Experimental and Numerical Study of Influence of Vertical Load on Laterally Loaded Single and Group Piles in Layered Sand

Amanpreet Kaur[1*], Dr. Harvinder Singh[2] and Dr. JagadaNand Jha[3]

[1]*Research Scholar, IKG Punjab Technical University, Jalandhar, Punjab, India.*

[2]*Professor,Department of Civil Engineering, Guru Nanak Dev Engineering College, Ludhiana, Punjab, India.*

[3]*Principal, Muzaffarpur Institute of Technology, Muzaffarpur, Bihar, India.*

Abstract: *This paper presents the results of an experimental and numerical study conducted on laterally loaded single and group piles embedded in two-layered sand in the absence and presence of vertical load. This study analyses the changes in lateral displacement and bending moment in pile foundations under combined vertical and lateral load. Pile embedment length was varied to study the effect of pile stiffness. Experimental results were validated with three-dimensional numerical analysis performed using finite element based software Plaxis 3D. Results indicated that lateral capacity of single piles decreases and bending moment increases in the presence of vertical load. Whereas, presence of vertical load resulted in increased lateral capacity and decreased bending moment in group piles. Effect of vertical load was more detrimental for lateral capacity of flexible piles. A generalized equation was developed for pile lateral capacity under combined load in terms of pile capacity under lateral load, normalized lateral displacem[1]ent, pile embedment ratio, number of piles in a group and ratio of sand layer thickness to pile embedment length. Empirical relationships between normalized lateral displacement and ratio of vertical load to lateral load were derived for single and group piles. Lateral displacement equal to 20 % of pile diameter is produced in single pile and pile group when ratio of vertical load to lateral load is 2.3 and 3 respectively. Equations for relationship of normalized lateral displacement with inclination of resultant load were also derived.*

Keywords: *Laterally loaded piles, lateral displacement, combined vertical and lateral load, bending moment, layered sand*

1. Introduction

Pile foundations are being increasingly used in various structural projects like high-rise buildings, offshore structures, harbors, bridges and earth retaining structures. These foundations pass through different layers of the soil with varying properties and are often subjected to vertical and lateral loads acting simultaneously. There are number of factors like direction of load, pile dimensions and stiffness, soil properties, arrangement and number of piles in a group etc., which affect the performance of these foundations.

Considerable research has been reported to study the behavior of laterally loaded piles using p-y method and continuum approach [1-5]. Studies were attempted to analyze the effect of layered soils on the lateral capacity of piles [6-8]. Limited numbers of experimental and finite element analyses have been reported for study of behavior of pilefoundations under combined vertical and lateral load [9-10]. Lee et al [11] reported on the basis of experimental study of model piles driven in sand that the presence of axial load is detrimental to the lateral capacity of piles as lateral displacement of pile head and bending moment increase in the presence of axial load. Contrary to this, presence of vertical loading causing slight increase in the lateral capacity of free headed piles embedded in sand was reported by Hussein et al through finite element modeling [12-13]. This increase was accredited to the increase in confining pressure in the sand because of the presence of vertical load. Karthigeyan and Rajagopal [14] reported on the basis of finite element analysis that the combined loading increases the lateral capacity of the pile group embedded in homogeneous sand and the influence depends on the sequence of loading and center to center spacing between the piles. Findings from a series of model tests reported by Xu, Huang and Rui [15] indicated that the lateral deflection decreases and bending moment increases with increase in vertical load on pipe piles embedded in standard and coral sand. However, on the contrary, Hazzar et al. [16] reported through finite differences modeling that the lateral resistance of piles is not influenced with the presence of vertical load in homogeneous sand. From the above discussion, it is clear that there are contradictions in the literature reported onthe influence of vertical load on lateral behavior of pile foundations. Moreover, most of the available literature on piles under combined load is limited to the pileswith aparticular stiffness embedded in homogeneous sand. There are limited or no data available in the literature which deals with the response of free-head piles of different stiffness characteristics, embedded in layered sands with different group arrangements under combined vertical and lateral load.

In view of the above mentioned issues, this paper presents the results of a series of model tests performed on single and group piles embedded in two layered sandy strata with different relative density in soil layers and subjected to pure lateral load as well as combined vertical and lateral load. Different pile lengths were used in this study to analyze the variation in lateral response of piles with change in their stiffness characteristics. The experimental test results were validated with numerical analysis performed with finite element method based software Plaxis 3D. Resultsare presented here in the form of load-displacement curves and bending moment profiles. Equations derived for the relationship of lateral displacement with ratio of vertical load to lateral load, and angle of inclination of resultant load with vertical are also presented in this paper. An expression developed for pile lateral capacity under combined load in terms of different parameters considered in the study is also presented here.

2. Experimental Study

Model tests were performed in a tank with internal dimensions 2m length x 2m width x 1m depth. The dimensions of the tank were chosen to minimize the boundary effects on the performance of the model piles. Influence of the tank base was minimized by keeping the thickness of the soil below the pile tip more than forty times the pile diameter (D). Tests were performed on single as well group piles arranged in pattern of 2x1 and 3x1 running parallel to direction of lateral load. Center to center spacing between the piles in a group was kept equal to three times pile diameter. Experimental test series was conducted in three phases. In first phase, single as well as group piles were tested under lateral load. Vertical pile load tests were performed in second phase and the load - settlement curves obtained from these tests were used to find ultimate vertical load carrying capacity of the piles. In the third phase, piles were tested under combined vertical and lateral load. For combined load tests, safe vertical load equal to 50% of ultimate vertical load carrying capacity as per IS 2911 Part 4: 2013 [17] was applied on the pile head prior to the application of lateral load increments.

2.1 Sand bed preparation

Particle size distribution curve and representative properties of the sand used in the model tests are given in Figure 1 and Table 1 respectively. Grain size effects were minimized as the ratio of pile diameter to the mean grain size (D/d50) in this study was 31.75 which was more than 25 as suggested by Ovesen [18]. Two layered sand bed was prepared using dry sand of two different relative densities. Prepared test bed consisted of 150mm thick upper layer and 850mm thick bottom layer. The required density in a particular layer was achieved by dropping sand from a movable spreader from a predetermined height using rainfall technique. Height of the spreader above the surface of the sand was varied from 50mm to 400mm. The required relative densities of 65% and 80% were achieved with free fall of 50 mm and 350mm respectively.

Table 1.Properties of Sand

Property	Units	Value
Specific gravity, G	--	2.64
Coefficient of uniformity, C_u	--	2.45
Coefficient of curvature, C_c	--	0.98
Minimum density	g/cc	1.59
Maximum density	g/cc	1.86
Classification	--	Poorly graded sand (SP)
Relative density of sand in upper layer	%	65
Relative density of sand in bottom layer	%	80
Unit weight of sand in upper layer, γ_u	kN/m^3	17.29
Unit weight of sand in bottom layer, γ_b	kN/m^3	17.70

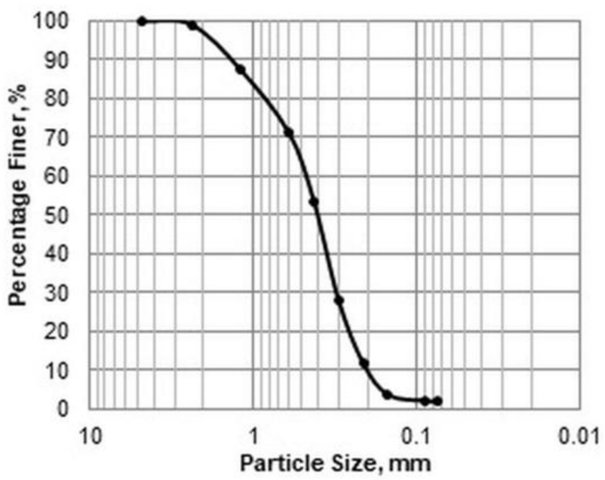


Figure 1. Particle Size Distribution Curve of Sand

2.2Model pile and instrumentation

Stainless steel pipes with 12.7 mm outer diameter (D) and 0.4 mm thickness were used as the model piles. Pile embedment length (L) was varied to have L/D ratio equal to 15, 20, 25 and 30. Modulus of elasticity of the model piles was determined through three point bending test and was equal to $1.5x10^5$ N/mm^2. Model pile was instrumented using foil type strain gauges of 120Ω resistance, gauge factor 2.1 and 5mm length which were fixed at three different locations along the pile length. Strain gauges were fixed at one-third and two-third of pile length from surface and at 5mm from pile base. Three linear variable differential transducers (LVDTs) were used to measure the lateral displacement of the pile head. Strain gauges and LVDTs were connected to a computer system through data logger. Bending moment was calculated from measured strain readings using a constant multiplier obtained from data of a three point bending test conducted on instrumented pile for calibration of strain gauge readings and bending moment. Lateral load was applied to the pile head with the help of a loading frame consisting of pulley and steel wire arrangement using slotted weights and hanger. Vertical load was applied through a pile cap carrying weights placed centrally over it. In the vertical load tests, load was applied through a hydraulic jack and was measured with help of S-shaped load cell. Three dial gauges were used to measure vertical settlement.Summary of the test series is given in Table 2. Schematic diagram of model test setup for combined vertical and lateral loading on single pile is shown in Figure 2. Vertical load used in combined load tests for various pile lengths is tabulated in Table 3.

Table 2.Model Test Series

Load application	Pile arrangement	Pile length, L (mm)	Pile embedment ratio (L/D)	Ratio of thickness of top layer of sand to pile length (h/L)
Lateral Load (LL), Vertical Load (VL), Combined Vertical and Lateral Load (CL)	Single Pile, Group 2x1, Group 3x1	191, 254, 318, 381	15, 20, 25, 30	0.79, 0.59, 0.47, 0.39

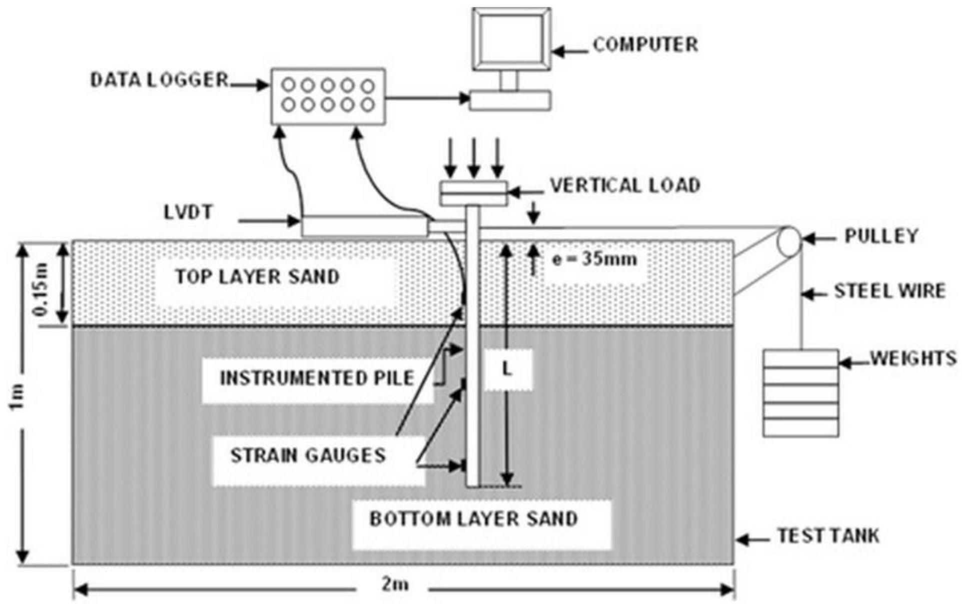


Figure 2. Schematic Diagram for Combined Load Test on Single Pile

Table 3. Vertical Load Used in Combined Load Tests

L/D	Vertical load applied in combined load tests (N)		
	Single Pile	Group 2x1	Group 3x1
15	75	170	275
20	103	215	325
25	120	245	350
30	148.5	300	450

Criteria for stiffness characteristics of pile foundations as suggested by Matlock and Reese [19] and as per IS2911Part1/Sect1:2010 [20] was used to understand flexibility behavior of piles based on their embedded lengths. Value of coefficient of subgrade reaction (η_h), characteristic length of pile (T) and L/T for various pile lengths is given in Table 4. As per the criteria used, for L/T ≤ 2, pile behave as short rigid pile and for L/T ≥ 4, pile behave as long flexible pile. Intermediate values of L/T will indicate pile behavior between rigid and flexible. In the present study, pile lengths with L/D ratio 15 and 20 were classified as intermediate piles (IP) and those with L/D ratio 25 and 30 were classified as long flexible piles (LP).

Table 4. Stiffness Parameters of Model Piles

Parameter	Units	Value			
Flexural rigidity, EI	N/mm^2	$438.9*10^5$			
Coefficient of subgrade reaction , η_h	MN/m^3	20			
Characteristic length of pile, $T = \sqrt[5]{EI/\eta_h}$	mm	73.84			
L/D	--	15	20	25	30
Embedded length of pile, L	mm	191	254	318	381
L/T	--	2.58	3.44	4.3	5.16
Pile Classification		IP	IP	LP	LP

3. Numerical analysis

For the purpose of numerical analysis and validation of experimental results, geometry models were created and analyzed using Plaxis 3D 2012. Finite element models were generated with the same dimensions as used in the experimental tests. Mohr–Coulomb model was used to define the soil properties. This model requires five parameters to define strength and stiffness characteristics of the soil namely Modulus of Elasticity i.e. stiffness (E'), Poisson's ratio (ν'), Cohesion (c'), Friction angle (φ') and Dilatancy angle (ψ). Value of modulus of elasticity obtained in drained triaxial test under a cell pressure of 100kN/m^2 for top layer and bottom layer sand was 25000kN/m^2 and 39000kN/m^{2}respectively. However, confining pressure in the sand layers varies linearly with depth, which indicates that the use of constant value of stiffness modulus in the numerical modeling would produce higher strength results than the actual strength obtained in the experimental testing. So, stiffness of the sandwas modeled as uniformly varying with depth by using an appropriate value of increment of stiffness per unit depth,E'_{inc} [21]. Stiffness at any depth z, (E'_Z) is calculated using the equation 1.

$$E'_z = E'_{ref} + (z_{ref} - z) \times E'_{inc} \qquad z < z_{ref} \tag{1}$$

Where, z_{ref} is the datum level. For any z coordinate above z_{ref}, value of stiffness is equal to E'_{ref}.

To choose values of $E'_{ref}$and $E'_{inc}$for numerical analysis, firstly depth z at which the confining pressure would be equal to 100kN/m^2 was calculated using relationship between unit weight of soil (γ) and vertical confining pressure at any depth z below the surface, $\sigma_z = \gamma z$. Equation (1) was used to calculate value of E'_{inc} for a specific soil layer by using value of E'_z equal to modulus of elasticity as determined in triaxial test and z_{ref} was taken as top surface of the sand layer. Value of E'_{ref} for the top sand layer was assumed and E'_{inc} for top layer was calculated by dividing the difference between $E'_z$and E'_{ref} by depth z corresponding to confining pressure of 100kN/m^2. Value of $E'_{ref}$for the bottom layer was taken equal to E'_z calculated at the base of the top layer. To finalize the value of $E'_{ref}$and E'_{inc}, several trials with different values of soil stiffness were run for the case of laterally loaded single and group piles with L/D ratio equal to 25. The load – displacement curve obtained from the finite element analysis of each trial was compared to the curves obtained in the experimental study. The parameters, which produced the most compatible results with respect to the experimental results, were selected to be used for the rest of numerical analysis.

Unit weight of sand and angle of friction as determined in the lab tests were assigned to both the layers. However, Poisson's ratio, cohesion, dilatancy angle and strength reduction factor (R_{inter}) were assigned as per the Plaxis manuals and data available in the literature [21-22]. Dilatancyangle is calculated from the relation as given in equation 2.

$$\text{For } \varphi > 30°,\ \psi \approx \varphi - 30° \quad and \quad For\ \varphi \leq 30°,\ \psi = 0 \tag{2}$$

The drainage behavior was selected as drained. This behavior is selected for dry soils and for highly permeable sands. No excess pore pressure is generated in this behavior. Properties assigned to sand in both the layers are given in Table 5. Table 6 shows properties assigned to model pile and pile cap. Both the lateral and combined loads were applied using point load option. After generating finite element mesh, calculation process was run in stage construction mode in which calculation process is divided into number of calculation phases defined in a particular sequence in accordance with the actual experimental testing.

Table 5. Properties Assigned to Sand in Numerical Analysis

Property	Units	Value	
		Top layer sand	Bottom layer sand
Material model	-	Mohr-Coulomb	Mohr-Coulomb
Drainage type	-	Drained	Drained
Dry unit weight, γ_{unsat}	kN/m^3	17.29	17.7
Saturated unit weight, γ_{sat}	kN/m^3	18.0	18.4
E'_{50}	kN/m^2	25000	39000
E'_{ref}	kN/m^2	200	843.2
z_{ref}	m	0	-0.15
E'_{inc}	kN/m^2/m	4288	6934
Poisson's ratio, ν	-	0.3	0.3
Cohesion, c'	kN/m^2	0.3	0.3
Angle of friction, φ'	°	30	34.6
Dilatancyangle, ψ	°	0	4.6
Strength reduction factor, R_{inter}	-	0.67	0.67

Table 6.Properties Assigned to Model Pile and Pile Cap

Property	Units	Value	
		Model pile	Pile cap
Modulus of elasticity, E	kN/m^2	150*10^6	200*10^6
Unit weight, γ	kN/m^3	73.37	78.5
Type	-	Circular Tube	Plate
Diameter	m	0.0127	-
Thickness	m	0.0004	0.004
Poisson's Ratio	-	-	0.265

4. Results and discussion

4.1 Numerical model verification

The numerical model was verified by comparing results of Plaxis 3D analysis and experimental results in the form of lateral load – displacement curves. A good match between experimental and numerical curves was found. Typical experimental and numerical curves for single and group piles with L/D ratio 30 under combined load are shown in Figure 3.

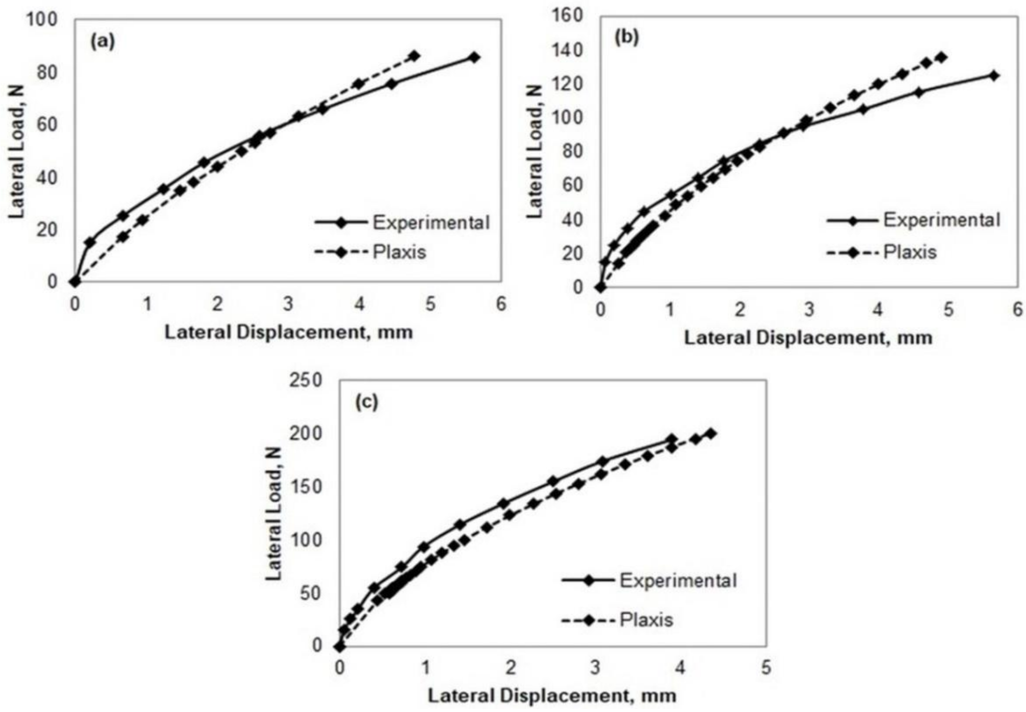


Figure 3. Comparison of Experimental and Numerical Analysis Curves of Combined Load Testfor (a) Single Pile, (b) Group 2x1 and (c) Group 3x1with L/D Ratio 30

4.2 Effect of presence of vertical load on lateral capacity

Typical lateral load-displacement curves obtained from model tests and numerical analysis of single and group piles with L/D ratio 15 and L/D ratio 25 under lateral load and combined load are shown in Figure 4 and Figure 5 respectively.

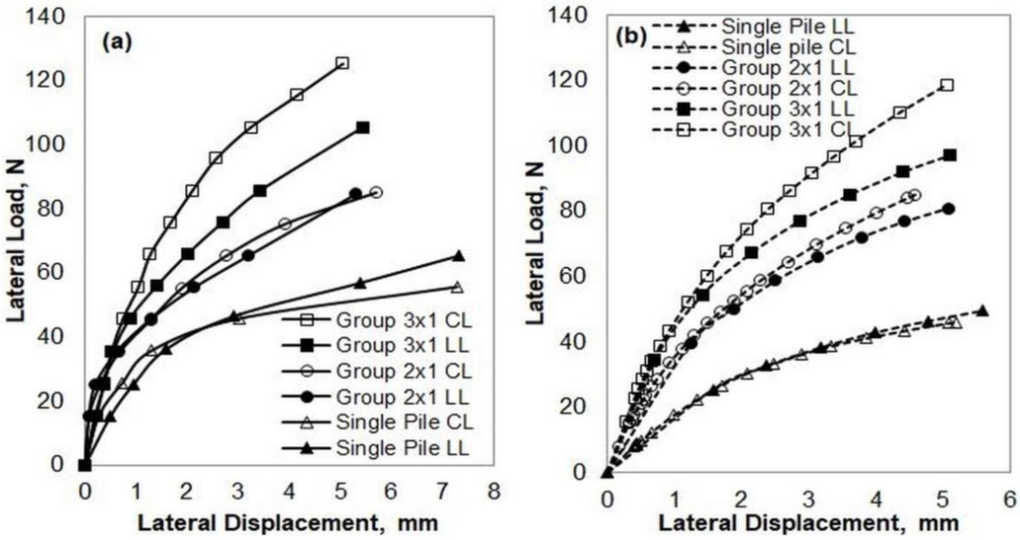


Figure 4. Lateral Load – Displacement Curves of Single and Group Piles with L/D Ratio 15 under Lateral Load and Combined Load from (a) Experimental and (b) Numerical Analysis

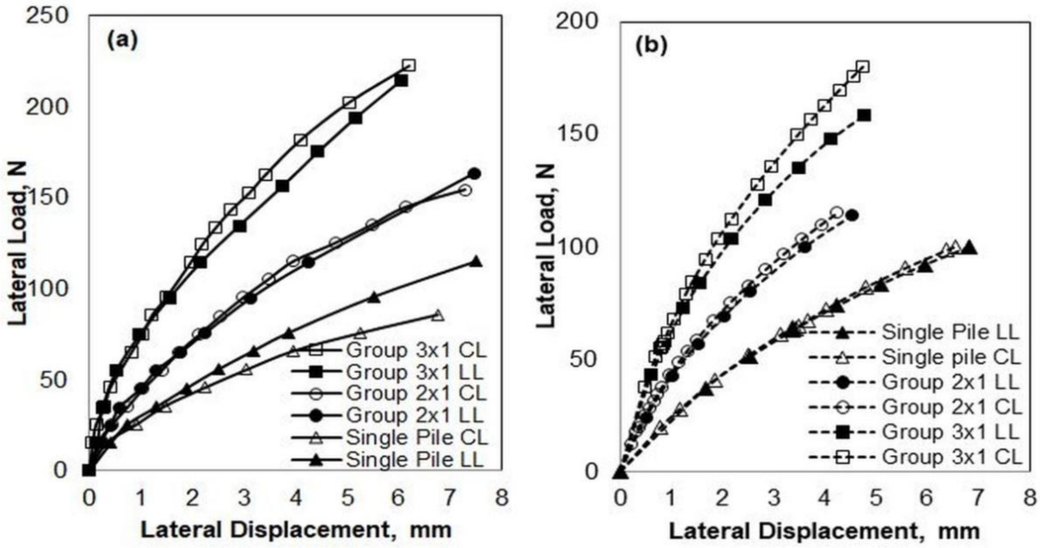


Figure 5. Lateral Load – Displacement Curves of Single and Group piles with L/D Ratio 25 under Lateral Load and Combined Load from (a) Experimental and (b) Numerical Analysis

The trends of the experimental curves clearly indicate difference of lateral deformation behavior of single and group piles in the presence of vertical load. Presence of vertical load causing a reduction in lateral capacity of single pile and an increase in the lateral capacity of group 3x1 piles is visible from the experimental curves. Whereas, a marginal increase in lateral capacity is noted for group 2x1 piles. It is also noticeable that the effect of vertical load on lateral capacity is not constantly same; rather it varies with the lateral displacement and also changes with the pile length. To quantify these observations, effect of combined load is expressed in terms of lateral capacity ratio (LCR) calculated as per equation 3.

$$LCR = \frac{P_{CL}}{P_{LL}} \quad (3)$$

Where, P_{CL} is lateral capacity of piles under combined vertical and lateral load at a particular value of lateral displacement and P_{LL} is lateral capacity of piles under pure lateral load at the same lateral displacement.

Variation in value of LCR with the change in lateral displacement for single pile and group 3x1 is plotted in Figure 6. The trends of the curves show a continuous reduction in LCR value with increase in lateral displacement for both types of pile arrangement with initial values of LCR more than 1. This initial increase may be attributed to the increased stiffness of sand because of presence of vertical load. However, lateral displacement increases due to the additional bending moment caused by the vertical load which results in decreased lateral capacity of the piles. This effect is more predominant in long flexible piles resulting in smaller values of LCR. LCR of group 3x1 for all pile lengths is greater than 1. More improvement is observed in smaller pile lengths of intermediate stiffness characteristics with LCR value ranging from 1.2 to 1.4. For single piles, value of LCR is more than 1 only at small displacements (< 10 % of pile diameter in flexible piles and < 20 % of pile diameter in intermediate piles). These trends clearly indicate that the presence of vertical load is more detrimental for lateral capacity of flexible piles. Value of LCR for group 2x1 varies from 0.9 to 1.01 indicating marginal effect of vertical load on lateral capacity. The adverse effect of presence of vertical load on lateral capacity is observed to be decreasing with increase in number of piles in the group. This may be due to increase in the surface area of pile group and increased density of the sand between the piles producing greater lateral stiffness as compared to that in case of single pile.

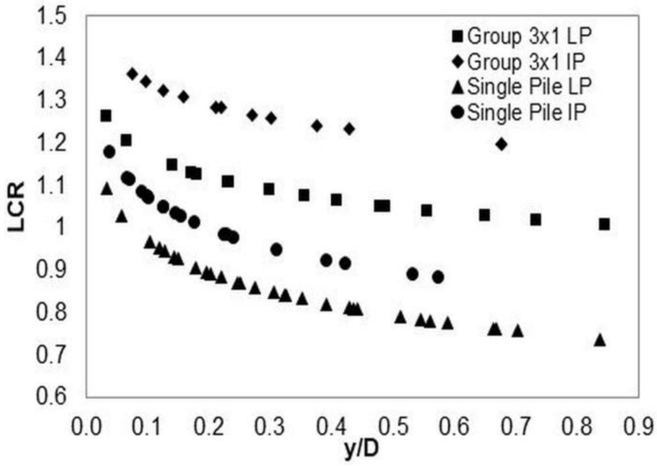


Figure 6. Variation in LCR with Change in Lateral Displacement

The results of finite element analysis also indicated an increase in LCR value with increase in number of piles. LCR value obtained from numerical analysis at displacement equal to 20% of pile diameter is around 1.0 for single piles representing negligible effect of vertical load on lateral capacity. For group piles, its value ranges from 1.05 to 1.14 with maximum value for Group 3x1. The observed results show that LCR is function of number of factors namely lateral displacement, number of piles in the group, embedded length of pile and thickness of upper sand layer. A generalized expression was derived for LCR in terms of normalized displacement (y/D), number of piles in group (n), ratio of top layer thickness to pile length (h/L) and L/D ratio as presented in equation 4.

$$LCR = \{0.9639 - 0.1373\, ln(y/D)\}(1.1325)^{n}(0.7960)^{\frac{h}{L}}(0.9895)^{\frac{L}{D}} \quad (4)$$

Value of P_{CL} was calculated using equation 3 and equation 4. A good agreement was found between predicted results and experimental data as shown in Figure 7. An average error of 0.67 % was observed.

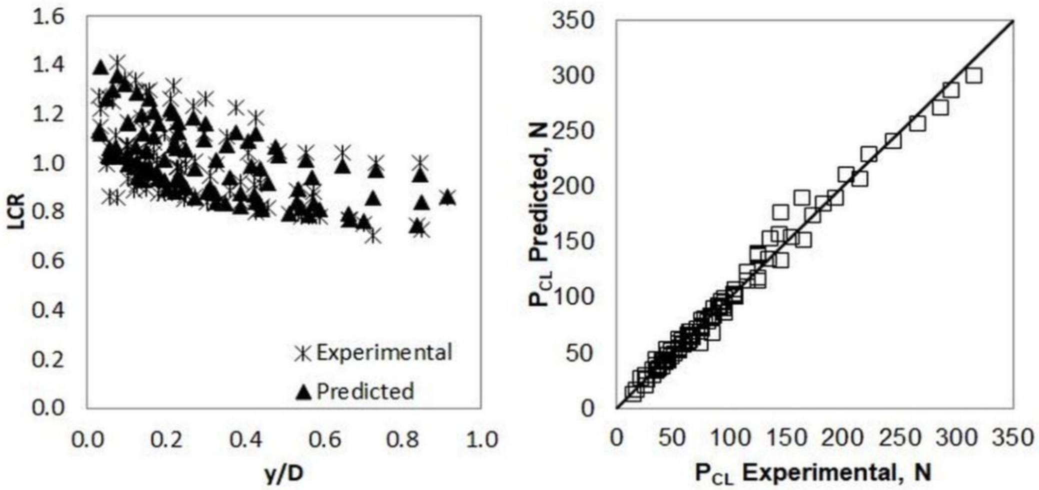


Figure 7.Comparison of Experimental and Predicted Results

4.3 Variation in lateral displacement with change in VL/LL ratio

In order to study the relative effect of vertical load and lateral load on lateral performance of piles, variation in lateral displacement was compared to the variation in ratio of vertical load to lateral load (VL/LL). Curves plotted between y/D and VL/LL indicated that the relationship between these two parameters is governed by a power law with general form as given in equation 5.

$$^{y}/_{D} = a\left(\frac{VL}{LL}\right)^{b} \tag{5}$$

Where, a and b are constants. Generalized equations for the relationship between y/D and VL/LL for single and group piles were obtained using generalized reduced gradient method to get minimum value of sum of squared residuals (SSR). Figure 8 shows the observed and predicted curves of single and group piles from experimental results. Values of constants a, b and corresponding values of SSR for single and group piles obtained from experimental and numerical analysis are given in Table 7.The predicted curves for both experimental and numerical analysis were found to be fairly agreeing with each other as shown in Figure 9.It was observed that for group piles, lateral load causing pile head displacement equal to 0.2D is about one-third of vertical load. For single pile, value of VL/LL corresponding to lateral displacement 0.2D is about 2.3. It is visible from the obtained curves that increase in the value of VL/LL beyond 3 does not affect the lateral displacement much. However, for VL/LL smaller than 3, displacement increases to a great extent even with a minor change in value of VL/LL, which clearly indicates failure of the piles. It was observed that the lateral load causing lateral displacement equal to 20% of pile diameter in the presence of vertical load varies from 30% to 40% of vertical load.

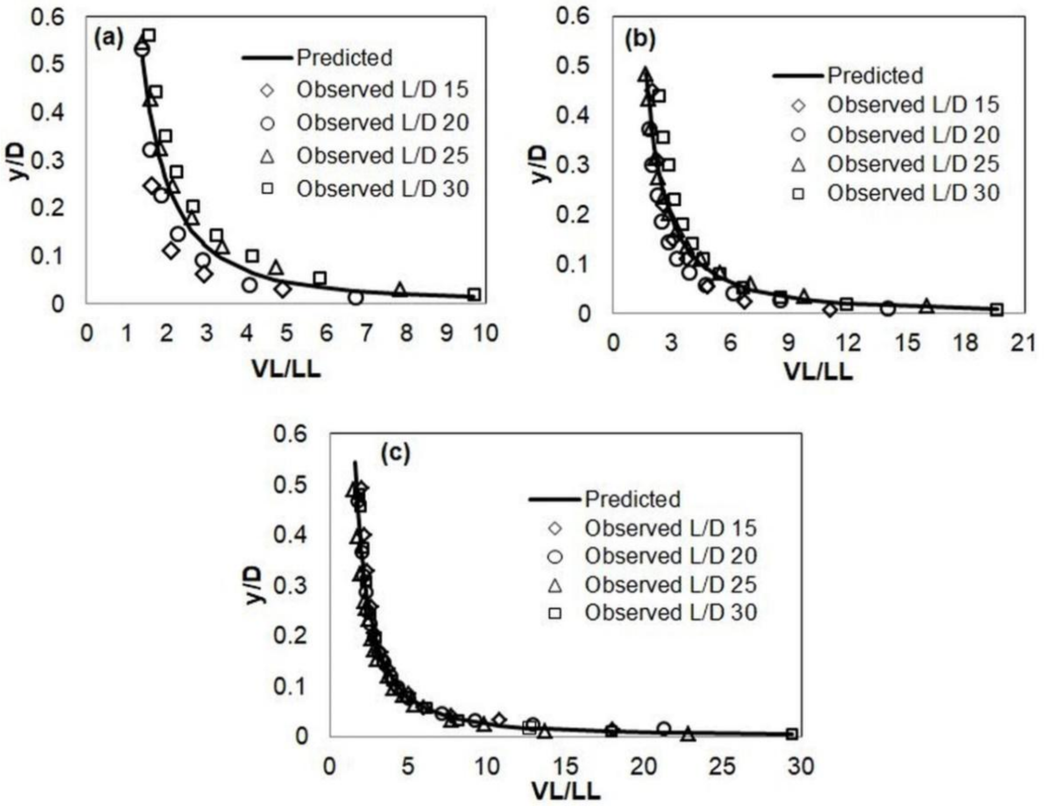


Figure 8. Predicted and Observed Trends of Experimental Data for Variation of y/D with Change in VL/LL for (a) Single pile, (b) Group 2x1 and (c) Group 3x1

Table 7. Constants and SSR Valuesofthe Generalized Equation between y/D and VL/LL for Single and Group Piles from Experimental and Numerical Analysis Results

Pile arrangement	Experimental results			Numerical analysis		
	a	b	SSR	a	b	SSR
Single Pile	0.8334	-1.725	0.08	0.658	-1.34	0.03
Group 2x1	1.1416	-1.63	0.09	0.986	-1.466	0.05
Group 3x1	1.1621	-1.676	0.06	1.1186	-1.422	0.08

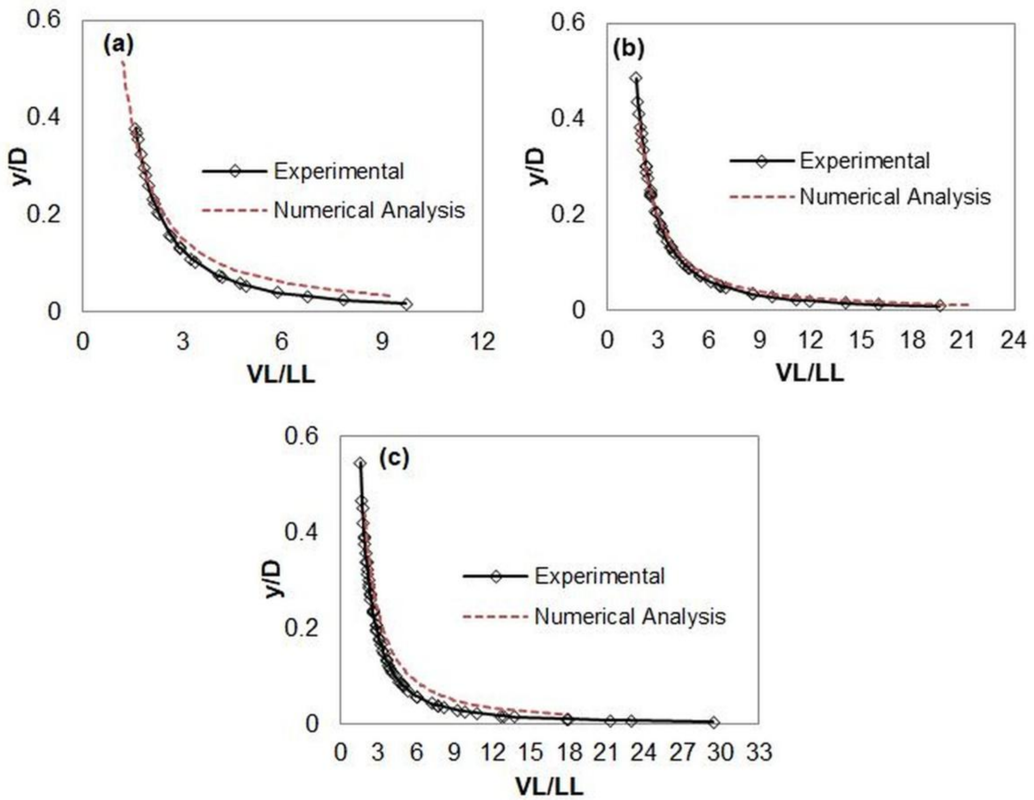


Figure 9. Comparison of Predicted Relationship between y/D and VL/LL from Experimental and Numerical Analysis for (a) Single pile, (b) Group 2x1 and (c) Group 3x1

4.4 Effect of direction of resultant load on lateral displacement

To analyze the effect of resultant load's direction, equations for normalized lateral displacement y/D in terms of inclination of resultant load with the vertical (θ) were obtained. Figure 10 shows observed and predicted curves for single and group piles from experimental results data. Trends of the curves indicate increase in lateral displacement with increase in θ. The general form of the observed relationship between y/D and θ is given in equation 6.

$$y/_{D} = c\,(\theta)^{d} \qquad (6)$$

Where, c and d are coefficients. Values of these coefficients and corresponding values of SSRfor the obtained generalized expressionfor the relationship between y/D and θ for single and group piles are given in Table 8. Predicted curves from both the experimental and numerical results are compared in Figure 11 which shows that the results from both the analyses are in good agreement.

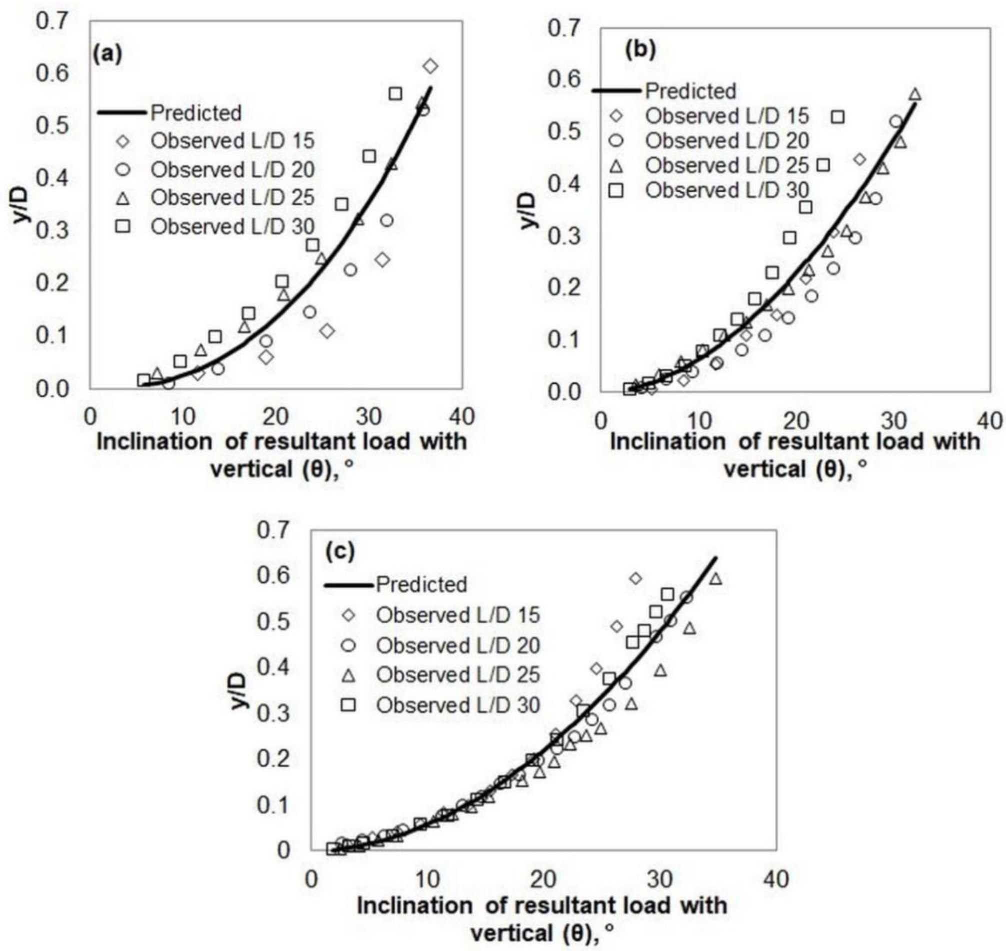


Figure 10 Predicted and Observed Trends of Experimental Data for Variation of y/D with Change in θ for (a) Single pile, (b) Group 2x1 and (c) Group 3x1

Table 8.Constants and SSR Values for the Generalized Equation between y/D and θfor Single and Group Piles from Experimental and Numerical Analysis Results

Pile Arrangement	Experimental Results			Numerical Analysis		
	c	d	SSR	c	d	SSR
Single Pile	0.0001	2.3886	0.107	0.0015	1.5795	0.036
Group 2x1	0.0009	1.8537	0.131	0.002	1.5715	0.048
Group 3x1	0.0007	1.9337	0.104	0.0029	1.5144	0.081

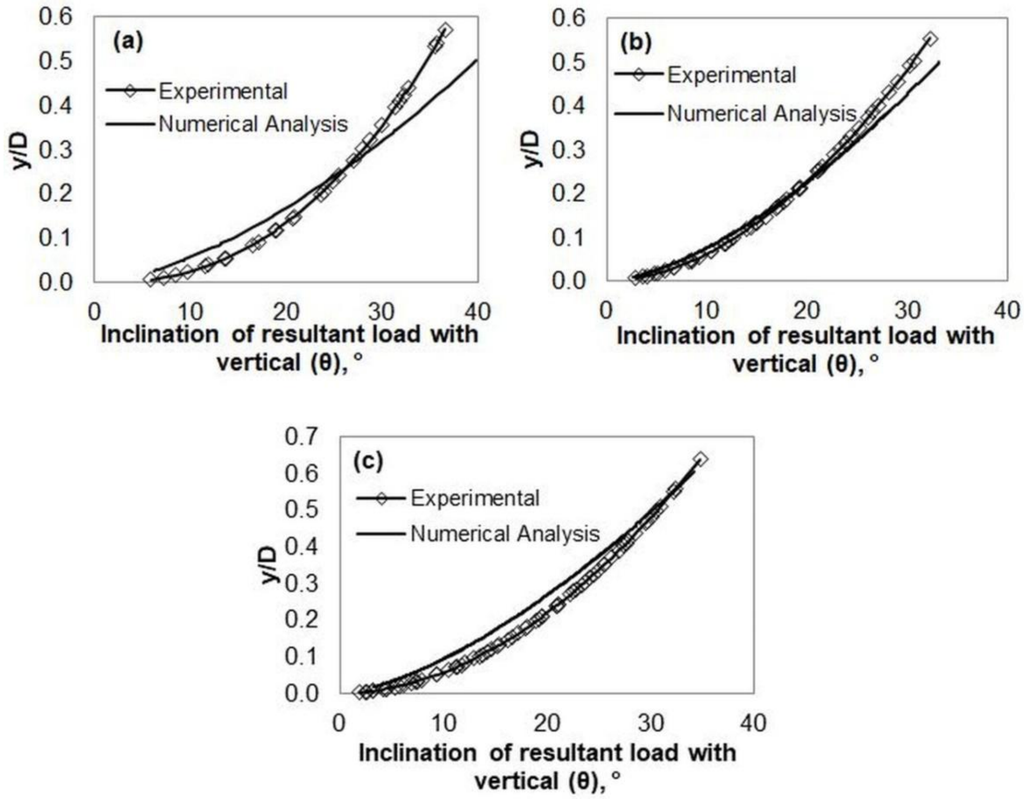


Figure 11. Comparison of Predicted Relationship between y/D and θ from Experimental and Numerical Analysis Results for (a) Single pile, (b) Group 2x1 and (c) Group 3x1

4.5 Effect of presence of vertical load on bending moment

Comparison between bending moment profile for single pile with L/D ratio 25 under lateral load and under combined load is shown in Figure 12. Trends of the curves clearly show that the combined vertical and lateral load results in larger bending moment in single pile as compared to that under pure lateral load. Variation in maximum bending moment at various load levels under combined load and lateral load for single pile with L/D ratio 25 and L/D ratio15 is shown in Figure 13. These results agree with the observations reported by Chatterjee et al. [23] that bending moment and normalized deflection of a single pile embedded in layered sand increases when vertical compressive load on the pile increases.

Results observed for group 2x1 piles indicated that the presence of vertical load causes marginal variation in bending moment in piles at smaller loads. However with increase in lateral load, larger bending moments are produced in the piles under combined vertical and lateral load as compared to those under pure lateral load. Variation in maximum bending moment of front and rear pile of group 2x1 with L/D ratio 25 and L/D ratio 20 under lateral load and combined load is shown in Figure 14. Bending moment distribution for front and rear piles of group 2x1 with L/D ratio 25 under lateral load and combined load is shown in Figure 15.

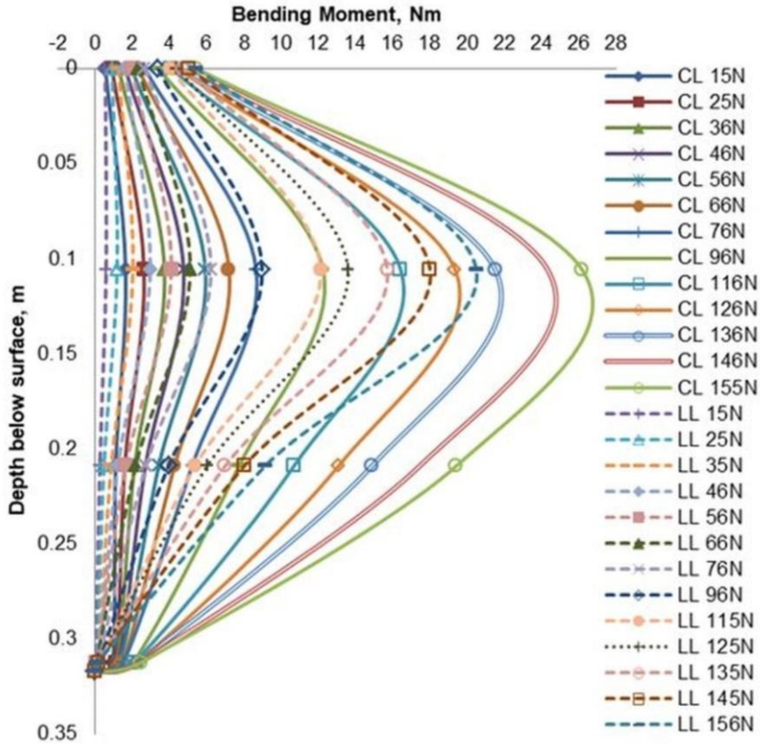


Figure 12.Bending Moment Distribution in Single Pile with L/D Ratio 25 under Lateral Load and Combined Load

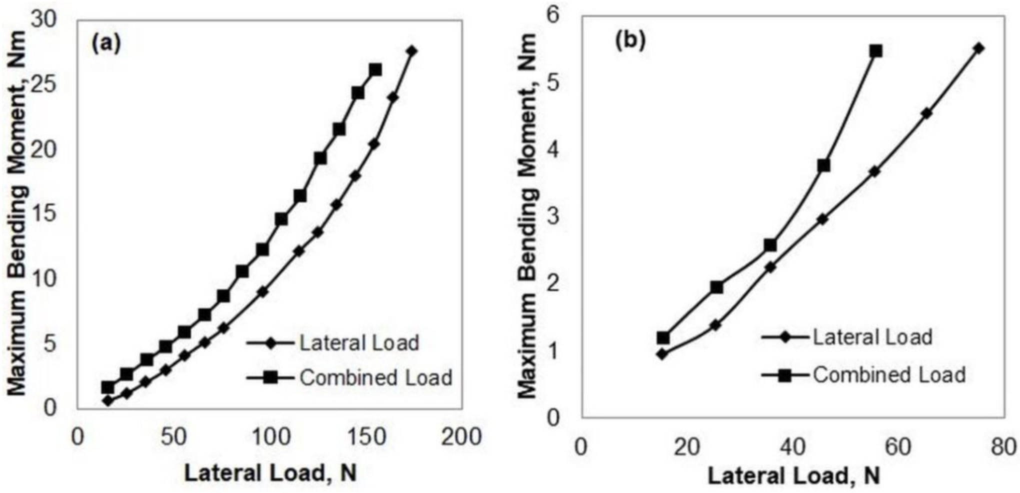


Figure 13. Variation in Maximum Bending Moment in Single Pile under Lateral Load and Combined Load for (a) L/D ratio 25 and (b) L/D ratio 15

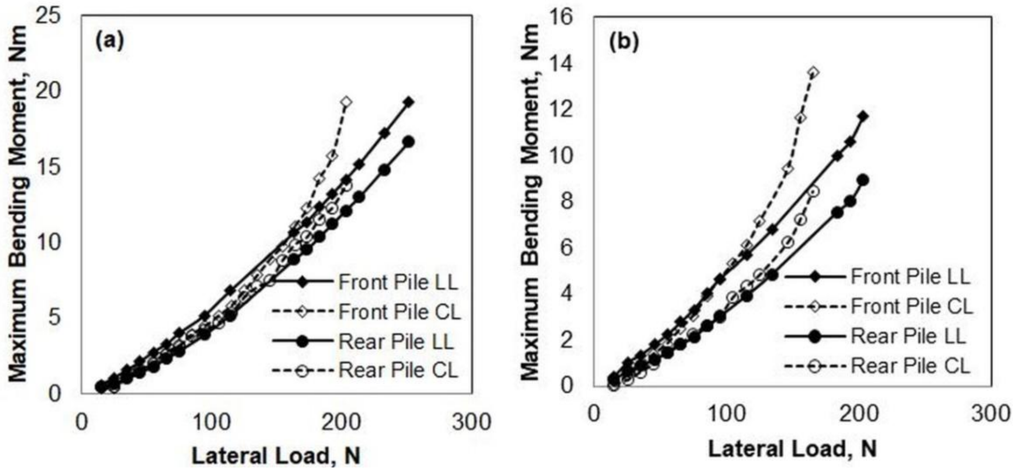
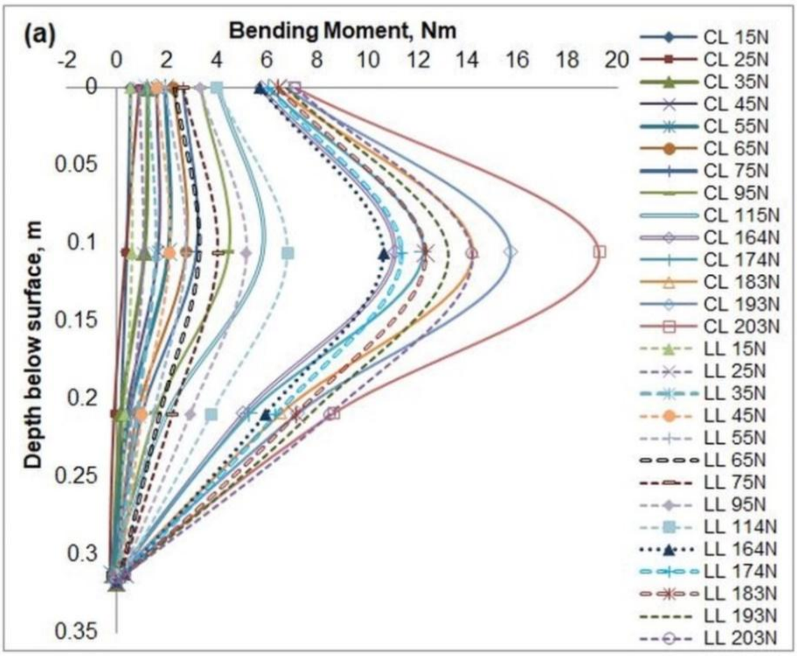


Figure 14. Variation in Maximum Bending Moment in Group 2x1 Piles under Lateral Load and Combined Load for (a) L/D Ratio 25 and (b) L/D Ratio 20

In group 3x1, maximum bending moment was found to be decreasing in the presence of vertical load in all the piles of the group. Figure 16 shows the variation of maximum bending moment under lateral load and combined load for group 3x1 with L/D ratio 30. Percentage variation in maximum bending moment in single and group piles with L/D ratio 25 under load corresponding to lateral displacement 0.2D is given in Table 9. Decrease in bending moment of group piles is accredited to the increased lateral capacity in the presence of vertical load causing smaller lateral displacements in the piles. Due to smaller displacements, there is a notable reduction in corresponding strains which results in reduced bending moments in the group piles in the presence of vertical load.



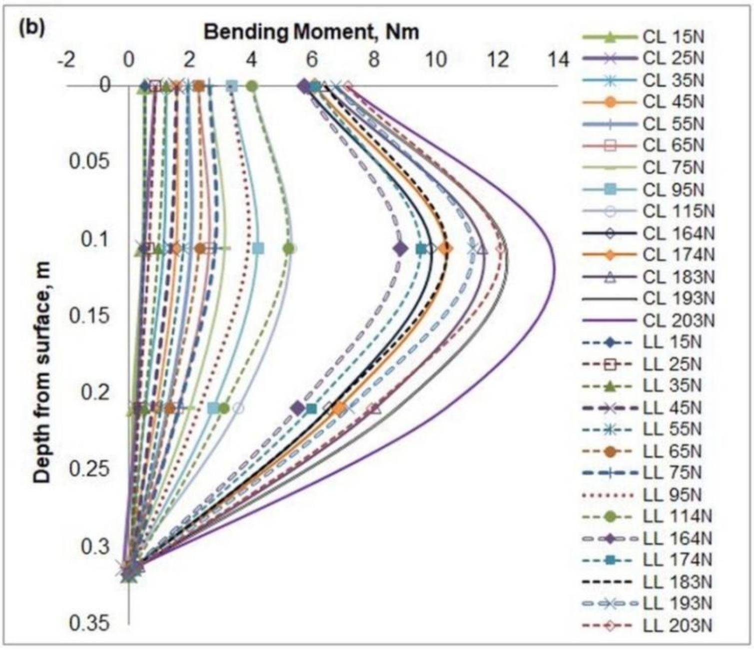


Figure 15. Bending Moment Profile in Group 2x1 Piles with L/D 25 under Combined Load and Lateral Load for (a) Front Pile and (b) Rear Pile

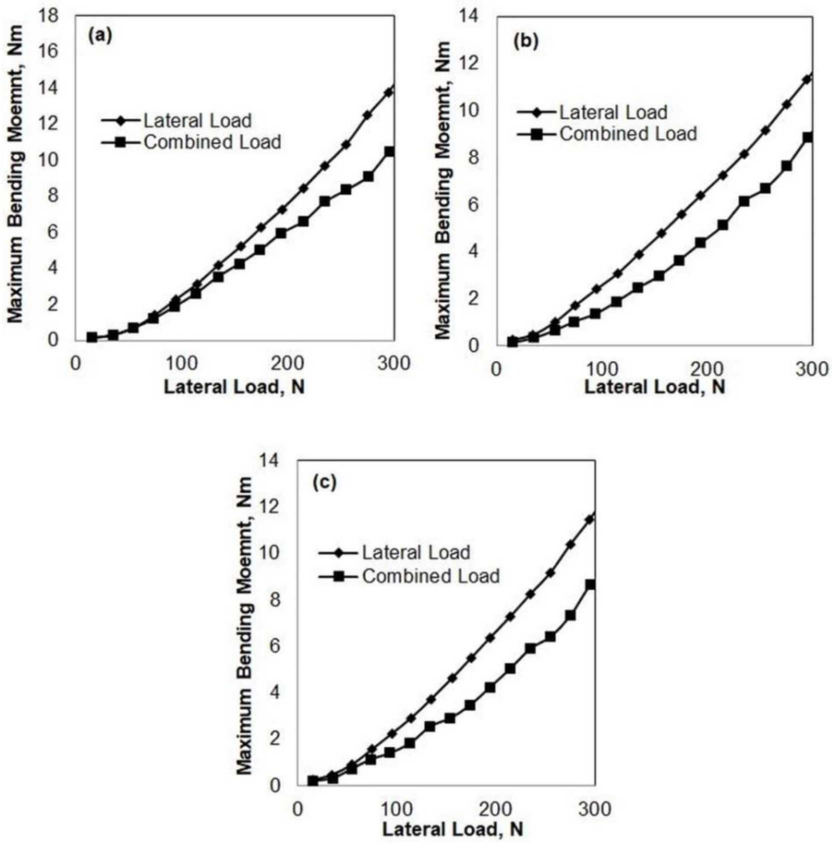


Figure 16.Variation in Maximum Bending Moment in Group 3x1 Piles with L/D Ratio 30 under Lateral Load and Combined Load for (a) Front Pile, (b) Middle Pile and (c) Rear Pile

Table 9. Variation in Maximum Bending Moment at Lateral Displacement 0.2D in Piles with L/D ratio 25 under Combined Load

Pile Arrangement	Lateral Load (N)	Position of Pile in Group	Bending Moment under Lateral Load (Nm)	Bending Moment under Combined Load (Nm)	Variation in Bending moment (%)
Single Pile	46	-	2.95	4.74	60.6
Group 2x1	75	Front Pile	4.02	3.16	-21.2
		Rear Pile	2.82	3.13	11
Group 3x1	134	Front Pile	3.99	3.79	-4.96
		Middle Pile	3.32	3.14	-5.43
		Rear Pile	2.66	2.45	-7.71

5. Conclusions

An experimental test series was conducted on free headed laterally loaded single pile and pile groups with 2x1 and 3x1 pattern, embedded in two-layered sand with different relative densities in the layers. Effect of presence of vertical load on lateral response of piles was studied by applying a vertical load equal to 50% of ultimate vertical load carrying capacity of the piles in addition to lateral load. Experimental results were validated through numerical analysis performed using finite element based Plaxis 3D software. It is concluded that the variation in lateral capacity of piles in the presence of vertical load depends on number of factors including lateral displacement, number of piles in the group, ratio of pile length to pile diameter and ratio of sand layer thickness to pile length. Presence of vertical load causes increase in lateral capacity of single pile at small displacements only and it causes reduction in lateral capacity at larger displacements. Lateral capacity of group piles increases in the presence of vertical load.Lateral capacity ratio for all pile arrangements reduces with increase in lateral displacement.Value of lateral capacity ratio for longer piles was smaller than the intermediate piles. A generalized expression was derived for lateral capacity ratio in terms of the mentioned parameters. Normalized lateral displacement decreases with increase in ratio of vertical load to lateral load. The relationship between the two parameters is governed by a power law. Lateral load equal to one-third of vertical load causes lateral displacement of 0.2D in group piles. For single piles, lateral displacement of 0.2D occurs at VL/LL equal to 2.3. Increase in the value of ratio of vertical load to lateral load beyond 3 does not affect lateral displacement much. For VL/LL less than 3, large increase in displacement occurs with a small change in VL/LL.Normalized lateral displacement increases with increase in angle of inclination of resultant load with vertical. The observed relationship between these is governed by a power equation. Effect of vertical load on bending moment varies for different pile arrangements. Increase in the bending moment in single piles and decrease in the bending moment in group piles was observed in the presence of vertical load.

Results of numerical analysis agreed fairly with the results of experimental study. Similar expressions for empirical relationships between different parameters were obtained from both the analyses. Derived relationships can be used to predict lateral displacement and ultimate lateral capacity for the given pile dimensions and known vertical and lateral loads. It is to be noted that the proposed relationships are applicable for a particular case of two- layered sand with relative density 65% and 80% in upper and bottom layers respectively. However, these results can be generalized for the cases of large sized piles as used in the field with same stiffness characteristics.

Acknowledgements

The authors are thankful to IKG Punjab Technical University, Jalandhar, Punjab, India and Civil Engineering department of Guru Nanak Dev Engineering College, Ludhiana, Punjab, India for the permission granted to use the research laboratories and Plaxis 3D software required in the study.

References

[1] P. J.Pise andN. R. Patra,"Ultimate lateral resistance of pile groups in sand", Journal of Geotechnicaland Geoenvironmental Engineering, vol. 127, no. 6, **(2001)**, pp.481-487.

[2] L. M.Zhang, M. C.McVay andP. Lai, "Numerical analysis of laterally loaded 3×3 to 7×3 pile groups in sand", Journal of Geotechnicaland Geoenvironmental Engineering,vol. 125, no. 11,**(1999),** pp.936-946.

[3] M.Ashour andG.Norris, "Modeling lateral soil-pile response based on soil-pile interaction"Journal of Geotechnicaland Geoenvironmental Engineering, vol. 126, no. 5, **(2000)**, pp. 420-428.

[4] V. S.Phanikanth andD.Choudhury, "Single piles in cohesionless soils under lateral loads using elastic continuum approach",Indian Geotechnical Journal, vol. 44, no. 3, **(2013)**,pp. 225-33. DOI: 10.1007/s40098-013-0072-4.

[5] Krishnamoorthy, N. B. S.Rao andN.Rao, "Analysis of group of piles subjected to lateral load", Indian Geotechnical Journal, vol. 35, no. 2, **(2005)**, pp.154-175.

[6] R.Li andJ.Gong, "Analysis of Laterally Loaded Pile in Layered Soils" ElectronicJournal of Geotechnical Engineering, vol. 13, no. J, **(2008),** pp.1-16.

[7] B. K.Gupta andD.Basu, "Analysis of laterally loaded short and long piles in multilayered heterogeneous elastic soil", Soils andFoundations, vol. 57, **(2017)**, pp.92–110.

[8] B. T.Kim andG. L. Yoon, "Laboratory modeling of laterally loaded pile groups in sand", KSCE Journal of CivilEngineering, vol. 15, no. 1, **(2010)**, pp.65-75.

[9] A.Kaur, H.Singh andJ. N.Jha, "Experimental study of behavior of free-head flexible piles in two-layered sand under lateral and combined load", Proceedings of 1st International Conference on Sustainable Waste Management through Design, Ludhiana, India, (2018),In Lecture Notes in Civil Engineering, Springer Cham.vol. 21, **(2019)**, pp.116-124. DOI: 10.1007/978-3-030-02707-0_15.

[10] F. Y. Liang, H. B. Chen and S. L. Chen, "Influences of axial load on the lateral response of single pile with integral equation method", International Journal for Numerical and Analytical Methods in Geomechanics, vol. 36, **(2012)**, pp. 1831-1845.

[11] J.Lee, M.Prezzi and R.Salgado, "Experimental investigation of the combined load response of model piles driven in sand", Geotechnical Testing Journal, vol. 34, no. 6, **(2011)**, pp. 653-667.DOI: 10.1520/GTJ103269.

[12] M. N.Hussien, T.Tobita, S.Iai andK. M.Rollins, "Vertical load effect on the lateral pile group resistance in sand response", Geomechanics andGeoengineering, vol.7, no. 4, **(2012)**, pp.263-282.

[13] M. N.Hussien, T.Tobita, S.Iai and M.Karray, "On the influence of vertical loads on the lateral response of pile foundation", Computers and Geotechnics, vol. 55, **(2014)**, pp. 392-403.

[14] S.Karthigeyan andK.Rajagopal, "Lateral response of 2 × 2 pile group under combined axial and lateral loading", Proceedings of Indian Geotechnical Conference, Guntur, India,**(2009)**, pp.665-669.

[15] D. S.Xu, F.Huang and R. Rui, "Investigation of single pipe pile behavior under combined vertical and lateral loadings in standard and coral sands", International Journal ofGeosynthetics and Ground Engineering, vol. 6, no. 20, **(2020)**, DOI: 10.1007/s40891-020-00203-4.

[16] L.Hazzar, M.Hussien andM.Karray, "Influence of vertical loads on lateral response of pile foundations in sands and clays", Journal of Rock Mechanics and Geotechnical Engineering, vol. 9, **(2017)**, pp.291-304.

[17] Indian standard design and construction of pile foundations - code of practice IS 2911 Part 4, Bureau of Indian Standards, New Delhi. **(2013)**,pp. 4.

[18] N. K.Ovesen, "Centrifuge tests of the uplift capacity of anchors", Proceedings of the 10th international conference on soil mechanics and foundation engineering, Stockholm:Balkema Rotterdam, **(1981)**,vol. 10, no. 1, pp.717-722.

[19] H.Matlock, L. C.Reese, "Generalized solutions for laterally loaded piles", Journal of Soil Mechanics and Foundation Division, ASCE,Vol. 86, no. SM5, **(1960)**,pp. 63-91.

[20] Indian standard design and construction of pile foundations - code of practice IS 2911 Part 1/Sec1, Bureau of Indian Standards, New Delhi. **(2010)**, pp. 12-13.
[21] Plaxis3D Material Models Manual, **(2012)**, pp. 34-40.
[22] M. D.Bolton, "The strength and dilatancy of sands", Geotechnique, vol. 36, no. 1, **(1986)**, pp. 65-78.
[23] K.Chatterjee, D.Choudhury andH. G.Poulos, "Seismic analysis of laterally loaded pile under influence of vertical loading using finite element method", Computers and Geotechnics, vol. 67, **(2015)**, pp.172-86.