Parametric Study of Laterally Loaded Pile Foundation

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Abstract: *The pile foundation is an effective foundation system commonly used to support high rise buildings. The use of pile foundation tends to reduce the chances of displacement. In conventional analysis & design of laterally loaded pile foundation hasbeen found that the effect of soil and rigidity of pile is generally correlate to each other. This research investigated the effect of the pile rigidity (pile- length, diameter), pile spacing under the pile cap, the corresponding variations of the bending moment, shear forces, deflection, skin friction and the soil behaviour surrounding the pile. Two major elements are performed: literature review and finite element analysis. The literature review has been conducted to update the current state of knowledge on the behaviour and design methodology for laterally loaded pile foundation. The finite element analysis is carried out to analyse the behaviours of pile foundation system subjected to lateral load.*

In the finite element analysis, the reinforced concrete pile characterized as embedded beam on elastic subgrade principles. The commercially available software PLAXIS 3D is adopted in the analysis.

The behaviour of pile foundation for lateral loading is analysed with consideration of influence factors. Influence factors considered are pile diameter, pile length and soil behaviour.

It has been observed that the increasing pile length induces higher bending moment in pile but, simultaneously control other effect such as shear force and settlement.

Based upon the results of analysis, the effect of various influence factors on foundation behaviour is determined. Also, the application to design of an economic foundation design is discussed. The result of this research will be useful in optimizing the design of laterally loaded pile foundations. Furthermore, future studies for laterally loaded pile foundations are recommended.

I. Introduction

A foundation (sub- structure) is the component of an architectural arrangement which connects it to the ground and transfers the loads from the super structure to the ground. A solid foundation of a building guarantees a durable future of the structure. For high-rise buildings or massive structures, the foundation also important for the stability of the structures for a long period. Using a strong foundation which carries the load of the super structures in such a way that the massive structures will stand for a long period without any sudden damage to life and property.

In designing laterally loaded pile foundations, controlling the displacement as well as the bending moments of the laterally loaded piles. The laterally loaded pile analysis depends on the various parameters such as soil and pile property.Due to uncertainty in the subsoil profile below the structure and unpredictable loading from architecture requirement point of view, the design of a proper pile foundation is a challenge for the design engineer. Hence a comprehensive study is proposed to demonstrate the effect of variation of parameters in the laterally loaded pile design performance. This shall be helpful to build a confidence level of the practicing engineers while designing the laterally loaded pile foundation.

II. Research Methodology

Introduction to PLAXIS 3D This software is based on the finite element method and intended for 2-Dimensional and 3-Dimensional analysis of deformation and stability of soil structures, as well as in geo-engineering applications such as excavations, foundations, embankments and tunnels and many more complex structures.

In case of PLAXIS-3D the basic element used for modelling is a 10-node tetrahedral element. These are created in the 3D mesh procedure.
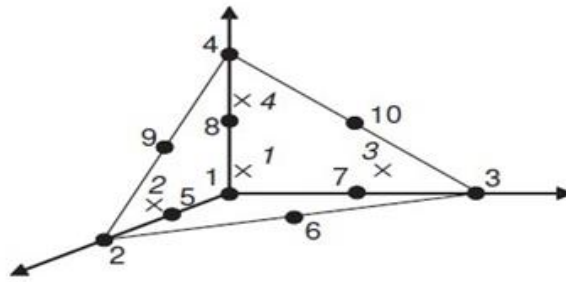

Figure1 Positioning of nodes (.) and integration points (×)

PLAXIS 3D Modelling: There are 5 basic steps in PLAXIS for modelling of structure. Those are
- Soil Mode
- Structure Mode
- Mesh Mode
- Flow Condition
- Staged Construction

Validation of Software: To verify the results of purposed software for analysis. For this a journal paper [reference no] has been undertaken where analysis has been carried out using finite element software ANSYS. Finally the result of this calculation is compared with commercially available geotechnical based finite element program PLAXIS 3D.A comparison between ANSYS and PLAXIS 3D outcomes were presented for deflection, shear force and bending moment criteria.[7]

Description: Here one laterally loaded pile have modelled and then compared with both ANSYS results and PLAXIS 3D results. Then the behaviour of deflection, shear force and bending moment has compared. This foundation has established in "cohesion-less soil". The soil and pile parameters were described below,

Pile Properties

PARAMETERS	SYMBOL/UNIT	VALUES
SIZE	B(m) X D(m)	0.5 X 0.5
Length	L (m)	8
Type of Pile	-	Concrete
Grade of concrete	-	M30
Young's Modulus	E (kN/m^2)	2.24×10^7
Unit Weight	Υ (kN/m^3)	25

Soil Properties

PARAMETERS	SYMBOL/UNIT	VALUES
Unsaturated unit weight	Υ_{unsat} (kN/m^3)	18.00
Saturated unit weight	Υ_{sat} (kN/m^3)	21.00
Young's Modulus	E (kN/m^2)	4.7×10^4
Poisson's Ratio	ν or μ	0.3
Friction Angle	φ (^{0})	30
Earth Pressure	K_0	0.5

Lateral Load – 240 kN   * Axial moment – 48 kN-m
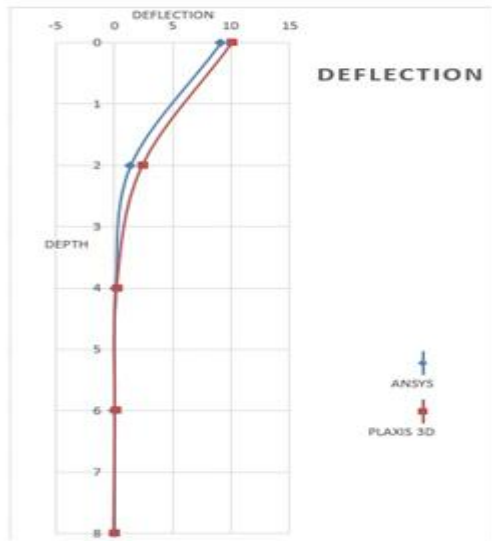
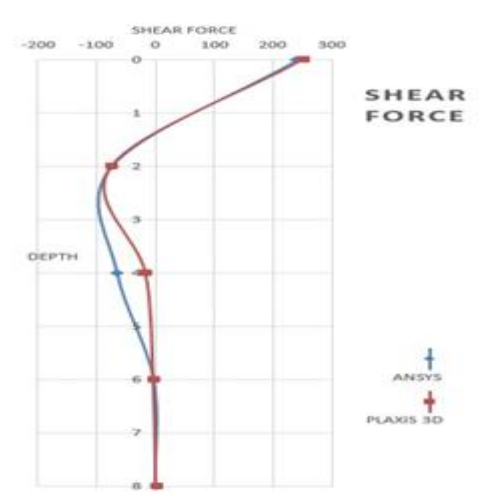| **Figure 1 – Deflection of pile along the length** | | |
| ANSYS | PLAXIS 3D | DIFFERENCE |
| 9.1mm | 10mm | 9.42% |

Figure 2 – Shear force of pile along the length		
ANSYS	PLAXIS 3D	DIFFERENCE
240 kN	249.9 kN	4.04%
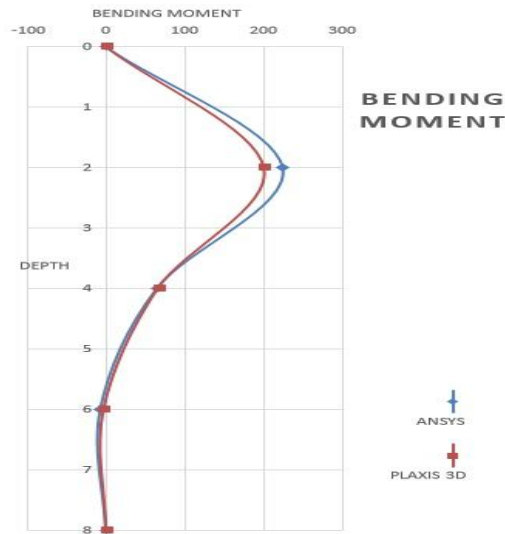
Figure 3 – Bending moment of pile along the length		
ANSYS	PLAXIS 3D	DIFFERENCE
189 kN-m	163 kN-m	11.02%

Theoretical Results
Pile of cross-section = 500mmx500mm
Modulus of elasticity of pile, $E = 2.24 \times 10^7 \text{kN/m}^2$
Moment of inertia,

$$I = \frac{bd^3}{12} \qquad I = \frac{0.5 \times 0.5^3}{12} = 0.00521 \text{m}^4$$

$$T = \sqrt[5]{\left(\frac{EI}{nh}\right)}, T = 1.173\text{m}$$

Relative stiffness factor,

Where; nh = Constant sub grade reaction

Maximum depth coefficient, $$Zmax = \frac{Ls}{T}$$

Where; Ls = Length of Pile below ground level = 8m

Zmax = 6.8 > 5, so it's a long pile.

Applied lateral load, H = 240kN

Moment applied to head of pile, M_t = 48kN

A_y & B_y = Deflection coefficients

A_v & B_v = Shearing force coefficients

A_m & B_m = Bending moment coefficients

i. Deflection:

y = $$y_A + y_B = \frac{A_y H T^3}{EI} + \frac{B_y M_t T^2}{EI}$$

Deflection, y = 10.1mm at the free end.

ii. Shearing force:

V = $$V_A + V_B = A_v H + \frac{B_v M_t}{T}$$

Shear force, V = 244 kN

iii. Bending moment:

M = $$M_A + M_B = A_m H T + B_m M_t$$

Bending moment, M = 160.6 kN - m

III. Results And Discussion
Table 1 – Comparison of results

	ANSYS	PLAXIS 3D	Theoretical
Deflection	9.1 mm	10 mm	10.1 mm
Shear Force	240 kN	249.9 kN	244 kN
Bending Moment	189 kN-m	163 kN-m	160.6 kN-m

From the above results it has been shown that some percentage differences occur in comparisons. Because ANSYS is a structural based finite element analysis software which enables to solve complex structural engineering problems and make better, faster design decisions. Whereas PLAXIS 3D is a geotechnical based finite element analysis program intended for three-dimensional analysis of deformation and stability in geotechnical engineering. PLAXIS 3D is a user friendly three dimensional geotechnical program which offering flexible and interoperable geometry, realistic simulation of construction stages for a complex geometry of soil – structure interaction problem which can be defined in two different modes. These modes are specifically defined for Soil or Structural modelling.

The results are shown in the above, which indicate the values of deflection, shear force and bending moment of PLAXIS3D with the Theoretical results were more similar. Therefore, it is concluded that PLAXIS 3D is an effective tool to carry out proposed parametric study with valid results.

IV. Parametric Study
Specification of model: The details specification of the proposed model is as given below:

Specification for parametric study

Specification	Model -1	Model -2	Model -3
Soil Type	Soft Clay	Medium Clay	Hard Clay
Pile Diameter	250mm, 500mm	250mm, 500mm	250mm, 500mm
Pile Length	5m, 10m, 15m	5m, 10m, 15m	5m, 10m, 15m

Material used for pile

Grade of concrete (f_{CK}): M20 (Characteristic Strength = 20N/mm^2)

Elastic modulus of concrete (E_c): 22360 N/mm^2

Poisson ration (ν_c): 0.15

Unit weight of concrete: 25kN/m^3

Grade of steel (f_y): 415 N/mm^2

Design Soil Parameters: A soil model were developed in Plaxis 3D for the study of parameters variations. The table shows the relevant soil parameters used in the design. Unit weights are chosen according to BS8002[5]. Modulus of elasticity, cohesion and Poisson's ratio are chosen according to Bowles [6].

Soil Parameters

Soil Description	Soft clay	Medium clay	Hard clay
Un-saturated unit weight Υ_{unsat} (kN/m^3)	17	18	20
Saturated unit weight Υ_{sat} (kN/m^3)	17	18	20
Modulus of elasticity, E (kN/m^2)	10 x 10^3	25 x 10^3	60 x 10^3
Poisson's ratio (v)	0.4	0.4	0.4
Cohesion c (kPa)	20	40	200

The pile loads: In pile foundation two types of load can act; i) vertical load, ii) horizontal load. But in this parametric analysis only horizontal load has applied. Horizontal or lateral loads occur due to wind, sea waves, and earth-quakes. These forces were naturally occurred for which a constant value couldn't be assumed.
So for this study 100 kN load has considered as lateral load.

Parametric study: The structural elements e.g. diameter, length, reinforcement etc. in a pile depends on various parameters such as the soil properties in which it is going to embedded, the lateral load coming from the earth quake or wind or sea waves, etc. Hence a parametric study is equally important to understand this behaviour under several possible conditions. This will help the practising engineers to economize the design and save the construction time.
The following parameters are pointed out based on the literature review and considered to be most appropriate in this present parametric study:
- Pile diameter
- Pile length
- Soil properties

The details of each study are elaborated below:

Pile diameter and length: Pile diameter and length is an important parameter which governs the cost of the project. It is absolutely required to understand whether the increase or decrease in dimensions can affect the stability of the pile. Following cases are considered to study the effect of pile dimensions on behaviour of laterally loaded pile foundation.

Table 2: Cases consider to study the effect of pile dimensions

SL No	Case	Model type as per table	Pile Length (m)	Pile Diameter (mm)
1	Case - I	Model -1,2,3	5	250
2	Case - II	Model -1,2,3	5	500
3	Case - III	Model -1,2,3	10	250
4	Case - IV	Model -1,2,3	10	500
5	Case - V	Model -1,2,3	15	250
6	Case - VI	Model -1,2,3	15	500

V. Results And Discussion

The parametric study is carried out in three stages:
1. Overall variation and analysis of results of deflection, shear force and bending moment with respect to the three types of cohesive soil.
2. Analysis of deflection results with respect to length and diameter of pile (slenderness ratio).
3. Analysing the result of skin friction for load carrying capacity of pile.

VI. Analysis Of Results

Case – I: In case – I three types of clay (soft, medium, hard) has used for parametric study with constant pile diameter (D) 0.25m and pile length of 5m. A 100kN of lateral load has applied on the tip of the pile. In table 3 the results were given;

Table 3: Results for case – I

Soil Type	Pile Length(m)	Pile Diameter (m)	Deflection (mm)	Shear Force (kN)	Bending moment (kN - m)
Soft Clay	5	0.25	10.2	83.9	31.6
Medium Clay	5	0.25	4.4	55.4	19.6
Hard Clay	5	0.25	2	34.1	11.5

In figure 4 study shows for 100kN of lateral load on pile whose diameter is 0.25m and length is 5m the maximum deflection occur in ground surface of soft clay with comparison to medium and hard due to relative stiffness of soil. From the above figure the deflection in all clays were zero at 3m depth from top of the pile.

In figure 5 and 6 the shear force and bending moment curves were presented respectively with respect to their length. Maximum bending moment and maximum shear force are occur in soft clay in between all three types of clays. Shear force is maximum at ground surface but maximum bending moment in between 0m to 1.5m. In the figure 6 the bending moment diagram represents with the 1m depth interval of pile length. For this the given result of bending moment in table 4 and figure - 6 are not same.
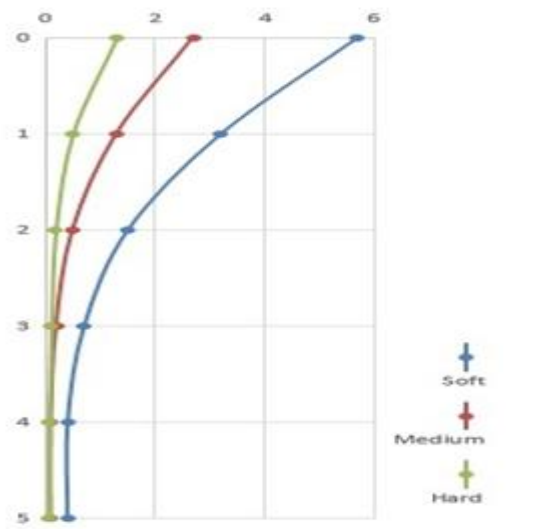

Figure 4 – Deflection of pile in different type of clay with respect to L=5m & D=0.25m
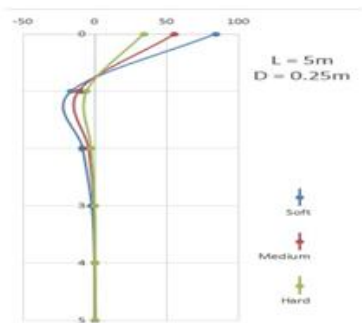
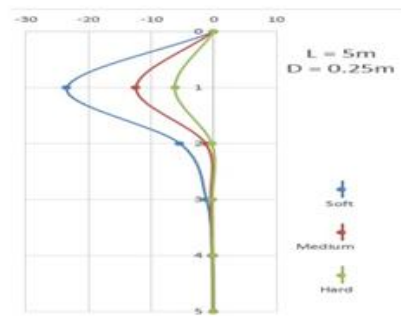**Figure 5 - Shear force diagram of pilein different type of clay with respect to length(L=5m & D=0.25m)**

Figure 6- Bending moment diagram of pilein different type of clay with respect to length(L=5m & D=0.25m)

Case – II: three types of clay (soft, medium, hard) has used for parametric study with constant pile diameter (D) 0.5m and pile length of 5m. A 100kN of lateral load has applied on the tip of the pile. In table 4 the results were given;

Table 4: Results for case – II

Soil Type	Pile Length(m)	Pile Diameter (m)	Deflection (mm)	Shear Force (kN)	Bending moment (kN - m)
Soft Clay	5	0.5	5.7	108.5	55.8
Medium Clay	5	0.5	2.7	103.6	44.9
Hard Clay	5	0.5	1.3	93.6	37.9
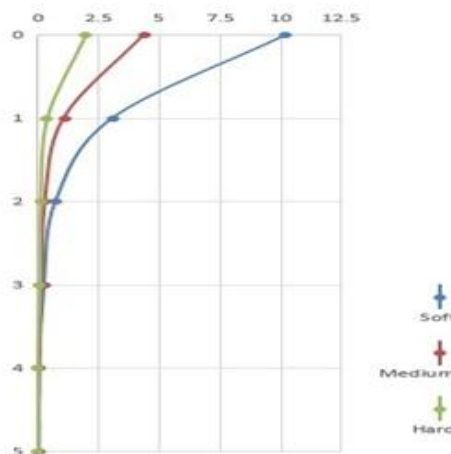
Figure 7 – Deflection of pile in different type of clay with respect to L=5m & D=0.5m

In figure 7 study shows for 100kN of lateral load on pile whose diameter is 0.5m and length is 5m the maximum deflection occur in ground surface of soft clay with comparison to medium and hard due to relative stiffness of soil. From the above figure the deflection in soft clay occur maximum at top of the pile and in respect to length the deflection linearly decreasing but the result is not zero at any depth. For this in soft clay the pile displacement in soil occur in whole length. Whereas in medium clay and hard clay the deflection is zero at 4m distance from the tip of the pile.

In figure 8 and 9 the shear force and bending moment curves were presented respectively with along to their length. Maximum bending moment and maximum shear force are occur in soft clay in between all three types of clays. Shear force is maximum at ground surface and at 2m depth the three values of shear are nearly close to each other, but maximum bending moment occur in between 0m to 2m. In the figure 9 the bending

moment diagram represents with the 1m depth interval of pile length. In the previous case bending moment tends to zero at some depth but due larger diameter the bending of pile in soil occur more in comparison to smaller diameter.
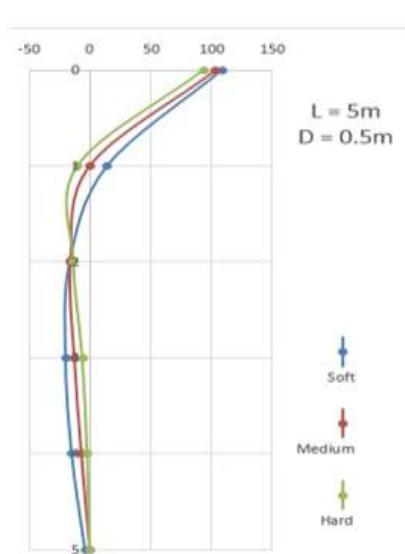

Figure 8 - Shear force diagram of pilein different type of clay with respect to length (L=5m & D=0.25m)
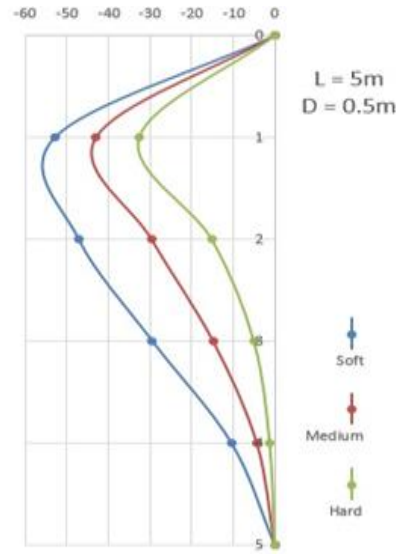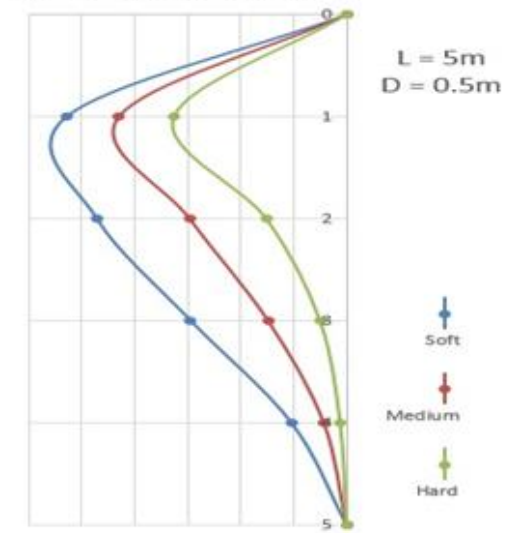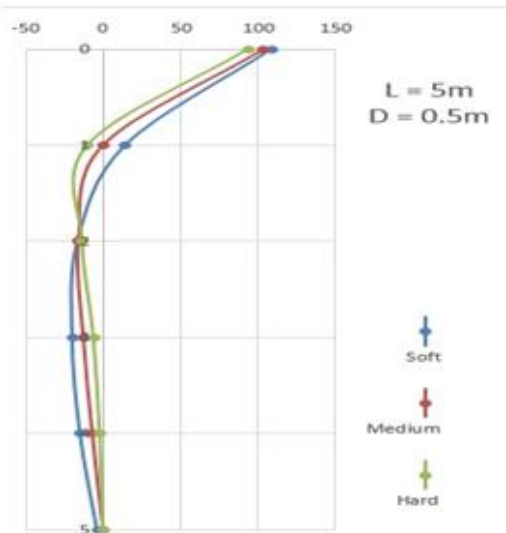
Figure 9 - Bending moment diagram of pilein different type of clay with respect to length(L=5m & D=0.5m)

Case – III In case – III three types of clay (soft, medium, hard) has used for parametric study with constant pile diameter (D) 0.25m and pile length of 10m. A 100kN of lateral load has applied on the tip o

f the pile. In table 7.3 the results were given;

Table 5: Results for case – III

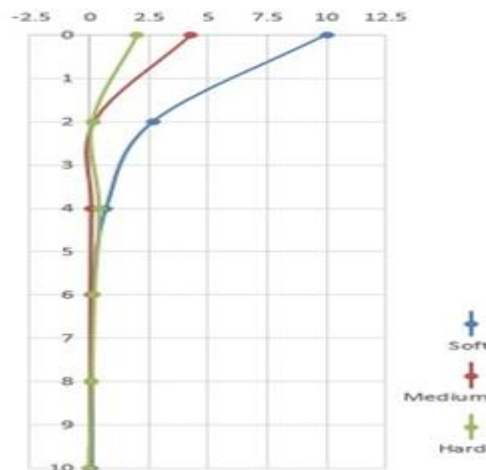| Soil Type	Pile Length(m)	Pile Diameter (m)	Deflection (mm)	Shear Force (kN)	Bending moment (kN - m)
Soft Clay	10	0.25	10	104.4	32.8
Medium Clay	10	0.25	4.3	76.8	22.7
Hard Clay	10	0.25	2	51.9	14.6

Figure 10–Deflection of pile in different type of clay with respect to L=10m & D=0.25m

In figure 10 study result shows for 100kN of lateral load on pile whose diameter is 0.25m and length is 10m, the maximum deflection occur in ground surface of soft clay with comparison to medium and hard due to relative stiffness of soil. From the above figure the deflection in soft clays is zero at 6m depth, in medium clay and hard clay the deflection is zero at 4m depth along the pile.

In figure 11 and 12 the shear force and bending moment curves were presented respectively with respect to their length. Maximum bending moment and maximum shear force are occur in soft clay in between all three types of clays. Shear force is maximum at ground surface but maximum bending moment in between 0m to 1m. In the figure 12 the bending moment diagram result represents with the 2m depth interval of pile length. In medium and hard clay bending moment of pile is zero at a depth of 3m. Whereas in soft clay bending moment of pile is zero at a depth of 4m. With respect to this the depth of fixity from where no bending occur towards the toe of pile is 4m for soft clay and 3m for medium and hard clay.
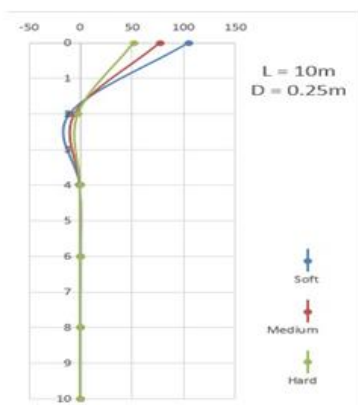

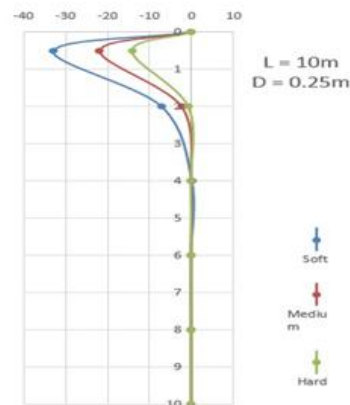| **Figure 11 - Shear force diagram of pilein different type of clay with respect to length** | **Figure 12 - Bending moment diagram of pilein different type of clay with respect to length(L=10m & D=0.25m)** |

Case – IV In case – IV three types of clay (soft, medium, hard) has used for parametric study with constant pile diameter (D) 0.5m and pile length of 10m. A 100kN of lateral load has applied on the tip of the pile. In table 6 the results were given;

Table 6: Results for case – IV

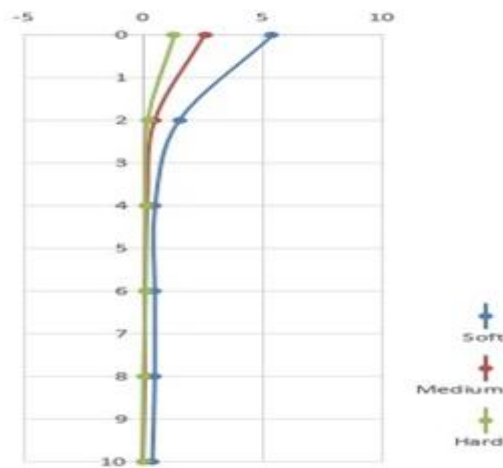| Soil Type	Pile Length(m)	Pile Diameter (m)	Deflection (mm)	Shear Force (kN)	Bending moment (kN - m)
Soft Clay	10	0.5	5.4	113.8	55.8
Medium Clay	10	0.5	2.6	112.7	44.7
Hard Clay	10	0.5	1.3	107.5	36.2

Figure 13 –Deflection of pile in different type of clay with respect to L=10m & D=0.5m

In figure 13 study shows for 100kN of lateral load on pile whose diameter is 0.5m and length is 10m the maximum deflection occur in ground surface of soft clay with comparison to medium and hard due to relative stiffness of soil. From the above figure the deflection in soft clay occur maximum at top of the pile and in respect to length the deflection linearly decreasing but the result is not zero at any depth. For this in soft clay the pile displacement in soil occur in whole length. Whereas in medium clay and hard clay the deflection is zero at 3m distance from the tip of the pile

In figure 14 and 15 the shear force and bending moment curves were presented respectively with along to their length. Maximum bending moments are occur in soft clay in between all three types of clays. Shear force is maximum at ground surface and the three values of shear are nearly close to each other, but maximum bending moment occur in between 0m to 2m. In the figure 15 the bending moment diagram represents with the 1m depth interval of pile length. Due to increase in length the diameter effect minimize and bending moment is zero at a depth of 6m for medium and hard clay, whereas 7m for soft clay
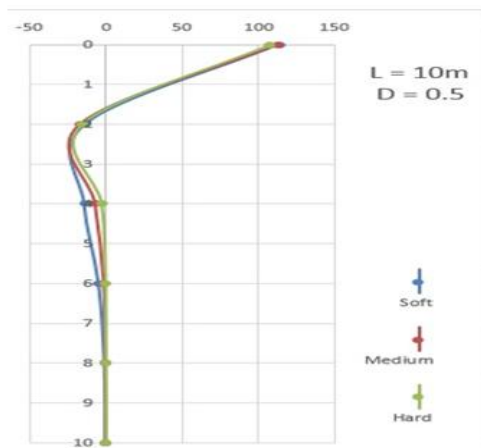

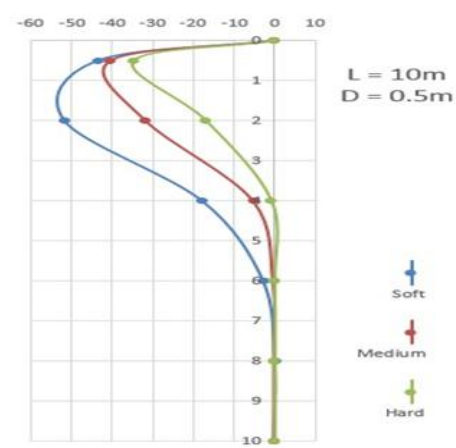**Figure 14 - Shear force diagram of pilein different type of clay with respect to length (L=10m & D=0.5m)**

Figure 15 - Bending moment diagram of pilein different type of clay with respect to length(L=10m & D=0.5m)

Case – V: three types of clay (soft, medium, hard) has used for parametric study with constant pile diameter (D) 0.25m and pile length of 15m. A 100kN of lateral load has applied on the tip of the pile. In table 6 the results were given;

Table 6: Results for case – V

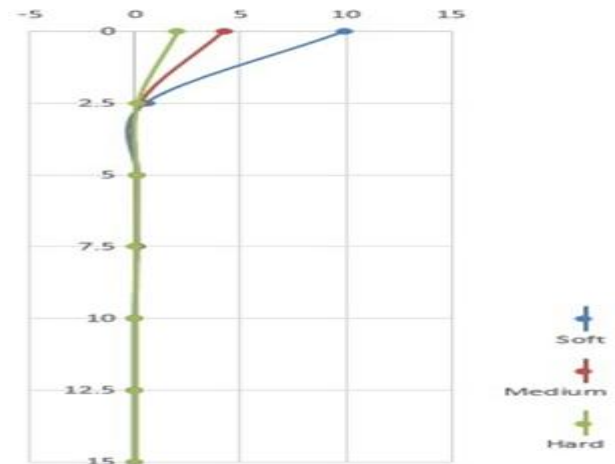| Soil Type	Pile Length(m)	Pile Diameter (m)	Deflection (mm)	Shear Force (kN)	Bending moment (kN - m)
Soft Clay	15	0.25	9.9	102.3	32.4
Medium Clay	15	0.25	4.2	74.7	22.4
Hard Clay	15	0.25	2	50.3	14.2

Figure 16–Deflection of pile in different type of clay with respect to L=15m & D=0.25m

In figure 16 study result shows for 100kN of lateral load on pile whose diameter is 0.25m and length is 15m, the maximum deflection occur in ground surface of soft clay with comparison to medium and hard due to relative stiffness of soil. From the above figure the deflection is zero at a 3m depth and maintained towards to the toe of pile.

In figure 17 and 18 the shear force and bending moment curves were presented respectively with along to their length. Maximum bending moments are occur in soft clay in between all three types of clays. Shear force is maximum at ground surface and the three values of shear are nearly close to each other, but maximum bending moment occur in between 0m to 2.5m. In the figure 18 the bending moment diagram represents with the 2.5m depth interval of pile length. Due to increase in length the diameter effect minimize and bending moment is zero at a depth of 4m for all clays.
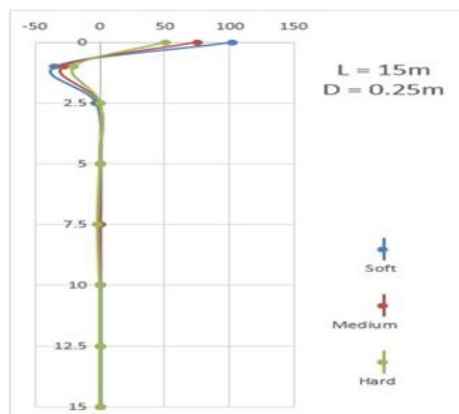

Figure 17 - Shear force diagram of pilein different type of clay with respect to length (L=15m & D=0.25m)
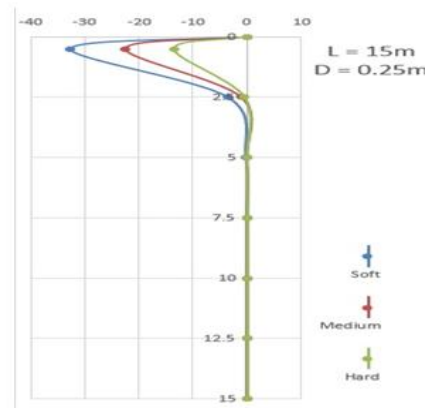

Figure 18 - Bending moment diagram of pilein different type of clay with respect to length (L=15m & D=0.25m)

Case – VI: three types of clay (soft, medium, hard) has used for parametric study with constant pile diameter (D) 0.5m and pile length of 15m. A 100kN of lateral load has applied on the tip of the pile. In table 7 the results were given;

Table 7: Results for case – VI

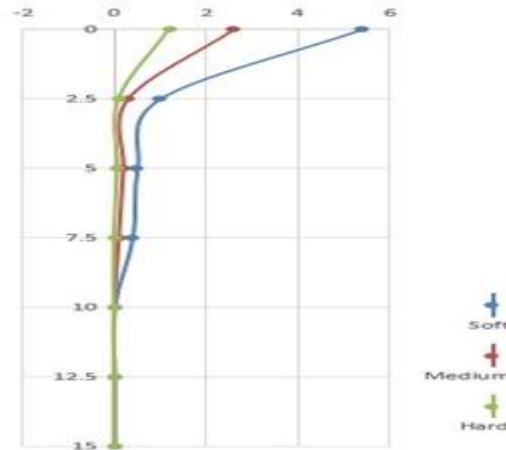| Soil Type	Pile Length(m)	Pile Diameter (m)	Deflection (mm)	Shear Force (kN)	Bending moment (kN - m)
Soft Clay	15	0.25	9.9	102.3	32.4
Medium Clay	15	0.25	4.2	74.7	22.4
Hard Clay	15	0.25	2	50.3	14.2

Figure19–Deflection of pile in different type of clay with respect to L=15m & D=0.5m

In figure 19 study result shows for 100kN of lateral load on pile whose diameter is 0.5m and length is 15m, the maximum deflection occur inc ground surface of soft clay with comparison to medium and hard due to relative stiffness of soil. From the above figure the deflection is zero at a 3m depth in hard clay, 9m depth in medium clay and 10m depth in soft clay.

In figure 20 and 21 the shear force and bending moment curves were presented respectively with along to their length. Maximum bending moments are occur in soft clay in between all three types of clays. Shear force is maximum at ground surface and the three values of shear are nearly close to each other, but maximum bending moment occur in between 0m to 4m due to larger in diameter. In the figure 21 the bending moment diagram represents with the 2.5m depth interval of pile length. Due to increase in length the diameter effect minimize and bending moment is zero at a depth of 7.5m for all clays.
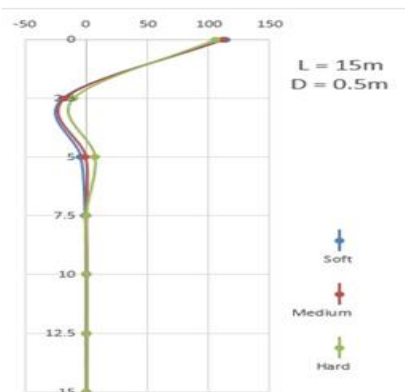

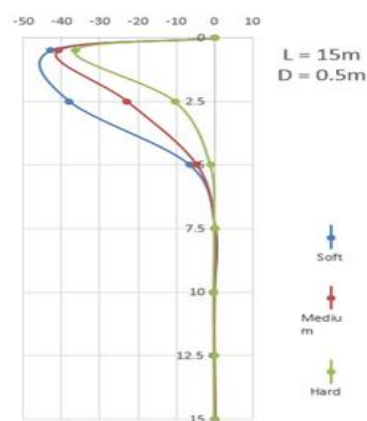**Figure 20 - Shear force diagram of pilein different type of clay with respect to length (L=15m & D=0.5m)**

Figure 21 - Influence of soil's stratified character on pile's bending moments(L=15m & D=0.5m)

Influence of skin resistance of pile

The load-carrying capacity of a pile depends on the properties of the soil in which it is embedded. Axial load from a pile is normally transmitted to the soil through skin friction along the shaft and end-bearing at its tip. A horizontal load on a vertical pile is transmitted to the soil primarily by horizontal subgrade reaction generated in the upper part of the shaft. Lateral load capacity of a single pile depends on the soil reaction developed and the structural capacity of the shaft under bending.

Figure 22 – Pile-soil behaviour upon lateral load

The ultimate load carrying capacity Q_u of a pile is equal to the base capacity plus the skin friction acting on the shaft (IS 2911 – Part 1).

Q_u = Base capacity (or, end bearing resistance) + Skin friction

$Q_u = A_p N_c c_p + \sum_{i=1}^{n} \alpha_i c_i A_{si}$

Where, A_p = pile tip cross-sectional area, in m^2;

N_c = bearing capacity factor, may be taken as 9;

c_p = average cohesion at pile tip, in kN/m^2;

α_i = adhesion factor for the ith layer depending on the consistency of soil;

c_i = average cohesion for the ith layer, in kN/m^2; and

A_{si} = surface area of pile shaft in ith layer, in m^2.

According to the above equation, the skin friction results are available exclusively on Plaxis 3D software, for which the calculation of total load carrying capacity of pile is much easier.
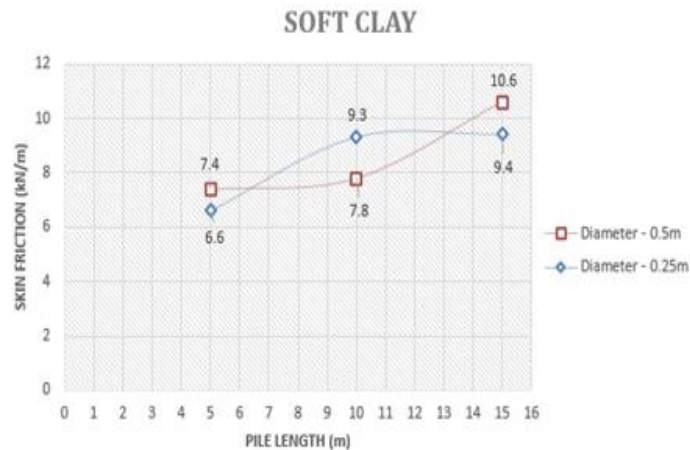

Figure 23.1 – Skin friction value on soft clay

In figure 23.1, 23.2 and 23.3 the skin friction results were showed for soft clay, medium clay and hard clay respectively. The result shows the value for one meter. To achieve the total skin friction result, first multiply the output result with their respective length (skin friction, kN/m X total depth of pile, in m). After this we can get the total skin friction.

Figure 23.2 – Skin friction value on medium clay

Figure 23.3 – Skin friction value on hard clay

VII.   Conclusion

Here an attempt has been undertaken to understand the behavior of pile foundation under lateral load for various conditions which shall affect the performance of the pile. Different soil models were developed in Plaxis 3D and parametric study of piles has been done. Based on the detailed parametric study, three distinct concluding behavior regimes were identified in the following:

1. **Variations of type of soil profile:** The behavior of pile also depends on relative stiffness of pile-soil interaction. The head deflection decreases as the relative stiffness increases. In soft clay the deflection occur more than medium clay and hard clay. Due to loose stiffness value of the soft clay, the soil can't pertained the pile against higher deflection. According medium to hard clay the stiffness or elastic constant gradually increases and the deflection value decreases.

2. **Variations of pile dimension:** From this parametric study a major finding occur on the pile dimension effect on bending moment and deflection values. In a same soil model the larger diameter pile gives minimum deflection but greater bending moment value. Whereas smaller diameter pile give maximum deflection but lesser bending moment value. This gives an approximately 55% difference in results. According to pile length, in larger pile deflection value lesser from shorter one. Which give an approximate 56% difference with respect to length. The slenderness ratio effects are also gives some other concluding remarks on it. When the slenderness ratio of a pile is greater than equal to the critical slenderness ratio is known as flexible pile. For long flexible piles, the length is so large that the pile base conditions do not affect the behavior of the head of the pile. But in short rigid piles, the length is so lesser that the pile base conditions affects on the behavior of pile head. With increasing slenderness ratio, the head deflection decreases.

3. Influence of skin resistance of pile: The total load carrying capacity of pile is the summation of end bearing resistance and skin friction. By the help of geotechnical software PLAXIS 3D, skin resistance value easily available on the simulation of program with respect to pile-soil parameters. By this the only end bearing resistance value will be calculate. According to the study, the load carrying capacity is high with respect to increase in length. Also soil stiffness vary the load carrying capacity. In high stiffer soil the pile carries higher load than less stiffer soil.

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