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Behaviour of Laterally Loaded Pile Group Study by Numerical Investigation

Babu S. Chawhan[1], Yogeendra R. Holebagilu [2], Vinayak Vijapur[3], Vijaykumar[4], Shreedhar K. R.[5]

[1] Associate Professor, Department of Civil Engineering, Govt. Engg. College, HUVINAHADAGALI, Ballary 583219, India.
[2] Associate Professor, Department of Civil Engineering, Govt. Engg. College, HUVINAHADAGALI, Ballary 583219, India.
[3] Associate Professor, Department of Civil Engineering, Govt. Engg. College, TALAKAL - 583 238, Koppal, India.
[4] Associate Professor, Department of Civil Engineering, Govt. Engg. College, RAICHUR – 584 135, India.
[5] Assistant Professor, Department of Civil Engineering, Govt. Engg. College, TALAKAL - 583 238, Koppal., India.

ABSTRACT
Piles under tall structure like chimneys, multistoried building and jetty structure etc. experience high lateral load. In those situations piles are to be properly designed against lateral load. With this in view, an attempt has been made in the present investigation to gain an insight into the behaviour of laterally loaded piles in cohesionless soil. An experimental investigation has been carried out with single pile and pile group model tests. The p-y method of analysis models, nonlinear behaviour, and is an effective method of designing deep foundations subjected to lateral loads, displacements and bending moments calculated using p-y analysis have usually been found to be in good agreement with field measurements. Numerical analysis has also been adopted by finite element method with the help of SoilWorks2D geotechnical software. An attempt has been made to study the variation of lateral loads with various design parameters like slenderness ratios (L/d), pile material, density, pile spacing, pile group and middle layer variation. Lateral displacements, bending moments, shear forces and soil reactions predicted by numerically have been found to be in good agreement with the case study the calculated values.
Keywords: *Model pile test, Laterally loaded pile group, Cohesionless soil, SoilWorks2D Software, Bending moment.*

1 INTRODUCTION

Pile foundations are used extensively in offshore and coastal structures such as jacket-type structures, berthing structures, and mooring dolphins. The forces on these structures are axial loads due to self-weight of a superstructure; stockpiled materials and traffic from trucks, cranes, etc.; impact loads from ships; and wave loads that are cycle in nature. Loads due to ship thrust on offshore structures, lateral loads due to earthquakes, bomb blasts are examples of dynamic loadings. Sustained lateral loads occur on piles used in the foundation of earth retaining structures and other similar types.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 first necessary to have a clear idea of the deformation behaviour of single piles of similar batter (vertical or inclined in the group) under lateral loads.In the above examples, there are some cases in which the external horizontal loads act atthe pile head (i.e., at the top section of the pile). Such loading is called active loading (Fleming et al. 1992; Reese and Van Impe 2001).Consequently, the response of a single pile differs from that of a pile placed within a pile group (Prakash and Sharma 1990; McVay et al. 1998; Ilyas et al. 2004; Bogard and Matlock 1983 andAshour et al. 2004).Each pile in a group, whether loaded axially or laterally, generates a displacement field of its own around itself. The displacement field of each pile interferes and overlaps with those of the adjacent piles; this results in the interaction between piles.Interaction between piles occurs in the case of laterally loaded pile group as well. In alaterally loaded pile group, each pile pushes the soil in front of it (i.e., in the direction of theapplied force).Movement of the piles placed in the first (leading) row in the direction of theapplied force is resisted by the soil in front of it. In contrast, the piles in the rows behind the firstrow (i.e., the piles in the trailing rows) push on the soil which in turn pushed on the piles in therows in front of them. The resistive forces acting on the trailing-row piles are ingeneral less than the resistive forces acting on the leading row (Salgado 2008; Ilyas et al. 2004 andAshour et al. 2004).

2 LITERATURE REVIEW

During the last few decades, many researchers have studied the behaviour of laterally loaded piles using both laboratory tests and theoretical studies.Bisaws et al. (2014) carried out experimental investigation of free-head model piles under lateral load in homogenous and layered sand. The experimental study was supplemented by numerical study to determine co-efficient of horizontal modulus of sub-grade reaction (η_h). Byung, Nak-Kyung et al. (1999)have observed that, testing of the pile embedded in Nak-Dong river sand, located in south Korea, under monotonic lateral loadings.The lateral loads and the soil-pile reactions of driven piles increase as the driving energies increase.Salini and Girish (2009) concluded that, the lateral-load capacity of pile group increases as the density of sand increases for the same slenderness ratio. The lateral-load capacity of pile increases with increase in length for same diameter hence passive resistance was mobilized to increase the embedment length of a pile.The lateral resistance of piles, the effect of the installation method and the pile head restraint condition were studied. The lateral load is highest in the free head condition and it decreases as the depth increases.Georgiadis (2012) carried out three-dimensional finite element analyses using PLAXIS 3D and presented the response of laterally loaded piles of different geometries, installed at several distances from slopes of various inclinations. From analysis, p–y curves are developed for the case of undrained lateral loading of piles near the crest of clay slopes and implemented the p–y curve into a commercial sub-grade reaction computer code to perform a series of parametric numerical analyses.Muthukkumaran (2014) investigated that, the lateral load pile capacity of the pile, lateral load-lateral displacement response of the pile at pile head, effect of slopes and embedment length on pile capacity and bending-moment (BM) profile along the pile shaft were studied.William Higgins et al. (2013) analysed laterally loaded piles embedded in single-layer elastic soil with constant and linearly varyingmodulus and in two-layer elastic soil with constant moduluswithin each layer using the Fourier Finite Element Method.Based on the analysis, it is observed that pile response is afunction of the relative stiffness of pile and soil, and of the pileslenderness ratio.In order to account for soil nonlinearity, modification of the linear one-parameter modelhas been done by replacing the linear Winkler springs with nonlinear springs by McClelland andFocht(1958). Based on pile group field tests, Davisson (1970) modified the elastic solution to account for nonlinearity using yield factors. The modulus of subgrade reaction approach was extended to account for the soil nonlinearity.For nonlinear springs, the spring constant kdependson the piledeflection Δ. Hence,the soil reaction per unit length p = kΔdoes not increase linearly with Δ. The nonlinearmodification of the one-parameter model culminated in the development of the p-y method(Reese and Cox 1969; Matlock 1970; Reese et al. 1974and Reese and Van Impe 2001). In thep-y method, k is no longer given as input; the nonlinear relationship of k with Δare given as inputs to the analysis in the form of p-Δcurves, which are widely knownin the literature as “p-y” curves. Soil layering is an important factor that affects laterally loaded pile response by Basu and Salgado (2007a). Layering has been taken into account approximately in some pile analyses by either assuming a linear variation of k with depth or by proposing different p-y curves for different soil depths according to Broms (1965); Matlock and Reese (1960); Madhav et al. (1971); Valsangkar et al. (1973); Scott (1981) andHsiung (2003). Such gradual variation of soil properties with depth has been assumed in many continuum-based analyses as well according to Poulos(1973); Randolph (1981);Budhu and Davies (1988) and Zhang et al. (2000). However, in real field situations, discrete soil layers are often present and the assumption of linear variation of soil properties does not properly represent the ground conditions. Analyses considering layers are rather limited. Davisson and Gill (1963) analyzed a two-layer system using the p-y method. Georgiadis (1983) developed a method of developing “p-y” curves for layered soil profiles. A few continuum-based numerical analyses are also available according to Pise(1982); Lee et al. (1987) and Veruijt andKooijman (1989). Sundaravadivelu (2008) reported the investigation oflaterally 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 was studied.Chae, Ugai and Wakai (2004) carried out numerous numerical studies with a 3D finite element model test and prototype test on laterally loaded short rigid piles and pier foundation located near a 30° slope. The lateral resistance of pile was observed to be decreasing with the change in location closer to the crest of the slope.Rathod et al. (2017) have investigated that, the effect of slope on soil reaction-lateral displacement (p-y) curves for laterally loaded piles 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.Sawant and Shukla (2013) carried out a three-dimensional finite element analysis to investigate theeffect of edge distance from the slope crest of a laterally loaded pile embedded in clayey soil of soft to medium consistency in the sloping ground for different slope angles and pile lengths. The results indicated that the pile top displacement and the bending moment in the pile decrease with an increase in the edge distance from the slope crest.Trochanis et al. (1991a.b) used a 3D model for modelling a vertical pile in a clay deposit by including the elastoplastic behaviour of soil and slippage of soil due to axial load. The results were compared with a simplified method where a 1D model is used to represent the pile-soil system and pile-soil interaction factors such as constant degradation and gap were considered.Bhusan et al. (1979); Nakashima et al. (1985) and Uto et al. (1985) modeled single pile on slopes using the subgrade reaction method. Modifications on either governing equations or relationships between the subgrade reaction and pile displacement were made to account for the effects of the slopping ground.From the literature, 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 layered cohesionles soils requires further study. However very little work has been reported on the numerical studies of laterally loaded piles, barring a few theoretical and laboratory test results. In this paper a nonlinear finite element model has been developed to study the behaviour of stainless steel pipe piles under static lateral loads, using the developed numerical model.

3 EXPERIMENTAL INVESTIGATION

The main objective of the experimental research program presented in this section is threefold. The first objective is to develop a model of pile and foundation soil in the laboratory. The second objective is to investigate the ultimate lateral capacity of a single stainless steel pipe pile at ground surface of a free head in multilayered cohesionless soil. The third objective is to study the behaviours of different pile group with different slenderness (L/d) ratios 25, 30 and 38 with 3D pile spacing in loose layer in-between dense layers soil medium to withstand lateral displacements induced by experimentally. The detail experimental investigation is carried out below;

3.1 Experimental set-up

The purpose of experimental investigation is prototype reduced to a model scale. For example, a 1/15 (1/N) scaled model would require that a prototype pipe pile of 14.60m long by 0.36m circular diameter modelled by stainless steel 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.

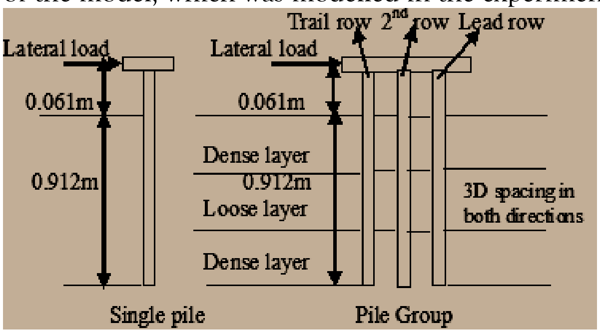


Figure 1. Layouts of single and pile group

The Young's modulus (E_m=1.903x10^{8}kN/m^2) and the moment of inertia of the model pile (I_m) determined as 4.787x10^{-9}m^4 and Poisson's ratio (μ) as 0.31. The bending stiffness, E_mI_m, of0.91096kN-m^2. The dimension of test tank is decided based on the influence zone of soil mass from pile. It is 10 times the pile diameter in the direction of loading for piles under static lateral load according toPoulos(1980) and NarasimhaRao et al. (1998). 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 is applied by means of dead weights (slotted type) placed on a hanger connected to a flexible steel wire, strung over a frictionless pulley supported by a loading platform as shown in figure 2.

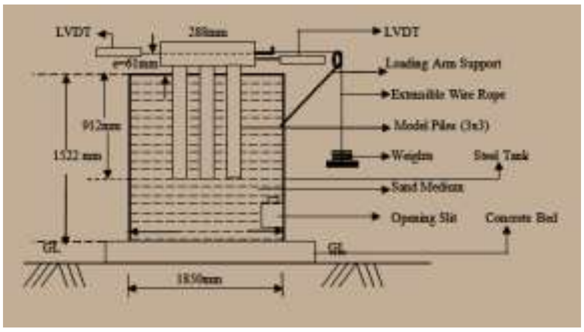


Figure 2. Experimental set-up for lateral load tests

3.1.1 Soil used in the Experimental Studies

A clean, dry sand (Indian standard sieve through 1.18mm passing and 75μ retained) was used as the foundation soil in this study. 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, and the uniformity coefficient (c_u) and coefficient of curvature (c_c) for the sand were 2.41 and 1.20, respectively. 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.

3.1.2 Experimental Procedure

Here soil medium of loose layer in-between dense layers have been used to carry out the experiment. Stainless steel pipe piles were used as the model pile in the experimental set up. In soil layer 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. 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 the pile was measured at pile head using LVDT instrument with display unit. When the lateral displacement of the pile ceases, the next lateral load increment was applied. The lateral load was applied till the lateral displacement reaches 10.50% of pile diameter (0.105d) and the corresponding load wastaken as allowable lateral load capacity of the pile according to NarasimhaRao et al. (1998) and Chandrasekaran et al. (2010).

4. FINITE ELEMENT MODEL

An important objective of this research is to determine bending moment, shear force, soil reaction and lateral load-lateral displacement behaviour of stainless steel pipe piles can be performed using the numerically.

4.1Pile-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. However, 2D finite element analysis would require more time and effort. 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 foundation soil and the piles can be best obtained by using 2-dimensional finite element model software. Description of the capabilities of SoilWorks 2D are presented below.

Soil Works 2013(v2.1) is all-in-one 2D Finite element analysis and analytical software for structural and geo-technical engineers.SoilWorks 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;

1. Geometry Modeling, 2. Properties / Meshing / Loads / Boundaries, 3.Analysis and 4.Post-Processing. The workflow of the foundation module of SoilWorks 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 and 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

Parameters	Notation	Stainless steel pipe pile
Material model	----	Linear elastic
Element type	----	2D 3node triangular element(beam element).
Diameter (m)	d_o	0.024
	d_i	0.020
Shape	----	Pipe
Material type	----	Stainless steel
Modulus of elasticity (kN/m^2)	E	$1.903X10^8$
Poisson's Ratio	μ	0.31
Unit weight (kN/m^3)	γ	78.50
Pile length (m)	L/d=25	0.600
	L/d=30	0.720
	L/d=38	0.912

Table 2. Material properties used in the analyses

Parameters	Name	Dummy soil	Dense sand	Loose sand
Material model	Model	Mohr-coulomb		
Material behaviour	Type	Drained		
Unsaturated unit weight (kN/m^3)	γ_{unsat}	0.001	19.90	16.00
Saturated unit weight (kN/m^3)	γ_{sat}	0.001	21.00	18.00
Young's modulus (kN/m^2)	E	0.010	21000	15000
Poisson's Ratio	μ	0.005	0.30	0.40
Cohesion (kN/m^2)	C	0.10	1	1
Friction angle (^{0})	Φ	1	36	31
Material type		Sandy soil (Rees et al.)		
Horizontal reaction (kN/m^3)	K_h	0.271	16300	7872

Strain at 50% stress	---	---	----	----
Unit ultimate skin friction (kN/m^2)	----	0.0069	40	21
Unit ultimate bearing capacity (kN/m^2)	q_u	0.0069	4000	600

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

Using the surfaces assigned with material properties, mesh is generated in SoilWorks 2D software. Figure3 shows the typical discretization of 2D finite element model of soil-pile-with pile raft structure for nine stainless steel 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.

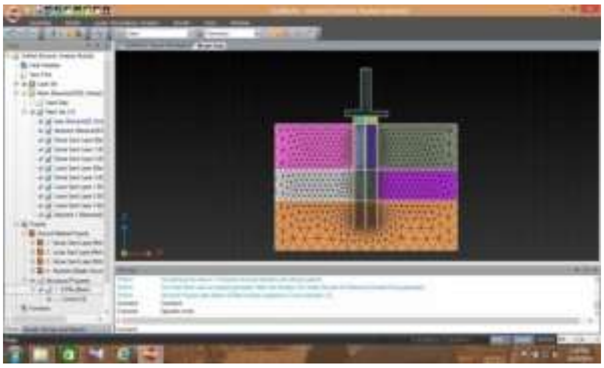


Figure3.2D Finite element model of soil-pile-with pile raft structure for nine stainless steel pipe pile group

The program contains default p-y curves that can be used for different types of soils. As an alternative, the program also allows the user to input p-y curves developed using other formulations. For the analyses carried out in this research the piles were discretized into 100 elements in the SoilWorks 2D program.

4.2Validation of the Proposed Numerical Model

The computer code developed for nonlinear static analysis was validated for field piles (Zhang et al. 1999) and for model piles (Ranjan et al. 1980; Rao et al. 1992)

4.2.1 Model pile (Zhang et al. 1999)

Lateral load tests on vertical piles were conducted in a centrifuge at 45 g. These tests simulated prototype square piles with 0.43-m wide and 13.7-m long, and embedment depth of 10.90m founded in loose and dense sand. The free length varied from 2.28m for groups founded in medium dense sand to 2.54m for single piles embedded in loose sand. All of the single pile tests were free-headed, and all of the pile group tests were fixed-headed. The Young'smodulus of the model aluminium was 73.1 MPa. The soil usedin the study was mixed sand with average particle diameter of 0.23 mm.The sand layer was prepared by dry pluviation through three rectangular sieves (US standard sieve No. 14) which were stacked on top of the rectangular sample container. Two sample densities were prepared for the tests: (1) loose sand and (2) dense sand. The dry unit weights corresponding to these relative densities were 14.05 and 14.50 kN/m^3, respectively.For the analyses reported herein, the following properties were employed for loose sand: friction angle Φ of 34.5°,coefficient of lateral subgrade reaction n_h of 1357kN/m^2,shear modulus G at a depth of 13.7m of 8230kN/m^2, ultimate skin friction τ_f at a depth of 13.70m of48.5kN/m^2, and ultimate tip capacity

Q_f of 800kN. In case of the dense sand these values were 37.1^0 for Φ, 2714kN/m^2 for n_h ,8960kN/m^2 for G, 55.2kN/m^2 for τ_f and 890kN for Q, respectively.The comparisons between the FD predictions and the reported data, corresponding to vertical piles in the loose and dense sands, are shown in Fig. 4. It should be noted that the combination of loads and pile rigidities adopted in the previous study (Zhang et al.1999) does not allow the piles to be deformed beyond their elastic limits as it is shown in Fig. 4. The 2D numerical resultsare fully consistent with the experimental results obtained byZhang et al. (1999).

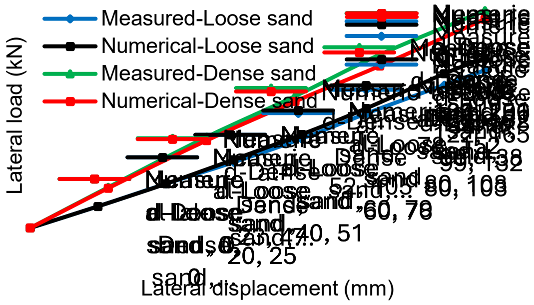


Figure 4.Comparison of lateral load-lateral displacement curve for vertical pile with measured results of Zhang et al. (1999)

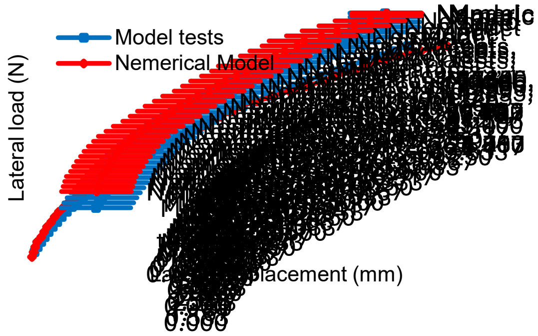


Figure5. Comparison of lateral load-lateral displacement curve for vertical pile with experimental results of Ranjan et al. (1980)

4.2.2 Model Pile (Ranjan et al. 1980)

A model aluminum pile embedded in soft clay was tested by Ranjan et al. (1980) at a horizontal load of 24.50N at the pile head. A nonlinearstatic analysis was performed on the pile. The pile and soil parameters used in the analysis are given in Table 3.

Table 3. Pile and soil parameters (Ranjan et al. 1980)

Parameters	Details
Soil	Liquid limit=54%, plastic limit=25%, consistency index=0.48, undrained shear strength Cu=15.2kPa, soil modulus E=600kPa, unitweight of soil γ=18kN/m^3, water content=40%.
Pile	Diameter D=9.5mm, wall thickness=1mm, embedded length of pile=360mm.

The comparison of results for the vertical piles are shown in Figure 5. The numerical results show a fairly good comparison with the experimental results. Hence, it could be concludedthat the numerical scheme adopted in the present investigationis capable of modeling the behaviour of vertical piles underlateral loads.

5 EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Lateral Load-Displacement Behaviour of Pile

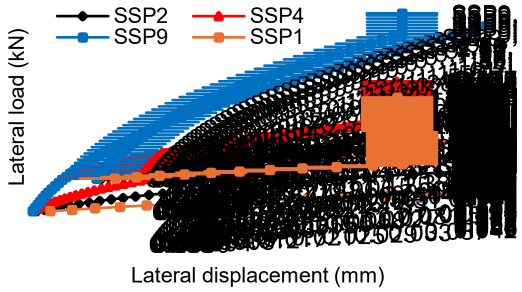


Figure 6.Comparison between single pile and pile group lateral load results of stainless steel pipe piles at 3D pile spacing in loose layer in-between dense layersas slenderness ratio=25

The lateral load behaviour of the piles studied by using lateral load and lateraldisplacement curves. Figure 6 shows a typical lateral load lateral displacement curves for L/d=25 for different stainless steel pipe pile configuration (single pile, two piles, four piles and nine piles). It is observed that when number of piles increases from single pile to nine piles, the behaviour of pile is almost nonlinear. It shows very clearly that at 2.5mm lateral displacement, the ultimate lateral load capacity increases from 0.05kN, 0.11kN, 0.20kN and 0.51kN by single pile, two piles, four piles and nine piles respectively at 3D pile spacing.

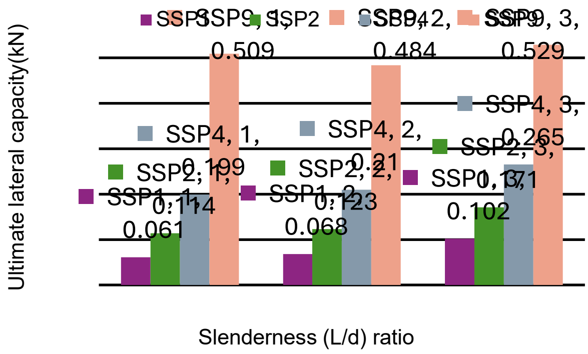
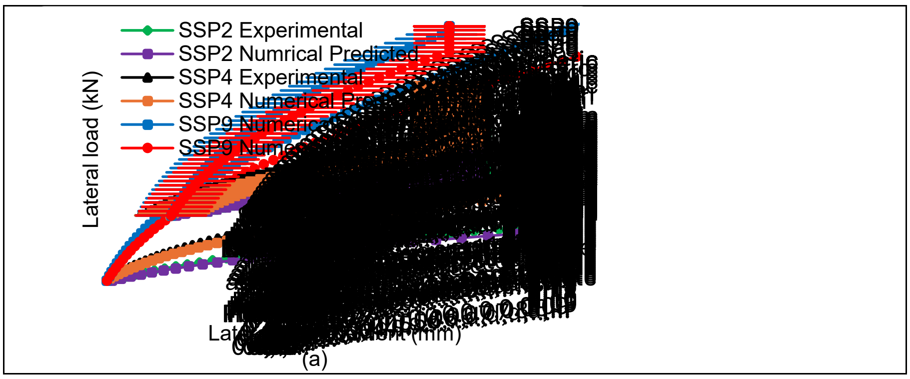


Figure 7. Effect of slenderness ratios on the pile capacity at 3D pile spacing of stainless steel pipe piles in loose layer in-between dense layers

Figure 7.shows a variation of the lateral load capacity of pile with different slenderness ratios of the stainless steel pipe pile in loose layer in-between dense layers.From figure 7, it is concluded that the increase in slenderness ratios increases the lateral load capacity. It is observed that the lateral load capacity increases when slenderness ratios changes from 25 to 30in loose layer in-between dense layers. When slenderness ratio changes from 25 to 38, the percentage increase in pile capacity is in the range of 7.27-7.85%, the percentage increase in pile capacity is quite low.

6 NUMERICAL RESULTS AND DISCUSSION

6.1Experimental and Predicted Lateral Load versus Lateral Displacement



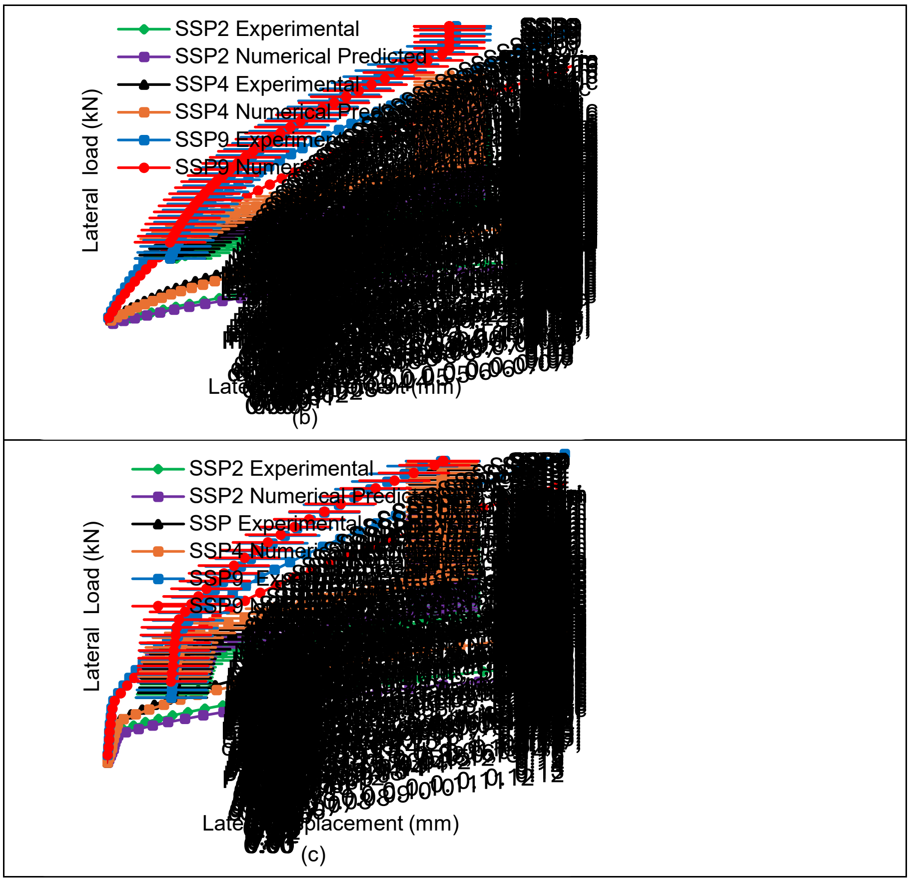
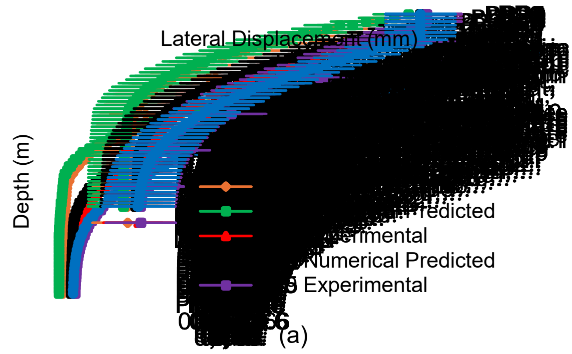


Figure 8. Comparison between the experimental and predicted lateral load results at 3D pile spacing of stainless steel pipe piles in loose layer in-between dense layers: a. SL=25; b. SL=30; c. SL= 38.

The lateral load-lateral displacement behavior of the stainless steel model pipe piles are studied by using lateral load-lateral displacement curves. The curves are drawn between the lateral load and lateral displacement at pile head in loose layer in-between dense layers at 3D pile spacing. Figures8(a to c) shows the typical comparison between the experimental and predicted lateral load results at 3D pile spacing of stainless steel pipe piles in loose layer in-between dense layers (a. SL=25; b. SL=30; c. SL= 38) for different pile group. It is observed that when two pile group to nine pile group, the behavior of pile is almost like two pile group. It shows very clearly that if pile group decreased from nine piles to two piles, the effect of two pile group is almost small on the lateral load pile capacity. The experimental results are compared with those obtained from finite element analysis (FEA) SoilWorks 2D and found to be in good agreement. From these figures, it observed that the slenderness ratio increases, the lateralload capacity increases significantly for both the cases, experimental and finite element analysis (SoilWorks 2D). This reduction in pile capacity for a loose layer in-between dense layers is because of the reduction in soil density and passive resistance of the soil in front of the pile.

Using the soil reaction-displacement (p-y) relationships the soil property values proposed in the standard (Rees et al. 1974) p-y formulation, the predicted lateral response for the test pile is shown in comparison to the experimental response in Figures 8(a to c). For the stainless steel pipe pile, the predicted and experimental lateral load are in good agreement initially, but the numerical predicted lateral load is less than the experimental maximum lateral load.



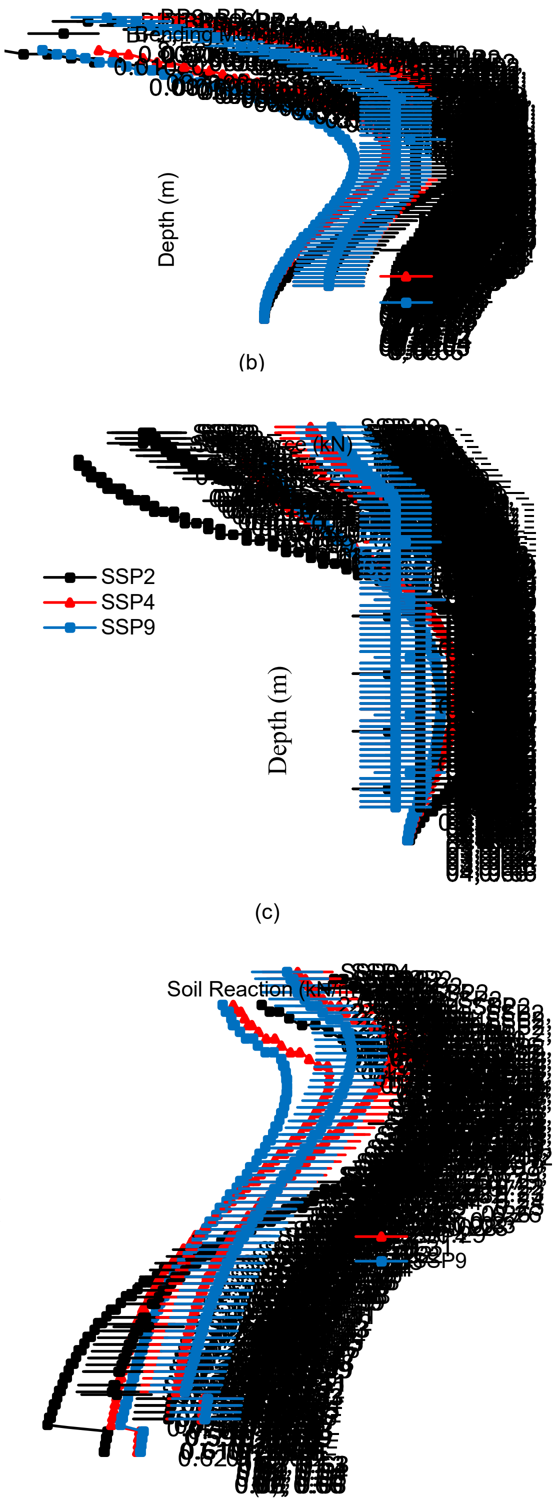
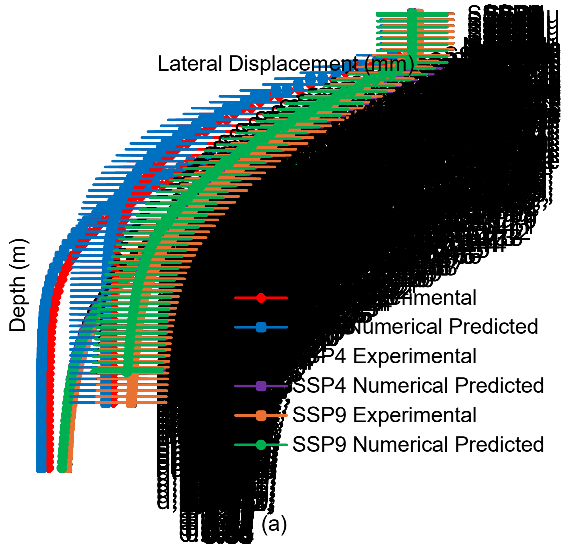
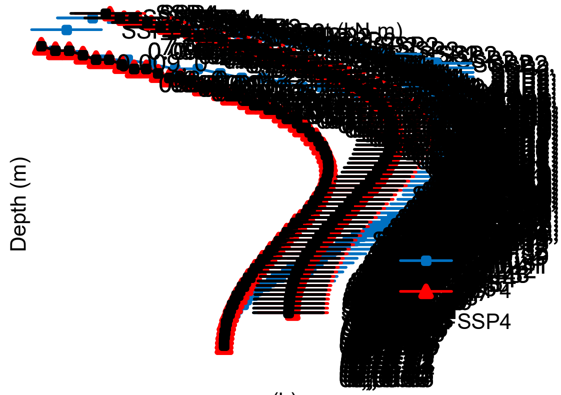
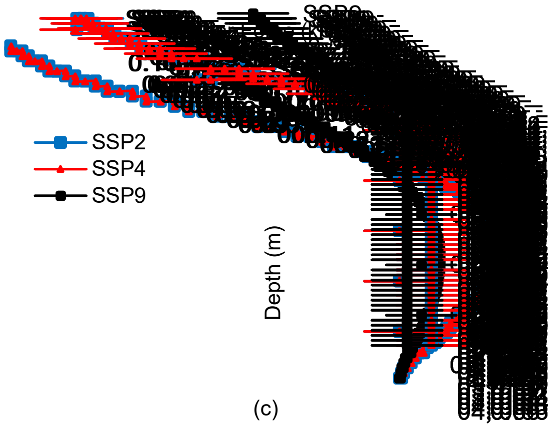
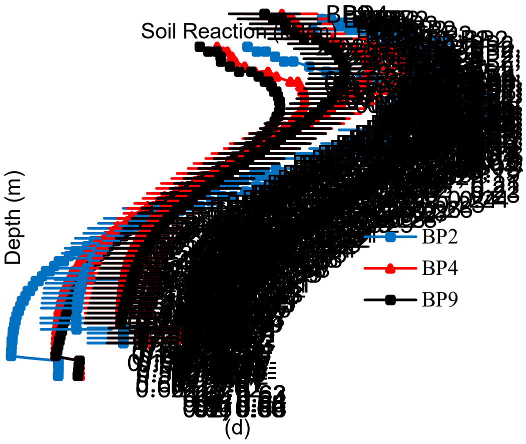


Figure 9(a to d). Lateral displacement, bending moment, shear force and soil reaction along the depth of stainless steel pipe pile group numerical predicted at 3D pile spacing in loose layer in-between dense layers for slenderness ratio=25.


Lateral Displacement (mm)
Depth (m)
SSP4 Numerical Predicted
SSP9 Experimental
SSP9 Numerical Predicted
(a)


Depth (m)
SSP4
(b)


SSP2
SSP4
SSP9
Depth (m)
(c)



(d)

Figure 10(a to d). Lateral displacement, bending moment, shear force and soil reaction along the depth of stainless steel pipe pile group numerical predicted at 3D pile spacing in loose layer in-between dense layers for slenderness ratio=30

6.2Bending moment variation along the pile depth

Figures 9b and10b, shows the bending moment along the depth ofstainless steel pipe pile group at 3D pile spacing in loose layer in-between dense layers. From these figures, it observed that, the maximum bending moment increases while decrease in the pile group. In addition, for the same length of pile (say 720mm), the bending moment is more in loose layer in-between dense layers for all slenderness ratios. Here, because of the decrease in the resistance at the top portion of the soil mass as there is a reduction in the soil mass in the loose layer in-between dense layers. In addition that, the depth at which the maximum bending moment (MBM) occurs at depth of fixity, then decreases with increase in the flexural stiffness of the pile and the soil because of the increase in the embedded length of the pile. Since the bending moment profile, it observed that the depth of fixity occurs almost at a depth of 10.83D and 11.25D below the soil surface for slenderness ratios, 25 and 30respectively. Here it observed that, there is little change in depth of fixity because of the changes in the soil layer.

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 small. Note that the two piles to nine pile group develop the same bending moment, because they have the same square pile configuration in both the direction. Also, the largest moments below the ground elevation are only 56.43% of their pile top values. Due to the uncertainty of lateral load direction (i.e., ship impact, earthquake), as well as scour effects, typical design (i.e., selection of cross-section and reinforcement) for the whole group is controlled by the largest individual pile stresses (i.e., bending moments). Consequently, the largest bending moments in all the piles of a group would occur in the two pile group and are typically used for design.

6.3Shear force variation along the pile depth

Figures 9c and 10c shows the shear force along the depth of stainless steel pipe pile groups at 3D pile spacing in loose layer in-between dense layers. From the figures, it is observed that the maximum shear force increases with decrease in the pile groups (nine pile group to two pile group). Also, for the same length of pile (say 720mm), the shear force is more for loose layer in-between dense layers. This is because of the decrease in the resistance at the top portion of the soil mass as there is a reduction in the soil mass in the loose layer in-between dense layers. Here it is observed that, the depth at which the maximum shear force occurs at depth fixity, decreases with increase in the flexural rigidity (EI) of the pile and the soil because of the increase in the embedded length of the pile. Since the shear force profile, it observed that, the depth of fixity occurs almost at a depth of 15.41D and 15.83D for stainless steel model pipe piles in loose layer in-between dense layers below the soil surface of slenderness ratios, 25 and 30 respectively. Here this is also observed that, there is little change in depth of fixity because of the variation in soil layer.

Note that, for each density, there is not a large difference between the maximum shear force for the different sizes (i.e., four pile to nine pile group). The latter is expected from the assumptions that, shear force is free of group size but only a purpose of pile position within the group. The differences were partly due to the slight variation in the free lengths of the individual pile groups.

6.4Distribution of Soil Reaction

The soil reaction can be readily obtained differentiating the shear forces down the pile as shown in Figures 9c and 10c. Figures 9d and 10d present the relationships between the soil reaction and the depth of pile at experimental lateral loads for slenderness ratio 25 to slenderness ratio 30 in loose layer in-between dense layers. Figure 9d reveals different pattern of lateral load transfer at the experimental load obtained for the different pile group configurations. For the pile in the uniform horizontal elastic medium, the soil reaction reduces along depth and has a maximum value at a depth 0.15m. Of course, this is in realistic. In a real situation, the soil below the ground surface will yield when its limiting shear strength is reached. Then the, soil reaction close to the depth of pile should be small. The numerical analyses consider yielding of the foundation; thus, more reasonable soil reaction distributions are obtained. For the nine pile group configurations, the soil reaction values are significantly smaller than those in the four pile group and two pile group configurations. Within the corresponding zone, due to the high compressibility of the soil. The average soil reaction in the upper 0.25Ldepth is only approximately 28% of that in the four piles and two pile group configurations. Such downward load transfer results in a significant lowering of the locations of the maximum soil reaction. The maximum soil reaction along occurs approximately at depth =0.17L in the nine pile group, which is significantly lower than at depth=0.25L in the two pile group. In allthree pile group configurations, the integration of soil reaction along depth of each case should be equal to the applied lateral load.

For the slenderness ratio as 30, the plastic zone infront of the pile extends to beneath the nine pile group configuration, if any, as demonstrated in Figure 10d. In the plastic zone, the effects of the nine pile group on the distribution of soil reaction become much lesser significant than those in slenderness ratio as 30. At both slenderness ratios, it can be seen that a larger value of the maximum soil reaction is resulted with a smaller pile group configurations. This is expected, because a pile behaves more flexibility in a stiffer foundation, the lateral load will be transferred to a shallower depth.

7 CONCLUSIONS

Following conclusions were drawn based on results obtained from experimentaland numerical programme on laterally loaded piles in layered soil;

1. It is observed that lateral load displacement behaviour of the pile and pile group is non linear in most of the cases studied with different combination of number of piles, stiffness of the pile material and density of sand layers.
2. The increase in slenderness (L/d) ratio increases the lateral load capacity of the pile. For a pile group with slenderness (L/d) ratio 30 and 38 in loose layer in-between dense layers percentage increase is 8.5% to 28.22%.
3. For pile groups with slenderness (L/d) ratios 25, 30 and 38 in loose layer in-between dense layers the percentage increase in pile group capacity is in the range of 15% to 28%.
4. 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 Stainless steel pipe pile group carries a load of 0.484kNat density 16.00kN/m^3.
5. The lateral load experimental test on stainless steel pipe piles showed similar behaviour to that from experimental study and numerical study. The maximum bending moment increases with decrease in the pile group. From the results, it is observed that the maximum bending moment increases almost 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.
6. Considering the results of experimentally and numerically, here it is concluded that agreement between the predicted maximum lateral displacement from experiments is ‘excellent’.
7. As the depth of fixity decreases with the increase in the slenderness ratios of the piles. This is because the increase in the flexural stiffness of the pile and the soil because of the increase in the embedded length of the pile. The depth fixity occurs almost at a depth of 10.83D, 11.25D and 11.70D below the soil surface for slenderness ratios, 25, 30 and 38 respectively. It can be seen that, there is little change in depth of fixity because of the difference in soil layer.
8. The soil around the piles moves along the movement of the pile cap. The relative movement between the pile and soil is therefore reduced, resulting in relatively low shear forces at the top of the pile.
9. The model predictions in terms of the pile displacement along the length of the pile are in good agreement with the experimentalresults.
10. Lateral displacements induced on pile due to lateral soil flow depend on its slenderness ratio. More slender a pile; more it is subjected to lateral displacement due to ground movements.

11.The bending moment, shear force and soil reactions are along the length of pile with same length and different slenderness ratios, a close matching between the results were obtained.

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