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# Static behaviour of 3x3 pile group in sand under lateral loading

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**Abstract**. This paper presents the static lateral load behaviour of single pile in comparison with 3x3 pile group in sand. The piled raft system is modelled using PLAXIS3D. Parametric studies of varying length to diameter (L/D) and spacing of piles in a group and diameter of piles (S/D) have been performed. The behaviour of group piles in terms of static lateral load capacity and group efficiency has been discussed.

## 1. Introduction

The analysis and design of piles in sand and clay for lateral loading is a common problem in foundation engineering. Tall structures, Power plants, Bridges, Off-shore buildings are designed mostly with piles which experience lateral loads. Various researches have been carried out on the behaviour of piles under lateral loadings. Though, piles are commonly used in groups, and very little information is available on the effect of soil-pile-structure interaction on the response of pile groups under lateral loading. Piles are not only designed to take vertical load they are designed to take even lateral loads. The sources of lateral loads are debris loading, ice forces, vessel impact, lateral earth pressures, slope movements, and seismic events. Since, the pile foundations are failed under such high lateral loads, increasing the pile size or the percentage of steel will not be sufficient. The behaviour of a single pile in a group is controlled by its location within a pile group and its fixity condition at pile head.

There have been many experiments and numerical analysis carried out to study the performance of piles subjected to lateral loads. The piles in the leading row in a group pile share a large amount of load than the other piles.The response of a pile to the applied lateral load is modelled by developing *p-y* curve *y* is the lateral displacement and *p* denotes the resistance of soil per unit length of the pile [5, 7, 10 and 13]. Loading of piles laterally due to waves and earthquakes ware cyclic in nature due to which there is an additional complexity in the soil-structure interaction problem [6].The effective depth of a flexible laterally loaded pile embedded in cohesion less soil is about16 times the pile diameter [9]. The interaction between these loads is not significant as the vertical and lateral loads are assumed to act independently [9]. A 3D finite element modeling approach is proposed to calculate the response of RC piles to horizontal loading [10, 16]. Alternate horizontal and moment loads cause a large amount of settlement for the foundations of pile group. The piled raft foundation can effectively reduce the settlement caused by the alternate loads [12, 17,18]. Flexible piles of series arrayed were more resistant than those parallel arrayed to lateral loadings [10]. It is been evidenced from the study that the position of piles in the group clearly affects the response of the 1x2 pile group subjected to eccentric lateral loads [13]. The three-dimensional Plaxis model is validated using load–displacement results from centrifuge tests of laterally loaded piles embedded in sand [16]. Piles in natural sandy gravels exposed to lateral loads would show some influence of dilatancy in their behaviour [11]. Dissimilarity in Piles may result due to uncertainties in soil condition or imperfection in pile construction [18]. For both cases of bored and driven piles with piled rafts, load sharing model shall be applied in order to properly identify the load takingability of individual foundation elements [15]. Corner and centre piles in a square group subjected to torsion; bear the greatest and least lateral loads respectively [19]. A new analytical approach using partial slip is adopted which is based on bond degradation [20]. The lateral load carrying capacity increases with increase in length to diameter ratio of the pile up to a particular optimum length, beyond which effect of increase in length on load carrying capacity starts decreasing with further increase in length [21]. Piles are used to support combination of vertical and lateral loads [23].

The main objectives of this paper are to study the static behaviour of 3x3 pile groups in sand subjected to lateral loads. A parametric study was carried out to investigate the effects of pile spacing and embedment length on pile group behaviour and estimate group efficiency under lateral load for different spacing.

## 2. Validation of FE Model

PLAXIS 3D [1] was used for developing and analysing combined piled raft (CPRF) systems. The modeling of CPRF system was done by Choudhary et al [1] using the experimental works carried out by Horikoshi et al. [2] which is used in this study for validation of finite element (FE) model.

### *2.1. Model Description*

In PLAXIS 3D, the soil structure was modelled with their boundaries as 28 m, 28 m and 16 m. Mohr coulomb constitutive law was used for defining sand properties. The values of various parameters which are required to model soil, pile and raft are given in Table 1. The boundary conditions of soil model were considered to be horizontally fixed in sides and fully fixed in base. The damping of the soil was assumed as 5%. The natural frequencies in first and second modes were calculated according to the formula given in Equation 1 proposed by Kramer [3] as 1.67 Hz and 5 Hz respectively.

$$\omega_n = \frac{V_s(2n-1)}{4H} \tag{1}$$

Where, $\omega_n$ = Natural frequency of soil layer, $n$ = n$^{th}$ frequency, $Vs$ = Shear wave velocity (m/sec), $H$ = depth of soil layer

### *2.2 Modelling of Piled Raft Systems*

Figure 1 gives detailed specifications of piled raft system which was developed for analysis. Plate element of size 4 m x 4 m and thickness of 1 m was defined for raft foundation. Four embedded beam elements of diameter 500 mm and length 9 m were defined for pile foundation with the centre to centre spacing of 2 m. To calculate the Rayleigh damping co-efficient α and β, the values of natural frequency of CPRF system is necessary. The frequency value is calculated using the formula given in Equation 2 proposed by Kang et al [4] and is found to be 1.275 Hz. The damping of the system is assumed as 5%.

$$\omega = 2\sqrt{\frac{EI}{m_{raft}L^3}} \tag{2}$$

Where, $EI$ = flexural rigidity of piles (kN-m$^2$), $m_{raft}$ = mass of raft alone (kN) and $L$ = length of pile.

**Table 1:** Properties of soilpile and raft (Horikoshi et al. 2003 a, b and Eslami et al. 2011)

| Parameters | Soil | Pile | Raft |
|---|---|---|---|
| Material | Toyoura Sand | Concrete | Aluminium |
| Young's Modulus (GPa) | 0.04 | 41.7 | 70 |
| Poisson's ratio (μ) | 0.3 | 0.2 | 0.35 |
| Unit weight (kN/m$^3$) | 16.3 | 24 | 27 |
| Friction angle(φ) | 31 | - | - |
| Dilation angle (c ) | 1 | - | - |
| Cohesion (kN/m$^2$) | 10 | - | - |

The axial forces of ground storey columns of all models were observed and the footings were designed according to Indian Standards. The safe bearing capacity of soft, medium and hard clay soils are assumed as 100 kN/m$^2$, 250 kN/m$^2$ and 450 kN/m$^2$ respectively. The dimensions of footings for *M1*, *M2* and *M3* for all types of soil conditions are given in Table 2.

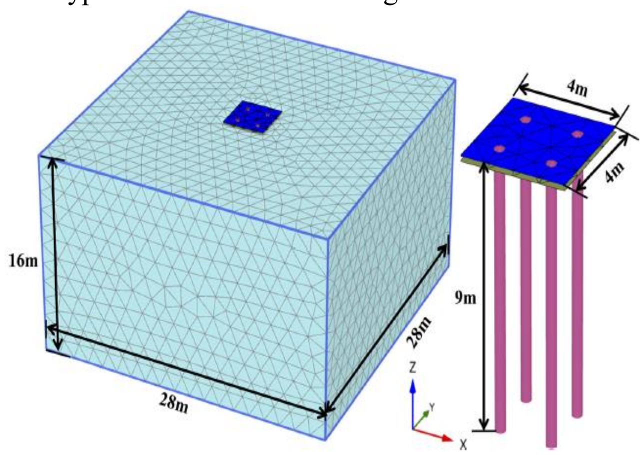
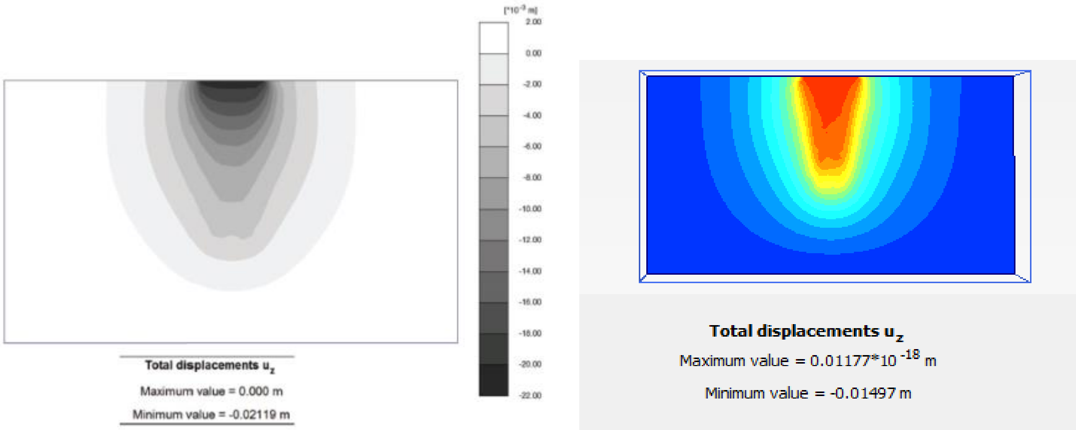



**Figure.1**.Piled Raft System (Choudhary et-al [1])

*2.3. Load-displacement behaviour:*

*2.3.1. Vertical Displacement*

Figure 2 presents the vertical displacement contour of 2x2 pile group in medium dense sand of relative density $D_r$ is equal to 60% under the vertical static pressure of 366.4 kN/m$^2$, which is equal to the self-weight of raft. The displacement obtained by PLAXIS 3D model in this study is 14.97 mm which is in close agreement with the values found by Choudhary *et al* and Horikoshi *et al*. in which the values reported are 21.6 mm and 15 mm respectively. The pressure bulb shown in the both the modeling indicates that the soil dimensions assumed in x, y and z directions in the modeling limit the boundary effects.

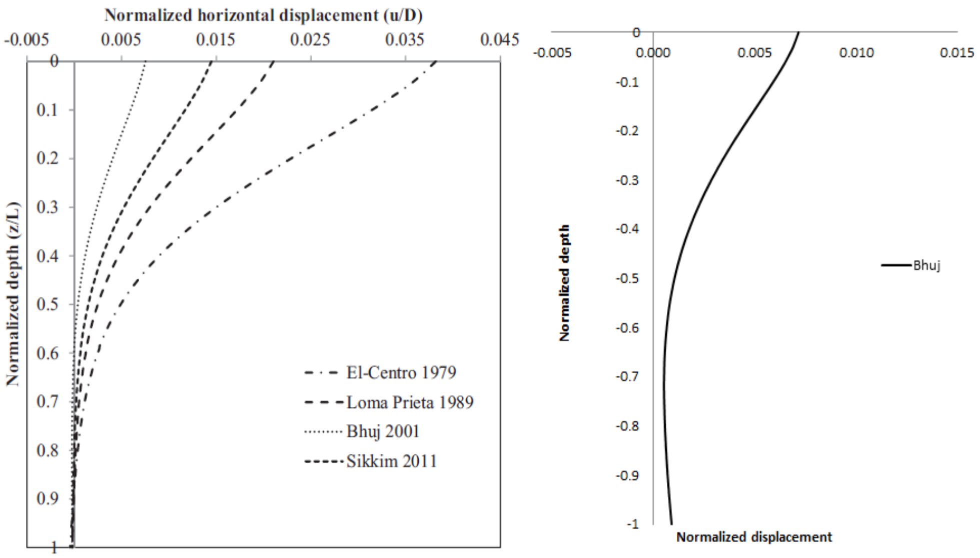



Choudhary-et-al. [1] Present study

**Figure 2**. Vertical displacement contour

*2.3.2. Lateral Displacement*

The lateral behaviour of 2x2 pile group was studied numerically using pseudo static method by Choudhary et al. [1]. The equivalent static loads of four earthquake ground accelerations were applied at the pile head. For validation of the lateral load behaviour, Bhuj earthquake motion has been considered in this study. The normalized horizontal displacement along the length of piles (*u/D*) with normalized depth (*Z/L*) has been plotted and shown in Figure 3. The results of pseudo static lateral loads resemble well with the Choudhary et al. [1] values.




Choudhary-et-al. [1]Present Study

**Figure 3.** Normalized lateral load displacement behaviour

*2.3.3 Bending Moment along Pile:*

Similar to normalized horizontal displacement, bending moment along the length of piles also drawn under pseudo-static loading conditions. Figure 4 depicts the bending moment of pile in Bhuj earthquake motions in comparison with Choudhary et al. [2] results. The maximum positive bending moment at the pile head is 75 kN-m and negative bending moment of 20 kN-m at a depth of 3.25 m below ground level are reported which nearly match with author's results.

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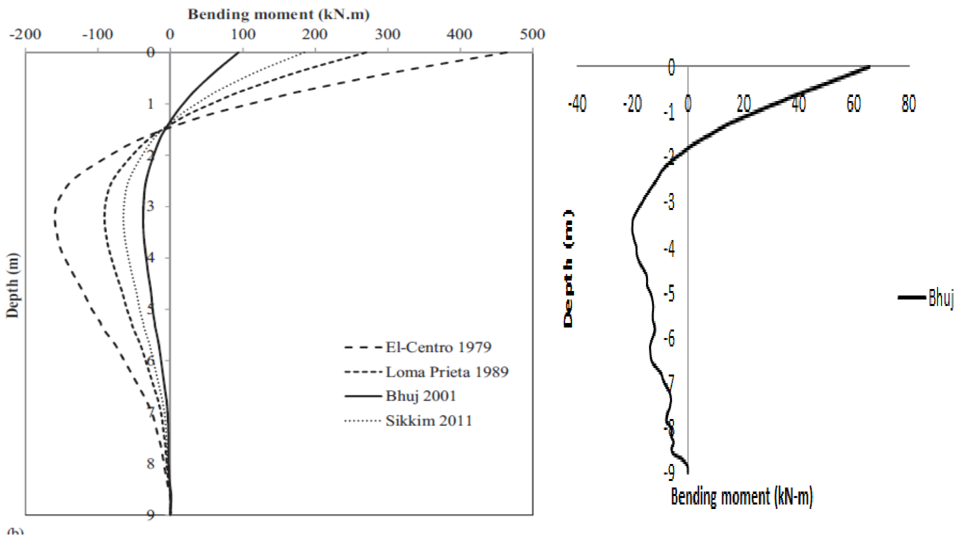


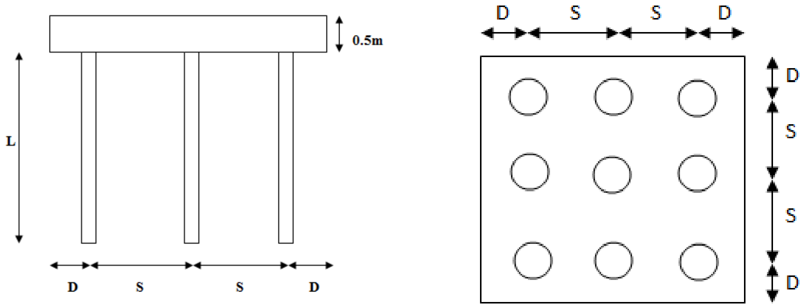

Choudhary-et-al Present Study

**Figure 4.** Bending moment under pseudo-static loading conditions

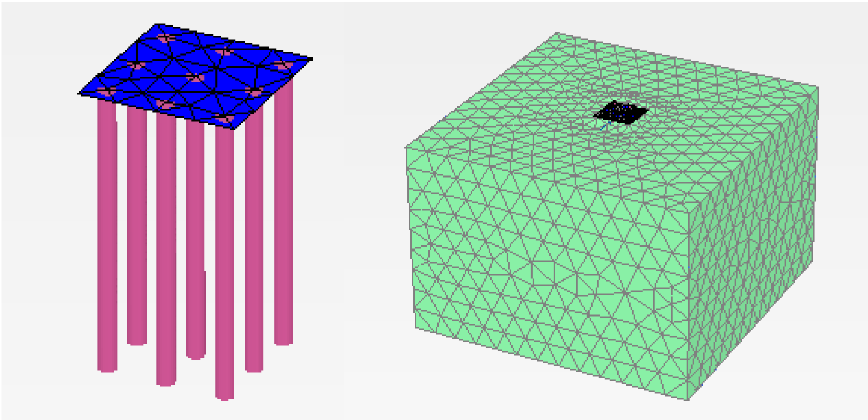
## 3. Modeling and Analysis

### *3.1. Finite element modelling*

To detail the static lateral response and the load carrying behaviour of piled rafts in sand, a numerical analysis was done with the commercial geotechnical finite element program PLAXIS-3D. Single pile and 3x3 group piles were considered and differentiated with various L/D ratios ranging from 15 to 40 with the interval of 5 and also with various spacing such as 3D, 5D, 7D and 9D, where L is the length of piles and D is the diameter of piles. The diameter of the piles and thickness of raft are assumed 0.5 m. The piles were modelled with embedded beam element and rafts were modelled with plate element. The length of pile and size of rafts are varied with respect to varying L/D and S/D ratios, where S is the spacing of piles. The length, width and depth of soil model are assumed as 60 m, 60 m and 40 m respectively. The dimensions of soil model considered are within the limits to eliminate the boundary effects as reported by Choudhary et al. [2], where the displacement of soil beyond pile in lateral and vertical directions are limited to 3 times and 1.5 times the length of piles respectively. The arrangement of 3x3 piled raft system and PLAXIS 3D model are shown in Figure 5. The Mohr-Coulomb failure criterion with undrained B condition is used for modeling the soil behaviour. The pile head is assumed to be fixed at top and free at bottom. The value of soil structure interface is given as 0.67. The first and second natural frequencies of soil model are calculated as per Kramer [4] and for the piled raft system as per Kang et al. [3]. The modeling properties of soil, pile and raft are as same as used in validation of the FE model.




(a) Sectional view (b) Pile arrangement in plan view



(c) Piled-raft system (d) Soil Model

**Figure 5**. Modeling description of piled-raft system

### *3.2. Analysis of single pile and 3x3 pile group*

The reference static lateral load of 400 kN and 2000 kN is applied at the pile head for the reference deflection value of 25 mm. The lateral load and deflection values of single pile and group pile at the pile head where the load is applied are noted. Figure 6 shows the lateral load versus deflection behaviour of single pile and 3x3 pile group spaced at 3D for the embedment length of 15D. It can be seen from the load deflection behaviour that static lateral load capacity of single pile is less as compared to pile group.

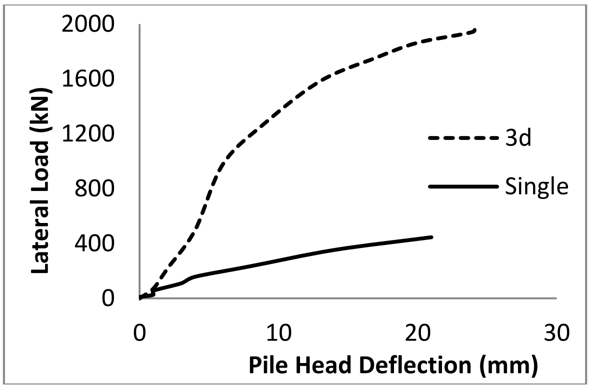



**Figure 6**. Lateral load response of single pile and 3x3 pile group of 3D spacing for L/D =15

## 4. Parametric study

A parametric study of varying embedment length (L) to diameter of pile (D) ratios and spacing of piles in raft (S) to pile diameter (D) was carried out to study the 3x3 pile group behaviour laterally in sand. The spacing of the piles was obtained as 1.5 m, 2.5 m, 3.5 m and 5.5 m for 3D, 5D, 7D and 9D respectively. Similarly embedment length of piles was calculated as 5 m, 7.5 m, 10 m, 12.5 m, 15 m, 17.5 m and 20 m for 15D, 20D, 25D, 30D, 35D and 40D respectively.

### *4.1. Load deflection behaviour*

The static lateral load and deflection behaviour of single pile under varying L/D ratios was compared with 3x3 pile group[8]. Figure 7 shows the load deformation curves of single and group pile models compared with varying spacing of all embedded lengths. In all the models, the reference deflection is assumed as 25 mm and loadings are correspondingly applied at the pile head.

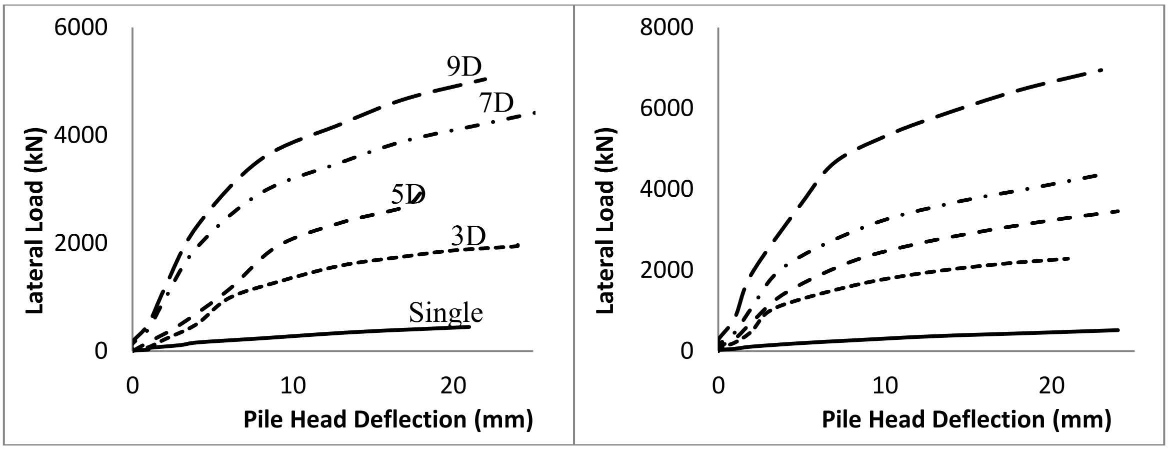
### *4.2. Ultimate Lateral Load Capacity*

Static ultimate lateral load capacity of single pile and group pile is calculated based on deformation criteria. As per Broms [4], ultimate capacity is considered as the load corresponding to the deflection equal to 20% of the diameter of piles i.e. 10 mm. Therefore, in this present study, the ultimate lateral load capacity is taken based on load corresponding to 10mm deflection. The values are calculated for single pile and 3x3 group pile of all the models from the load deformation curves and presented in Table 2.

**Table 2** static lateral load capacities of single pile and 3x3 pile group

| Pile Group | S/D | L/D | | | | | |
|---|---|---|---|---|---|---|---|
| | | 15 | 20 | 25 | 30 | 35 | 40 |
| Single Pile | Nil | 214 | 205.87 | 269.22 | 340 | 238.09 | 307.68 |
| 3 x 3 | 3 | 1286 | 1646.96 | 1846.08 | 1840 | 1761.94 | 1807.62 |
| | 5 | 2000 | 2352.8 | 2538.36 | 2480 | 2523.86 | 2538.36 |
| | 7 | 3095 | 3117.46 | 3230.64 | 3280 | 3119.11 | 3230.64 |
| | 9 | 3762 | 5117.34 | 3999.84 | 4000 | 3761.92 | 3730.62 |

*4.2.1. Effect of embedded length.* The lateral load capacity of 3x3 pile group for all spacing of piles with varying embedded length is shown in Figure 8. It is observed that the lateral load capaity increases as the spacing of piles increases. Also, it depicts the linear variation with respect to S/D ratio. Moreover, load values shows small variation with change in embedded length[14]. The average percentage increase in lateral capacity of piles in comparison to the embedded length of 15D and spacing of 3D is confined to 35%. The same kind of results for the effect of embedded length of piles in clay for 3x3 group pile are reported in Chandrasekaran et al. [4]




(a) L/D = 15 (b) L/D = 20

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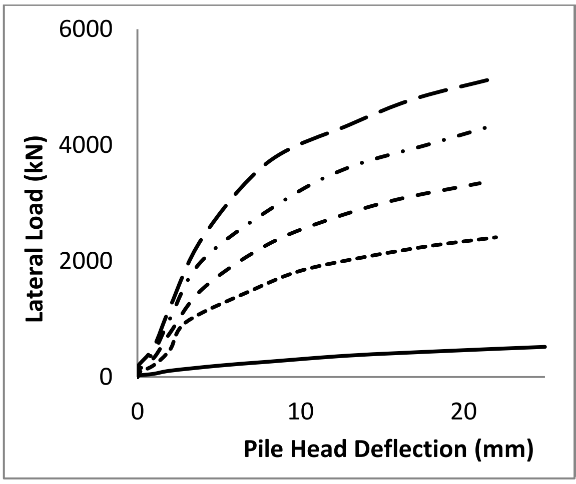
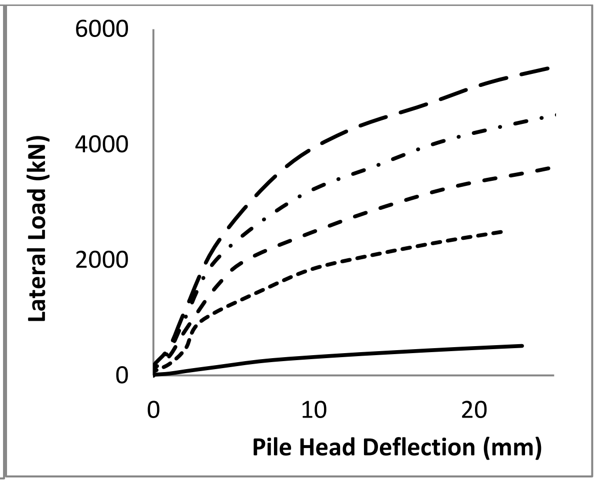
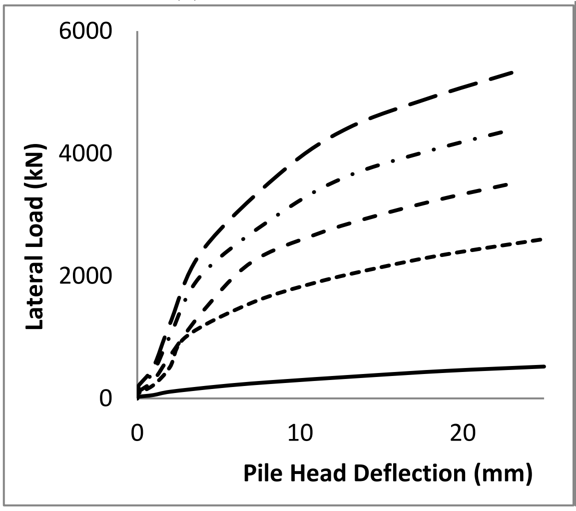


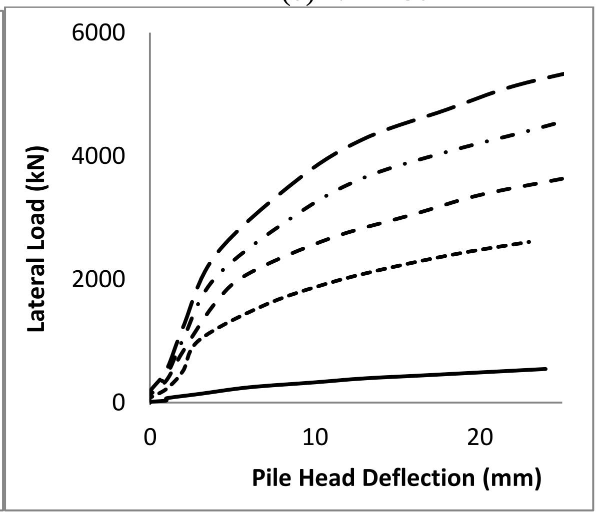

(c) L/D = 25




(d) L/D = 30




(e) L/D = 35




(f) L/D = 40

**Figure 7**. Load deformation behaviour of single pile and 3x3 pile groups for varying S/D

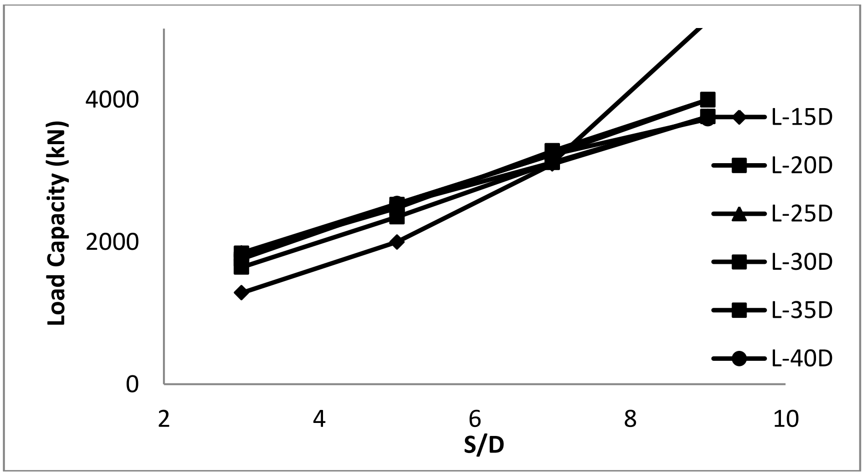



**Figure 8**. Lateral load strength of single pile and 3x3 pile group for varying L/D

*4.2.2. Effect of spacing of piles in a group*. Figure 9 shows the variation in lateral load capacity in terms of varying L/D ratio and S/D ratio. The load capacity of piles in group is maintaining constant as the length of piles is increased. Furthermore, the spacing of piles changes the lateral load capacity of group. The values are increased to 1.5, 2.5 and 3 times to the values of 3D spacing piles for 5D, 7D and 9D respectively for the L/D ratio of 15. Similarly, for other L/D ratio of piles, the same kinds of values are reported.

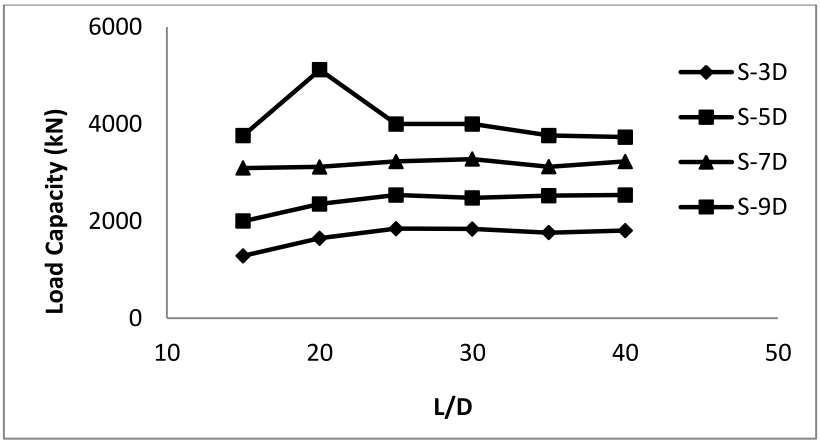



**Figure 9**. Lateral load strength of single pile and 3x3 pile group for varying S/D

*4.3. Group Efficiency*

The group interaction effect is also studied for pile group by calculating the group efficiency. The group efficiency of the pile group is calculated using the formula given as follows.

$$\text{Group Efficiency, } \eta = \frac{Q_G}{n_g Q_S} \quad (3)$$

Where, $Q_G$ is the ultimate lateral load capacity of group, $Q_S$ is the ultimate lateral load capacity of a single pile and $n_g$ is the no of piles in the group.The group efficiency obtained from the lateral load capacity of single pile and group pile from Table 2 is plotted in Figure 10 for varying S/D and L/D ratios. It is observed that the efficiency of 3D spacing pile group for the entire L/D ratio is lesser than 100. Moreover, the average percentage increase in efficiency for 3D spaced pile group for all L/D ratios in comparison with L/D = 15 is 74% which is close resemblance with the value reported as 0.73 for 3x3 pile group in clay by Chandrasekaran et al. [4]. As the pile spacing increases, the efficiency approaches to more than 100%.

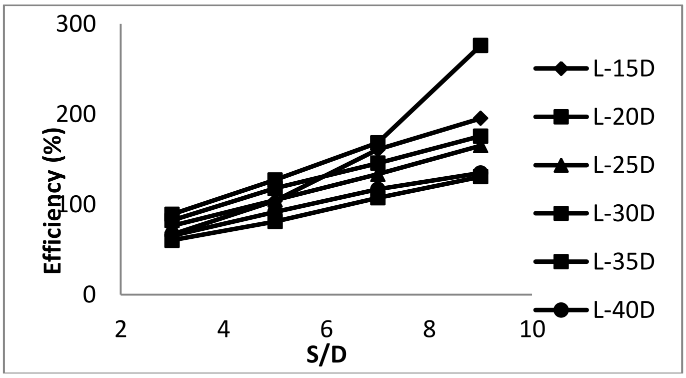



**Figure 10**. Efficiency of 3x3 pile group for varying S/D and L/D ratios.

## 5. Conclusion

The main objective of this study is investigate static lateral load response of single pile and 3x3 group pile in sand is under varying L/D ratios and S/D ratios. The key points observed and resported are as follow

- Ultimate static lateral capacity of 3D spaced pile group is lesser in all embedded length which is mainly due to the shadowing effects of soil in closed spaced piles.
- The L/D ratio of pile also influence the lateral load capacity. As the ratio increases, the percentage increase in the load values increases to 35% for all S/D ratio group piles.
- As the spacing of piles increases, the lateral load capacity of pile group increase to 1.5, 2.5 and 3 times to the values of 3D spacing piles for 5D, 7D and 9D respectively for the L/D ratio of 15.
- The efficiency of 3D spacing pile group for the entire L/D ratio is lesser than 100. The average percentage increase in efficiency for 3D spaced pile group for all L/D ratios in comparison with L/D = 15 is 74%. As the pile spacing increases, the efficiency approaches to more than 100%.

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