An Evaluation of the Axial Bearing Capacity of Piles in Soft Cohesive Soils Using Standard Methods and Numerical Simulation

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ABSTRACT

This study focuses on evaluating the axial bearing capacity of piles in soft, cohesive soils, which is a critical issue for construction projects in Vietnam's coastal plains. The following four methods were compared: the design of pile foundations (Vietnam standard TCVN 10304:2014), the highway bridge design specification (Vietnam standard TCVN 11823:2017), the , the Standard Penetration Test (SPT)-based Schmertmann method, and the finite element simulation method using Plaxis 3D. The results revealed significant differences among the methods. That is, the design of pile foundations and the highway bridge design specification showed axial capacities of 85.5 T and 87.8 T, respectively, which are higher than the 76.5 T value obtained from the static load test, indicating a conservative design approach. The Schmertmann method had the lowest value (66.7 T), while the Plaxis 3D simulation agreed with the experimental results (82.0 T), with a deviation of 7%, demonstrating the accuracy of Plaxis 3D in modeling soil-pile interaction. The correction factor (F_{hc}) ranged from 0.871 to 1.147, reflecting discrepancies between theoretical models and actual soil behavior. This study proposes adjusting Vietnamese design standards to reflect the geotechnical characteristics of soft coastal soils, improving the safety and economic efficiency of pile foundation design.

Keywords-reinforced concrete pile foundation; bored pile; pile bearing capacity; Schmertmann

I. INTRODUCTION

In Vietnam's coastal plains, where soft, cohesive soil conditions are common, accurately determining the axial bearing capacity of piles is key to ensuring the safety, stability, and economic efficiency of foundation design [1, 2]. In areas with complex geological conditions, particularly where thick, variable layers of soft clay and silt are present, determining pile bearing capacity poses a significant challenge to geotechnical engineers [3]. Current design standards, such as the design of pile foundations [4] and highway bridge design specifications [5], provide different theoretical bases for calculating pile resistance. Meanwhile, empirical methods, such as the Standard Penetration Test (SPT) and Cone Penetration Test (CPT), and numerical simulations (Plaxis 3D) offer results with varying reliability [6-8]. There is a significant discrepancy between theoretical calculations and field static load test results, especially in soils with low bearing capacity and highly nonlinear behavior. In this context, this study aims to compare and evaluate the accuracy of four methods for determining the axial bearing capacity of piles in soft cohesive soils. By determining the correction factor (F_{hc}) and comparing it with static load test results, this study seeks to establish a rational basis for selecting appropriate calculation methods under similar geotechnical conditions in Vietnam, contributing to the refinement of pile foundation design models for soft coastal soils.

II. MATERIALS AND METHODS

The study site is situated in the coastal region of southern Vietnam, specifically in Can Gio District, Ho Chi Minh City. The former is characterized by thick deposits of soft marine clay, while the soil data were obtained from a geotechnical examination at the site. The subsurface profile consists of three main layers, as shown in Table I. Layer 1 consists of grayish-black clay with significant silt content, exhibiting a soft-to-fluid consistency with an N-SPT of 1–5 blows per 30 cm, a unit weight of 1.50 g/cm³, and a natural water content of 79.4%. The internal friction angle of layer 1 ($\varphi = 30° 43'$) was obtained from Unconsolidated Undrained (UU) triaxial tests on samples collected in Can Gio District, Ho Chi Minh City. The relatively high φ value of this layer, which is classified as soft to fluid silty clay, is attributed to its significant silt content, the heterogeneous nature of the coastal marine deposits, and possible partial drainage during sampling and specimen preparation. Its cohesion c is 0.044 kg/cm², indicating very low shear strength. Layer 2 is stiff, grayish-brown clay with *N-SPT* = 9–16, γ = 1.97 g/cm³, W = 25.3%, φ = 19°26′, and c = 0.479 kPa, and it acts as the main load-bearing stratum. Layer 3 consists of light yellowish silty sand in a moderately dense state. It has an *N*-SPT of 8–33, a φ of 26°20′, and a c of 0.097 kg/cm², serving as the toe-bearing layer for pile embedment, as illustrated in Figure 1.

TABLE I. GEOTECHNICAL PARAMETERS

Soil layer	Composition	SPT	Unit weight γ (g/cm³)	Water content W (%)	Internal friction angle φ (°)	Cohesion c (kg/cm²)
1	Silty clay	1 – 5	1.50	79.4	3°43′	0.044
2	Clay	9 – 16	1.97	25.3	19°26′	0.479
3	Silty sand	8 – 33	1.97	22.4	26°20′	0.097

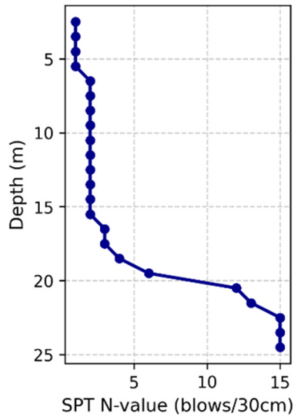

Fig. 1. SPT N-value versus depth.

This study determined the axial bearing capacity of piles using four approaches that combined national design standards, empirical methods, and numerical simulation techniques, as depicted in Figure 2. According to the design of pile foundations, the standard axial bearing capacity of a pile is:

$$Q_{DoPF} = m(m_R q_P A_P + u \sum m_f f_s l_i) \tag{1}$$

where the safety factor is taken as 1.4 [9]. This method considers both end-bearing and shaft resistance, reflecting the mechanical properties of each soil layer at different depths- an appropriate design method for pile foundations subjected to static loading under complex geotechnical conditions. Meanwhile, the highway bridge design specification, which is based on the AASHTO LRFD framework, defines axial resistance as:

$$QQ_R = \varphi_q Q_p + \varphi_s Q_s \tag{2}$$

where φ_q and φ_s are the resistance factors corresponding to tip resistance and shaft friction, respectively, which differ for cohesive and cohesionless soils [10]. This approach emphasizes limit-state design and allows the integration of field test results, such as SPT or CPT, to calibrate design values [11]. Additionally, the SPT-based Schmertmann method is used to predict pile bearing capacity directly from the SPT index (N_{60}) [12, 13]. The soil profile is divided into four groups—clay, clay-silt-sand mixtures, sand, and soft limestone—to determine shaft (Q_s) and tip (Q_p) resistance using empirical correlations that describe the relationships among N_{60}, depth, and soil type.

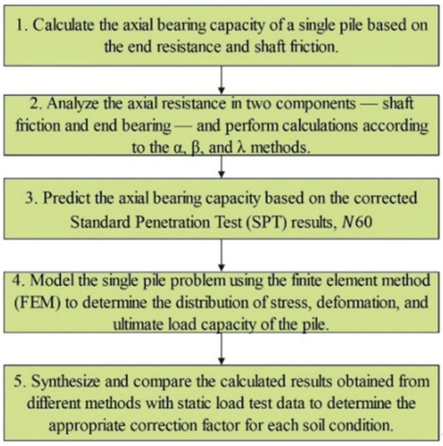

Fig. 2. Data processing procedure.

Finally, the finite element method (Plaxis 3D 2021.1, build 21.01.00) was used to simulate the soil-pile interaction process in detail, based on the Mohr-Coulomb constitutive model, as displayed in Table II [14, 15]. This enabled the evaluation of stress distribution, settlement, and mobilization of axial resistance along the pile.

TABLE II. INPUT PARAMETERS FOR NUMERICAL SIMULATION (PLAXIS 3D FOUNDATION)

Parameter	Symbol	Unit	Cohesive soil		
			Layer 1	Layer 2	Layer 3
Material model	Md		MC	MC	MC
Material behavior	Type		Undrained	Drained	Drained
Layer thickness	L	m	18.5	2.2	12.7
Unsaturated unit weight	γ_{unsat}	kN/m³	8.4	15.7	16.1
Saturated unit weight	γ_{sat}	kN/m³	15.0	19.7	19.7
Elastic modulus	E	kN/m²	7.2×10³	1.26×10⁴	1.9×10⁴
Poisson's ratio	v		0.3	0.3	0.3
Cohesion	c	kN/m²	19	3.5	2.8
Internal friction angle	φ	°	3°43′	19°26′	26°20′
Dilatancy angle	ψ	°	0	0	0

The Mohr–Coulomb model was adopted to allow direct comparison with national standard methods and for simplicity, as it requires only a limited number of input parameters that are easily obtained from routine site investigations and laboratory tests. Furthermore, this model is commonly used in engineering practice for preliminary and comparative analyses of pile behavior, especially in soft cohesive soils, providing a reasonable representation of soil strength under working load conditions. The safety factor (Fs) was determined using the Strength Reduction Method (SRM), which reduces shear parameters c and φ until failure occurs. The model consisted of approximately 52,000 nodes. The boundaries were fixed laterally and vertically at the base. The domain size was 15 m × 15 m × 30 m, and the mesh density was medium with local refinement near the pile, validating and calibrating theoretical predictions against actual static load test results. The static load test was conducted according to the standard test method for piles under axial compressive load (Vietnam standard TCVN 9393:2012) to determine the pile's ultimate load capacity at a settlement of 10% D. This procedure enables evaluating the pile's actual load-bearing performance and calibrating the theoretical calculation results, as shown in Figure 3.

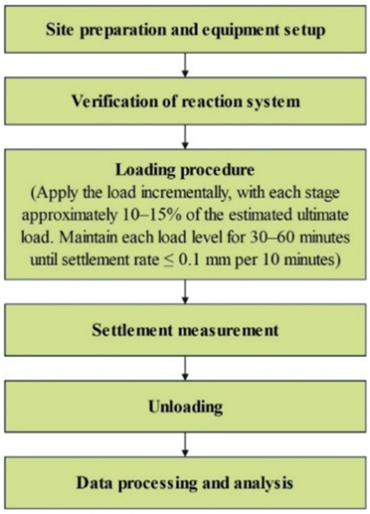

Fig. 3. Static load testing procedure.

III. RESULTS

As presented in Table III and Figure 4, the calculated axial bearing capacity results of the piles differ significantly, depending on the method applied. According to the design of pile foundations, the ultimate load capacity is 85.5 tons, as shown in Table IV, meaning that it is higher than the static load test result, and the correction factor is F_{hc} = 0.895, as demonstrated in Figure 5.

TABLE III. COMPARISON OF CALCULATED AXIAL BEARING CAPACITY AND CORRECTION FACTORS WITH STATIC LOAD TEST RESULTS

Pile name	Design of pile foundations	Highway bridge design specification	Schmertmann (SPT-based)	Plaxis 3D	Static load test
Q_n (T)	85.5	87.8	66.7	82.0	76.5
F_{hc}	0.895	0.871	1.147	0.933	1.00

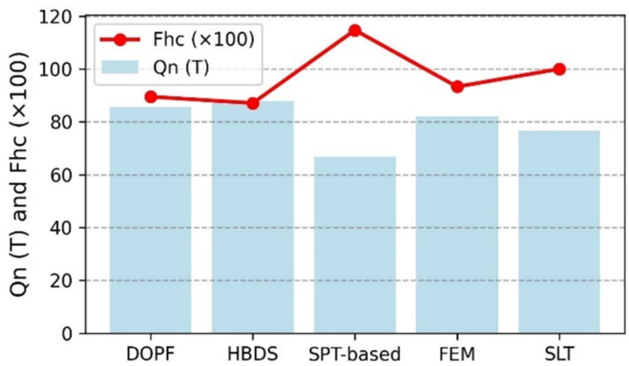

Fig. 4. Comparison of pile axial bearing capacity and correction factors.

Similarly, the highway bridge design specification yielded 87.8 T (F_{hc} = 0.871), as illustrated in Table V and Figure 6. In contrast, the Schmertmann (SPT-based) method produced a significantly lower result of 66.7 T, compared to the experimental result of F_{hc} = 1.147, as shown in Table VI and Figure 7.

TABLE IV. AXIAL BEARING CAPACITY OF PILE ACCORDING TO THE4 DESIGN OF PILE FOUNDATIONS (VIETNAM STANDARD – TCVN 10304:2014)

Soil layer	H_i (m)	l_i (m)	u (m)	f_{si} (T/m²)	$u \cdot m_f \cdot f_{si} \cdot l_i$ (T)
1	2.50	1.00	1.200	0.45	0.540
2	3.50	1.00	1.200	0.50	0.600
3	4.50	1.00	1.200	0.55	0.660
4	5.50	1.00	1.200	0.60	0.720
5	6.50	1.00	1.200	0.60	0.720
6	7.50	1.00	1.200	0.60	0.720
7	8.50	1.00	1.200	0.60	0.720
8	9.50	1.00	1.200	0.60	0.720
9	10.50	1.00	1.200	0.60	0.720
10	11.50	1.00	1.200	0.60	0.720
11	12.50	1.00	1.200	0.60	0.720
12	13.50	1.00	1.200	0.60	0.720
13	14.50	1.00	1.200	0.60	0.720
14	15.50	1.00	1.200	0.60	0.720
15	16.50	1.00	1.200	0.60	0.720
16	17.50	1.00	1.200	0.60	0.720
17	18.50	1.00	1.200	0.60	0.720
18	19.50	1.00	1.200	0.60	0.720
19	20.50	1.00	1.200	8.00	9.600
20	21.50	1.00	1.200	8.10	9.720
21	22.50	1.00	1.200	5.80	6.960
22	23.50	1.00	1.200	5.90	7.080
23	24.60	1.10	1.200	6.10	8.052

Total shaft resistance (Q_s) = 54.012 T, End bearing resistance: $Q_p = mR_{qp}A_p$ = 1×350×0.09 = 31.5 T, Standard axial resistance: $Q_{tc} = m(Q_p+Q_s)$ = 85.5 T, Design axial resistance (K_{tc} = 1.4): $Q_a = Q_{tc} / K_{tc}$ = 61.1 T (≈ 599.2 kN)

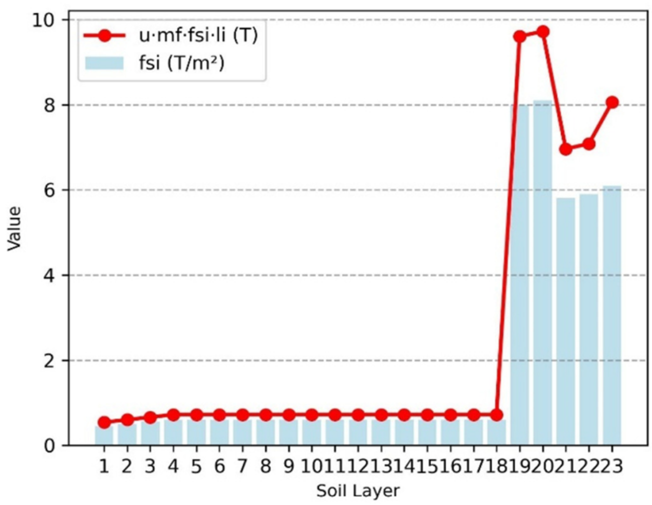

Fig. 5. Axial bearing capacity of pile according to the design of pile foundations.

As displayed in Figure 8, the finite element simulation (Plaxis 3D) produced a result of 82.0 T, which is closest to the static load test value of 76.5 T, shown in Table VII. This result confirms the highest reliability among all evaluated methods, as portrayed in Figure 9.

TABLE V. AXIAL RESISTANCE AND CALCULATION RESULTS OF THE PILE ACCORDING TO THE HIGHWAY BRIDGE DESIGN SPECIFICATION (VIETNAM STANDARD – TCVN 11823:2017)

SPT Index	H (m)	N	γ_i (T/m³)	S_u (MPa)	σ'_v (MPa)	q_s (MPa)	Q_s (kN)
2.50	1	1.50	0.005	0.018	0.005	5.408	2.974
3.50	1	1.50	0.006	0.023	0.005	6.470	3.558
4.50	1	1.50	0.006	0.028	0.006	7.532	4.143
5.50	1	1.50	0.006	0.033	0.007	8.595	4.727
6.50	2	1.50	0.006	0.038	0.008	9.657	5.311
7.50	2	1.50	0.007	0.043	0.009	10.719	5.896
8.50	2	1.50	0.007	0.048	0.010	11.781	6.480
9.50	2	1.50	0.007	0.053	0.011	12.844	7.064
10.50	2	1.50	0.007	0.058	0.012	13.906	7.648
11.50	2	1.50	0.008	0.063	0.012	14.968	8.233
12.50	2	1.50	0.008	0.068	0.013	16.031	8.817
13.50	2	1.50	0.008	0.073	0.014	17.093	9.401
14.50	2	1.50	0.009	0.078	0.015	18.155	9.985
15.50	2	1.50	0.009	0.083	0.016	19.218	10.570
16.50	3	1.50	0.009	0.088	0.017	20.280	11.154
17.50	3	1.50	0.009	0.093	0.018	21.342	11.738
18.50	4	1.50	0.010	0.098	0.019	22.405	12.322
19.50	7	1.50	0.010	0.103	0.020	23.467	12.907
20.50	11	1.97	0.120	0.204	0.071	85.150	46.833
21.50	12	1.97	0.123	0.214	0.074	88.327	48.580
22.50	13	1.97	0.120	0.223	0.025	29.640	13.338
23.50	14	1.97	0.125	0.233	0.027	31.920	14.364
24.60	14	1.97	0.130	0.244	0.027	35.112	15.800

Total: Q_s = 5 30.20 kN, $\varphi_{qs}Q_s$ = 281.84kN, End bearing resistance (AASHTO LRFD): Q_p = 35.5 Tons, Ultimate axial resistance: $Q_n = Q_p + Q_s$ = 87.8 Tons

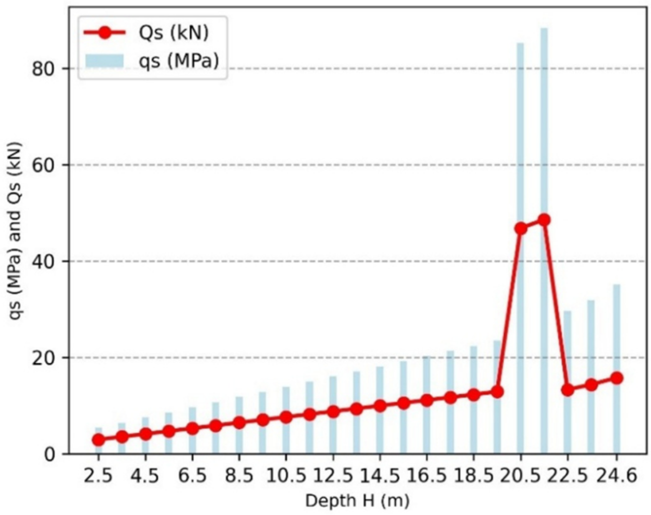

Fig. 6. Axial bearing capacity of pile according to the highway bridge design specification.

IV. DISCUSSION

A comparison of four methods for calculating the axial bearing capacity of piles reveals differences between theoretical models, empirical approaches, and numerical simulations. According to the design of pile foundations, the ultimate load capacity was 85.5 T, 11.8% higher than the experimental result (F_{hc} = 0.895). This indicates that the method is conservative and suitable for soft, cohesive soils, but slightly overestimates pile capacity. The highway bridge design specification yielded a capacity of 87.8 T (F_{hc} = 0.871), which is 14.8% higher than the static test result. However, it better represents the load–settlement relationship due to its distinction between tip resistance (φ_q) and shaft resistance (φ_s), providing a more realistic reflection of soil behavior.

TABLE VI. CALCULATED AXIAL BEARING CAPACITY OF THE PILE ACCORDING TO THE SCHMERTMANN (SPT-BASED) METHOD

Soil type	H (m)	H_i (m)	u_i (m)	q_{si} (MPa)	Q_s (kN)
Clay	2.50	1.00	1.200	6.252	6.252
Clay	3.50	1.00	1.200	6.252	6.252
Clay	4.50	1.00	1.200	6.252	6.252
Clay	5.50	1.00	1.200	6.252	6.252
Clay	6.50	1.00	1.200	12.390	12.390
Clay	7.50	1.00	1.200	12.390	12.390
Clay	8.50	1.00	1.200	12.390	12.390
Clay	9.50	1.00	1.200	12.390	12.390
Clay	10.50	1.00	1.200	12.390	12.390
Clay	11.50	1.00	1.200	12.390	12.390
Clay	12.50	1.00	1.200	12.390	12.390
Clay	13.50	1.00	1.200	12.390	12.390
Clay	14.50	1.00	1.200	12.390	12.390
Clay	15.50	1.00	1.200	12.390	12.390
Clay	16.50	1.00	1.200	18.413	18.413
Clay	17.50	1.00	1.200	18.413	18.413
Clay	18.50	1.00	1.200	24.321	24.321
Clay	19.50	1.00	1.200	41.358	41.358
Clay	20.50	1.00	1.200	52.056	62.467
Clay	21.50	1.00	1.200	56.214	67.457
Sand	22.50	1.00	1.200	24.392	28.392
Sand	23.50	1.00	1.200	25.480	30.576
Sand	24.60	1.10	1.200	25.480	33.634

Total: Q_s = 473.94 kN, Shaft resistance (Qs): 47.4 T, End bearing resistance (Q_p): 38.6 T, Mobilized axial resistance (Q_{hd}): 66.7 T

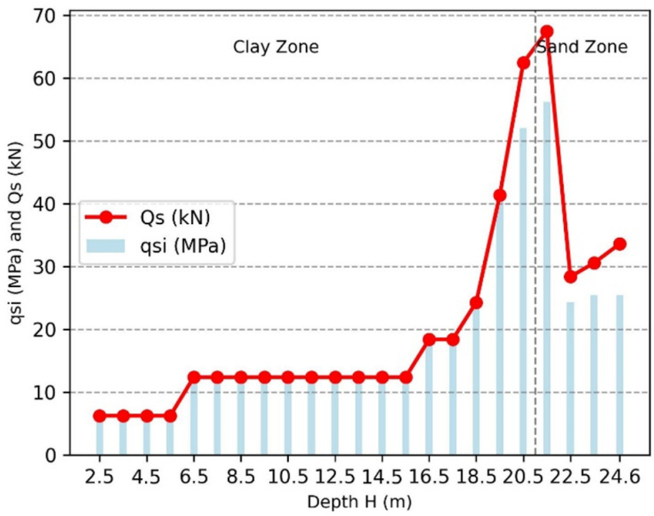

Fig. 7. Axial bearing capacity of pile according to the Schmertmann method.

On the other hand, the Schmertmann (SPT-based) method yielded a value of Qhđ of 66.7 T (F_{hc} of 1.147), which is approximately 12.8% lower than the experimental result. This discrepancy arises because the method relies solely on the N_{60} value, without accounting for variation in strength or saturation conditions. The Plaxis 3D numerical model produced a result of 82.0 T (F_{hc} = 0.933), with a deviation of only ~7%. This model accurately captured the soil–pile interaction and nonlinear mobilization of resistance with depth, demonstrating the closest agreement with the field tests.

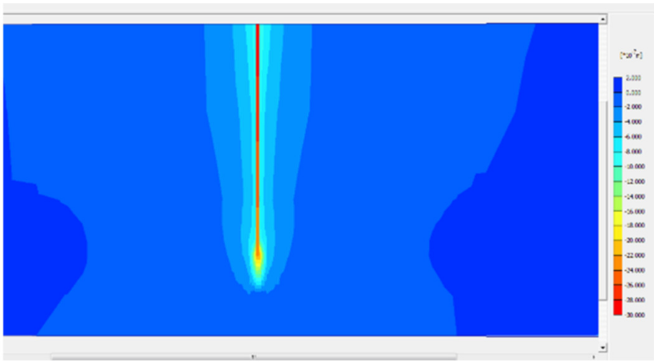

Fig. 8. Single pile model results (soft cohesive soil).

TABLE VII. STATIC PILE LOAD TEST RESULTS – RELATIONSHIP BETWEEN LOAD AND SETTLEMENT DURING LOADING AND UNLOADING CYCLES

Load (T)	Loading cycle 1	Unloading Cycle 1	Loading cycle 2	Unloading cycle 2
147	–	–	–	–
130	–	–	8.0	8.0
122.5	–	–	7.0	7.8
110.3	–	–	5.9	7.7
98.0	–	–	5.1	7.6
85.8	–	–	4.6	7.5
73.5	–	–	3.9	7.2
61.3	–	–	3.4	6.8
49.0	2.3	2.3	3.0	6.0
36.8	1.6	2.1	2.6	5.0
24.5	1.2	2.1	2.2	4.4
12.3	0.8	2.1	2.1	3.6
0	0	2.0	2.0	3.0

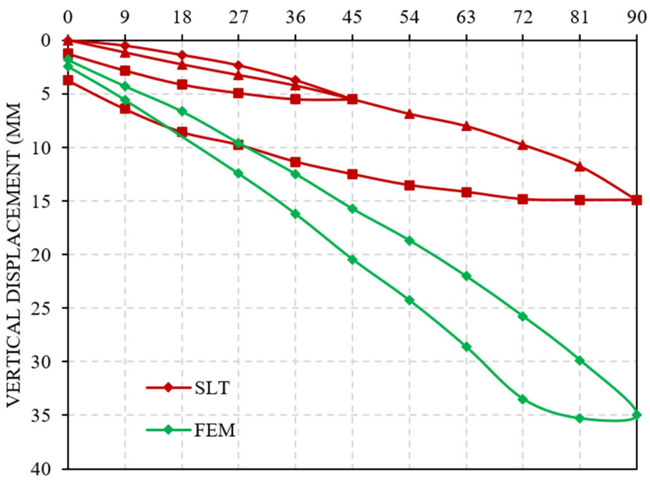

Fig. 9. Load–settlement relationship diagram.

Overall, Vietnamese standards are based on linear assumptions. However, Plaxis 3D can simulate the entire load-settlement process and stress distribution around the pile tip. In Table VIII, the summarized results indicate that Plaxis 3D provides the most accurate and reliable predictions, followed by the design of pile foundations and the highway bridge design specification. However, the Schmertmann method remains overly conservative and unsuitable for soft cohesive soils, as depicted in Figure 10.

TABLE VIII. SUMMARY OF RESULTS

Method	Q_u (T)	Deviation (%)	Remarks
Design of pile foundations	85.5	+11.8	Conservative; suitable for preliminary design.
Highway bridge design specification	87.8	+14.8	Accurately reflects soil behavior.
Schmertmann	66.7	–12.8	Overly conservative; unsuitable for cohesive soils.
Plaxis 3D	82.0	+7.2	Closest to experimental results; highly reliable.

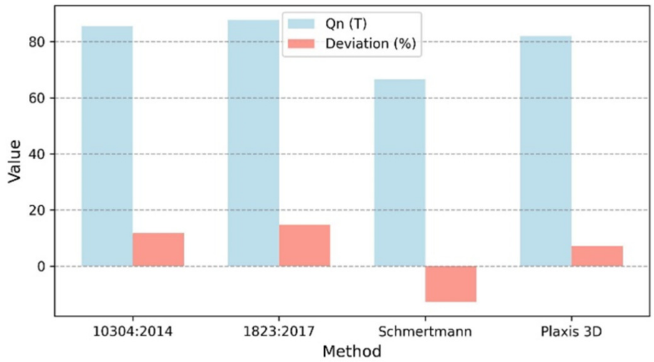

Fig. 10. Comparison of axial bearing capacity methods.

V. CONCLUSIONS

This study evaluated the axial bearing capacity of piles in soft, cohesive soils using four approaches: two Vietnamese design standards, Design of pile foundations (TCVN 10304:2014), Highway bridge design specification (TCVN 11823:2017), the SPT-based Schmertmann metho, and numerical simulation with Plaxis 3D. The results indicate that the two national standards yield more conservative estimates than the static load test. In contrast, the Schmertmann method tends to underestimate pile capacity and is not suitable for soft cohesive soils. Of all methods, Plaxis 3D simulation showed the closest agreement with the experimental results, demonstrating its superior capability in modeling soil-pile interaction and nonlinear behavior. These findings underscore the importance of numerical simulations and suggest that Vietnamese design standards should be calibrated locally using field and numerical data to enhance prediction accuracy and design efficiency in soft coastal soils.

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