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Experimental and Numerical Investigations of Laterally Loaded Pile Group in Multilayered Cohesionless soil

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ABSTRACT

This paper presents the results of experimental and numerical analysis of laterally loaded bamboo pipe piles embedded in multilayered cohesionless soil. An experimental investigation on model piles had been carried out using bamboo pipe pile with outer diameter of 24mm and inner diameter of 20mm in a multilayered cohesionless soil. In first case, a loose layer is maintained between the dense layers with H/D ratio of 0.50 and in second case, only dense sand layer of H/D ratio 0.0 is maintained with the depth of 0.0m. Where, H is the depth of middle soil layer and D is the embedment depth of pile of different slenderness (L/d) ratio of 25, 30 and 38. An experiment was carried out to study the behaviour of lateral load on bamboo pipe piles of different slenderness ratio of 25, 30 and 38. The experimental results of first case and second case show that the lateral load – lateral displacement response depends on the slenderness ratio of the piles. The experimental program was further verified by a two dimensional finite-element technique. The experimental results were compared with numerical analysis and are in a close agreement.

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1. Introduction

The deformation behaviour of a single pile subjected to horizontal loads is a well known method for modelling the soil reaction-lateral displacement (p-y) approach. To understand the deformation behaviour of each of the pile in a pile group, subjected to lateral loads or a combination of vertical and lateral loads, it is very essential to know the clear idea of the deformation behaviour of single piles of similar batter under lateral load cases. The behaviour of a single pile is controlled by it's location in the group and it's pile head fixity. The lateral resistance of a pile is influenced by the "shadowing effects" as explained by Brown et al. [1] for both the horizontal subgrade modulus and the ultimate lateral resistance in a group are decreased because of the overlapping of the stress zones in the close soil. In fixed-head pile group, bending moments and shear forces are developed at the pile heads and surrounded by the pile cap. The later were negligible under vertical forces within the piles, which were transfer to skin and tip resistances along each pile. The importance of such limit was studied for both battered and driven pile group in loose sand by McVay et al. [2] to facilitate the characterize both the vertical and horizontal behaviours of piles is essential to model a group response subjected to lateral loads.

Few methods were proposed and implemented to models of lateral group response by Focht and Koch [3] proposed a method that combines the soil reaction-lateral displacement (p-y) approach for single pile by Poulos [4] approach for pile group. They have developed a group amplification procedure based on pile group field tests. Davisson [5] modified the elastic solution to account the non-linearity using yield factors and the modulus of subgrade reaction approach was extended to account for the soil non-linearity. Byung, Nak-Kyung et al.[6] have observed that, testing of the pile embedded in Nak-Dong river sand, located in south Korea, under monotonic lateral loadings. The lateral resistance of piles, effect of the installation methods and pile head restraint conditions were studied. The lateral load is highest in the free head condition and it decreases as the depth increases. Shamsher Prakash and Sanjeev kumar [7] concluded that, the modulus of subgrade reaction depends on the relative density of sands and depth of the ground water-table. Narasimha Rao S. et al. [8] concluded that, results of the lateral load capacity of pile groups depends mainly on the rigidity of pile soil system for different configurations of piles within the group. Chandrasekaran et al. [9] investigated the effects of pile spacing, number of piles, embedment length and configurations on pile-group interaction, the experimental results found that the lateral capacity of piles in nine pile group at three-diameter spacing is about 40% less than that of the single pile and causes 20% increase in the maximum bending moment when compared with a single pile. Salini and Girish [10] concluded the lateral-load capacity of pile group increases as the density of sand increases for the same slenderness ratio. The lateral-load capacity increases with increase in length for same diameter hence passive resistance was mobilized to increase the embedment length of a pile. Mohamedzein et al. [11] found that, the ultimate lateral capacity increases with the increase in slenderness ratio and the pile diameter. It is also observed that, the maximum bending moment (BM) occurs at a depth varying from 0.13 to 0.32L and the bored method of installation gives greater ultimate soil resistance than the pre-installed method for both concrete and steel piles. Sawant and Shukla [12] found that, the pile top lateral deflection and the bending moment (BM) of the pile decreases with an increase in the edge distance from the slope crest. They have been also concluded that, an increase in the ground slope causes the pile deflection and bending moments at any depth of the pile. Mahmoud and Burley [13] observed that, the lateral ratio H/H_{100} and displacement ratio x/B of piles are related in a non-linear fashion. In the analysis of the influence of pile size, the effect of the cross-sectional shape of piles is important. Square piles consistently exhibit greater load capacity than circular piles, although the difference becomes less marked at high displacement ratios. Muthukkumaran [14] investigated that, the horizontal load capacity of the pile, lateral load-lateral displacement response, effect of slopes and embedment length on pile capacity and bending-moment (BM) profile along the pile shaft were studied.

Sundaravadivelu [15] studied the results of laterally loaded pile in soft clay, the iterative procedure was adopted to present a non-linear finite element analysis and the effect of static lateral load on load-deflection behaviour. Kahyaoğlu et al. [16] have analyzed the model of passive piles; the pile spacing gets larger, as the lateral-loads acting on the pile groups are increased. However, for the pile spacing greater than eight times of the diameter spacing's, each pile behave like a single pile without arching effect. The numerical results indicate that the pile spacing increases, as the horizontal-load acting on the soil mass between piles increased. Chae, Ugai and Wakai [17] carried out numerous numerical studies using a 3D finite element model and prototype tests on laterally loaded short rigid piles and pier foundation located near a 30° slope. The lateral resistance of pile was found to be decreasing with the change in location closer to the crest of the slope. Zhao et al. [18] results revealed that, the pile groups adjacent to surcharge load results in a significant lateral movement of soft soil and considerably applies pressure on the pile groups, when the pressure acting on a row near to the surcharge load is higher than that of the other row due to arching effects of pile group. Georgiadis, K and Georgiadis M. [19] carried out 3D finite element analysis to study the behaviour of piles embedded in cohesive soil in sloped ground under the un-drained lateral-loading conditions for a piles of different diameter and lengths were considered. In this analysis, analytical formulations were also derived for the ultimate load per unit length and the initial stiffness of hyperbolic *p–y* curves. Zhang et al. [20] analyzed laterally loaded pile groups in sand, the maximum bending moments (BM) were developed in leading row piles and minimum in the trailing row piles. The lateral pile responses over vertical piles were 4% in very loose, 14% in loose, 24% in medium dense and 50% in dense sands. Bisaws et al. [21] carried out experimental investigation of free-head model piles under lateral load in homogenous and layered sand, in this experimental study supplemented by numerical study to determine co-efficient of horizontal modulus of sub-grade reaction (η_h). Relative density of sand, slenderness ratio and embedment ratio of pile were varied. The numerical results were found considerably well with the experimental ones for both long and short piles in homogeneous and layered sand media. It is observed that for layered medium density sand, η_h increased as the overlying weaker sand layer thickness decreased. For short piles, η_h increased with increase in sand compactness and slenderness ratio of pile. Whereas in case of long piles, it increased with sand compactness and decreased with the slenderness ratio of pile beyond the slenderness ratio as 40. Rathod D. et al. [22] have investigated the effect of slope on soil reaction-lateral displacement (p-y) curves for a laterally loaded pile in soft clay. The results show that the pile top displacement and the bending moment

(BM) in the pile decrease with an increase in the slope. Also increase in the ground slope causes an increase in pile displacement and bending moments at any depth of the pile.

From the earlier study, it is clear that only a few limited research works have been carried out on piles subjected to lateral load in layered cohesionless soil, and the behaviour of pile embedded in multilayered of cohesionles soil requires further study. Hence, this paper aims to fill this gap an experimental investigation is carried out on single pile and pile group embedded in cohesionless soil under static lateral load. The main objective of the present investigation is to study the lateral response of the piles located in multilayered cohesionless soil with different pile configuration and slenderness ratios (L/d 25, 30 and 38) under lateral load, and also to carry out the finite element analysis using “SoilWorks 2D” and comparing the results with experimental values.

2. Experimental investigation

2.1. Experimental set-up

Here experimental investigation of prototype is reduced to a model scale of 1/15 (1/N) scaled model would require that a prototype pipe pile of 14.60m long by 0.36m circular diameter modelled by bamboo pipe pile of 0.973m long (overall length) and 24mm external diameter with 2mm wall thickness was used as a model pile (prototype dimension/N). Figure 1 is the layouts of single and pile group of the model, which was modelled in the experimental investigation at 1/15 scale. The Young’s modulus (E_m=1.617x10^8kN/m^2) and the moment of inertia of the model pile (I_m) determined as 4.787x$10^{-9}$$m^4$ and Poisson’s ratio (μ) as 0.30. The bending stiffness, E_mI_m, of 0.774058kN-m^2. The dimensions of test tank is decided based on the influence zone of soil mass of pile about 10 times the pile diameter in the direction of loading for piles under static lateral load by Poulos [23] and Narasimha Rao et al. [8]. Hence, the static lateral load tests were conducted in a test tank with a dimension of 1850mm x 1850mm x 1522mm placed on a loading platform. The static lateral load was applied by means of dead weights (slotted type) placed on a hanger connected to a flexible steel wire, passed over a frictionless pulley supported by a loading platform as shown in figure 2.

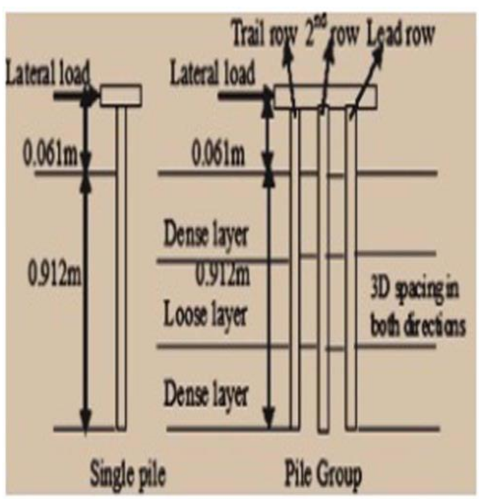

Fig. 1. Layouts of single and pile group.

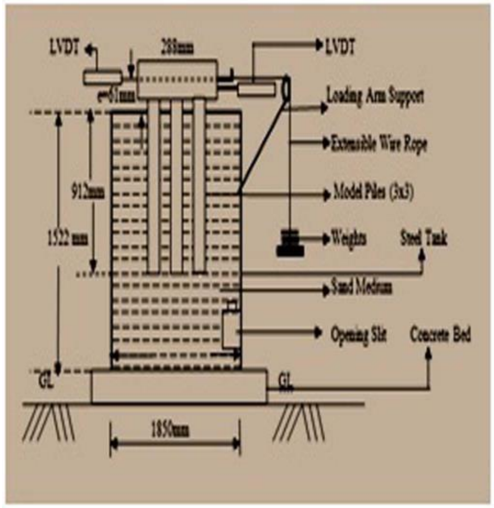

Fig. 2. Experimental set-up for lateral load tests.

2.2. Soil used in the experimental studies

In this study a clean dry sand (Indian standard sieve through 1.18mm passing and 75µ retained) is used as the foundation soil. The specific gravity of sand was found to be 2.67, the minimum and maximum dry unit weights of sand were found to be 16.00 and 19.90kN/m^3 respectively. The particle size distribution was determined using the dry sieving method, the uniformity coefficient (c_u) and coefficient of curvature (c_c) for the sand were 2.41 and 1.20 respectively. A grain size distribution curve of the sand is given in figure 3.

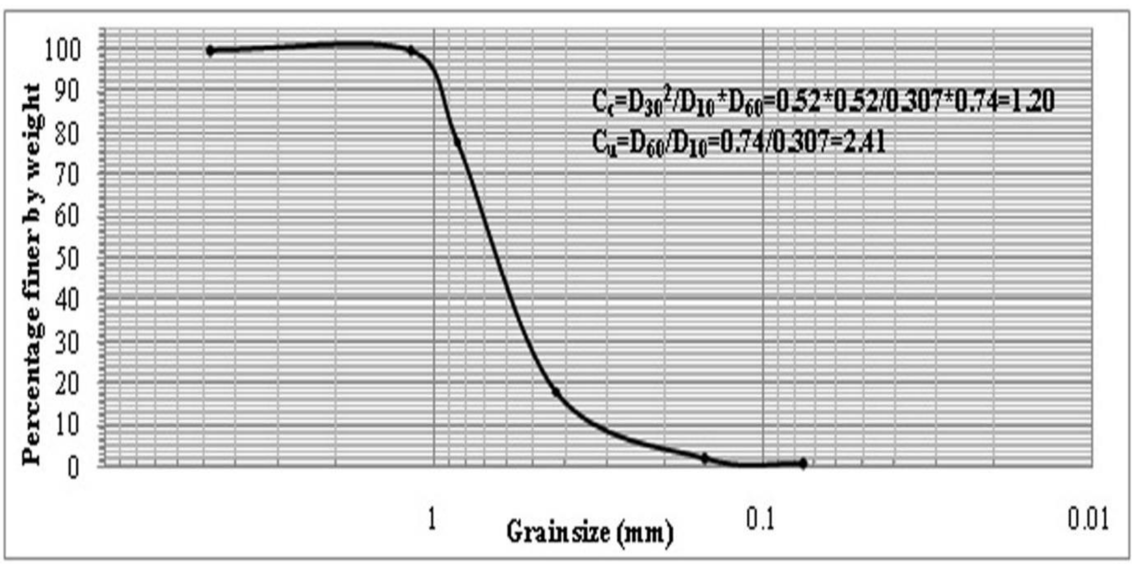

Fig. 3. Grain size distribution curve for sand.

The laboratory model tests were conducted on sand with maximum and minimum void ratios 0.637 and 0.316, for loose sand and dense sand respectively. The relative densities of the sand were 30% and 90% respectively, and the angles of internal friction were 31^0 and 36^0 respectively.

2.3. Experimental procedure

Two different soil medium of loose layer in-between dense layers and dense sand layer were used to carry out the experiment. The two soil mediums were considered as first case and second case respectively in the experiment. Bamboo pipe piles were used as the model pile in the experimental set up. In first case external lateral load is applied on the model pile embedded in the cohesionless soil with a depth of 0.456m. The depth of soil was calculated using H/D ratio of 0.50. i.e., H=Dx0.50=0.912x0.50=0.456m. The top and bottom sand layers depth were calculated to be 0.228m each. Using sand raining technique from the height of 600mm from bottom of tank the sand is filled into the tank to get dense state. In second case the depth of the cohesionless soil was found to be 0.0m which was derived using H/D ratio. The model piles were placed in their positions at the top of the bearing stratum (dense sand layer). The middle layer is filled with the sand from a height of fall 10mm to get loose state; remaining top layer is filled by sand raining technique from a height of 600mm to get dense state. For slenderness (L/d) ratio 25, 30 and 38, the embedment length would be 600, 720 and 912mm respectively from the pile toe. The lateral load is applied at pile head (61mm above the ground surface). For each increment of lateral load, the lateral displacement of pile was measured at pile head using LVDT (Linear varying differential transducer) instrument with display unit. When the lateral displacement of the pile ceases, the next lateral loads increment was applied till the lateral displacement reaches 10.50% of pile diameter (0.105d) and the corresponding load was taken as allowable lateral load capacity of the pile by Narasimha Rao et al. [8], Chandrasekaran et al. [9].

3. Numerical investigation

3.1. Pile-soil models and parameters

The interactions between the foundation soil and the piles would be the best modeled by a finite element program capable of solving two-dimensional problems. To give some understanding of the complex interactions between foundation soil and piles it was decided to use the computer program “SoilWorks 2D” for numerical investigation. The interactions between the soil and the piles can be completely obtained by using 2-dimensional Finite Element analysis software. Description of the capabilities of “SoilWorks 2D” are presented below.

SoilWorks 2013(v2.1) is all-in-one 2D Finite element analysis and analytical software for structural and geo-technical engineers. SoilWorks 2D is fully integrated pre/post and solve, complete FEM Software package, CAD based environment, intuitive, automation and robust. This software workflow is as mentioned below;

Geometry Modeling, 2. Properties / Meshing / Loads / Boundaries, 3. Analysis and 4. Post-Processing.

The workflow of the Foundation module of “SoilWorks 2D” was used as a basis for undertaking p-y analysis is as follows: Step1- define ground material properties; Step 2- define pile material properties; Step3- Input ground layer thickness, assign ground properties and ground water level; Step 4- define foundation type (Pile layout & length); Step 5- specify forces applied to foundation; Step 6- define analysis cases and design options; Step7- execute analysis and step 8, analyze results. The input parameters used in this analysis are presented in Table 1.

Table 1
Pile properties.

Sl. No.	Parameters	Notation	Bamboo pile
1	Material model	----	Linear elastic
2	Element type	----	Beam element
3	Diameter (m)	D	0.024
4	Shape		Pipe
5	Material type		Bamboo
6	Modulus of elasticity (kN/m^2)	E	1.617X10^8
7	Poisson's ratio	µ	0.30
8	Unit weight in kN/m^3	γ	04.00
9	Pile length (m)	L/d=25	0.600
		L/d=30	0.720
		L/d=38	0.912

In an embedded pile consists of beam elements with special interface elements provided such that, the interaction between the beam and the surrounding soil. The beam elements are considered as linear elastic and its behaviors are defined using the elastic stiffness properties. Also the behaviour of interfaces for the modeling of soil-pile interaction is considered with elastic-plastic model. The beam elements are of three-node line elements with six degrees of freedoms per node, three translational degrees of freedoms (u_x, u_y, and u_z) and three rotational degrees of freedoms (φ_x, φ_y, and φ_z). In this present study, the pile is modeled as embedded pile with free connection at it's top. The material parameters of the embedded pile distinguish between the parameters of beam, skin resistance and foot resistance. The properties of pile used in analysis are presented in Table 2.

Table 2
Summarizes the material (ground) properties used in the analyses.

Sl. No.	Parameters	Name	Dummy soil	Dense sand	Loose sand	Dense sand
1	Material model	Model	Mohr-coulomb	Mohr-coulomb	Mohr-coulomb	Mohr-coulomb
2	Material behavior	Type	Drained	Drained	Drained	Drained
3	Unsaturated unit weight(kN/m^3)	γ_{unsat}	0.001	19.90	16.00	19.90
4	Saturated unit weight (kN/m^3)	γ_{sat}	0.001	21.00	18.0	21.00
5	Young's modulus (kN/m^2)	E	0.010	21000	15000	15000
6	Poisson's ratio	µ	0.005	0.30	0.40	0.30
7	Cohesion (kN/m^2)	C	0.1	1	1	1
8	Friction angle (^{0})	Φ	1	36	31	36
Material type		----	Sandy soil (Rees et al.)	Sandy soil (Rees et al.)	Sandy soil (Rees et al.)	Sandy soil (Rees et al.)
9	Horizontal reaction (kN/m^3)	K_h	0.271	16300	7872	16300
10	Strain at 50% Stress		----	----	----	----
11	Unit ultimate skin friction (kN/m^2)	----	6.90x10^{-3}	40	21	40
12	Unit ultimate bearing capacity (kN/m^2)	q_u	6.90x10^{-3}	4000	600	4000

Using the surfaces assigned with material properties, mesh is generated in "SoilWorks 2D" software. Figure 5 shows the typical discretization of 2D finite element model of soil-pile-with pile raft structure for nine bamboo pipe pile group in loose layer in-between dense layers at an eccentricity of 61mm above the ground level for soil model of slenderness ratio (L/d) 38.

The program contains p-y curves which can be used for different types of soils. The program also allows the user to input p-y curves developed using the other formulations. The analyses carried out in this study for the piles were discretized into 100 elements in the "SoilWorks 2D" program.

To explain the laterally loaded single pile behaviour, "SoilWorks 2D" uses the soil reaction-lateral displacement *(p-y)* curves as suggested by Reese et al. [3] for the horizontal displacement and soil-pile interaction. The soil modulus of the initial linear part k is assumed to be increase linearly with embedded depth z by Eq. 1 below:

$$k = n_h z \quad (1)$$

Where, $\boldsymbol{n_h}$= constant of modulus of subgrade reaction. The ultimate soil resistance is mobilized at a lateral displacement of 0.0375times the pile diameter (3b/80) where b is the diameter of model piles.

The model layouts for the single pile and the pile group are shown in figure 4.

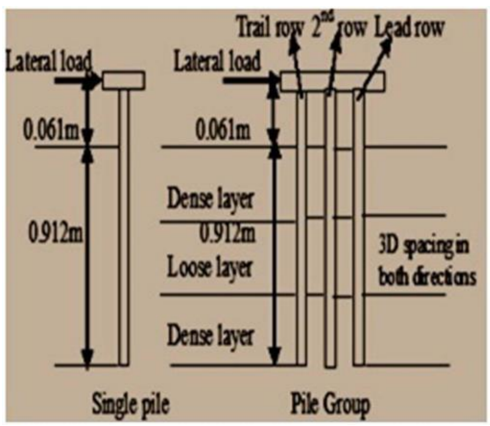

Fig. 4. Layouts of single and pile group.

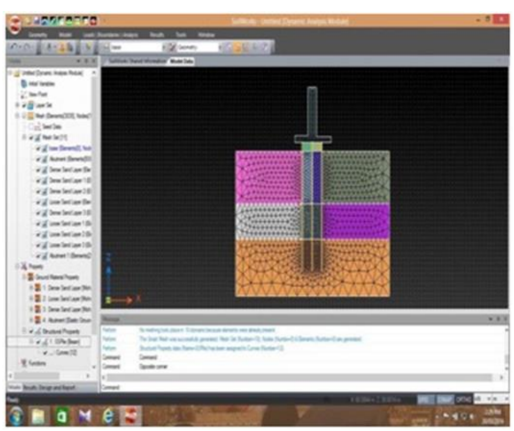

Fig.5. 2D Finite element model of soil-pile-with pile raft structure for nine pipe pile group in loose layer in-between dense layers at an eccentricity 61mm above the ground level.

4. Discussion of the experimental and numerical investigation results

The lateral-load behaviour of the bamboo piles was studied by the lateral load and lateral displacement plots. The plots are drawn for the lateral-load and lateral-displacement pile head. Figure 6 shows a typical lateral load-lateral displacement curves for slenderness (L/d) ratio as 25. For a single bamboo pile (BP1) and groups of bamboo piles (BPn). It is observed that when number of piles increases from single pile to nine piles, the behaviour of pile is almost non-linear. It shows very clearly that at 2.5mm lateral displacement, the ultimate lateral load capacity increases to 0.05kN, 0.11kN, 0.19kN and 0.51kN for single pile, two piles, four piles and nine piles respectively in loose layer in-between dense layers at 3D pile spacing. Pile response under lateral loading is typically controlled by

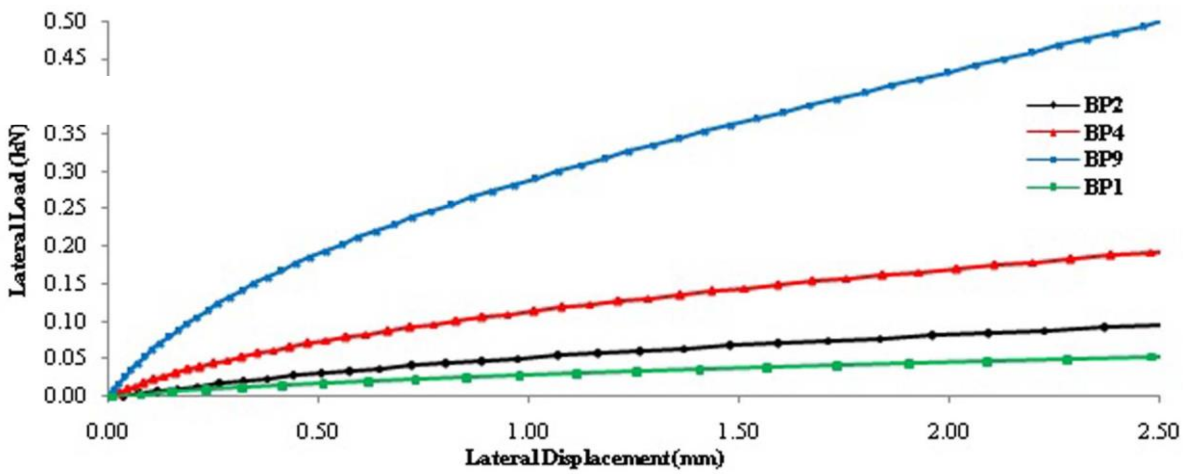

Fig. 6. Comparison between single pile and pile group lateral load results of bamboo pipe piles at 3D pile spacing in loose layer in-between dense layers and dense sand layer for slenderness ratio as 25.

the soil density, flexural rigidity of pile and soil–pile interface interaction. In this experiment, lateral displacement response is mainly controlled by the piles flexural stiffness E_mI_m and interface interaction because type of soil layer and type of pile configuration are approximately equal. There are some abnormalities in the initial part of the figures due to change in soil properties and disturbance created when the piles were driven. In general, the lateral loads drop from their initial values, until a lateral displacement level of about 2.5mm a critical, where they remain relatively constant. An initial decrease in resistance with increasing lateral displacement would be estimated for closely spaced piles in a pile group. As the lateral displacements increases, the shear zones began to develop and start to overlap.

The lateral load and lateral displacement responses of the piles are measured by experimental investigations and the detailed bending moment, shear force and lateral load versus lateral displacement responses analysed by "SoilWorks 2D" software are explained below.

4.1. Model pile group

The pile group responses were predicted using "SoilWorks 2D". The experimental group lateral loads were used in the "SoilWorks 2D" software. Here, the lead row or trail row is defined as per the loading direction. Also, the soil reaction-displacement (p-*y)* curve and the recommended experimental group lateral loads are at present for monotonic lateral loading only.

Figures 7 to 10 shows the experimental and predicted lateral load vs. lateral displacement of the pile group in loose layer in-between dense layers and dense sand layer, respectively. The evaluated values are closely match with experimental data quite well. The measured response of the nine pile groups in loose layer in-between dense layers is significantly larger than the predicted response.

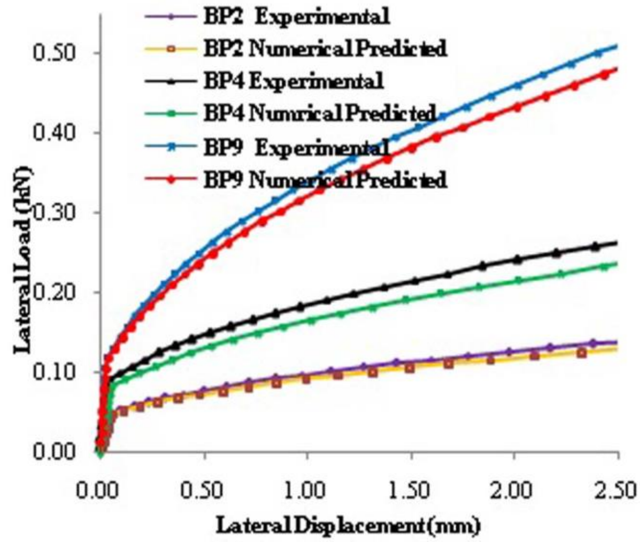

Fig. 7. Comparison between the experimental and predicted lateral load results at 3D pile spacing of bamboo pipe piles in loose layer in-between dense layers for slenderness ratio as 38.

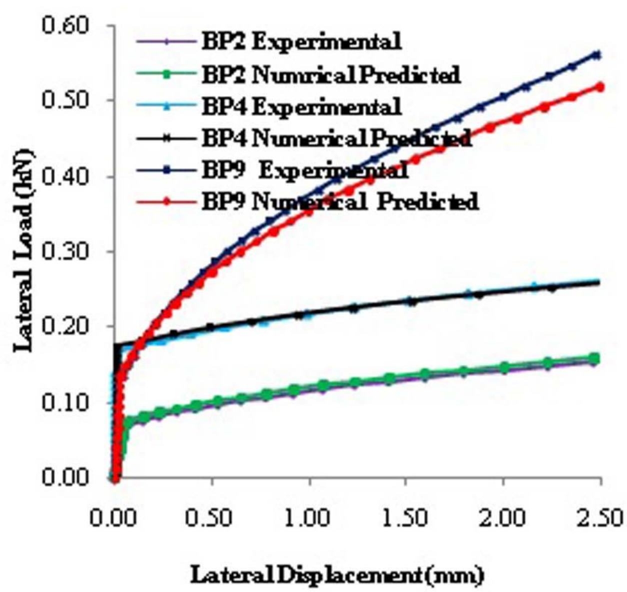

Fig. 8. Comparison between the experimental and predicted lateral load results at 3D pile spacing of bamboo pipe piles in dense sand layer for slenderness ratio as 38.

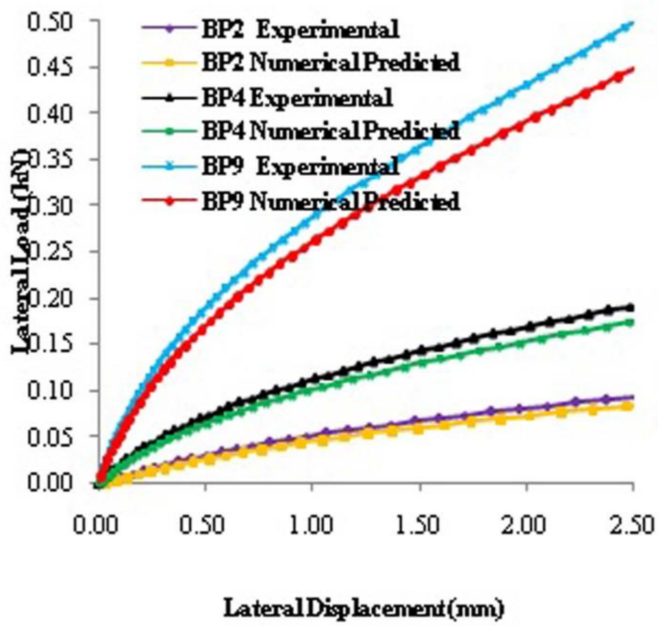

Fig. 9. Comparison between the experimental and predicted and lateral load results at 3D pile spacing of bamboo pipe piles in of loose layer in-between dense layers for slenderness ratio as 25.

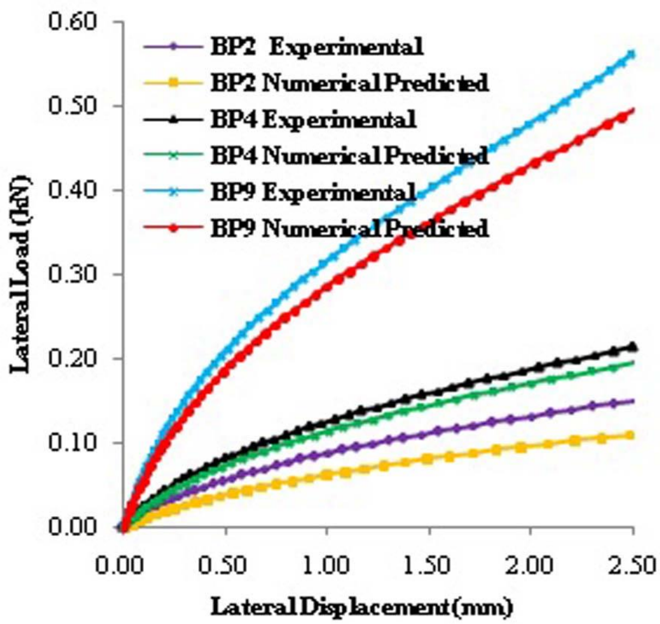

Fig. 10. Comparison between the experimental predicted lateral load results at 3D pile spacing bamboo pipe piles in dense sand layer for slenderness ratio as 25.

For a typical foundation design, pile embedment to pile caps is greater than 2 times pile-diameters to make sure maximum bending moment (BM) transfer between the pile and pile cap. In this study, the piles were embedded 2.54 times pile-diameters into the pile cap. In case of pile head is allowed to rotate, then the maximum bending moment (BM) may occur below its head. It may occur for small fixed-headed group if the pile cap is allowed to rotate.

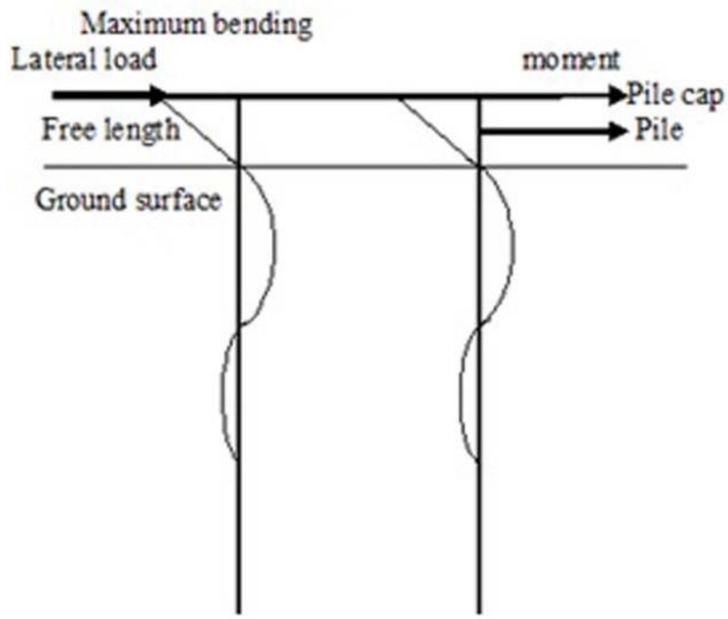

Fig. 11. Sketch of bending moment distributions free head pile group.

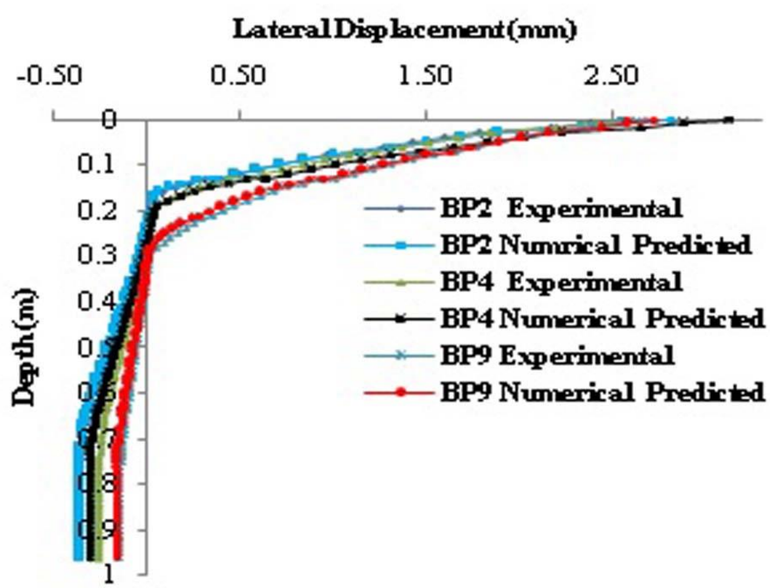

Fig. 12. Lateral displacements along the depth of bamboo pipe in pile group at 3D pile spacing in loose layer in-between dense layers for slenderness ratio as 38.

adequately. Figure 11 showed the typical bending moment (BM) distribution along the pile for this study. The calculated maximum bending moments (BM) for the entire group occurred at the top of each pile or at the pile cap. Hence the maximum bending moments occurring below the ground surface. So that the maximum bending moments and their stresses that control design and consequently has to be modelled accurately.

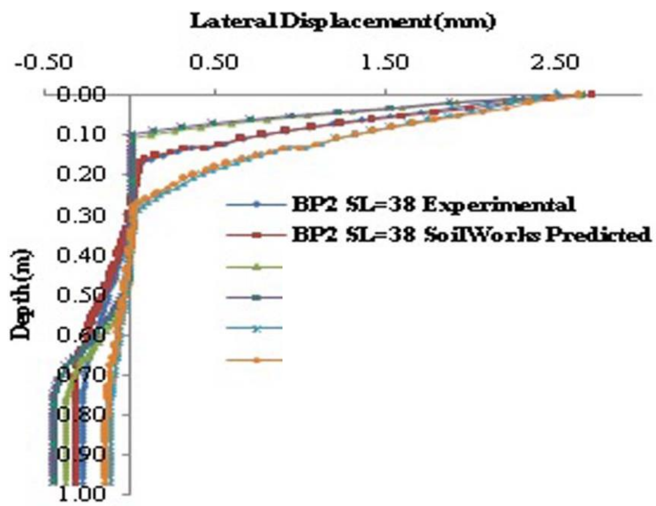

Fig. 13. Lateral displacements along the depth of bamboo pipe pile groups at 3D pile spacing in dense sand layer for slenderness ratio as 38.

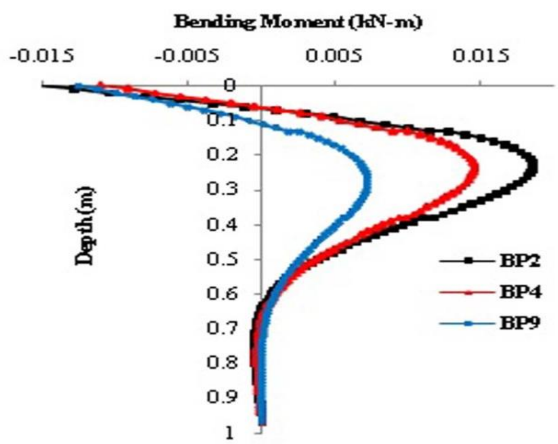

Fig. 14. Predicted different pile group bending moments at 3D pile spacing of bamboo pipe piles in loose layer in- between dense layers for slenderness ratio=38.

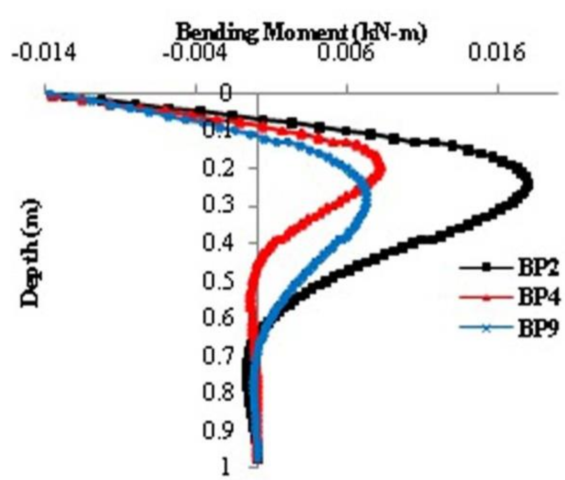

Fig. 15. Predicted different pile group bending moments at 3D pile spacing of bamboo pipe piles in dense sand layer in-between layer for slenderness ratio as 38.

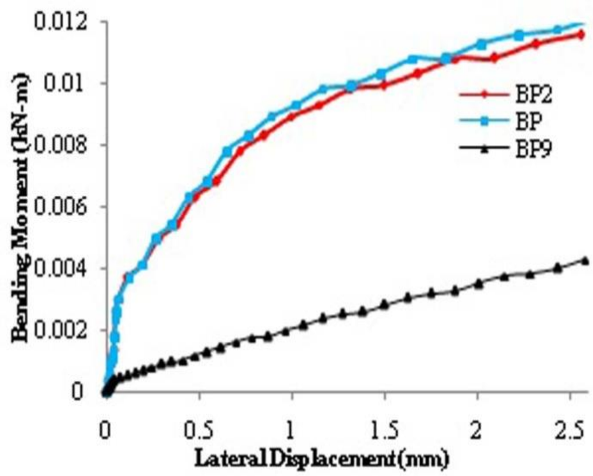

Fig. 16. Predicted different pile group bending moment results at 3D pile spacing of bamboo pipe piles in loose dense layers for slenderness ratio as 38.

Figure 12 and 13 illustrates the predicted distributions of lateral displacement along the piles for the different pile group and figure 14 and 15 shows the bending moments along the piles for the different pile group of slenderness ratio 38 in the two different soil medium. It has been observed that the lateral displacements increases with decrease in pile group, and the maximum displacements occur at the pile cap elevation. The maximum bending moments (BM) of pile group as shown in figure 14 and 15. Because of the number of piles, the individual pile group (two, four, and nine piles) moments differ significantly, but within a four pile and nine pile group, the difference is negligible. Note that the four piles to nine pile groups develop the same bending moment, because they have the same square pile configuration in both the direction. Also, the maximum moments below the ground elevation are only 56.43% of their pile top values.

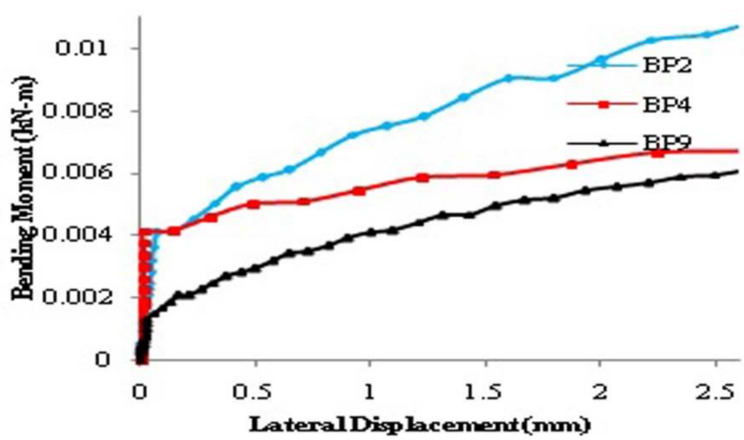

Fig. 17. Predicted different pile group bending moment results at 3D pile spacing of bamboo pipe piles in dense sand layer for slenderness ratio as 38.

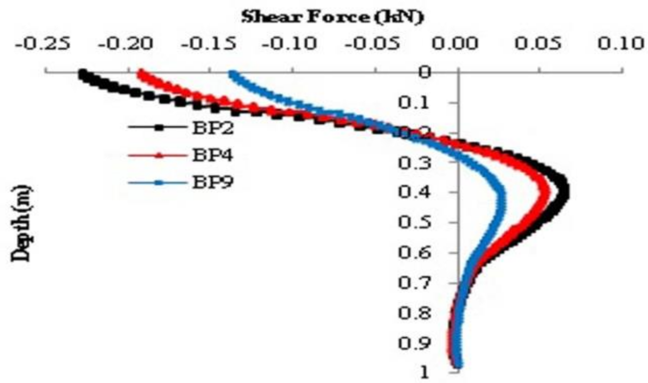

Fig. 18. Predicted different pile group shear force results at 3D pile spacing of bamboo pipe piles in loose layer in-between dense layers for slenderness ratio as 38.

Figure 16 and 17 shows the predicted bending moments in each slenderness ratio of the different pile group founded in the two different soil medium. Therefore, the different soil density, this is a small difference between the maximum bending moments for the different pile groups configurations. The later is expected from the findings that shear and a moment are independent of pile configuration but is only a function of pile position within the pile group. In different soil densities, however, the bending moments were 21.68% more in the loose layer in-between dense layers than in the dense sand layer.

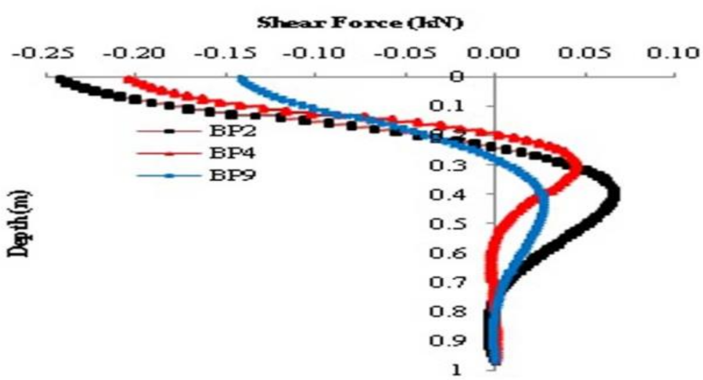

Fig. 19. Predicted different pile group shear force results at 3D pile spacing of bamboo pipe piles for slenderness ratio as 38.

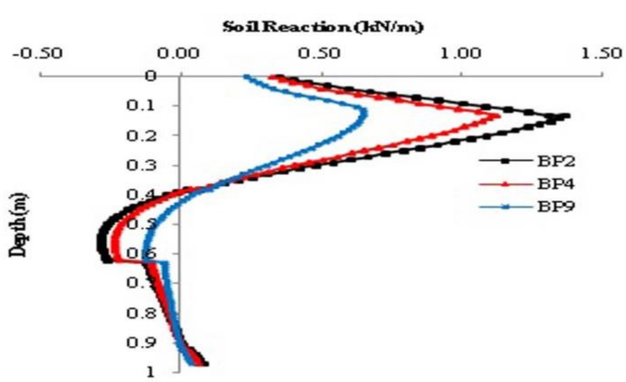

Fig. 20. Predicted different pile group soil reaction results at 3D pile spacing of bamboo pipe piles in loose layer in-between dense layers for slenderness ratio as 38.

Figure 18 and 19 shows these shear force in each slenderness ratio of the different pile group in different soil medium. Here, for different soil density, there is no much difference between the maximum shear force for the different pile group configuration. The differences were fairly due to the slight deviation in the free lengths of the individual pile group. In different soil densities, however, the shear force was 19.19% larger in the loose layer in-between dense layers than in the dense sand layer. Figure 20 show the predicted (SoilWorks 2D software) different pile group soil reaction results at 3D pile spacing of bamboo pipe piles in loose layer in-between dense layers for slenderness ratio as 38. The soil reaction was 7.07% more in the dense sand layer than in the loose layer in-between dense layers.

5. Conclusions

The following conclusions were made by the results obtained from the experimental and numerical analysis using “SoilWorks 2D” carried out on the large number of laterally loaded different pile group in the two different soil medium. The results obtained from experiments and numerical analysis were compared and found to be in good agreement.

a. The experimental group lateral loads are found to be dependent on different soil density and pile group configuration.
b. The load carrying capacity of nine piles placed in a group has 5 to 8 times greater load carrying capacity of single pile in loose layer in-between dense layers. The bamboo pipe piles carry a load of 0.472kN at density 16.00kN/m^3.
c. The ultimate lateral load is considerably reduced when the soil layer changes from loose layer in-between dense layers to dense sand layer. The dense sand layer carries more lateral loads compared to loose layer in-between dense layers for all slenderness ratios. This decrease in pile capacity for loose layer in-between dense layers is because of the reduction in passive resistance of the soil in front of the piles.
d. It is found that the lateral load-lateral displacement behaviour is still non-linear with the presence of lateral load and the load carried by 3D pile spacing in loose layer in-between dense layers soil.
e. The behaviour of pile group under lateral loads not only depends on the lateral load and number of piles in a group, but also depends on the soil layer condition and flexural rigidity of pile material.
f. The load carrying capacity of nine piles placed in a group is about 13% greater than that of the single pile in loose layer in-between dense layers.
g. The lateral load experimental test on the bamboo pipe piles showed similar behaviour to that from experimental study and numerical study. The maximum bending moment increases with decrease in the pile groups. Based on the results, it seen that the bending moment (BM) increases in the range of 23.21-109%, 22.22-29.41%, 108.95-79.48% and 26.31-26.36% respectively for single pile, two piles, four piles and nine piles in loose layer in-between dense layers for increase in slenderness (L/d) ratio 30 to 38 and 22.58-100%, 12.50-38.46%, 30.26-15.11% and 7.69-44.44% respectively for single pile, two piles, four piles and nine piles in

dense sand layer for increase in slenderness (L/d) ratio 25 to 38 irrespective of the model bamboo pipe pile group at 3D pile spacing in loose layer in-between dense layers and dense sand layer.

h. Pile group displacement in relatively loose layer in-between dense layers, is larger than the lateral displacements happens in pile group in dense sand layer as expected.

i. As pile slenderness ratio increases, maximum bending moment and shear force occurred decrease is about 27.75% and 40% respectively under the same pile group configuration considered. However, in case of bending moment (BM) and shear force, the variation due to pile group have clearly observed in all piles.

j. The load-carrying capacity of a pile group increases with the increase in slenderness ratio of bamboo pipe piles in dense sand layer.

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