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Behaviour of Pile in Layered Soils Under Combined Loading Using Lpile

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Abstract — *This study explores the behaviour of single vertical piles embedded in layered soils under combined lateral and axial loads, focusing on how deflections and internal force distributions vary along the pile and across different diameters. The impact of pile head conditions, free-head versus fixed-head, on lateral performance is examined in detail. The main goal is to quantify the pile's mechanical response and interaction with stratified soils under realistic boundary conditions and loading scenarios. A series of numerical simulations using LPile software was conducted, incorporating nonlinear p-y, t-z, and q-z curves to model soil-pile interaction accurately. Pile diameters from 0.8m to 2.0 m were tested under combined axial loads up to 1501.90 kN and lateral loads up to 294.12kN. The soil profile included alternating layers of medium-stiff clay and medium sand to represent typical field conditions. Outputs measured included pile head deflection, bending moments, and shear force distribution along the pile shaft. Results indicated that larger diameters significantly reduced lateral deflections due to increased stiffness. Fixed-head piles exhibited less lateral deflection compared to free-head piles, especially in the top 5 meters. Conversely, bending moments near the head were higher in fixed-head piles, showing a trade-off between deflection control and internal forces. Transition zones between soil layers caused local variations in internal forces, with sharper gradients in mixed profiles. Overall, pile response under combined loads depends heavily on head fixity and diameter.*

Keywords: Layered Soil, Pile head deflection, Combined load, Head fixity

I. INTRODUCTION

Pile behaviour during combined axial and lateral loading is vital for the economical and safe design of infrastructure like bridges, tall buildings, and offshore structures [1]. In practice, piles are usually embedded in layered soil profiles. Strength and stiffness properties vary considerably with depth. The interaction between these stratified soils and the pile, especially concerning deflection and internal force distribution, presents complex challenges in geotechnical engineering [2]. Much existing research focuses on the response of a pile under isolated loading conditions, either axial or lateral. However, few studies have examined combined loading, particularly in layered soils, where changes in stiffness can affect stress transfer [3]. Additionally, the influence of pile diameter and head fixity is not sufficiently addressed by conventional design models. Most earlier approaches assume homogeneous soil profiles, which do not reflect real field conditions and limit their applicability. Furthermore, the role of pile head restraint, whether fixed or free, is often underestimated despite its significant impact on lateral deflection and bending moments [4]

To address these gaps, this study uses LPile software to simulate pile performance under realistic boundary conditions and combined loading in stratified soils. The analysis develops nonlinear p-y, t-z, and q-z models to capture soil-pile interaction [5]. Piles with varying diameters and head restraints are analysed to identify behavioural trends and quantify design-sensitive variables. The findings show how soil layering and boundary conditions affect deformation and internal stress. This supports more accurate and efficient foundation designs in layered soil environments.

II. SITE LOCATION

The project site is in Nepal's Terai region, specifically within Sarlahi district. This area, part of the Gangetic Plain or Terai Zone, extends from the Indian Shield in the south to the Sub-Himalayan (Siwalik) Zone in the north [6]. The plain, lying below 200 metres in elevation, contains up to 1500 metres of alluvial sediments, mainly boulders, gravel, silt, and clay [7]. Notably, the Terai Zone forms a nearly continuous east-west belt 10 –50 km wide along Nepal's southern border. As a foreland basin, it accumulates sediments transported from the northern Himalayan ranges. Its northern boundary is marked by the Main Frontal Thrust (MFT), where Siwalik rocks locally overlie recent alluvium, highlighting the dynamic geological processes shaping the region [8].

III. METHODOLOGY

Many pile design methods rely on empirical data. This study analyses bridge pile capacity using the LPile software. Using LPile software, a specialised program for analysing pile foundations, this study examined the behaviour of single piles in layered soils under lateral and combined axial and lateral load. The study varied pile length, diameter, and head fixity (e.g., "fixed-head" and "free-head").

Assumptions

- The cantilever length above ground/bed to the point of load application (e) is neglected.
- This study focuses on a single bored cast-in-situ pile foundation for analysis.
- The cut-off level is considered zero. The maximum permissible deformation criterion is 1% of the pile diameter (Clause 709.3.5.2 of IRC 78:2014) [9].
- Load Supported by Pile cap=0%
- Scour effects are neglected during this analysis.

3.1. Soil Exploration

Standard penetration tests (SPT), a method of measuring soil resistance using a split-barrel sampler driven into the ground, were conducted at intervals of 1.5 m or at each change in strata, whichever occurred first. Groundwater levels were recorded in all boreholes. Selected disturbed and undisturbed samples were tested at the Geotech and Structure Lab in Khumaltar, Lalitpur, to determine shear parameters, which reflect the soil's strength under stress. Based on field and laboratory data, the soil profile was classified into three layers: a 9 m thick medium sand layer sandwiched between medium-stiff clay layers, 9 m thick at the top and 12 m thick at the bottom. The groundwater table was observed at the ground surface level.

Table 1. ***Properties of subsoil used for studies from field and laboratory tests***

Layer Number	Soil Type Name	Soil Type Name P-y curve Type (LPile)	Layer Depth m	Effective Unit Weight kN/m^3	Undrained Cohesion kPa	Angle of Friction Degree	E50 or krm	Kpy kN/m^3	Navg
1	Medium Stiff Clay	Stiff Clay with free water	0	7	48	-	0.005	3460	20
			9	7	48	-	0.005	3460	
2	Medium Sand	Sand (Reese, et al.)	9	7	-	30.5	-	3560	30
			18	7	-	30.5	-	6440	
3	Medium Stiff Clay	Stiff Clay with free water	18	7	48	-	0.005	3460	30
			30	7	48	-	0.005	3460	

kpy: Modulus of Subgrade Reaction, Navg: Avg.SPT value, E50: Strain Factor

3.2. Analysis

The calculation of loads acting on the pile was carried out according to the procedure specified in Indian Roads Congress (IRC) 78, clause 706. Load combinations I, II, and III were evaluated. For each combination, the analysis included live load, wind load, buoyancy force, longitudinal force from braking, centrifugal force, deformation effects, horizontal force, wave pressure, temperature effects, water current, secondary effects, frictional force at bearings, erection effects, seismic force, earth pressure, and impact from floating bodies. These combinations were used to determine the total horizontal and vertical loads on a single vertical pile [9].

Table 2. ***Input Load For Analysis obtained from IRC 78, 2014, clause 706.***

Load Combinations	Vertical Force Q (kN)	Horizontal Force P (kN)
I	1232.70	147.88
II	1501.90	294.12
III	1460.20	294.12

1-Load Case 1: Q=1501.90, P=294.1 KN, Moment=0 (Free Head Pile)
2-Load Case 2: Q=1501.90, P=294.1 KN, Slope=0 (Fixed Head Pile)

Lpile Software. LPile is commercial software developed by Ensoft Inc. and is widely used for analysing deep foundations subjected to lateral loading. The program models nonlinear soil–pile interaction using the p-y curve method, which characterises soil response based on lateral deflection. LPile accommodates various soil types, including clay, sand, and layered profiles. It incorporates parameters such as pile stiffness, fixity conditions, and moment-curvature relationships. The software supports both free-head and fixed-head pile conditions, and it predicts pile deflection, moment, shear, and soil resistance along the shaft. Additional features include load combinations, soil degradation effects, p-y multipliers, and user-defined soil models. LPile is well-suited for complex geotechnical designs and is often used in the design of bridge foundations, offshore structures, and retaining systems subjected to lateral forces from wind, seismic activity, or earth pressure [5]**.**

Modulus of Subgrade Reaction. The figure below shows the results of the horizontal bearing capacity analysis for a single pile, using the "Input by Distribution" method to determine the subgrade reaction modulus (kh). Due to layered soil, the modulus values change as shown in Fig. 1. This approach is based on IS 2911 Part 1 Section 2 (2010) with Annex C. The curve in Figure 1 displays the interpolated values from this method [10]

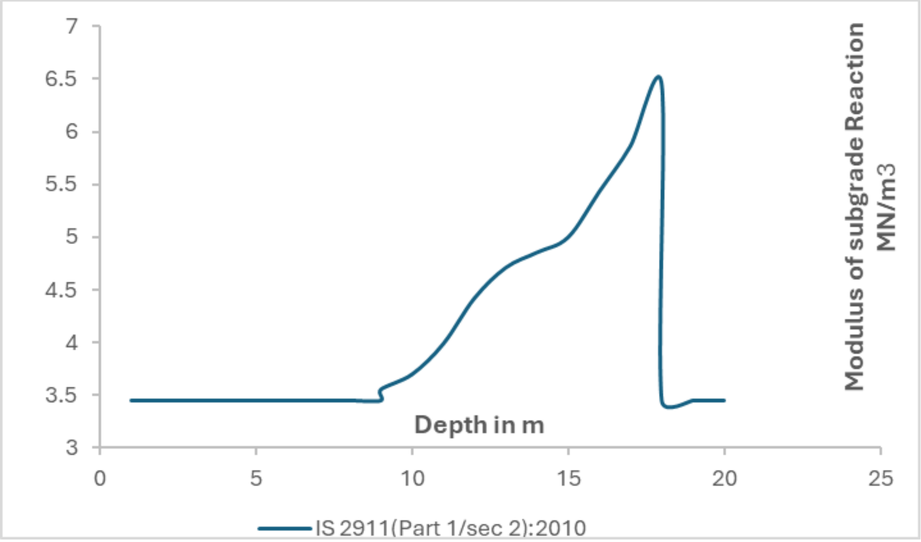

Fig. 1. Variation of modulus of subgrade reaction with depth.

IV.RESULTS AND DISCUSSION

4.1. Influence of Depth on Lateral Deflection Behaviour of Fixed-Head and Free-Head Single Pile

To examine how depth influences the lateral deflection of single piles, the pile diameter was maintained at 1m in all analyses. The model was constructed using LPile software and included a layered soil profile based on field data. Two cases were studied: fixed-headed and free-headed conditions. Pile embedment depths ranged from 8 m to 20 m (since the pile tips move, the depth below 8 m is not considered), with a constant lateral and axial load applied at the pile head for each case. For every combination of depth and boundary condition, simulations were conducted to measure lateral deflection and bending moment along the pile. The results were then compiled for comparison, allowing a direct assessment of the effects of depth and head condition as shown in Table 3.

Table 3. ***Comparison of Lateral Deflection and Resisting Moment with Increasing Pile Length***

S.NO	Length/m	Diameter/m	Total Weight /kN	yp/m	yt/m(I)	M/kN-m(I))	yt/m(II)	M/kN-m(II)
1	8	1	151.62	0.01	0.02993	635.2841	0.00987	-949.624
2	10	1	189.52	0.01	0.02344	682.2537	0.00886	-881.455
3	12	1	227.42	0.01	0.02163	724.0101	0.00802	-843.763
4	14	1	265.33	0.01	0.02154	731.0991	0.00774	-838.872
5	16	1	303.23	0.01	0.02154	731.6204	0.0077	-839.122
6	18	1	341.13	0.01	0.02157	730.7641	0.00768	-842.898
7	20	1	379.04	0.01	0.02161	731.6139	0.00772	-837.581

I: Load Case 1(Free Head Pile), II: Load Case 2(Fixed Head Pile), yp: Permissible deflection (1% of Pile Dia), yt: Top Deflection, M: Maximum Moment

4.2. Influence of Diameter on Lateral Deflection Behaviour of Fixed-Head and Free-Head Single Pile

To examine how pile diameter influences lateral deflection, the pile length was initially set at 20 m, with the diameter increased incrementally from 0.8 m to 2.0 m. Subsequently, the pile–soil interaction was modelled in LPile using a layered soil profile derived from the site investigation. The analysis then considered two boundary conditions: fixed-head and free-head. In each model, a uniform lateral and axial load was applied at the top of the pile. For each diameter and boundary condition, simulations were conducted, and the resulting lateral deflection and bending moment profiles were recorded for comparison, as shown in Table 4.

Table 4. ***Comparison of Lateral Deflection and Resisting Moment with Increasing Pile Diameter***

S.NO	Length/m	Diameter	Total Weight/ KN	yp/m	yt/m(I)	M/kN-m(I)	yt/m(II)	M/kN-m(II)
1	20	0.8	242.58	0.008	0.04097	718.1845	0.0112	-689.89
2	20	1	379.04	0.01	0.02161	731.6139	0.00772	-837.58
3	20	1.2	545.80	0.012	0.01395	891.115	0.00548	-1015.0
4	20	1.4	742.90	0.014	0.01015	1036	0.00387	-1235.0
5	20	1.6	970.32	0.016	0.00824	1143	0.00316	-1371.0
6	20	1.8	1228.06	0.018	0.00691	1240	0.00265	-1510.0
7	20	2	1516.13	0.02	0.006	1318	0.0023	-1655.0

I: Load Case 1(Free Head Pile), II: Load Case 2(Fixed Head Pile), yp: Permissible deflection (1% of Pile Dia), yt: Top Deflection, M: Maximum Moment

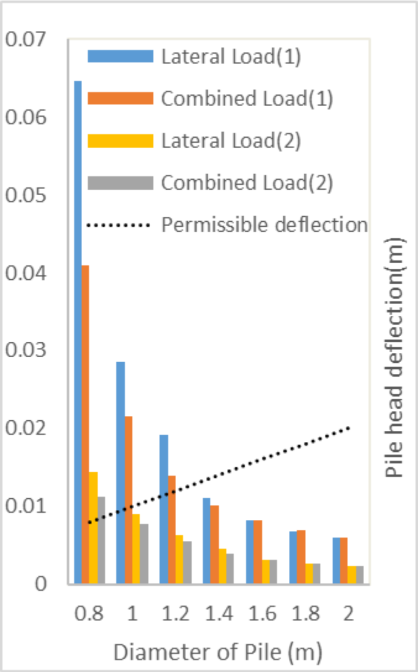

Fig. 2. Variation of displacements (m) at the top of the pile for different diameters.

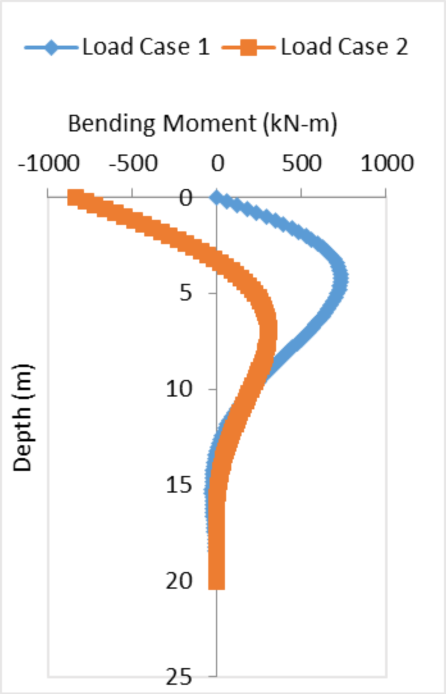

Fig. 3. Variation of moments for different lengths.

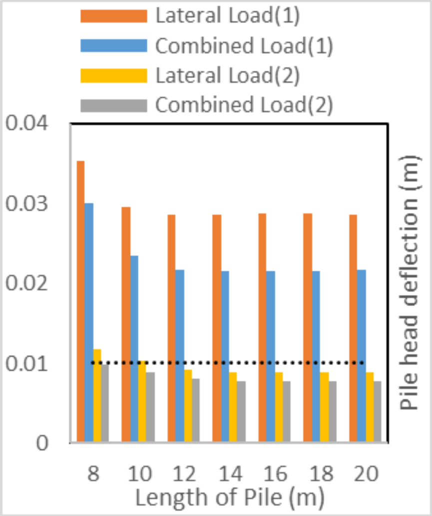

Fig. 4. Variation of displacements (m) at the top of the pile for different lengths.

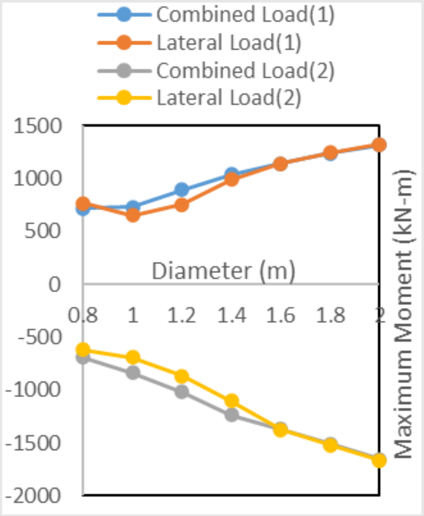

Fig. 5. Variation of moments for different diameters.

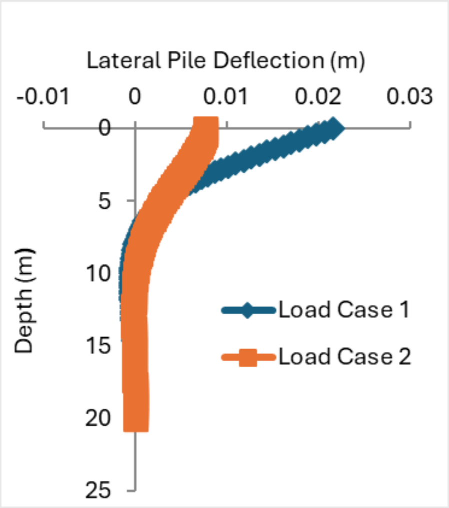

Fig. 6. Variation of lateral Pile Deflection with depth.

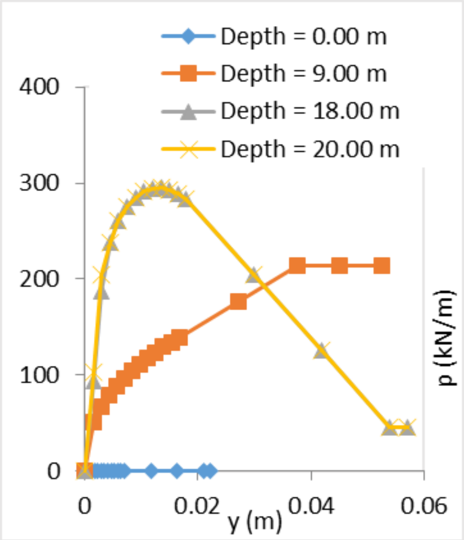

Fig. 7. p-y curve along the depth

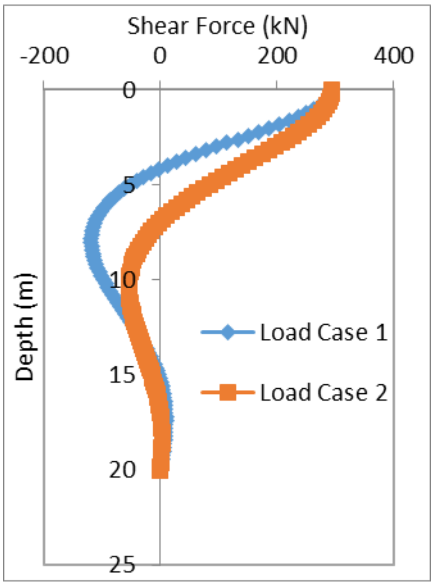

Fig. 8. Variation of Shear Force with depth.

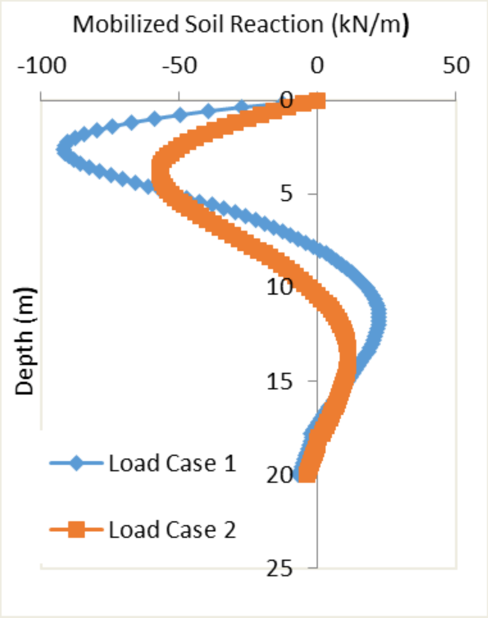

Fig. 9. Mobilized Soil Reaction along the depth.

Pile head deflection decreases by increasing pile length for both free-head and fixed-head conditions up to the critical depth of 9.2 meters, as illustrated in Figure 6. Beyond this depth, additional length does not significantly reduce deflection. At a length of 8 meters, the free-head pile shows a deflection of 0.032 meters, which is substantially higher than the 0.009 meters observed for the fixed-head pile. Deflections are greater under pure lateral loading than under combined axial and lateral loading, as shown in Figure 4, due to the increased soil resistance mobilized by axial stress. The fixed-head configuration remains well below the permissible deflection limit, whereas the free-head condition approaches this threshold at shorter pile lengths. For free-head piles, the maximum moment increases slightly from approximately 630 kN·m to 740 kN·m. For fixed-head piles, it decreases from around (–)950 kN·m to (–)840 kN·m, as shown in Fig. 3.

The graph (Fig. 4) displays the pile head deflection against the pile diameter under lateral and combined force for both the free-head (1) and fixed-head (2) scenarios. Free-head piles exhibit a sharp reduction in deflection from approximately 0.042 m at 0.8 m diameter to less than 0.01 m beyond 1.6 m. Deflection rapidly decreases as diameter increases up to about 1.4 m; after that, there is no improvement. The allowable deflection line, which is 1% of pile diameter, ensures that fixed-

head piles with diameters greater than 1.0 m and free-head piles with diameters greater than 1.2 m remain within safe bounds.
Figure 5 shows the variation in the maximum bending moment with increasing pile diameter for both free-head and fixed-headed conditions. Once the diameter is above 1.4 m, the bending moments for both loading conditions (lateral and Combined load) become similar. For fixed-head piles with diameters over 1.6 m, this similarity persists. Fixed-head piles also show much larger negative bending moments because the pile head is restrained.

Figure 7 shows the relationship between soil resistance (p) and lateral deflection (y) measured at four different pile depths: 0 m, 9 m, 18 m, and 20 m. At 0 m, the resistance remains low even as the deflection increases. As the depth increases, both resistance and stiffness rise, reaching their highest values between 9 m and 20 m.

Figure 8 shows that the shear force decreases with depth for both free-head and fixed-head piles. Fixed-head piles carry higher shear near the top due to head restraint, while free-head piles show a more gradual reduction. Maximum shear (294.10 kN) occurs at the pile head in both cases, with a sharper decline in fixed-head piles below 10 m depth.

Figure 9: The graph shows the mobilised soil reaction versus depth for two load cases, where Load Case 1 and Load Case 2 conditions are considered. The fixed-head pile mobilises higher soil resistance between 5 m and 18 m, indicating greater stiffness and restraint compared to the more flexible free-head pile

The effect of soil layering is clear in the deflection behavior. In the upper 9 m stiff clay layer, lateral resistance is limited, so deflection is relatively higher when the pile is short. As the pile penetrates deeper into the 9–18 m medium sand layer, which has higher stiffness and provides stronger lateral resistance, deflection reduces significantly up to the critical depth of about 9.2 m. Beyond this point, additional penetration into the sand and the lower 18–20 m stiff clay layer does not meaningfully decrease deflection, since most of the lateral resistance has already been mobilized in the sand layer

4.3. Validation of the result

The outcome from the investigation by P. Jeyalakshmi and V. Jeyanthi Vineetha (2014) (International Journal of Research in Engineering and Technology: IJRET fig 2) was like the LPile outcome [11]. The findings reported by Pathak and Anantanaskul (2019) for free head pile closely align with the results obtained in this study [12].

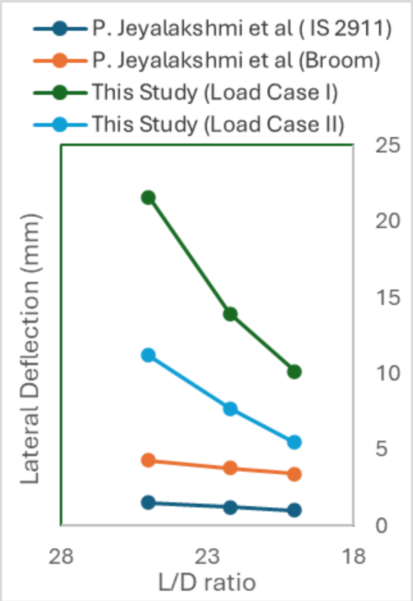

Fig. 10. Comparison of the lateral deflection of a pile of varying diameter obtained from [11] and this study.

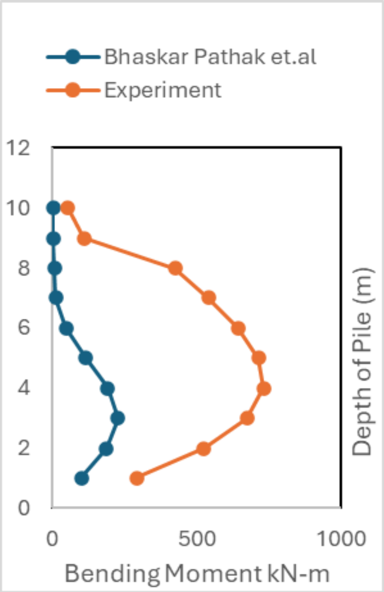

Fig. 11. Comparison of the Bending Moment of piles in depth obtained from [12] and this study.

V.CONCLUSION

The study finds that increasing pile length reduces head deflection up to a critical depth, after which further embedment adds little benefit. Fixed-head piles have lower maximum bending moments and remain within acceptable deflection limits, while free-head piles often exceed these limits under lateral and combined loads. Larger pile diameters increase rigidity and reduce deflection but also raise bending moments for fixed-head piles. Axial loads increase soil resistance and further reduce deflection compared to lateral loads alone. Key factors for controlling deflection are axial load, fixed-head restraint, and increasing diameter (up to 1.4 meters). Subgrade stiffness also influences performance: the medium sand layer controls most deflection, the upper stiff clay affects initial flexibility, and the lower stiff clay has a minor impact. Overall, pile stiffness, boundary conditions, axial load, and soil layering are critical for managing internal forces and displacement. These results are consistent with theory, support using LPile for layered soil analysis, and offer practical strategies for pile design under lateral loads.

Further work should include an assessment of pile behaviour under scour and cut-off conditions, and a comparison of lateral capacity using the IS Code, Eurocode, Broms, Poulos, Matlock, and Reese methods, validated with LPile, AllPile, and Plaxis 3D.

V.ACKNOWLEDGEMENTS

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VI.DATA AVAILABILITY

Data will be made available on request.

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