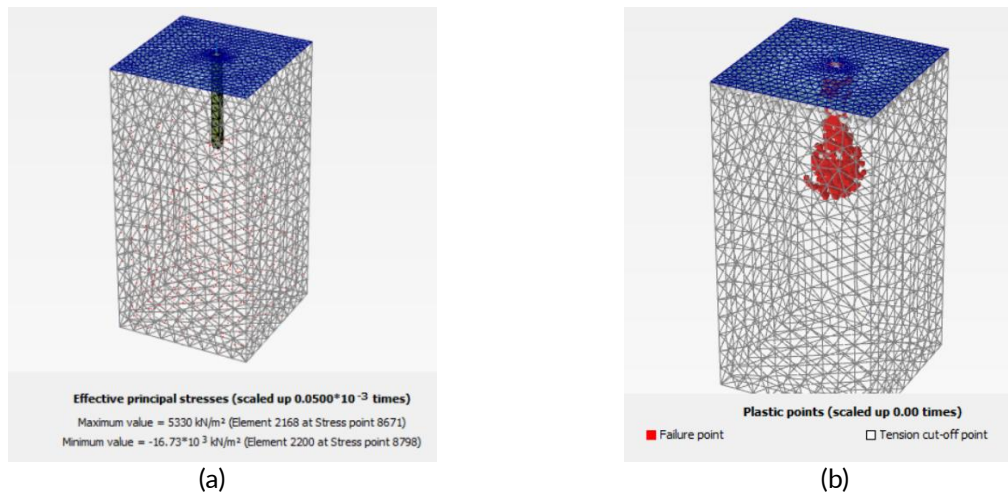


Figure 4. Soil response under axial loading: (a) effective principal stresses; (b) plastic points distribution

Figures 4(a) and 4(b) present the distributions of effective principal stresses and plastic points obtained from the PLAXIS 3D analysis. The maximum effective principal stress reached 5,330 kN/m² and was concentrated around the pile, indicating efficient load transfer from the foundation to the surrounding soil. The plastic points were primarily localized near the pile shaft and loading area, suggesting that yielding occurred only within a limited zone. Since the plastic zone did not develop into a continuous failure mechanism, the soil–foundation system remained stable under the applied axial load. These findings indicate that the pile foundation possesses adequate bearing capacity and exhibits satisfactory structural performance under the applied loading conditions.

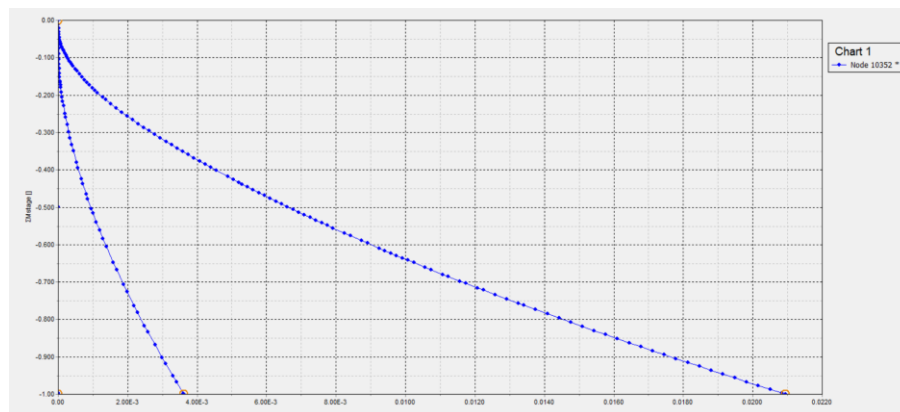


Figure 5. Relationship between load factor (ΣM_{stage}) and foundation settlement

The load–settlement relationship was evaluated using the ΣM_{stage} parameter obtained from the PLAXIS 3D analysis. The ΣM_{stage} value represents the proportion of the applied load relative to the maximum structural load carried by the foundation. In this study, the analysis was performed up to the allowable settlement limit of 15.67 mm in accordance with SNI 8460:2017. The relationship between ΣM_{stage} and settlement was subsequently used to determine the foundation bearing capacity corresponding to the allowable deformation criterion.

Based on the ΣM_{stage} -settlement relationship shown in Figure 5, a settlement of 15.4 mm corresponded to a ΣM_{stage} value of 0.82. Considering the maximum structural load of 2,360 kN obtained from the ETABS analysis, the foundation bearing capacity was calculated as :

$$Q = 0.82 \times 2360 = 1935.2 \text{ kN}$$

Based on the analysis, the estimated foundation bearing capacity corresponding to the allowable settlement condition is 1,935.2 kN. This value represents the maximum load that can be sustained by the foundation while satisfying the allowable settlement criterion.

RESULTS AND DISCUSSION

This section presents a comparison of the ultimate bearing capacity and settlement of the pile foundation obtained from empirical methods, PLAXIS 3D numerical analysis, and Pile Driving Analyzer (PDA) test results. The comparison aims to evaluate the accuracy and consistency of each approach in predicting pile foundation behavior. The results are presented in tables and figures to facilitate the interpretation and discussion of the differences among the evaluated methods.

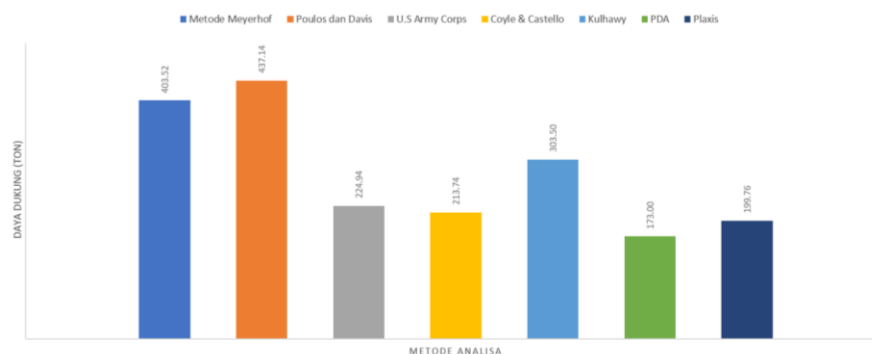


Figure 6. Comparison of Bearing Capacity

The comparison of ultimate bearing capacity (Q_{ult}) values obtained from the empirical methods, PLAXIS 3D analysis, and PDA testing is presented in Figure 6. Among the empirical methods evaluated, the Poulos and Davis method produced the highest ultimate bearing capacity, with a value of 437.14 tons, followed by the Meyerhof method at 403.52 tons. The Kulhawy method yielded an ultimate bearing capacity of 303.50 tons, whereas the U.S. Army Corps and Coyle and Castello methods resulted in capacities of 224.94 tons and 213.74 tons, respectively.

The PDA test indicated an ultimate bearing capacity of 173.00 tons, which was adopted as the reference value for evaluating the accuracy of the prediction methods. Relative to the PDA result, the Poulos and Davis method exhibited the largest deviation, amounting to 152.68%, followed by the Meyerhof method (133.25%), the Kulhawy method (75.43%), the U.S. Army Corps method (30.02%), and the Coyle and Castello method (23.55%). Among the empirical approaches, the Coyle and Castello method provided the closest agreement with the PDA measurement.

The PLAXIS 3D analysis predicted an ultimate bearing capacity of 199.76 tons, corresponding to a relative difference of 15.47% from the PDA result. This deviation is lower than those obtained from all evaluated empirical methods, indicating that the PLAXIS 3D prediction is the most consistent with the PDA test result. The relatively small percentage difference demonstrates the capability of PLAXIS 3D to realistically represent pile foundation behavior under the investigated soil conditions and loading characteristics.

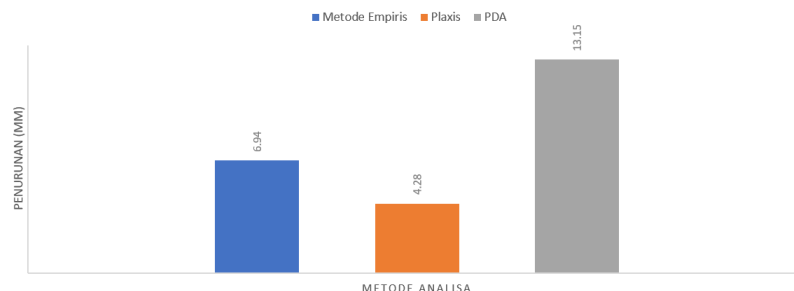


Figure 7. Comparison of Pile Foundation Settlement

Figure 7 presents a comparison of pile foundation settlement values obtained from the empirical method, PLAXIS 3D analysis, and PDA testing. The empirical method predicted a settlement of 6.94 mm, corresponding to a difference of 47.21% relative to the PDA measurement. The PDA test recorded a settlement of 13.15 mm, which was adopted as the reference value for evaluating the accuracy of the prediction methods.

The PLAXIS 3D analysis predicted a settlement of 4.28 mm, resulting in a difference of 67.45% relative to the PDA measurement. This deviation is greater than that obtained from the empirical method. Nevertheless, all predicted settlement values remained below the allowable settlement limit of 15 mm, indicating that the pile foundation satisfies the serviceability requirements. Based on the comparison with the PDA measurement, the empirical method provided a closer representation of actual field conditions than the PLAXIS 3D analysis.

Regarding the significant difference in settlement values—where the field PDA test recorded 13.15" mm" compared to 6.94" mm" from the empirical elastic formulation and 4.28" mm" from PLAXIS 3D—the variation is governed by three key physical mechanisms:

Dynamic Installation Effects & Local Grain Crushing: The PDA test captures actual field response under dynamic impact loading, including localized gravel particle degradation at the pile tip and soil remodeling around the shaft during driving. These dynamic driving stresses temporarily reduce soil stiffness and create a disturbed zone around the pile, resulting in larger initial elastic compliance (13.15" mm").

Simplification of Continuum Assumptions in Empirical Calculations: Empirical settlement formulations assume ideal elastic half-space behavior based on static SPT-N correlations. While they offer a closer approximation (6.94" mm") than PLAXIS 3D, they do not reflect localized particle rearrangement or dynamic pile driving histories.

Constitutive Model Stiffness in PLAXIS 3D: The PLAXIS 3D numerical model utilized the linear elastic-perfectly plastic Mohr–Coulomb model with a constant operational elastic modulus (E') under drained conditions. Because Mohr–Coulomb does not account for strain-dependent small-strain stiffness non-linearity or pile-driving-induced soil degradation, the numerical continuum exhibits a stiffer response, yielding a lower-bound settlement estimate (4.28" mm").

Despite these conceptual variations, all predicted and measured settlements remain safely within the allowable serviceability limit (15.67" mm") specified by SNI 8460:2017 for a 40×40" cm" pile peninsulas. This underscores that while PDA serves as the true physical benchmark for operational compliance, PLAXIS 3D provides a reliable lower-bound limit for structural displacement evaluation.

Based on the comparative analysis, the deviation between the ultimate capacity of empirical methods and PDA testing is influenced by the assumptions of load transfer parameters at the soil-pile interface. The Coyle & Castello method showed the lowest percentage of difference compared to the PDA data, which confirms the suitability of its formulation for the characteristics of sandy-gravelly soil. Meanwhile, the PLAXIS 3D numerical analysis indicated settlement patterns that satisfy serviceability limit criteria, proving that the foundation system's stiffness is capable of optimally controlling structural deformation (Nugroho & Setiawan, 2025).

Overall, the integration of field test data, selected empirical approaches, and state-of-the-art numerical modeling provides a comprehensive evaluation framework for foundation design in high-rise building structures. This cross-validation not only strengthens the scientific validity of the research findings but also minimizes the risk of geotechnical uncertainty in the field. The recommended analytical methods, which proved most accurate, are expected to serve as an applicable reference for the design of similar infrastructure projects in the future (P. Santoso & Darmawan, 2021).

CONCLUSION

Based on the investigation and comparative analysis conducted at the Berawa Hotel project site, the evaluation of driven pile foundation performance in sandy gravel soil yields specific conclusions regarding bearing capacity and settlement behavior. Among the five evaluated Standard Penetration Test empirical methods, the Coyle and Castello method provided the closest prediction of ultimate bearing capacity ($Q_{ult} = 213.74$ tons), exhibiting a relative difference of 23.55% compared to the field Pile Driving Analyzer reference result at pile TP383 (173.00 tons). The finite element analysis using PLAXIS 3D predicted an ultimate bearing capacity of 199.76 tons, corresponding to a relative difference of 15.47% from the test measurement. Regarding deformation response under working loads, the field test recorded a maximum total settlement of 13.15 mm, whereas the empirical elastic calculation and PLAXIS 3D numerical model yielded lower-bound predictions of 6.94 mm and 4.28 mm, respectively. These discrepancies stem from dynamic pile installation disturbances, localized gravel particle degradation, and the constant modulus assumption inherent in Mohr-Coulomb constitutive continuum modeling. Nevertheless, both predicted and measured settlement values satisfied the allowable serviceability limit of 15.67 mm specified by SNI 8460:2017 for the 40×40 cm square driven pile. Under the specific subsurface stratigraphy and loading conditions investigated, the Coyle and Castello formulation offers the most realistic empirical capacity estimation, while PLAXIS 3D serves as a conservative numerical verification tool for structural serviceability evaluation.

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