International Journal of Advanced Engineering, Management and Science (IJAEMS)
Peer-Reviewed Journal
ISSN: 2454-1311 | Vol-11, Issue-6; Nov-Dec, 2025
Journal Home Page: https://ijaems.com/
DOI: https://dx.doi.org/10.22161/ijaems.116.12

Evaluation of Lateral Capacity of Pile Foundation in Layered Soils

Sushil Acharya[1], N.P. Kaushik[2], Pooja Singh [3]

[1] Research Scholar, Dept. of Civil Engineering, Om Sterling Global University, Hisar, 125001, India
Email: sushilciv212@osgu.ac.in, sacharya462@gmail.com
Orcid: 0009-0005-3506-3962
[2] Professor, Dept. of Civil Engineering, School of Engineering and Technology, Om Sterling Global University, Hisar, 125001 India Email: vc@osgu.ac.in
[3]Civil Engineer, Geotech and Structure Lab Pvt.Ltd, Khumaltar, Lalitpur, Nepal
Email: poojasingh1839@gmail.com
*Corresponding Author

Received: 27 Oct 2025; Received in revised form: 25 Nov 2025; Accepted: 01 Dec 2025; Available online: 07 Dec 2025

***Abstract*— *This paper examines the lateral capacity of pile foundations embedded in layered soils. The main aim is to determine the lateral load at which the maximum bending moment occurs while keeping serviceability within acceptable limits. Piles were modelled with a fixed length of 20 m, with diameters ranging from 0.8 m to 2.0 m to examine the influence of cross-sectional size. A deflection limit of 1% of the pile diameter served as the governing criterion. Lateral capacities were initially estimated using the provisions of IS 2911, Part 1, Section 2, then verified through numerical simulations with L-Pile and Plaxis 3D software. The comparison illustrates how soil layering influences pile response, showing that increasing the diameter significantly enhances lateral resistance along the pile. The findings provide practical guidance for selecting appropriate pile dimensions in layered profiles, ensuring sufficient lateral performance and controlled deflections.*

***Keywords*— Pile foundation, Layered Soil, Lateral Capacity, Permissible deflection, LPile and Plaxis 3D**

I. INTRODUCTION

Piles are used to transfer loads to bedrock or more durable soil layers when the upper layers are highly compressible and cannot support the weight of the superstructure. If bedrock is not available at a suitable depth, piles are employed to transfer the load to the soil gradually. The primary resistance to the structural load is friction at the soil-pile interface. When horizontal forces act on them, pile foundations bend to resist these forces while maintaining their vertical load-bearing capacity from the superstructure. This situation is common during the design and construction of foundations for large buildings, bridges, and earth-retaining structures subject to strong winds or earthquakes [1].

The IS 2911 standard offers detailed guidance for bored cast-in-situ concrete piles, explaining their load transfer mechanisms, including axial and lateral capacities, as well as their intended uses. Piles may face lateral forces from sources such as wind, earthquakes, or water currents. Their lateral load capacity depends on the horizontal subgrade stiffness of the surrounding soil and the structural strength of the pile shaft against bending [2]. The PLAXIS 3D FOUNDATION program is finite element software designed for analysing foundation structures, including bridge foundations. It features straightforward graphical input methods for automatically generating complex finite element models, along with advanced output options and reliable calculation methods. This makes it a comprehensive tool for foundation analysis [3]. LPILE is specialised software for analysing deep foundations like piles. It calculates key parameters such as deflection, shear, bending moment, and soil response in layered soils. The program models soil and rock using lateral load-transfer (p-y) curves, which can be generated internally or supplied by users, and includes specific procedures for layered soil profiles. It supports various pile-head loading conditions, allows for different pile structural properties, and provides guidelines for rebar arrangements based on the ACI 318 code [4].

Current research investigates the behaviour and load-bearing pattern of a single vertical bore pile in layered soil. Results from IS2911Part1 (sec 2) using the Lpile and PLAXIS 3D techniques are compared. Additionally, lateral loads for a fixed-headed pile with different diameters and deflection values are calculated and presented.

II. SITE DETAILS

The Department of Local Infrastructure Development and Agricultural Roads (DOLIDAR) of the Government of Nepal has identified this location as the proposed site for the bridge. It is located southeast of Kathmandu in Nepal's Sarlahi district, part of the country's Terai region. The Terai zone is primarily flat terrain situated below 200 meters above sea level. It has a thick layer of alluvial sediment, about 1,500 meters deep, composed of boulders, gravel, silt, and clay. The Terai stretches from the Indian Shield in the south to the Siwalik zone in the north. Its width varies from 10 to 50 kilometres, forming a nearly unbroken east-west strip, except where the Siwalik zone interrupts it in two locations. The Main Frontal Thrust (MFT), an active fault, runs along the northern edge of the Terai near the Siwalik hills [5].

III. GEOTECHNICAL INVESTIGATION

A Standard Penetration Test (SPT) was conducted to a depth of 30 meters during the field investigation to observe the behaviour of the underlying soil layers. The investigation revealed that the soil consists of several layers, including a 9-meter-thick layer of medium sand sandwiched between two layers of medium-hard clay. The top clay layer extends down to 9 meters, while the medium sand layer ranges from 9 to 18 meters. Additionally, there is a second layer of medium-stiff clay that extends from 18 to 30 meters. The water table is located at the land surface. Both disturbed and undisturbed samples were collected for laboratory analysis to determine the soil properties. The values of the modulus of subgrade reaction (K) were obtained from IS 2911 Part I, Section II. For cohesive soils, the value remains constant, while for cohesionless soils, it varies linearly. According to IS 6403:1981, Table 1, Clause 5.1.1, for φef = 30.5 degrees, the bearing capacity factors are taken as Nc = 9 and Nq = 18.4. An adhesion factor α = 0.9 for pile design in cohesive soils.

Table 1. Geotechnical Parameters of Soil Determined from Field and Laboratory Investigations.

Layer	v	K(kN/m³)	E50	Navg	γ (kN/m³)	γsub (kN/m³)	Cu (kN/m²)	φef
1	0.35	3460	0.005	20	17	7	48	0
2	0.30	6440	-	30	17	7	0	30.5
3	0.35	3460	0.005	30	17	7	48	0

v: Poisson's ratio, E50: Strain Factor, K: Modulus of Subgrade Reaction, Navg: Avg.SPT value, γ: Unit Weight, γsub: Submerged Unit Weight, Cu: Undrained Shear Strength, φef: Angle of internal friction(degree),

IV. METHODOLOGY

Method I: IS 2911 (Part 1/section 2)- 2010 outlines the procedure for determining the lateral load capacity of piles, as specified in Annex C of the standard. It recognises the complexity of the interaction between the pile and the soil as the load approaches its ultimate value. This interaction involves both elastic and plastic deformation of the soil. An approximate solution is provided for most cases, but scenarios requiring a more detailed analysis should be approached accordingly. The first step involves determining whether the pile acts as a short, rigid unit or an infinitely long, flexible member by calculating the stiffness factor (R or T) for the specific pile-soil combination. Once the stiffness factor is determined, criteria related to the pile's embedded length (L) are used to classify its behaviour. Next, the depth from the ground surface to the point of virtual fixity is calculated and then utilised in conventional elastic analysis to estimate lateral deflection and bending moment. For granular soils and normally consolidated clays, the lateral soil resistance is modelled using a variable soil modulus, whereas for preloaded clays, it is modelled with a constant soil modulus [2].

Method II: The working principle of pile foundation analysis in PLAXIS 3D is based on the Finite Element Method (FEM), where the soil–pile system is discretized into finite elements, soil behavior is defined using constitutive models (e.g., Mohr–Coulomb, Hardening Soil), and pile–soil interaction is modeled through interface elements to simulate realistic load transfer along the pile shaft and tip. Construction stages, including pile installation, consolidation, and loading, are modelled stepwise, and FEM equations are solved iteratively to capture the nonlinear soil response under different loading conditions. The Output program provides results such as settlement profiles, lateral deflections, bending moments, shear forces, axial forces, and load–load-displacement curves, along with stress–strain distribution and pore pressure changes in soil. This enables a comprehensive understanding of the pile's performance, failure mechanisms, and overall stability of the foundation system under axial, lateral, or combined loads [3].

***Method III*:** LPile software models the pile as a beam on an elastic or nonlinear foundation, dividing it into finite elements along its length. For each component, LPile employs iterative numerical methods to satisfy equilibrium between the applied lateral load and the soil resistance. A predefined lateral deflection criterion (e.g., 1% of pile diameter as per IRC:78-2014) is established as the permissible limit. The software incrementally increases the lateral load until the pile head or any point along its length reaches this deflection limit, thereby determining the ultimate lateral load capacity corresponding to the specified deflection. The bending moment distribution is then calculated from the derived pile deflection profile using principles of structural analysis. LPile computes slope, shear, and moment at each depth by solving the governing differential equation of a beam on elastic foundation EI d4y /dx4 + p(y)=0, where EI is the pile stiffness, y is the lateral pile deflection, and p is the soil reaction [4].

The results from these three methods are presented graphically to demonstrate the differences in predicted capacities and moments, allowing for an evaluation of how advanced numerical modelling (LPile and Plaxis 3D) compares with traditional analytical and semi-empirical approaches for safe and cost-effective pile design.

Material Properties: The pile material is made from M35 grade concrete with a characteristic compressive strength (fck) of 35 MPa, a tensile strength (fcr) of 4.14 MPa, an elastic modulus (Ec) of 29,580 MPa, and a shear modulus (G) of 12,325 MPa. The longitudinal and transverse reinforcement is provided using Fe 500 steel, which has a characteristic tensile strength (fyk) of 500 MPa, ensuring sufficient strength and ductility to resist axial, bending, and shear forces effectively.

Pile Geometry: The pile has a circular cross-section with a diameter up to 2m and a fixed length of 20 m. For a 1 m diameter, its cross-sectional area is 0.785 m^2, and the moment of inertia is 0.0491 m^4, indicating the pile's stiffness and strength under axial and lateral loads.

V. RESULTS AND DISCUSSION

a. Calculation of Lateral Capacity

The analysis is conducted to investigate the impact of pile geometry on lateral load capacity, subjected to a predefined deflection limit of 1% of the pile diameter, which serves as the boundary condition. The pile diameter varies from 0.80 m to 2.0 m while maintaining the pile length constant of 20 m. The pile head is assumed to be restrained (fixed-head condition). The lateral load capacity is determined using both the analytical approach and the (LPile, PLAXIS 3D) software.

PLAXIS 3D) software.

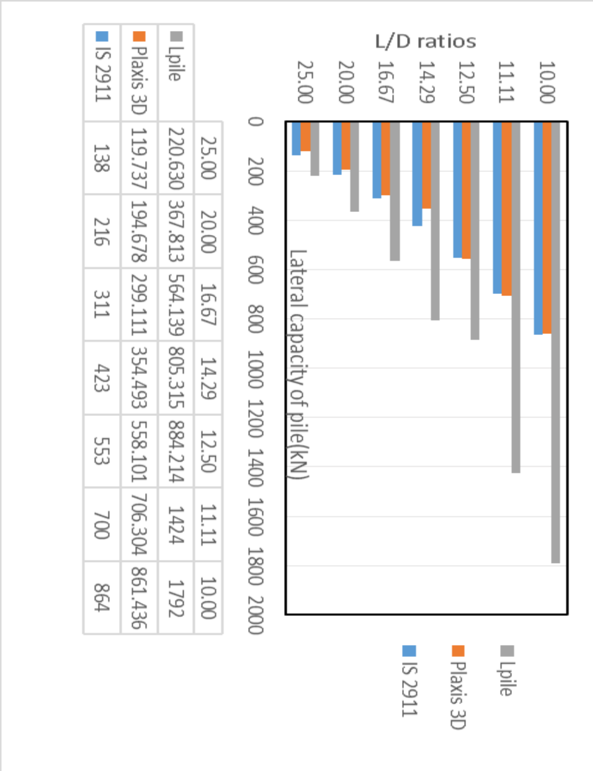

Fig. 1. Variation of Lateral Load Capacity with increasing diameters of pile

The above graph illustrates how lateral pile capacity varies with different L/D ratios, based on results from IS 2911, Plaxis 3D, and LPILE. In all three methods, lateral capacity decreases as the L/D ratio increases, indicating that piles have less resistance. At lower L/D ratios, LPILE gives much higher capacity values than IS 2911 and Plaxis 3D, but these differences decrease at higher ratios. IS 2911 and Plaxis 3D produce similar results throughout, showing that the code and the numerical analysis are consistent.

VI. VALIDATION OF THE RESULT

The figure below compares experimental results with those of Abhipriya Halder and Kaushik Bandyopadhyay (IGC 2016) [7]. In both cases, lateral load capacity increases as pile diameter increases, showing a clear positive correlation. The curves look similar, and both rise sharply at larger diameters. This means that our results and those from literature show the same basic pile behaviour. Although Experiment (III) shows higher values, the overall trend and proportional increase are consistent.

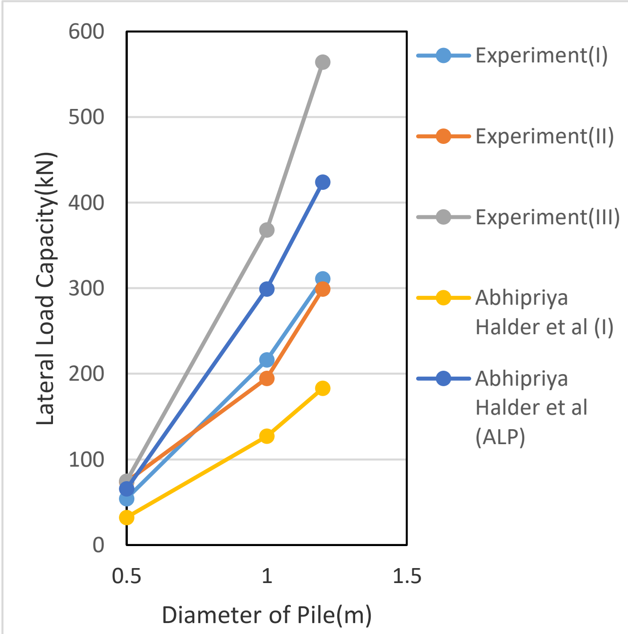

Fig. 2. Comparison of the lateral load capacity of piles of varying diameter obtained from this research and [7].

I: IS 2911, II: Plaxis 3D, III: LPile and ALP: Analysis of laterally loaded pile (Software)

VII. CONCLUSION

This research demonstrates that pile slenderness, soil layering, and analytical technique all have a significant impact on pile lateral capacity. The data clearly illustrate that when the L/D ratio increases, capacity diminishes. Among the three approaches, LPile predicts the highest capacities at low L/D, due to its p–y curve formulation and stiffer soil response assumptions. Plaxis 3D and IS 2911 yield lower but closely consistent capacities, providing more conservative estimates. At higher L/D ratios, the predictions from all three techniques converge. This type of soil has a strong effect on how piles behave. When the middle sand layer is engaged, it significantly increases lateral resistance. However, the clay layers above and below, which have a lower subgrade modulus, decrease pile capacity as depth increases. As sand gets stiffer with depth, it further boosts lateral resistance where bending is most critical. The response of the clay layers depends significantly on the chosen subgrade modulus. Also, the stiffness of the pile itself, measured by its flexural rigidity (EI), plays a big role in how much the pile head moves. Stiffer piles can carry more load while staying within the 1% deflection limit.

The results show that when designing piles in layered soils, it is essential to account for changes in soil stiffness, the arrangement of the layers, and to select the appropriate analysis method. To enhance the reliability of design practices, integrating continuum-based numerical modeling using Plaxis 3D with simplified p–y or code-based approaches such as LPile and IS 2911 is advisable. This combined methodology enables a more accurate representation of soil–pile interaction while ensuring conservative design outcomes.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the Ministry of Urban Development, Department of Local Infrastructure (DoLI), Local Bridge Section, Shreemahal, Pulchowk, Lalitpur, Government of Nepal, and the consultant NREC-GSLP-AEC JV, Lalitpur, for providing the necessary data and support for this research. Their cooperation and assistance have been invaluable in completing this study.

REFERENCES

[1] B. M. Das, Principles of Foundation Engineering, Eighth. Global Engineering: Timothy L. Anderson, 2016.

[2] Bureau of Indian Standards, Design and Construction of Pile Foundations — Code of Practice, Part 1: Concrete Piles, Section 2: Bored Cast-in-situ Concrete Piles [CED 43: Soil and Foundation Engineering]. Bureau of Indian Standards, 2011.

[3] "PLAXIS 3D FOUNDATION Tutorial Manual version 1.5."

[4] W. M. Isenhower, P. E. Shin-Tower, and P. E. Wang, "User's Manual for LPile 2016 (Using Data Format Version 9) A Program to Analyse Deep Foundations Under Lateral Loading," 2016, Ensoft, Inc.

[5] R. Kshetri, "Physiographical-and-Geological-Division-of-Nepal," Article in Journal of Geology & Geophysics, 2023, doi: 10.35248/2381-8719.23.12.1131.

[6] Indian Road Congress, Standard Specifications and Code of Practice for Road Bridges, Section: VII Foundations and Substructure (Revised Edition), vol. VII. New Delhi: Indian Road Congress, 2014.

[7] A. Halder1 and K. Bandyopadhyay, "Lateral Load Carrying Capacity of Piles in Layered Cohesive Soil," 2016.