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Research Paper

Modulus and stiffness of laterally loaded single free headed pile in stratified soil

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ABSTRACT

Laterally loaded piles gained its attention when structures like transform towers, offshore structures etc., met huge horizontal loads. Initially, to study the behaviour of laterally loaded piles, homogeneous soil is assumed; whereas in reality the soil stratum would be stratified/ multi-layer soil with various consistency and relative density. Considering this real field situation, an 1g experimental investigation is carried out on a single pile embedded in layered soil by varying the number of layers with respect to the length of the pile. With a sand layer on top and in-between, it increases the lateral capacity of the pile. The main soil-structure interaction parameters are modulus and stiffness factor, the modulus of the homogenous sand layer is very high when compared to the clay layer sandwiched between the sand layer.

1 Introduction

Pile is subjected to large loads, which can be vertical, lateral, oblique or of any above-said combinations. The behaviour of laterally loaded piles in homogenous soil is well established [1-10]. The laboratory studies are generally carried out by placing the pile in a uniform/ homogenous layer as a critical condition; but in general, it is installed in a stratified profile whether it is an end bearing or friction pile. To understand the behaviour of piles under lateral load, the fundamentals were

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simplified as per the Reissner model and further developed to layered soil by various researchers and insisted on the importance of layering of soil [11-14].

The soil-structure interaction of piles subjected to lateral load is majorly governed by the stiffness of the soil at shallow depth [15] and the depth of maximum bending moment gets changes when soil is stratified. In a multilayered soil, when the top layer is clay it shows prominence in nonlinear behaviour and reaches the plastic limit under failure load conditions, while sandy layers, commonly behaving as elastic, show at most bilinear behaviour [16]. The maximum deflection is observed in soil with a combination of sand with clayey layers compared to cohesionless soil [17]. The failure in pile is due to the vertical load, this load punches the soil by the tensile fissures in the bottom layer and H/D ratio [18]. The deflection of the pile is larger when the soil–pile separation happens [13].

For a single pile, the effect of socketing with minimum free standing is less significant, whereas, for a pile with a large free-standing height, the minimum socket depth is 1.5 times the pile diameter [14]. The equation proposed by Benerjee and Davies [19], for a single pile embedded in multi-layer soil with increasing modulus helps in applying the same in the field.

Salgado et al.,[20] proposed a semi-analytical solution to understand the response of soil in pile groups founded in multi-layered soil; the response is calculated by multiplying pile displacement with the decay function. In a pile group, the overlapping of stress influences the load-carrying capacity of rear piles; it varies along the pile length and changes from soil layer to layer [21]. If a pile is driven in the sand, the lateral deflection increases for a laterally loaded pile when loaded axially [22] but the influence of axial load is negligible in laterally loaded piles found in clayey soil [23].

From the literature review it is realised that the main researchers focus on the lateral response of piles in two -layer systems; the number of layer along the pile length is not given much importance. To felicitate this, an attempt is made in the present study to bring out the lateral load behaviour of a single pile in layered soil which is a combination of clay and sand placed alternatively in the test tank with various thicknesses. The response of a pile embedded in a layered soil system is further compared with that of single-layered soil profile comprises of the top layer of soil of a layered system.

2 Materials Used

2.1 Tank

A steel circular tank of 600 mm in diameter and height of 800 mm is used which is free from sidewall effects; as the diameter of the tank is more than 8 times the diameter of the pile [24]. A hollow Aluminum pipe of 19 mm diameter with 1 mm thickness with the bottom plugged is used as a model pile. A length/ diameter (L/D) ratio of 24 was opted to simulate flexible behaviour for long piles as suggested by Broms [25] with the length of the pile as 456 mm in total.

2.2 *Soil Profile*

The soil used for preparing soil bed for conducting experiments is cohesive (Clay) and cohesionless (Sand) soil. Their properties were found using relevant Indian standard codes and it is listed in Table 1.

2.3 Placement of soil layer

The clay soil is added with the required quantity of water for maturation and allowed for 48 hours so that a uniform clay of 0.2 consistency is obtained. The sand is filled in the tank from bottom to top or the required depth using sand pouring technique to the desired thickness and is prepared for a relative density of 50%. With the finalised consistency (clay) and relative density(sand), the soil is placed in the tank in an alternative thickness.

2.4 *Parametric Study*

The total length of the pile is 456 mm and the height of layers varied with respect to the length of the pile, denoted as L, the various parameter involved in this study is listed in Table 2 along with the notation. The number of layers considered for the study is 1, 2, 3 and 4.

Table 1 – Properties of Soil

Nature of Soil	Parameter	Symbol	Value	Indian Standard Code
Sand	Maximum Dry unit weight, kN/m^3	γ_{max}	16.98	IS 2720 – part [26]
	Minimum dry unit weight, kN/m^3	γ_{min}	13.56	
	Maximum void ratio	e_{max}	0.85	
	Minimum void ratio	e_{min}	0.5	
	Specific Gravity	G	2.65	[27]
	Coarse sand, %	-	2	[28]
	Medium Sand,%	-	72	
	Fine Sand,%	-	26	
	Effective grain size, mm	D_{10}	0.2	
	Co-efficient of Uniformity	Cu	3.55	
	Co-efficient of Curvature	Cc	0.86	
	Classification (Fig. 1)	SP – Poorly graded Soil		[29]
Clay	Specific Gravity	G	2.77	[27]
	Clay,%	-	66	[28]
	Silt, %	-	22	
	Sand, %	-	12	
	Liquid Limit, %	w_L	55	[30]
	Plastic Limit, %	w_P	24	
	Shrinkage Limit, %	w_S	12	
	IS Classification	CH – Highly plastic Clay		[29]

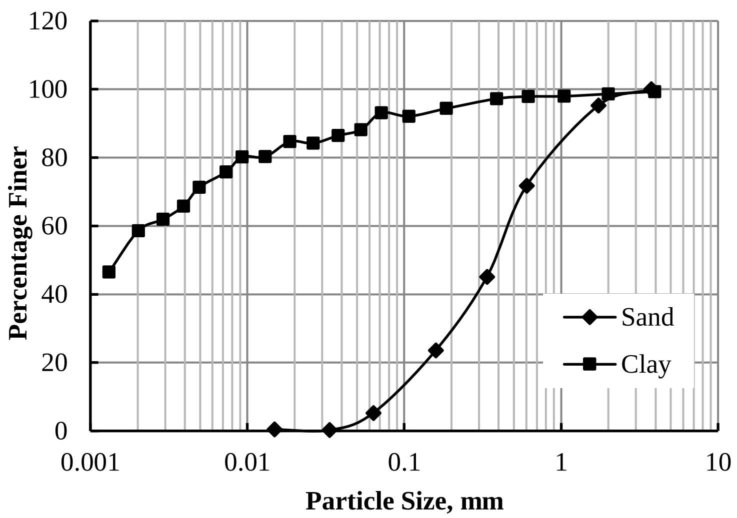

Fig. 1 - Particle size distribution

2.5 Loading pattern

While layering the soil, the pile is placed vertically in the required position. The top of the pile is connected to a high-tension wire and passed through a pulley system, where dead loads are added with help of a hanger. The deformation is read from the dial gauge connected at the pile head Fig2.

Table 2 – Parametric Study

Layering of soil (Bottom- Middle layers -Top)	**Layers**	**Layer thickness in terms of pile length (L)**	**Notation**
Sand	1	L	S
Clay	1	L	C
Clay and Sand	2	L/2: L/2	C-S
Clay, Sand and Clay	3	L/3: L/3: L/3	C-S-C
Clay, Sand,Clay and Sand	4	L /4: L /4: L /4: L /4	C-S-C-S
Sand and Clay	2	L /2: L /2	S-C
Sand, Clay and Sand	3	L /3: L /3: L /3	S-C-S
Sand, Clay, Sand and Clay	4	L /4: L /4: L /4: L /4	S-C-S-C

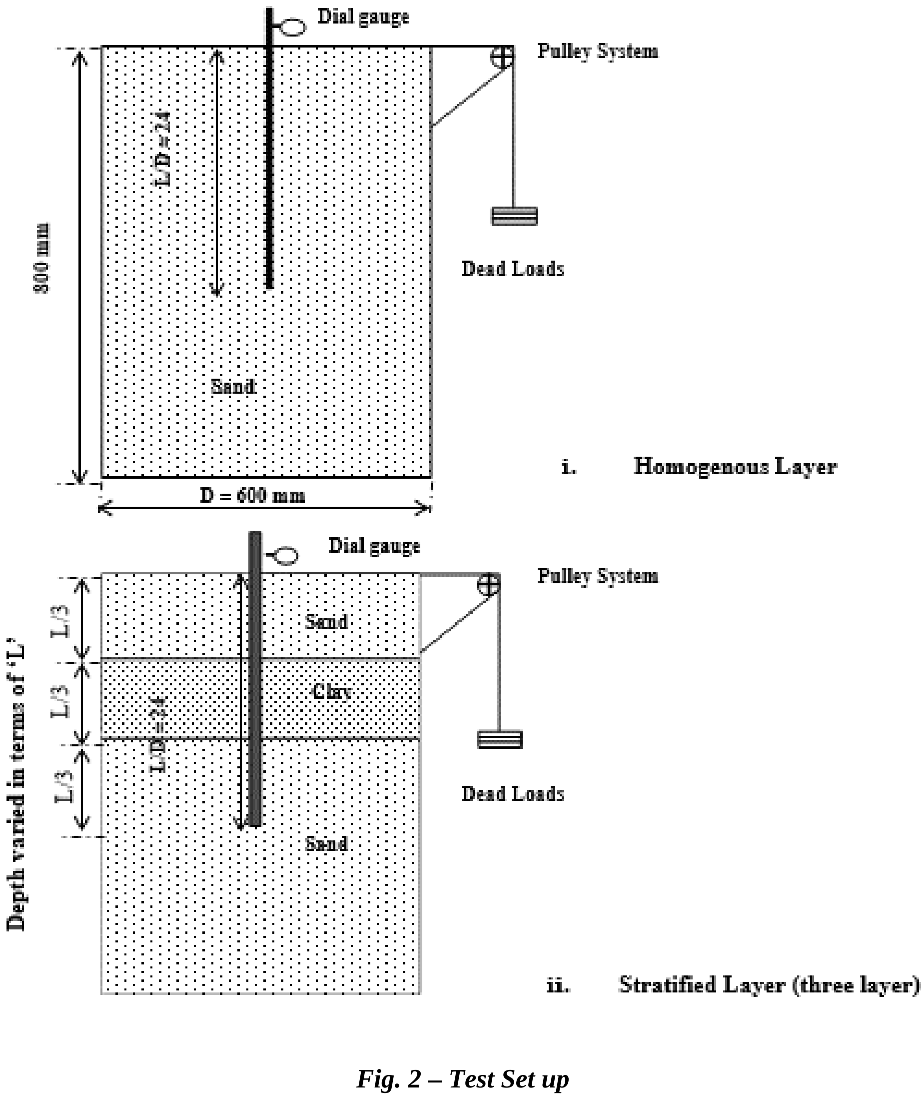

Fig. 2 – Test Set up

3 Results And Discussion

The initial tests were conducted in a single pile in a homogenous layer of sand and clay separately. The lateral load-deformation curve of sand shows its ability to carry even more lateral load, whereas clay has started showing a flattened profile for lower loads. In the current study, the deflection corresponding to 25 mm is taken as the ultimate load, as the failure of the pile occurs due to the surrounding soil beyond 25 mm. The lateral load is calculated as 234 N and 82 N for homogenous sand and clay respectively (Fig. 3); these values are used as base values for further comparison. The load is reduced by 64.96% when it is installed in the clay layer compared to sand layer.

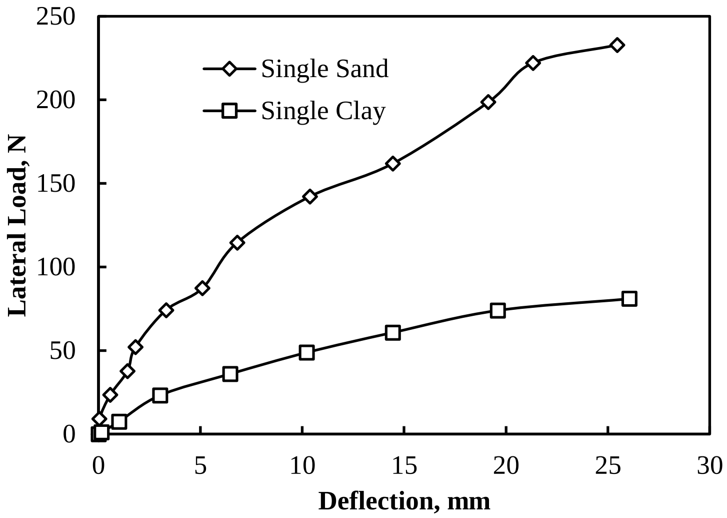

Fig. 3 - lateral load behaviour of pile in single layered soil

3.1 Influence of layer Stratification in lateral capacity

3.1.1 Two Layers

For comparison, two different layers of soil are considered in the study; case i. first half of the layer as sand (S) for a depth of 228 mm and the second half (228 mm) of the layer as clay (C) and for case ii. condition it is vice versa. The lateral load capacity of the pile with the top layer as clay has 104 N and sand has 208 N (Fig. 4). The load carried by C-S is much more than the S-C combination, this is mainly due to the fact that the top layer plays a major role in bearing the load. There is a significant reduction in the percentage of reduction to 50 % from 64.96%. While comparing the top layer soil with a single layer of the same type, the clay layer shows an increase in capacity by 21.15%(S-C) and with the top sand layer (C-S) there is a reduction in capacity by 11.11%. The reduction in capacity with top sand is mainly due to the presence of a clay layer in the second half of the length; which is reverse for the top clay layer, with the top clay layer the capacity increases.

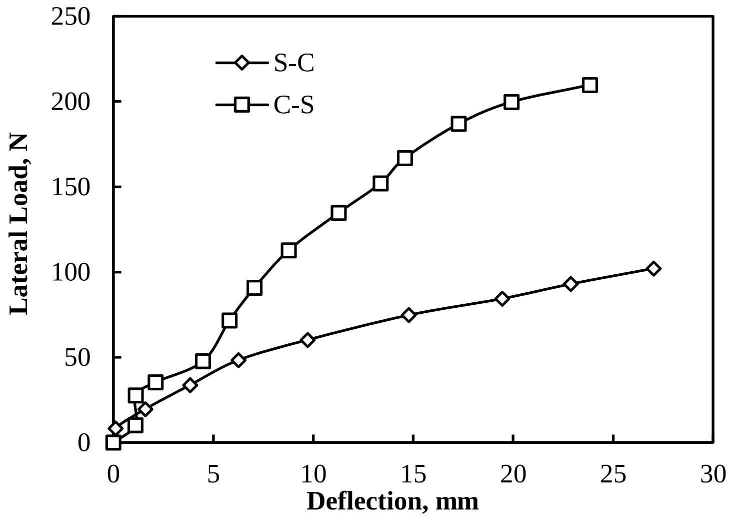

Fig. 4 – Lateral load behaviour of two-layer soil profile

3.1.2 Three-layer

Each layer is laid for a depth of 152 mm for three-layer soil, i.e C-S-C and S-C-S. The ultimate lateral capacities are 94 N and 218 N for C-S-C and S-C-S respectively (Fig. 5). The capacity increases to 12.77% and is reduced to 6.84 % compared to single clay and sand layer respectively. In C-S-C layer, the capacity increases to 94 N from 82 N, however, the capacity reduces from 104 N of the two-layer (S-C). For S-C-S layer, there is an increase in capacity from 208 N(C-S) to 218 N of three layers, which is less than the single-layer capacity.

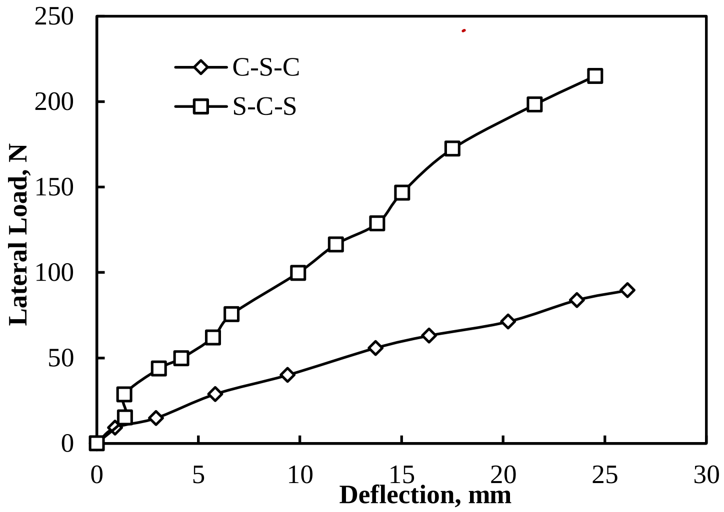

Fig. 5 - Lateral load behaviour of three-layer soil

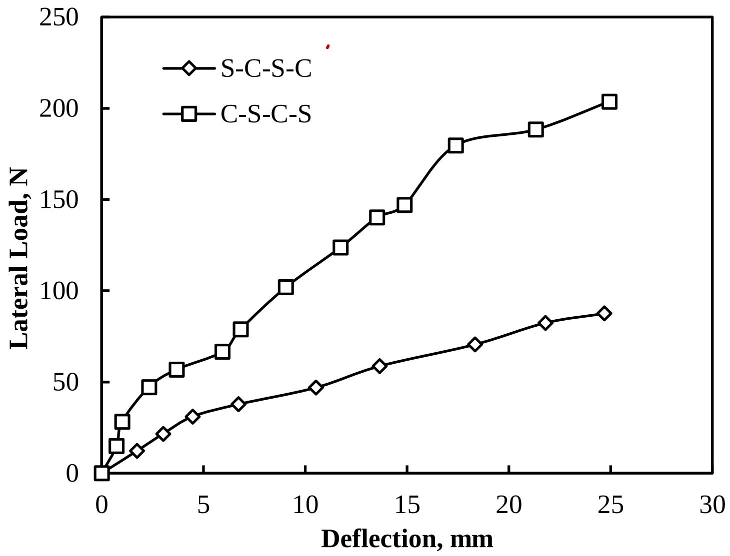

Fig. 6 – Lateral load behaviour of four layers

3.1.3 Four Layer

For a soil stratification of four layers, a combination of S-C-S-C and C-S-C-S layers was laid for a layer thickness of 114 mm. The ultimate lateral capacities are 110 N and 212 N for the former and latter(Fig. 6 – Lateral load behaviour of four layers. The lateral capacity increases to a large percentage of 25.45% for the S-C-S-C combination compared to a single layer of clay. But for the C-S-C-S layer, the capacity reduces to 9.4 % compared to a single sand layer. However, C-S-C-S is higher than the two-layer(C-S) marginally by 1.92%, while comparing it to three-layer (S-C-S) there is a reduction in capacity from 218 to 212 N.

3.2 Influence of layer Stratification in soil-structure interaction

The relative stiffness factor is calculated using the equations 1 and 2. With the calculated stiffness value, the modulus is calculated.

$$u = \frac{A_u PT^3}{EI} \quad (1)$$

$$T = \sqrt[3]{\frac{EI}{k_h}} \quad \Longrightarrow \quad k_h = \frac{EI}{T^3} \quad (2)$$

where, P – Lateral Load, N; u - deflection, mm; T - Relative stiffness factor, mm; A_u -displacement constant for a free head pile at ground level (2.42); k_h – co-efficient of horizontal subgrade reaction N/mm^2; EI - flexural Stiffness, N.mm^2.

A comparison is made between the modulus of top layer. With clay as a top layer for a homogenous single-layer, the value is 15.96 N/mm^2. When a sand layer is laid below the second half of the pile length the modulus value increases to 22.033 N/mm^2 for 38.05%. For a three-layer system with C-S-C combination, the end of the pile rests on clay layer with low consistency, which reduced the modulus to 13.34 N/mm^2. With a further increase in the number of layers to four for a combination of S-C-S-C, the modulus shows a tremendous increase in modulus to 35.37 N/mm^2; this is almost 2.25 times more than the single clay layer modulus(Fig. 7).

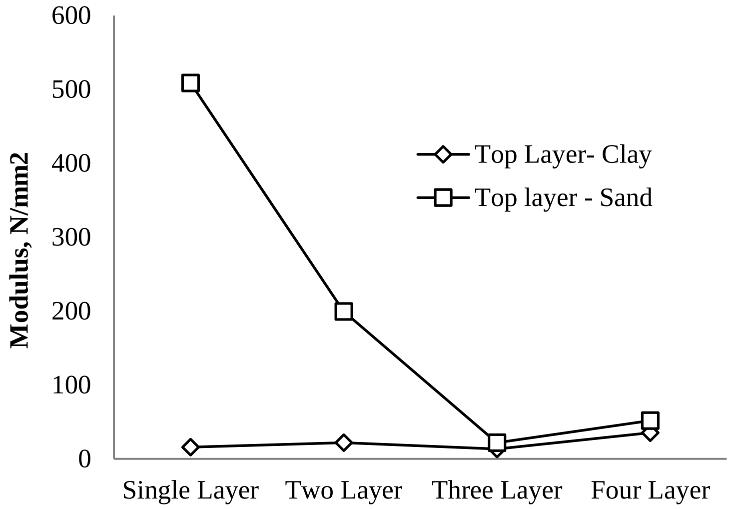

Fig. 7 – Modulus value for various layer combinations

The trend is different for the top sand layer. The modulus of a homogeneous sandy layer is tremendously high, as it has a value of 508.70 N/mm^2. With the end of the pile resting in clay layer, the load-bearing capacity reduces, in turn, reduces the modulus value to 199.44 N/mm^2; which is 60.8%. For three layers of soil, there is even more reduction in modulus to 21.83 N/mm^2, this is mainly due to the effective length of the pile lies within the first two layers. For four layers C-S-C-S, the modulus started increasing and showed a raised value of 51.83 N/mm^2; however, it is not even higher than the two-layer system (Fig. 7).

The relative stiffness factor is calculated using equation 2. A stiffness ratio factor is introduced which is the ratio of multilayer to single-layer stiffness. A graph is plotted for the various layer combinations (Fig. 8). For the top clay layer, the ratio is 0.898, 1.06 and 0.767 for 2,3 and 4 layers respectively. In the three-layer system, the ratio achieved a value more than I, which indicates that the sand layer contributes more to the soil-interaction behaviour of multi-layered soil; this further reduces in a four-layer system.

With the top sand layer, the ratio reduces with an increase in layers of soil. For C-S, S-C-S and C-S-C-S, the ratio is 0.39, 0.0429 and 0.102 respectively. The values are very less than the top sand layer combination. This is mainly due to the factor that it is behaving more like a friction pile than an end-bearing pile. It has started to pick- up with more sand layers i.e C-S-C-S.

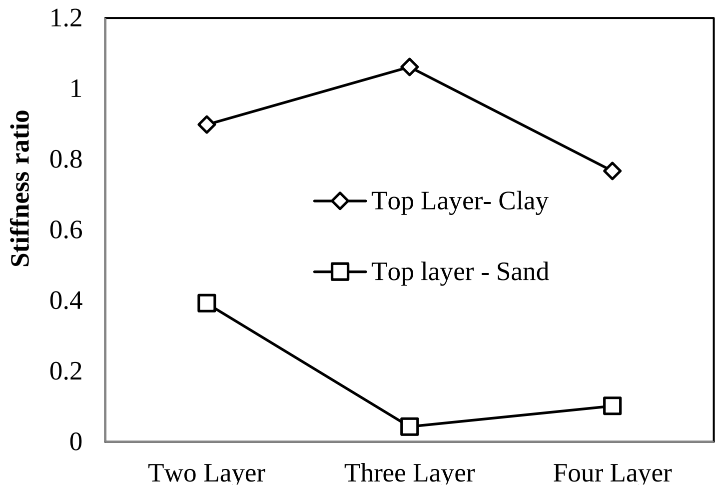

Fig. 8 – Stiffness ratio for stratified soil

4 Conclusion

A laboratory study is carried out to understand the stratification of the soil layer in the lateral load behaviour of the pile found in it. In the experiments, the thickness of the clay and sand layer are varied with respect to the length of the pile as 2, 3 and 4 layers. Based on the experimental analysis, the following salient points are brought out by comparing the results with the top layer soil;

- In two-layer conditions, with a clay layer in the bottom and sand layer in the top, the capacity reduces by 10.25% with a homogenous sand layer. Where when the bottom layer is filled with sand and clay layer in the top, the capacity increases 24.57% with the homogenous clay layer. The sand layer increases the modulus of the soil because of its interlocking behaviour.
- In three-layer conditions, with top layer as clay the capacity shows an increase of 9.19% when compared to the homogenous clay layer. While comparing sand as top layer, the capacity reduces by 8.1% with a clay layer is sandwiched between the sand layer.
- In four-layer conditions, the capacity increases by 6.76% for top layer as clay and there is a reduction in capacity by 12.96% with top layer as sand layer. The capacity of the pile mainly depends upon the consistency of the layer where it is rested. It is mainly due to the fact the pile at firm strata will have more resistance.
- Since all the piles considered are long flexible piles, the point of contra flexure moves down with an increase in the thickness of clay layer. The key soil–structure interaction parameter, modulus increases with an increase in the thickness of sand layer.

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