Analysis of Pile Foundations Under Vertical and Lateral Loads on Multilayered Soil Using AllPile

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***Abstract* - This study examines the behaviour of a single pile embedded in multi-layered soil using ALLPile software. The analysis estimates the distributions of settlement, deflection, bending moment, and shear force. Variations in these parameters are evaluated along the pile length and at different pile diameters. The influence of free-head and fixed-head boundary conditions on the lateral and axial performance of the pile is also assessed. Fixed-head piles showed less lateral movement and higher bending forces near the top of the pile. Free-head piles showed greater movement, with peak bending forces occurring at a deeper point along the shaft. Deeper, stiffer soil layers mainly influenced vertical load capacity, while lateral performance was affected by softer surface soils. Softer intermediate layers increased bending forces for both pile head types. These findings offer practical guidance for optimising pile design in complex geotechnical environments, thereby enhancing safety and cost efficiency in foundation engineering.**

Keywords - lateral and vertical load; allPile Software, multilayered Soil, freehead and fixed head pile

I. INTRODUCTION

Pile foundations are commonly utilised to transfer structural loads to deeper and more competent soil layers, especially in areas where near-surface soils lack sufficient bearing capacity [1]. In practice, piles are seldom subjected to only vertical loads. They typically encounter combined axial and lateral forces from wind, seismic activity, water flow, earth pressure, or unbalanced loading [2]. Combinations of vertical and horizontal loads are carried where piles are used to support retaining walls, bridge piers and abutments, and machinery foundations [1]. Accurate evaluation of pile performance under combined vertical and lateral loads is crucial for maintaining structural safety and ensuring long-term serviceability. The bearing capacity of an individual pile primarily depends on the installation method and soil type. At the same time, pile dimensions (length and diameter) also influence capacity, with larger sizes generally supporting greater loads. Groundwater fluctuations can significantly affect performance [3].

AllPile integrates vertical and lateral pile analysis while accounting for soil stratification, pile geometry, and head fixity conditions. The study builds upon established soil–pile interaction theories and employs numerical modelling to evaluate displacement profiles, bending moments, shear forces, and ultimate capacities under both fixed-head and free-head conditions [4].

II. PROJECT SITE

The project site is in Nepal's Terai region, specifically within Haripurwa Municipality 3, near Safa Khola Bridge in Sarlahi district, Nepal. The Terai Plain is composed of sediments from the Pleistocene to the Holocene. It is part of the Ganga foreland basin [5]. Within Nepal, the Terai plain gradually rises from about 100 meters in the south to 200 meters in the north [6].

III. METHODOLOGY

This study evaluates the load-bearing capacity of bridge piles through computational modelling with the ALLPile software.

This study focuses on a single, vertically bored cast-in-situ pile foundation in accordance with Clause 709.3.5.2 of IRC 78:2014. The pile cap is not subjected to any load, and the cantilever length above the ground or bed up to the point of load application is disregarded. Additionally, the effects of scour are not considered in this analysis.

A. Soil Exploration

The Standard Penetration Test was conducted by drilling a borehole to the required depth. The split-spoon sampler was lowered and driven into the soil with the standard 63.5 kg hammer. The number of blows needed to drive the sampler through the final 300 mm was recorded, providing the SPT N-value for soil analysis. The depth of the groundwater table was recorded in all boreholes. Disturbed and undisturbed soil samples were tested at the Geotech and Structure Lab in Khumaltar, Lalitpur, to assess shear properties. Field and laboratory data indicate that the soil profile consists of three layers: a 9 m thick medium sand layer situated between a 9 m thick medium-stiff clay layer at the top and a 12 m thick medium-stiff clay layer at the bottom. The level of groundwater was found to be the same height as the ground surface.

Table 1. Geotechnical Properties of Soil Layers (Soil Data)

Depth m	Soil Type	γsub kN/m3	φ °	C kN/m2	K MN/m3	e50 or Dr %	Navg
0	Medium Stiff Clay	7	0	48	3.46	0.57	20
7.5					3.46	0.53	
9					3.46	0.53	

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9	Medium sand	7	30.5	0	3.56	60.29	30
16.5					5.46	65.7	
18					6.44	65.7	
18	Medium Stiff Clay	7	0	48	3.46	0.49	30
20					3.46	0.45	
30					3.46	0.45	

γsub: Submerged UnitWeight, K: Modulus of Subgrade Reaction, Navg: Avg.SPT value, e50: Strain Factor, Dr: Relative Density, C: Undrained Shear Strength, φ: Soil internal friction angle (between soils

B. Analysis

IRC:78-2014 specifies three fundamental load conditions for bridge design. Load Condition I corresponds to serviceability conditions, taking dead load, superimposed dead load, live load plus impact, and temperature action. Load Condition II further extends this by considering wind forces and vehicle retardation or adhesion action to evaluate stability when subjected to environmental and traffic loads. Load Condition III substitutes wind forces with earthquake forces, typically accompanied by reduced live loads, to ensure safety and durability during earthquake loading [7].

Table 2. Load Condition for Single Pile (IRC 78, 2014).

Load Condition	Vertical Load Q (kN)	Shear Load P (kN)
I	1232.70	147.88
II	1501.90	294.12
III	1460.20	294.12

Taking the maximum value from load combinations I, II and III for further analysis.

C. AllPile Software

AllPile for Windows provides rapid and precise analysis of pile load capacity. The software accommodates a comprehensive range of pile types, such as drilled shafts, driven piles, auger-cast piles, steel pipe piles, H-piles, timber piles, tapered piles, bell piles, and shallow foundations. Users can define custom pile types and input parameters according to regional engineering standards and empirical data, enabling project-specific solutions. AllPile performs calculations for lateral capacity and deflection, vertical capacity and settlement, group vertical and lateral analysis, Federal Highway Administration (FHWA) SHAFT analysis, static and cyclic loading conditions, negative and zero friction, shallow footing, and tower foundation analysis [4].

Head Conditions for Single Pile. AllPile software provides six possible head conditions for single piles. Of these, two conditions are most appropriate for fixed-head and free-head pile loading scenarios.

Load Case I: Q=1501.90, P=294.1 KN, Moment (M)=0.

This condition is a special case of condition 1where moment M is zero. Only lateral shear load (P) is acting on the pile (commonly called free-head condition).

Load Case II: Q=1501.90, P=294.1 KN, Slope (St) =0

Commonly called fixed head, there is no rotation in the pile head, since St=0. Moment will be generated at the pile head.

Q: Downward and uplift working load at pile top, P: Lateral working load at pile top, M: Working moment on the pile head, St: The known slope angle at the pile head.

D.Modulus of Subgrade Reaction.

The lateral subgrade modulus (Kh) and vertical subgrade modulus (Kv) of soil are determined by the Indian Standard (IS) Code 2911 Part I, Section II. (2010) with Annexe C, Table 2 shows the values obtained through the chosen interpolation technique [8].

Table 3. Modulus of subgrade reaction based on N values and qu (IS 2911).

Depth m	qu KN/m2	N (Blows/30 cm)	K MN/m3 IS 2911	Remarks	Soil Type
1 - 9	96	-	3.456	Constant	Cohesive
9		25	3.56	Linear	Cohesionless
10		26	3.704		
11		28	3.992		
12		31	4.424		
13		33	4.712		
14		34	4.856		
15		35	5.000		
16		38	5.432		
17		41	5.864		
18		45	6.440		
18-30	96	-	3.456	Constant	Cohesive

IV. RESULTS AND DISCUSSION

A.Effect of Pile Depth on Capacity and Deformation Parameters at Constant Diameter (Fixed vs. Free Head)

The effect of pile depth on load-carrying capacity and deformation characteristics was examined by changing the pile length from 8 m to 20 m while maintaining a constant diameter of 1 m. The analysis was performed using ALLPile software to identify key parameters, including maximum bending moment, axial capacity, allowable load-carrying capacity, uplift resistance, pile head displacement, and settlement. The results demonstrate how increasing pile depth significantly impacts both the strength and deformation behaviour of the foundation system under fixed-head and free-head conditions. A detailed summary of the calculated results is provided in Table 4.

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Table 4. Variation of Lateral Deflection, Bending Moment, and Settlement with Pile Length

S. No	L m	D m	L/D Ratio	W (kN)	yt (I) mm	yt (II) mm	yp (mm)	M (I) kN-m	M (II) kN-m	Se (I) mm	Se (II) mm
1	8	1	8.00	151.62	10.48	2.4	10	533	607	7.3528	7.3528
2	10	1	10.00	189.52	9.56	2.14	10	590	594	3.1514	3.1514
3	12	1	12.00	227.42	9.21	2.14	10	597	593	2.61	2.61
4	14	1	14.00	265.33	9.18	2.13	10	597	593	2.2702	2.2702
5	16	1	16.00	303.23	9.18	2.13	10	597	593	2.0564	2.0564
6	18	1	18.00	341.13	9.16	2.13	10	598	593	1.9492	1.9492
7	20	1	20.00	379.04	9.17	2.13	10	598	593	1.7121	1.7121

L: Length of Pile, D: Diameter of Pile, W: Total Weight of Pile Shaft, I: Load Case I (Free Head Pile), II: Load Case (Fixed Head Pile), yp: Permissible deflection (1% of Pile Dia), yt: Top Deflection, Se: Settelement, M: Maximum Moment, L/D: Embedment Ratio

B. Effect of Pile Diameter on Capacity and Deformation Parameters at Constant Depth (Fixed vs. Free Head)

In this analysis, the pile diameter ranged from 0.6 m to 2.0 m while maintaining the same pile length. Using ALLPile software, the related changes in bending moment, allowable axial capacity, ultimate capacity, and uplift resistance were examined. The study also evaluated pile head deformation and settlement under both fixed-head and free-head boundary conditions. The results clearly show how increasing pile diameter improves load-carrying capacity while affecting deformation characteristics. A detailed comparison of these results is summarised in Table 5.

Table 5. Variation of Lateral Deflection, Bending Moment, and Settlement with Pile Diameter

S.NO	L m	D m	L/D Ratio	W kN	yt (I) mm	yt (II) mm	yp (mm)	M (I) kN-m	M (II) kN-m	Se (I) mm	Se (II) mm
1	20	0.6	33.33	136.46	52.1	11.3	6	583	532	4.3877	4.3877
2	20	0.8	25.00	242.58	19.2	4.41	8	584	565	2.1361	2.1361
3	20	1	20.00	379.04	9.17	2.13	10	598	593	1.7121	1.7121
4	20	1.2	16.67	545.80	5.04	1.18	12	612	617	1.4976	1.4976
5	20	1.4	14.29	742.90	3.05	0.721	14	625	641	1.4164	1.4164
6	20	1.6	12.50	970.32	1.97	0.465	16	637	637	1.3583	1.3583
7	20	1.8	11.11	1228.06	1.35	0.321	18	648	680	1.3143	1.3143
8	20	2	10.00	1516.13	0.953	0.226	20	657	695	1.279	1.279

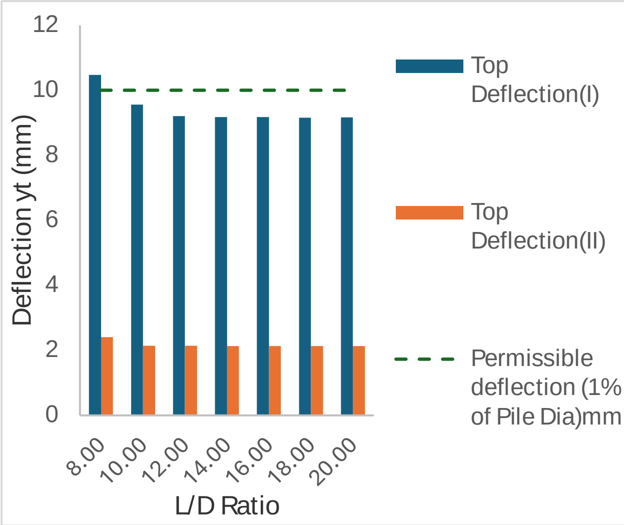

Fig. 1. Influence of Pile Length on Lateral Deflection Behavior (Load Cases I and II)

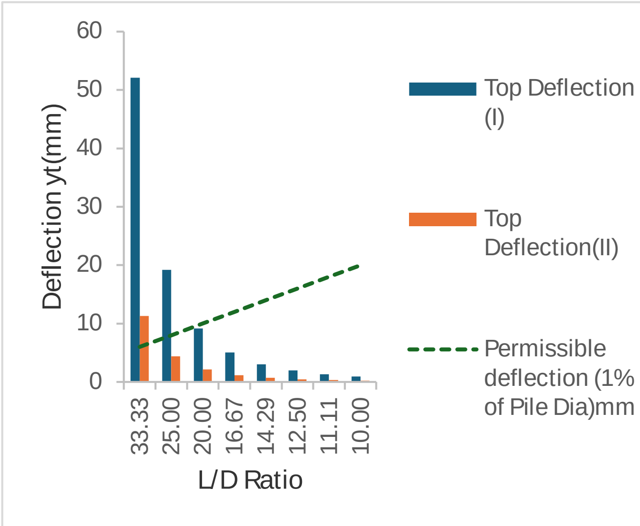

Fig. 2. Influence of Pile Diameter on Lateral Deflection Behaviour (Load Cases I and II)

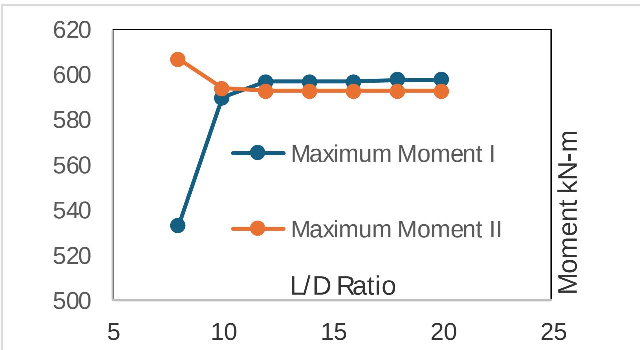

Fig. 3. Maximum Bending Moment with Varying Pile Length.

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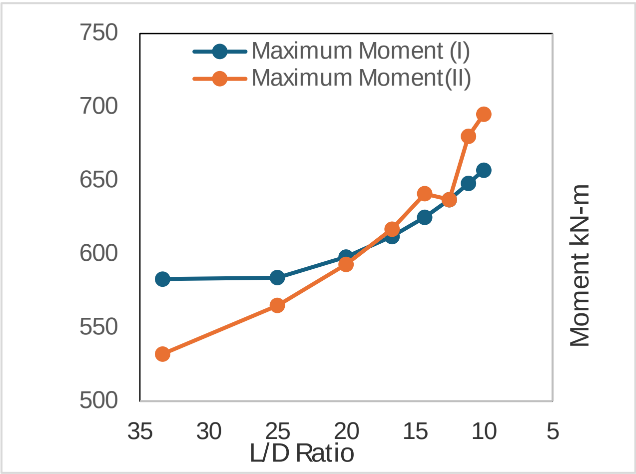

Fig. 4. Maximum Bending Moment with Increasing Pile Diameter.

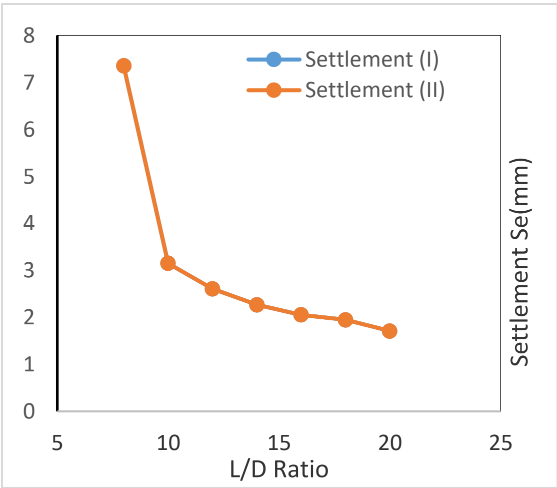

Fig. 5. Variation of Settlement with Pile Length.

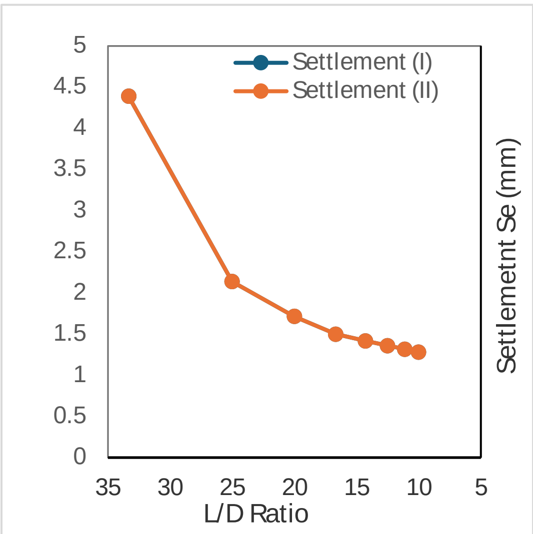

Fig. 6. Settlement with Increasing Pile Diameter.

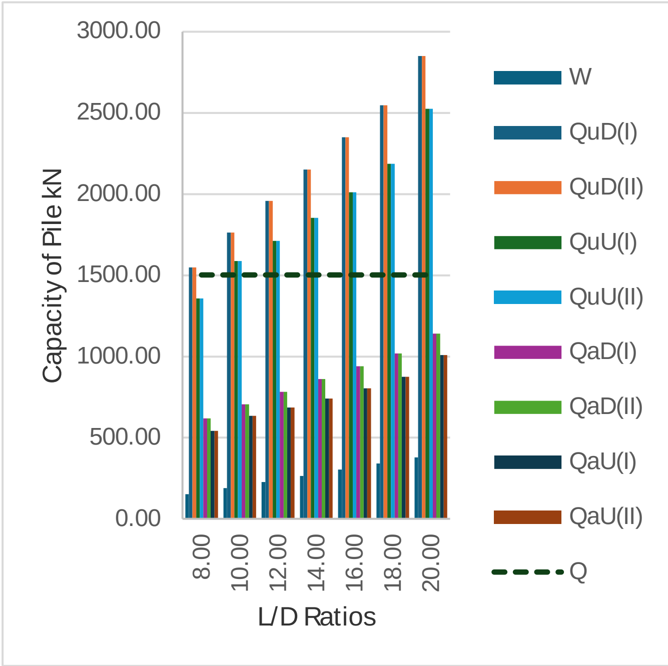

Fig. 7. Variation of Capacity and Deformation Parameters with Depth for load cases I and II.

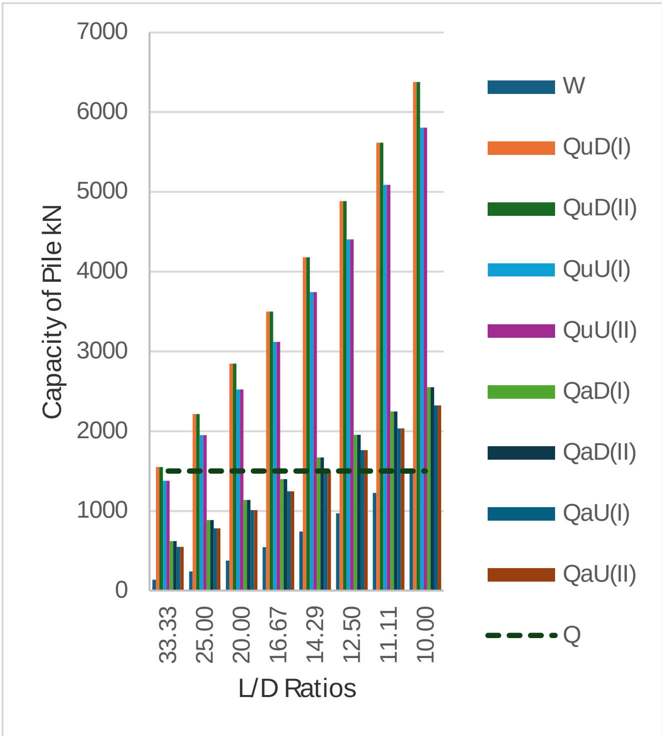

Fig. 8. Variation of Capacity and Deformation Parameters with Diameter for load cases I and II.

W: Weight of the Pile Shaft, I: Load Case I (Free Head Pile), II: Load Case II (Fixed Head Pile), QuD: Ultimate downward capacity (Qtip + Qside_dw), QuU: Ultimate Uplift capacity

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(Weight + Qside_up), Qa: Vertical allowable load, Qult/F.S, Q: Vertical working load applied to pile.

As shown in Figure 1**,** a pile with a 1.0 m diameter requires a minimum length of 8 m to ensure stability. Shorter lengths lead to deflection exceeding the acceptable limit. However, beyond this critical length, deflection stays within the permissible range, showing no significant variation. Additionally, the results show that deflection decreases with increasing pile diameter, highlighting the need for diameters larger than 1.0 m to maintain safe limits, as demonstrated in Figure 2**.**
As the pile length increases while keeping the diameter constant for both load cases (Figure 3), the maximum moment initially increases and then becomes nearly constant. Beyond a certain pile length, further increase has little influence on the maximum moment, indicating that the bending response stabilizes. Increasing the pile diameter significantly improves maximum moment capacity by improving bending strength and stiffness, enabling the pile to resist higher moments (Figure 4).
Figures 5 and 6 illustrate the settlement behavior of piles. Larger and longer piles exhibit lower settlement values, indicating enhanced performance. Notably, the settlement patterns are consistent across both free-head and fixed-head load scenarios, confirming that axial settlement is unaffected by pile head fixity
As the pile diameter remains constant and the pile length increases, the overall performance parameters also increase. The self-weight of the pile shaft, ultimate axial load-carrying capacity, uplift capacity, and vertical allowable load all increase with pile length, as shown in Figure 7. The ultimate downward capacity, ultimate uplift capacity, and vertical allowable load values remain nearly unchanged for both load cases (Fixed and Free Head). This is due to the pile–soil interaction in the axial direction primarily controlling these capacities, which is unaffected by the pile head's fixed or free status. For a 1.0 m diameter pile and lengths up to 20 m, the analysis shows the Allowable load capacity (Qa) is less than the applied vertical load (Q) on a single pile, indicating a not-good (NG) condition. Furthermore, the pile tip shows noticeable movement up to about 8 m depth, suggesting the pile is too short to resist the applied loads effectively. Thus, a minimum pile length of over 8 m is recommended for safety and serviceability.
For pile diameters greater than 1.2 meters, the allowable load capacity of the pile is found to exceed the applied vertical load, as illustrated in Figure 8**.** This indicates that using piles with diameters larger than 1.2 m provides a safe margin and is therefore recommended.

V. VALIDATION OF THE RESULT

The results reported by P. Jeyalakshmi and V. Jeyanthi Vineetha (2014) in IJRET Figure 2 match those produced by ALLPile Software [9]. The findings of Riya T Johnson et al. (2016), presented at the Indian Geotechnical Conference IGC2016, are consistent with the results of this study [10].

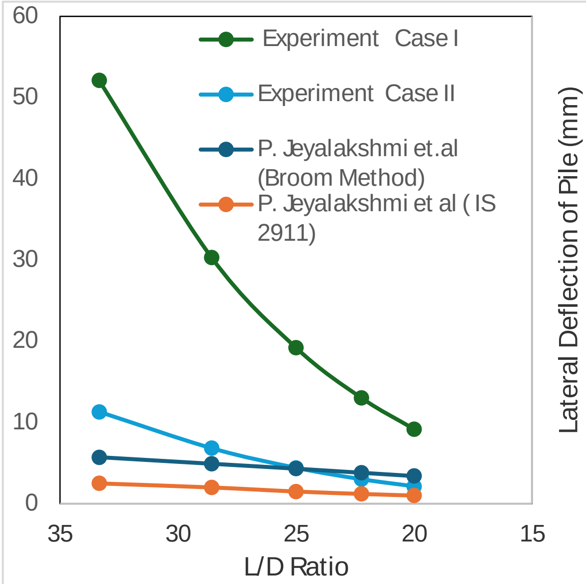

Fig. 9. Lateral Deflection of Piles with Different Diameters: A Comparison between [9] and this Study.

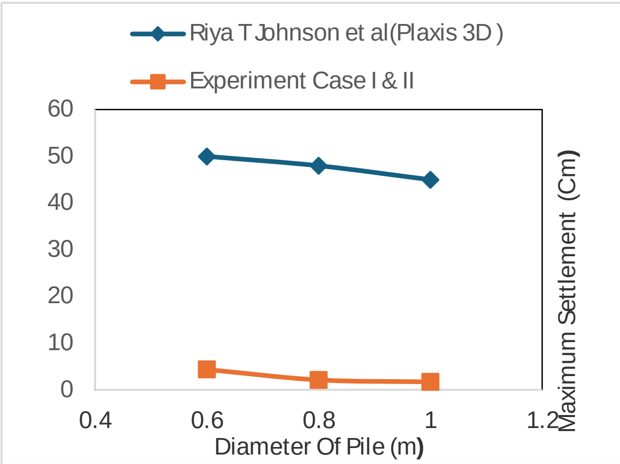

Fig. 10. Settlement of Piles with Different Diameters: A Comparison between [10] and this Study.

VI. CONCLUSION.

This study demonstrates that pile geometry and soil layering have a significant impact on foundation performance under both axial and lateral loads. Increasing the pile diameter and length enhances both axial and uplift capacities, while reducing settlement and deflection. These improvements result from more effective stress transfer across soil strata. The maximum bending moment increases with diameter but remains unchanged primarily with length. Both ultimate and allowable capacities improve with geometry changes yet remain nearly identical for free-head and fixed-head piles in both load cases. Settlement behavior varies little between head restraints, indicating that geometry–soil interaction is the main governing factor. Piles with diameters exceeding 1.2 meters

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and lengths exceeding 8 meters are recommended for enhanced stability and reduced deformations in layered soils. Future studies should focus on cyclic loading, soil variability, and cost efficiency to enhance design practices.

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