

Article

Behavior of Vertical Piles in Layered Soils Under the Influence of Vertical and Lateral Loading Conditions

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Abstract

Pile foundations used for structures, such as tall buildings and bridges, especially in coastal and heavily flooded areas, experience uncertain lateral loads. The wave action of water applies a lateral load on the pile, which cannot be predicted accurately. However, the impact of the vertical load significantly increases the pile's lateral capacity. This suggests more specific research is required into this particular area, especially considering the complex interactions involved. This study focused on the lateral strength of a single pile with a vertical load in layered soils. Using an experimental setup, the horizontal deformation of the pile with an increasing applied compression effect in different soil beds was determined. Analyses were extended using FEM for various combinations of clay and sand layers under varying vertical loads. Initially, the vertical behavior of each pile was determined to varying percentages. The results indicate that the lateral capacity of the pile increases significantly up to 60% of the applied vertical load in both sand and clay. But for clay–sand layer combinations, for an applied vertical load, 100% lateral capacity showed 1.34 times improvement. FEM findings are similar to the experimental results; as the vertical load reaches up to 60% on various soil layers, the lateral capacity improves.

Keywords: pile; lateral load; vertical load; combined load; clay; sand; L/D ratio; capacity; layer soil

1. Introduction

Piles are preferred as a foundation type where the topsoil experiences high differential settlement and the bearing of the load by soil is very low. Piles that are used in the above-mentioned condition tend to support the combination of vertical and horizontal loads. Normally, pile foundations have been widely adopted for engineering structures such as multi-storey buildings, offshore wind turbines, and bridges, as they are required for resisting not only the vertical load (VL) but also significant lateral forces induced by natural events such as earthquakes and wind action [1]. Soil structure interaction refers to the way in which the behavior of piles responds to loads and determines the maximum capacity of a structure. By adding a load on a pile, the deformation was first controlled by the side friction and the resistance developed around the surface of the pile. Subsequent to full mobilization on-side resistance up to the shear strength of soil, the pile end supports the remaining load. The ultimate, or maximum, load tolerance of a pile is defined by the point at which the soil fails, typically in punching shear. To satisfy the equilibrium, the soil provides a reaction to counteract the applied loads and moments along the pile's length. Design engineers are more interested and experienced in understanding how piles respond



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to the lateral load (LL) when combined with vertical loads due to their inadequate design. However, the given complexities of analyzing when piles experience combined forces are typically evaluated by assessing them separately, assessing their capacity and settlement for vertical loads, and examining their bending behavior for lateral loads.

Methods used to analyze VL on piles include the subgrade reaction method [2,3], elastic continuum approaches [4] and finite element methods [5]. Similarly, for LL on piles, predicting methods include the limit state method [6], p-y method [7,8] and finite element methods [9–13]. Past studies found that vertical loads of 0.6Vult do not significantly affect the LC of piles in the clay bed, as long as the vertical load is below a certain level. However, at higher VL levels, the LC decreases by up to 20% [14,15]. Rahman and Achmus investigated the performance of vertical piles with combined load in sandy soil and found that the vertical load causes a compression effect that tends to increase pile stiffness and capacity, which is stimulated by a horizontal load [16]. Phanikanth et al. derived the performance of a single pile in sand that has less cohesion for varying density in dry and submerged conditions [17]. The pile response increased by 2.69 times in loosely packed sand compared to densely packed sand without water table conditions and with water table conditions; the pile response was amplified by 3.57 times in the loose state compared to the dense state of soil. Guo and Ghee stated that the pile group subjected to axial load and horizontal movement of soil, the performance are higher compared to that of pile group without axial loading [18]. Zamri et al. stated that depending on the intensity of the load's width and depth, the pile varies accordingly [19]. Al-Amery and Al-Dahlaki studied the performance of piles subjected to both VL and LL by varying L/D as 20, 25 and 30. The results indicate an L/D of 30, where the pile response for the VL increases the LC [20]. While considerable information is available in the referred literature on the vertical load behavior and lateral load response of the pile and pile group independently, data on the combination of both the vertical and lateral loads is rather limited under varying parameters such as the number of piles, type of soil layer, spacing and L/D ratio. But the problem is the worst under the combination of both loads. These limitations necessitate carrying out a study examining the combination of vertical and lateral loaded piles. Hence, the objective of the present study is to focus on the impact of L/D of 12 and 24 and layered soil on the VC and LC of a pile. Also, the impact of VL on LLCC of a pile is determined for varying the percentage of the applied vertical loading in clay, sand and layered soil stratum.

2. Materials

2.1. Clay

The clay sample utilized for this research was collected from Thuraipakkam, Chennai, India. Experiments were performed to establish the index properties of clay [21]. The percentage of clay present in the collected sample was determined using the sieve analysis test and the results are illustrated as a curve in Figure 1 [22]. These samples included clay and sand fractions. Table 1 defines the clay as CH, which represents high plasticity clay according to Indian Standard Soil classification [23].

Table 1. Index properties of clay.

S. No.	Property	Value
1	Specific gravity (Gs)	2.77
2	Clay (%)	66
3	Silt (%)	22
4	Sand (%)	12
5	Liquid limit (%)	55
6	Plastic limit (%)	24

Table 1. Cont.

S. No.	Property	Value
7	Shrinkage limit (%)	12
8	Soil classification	CH

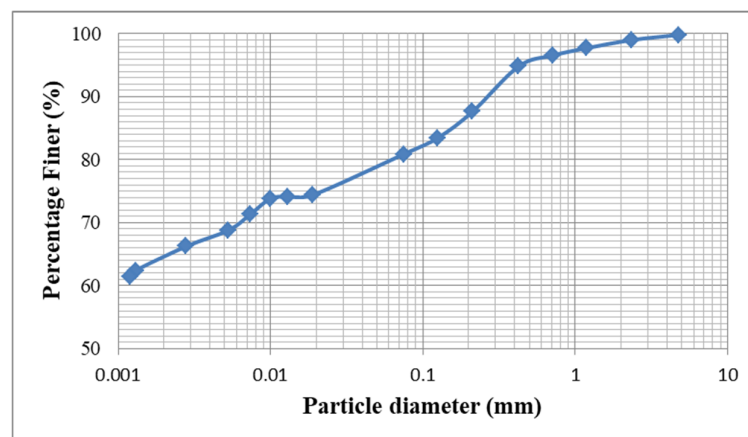


Figure 1. Grain size distribution curve of clay.

2.2. Sand

The sand was acquired from a local supplier in Chennai. Analysis of the particle size distribution was conducted, and the results are presented in Figure 2 [22]. According to the curve, medium sand is predominant. Table 2 represents the sand's properties, in which the collected soil is classified as SP, which represents poorly graded sand [23].

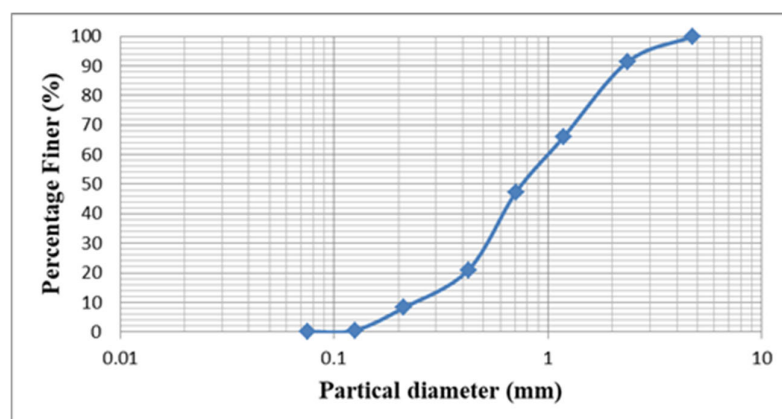


Figure 2. Grain size distribution curve of sand.

Table 2. Index properties of sand.

S. No.	Property	Value
1	Maximum dry unit weight	16.89 kN/m ³
2	Minimum dry unit weight	13.76 kN/m ³
3	Coarse Sand (%)	2
4	Fine Sand (%)	26
5	Medium Sand (%)	72
6	Specific gravity (Gs)	2.45
7	Soil classification	SP

2.3. Model Pile and Tank

A circular hollow aluminum rod with a diameter of 10 mm and 1.5 mm of thickness was used as the pile model is shown in Figure 3 [24]. The embedment depths adopted were 120 mm as well as 240 mm based on the L/D ratio for 12 and 24, respectively [24,25]. An aluminum plate with 3 mm thickness, together with 45 mm × 45 mm plan dimensions, served as the pile cap. The experimental work contains a steel tank measuring 500 mm × 500 mm, and 700 mm in height, which was utilized as the model container for conducting the load tests [24]. Due to the ample width of the model tank, which is 5–15 times the pile diameter, boundary effects are negligible and do not influence the results [26].

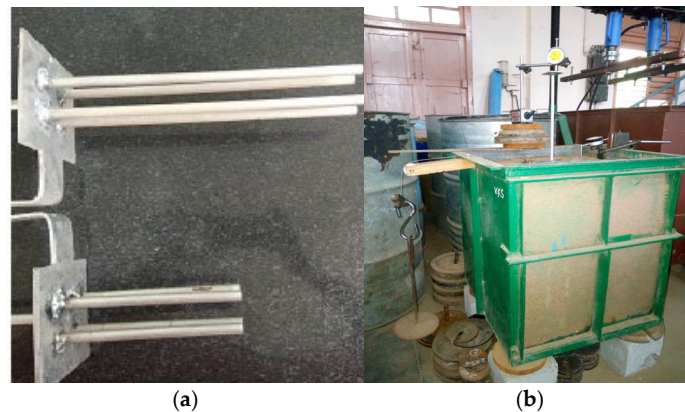


Figure 3. (a) Model pile; (b) model tank.

Calculation of Dimensions of the Model Pile

To investigate the lateral characteristics of the full-scale prototype soil–pile systems, firstly, the dimensions of the small-scale model are converted to the equivalent dimensions of the prototype pile with the use of the similitude scaling law proposed by [27]. The prototype of the pile is scaled in to model the pile with the following relation [27,28].

$$n_E n_I = n_G n_L^4$$

Assuming the soil's stiffness is the same for the model and the prototype,

$$n_E n_I = 1/n_L^4$$

where

n_E = Scaling factor of Young's modulus of pile material, in GPa;

n_I = Scaling factor of Moment of inertia of the pile cross section, in mm⁴;

n_L = Scaling factor of length of pile, in mm.

Dimensions of the prototype:

Diameter of the pile = 1 m;

Length of the pile = 10 m;

Young's modulus of the concrete pile = 32 GPa (for M40 concrete grade).

Dimensions of the Model Pile: (Short Pile)

Diameter of the pile = 10 mm;

Young's modulus of the aluminum pile = 69 GPa.

$$n_E n_I = 1/n_L^4$$

Substituting the above values,

$$(69/32)(\pi \times 10^4/64)/(\pi \times 1000^4/64) = 1/n_L^4$$

$$n_L = 82.52$$

$$\text{Length of model pile} = (10,000/82.52) = 121.18 \text{ mm} \sim 120 \text{ mm}.$$

Hence, an aluminum pile of 10 mm diameter is used for the pile. The length-to-diameter ratio of the pile (L/D) is considered as 12, which is classified as a short pile, and was used throughout the experimental study.

Dimensions of the prototype:

Diameter of the pile = 1 m;

Length of the pile = 20 m;

Young's modulus of the concrete pile = 32 GPa.

Dimensions of the Model Pile: (Long Pile)

Diameter of the pile = 10 mm;

Young's modulus of the aluminum pile = 69 GPa

$$n_E n_I = 1/n_L^4.$$

Substituting the above values,

$$(69/32)(\pi \times 10^4/64)/(\pi \times 1000^4/64) = 1/n_L^4$$

$$n_L = 82.52$$

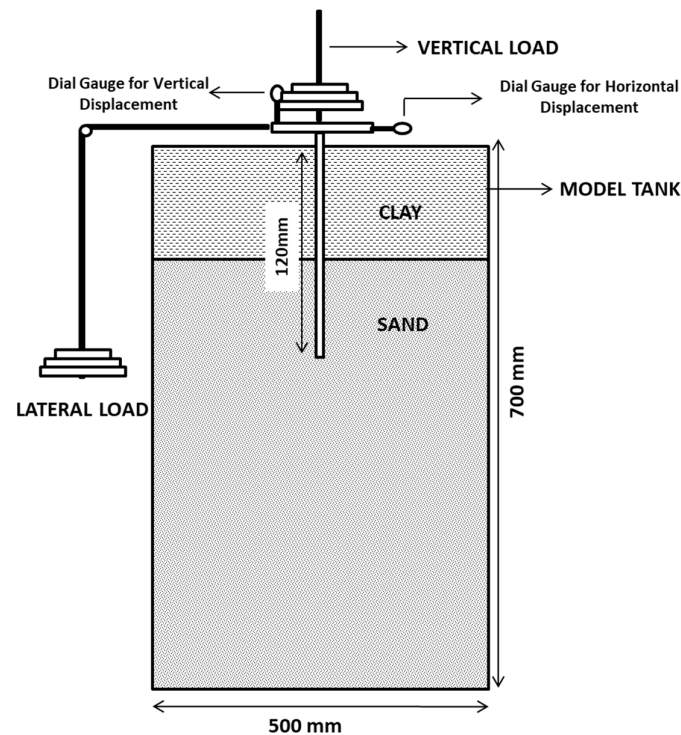
$$\text{Length of model pile} = (20,000/82.52) = 242.36 \text{ mm} \sim 240 \text{ mm}$$

Hence, an aluminum pile of 10 mm diameter is used for both pile and pile groups. The length-to-diameter ratio of the pile (L/D) is considered as 24, which is classified as a long pile, which was used throughout the experimental study.

3. Methods

3.1. Experimental Method

The clay sample was first air-dried, after which water corresponding to the consistency of medium-stiff was added based on the soil's dry weight. In the case of the clay bed, the hand-remolded clay sample is carefully placed at an initial moisture content of 68%, which corresponds to a consistency of 0.2. A vane shear test has been carried out to find out the shear strength of the clay. The shear strength of clay at the consistency of 0.2 is 7.3 kN/m². The moistened clay had been completely mixed to achieve uniformity and stored in plastic, airtight bags. To prevent any moisture loss, the material was further sealed using plastic wrap. The prepared sample was considered at ease at room temperature for the 24 h period to verify even moisture distribution throughout the clay. A relative density of 60% was selected for sand. The weight of the sand is calculated using the maximum dry unit weight of 16.89 kN/m³, and it is filled in the model tank using the rainfall technique. Based on the graph established between the height of the fall and relative density, the medium-dense state of sand was ensured. If the volume of the tank is fully covered with the calculated amount of sand, then it is deemed that it has 60% relative density. Figure 4 illustrated the base of the model tank had initially been packed with sand compacted to the 60% relative density (representing a medium-dense condition ranging from 40% to 60%) up to the level where the pile tip was to be positioned [29]. Subsequently, the model pile gets installed at the tank center. Once the model pile was placed in the position, the uniformly combined clay at 0.2 consistencies was filled over the tank using the kneading compaction method up to the top by the non-displacement method of pile installation [24].



(a)



(b)

Figure 4. (a) Schematic representation of combined load test; (b) Lateral and vertical pile load test setup.

The model tank was filled with a soil sample with respect to embedded pile length, as shown in Figure 4. After filling the tank up to a height of the bottom of the pile, the model pile is placed in a soil sample with an embedded length, followed by a free-standing length of 20 mm above the soil bed. The rest of the tank is filled with soil samples surrounding the pile with respect to L/D ratios for 12 as well as 24. For each test, a new soil layer bed is prepared depending upon the embedded length (L) of the pile; the thickness of layers of soil is calculated and varied accordingly, as shown in Figure 5. For understanding their response under lateral loading, the pile head had been connected to the loading frame by high-tension wire. Dial gauges were employed in measuring both laterals along with vertical displacements at the pile head. IS 2911 (part 4)—2013, Section 7.2. The Maintained Load Method was followed with regard to the application of load increment. Test weights are used for applying load. The increment of loads to be applied was derived from trails.

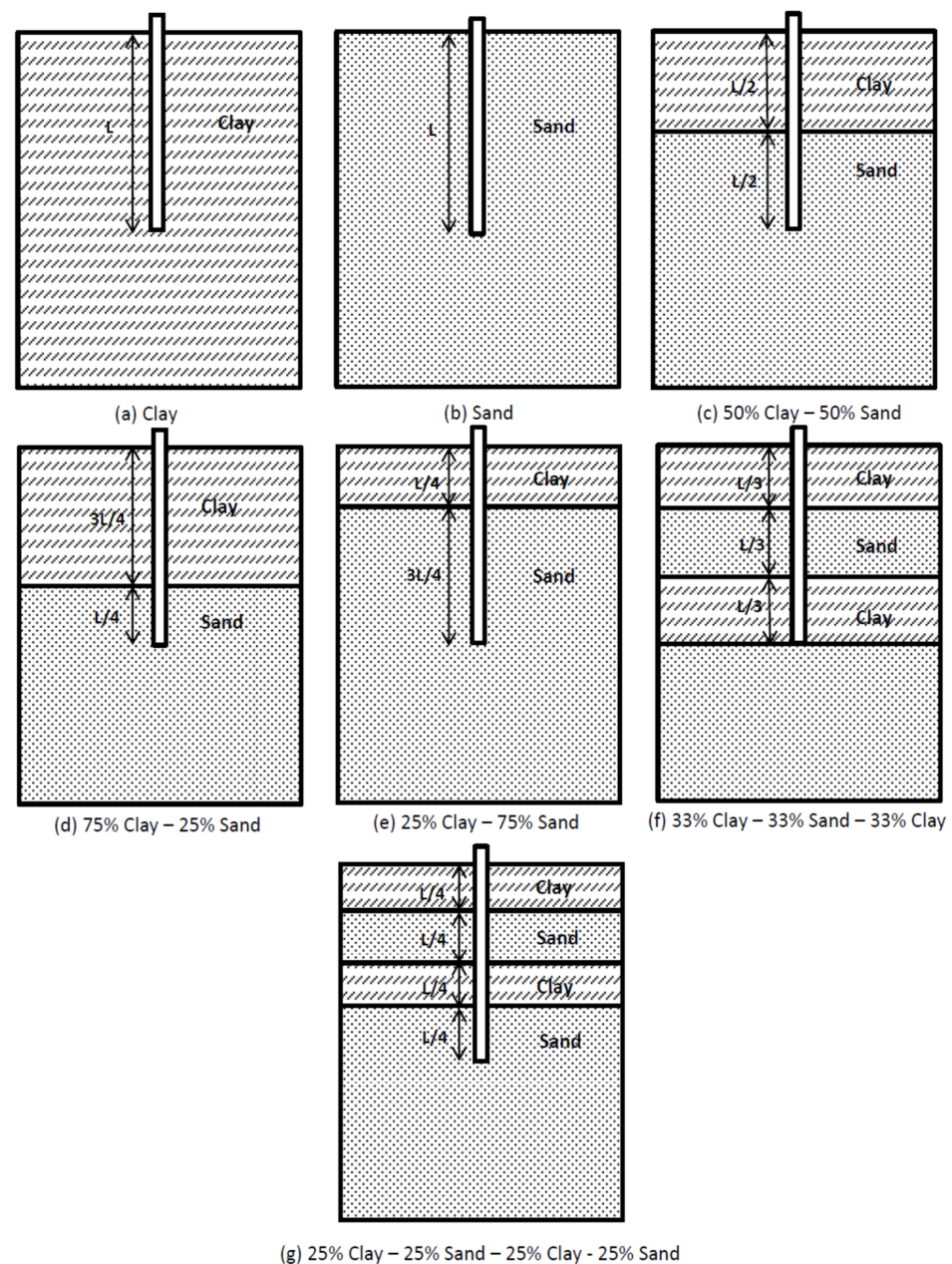


Figure 5. (a–g) Schematic representation of different combinations of soil layers used for vertical/lateral pile load tests.

After application of loads, together with corresponding pile head displacements had been recorded at regular intervals, awaiting a maximum displacement of 12 mm was reached for both vertically as well as laterally loaded piles [30]. As per IS: 2911 (Part 4), 2013 Section 8.4, the load corresponding to any other specified displacement as per performance or design requirements is considered the criterion followed in the present research work [30]. The criterion based on deflection is well established and recommended in many previous research works [24,28,31].

Initially, the pile is subject to vertical load along with lateral load independently. The vertical capacity had been obtained from the load–settlement curve corresponding to 12 mm settlement [30]. To understand the study about the vertical load on pile lateral capacity impact, it had been implemented using a set of experiments that were conducted through initiating vertical load alone for each pile load test of varying percentages (0, 20, 40, 60, 80 and 100% of pile with vertical capacity) [14,15]. After the vertical load application, the

lateral loading was started gradually at a regular interval based on the pile deflection report. The lateral load-carrying capacity was accomplished from a load-deflection curve corresponding to a 12 mm deflection [30]. Due to certain limitations, data for research were collected from a single test for each case, which is noted as a constraint of this research. For the soil, a constitutive model such as the Mohr Coulomb model is typically chosen to capture the non-linear, stress-dependent behavior, particularly in clays. For the pile, a linear elastic model is usually deemed sufficient given the expected elastic range under the applied loading conditions.

3.2. Finite Element Model Development

Table 3 shows the pile and soil properties that were employed as input parameters of numerical analysis. From experimental results, a pile with an L/D ratio of 12 seems to need more attention and evaluation. Hence, a Finite Element Model (FEM) with 3D had been developed for simulating the interaction behavior of pile–soil with a single pile under both axial and lateral loading conditions. The Mohr-Coulomb model was adopted as a material model for clay and sand. The soil domain was designed as a continuum using eight-node solid elements, while the hollow aluminum pile was mentioned as a 3D linear elastic element to accurately capture axial force, bending moment, and deformation behavior. The elastic modulus and yield strength of aluminum used for the study were 69,000 MPa and 276 MPa. An elastic model was used as a material model for the pile. To neglect boundary effects, the lateral boundaries of the model were maintained at a distance of a minimum of $5 \times$ diameter, with the base completely fixed, which prevents movement in any direction, and the vertical boundaries limit horizontal motion. The boundary dimensions of $500 \times 500 \times 700$ mm were used. The coarseness of the mesh chosen for the analysis is a medium mesh of average element size 34.02 mm, which was adopted over the interface vicinity in the pile–soil for ensuring accurate stress transfer along with displacement continuity, while a comparatively coarser mesh was used away from the pile to improve computational efficiency. The mesh used in the analysis was 10-node triangular elements. Contact/interface elements had been introduced among the pile along with surrounding soil to model realistic interaction behavior, allowing slippage and separation under loading. The interface strength reduction factor (Rinter) 1 was used for both clay and sand material. The initial geostress state was set by a K_0 procedure (formula: $\sigma_{h0} = K_0 \times \sigma_{v0}$). The K_0 values used for clay and sand were 0.5 and 0.577, respectively. The default value of 0.01 is used as the tolerated error of convergence criteria. The loading step that was followed in the current study was initial condition, activation of pile and pile cap, activation of vertical load, and activation of prescribed displacement. The numerical model was solved using an incremental-iterative nonlinear solution algorithm, enabling effective simulation of material nonlinearity, geometric nonlinearity, and load interaction effects under combined load [32].

Table 3. Properties of Pile together with soil used for Numerical analysis.

Pile Description	Specification Value	Soil Description	Clay	Soil Description	Sand
Pile Type	Aluminum	Drainage type	Undrained B	Drainage type	Drained
Material Model	Elastic	Material model	Mohr Coulomb	Friction angle	Mohr Coulomb
		Undrained cohesion	15 kPa	Friction angle	34°
Elastic Modulus	69,000 MPa	Elastic Modulus	3 MPa	Elastic Modulus	50 MPa
Unit Weight	26 kN/m ³	Unit Weight	19 kN/m ³	Unit Weight	18 kN/m ³
Poisson's ratio	0.33	Poisson's ratio	0.40	Poisson's ratio	0.30

4. Results and Discussions

4.1. Results of Experimental Work

4.1.1. Influence of Length to Diameter Ratio on Vertical Capacity of Piles

For the combined load test (vertical + lateral), initially the VLCC for 12 and 24 as L/D of the pile in clay, sand, and 50% clay–50% sand layer were evaluated. The value of load corresponding to 12 mm settlement was considered the vertical capacity of each pile. The value of vertical capacity is considered to be 100% of VL that would be applied during a combined load test. From 100% of the vertical load, 20%, 40%, 60%, and 80% of the vertical load was obtained from the combined pile load test. Figure 6 illustrates the variations in vertical capacity characteristics. The results revealed that the VC increased with an increasing L/D ratio. Specifically, a pile with L/D = 24 embedded in sand increased to 148.9 N. Comparatively, 50% clay–50% sand result in 1.4 and 2 times increased vertical capacity compared to clay of a pile with L/D as 12 and 24, respectively. The outcomes indicate that the type of soil significantly impacts the vertical load performance of piles, with the presence of a layer of clay tending to reduce the vertical capacity.

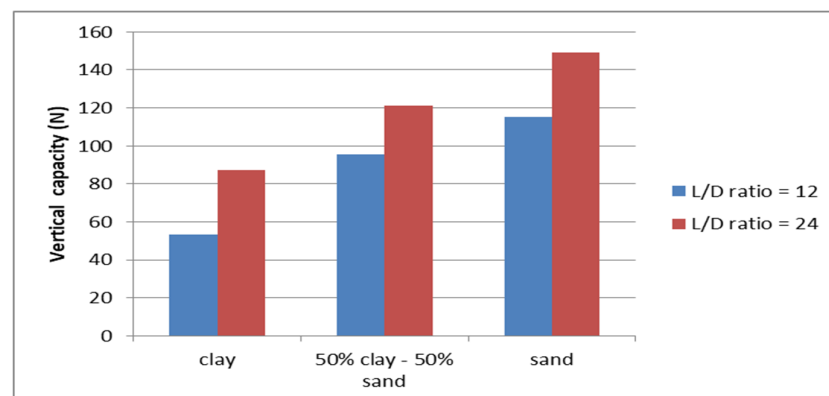


Figure 6. Variation in vertical capacity with L/D of 12 and 24 for different soils.

4.1.2. Impact of VL on the LC and Soil Type

Figure 7 represents the change in the behavior of LC and deflection in a pile with L/D = 12 for varying percentages of vertical load. From the LL-deflection curve, the loads associated with 12 mm deflection are the lateral capacities of each pile [30]. The applied vertical loads were varied individually at 0%, 20%, 40%, 60%, 80%, and 100%. The results show that the LC increased with increasing VL for a pile embedded in 50% clay–50% sand is presented in Figure 7b. Furthermore, with 100% of vertical load, lateral capacity has increased by 33% compared to without vertical load. The VL, which acts on the pile head, exhibits a compression effect that decreases the deflection of the pile laterally.

Figure 7a,c shows the LLCC of a pile embedded in clay and sand. In both clay and sand, a similar increasing trend of load deflection curves is noticed. A pile that is embedded in clay has an increasing range of lateral capacity up to 60% of applied vertical load from 0% of vertical load. That is, an 18% increment was observed when compared to the LC of without VL. Similarly, sand has a 10% increment noticed. Likewise, for VL behavior, the LC becomes highest for piles recognized solely in sand. Because the sandy soil, which exhibits the surrounding of the pile, offers frictional resistance to the pile surface, it improves the load-carrying capacity.

However, for 80% and 100% of the VL, the pile-carrying capacity of the lateral load reduces because of the higher vertical load impact, which deflects the pile with L/D = 12. The reduction in the pile LLCC applies to both the initial soil failure and pile-soil interfaces when vertical loads are present.

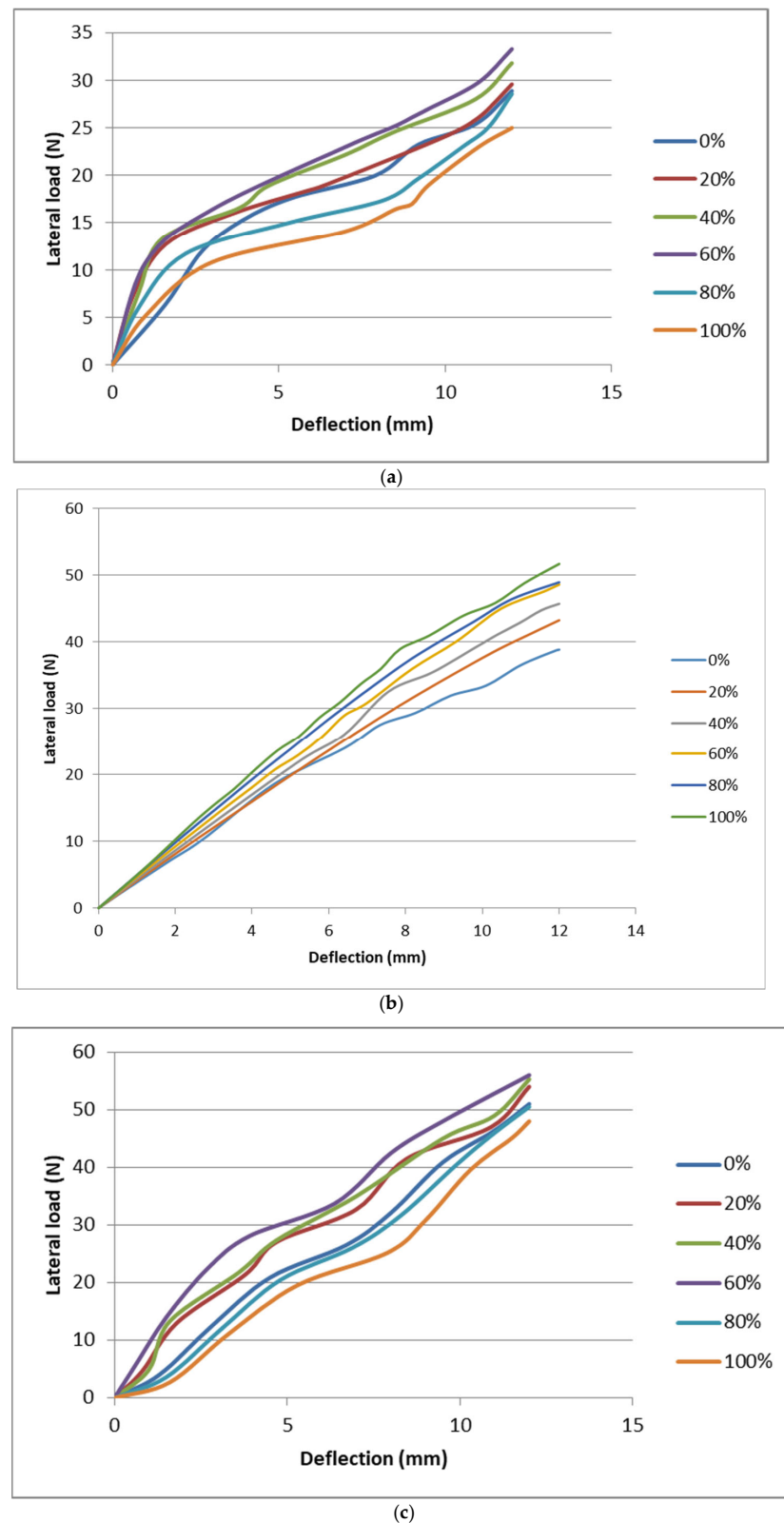


Figure 7. LL-deflection of single pile for $L/D = 12$ in (a) clay; (b) 50% clay–50% sand; and (c) sand.

After the interface among the pile and surrounding soils fails, further pile lateral deformation does not result in increased lateral stresses over the soil around the pile. Similar results were obtained by Zadeh and Kalantari, wherein the pile capacity of lateral load over sandy soils was enhanced by 40% with the vertical load's presence depending on the levels of vertical load [33].

Figure 8 shows the increment of LL with applied VL and the deformation behavior. The pile has $L/D = 24$. The results showed that LC increased with increasing VL. From Figure 8c, the LC of the pile embedded in sand exhibited a substantial increment, increasing from 63 N to 75 N for the applied vertical load of 0% to 100%, respectively. Similarly, for clay and 50% clay–50% sand soil profiles, an increase in lateral capacity of 16% and 51%, respectively, was observed, as illustrated in Figure 8a,b.

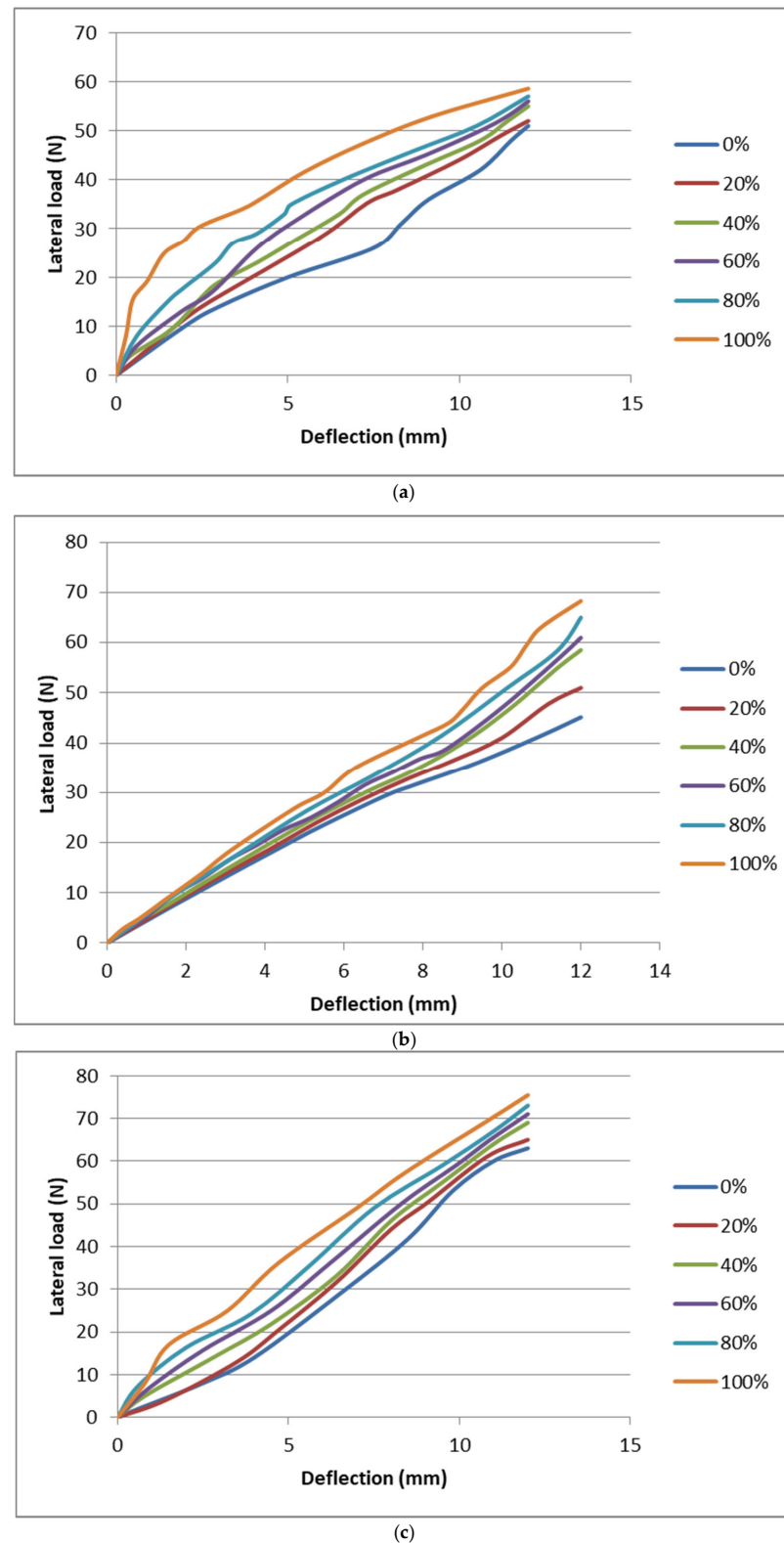


Figure 8. LL-deflection of single pile for L/D 24 in (a) clay; (b) 50% clay–50% sand; and (c) sand.

A noticeable increment in the LC of the pile was observed in a 50% clay–50% sand soil layer profile. Compared with clay and sand, the layered soil profile of 50% clay and 50% sand exhibited a high response to the introduction of a vertical load on a pile.

4.1.3. Impact of L/D Ratio on Combined Loading

Figure 9 presents the changeover of LC of pile for L/D of 12 as well as 24 when VL is applied at the increments of 0%, 20%, 40%, 60%, 80%, and 100%. The L/D ratio has an important impact on single-pile deformation behavior, especially in clay soil. While the length-to-diameter ratio increases, the pile becomes more slender and engages a larger surface area in contact with the surrounding clay, which leads to greater mobilization of skin friction and improved load transfer over the pile shaft [34]. Consequently, for a higher L/D ratio, the pile head settlement generally decreases under the same applied load, because the load is distributed over a larger embedded length. L/D of 24 for an individual pile embedded in a clay bed alone, the LLCCs are 1.3, 1.2, 1.5, 1.5, 2.7, and 3 times higher when compared to L/D of 12. However, the pile LLCC for L/D = 24 in the sand bed is 1.8, 1.7, 1.6, 1.5, 1.9, and 2.1 times for a pile with L/D = 12. Furthermore, a similar trend is obtained for a 50% clay–50% sand soil layer profile, as the pile of L/D = 24 gives enhanced capacity compared to the L/D ratio of 12. Therefore, increasing the L/D ratio enhances axial stiffness, improves load-carrying efficiency, and reduces vertical deformation, making it a critical design parameter for controlling displacement in singular pile foundations.

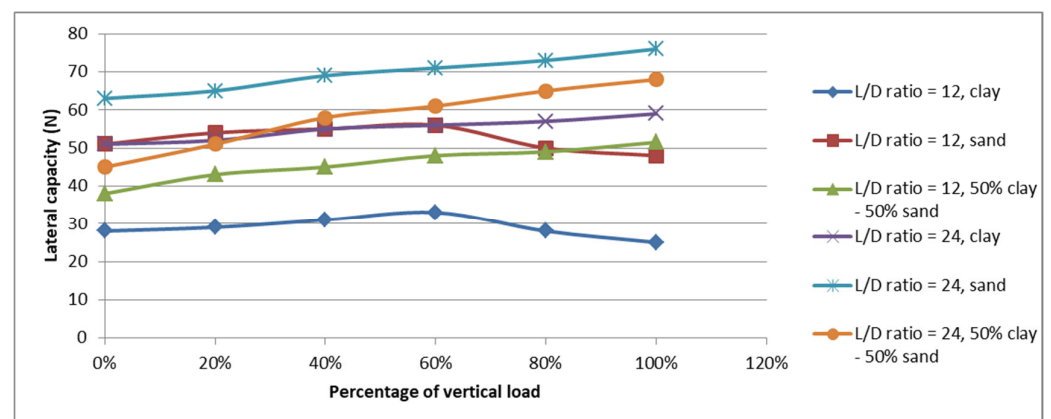


Figure 9. Variation in the LC of pile for L/D 12 and 24 with varying percentage of VL.

As demonstrated in Figure 9, an LC of 12 as L/D of a pile surrounded by a sand bed shows similar values when compared to a pile with L/D = 24 in clay.

4.2. Numerical Results Validation

The numerical results were validated for a single pile in a clay bed for varying vertical loads of 0%, 60% and 100%. The lateral load–deflection response for different percentages of vertical load, detailed in Figure 10, and the findings support the idea that both methods exhibit the same trend. From Figure 10, a deviation of less than 15% was observed in the lateral load values obtained through experimental and numerical methods. Experimental data closely matched the predictions of the advanced numerical model, confirming its effectiveness to realistically simulate pile–soil interaction behavior and thus providing strong confidence for its application in parametric studies involving combined loading conditions.

The observed trend for LC of 60% of applied VL shows the maximum bearing capacity obtained, which points to a better load transfer response for increased VL. When the applied VL was 60%, the LL values were obtained as 33.18 N and 34.92 from the experiment and FEM, respectively, for L/D = 12 embedded in clay. Table 4 clearly illustrates that the LL

for deflections of 4 mm, 8 mm, and 12 mm shows a variation of less than 15% between the experimental and numerical results.

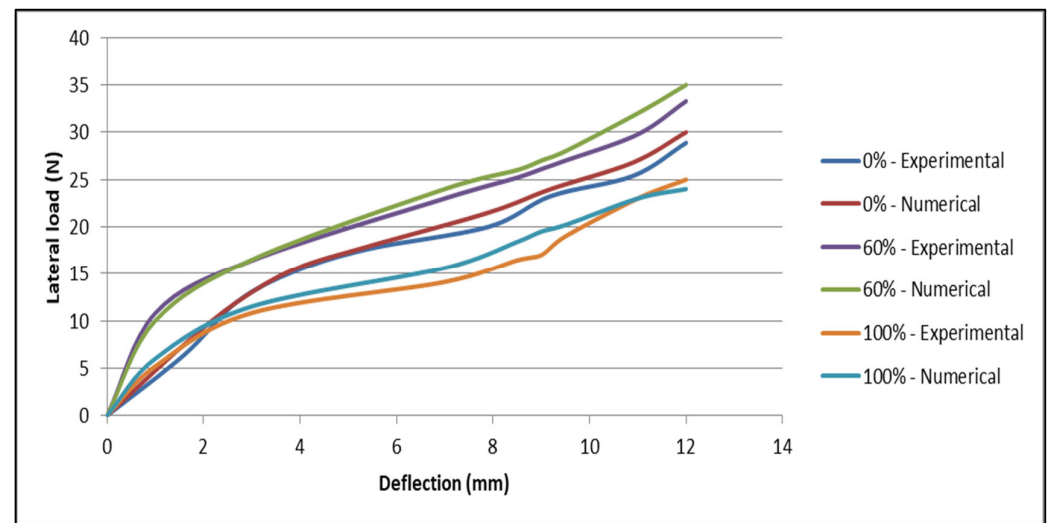


Figure 10. LL-deflection curve of experimental and FEM analysis of clay bed with L/D ratio 12 for varying percentage of vertical load.

Table 4. Comparison of the LL for different deflections from the experimental and numerical results of the clay bed with an L/D ratio of 12 for varying percentages of the vertical load.

Percentage of Vertical Load	Analysis Method	Lateral Load (N)		
		4 mm	8 mm	12 mm
0%	Experimental	15.26	20	28.88
	Numerical	15.5	21.5	30
60%	Experimental	16.42	25.2	33.28
	Numerical	16.5	26	34.8
100%	Experimental	10.82	16.44	25.3
	Numerical	11.5	17.4	24.8

4.3. FEM Results

4.3.1. Effect of the Layered Soil on the Vertical Load Carrying Capacity

Likewise, for the combined load test (vertical + lateral) in numerical analysis, initially the VLCC of the pile with L/D = 12 in clay, sand, 25% clay–75% sand, 75% clay–25% sand, 33% clay–33% sand–33% clay (three-layer soil stratum), and 25% clay–25% sand–25% clay–25% sand (four-layer soil stratum) layers were evaluated. Figure 11 illustrates the variations in vertical capacity characteristics obtained from FEM (Plaxis 3D). This behavior of the curve clearly illustrates the strong influence of introducing a sand layer on the pile's performance on vertical capacity. Based on the given settlement, the pile in sand consistently carries the highest VL, indicating superior shear strength of sand, whereas the pile in clay shows the lowest vertical capacity. The layered soil cases fall between these two extremes, with load capacity progressively increasing as the proportion of the sand layer's thickness increases along the pile's length.

The displacement contour occurred in a pile that has L/D = 12 after deformation, as shown in Figure 12. Based on the settlement pattern, it is clear that the pile has undergone a maximum settlement of 35.54 mm.

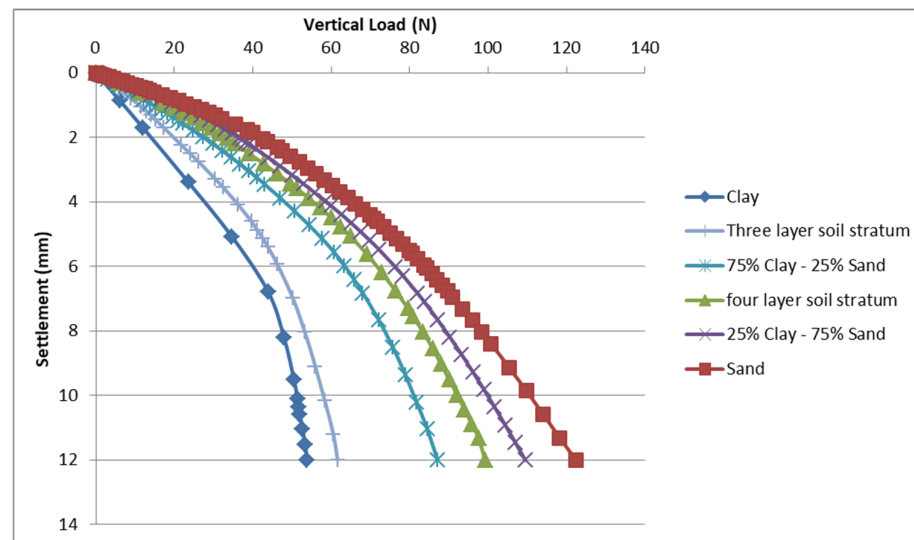


Figure 11. VL versus settlement curves of the effect of a pile with an L/D ratio of 12 towards a varying soil medium.

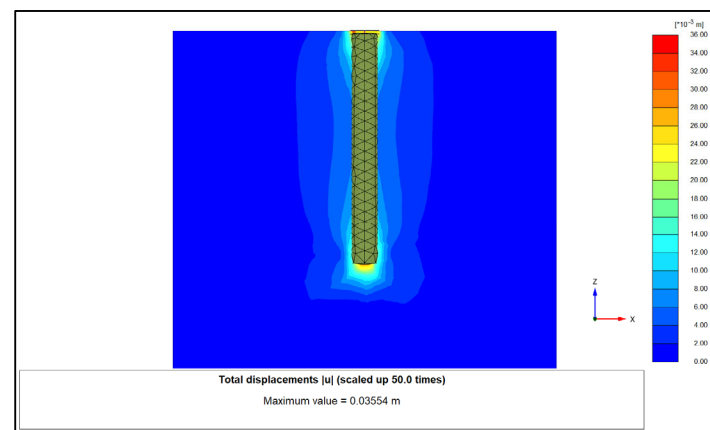


Figure 12. Displacement pattern of pile with L/D 12 in clay soil from Plaxis.

4.3.2. Impact of VL on LC

The impact of VL on LLCC was a major part of the analysis in this work. The magnitude of vertical capacity associated with 12 mm is determined and considered to be 100% of the VL applied as the vertical load in the combined pile load test. From 100% of the vertical load, 20%, 40%, 60%, and 80% of VL were derived for the combined pile load test. From the experimental results, a pile with L/D = 12 seems to need more attention and evaluation. Hence, the combined pile load test (vertical + lateral) for L/D = 12 in the Finite Element Model (FEM) with Plaxis-3D was developed for simulating the interaction behavior of the pile–soil system. Performed a wide range of testing across different soil layers, which were not analyzed in experimental work. The differentiated soil layers are 75% clay–25% sand, 25% clay–75% sand, a three-layer soil stratum (33% clay–33% sand–33% clay), and a four-layer soil stratum (25% clay–25% sand–25% clay–25% sand) corresponding to the embedded length of the pile. The LC was enhanced on the pile with VL, but the degree of improvement varies with soil type.

Figure 13 shows the variations in the lateral capacity characteristics of the piles in 75% clay–25% sand. While the lateral capacity of the pile increased from 38.1 N at 0% vertical load to 41.6 N at 60% vertical load, the lateral capacity decreased from 41.6 N to 39.6 N for 80% of vertical load, corresponding to 12 mm deflection. This trend was also observed with 100% vertical load at 8 mm deflection. Overall, the clay-rich mix behaves

more ductily, with the vertical load enhancing the lateral performance but to a lesser extent than in sand-dominated soils. The curves describe a gradual increase in lateral resistance as vertical load rises from 0% to 60%. Due to the clay-dominant profile, the pile exhibits lower stiffness and higher deflections than in sand-rich soils.

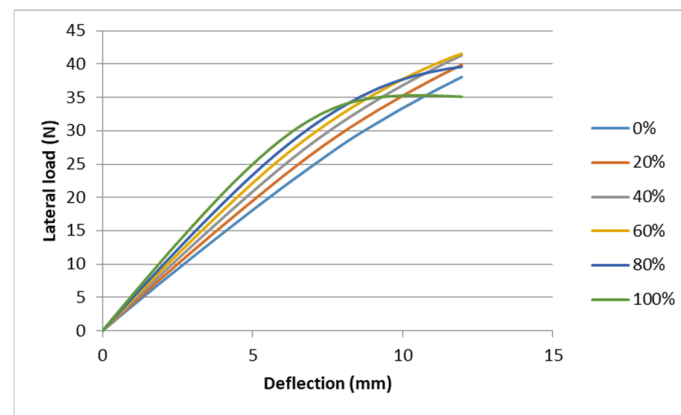


Figure 13. LL-deflection curve of the pile with L/D of 12 with a varying vertical load in 75% clay–25% sand soil layer.

In contrast, a pile embedded in a sand-rich soil combination of 25% clay–75% sand shows similar results to 75% clay–25% sand, but with improvements under the vertical load being noticeable, as is represented in Figure 14. Sand offers high resistance to deflection. Lateral capacity improves slightly up to 40% of the vertical load. Corresponding to a 12 mm deflection for 60%, 80% and 100%, the lateral load reduced to 43 N, which is the value of lateral capacity without the vertical load. In this soil profile, the combined load mechanism does not effectively determine the increment of the vertical load.

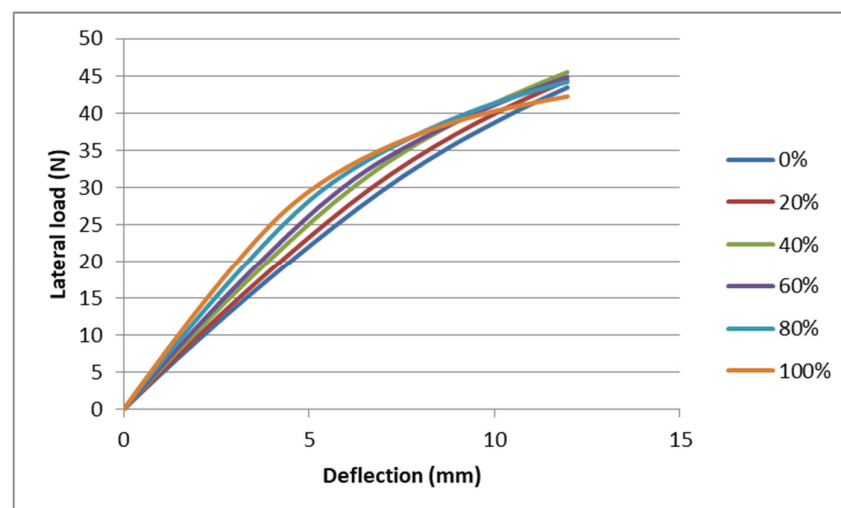


Figure 14. LL-deflection curve of a single pile for $L/D = 12$ with a varying vertical load in 25% clay–75% sand soil layer.

Figure 15 illustrates the LL behavior of a pile of $L/D = 12$ in a three-layer soil stratum as the number of layers increases. Specifically, a layer of sand bed is introduced between the clay beds. From the results, it is noticed that the VL improves the LC, which causes the curves up to 60% to shift upward, and for 80% and 100% nearly 10 mm of deflection, the pile shows a higher lateral capacity at smaller deflections due to clay yielding. But for a deflection of about 10 mm, the lateral capacity decreased and converged.

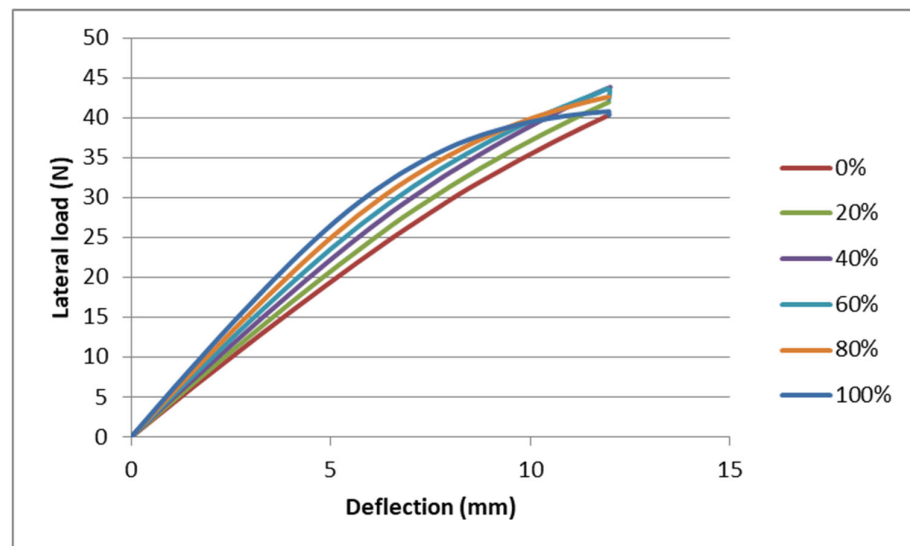


Figure 15. LL-deflection curve of a pile with $L/D = 12$ for a varying vertical load in a three-layer soil stratum.

Figure 16 shows that the four-layer soil stratum steadily increases lateral resistance as vertical load rises from 0% to 80%. Vertical load enhances confinement and passive resistance, causing the curves up to 80% of the vertical load to shift upward. At 100% of the applied vertical load, a slight reduction in lateral capacity at larger deflections suggests partial yielding or reduced sand stiffness. The increment values of the lateral load between the increasing vertical capacities from 0% to 26%.

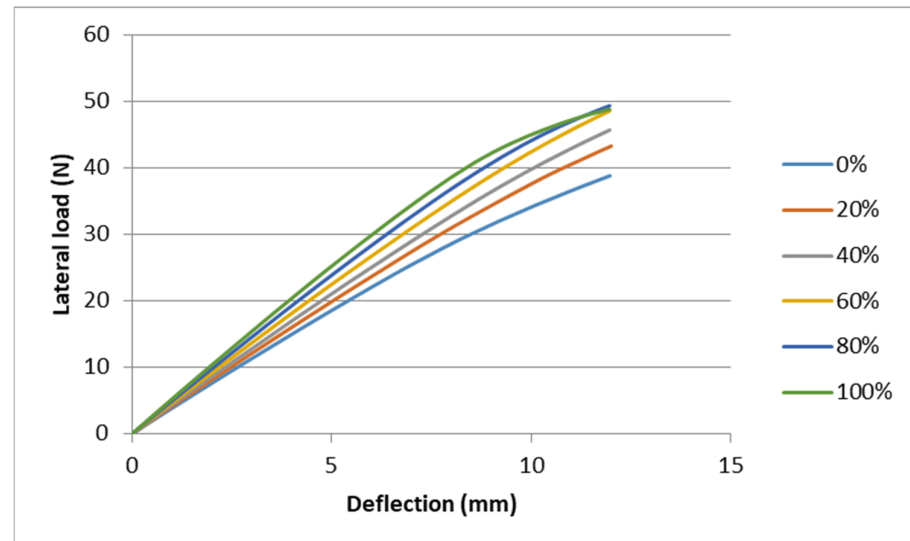


Figure 16. LL-deflection curve of a pile with $L/D = 12$ with a varying vertical load in a four-layer soil stratum.

4.3.3. Influence of Soil Layer on Combined Loading

The combined pile load tests were conducted on four sets of soil layers: 75% clay–25% sand, 25% clay–75% sand, three soil layer, and four soil layer. All evaluated soil profiles for piles with $L/D = 12$, as shown in Figure 17, the lateral load-deflection curves consistently show that increasing vertical load enhances lateral stiffness and capacity. The capacity experienced steady growth differently because of the varying soil layers. The behavior depends on the thickness of the introduced sand layer.

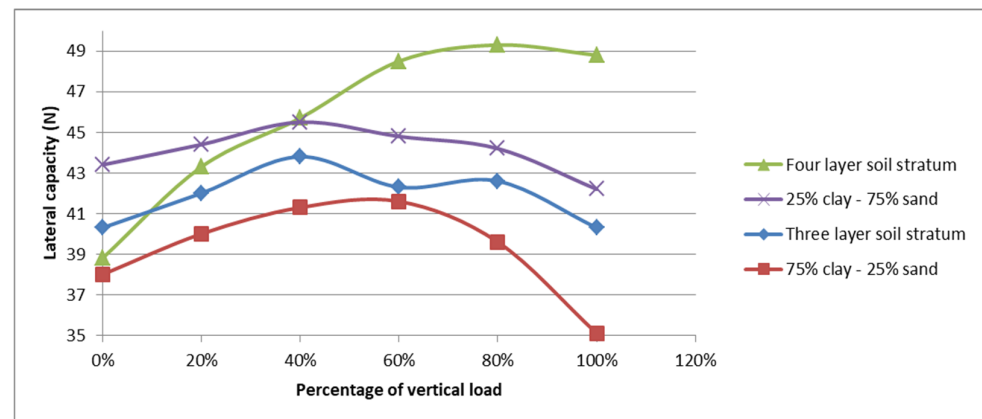


Figure 17. Lateral capacity—percentage of the vertical load curve in different layered soils.

The sand-rich layer, which is 25% clay–75% sand, provides constant lateral performance with varying vertical loads, whereas exhibiting the applied vertical load offers low performance in improving the lateral capacity. Especially in the 75% clay–25% sand and three-layer soil stratum, the impact of VL on LLCC shows an increasing trend up to 40% of the applied vertical load. But for 60%, 80%, and 100% of VL, the LC has a reduction of about 20%. Thus, the present work implies that at a higher VL level from 60% to 100% with deductions, it becomes significant.

Figure 17 illustrates the LC versus deformation behavior of the pile in a four-layer soil stratum, showing a prominent increase in lateral resistance as the percentage of the vertical load rises from 0% to 80%. With no vertical load, the pile exhibits the least stiffness, leading to larger deflections. Increasing the vertical load enhances the confinement and side friction, shifting the curves upward and reducing deflection.

The increase in the number of layers of the sand fraction improves stiffness, while clay adds adhesion under compression, giving a balanced soil response. At 100% of VL, the pile achieves its highest LC and lowest deflection for equivalent loads, demonstrating the strong influence of VL on lateral performance in layered soil.

Overall, high stratification in the soil layers is the most favorable lateral load-deflection behavior under varying vertical loads for $L/D = 12$, making it the best-performing soil condition among those compared.

5. Conclusions

- The research indicates that the synergistic effects of vertical and horizontal deformation of the pile with length-to-diameter ratios of 12 and 24 embedded in the layered soil enhance the lateral behavior of the foundation. Increasing the load on top of the pile produced a higher compression load and improved pile capacity and reduced the deflection component of the pile. The addition of sand layers to the clay bed further strengthened the bearing capacity by forming friction that bound the pile and soil and exhibited an enhanced, stiff load-bearing substructure. The experimental results of the combined pile load tests show the L/D ratio as a significant variable, with a larger $L/D = 24$ providing superior deflection resistance and achieving the highest lateral capacity. Likewise, by imposing an increased vertical load, increased LLCC modifies the stress transfer mechanism and also enhances deflection resistance. For $L/D = 12$, the LC of the pile embedded in sand exhibited a substantial increment, increasing from 63 N to 75 N for the applied vertical load from 0% to 100%. The LC increased 33% with 100% of VL for a pile embedded in 50% clay–50% sand compared to 0% of VL. Similarly, for a pile with $L/D = 24$ in clay and a 50% clay–50% sand soil profile, an

increase in the lateral capacity of 16% and 51% was observed, respectively, with 100% of VL when compared to 0% of VL.

- The findings elucidate the synergistic vertical settlement and lateral deflection resistance mechanism inherent in layered soil, pile–soil bonding from vertical loading as a compression load, and lateral deformation resistance from the layered soil surrounding the embedded length of piles. The lateral capacity with a vertical load produces improvements significantly superior to those achieved by the lateral capacity without vertical load. The improved lateral bearing capacity and decreased deflection are primarily influenced by applied vertical load, introducing a sand layer under clay, and increasing the ratio of L/D . This research delivers experimentally confirmed design guidance for selecting an effective design to support combined loads and the sustainable use of clay soil profiles with the introduction of sand layers. The FEM analysis confirms the trends that are shown in the experiments and gives us a better model to use for finding the best parameters later.
- From extended numerical analysis, the lateral capacity is enhanced by increases in the number of sand layers with an increase in the percentage of the applied vertical load. The findings significantly indicate that the lateral capacity of $L/D = 12$ in a four-layer soil stratum steadily increases lateral resistance as the vertical load rises from 0% to 80%. The increment values of lateral load are between the increasing vertical capacities from 0% to 26%. Overall, increasing the layer's count in the soil is the most favorable lateral load-deflection behavior under varying vertical loads for $L/D = 12$, making it the best-performing soil condition among those compared. The research findings are constrained by the small-scale laboratory methodology. Due to the experimental work of this study, several challenges were encountered during the test phase. Therefore, the testing was limited to a maximum deflection of 12 mm to evaluate capacity, and tests that resulted in failure were subsequently retested to ensure accuracy. Restricting the study to deflection parameters, extensively varied other factors, including the L/D ratio, soil layers, and percentage of vertical loads, resulting in a comprehensive analysis of the parametric variations within the scope of the study. Generalizing the results requires future work to expand to field validation and employ more complex constitutive models.

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Abbreviations

The following abbreviations are used in this manuscript:

V_{ult}	Ultimate vertical capacity
VLCC	Vertical load carrying capacity
LLCC	Lateral load carrying capacity
L/D	Length to Diameter ratio
LL	Lateral load
VL	Vertical load

VC	Vertical capacity
LC	Lateral capacity
FEM	Finite element method
C	Clay
S	Sand
N	Newton
kN	KiloNewton
mm	Millimeter
CH	High plasticity clay
SP	Poorly graded sand

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