An Experimental and Numerical Study on Behaviour of Single Pile and Group of Piles in Layered Soils under Vertical Load

Plaban Deb[1], Dr. Sujit Kumar Pal[2]
[1]Post-Graduate Student,[2] Associate Professor
Dept. of Civil Engineering, NIT Agartala
Tripura, India

Abstract— **The behaviour of single and group pile in multiple layered soils is studied herein. This paper describes a prototype test on model pile groups of configuration 1×1, 2×2, and 3×3, for embedment length to diameter ratios (L/D) of 5, 6, 7 and 8, and spacing 3 times of diameter, subjected to vertical loads are conducted on three layers of different soil type maintaining equal depth for each of the layers. The model piles used for the test are 250 mm in length with 25mm diameter and a test tank of dimension 700mm × 700mm × 600mm was used. This work also uses 3D finite element modelling on ABAQUS to analyse the effect of soil properties, pile length-to-diameter ratio and time-dependent load-settlement behaviour on the capacity of a pile. Experimental investigations are made to relate the load-settlement characteristics of different pile configuration with their respective length-to-diameter ratio, ultimate load with respect to their length to diameter ratio, load improvement ratio with number of pile and efficiency of pile group in each pile configuration. The test results indicate that pile capacity increases with the increase of number of pile and length-to-diameter ratios and load improvement ratio increases with increase of number of piles. It is perceived that 3×3 group piles have almost 5-8 times and 2×2 group piles have almost 2-3 times greater load carrying capacity than the single piles. The numerical analyses i.e. finite element analyses (FEA) describe the variation of stress, strain and stain energy with respect to time and demonstrate the variation of pile-soil stress ratio with different embedded length.**

Keywords— Single and group pile, Embedment length to diameter ratio, Pile capacity, Load improvement ratio, FE analysis, Stain energy and Pile-soil stress ratios.

I. INTRODUCTION

In the early stages of development, villages and towns were located in the close vicinity of lakes and rivers due to the availability of water, and, also, to ensure proper protection of the area. Therefore, the weak bearing ground was reinforced by the use of piles that were either manually forced into the ground, or fixed in holes that were filled with stones and stand. More recently, the growing need for housing and construction has forced the various agencies to exploit lands with poor soil characteristics. This has led to the development and improved piles and pile driving systems. A pile is a vertical structural element of a deep foundation, driven deep into the ground at the building site. Pile foundations are generally preferred when the strata at or just below the ground surface is highly compressible and very weak to support the load transmitted by the structure. Pile foundations are also used to resist horizontal forces in addition to support the vertical loads in earth-retaining structures and tall structures that are subjected to horizontal forces due to wind and earthquake. Piles are generally designed to resist axial loads which normally act on the pile head by developing positive shaft resistance (PSR) and end-bearing resistance [1]. The pile driving process can potentially create large stresses and deformations in the neighbouring soils [2]. The deformation of clayey soil is affected by the load increment at which the external load is applied. If soft compressible layers are present below the pile tips, pile group can undergo for substantial settlements, whereas the settlement of a single pile is almost unaffected by the compressible layer[3]. The effect of the underlying compressible layer on the group settlement is mostly suitable for larger pile group [4]. Due to the interaction of neighboring piles, the behavior of pile groups under the applied loads is generally different from that of a single pile. The overall behavior of a pile group is given by the efficiency of the group. The increase of the number of piles in-group decreased group efficiency owing to the increased overlapping zones and active wedges [5].

The behaviours' of piles are usually investigated with pile load test in the field. However, it requires very high cost for conducting full-scale pile tests in the field and the inherently high variability of the field conditions make them impractical for research purposes. Therefore, model tests are usually used for investigating the behaviour of piles. Many researchers have conducted the pile load test in prototype models and have showed different variation with several parameters of load- settlement behaviours.

The behaviour of single and group pile under axial loading is examined by many investigators and the outcomes illustrate that piles are most effective when combined in groups and the behaviour of pile groups under the applied loads is generally different from that of a single pile due to the interaction of neighbouring piles. But not many works is done on the behaviour of piles in layered soil and hence it has very limited demonstrations. So, this paper is going to study the behaviour of single and group pile in multiple layered soils. The purpose of this study is to investigate the load-settlement behaviour of axially loaded pile embedded in layered soil. The load-settlement characteristics of single and group piles are made with different embedded lengths of piles.

II. EXPERIMENTAL WORK

A. Methodology

Model experiments are carried out in the laboratory to measure the pile behaviour under static vertical load. Models are properly scaled down so that the load-settlement behaviour of pile measured from the small-scale models can be used to interpret the behaviour of prototype pile foundations. The height of the soil is selected 2 times greater than the maximum embedded length of pile to ensure insignificant effect of a rigid base behaviour of piles [6]. Experiments are carried out on a model single pile and group pile embedded in locally available soils. The experimental work shows the physical and engineering properties of material used in the present work and testing procedure. Details of experiments conducted are discussed in the following sections.

B. Materials used

1) Soils: The soil condition at the site for any proposed structure illustrates the choice of suitable foundation to support various structures. In the present investigation, three types of soil are used in the test viz. clayey silt, sandy silt and sand. The soils are collected from locally available fields. The physical and engineering properties of the collected soil samples are determined through laboratory tests as per the standard procedures recommended by the ASTM codes. The summary ofindex and engineering properties of soil is shown in Table 1.

2) Model piles and pile cap: The model pile used in the experiment are smooth, hollow and of circular cross-section. The piles are made of aluminium of outer diameter of 25 mm and inner diameter of 23 mm and 250 mm length. The range of prototype dimensions represented by the model pile for different scale factors is calculated using the following formula [7 & 8]

$$\frac{(EI)_P}{(EI)_m} = n^{4.5}$$

Where n = scale factor; (EI)p and (EI)m = flexural rigidity of prototype pile and model pile, respectively. Length to diameter ratios (L/D) of 5, 6, 7 and 8 are used in the present investigation for simulating short piles in the model experiments. Pile spacing for group pile used in the model experiment is 3 times the diameter of pile. Pile group used in the model experiments are single, 2×2 and 3×3. Piles caps are made of steel. The dimensions of pile cap are 35mm × 35mm × 5mm, 180mm ×180mm × 5mm and 240mm × 240mm × 5mm.The pile length includes the embedment length required for a particular L/D ratio, plus a free standing length for avoiding contact of the pile cap with the soil. This would ensure that the behaviour measured from the experiments is only due to interaction of pile and soil.

TABLE 1. PROPERTIES OF SOILS

Properties	Clayey silt	Sandy silt	Sand
Co-efficient of Curvature, C_c	1.58	1.8	0.95
Uniformity Co-efficient, C_u	9.48	3.45	11.2
Specific gravity, G	2.71	2.63	2.56
Maximum Dry Density, γ_d (kN/m^3)	18.05	18.41	12.95
OMC(%)	23.5	12.6	8.5
Liquid Limit (%)	45.2	26.32	-
Plastic Limit (%)	28.78	20.12	-
Plasticity Index (%)	16.49	6.2	NP
Cohesion, C (kN/m^2)	21.22	16.4	-
Angle of internal friction, φ (degree)	27.54	23.4	31.2

Note: OMC= Optimum Moisture Content, NP = Non-Plastic

C. Test Setup

The test setup for static vertical load tests on piles is shown in Fig 1, consisting of soil tank, piles and pile cap, screw gear wheel, loading frame, proving ring and dial gauges are used to conduct tests. Vertical load is applied through a screw gear mechanism by a movable wheel. A calibrated proving ring of capacity 25kN and dial gauge of sensitivity 0.01mm are used for measuring loads and pile displacement respectively.

D. Bed Preparation and Pile Installation

The test has been conducted on three layers of soil maintaining equal depth for each of the layers. Clayey silt is on the top layer, sandy silt on the middle layer and sand is given on the bottom layer. Each layer of soil is further semi divided into three layers for better compaction. The soil is compacted with a steel plate hammer (with light compaction energy) in each layer. The density achieved is confirmed by collecting samples in small container of known volume placed at different positions of each layer in the test tank at the time of filling and density of each soil layer is determined. The soil bed prepared is homogeneous for all the tests and the method adopted in this work ensures the uniformity of work.

Initially, the soil is filled up to the pile tip and then the pile is kept vertically in its position. After that, soil is again filled up to the required height. During this process, it ensures that the pile remains vertical. This procedure of pile fitting is assumed to simulate the stress conditions around piles cast-in- situ. After each test, all of the soil and pile are removed from the tank and the process is repeated for conducting the next test.

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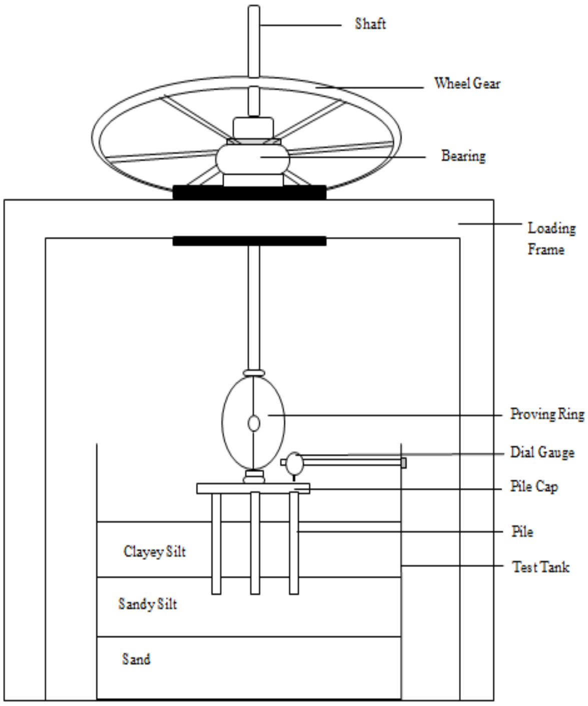

Fig.1.Test setup

IV. TEST PROCEDURE

The schematic diagram of the test setup, loading arrangement and model pile group with pile group is shown in Fig.1.Soil was placed in the test tank in three layers of 15 cm each where each layer was semi divided into three equal layers for obtaining the required density. The model pile was placed on the centre line alignment for equal distribution of load on the pile cap. The sequence of pile installation was started with the inner pile, then corner pile and finally the edges pile. The inclination of the piles was checked carefully by a level during installation. Each test was carried out after 1 day from the day of preparing the soil bed because it was allowed to cure the soil bed at room temperature for about 24 hours to permit uniform distribution of moisture content. The vertical load was applied in the model pile using screw gear mechanism by a movable wheel. In each test, the loading was applied to the model till the settlement reached about 25 mm.

V. FINITE ELEMENT ANALYSIS OF MODEL PILE

The analysis of single and group pile is also investigated by 3D FEA software, ABAQUS 6.12. Soil model is made in three different layers on a single part, keeping the depth and dimensions as same as the experimental data. The piles and pile caps are also made using the dimensions from test data. The property given in every part is consisted of their actual experimental value which is described in Table 2. All the assembled parts are made as solid, elasto-plastic and homogeneous [9].It is assumed that the soil and pile are both deformable bodies.The pile soil interface is considered as no frictionless with no sliding [10]. The interface given between the pile and soil are considered as tie contact to ensure the proper load transfer from pile to soil [11]. The boundary provided at the bottom is pinned and the lateral boundary is supported by roller. The meshing put on to the model are a combination of different mesh densities where a relatively finer mesh is used near the pile soil interface to attain large shear strain variation and thinner mesh is applied further away from the pile [1]. Different models are made for different L/D ratio and different group of pile. Single, 2×2 and 3×3 pile group model are prepared using ABAQUS.

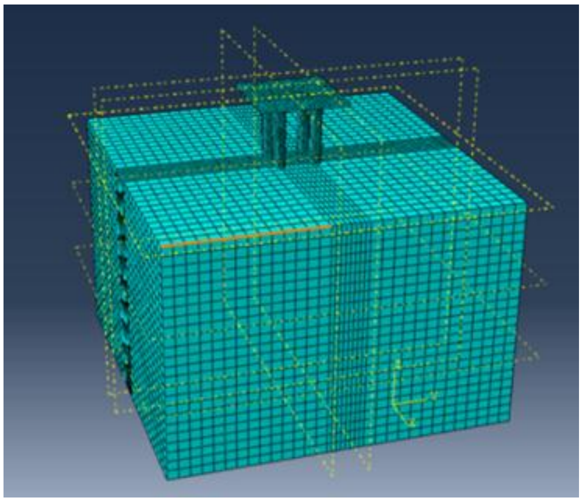

Fig.2. Mesh for 2×2 Pile group

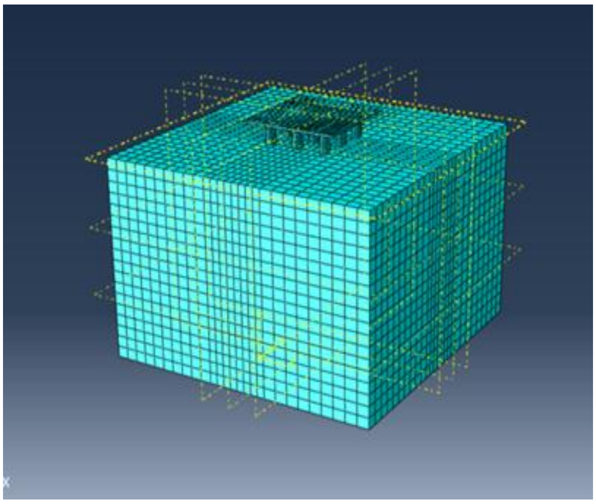

Fig.3. Mesh for 3×3 pile group

From the finite-element analysis, the time-dependent variations are obtained for each pile group and each L/D ratio. The variation of stress, strain and energy with respect to time is developed from the software. The meshing pattern is shown in Fig.2 and Fig.3.

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TABLE 2. PROPERTIES OF MATERIALS USED FOR MODELLING

Materials	Modulus of Elasticity (kPa)	Poisson's ratio	Density (kN/m^3)
Clayey silt	6×10^3	0.5	18.05
Sandy silt	3×10^4	0.35	18.46
Sand	2.5×10^4	0.38	12.95
Pile	6.9×10^7	0.32	27
Pile Cap	2.1×10^8	0.3	78.7

VI. RESULTS AND DISCUSSIONS

E. Load–Settlement Curves

Typical results of load versus settlement of single pile and group pile with respect to their length to diameter ratio are shown in Figs.4 to 6. All other test results show similar behaviour. It can be seen from these figures that the load at a specific settlement increases as the L/D ratio increases. The load–settlement curves for all tests indicate that the load–settlement curves do not show a peak behavior i.e. with increase in pile settlement the vertical load increases. The experimental data represented that for each type of pile either group or single, the load carrying capacity increases with the increase of L/D ratio. That means with higher L/D ratio a pile group can sustain substantial amount of load. Experimentally tested result also showed that for 25 mm settlement, 3×3 group piles are almost 5-8 times greater load carrying capacity than the single piles and 2×2 group piles are almost 2-3 times greater load carrying capacity than the single piles. So it can be concluded that with increasing L/D ratio and with increasing number of pile group, the load carrying capacity is also improved.

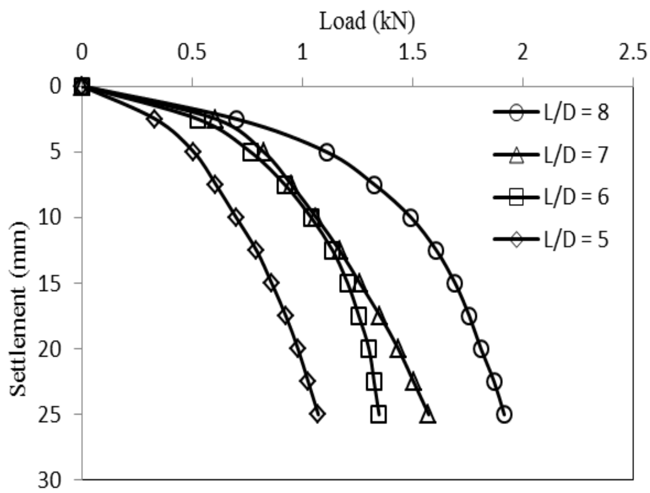

Fig.4. load vs. settlement curve for single pile

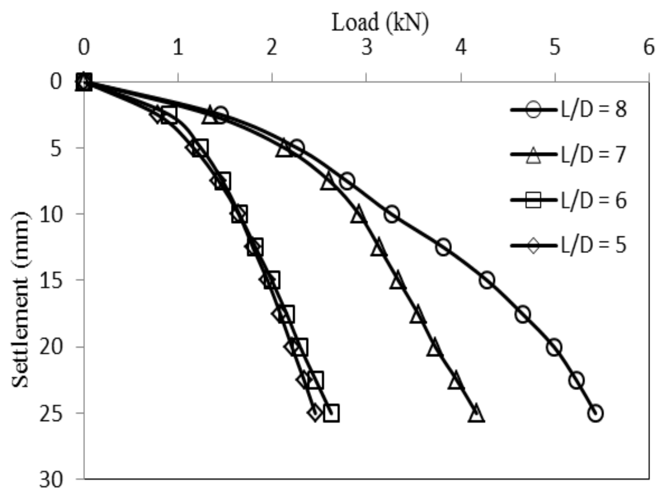

Fig.5. load vs. settlement curve for 2×2 pile group

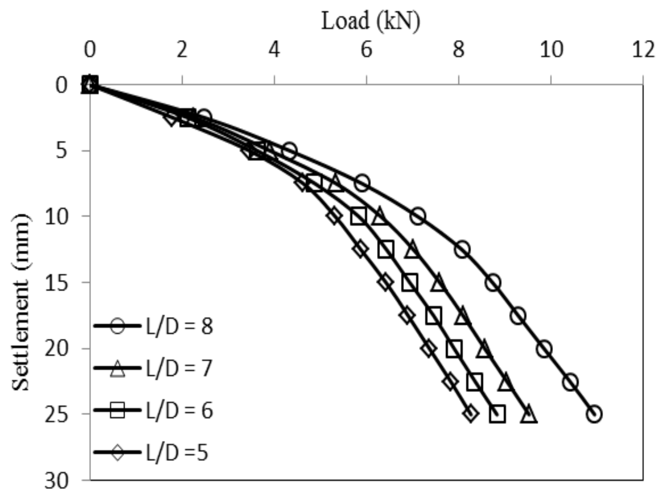

Fig.6. load vs. settlement curve for 3×3 pile group

F. Ultimate failure load

Several interpretation methods to evaluate the ultimate failure loads is shown in Table 3.

TABLE 3. SUMMARY OF FAILURE CRITERIA FOR INTERPRETING ULTIMATE LOAD

Failure criterion	**Description**
Slope-tangent method based on the Q−S curve [12]	Failure load is defined at the intersection point of the initial and final tangent lines to the Q−S curve
Limiting displacement-rate method based on the ΔS−log t curve [13]	Failure load is defined as the load at which the displacement rate reaches its maximum value for the pile settlement to be convergent
Reference-displacement method [14]	Failure load is defined as the load at a displacement of 10% of the pile width.

Note: Q=applied load; S=pile group settlement; ΔS =pile group settlement increment at a load step; and t =loading time at a load step.

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For present study the ultimate load was determined by tangent intersection method. In this method a tangent from initial point and another tangent at the point where the curved part of the load settlement curve changes to a steep straight line has been drawn and their intersecting point give the value of ultimate load. The evaluation of ultimate pile capacity of each pile group is shown in Figs.7 to 9 and the obtained ultimate pile capacities are tabulated in Table 4.

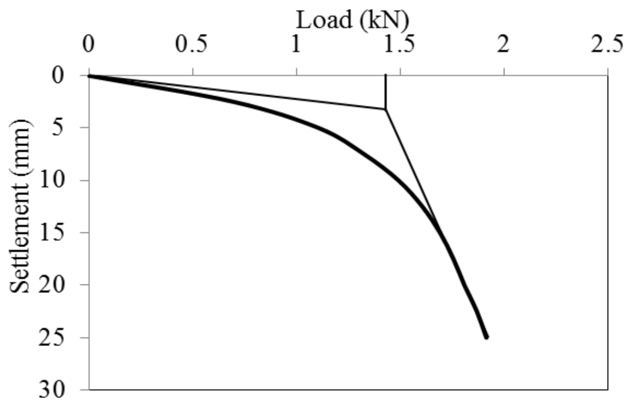

Fig.7. Ultimate load on Single Pile for L/D = 8

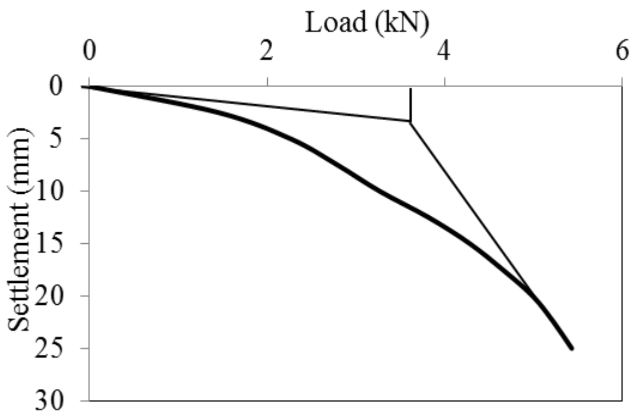

Fig.8. Ultimate load on 2×2 pile group L/D = 8

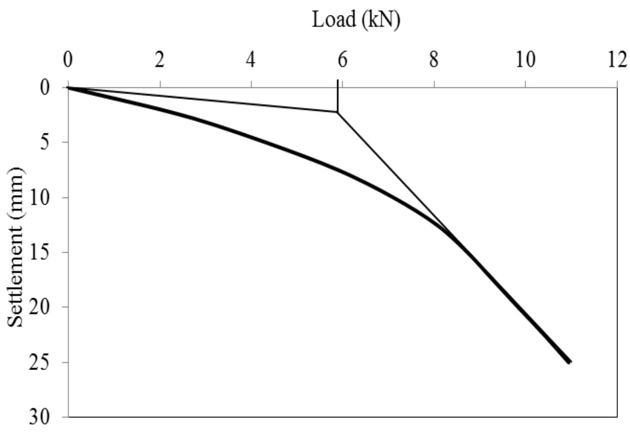

Fig.9. Ultimate load on 3×3 Pile group for L/D = 8

TABLE 4. ULTIMATE LOAD ON DIFFERENT PILE GROUP

L/D	Ultimate load (kN)		
	SINGLE	*2×2*	*3×3*
5	0.70	1.095	4
6	0.89	1.25	4.81
7	0.95	2.21	5.62
8	1.46	3.65	5.95

The variation of ultimate load vs. length to diameter ratio is shown in Fig.10. The result shows that 3×3 pile group possesses maximum ultimate load with maximum length to diameter ratio. From the test result, it can be concluded that, 3×3 pile group can withstand more load when compared to single pile and 2×2 pile groups. From Fig.10, it is observed that the ultimate load always increases with L/D ratio for each type of pile group. Another point that can be obtained from the result is that 2×2 pile group with L/D ratio 8 gives almost similar value as given by 3×3 pile group with L/D ratio 5. So, where we need to provide 3×3 pile groups, we can also go for 2×2 pile group with higher L/D ratio.

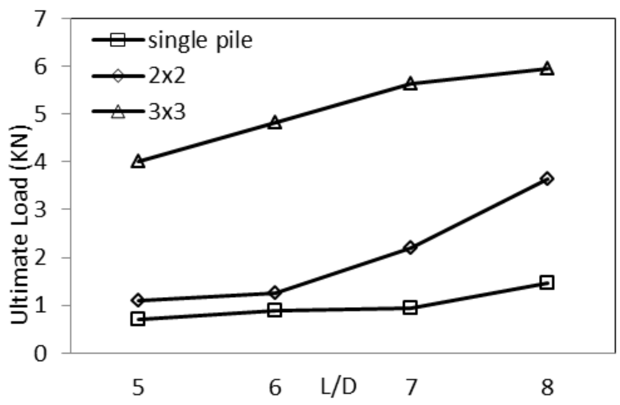

Fig.10. Ultimate load vs. L/D curve

G. *Load improvement ratio corresponding to each L/D ratio for different settlement*

Load improvement ratio (LIR) is the load carried by the group pile to the load carried by the single pile. It is an approach to determine the load increment of a group pile when compared to a single pile. The higher the LIR value, higher will be load carrying capacity of group pile. LIR vs. L/D curves are shown in Figs.11 and 12. LIR vs. L/D curves for 2×2 pile group indicate that with increasing L/D ratio the value of LIR first decreases up to a certain point and then started increasing. For 5 mm and 10 mm settlement, the LIR values are maximum at L/D ratio 7. But for 20 mm and 25 mm settlement the behavior of both the curves are very similar in nature and show their maximum value at L/D ratio of 8. LIR vs. L/D curve for 3×3 pile group show some different result from 2×2 pile group. The results indicate that with increase in L/D ratio LIR value gradually decreases. It is due to the reason that with the increase of number of pile and embedded length, the stress overlap zone also increases causing the gradual decrease of LIR value.

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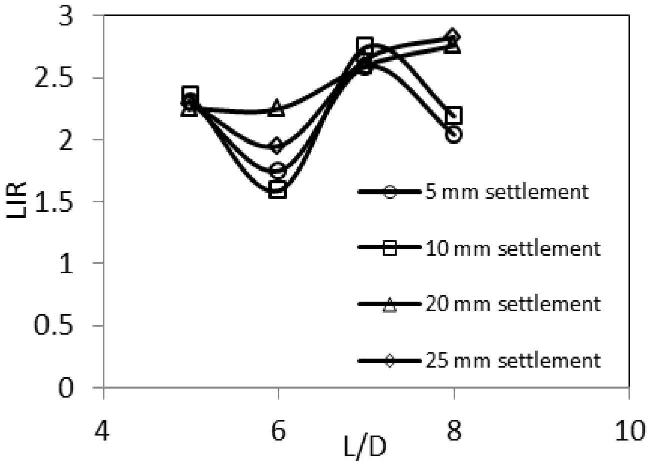

Fig.11. LIR vs. L/D curve for 2×2 pile group

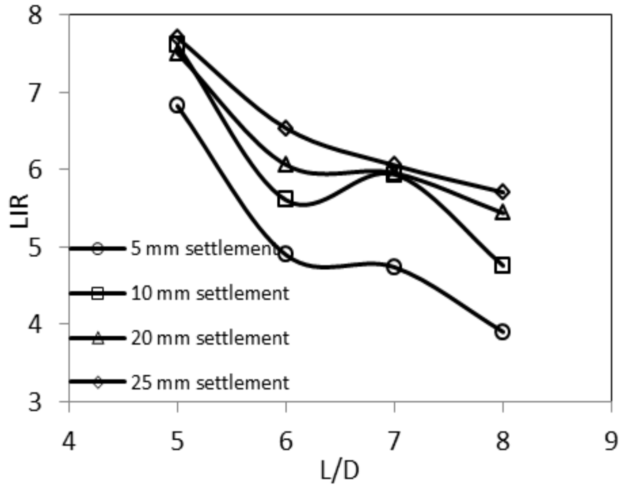

Fig.12. LIR vs. L/D curve for 3×3 pile group

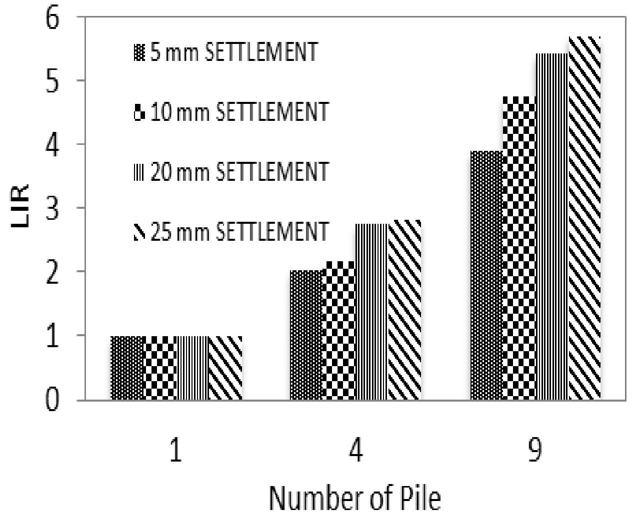

Fig.13. LIR vs. number of pile for L/D ratio 8

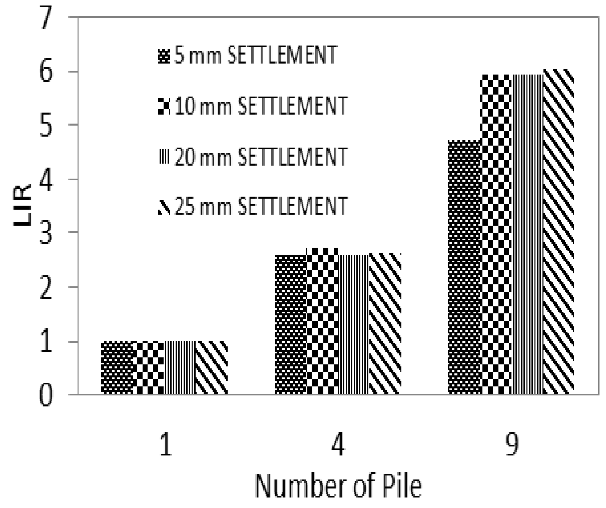

Fig.14. LIR vs. number of pile for L/D ratio 7

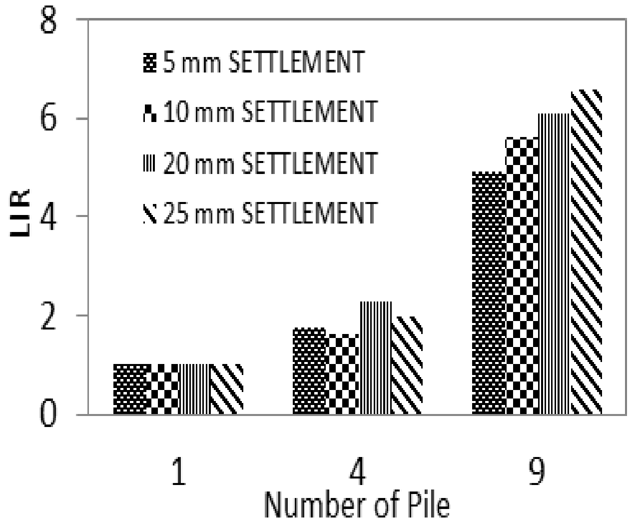

Fig.15. LIR vs. number of pile for L/D ratio 6

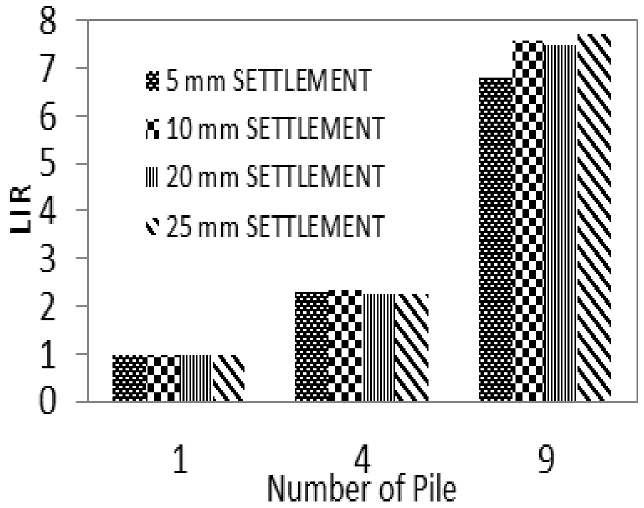

Fig.16. LIR vs. number of pile for L/D ratio 5

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LIR vs. L/D curve for 3×3 pile group show some different result from 2×2 pile group. The results indicate that with increase in L/D ratio LIR value gradually decreases. It is due to the reason that with the increase of number of pile and embedded length, the stress overlap zone also increases causing the gradual decrease of LIR value.

The charts (Figs. 13 to 16) of LIR vs. number of pile indicate that with the increase of no. of pile the LIR value started increasing [15]. But LIR values corresponding to settlement have shown mixed results. For 3×3 pile group, i.e. with number of pile 9, at 5 mm settlement, it showed minimum value of LIR where at 25 mm settlement it showed the maximum value. Similarly with 2×2 pile group, i.e. number of pile 4, with L/D ratio 8 and 7, LIR values increase with increasing settlement, but with L/D ratio 6, at 10 mm settlement, it showed minimum value of LIR where at 20 mm settlement, it showed the maximum value and at L/D ratio 5 LIR values are almost same for different settlement which ensures that at L/D ratio 5, the increment of LIR value for different settlement is very less.

H. Variation of efficiency w.r.t L/D ratio

The efficiency (η) of a pile group is defined as the ratio of the group capacity to the sum of the capacities of the number of pile in group. The result obtained from L/D vs. efficiency curve indicate that for 3×3 pile group, the efficiency decreases with increasing L/D ratio in both the case of 0.1D settlement and 25 mm settlement. This can be attributed to the increased area of overlapping zones between piles and active wedges. For 2×2 pile group, efficiency first decreases and then increases with L/D ratio. At L/D ratio 8 the efficiency is more for 2×2 pile compare to 3×3 pile. Efficiency at 25 mm settlement is more than 0.1D settlement.

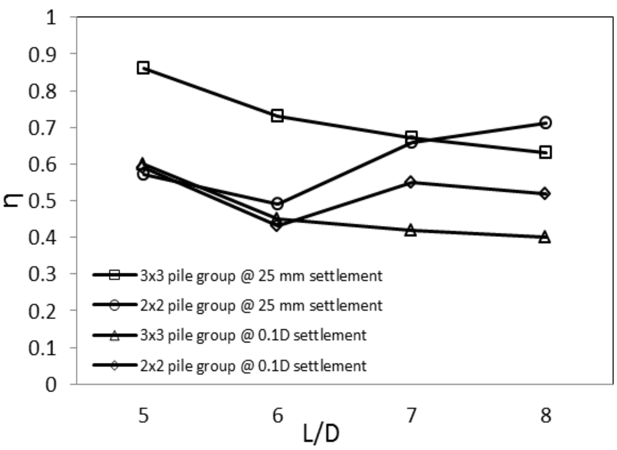

Fig.17. Efficiency vs. L/D for 2×2 and 3×3 pile group

I. Time dependent behavior of single and group pile

FE analysis of model pile indicates the variation of different parameters with respect to time and length to diameter ratio. Stress, strain and strain energy have been evaluated for every pile group with different L/D ratio. The results have been verified by means of stress vs. time, strain vs. time and strain energy vs. time curves which concludes to the deduction that the stress, strain and strain energy value will increase as the time passes. The values also increase with different L/D ratio. With the increment of time, the loading is gradually increasing up to the load corresponding to 25 mm settlement; hence the failure wedge is increasing that causes the increment of active wedge volume which depicts the reason of increment of strain energy with the passage of time. The stress vs. time, strain vs. time and strain energy vs. time curves are shown in Figs 18 and 19 which shows a non-linear

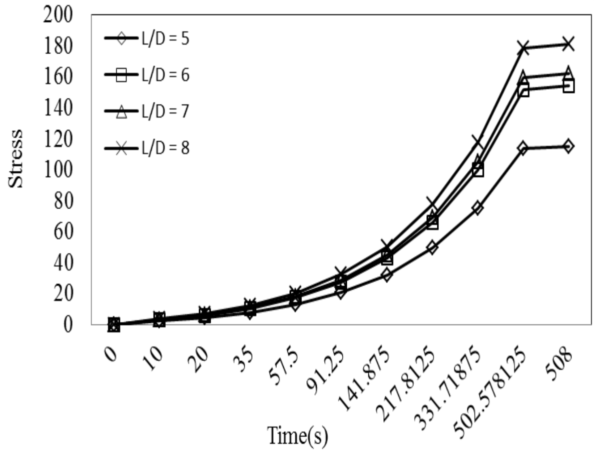

Fig.19. Stress vs. time curve for 3×3 pile group

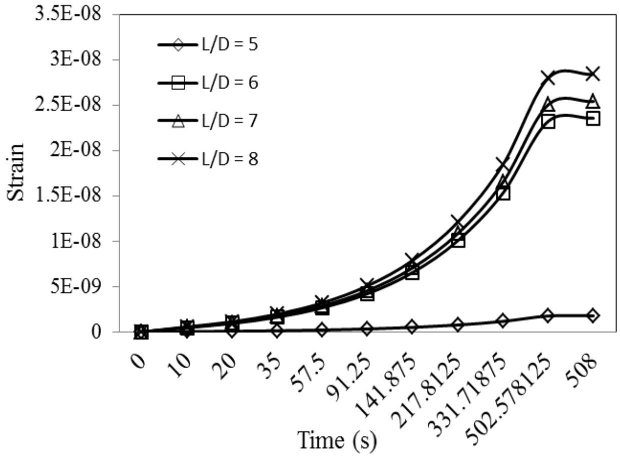

Fig.20. Strain vs. time curve for 3×3 pile group

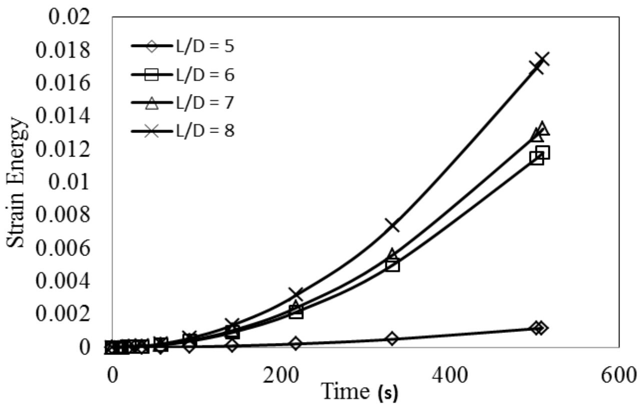

Fig.21. Strain energy vs. time curve for 3×3 pile group

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behaviour of stress, strain and strain energy with time. The curves presented here are showing the variation for 3×3 pile group; the variation type for other two pile groups is same and hence those are not figured here.

J. Pile soil stress ratio

Pile soil stress ratio has been evaluated with respect to different L/D ratio for three types of pile group. For single pile, the pile soil stress ratio remains almost same for different embedded length where for 2×2 pile group; pile soil stress ratio is maximum for L/D ratio of 6. For 3×3 pile group pile soil stress ratio is increasing with the increase of L/D ratio and shows the maximum value at L/D ratio of 8. It indicates that with the increase of L/D ratio pile is taking more load than the soil which ensures that soil is taking relatively less stress than the pile which ultimately interrupts the failure of foundation soil. The variation of pile soil stress ratio at different layers indicates that top layer is taking more stress as pile is resting mostly on top layer and the layer beyond the pile tip are taking relatively less stress which illustrates that with the increment of soil depth below the foundation soil will take relatively lesser stress. The curves showing pile soil stress ratio are shown in Figs.22 to 24 and the stress contours for different pile groups are indicated in Figs.25 to 27. From the numerical analysis it is evident that 3×3 pile group is taking maximum stress value which directs that the stress on soil will be very less and it will lead to better stability.

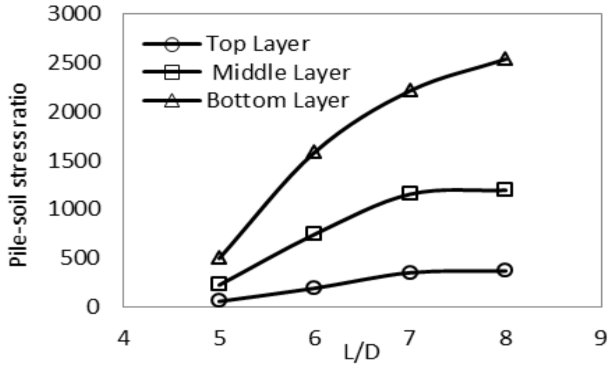

Fig.22. Pile-soil stress ratio vs. L/D curve for 3×3 pile group

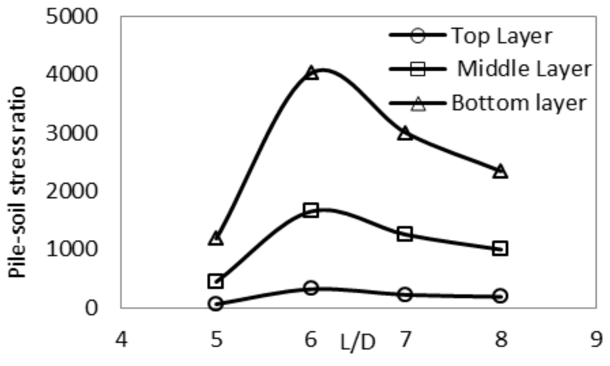

Fig.23. pile soil stress ratio vs. L/d curve for 2×2 pile group

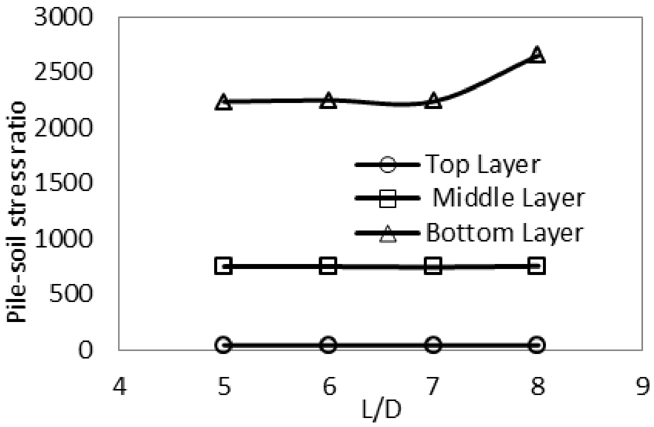

Fig.24. Pile-soil stress ratio vs. L/D curve for single pile

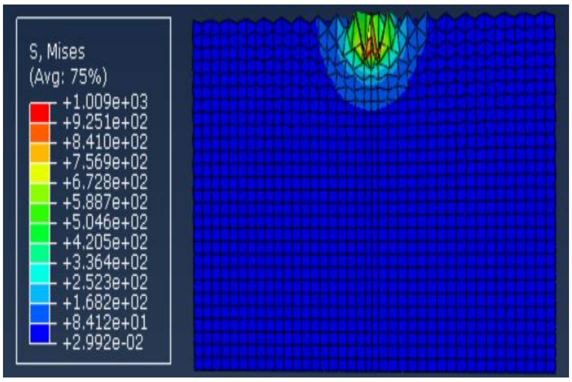

Fig.25. Stress contour for single pile

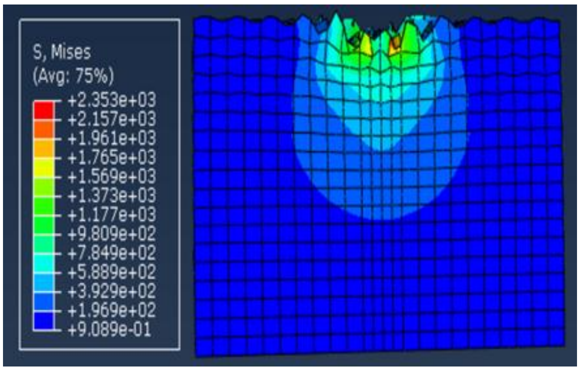

Fig.26. Stress contour for 2×2 pile group

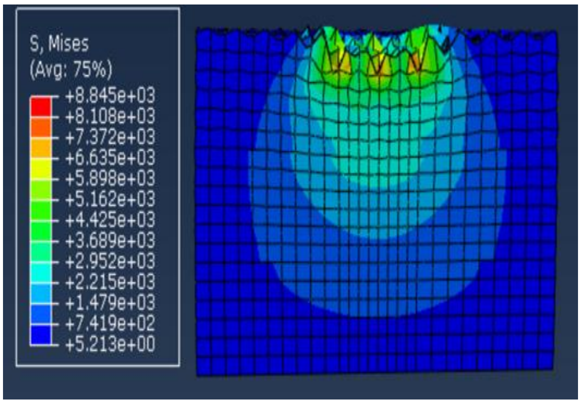

Fig.27. Stress contour for 3×3 pile group

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VII. SUMMARY AND CONCLUSION

The need for research on pile behaviour under vertical load in different layered soil is addressed by conducting experiments on model piles. Three different type of soil sample are taken to perform the test and dimensions of pile are modelled using proper scaling laws. The experimental setup is designed and fabricated carefully to avoid boundary effects. Experiments are carried out on piles subjected to vertical loading with different length to diameter ratio. FE analysis of single and group pile is done using ABAQUS. From the finite-element analysis, the time-dependent variations were obtained for each pile group and each L/D ratio. The variation of stress, strain and energy with respect to time was developed from the software. From the results of laboratory investigation and 3D FE analysis of behaviour of pile groups in layered soil under axially loaded modelled circular piles, the following conclusions are drawn:

1. The ultimate load increases with increase in length to diameter ratio for each type of pile group.
2. The behaviour of load vs. settlement curve is non-linear and for all tests indicate that the load–settlement curves do not show a peak behavior i.e. with increase in pile settlement the vertical load increases. For 25 mm settlement, 3×3 group piles are almost 5-8 times greater load carrying capacity than the single piles and 2×2 group piles are almost 2-3 times greater load carrying capacity than the single piles.
3. At 5mm, 10mm, 20mm and 25mm settlements, the load improvement ratio (LIR) increases as the number of pile increases.
4. The result obtained from length to diameter vs. efficiency curve indicate that for 3×3 pile group, the efficiency decreases with increasing length to diameter ratio in both the case of settlement at 10% of diameter and 25 mm settlement. For 2×2 pile group, efficiency first decreases and then increases with length to diameter ratio. At length to diameter ratio 8 the efficiency is more for 2×2 piles compare to 3×3 piles. Efficiency at 25 mm settlement is more than settlement at 10% of diameter of pile.
5. Stress, strain and strain energy increases as the time passes and the behavior of stress, strain and strain energy with time is non-linear.
6. For single pile, the pile soil stress ratio remains almost same for different embedded length where for 2×2 pile group, pile soil stress ratio is maximum for L/D ratio of 6, and for 3x3 pile group, pile soil stress ratio is increasing with the increase of L/D ratio

7. The variation of pile soil stress ratio at different layers indicates that with the increment of soil depth below the foundation soil will take relatively lesser stress.

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