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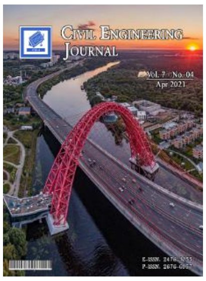

Numerical Study of Laterally Loaded Piles in Soft Clay Overlying Dense Sand

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Abstract

This paper presents the results of three dimensional finite element analysis of laterally loaded pile groups of configuration 1×1, 2×1 and 3×1, embedded in two-layered soil consisting of soft clay at liquid limit overlying dense sand using Plaxis 3D. Effects of variation in pile length (L) and clay layer thickness (h) on lateral capacity and bending moment profile of pile foundations were evaluated by employing different values of pile length to diameter ratio (L/D) and ratio of clay layer thickness to pile length (h/L) in the analysis. Obtained results indicated that the lateral capacity reduces non-linearly with increase in clay layer thickness. Larger decrease was observed in group piles. A non-dimensional parameter F_x ratio was defined to compare lateral capacity in layered soil to that in dense sand, for which a generalized expression was derived in terms of h/L ratio and number of piles in a group. Group effect on lateral resistance and maximum bending moment was observed to become insignificant for clay layer thickness exceeding 40% of pile length. For a fixed value of clay layer thickness, lateral capacity and bending moment in a single pile increased significantly with increase in pile length only up to an optimum embedment depth in sand layer which was found to be equal to three times pile diameter and 0.21 times pile length for pile with L/D 15. Scale effect on lateral capacity has also been studied and discussed.

Keywords: Laterally Loaded Piles; Lateral Displacement; Lateral Capacity; Layered Soil; Bending Moment; Soft Clay; Dense Sand; Finite Element Analysis.

1. Introduction

Study of behavior of laterally loaded pile foundations embedded in different subsoil strata has always been a challenging field for the researchers since the commencement of the use of these foundations in various geotechnical projects. After the pioneer research on laterally loaded piles done by Matlock and Reese (1962) [1] and Broms (1964,1965) [2-4], a vast research has been reported based on theoretical as well as practical studies conducted on laterally loaded piles embedded in homogeneous sands and clays using various experimental and numerical approaches. Majority of the reported initially studies used p-y method based on subgrade reaction approach, but with further advancement in the research, different numerical methods based on elastic continuum approach have been reported. Ashour and Norris (2000) recommended the use of strain wedge model rather than traditional p-y method to

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characterize influences of pile stiffness, pile cross sectional shape, pile head fixity and pile head embedment and soil properties on p-y curves [5]. Patra and Pise (2001) conducted an experimental study on model pile groups in dry sand and proposed analytical methods to predict ultimate lateral capacity of single and group piles based on pile friction angle, length to diameter ratio, soil properties, pile configuration and spacing of piles in group [6]. Ilyas et al. (2004), through a series of centrifuge model tests on laterally loaded pile groups in normally consolidated and over-consolidated clays, reported a decrease in group efficiency with increase in number of piles in the group and shadowing effect phenomenon showing that the front piles experience larger load and bending moment than the trailing piles [7]. Krishnamurthy et al. (2005) studied the behavior of laterally loaded single and group piles using non-linear finite element method incorporating a hypoelasticity constitutive model to model soil behavior and reported the effect of various parameters including pile spacing, direction of load, arrangements of piles in a group and thickness of pile cap on lateral load capacity of each pile in a group [8]. Phanikanth and Choudhary (2014) performed parametric analysis of single pile with floating tip in cohesionless soil using elastic continuum method and modulus of subgrade reaction approach and then proposed algebraic equations for free headed and fixed headed floating tip piles [9].

Reasonable application of finite element method or finite difference method based analytical software tools like Plaxis 3D and FLAC 3D to analyze the behavior of pile foundations has also been reported in various studies. Sivapriya and Gandhi (2013) conducted experimental model tests and numerical study with Plaxis 3D to evaluate behavior of a laterally loaded single pile in sloping clay. Based on the analysis results, non-dimensional charts were prepared for lateral capacity of pile in sloping ground [10]. Gouw (2017) reported the results of 3D finite element analysis of pile groups of configuration 5×5 and 9×9 using Plaxis 3D. Effects of pile spacing, number of piles in a group and magnitude of pile head lateral movement on pile group lateral efficiency were reported in the study [11]. Abhishek and Sharma (2019) reported the results of numerical analysis of uplift performance of granular pile anchors in expansive soils using Plaxis 3D by applying prescribed displacement of 10% of pile diameter at the center of pile top. Effect of pile length, pile diameter, number of group pile anchors at different spacing and modulus of elasticity on uplift capacity was studied [12]. Choi et al. (2018) investigated lateral behavior of pile foundations socketed into bedrocks using FLAC 3D and studied the influence of bedrock depth on pile deflection profiles, bending moment distribution in piles and p-y curves. It was reported that effect of bedrock gradually decreases with increase in bedrock depth and disappears at bedrock depth of 10 times diameter or more [13].

Many studies based on different analytical approaches have been reported on laterally loaded piles embedded in layered strata. Yang and Liang (2006) proposed a numerical solution using beam on an elastic foundation model for analysis of laterally loaded piles incorporating a variation in soil stiffness in layered soil [14]. Li and Gong (2008) developed an analytical method based on basic structural mechanics to obtain equations for deflection, bending moment and soil reaction in fixed and free head laterally loaded single pile in layered soils [15]. Hirai (2012) used Winkler model approach for the analysis of single pile and pile groups subjected to vertical and lateral load in non-homogeneous soils [16]. Ai et al. (2013) proposed a theory based on boundary element method for static analysis of laterally loaded piles in multilayered transversely isotropic soils [17]. Gupta and Basu (2017) developed a continuum-based method to analyze laterally loaded piles in multilayered heterogeneous elastic soil with soil modulus varying linearly or non-linearly with depth in soil layers [18]. Gerolymose et al. (2020) derived analytical expressions for failure envelope of piles subjected to horizontal and moment loading and verified the derived relations through numerical methods based on Winkler analysis and continuum mechanics analysis and also validated the results through experimental model tests. The effects of parameters like mesh density, soil strength properties, interface non–linearities and soil constitutive models on post failure response of pile –soil system was investigated [19]. Gupta and Basu (2020) developed a method of analysis for short rigid laterally loaded piles in multi-layered elastic soil using the variational principals of mechanics and obtained equilibrium equations for pile and soil displacements using principal of virtual work which were solved using an iterative algorithm. The soil resistance against pile movement was related to the soil elastic constants and pile head displacement and rotation were calculated through the developed analytical method [20].

Stiffness of clayey soil varies largely with its plasticity, consistency and water content. Highly plastic soft clay at liquid limit possessing only a marginal stiffness is usually encountered in the field constructions near coastal areas. However, research reported on laterally loaded piles embedded in clayey soil or multilayered soil deposits mostly consider stiff clays or soils possessing a considerable amount of stiffness modulus [10, 13, 17]. A limited work has been reported on laterally loaded piles embedded in soft clay [21, 22]. However, research data on behavior of laterally loaded piles in layered soil consisting of soft clay at liquid limit overlying dense sand is still meager. Considering this issue, an attempt has been made through this paper to present the results of a finite element study conducted on laterally loaded single and group piles embedded in two layered soil consisting of a layer of soft clay with water content equal to liquid limit overlying a layer of dense sand. Finite element analysis was performed using Plaxis 3D version 2012 to study lateral load capacity of piles in different arrangements of layer thickness and pile dimensions. The present analysis was extended from the experimental model testing by Kaur et al. (2021) [23]. Firstly, finite element analysis was performed on small models with dimensions and soil properties similar to laboratory model tests to validate the numerical models. Numerical analysis was then performed on large prototype models with different scales. In this paper, results obtained from finite element analysis of prototype models are presented and effects of variation in pile length and clay layer thickness on lateral capacity and bending moment profile of pile foundations are discussed. Scale effect on lateral capacity evaluated from the obtained results is also presented in this paper.

Section 2 briefly discusses the research methodology which includes development of finite element models, selection of various parameters including soil properties, thickness of soil layers, pile dimensions, pile group arrangements and different scales of the numerical models. Section 3 presents the validation record of finite element modeling by comparing the numerical analysis results to the experimental model test results. Section 4 presents results and discussions which include effect of variation of clay layer thickness and pile length on lateral capacity and bending moment profile of piles and effect of scale of numerical model on pile lateral capacity. Conclusions are drawn in section 5. The research process followed in this study is shown in Figure 1.

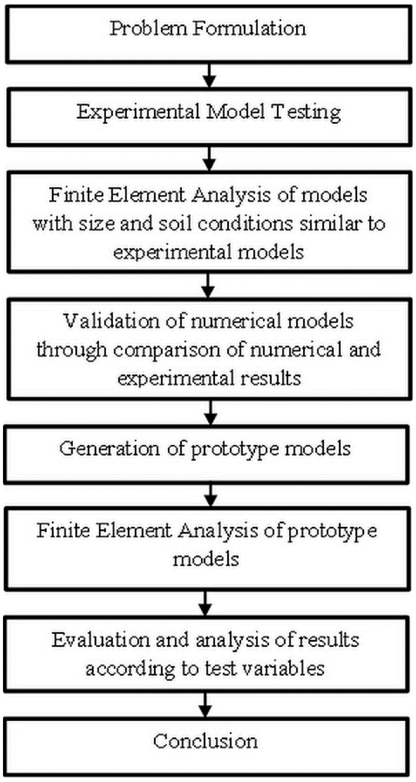


Figure 1. Research Methodology

2. Finite Element Modeling

2.1. Generation of Prototype Soil Model

A prototype model with size equal to 20 times size of experimental model, consisting of a two-layered soil strata of dimensions 40×40×20 m was generated for the finite element analysis in which upper layer consisted of CH clay at liquid limit and lower layer was of dense sand with relative density of 80%. Three different types of pile arrangements employed in the analysis were single pile (1×1), two piles in a row (2×1) and three piles in a row (3×1) with pile spacing equal to three times pile diameter. Figure 2 shows the general layout of the model generated with pile group 3×1.

In Plaxis 3D, 10-node tetrahedral elements are used to discretize the soil elements in the finite element mesh. In addition to the soil elements, 3-node line elements are used for beams, 6-node elements for plates and 12-node interface elements of zero thickness are used to model soil-pile interaction. Mohr- Coulomb model was used to simulate the soil behavior. This model requires five parameters to define strength and stiffness characteristics of soil which include stiffness (E'), Poisson’s ratio (ν'), cohesion (c'), friction angle (φ') and dilatancy angle (ψ) [24]. Properties assigned to the clay layer and the sand layer are listed in Table 1. Assigned values of unit weight of both the soils and stiffness and shear parameters of dense sand were determined through values of unit weight of soils in both the layers, stiffness and shear parameters of dense sand were determined through laboratory model tests. Dilatancy angle for both the soils was selected as per recommendations by Bolton i.e. for sands with $\varphi \geq 30°$, $\psi \approx \varphi-30°$ and for clays, $\psi \approx 0$ [25]. To avoid complications in the analysis, Plaxis recommends to use a small value of cohesion for sand greater than 0.2 kN/m^2, so a value of 0.3 kN/m^2 for cohesion of sand layer was used in the analysis. Stiffness and shear parameters of soft clay at liquid limit were selected as per available literature [26-29]. Obrzud and Truty (2018) [26] compiled typical values of stiffness modulus for clayey soils from reports of Kezdi (1974) [27] and Prat et al. (1995) [28] that stiffness modulus for CH soil of very soft to soft consistency varies from 0.35 to 4 MPa. Sridharan (1991) reported that soils at liquid limit possess a definite but small shearing strength of order of 15-30 g/cm² [29]. The stiffness modulus of 0.35 MPa i.e. 350 kN/m² and shear strength of 15 g/cm² i.e. 1.472 kN/m² were adopted after performing various trial numerical analyses with different values of these parameters in small scale numerical modeling.

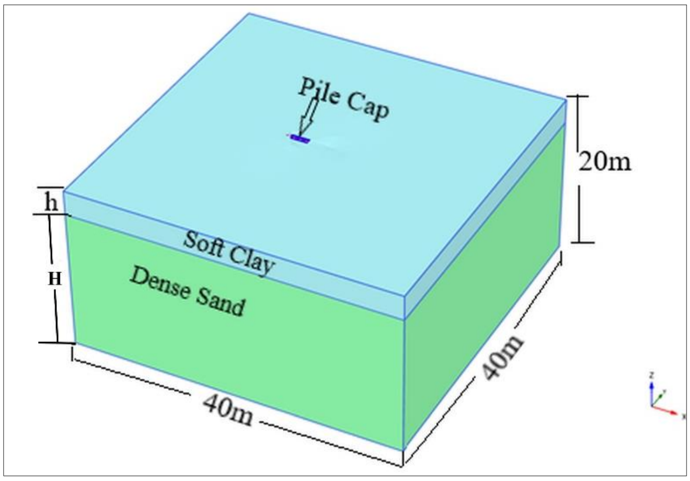


Figure 2. General layout of the finite element model

2.2. Modeling of Piles and Pile Cap

Model piles were created using embedded pile option. An embedded pile is composed of beam elements and embedded interface elements to interact with soil elements at its surface and foot. Dimensions of the pile used in numerical prototype modeling were scaled from dimensions of model steel pipe piles used in experimental tests using a scale of 20. Properties assigned to the model pile are given in Table 2. Pile cap was modeled as a concrete cap of M40 grade using the plates option which is used to model thin structures with a significant flexural rigidity. Properties assigned to the pile cap are given Table 3.

Table 1. Soil Properties used in numerical analysis

Property	Unit	Value	
		Top Layer Clay	Bottom Layer Sand
Material Model	-	Mohr-Coulomb	Mohr-Coulomb
Drainage Type	-	Drained	Drained
Dry unit weight, γ_{unsat}	kN/m³	15.3	17.7
Saturated unit weight, γ_{sat}	kN/m³	18.74	18.4
Stiffness, E'	kN/m²	350	39000
Poisson's Ratio, ν'	-	0.4	0.3
Cohesion, c'	kN/m²	1.472	0.3
Angle of Friction, φ'	°	0	34.6
Dilatancy Angle, ψ	°	0	4.6
Strength Reduction Factor, R_{inter}	-	0.67	0.67

Table 2. Properties of model pile

Property	Unit	Value
Modulus of Elasticity, E	kN/m²	150×10^6
Unit Weight, γ	kN/m³	73.37
Pile Type	-	Circular Tube
Outer Diameter, D	m	0.254
Wall Thickness, t	m	0.008
Embedded Length, L	m	7.62

Table 3. Properties of pile cap

Property	Unit	Value
Thickness, d	m	0.5
Unit Weight, γ	kN/m^3	25
Modulus of Elasticity, $E = 5000\sqrt{f_{ck}}$	kN/m^2	31.6×10^6
Poisson's Ratio	-	0.15

2.3. Analysis Scheme

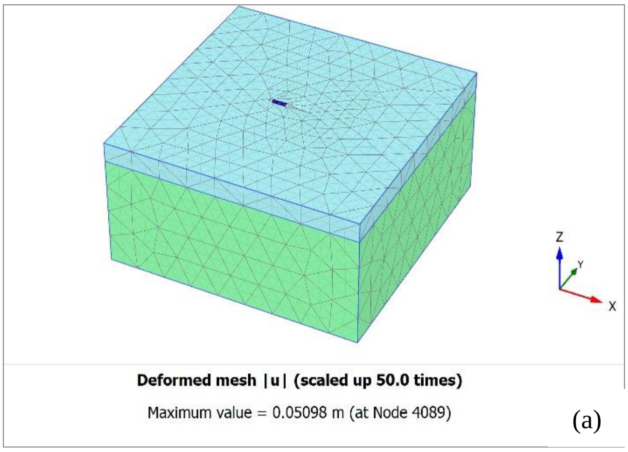
Finite element mesh was generated after completing the model. After that calculations were performed in phases through stage construction mode. In first phase, initial stresses were calculated using K_0 procedure. Soil in both the layers and various structural elements were activated in next phases. Model piles were subjected to point displacement equal to 20% of pile diameter acting at pile head. Prescribed point displacement was activated in the last phase of calculation process. The lateral load (F_x) corresponding to the applied displacement was obtained using charts of load – displacement curves at the selected nodes.

2.4. Parametric Study

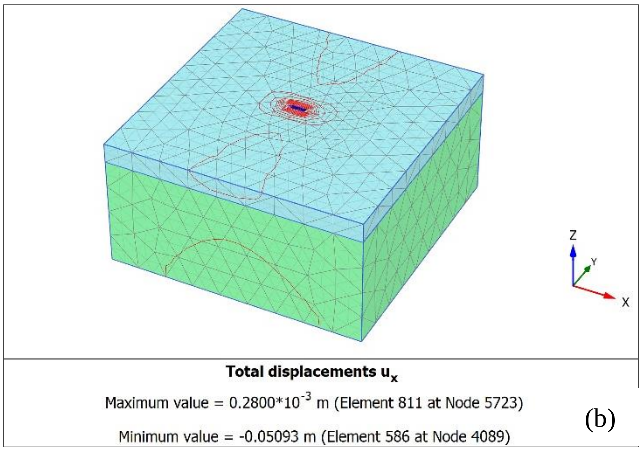
A number of parameters were varied to analyze their effect on lateral response of pile groups. While keeping the diameter of the piles constant, pile length was varied to use various values of length to diameter ratio (L/D) in the analysis. Clay layer thickness was varied from 0 to L i.e. equal to pile length and hence the value of h/L was varied from 0 to 1. h/L = 1 represent the case of pile embedded in single layer of clay only, whereas h/L = 0 represent the case of pile embedded only in dense sand layer. Also, value of L/D was varied from 11.8 to 60 for soil strata with a constant value of clay layer thickness of 3m to study the effect of pile embedment in lower dense sand layer on the lateral load capacity of pile. Details of other parameters used in the study are given in Table 4. Figures 3(a) - 3(c) show typical Plaxis output showing deformed mesh, total displacements (u_x) and pile deflection respectively at lateral displacement of 0.2D for group 3x1 with L/D =30 and h = 3m.

Table 1. Details of the parameters used in the numerical analysis

Thickness of clay layer, h (m)	Pile Length, L (m)	L/D	h/L	Number of piles, n
0, 1, 1.5, 2, 2.5, 3, 3.81	3.81	15	0, 0.26, 0.39, 0.52, 0.66, 0.79, 1	1
0, 1, 2, 2.5, 3, 4, 5.08	5.08	20	0, 0.2, 0.39, 0.49, 0.59, 0.79, 1	1
0, 1, 1.5, 2, 3, 4, 5, 6.35	6.35	25	0, 0.16, 0.24, 0.31, 0.47, 0.63, 0.79, 1	1
0, 1, 2, 3, 4, 5, 6, 7.62	7.62	30	0, 0.13, 0.26, 0.39, 0.52, 0.66, 0.79, 1	1, 2, 3
3	3, 3.048, 3.429, 3.81, 5.08, 6.35, 7.62, 11.43, 15.24	11.8, 12, 13.5, 15, 20, 25, 30, 45, 60	1, 0.98, 0.87, 0.79, 0.59, 0.47, 0.39, 0.26, 0.2	1



(a)



(b)

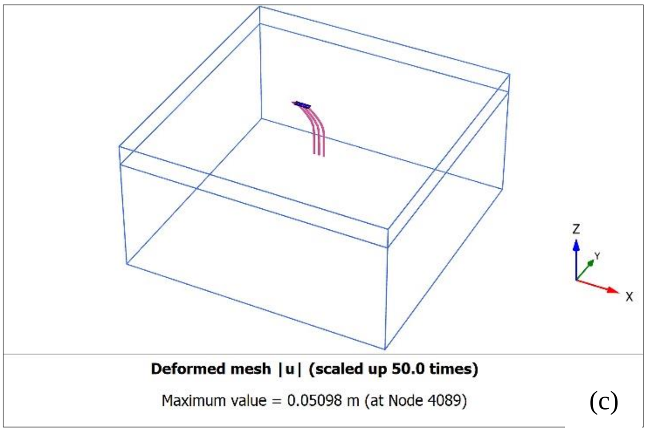


Figure 3. (a) Deformed mesh at lateral displacement equal to 0.2D; (b) Total displacements u_x; (c). Pile deflection at lateral displacement equal to 0.2D

3. Validation of Finite Element Model

Before generation of prototype models, the adopted small finite element model was validated by comparing the results of finite element analysis to the laboratory model tests performed on single pile and group piles of patterns 2×1 and 3×1 embedded in soft clay overlying dense sand in the test setup reported by Kaur et al. (2021) [23]. The laboratory model tests were performed on steel pipe piles of 381 mm length, 12.7 mm outer diameter and 0.4 mm wall thickness in a tank of square cross section of 2×2 m and 1 m depth. Thickness of clay layer and sand layer were 150 mm and 850 mm respectively. For numerical analysis, a finite element model of same size and similar pile dimensions and soil conditions as in laboratory model tests was created using Plaxis 3D. Comparison of laboratory test results and the results obtained from finite element modeling of single and group piles are shown in Figures 4(a) to 4(c). A marginal difference between the experimental and Plaxis curves indicated a good agreement between the results from laboratory tests and finite element analysis. The obtained comparative data showed relevancy of the adopted model for simulating the pile – soil interaction and analysis of behavior of pile foundations.

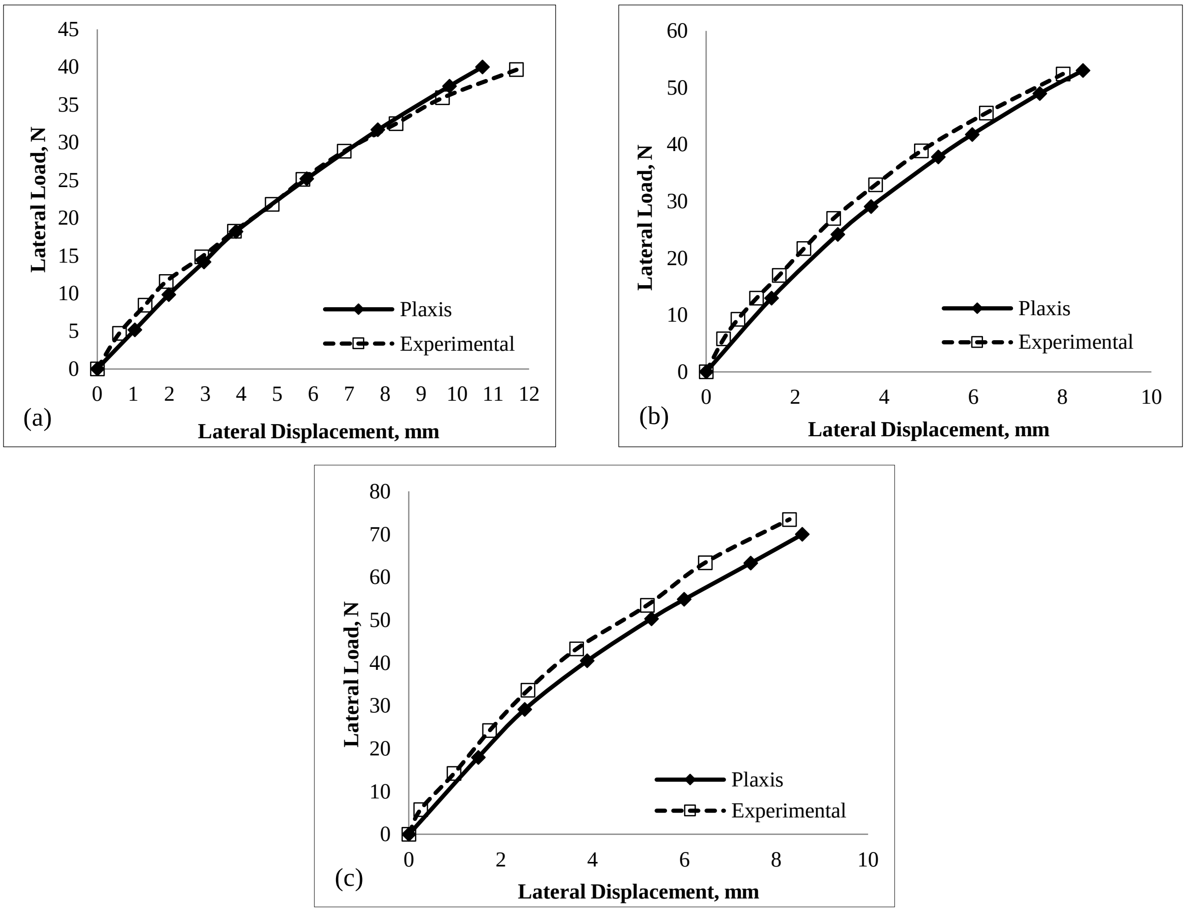


Figure 4. Comparison of finite element analysis results with experimental test results for (a) Single Pile; (b) Group 2×1 and (c) Group 3×1

4. Results and Discussion

4.1. Effect of Clay Layer Thickness on Lateral Capacity

Figure 5 shows the lateral displacement -lateral load curves obtained for single piles with L/D ratio 30 for different values of clay layer thickness. Trends of the curves indicate a decrease in lateral capacity of the piles with increase in the thickness of clay layer. Similar trends were observed for group piles also. This variation was studied by comparing change in lateral load corresponding to lateral displacement of 0.2D to the variation in h/L for pile length 7.62m as shown in Figure 6. Successive reduction (%) in lateral capacity for all the pile group arrangements with change in h/L ratio is shown in Figure 7. It is visible from Figures 6 and 7 that for single as well as group piles, rate of reduction in lateral capacity with increase in clay layer thickness is higher at smaller values of h/L. The maximum reduction is observed for h/L varying from 0.26 to 0.39. The rate of reduction diminishes as value of h/L exceeds 0.39. Value of h/L of 0.39 corresponds to clay layer thickness of 3 m and depth of pile embedment in dense sand (H) equal to 4.62 m which is about 18 times pile diameter i.e. H/D = 18. The major reduction in lateral capacity was observed when depth of pile embedment in dense sand reduced from 30D to 18D for the considered pile length of 7.62 m with L/D = 30.

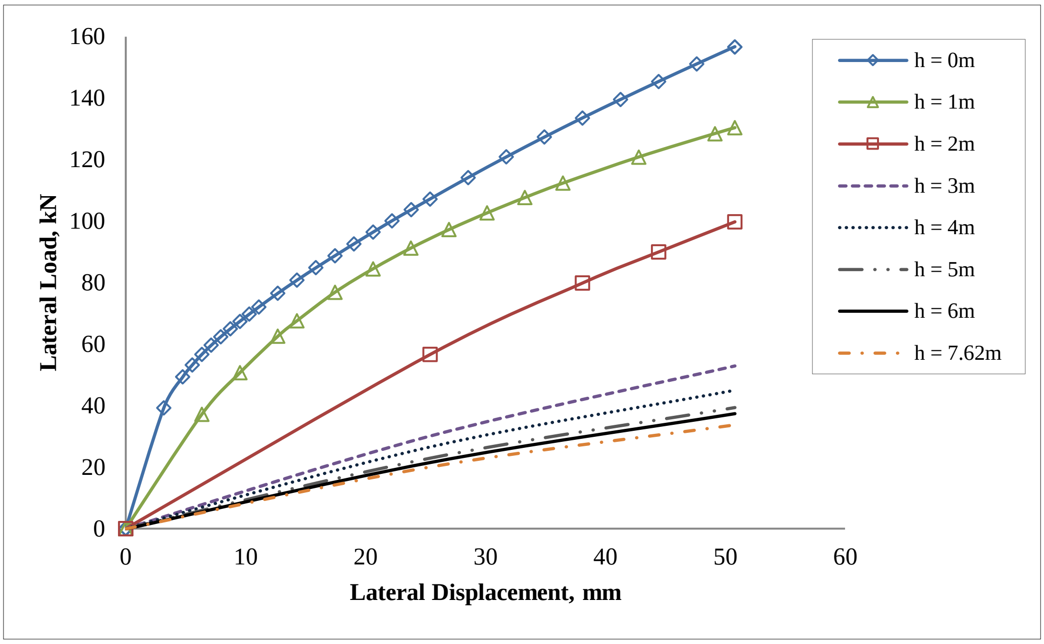


Figure 5. Lateral displacement versus lateral load curves for single pile with L = 7.62m, L/D = 30

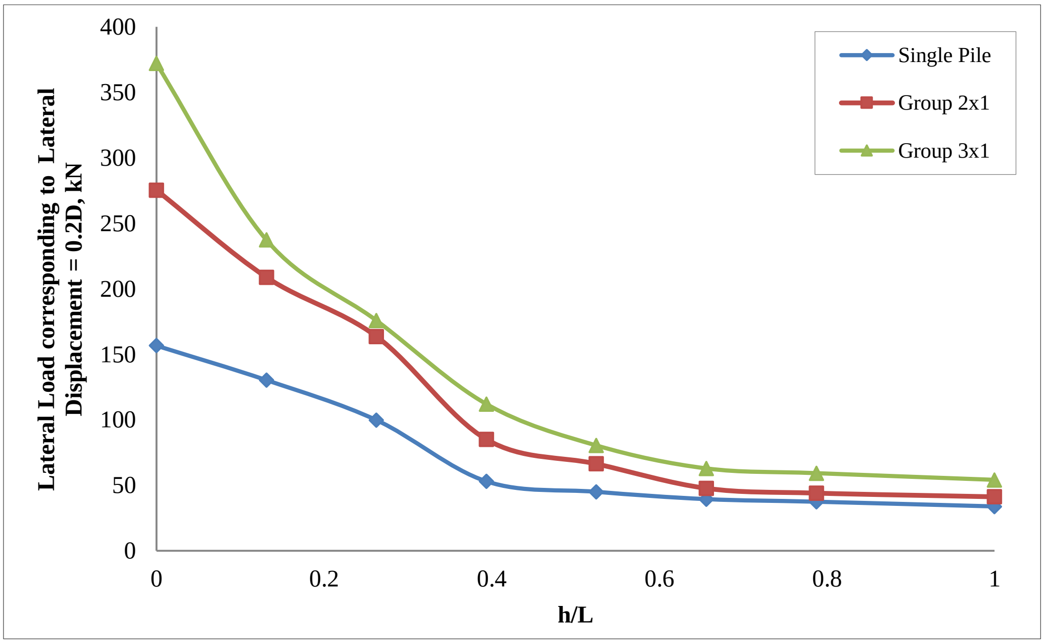


Figure 6. Variation in lateral capacity with change in h/L for L = 7.62m, L/D = 30

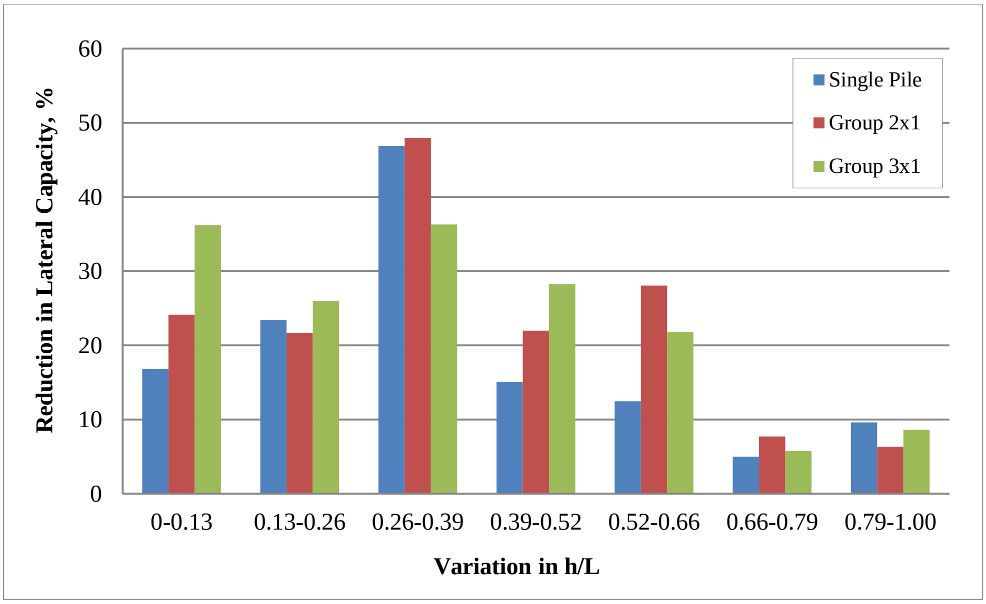


Figure 7. Successive reduction in lateral capacity with variation in h/L

Figure 8 shows that at h/L = 0.39, there is a reduction of order of 66.2, 69.1 and 70% in lateral capacity of single, group 2×1 and group 3×1 piles respectively with respect to the lateral capacity of piles in dense sand (h/L = 0). For piles embedded in soft clay (h/L = 1), lateral capacity of single, group 2×1 and group 3×1 piles reduces to 78.4, 85 and 85.5% respectively in comparison to piles embedded in dense sand (h/L = 0). Figure 8 clearly indicates that percentage reduction in lateral capacity in layered soil with respect to dense sand increases with increase in number of piles and is the largest for group 3×1 piles. However, it is also noticeable that group effect on variation in lateral capacity diminishes with the increase in clay layer thickness.

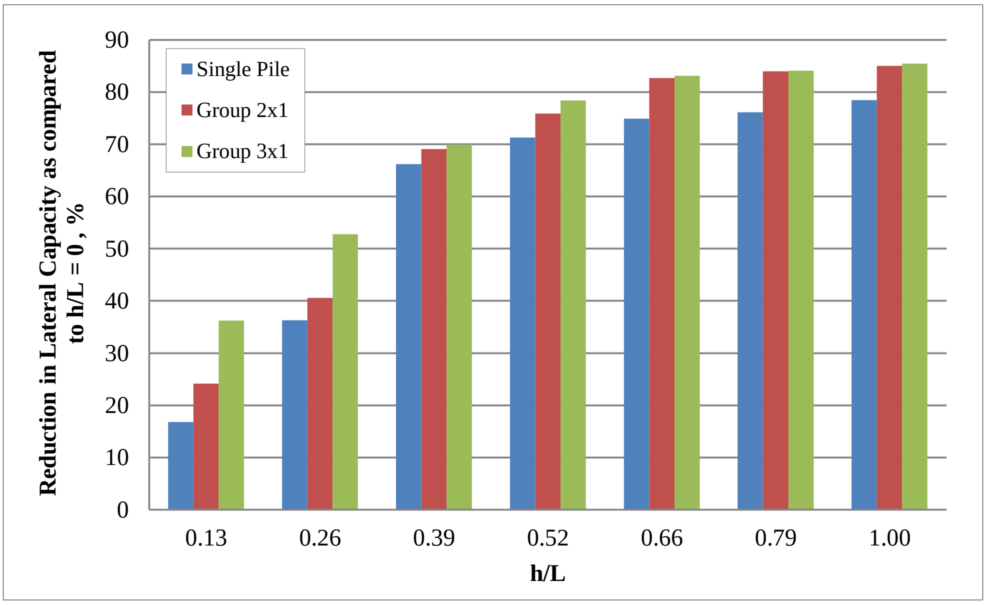


Figure 8. Reduction in lateral capacity in layered soil in comparison to dense sand

Change in lateral capacity was studied in terms of a non-dimensional parameter F_x Ratio which relate the lateral capacity of piles in layered soil (h > 0) to that in dense sand (h = 0) and is defined as per Equation (1). Variation in F_x Ratio with change in h/L for single pile with different values of L/D ratio is shown in Figure 9 which shows that F_x Ratio decreases non-linearly with increase in h/L.

$$F_x\ Ratio = \frac{F_x\ at\ lateral\ displacement\ 0.2D\ in\ layered\ soil}{F_x\ at\ lateral\ displacement\ 0.2D\ in\ dense\ sand} \quad (1)$$

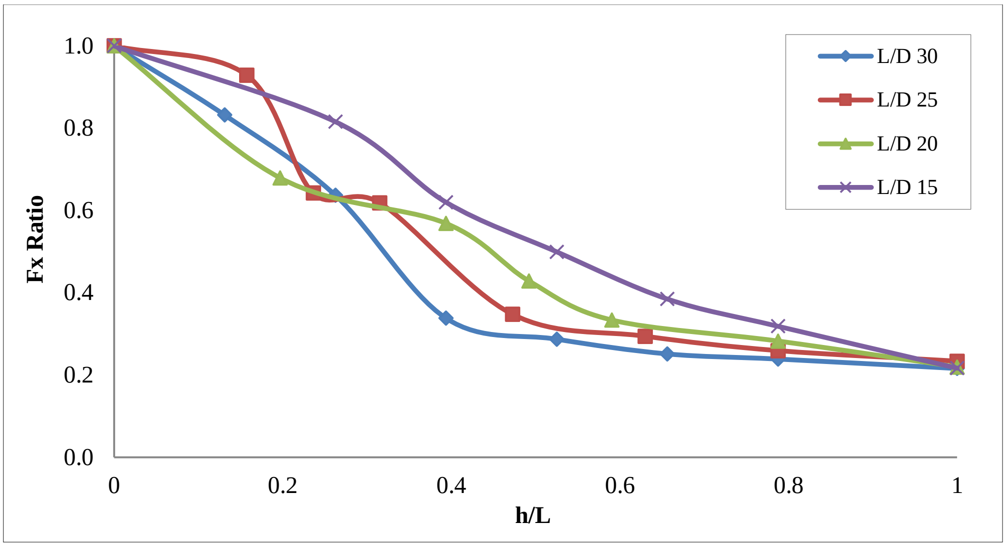


Figure 9. Variation in F_x ratio with change in h/L for single pile

Observed results of the numerical analysis showed that the lateral capacity of group piles and single pile embedded in soft clay (h/L = 1) ranges from 0.145 to 0.216 times the lateral capacity in dense sand (h/L = 0). It was observed that for all the pile group arrangements, F_x Ratio reduces exponentially with increase in h/L. Nonlinear generalized reduced gradient approach was used to predict relationship between the two parameters which is applicable for single as well as group piles as given in Equation 2. Sum of squared residuals for the predicted relationship was 0.095 which indicated a good match between observed and predicted data. However, to apply correction for number of piles in the group (n), Equation 2 was revised to Equation 3 which produced a better match with smaller value of sum of squared residual of 0.075. Observed variation in F_x Ratio with change in h/L ratio for single as well as group piles and the trends of predicted equations are presented in Figure 10. It is noticeable from the figure that the predicted expressions reasonably match with the observed trends.

$$F_x\ Ratio = 1.0015\ e^{-2.413\ h/L} \tag{2}$$

$$F_x\ Ratio = \left(1.0728\ e^{-2.389\frac{h}{L}}\right) \times n^{-0.1226} \tag{3}$$

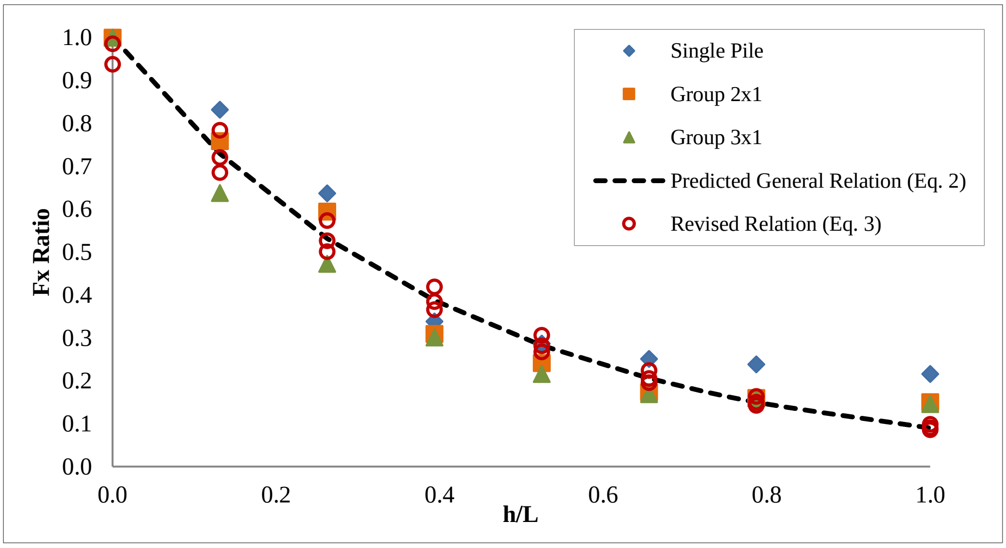


Figure 10. Observed and predicted trends of variation in F_x ratio with change in h/L

Observed trends of variation of lateral capacity with change in h/L ratio fairly agree with the observations reported by Uncuoğlu and Laman [30] that lateral load capacity of piles in the layered sand conditions decreases non-linearly as the thickness of the upper layer increases. Similar observations were also suggested by Kim and Kim [31] that the effect of height ratio of non-homogeneous soil on deflection is exponential function with height ratio. Furthermore, it is to be noted that the predicted expressions are applicable only for similar conditions of soil stiffness, pile geometry and pile end conditions as considered in the present analysis.

4.2. Effect of Clay Layer Thickness on Lateral Deflection and Bending Moment

Variation in deflected shape of single pile and group 2×1 with increase in clay layer thickness is shown in Figures 11(a) and 11 (b) respectively. It can be seen from the figure that the lateral deflection of the pile at a particular depth increases with increase in the thickness of clay layer. It occurs due to reduction in lateral stiffness of the soil which causes reduced lateral capacity of the piles. Bending moment profiles of single and group piles embedded in dense sand (h = 0) and in soft clay (h = 7.62 m) are compared in Figures 12(a) to 12(c). The maximum bending moment in the piles embedded in soft clay is noted to be in the range of 20% to 26% of the maximum bending moment in piles embedded in dense sand. Figure 13 shows a clear variation in bending moment profile of single pile with different values of clay layer thickness. Similar trend is noted in group piles also. Variation of the maximum bending moment with change in h/L ratio for single and group piles is presented in Figures 14(a) to 14(c).

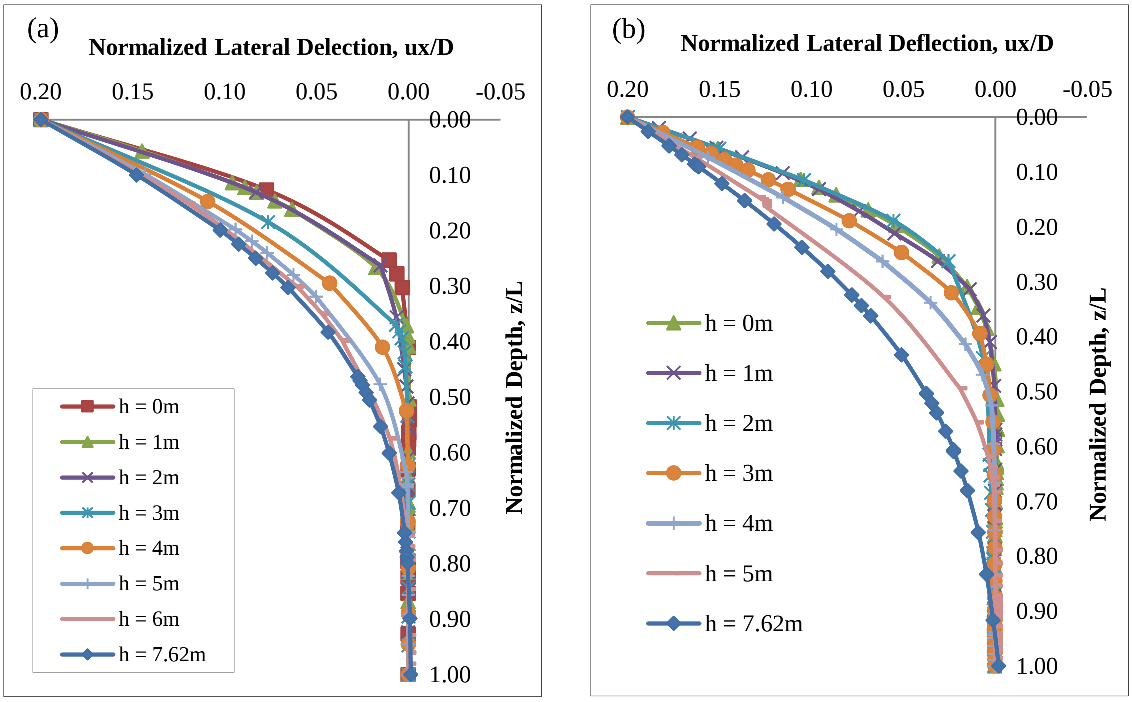


Figure 11. Lateral deflection profile for (a) Single pile and (b) Group 2×1

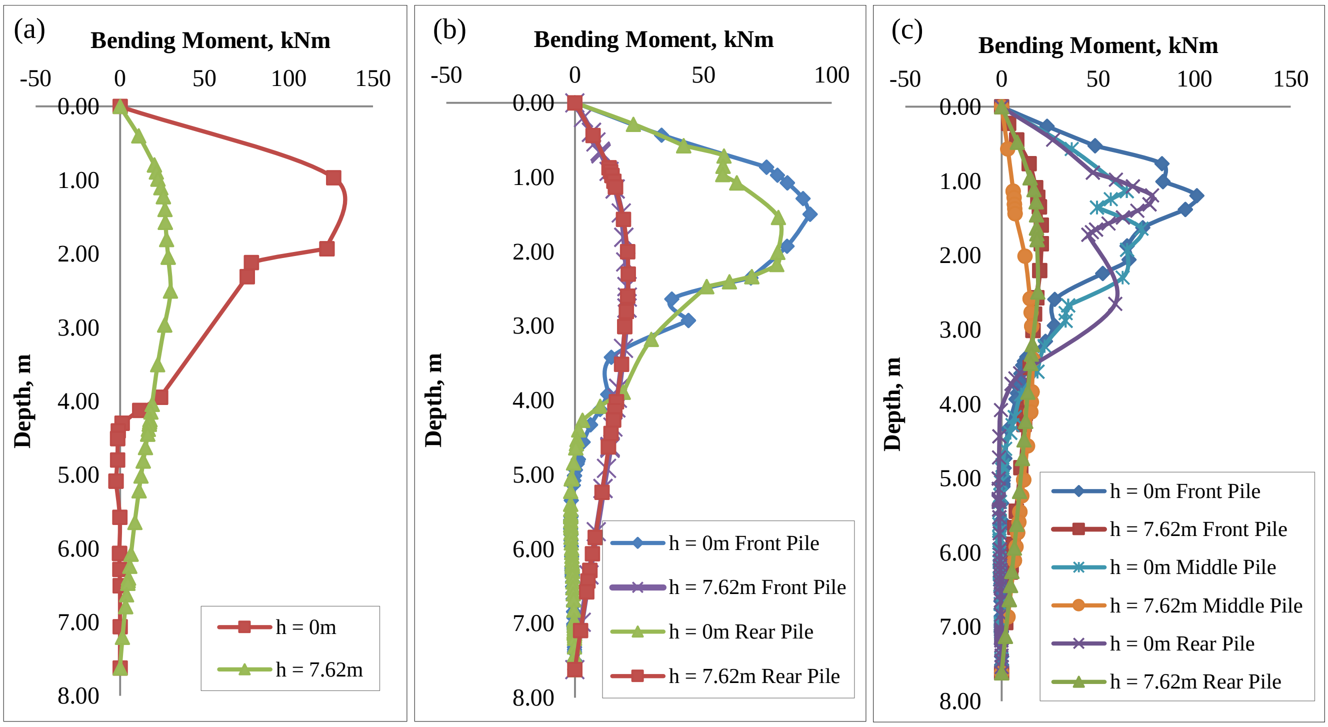


Figure 12. Comparison of bending moment profile in sand (h= 0) and clay (h= 7.62 m) for (a) Single pile, (b) Group 2×1 and (c) Group 3×1

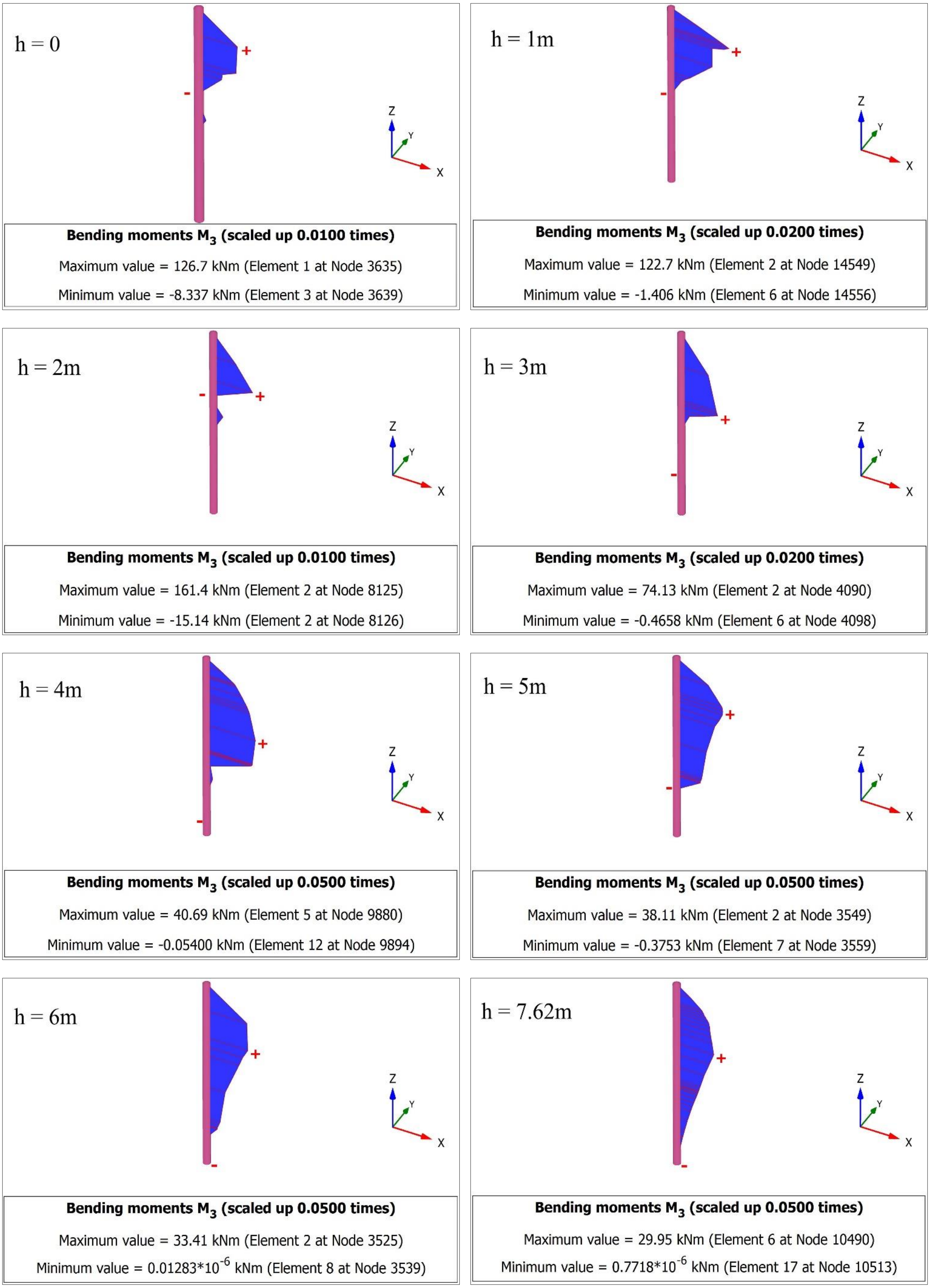


Figure 13. Plaxis output for bending moment profile of single pile with L =7.62 m for different values of h

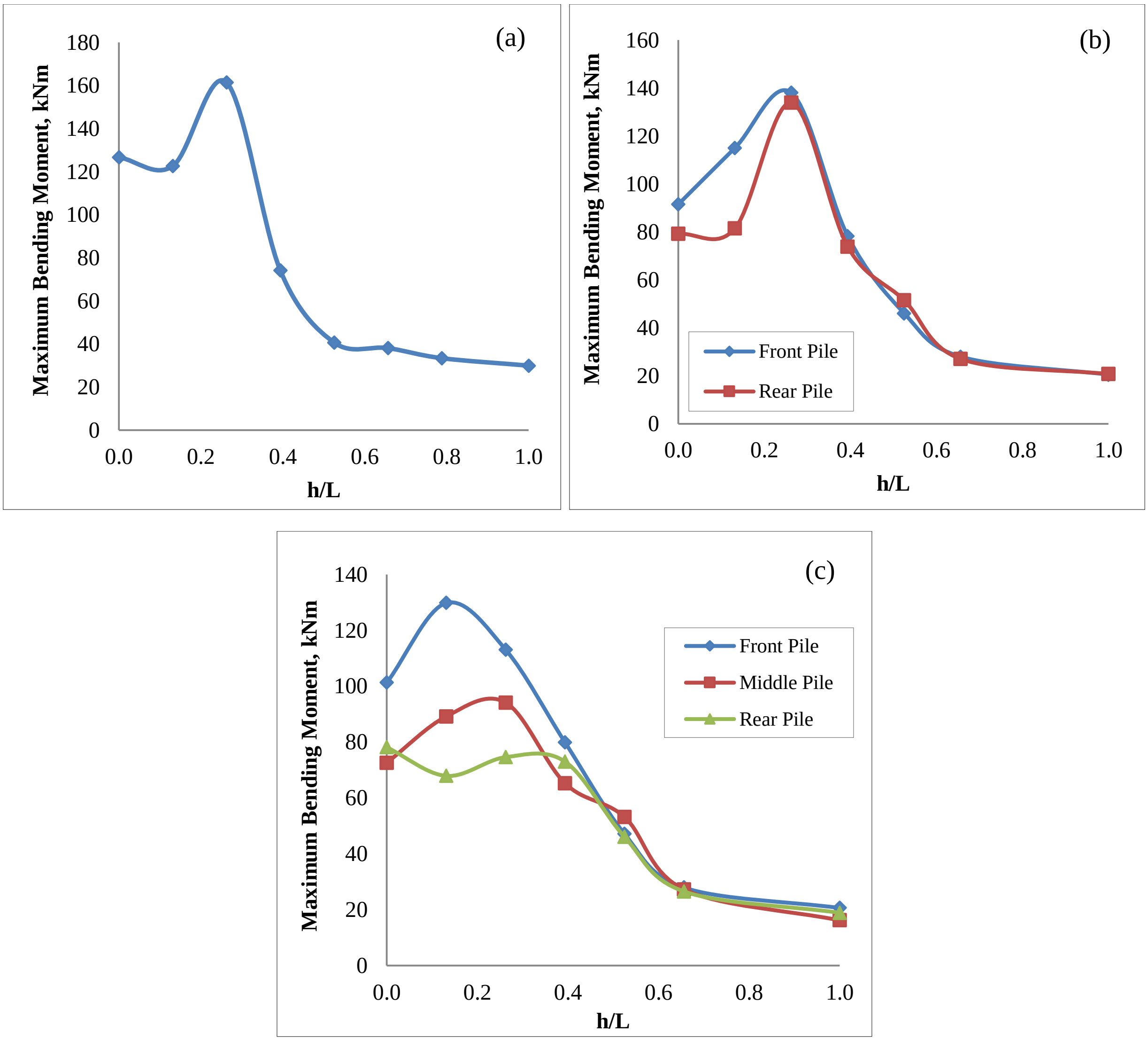


Figure 14. Variation in maximum bending moment with change in h/L for (a) Single pile, (b) Group 2×1 and (c) Group 3×1

It is observed that for all the three pile setups, maximum bending moment in an individual pile initially increases with increase in h/L ratio. The largest value of maximum bending moment in all the piles is obtained at h/L = 0.26, except for front pile of group 3×1, in which the largest value of maximum bending moment is obtained at h/L = 0.13 and this value decreases with further increase in h/L ratio. It is also observed that at smaller values of h/L, maximum bending moment occurring in single pile is larger than the group piles and its value reduces with increase in number of piles in the group. But for h/L more than 0.39, there is not much difference in value of maximum bending moment for single and group piles. It is also observable that the bending moment in front pile of a group is larger than that in the trailing piles for h/L less than 0.39 and this trend also disappear for h/L greater than 0.39. These observations clearly show that group effect on lateral resistance as well as bending moment reduces as thickness of soft clay layer increases and it becomes negligible as clay layer thickness exceeds 40% of pile length.

4.3. Effect of Pile Length Variation on Lateral Capacity and Bending Moment Profile of Single Pile

To study the effect of variation in pile length on lateral capacity of single pile in layered soil, pile length was varied while keeping a constant clay layer thickness of 3m. Minimum length of the pile used in the analysis was taken equal to the thickness of clay layer i.e. 3m with value of L/D =11.8. Change in lateral capacity with increase in pile length is presented through the lateral displacement versus lateral load curves as given in Figure 15. Trends of the curves clearly indicate a significant enhancement in lateral capacity with increase in length up to L/D equal to 15. However, for higher values of L/D ratio, there is only a negligible increase in lateral capacity.

These results fairly agree with the observations of Reese and Van Impe (2010) [32] who reported that the depth up to 10D is of predominantly importance in soil-pile interaction in case of lateral loading. Abdrabbo and Gaaver [33] also suggested that the effective depth of a flexible laterally loaded pile embedded in cohesionless soil is about 16 times the pile diameter.

An attempt was made to understand the effect of pile length variation in terms of depth of pile embedment in dense sand layer, H. It was observed that lateral capacity increases initially with increase in pile length because of increased stiffness of dense sand along depth until the pile attains an optimum embedment depth in dense sand beyond which there is not any significant change in lateral capacity with further increase in pile embedment. Observed data in the present combination of layered soil with clay layer thickness of 3m, showed that significant improvement in lateral capacity occurs till the embedment depth of pile in dense sand reaches a depth equal to three times pile diameter i.e. H/D =3 as shown in Figure 16.

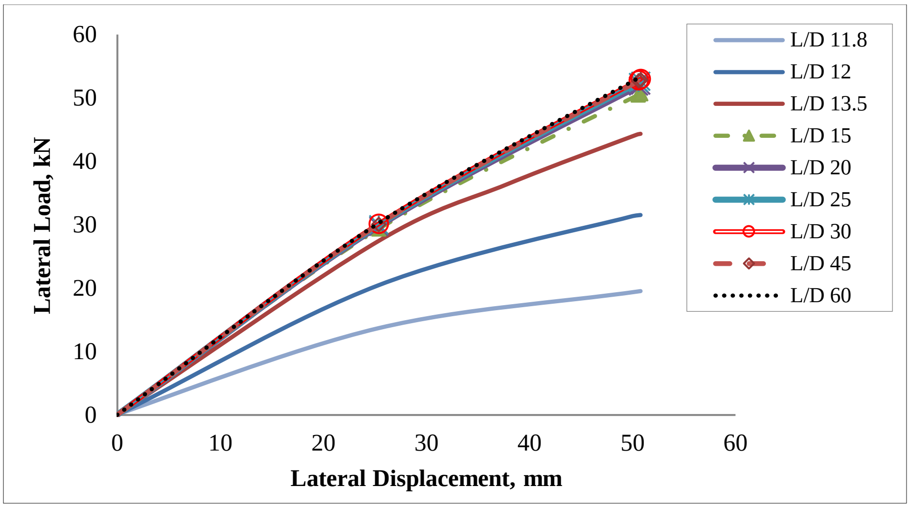


Figure 15. Lateral displacement versus lateral load curves for single pile, h = 3 m

The improvement in lateral capacity with increase in pile length was also studied by comparing the variation in the ratio of lateral capacity in layered soil to the lateral capacity in soft clay ($F_x/F_{x\text{-clay}}$) and the change in normalized depth of embedment in dense sand in terms of pile length i.e. H/L as shown in Figure 17. The obtained curve clearly shows that optimum embedment depth in dense sand is about 21% of pile length i.e. H/L = 0.21 corresponding to value of $F_x/F_{x\text{-clay}}$ = 2.6, indicating about 160% increase in lateral capacity in layered soil as compared to the soft clay. Maximum value of $F_x/F_{x\text{-clay}}$ is 2.73 for H/L = 0.8, which clearly indicates a marginal improvement in lateral capacity with increase in H/L beyond 0.21. It shows that major improvement in lateral capacity is achieved when 21% of pile length is embedded in dense sand in the soil layer combination adopted in the present analysis.

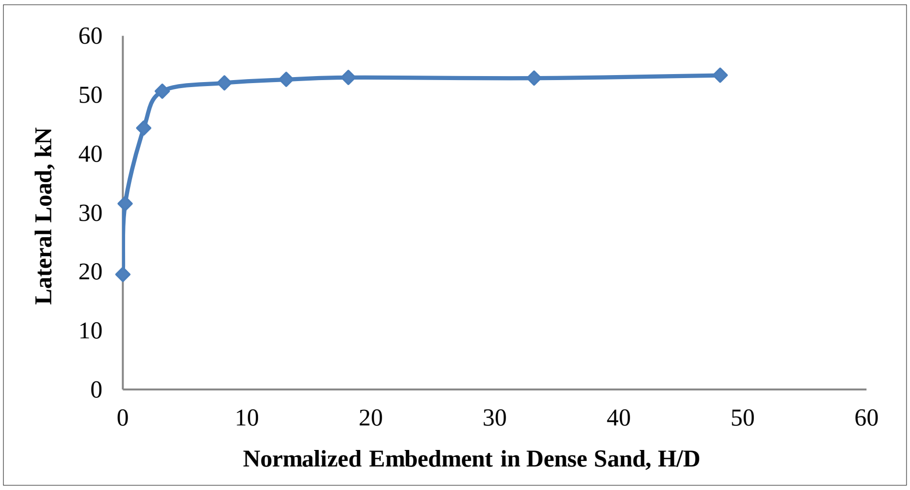


Figure 16. Variation in lateral capacity of single pile with change in H/D in layered soil with h = 3 m

Bending moment profile of single pile for different values of L/D ratio in layered soil with clay layer thickness of 3m is shown in Figure 18. A significant increase in maximum bending moment with increase in pile length up to L/D 15 is noticeable from the observed results. Maximum bending moment observed in pile with L/D 11.8 was 14.99 kNm which increased to 65.24 kNm at L/D 15. However, a negligible increase in maximum bending moment was observed with further increase in pile length. It changed from 70.54 kNm for L/D 20 to 75.47 kNm for L/D 60. A small amount of negative bending moment was also observed in pile lengths with L/D equal to 25 and more.

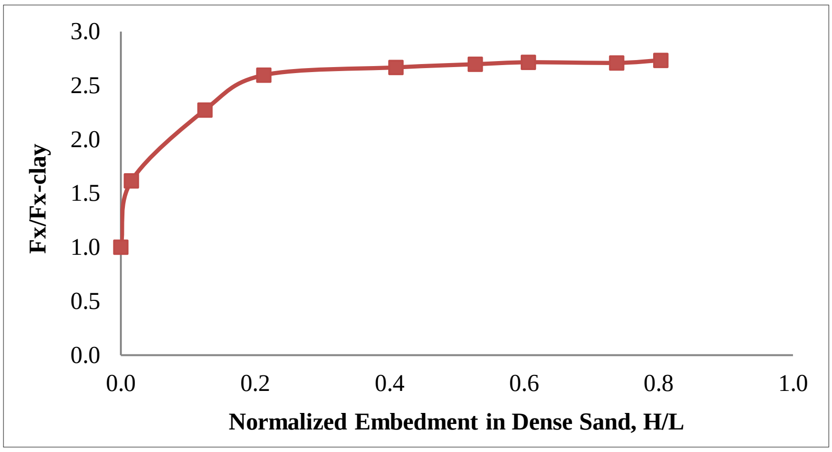


Figure 17. Variation in $F_x/F_{x\text{-clay}}$ with change in H/L for h = 3 m

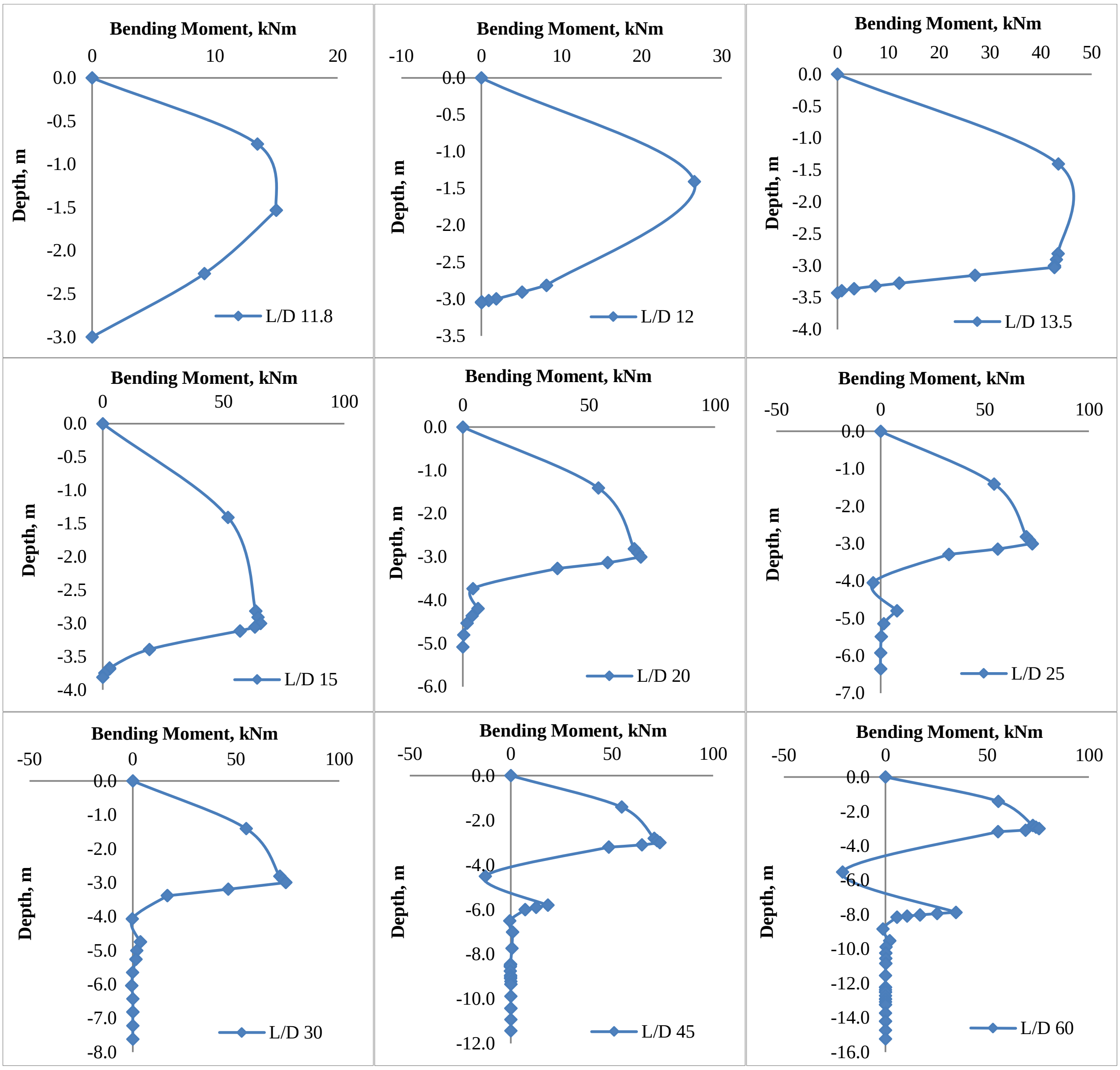


Figure 18. Bending moment profile of single pile with different L/D ratio values for h = 3 m

4.4. Scale Effect on Lateral Capacity

In addition to the parametric study conducted in the numerical analysis, an effort was also made to study the scale effect on lateral load capacity. The size of prototype finite element model was varied using variety of scales (s times the size of experimental model) while keeping soil properties and pile end conditions similar. Different values of scale (s) employed in the finite element analysis were 20, 30, 40, 50 and 60. Scale effect was measured by comparing the variation in non-dimensional factor lateral capacity ratio (LCR) with the variation in the scale. LCR is defined as given in Equation 4.

$$LCR = \frac{F_{xp}}{F_{xm}} \quad (4)$$

Here, F_{xp} is lateral load capacity of finite element model of prototype size with scale, s and F_{xm} is lateral load capacity of small finite element model with size equal to experimental model. Figure 19 shows that values of LCR corresponding to lateral displacement 0.2D and 0.1D vary by power law as the scale of the prototype varies. The obtained equations indicated that the value of ratio of lateral capacity of a prototype to a small model is around 10 times the square of the scale used. R^2 values for the predicted relationships as given in Equations 5 and 6 for lateral displacement 0.2D and 0.1D respectively are 0.999 and 0.997, which show a good match with the data of finite element analysis results.

$$LCR\ at\ lateral\ displacement\ 0.2D = 10.053\ s^{2.03} \quad (5)$$

$$LCR\ at\ lateral\ displacement\ 0.1D = 9.983\ s^{2.065} \quad (6)$$

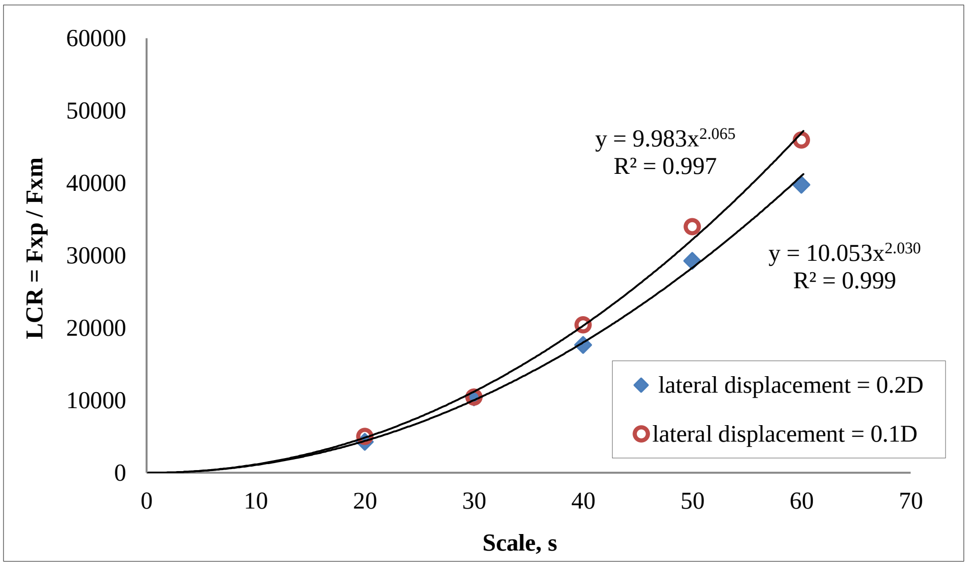


Figure 19. Scale effect on LCR at lateral displacement 0.2D and 0.1D

5. Conclusions

A three dimensional numerical analysis was performed using Plaxis 3D software to study the lateral capacity and bending behavior of single and group piles embedded in two-layered soil consisting of upper soft clay layer with water content equal to liquid limit overlying a dense sand layer with 80% relative density. Effects of variation in pile length and thickness of clay layer on lateral resistance and bending profile of the piles were studied.

It is concluded that increase in clay layer thickness has a detrimental effect on the lateral load resistance of piles. It causes larger decrease in lateral capacity of group piles. For piles embedded in soft clay in comparison to the piles in dense sand, the noted reduction in lateral capacity is 78.4, 85 and 85.5% in single, group 2×1 and group 3×1 piles respectively. Lateral capacity of piles in the layered soil decreases non-linearly with increase in the thickness of soft clay layer. F_x ratio reduces exponentially with increase in h/L ratio. Minimum value of F_x ratio is obtained for h/L =1 and it remains between 0.145 and 0.216 for group piles and single pile respectively. A generalized expression was developed for relationship between F_x ratio and h/L ratio which is applicable for single piles as well as group piles. The maximum bending moment in the piles embedded in soft clay at liquid limit is found to be in the range of 20 to 26% of the maximum bending moment in the piles embedded in dense sand. It is also concluded that the group effect on lateral resistance and bending moment in the piles reduces with increase in thickness of clay layer. There is a marginal difference in maximum bending moment in individual piles in a group and single pile in layered soil with clay layer thickness more than 40% of pile length. For a fixed value of clay layer thickness, lateral capacity and maximum bending moment in single pile increases with increase in pile length up to an optimum embedment depth in dense sand. Further increase in the pile length beyond optimum embedment depth has marginal effect on lateral resistance of pile. The optimum embedment depth in dense sand is about three times pile diameter and 0.21 times pile length in layered soil combination considered in the present study. The optimum value of L/D ratio for single pile is 15 in the considered layered soil with clay layer thickness of 3m. Lateral capacity of pile embedded up to the optimum depth in layered soil is 2.6 times the lateral capacity of the pile embedded in soft clay. A generalized expression was developed for scale effect on the ratio of lateral capacity of prototype to that of model which is governed by a power law.

6. Declarations

6.1. Author Contributions

A.K., H.S. and J.N.J. contributed to the conception and design of the study; A;K. performed the experimental tests and numerical study and analysed the data; A.K. wrote the first draft of the manuscript; J.N.J. and H.S. guided and supervised the research work and commented on the previous version of the manuscript. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in article.

6.3. Funding

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6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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