Coupled Systems Mechanics, Vol. 1, No. 1 (2012) 1-7
DOI: http://dx.doi.org/10.12989/csm.2012.1.1.001

Parametric study of laterally loaded pile groups using simplified F.E. models

H.S. Chore*[1], R.K. Ingle[2] and V.A. Sawant[3]

[1]*Department of Civil Engineering, Datta Meghe College of Engineering, Sector-3, Airoli, Navi Mumbai-400 708, India*
[2]*Department of Applied Mechanics, Visvesvaraya National Institute of Technology (VNIT), Nagpur-440 010, India*
[3]*Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee-247 667, India*

(Received September 7, 2011, Revised February 5, 2012, Accepted February 6, 2012)

Abstract. The problem of laterally loaded piles is particularly a complex soil-structure interaction problem. The flexural stresses developed due to the combined action of axial load and bending moment must be evaluated in a realistic and rational manner for safe and economical design of pile foundation. The paper reports the finite element analysis of pile groups. For this purpose simplified models along the lines similar to that suggested by Desai *et al.* (1981) are used for idealizing various elements of the foundation system. The pile is idealized one dimensional beam element, pile cap as two dimensional plate element and the soil as independent closely spaced linearly elastic springs. The analysis takes into consideration the effect of interaction between pile cap and soil underlying it. The pile group is considered to have been embedded in cohesive soil. The parametric study is carried out to examine the effect of pile spacing, pile diameter, number of piles and arrangement of pile on the responses of pile group. The responses considered include the displacement at top of pile group and bending moment in piles. The results obtained using the simplified approach of the F.E. analysis are further compared with the results of the complete 3-D F.E. analysis published earlier and fair agreement is observed in the either result.

Keywords: pile; pile cap; spacing; diameter; series arrangement; parallel arrangement; simplified models

1. Introduction

The pile foundations are generally preferred when heavy structural loads have to be transferred through weak subsoil to firm strata. Besides vertical loads, these foundations in some situations are subjected to the significant amount of lateral loads. The lateral forces may be due to impact of ships during berthing and wave action in case of off-shore structures. Pile supported foundations of earth retaining and transmission tower structures will also be subjected to the lateral loads. The building frames supported by the pile foundation exposed to wind forces also fall under the category of the structures/ sub-structures subjected to lateral loads. The problem of laterally loaded piles or pile group involves particularly complex soil- structure interaction between the piles and pile cap.

The conventional approaches available to analyze the laterally loaded piles include elastic continuum approach (Spillers and Stoll 1964, Poulos 1971, Banerjee and Davis 1978) and modulus

* Corresponding author, Dr., E-mail: hschore@rediffmail.com

of subgrade reaction approach (Reese and Matlock 1956, Georgiadis and Butterfield 1982, Sawant and Dewaikar 1996). The last three decades have witnessed a tremendous growth in the numerical methods and it is now possible to obtain a more realistic and satisfactory solution for any soil-structure related problems. Among the numerical methods, the most versatile, prominent and successful procedure is the finite element method (F.E.M.) which overcomes the drawbacks of the conventional approaches. The physical modeling of the structure (foundation) -soil media is possible through the use of variety of elements. Many studies reported in the literature on the analyses of piles and pile groups in the context of linear and non-linear analysis using F.E.M. include that by Yegian and Wright (1973), Desai (1974), Desai and Abel (1974), Desai and Appel (1976), Kuhlmeyer (1979), Desai *et al.* (1981), Zaman *et al*. (1993), Narsimharao and Ramkrishna (1996), Bransby and Springman (1999), Ng and Zhang (2001), Sawant and Dewaikar (2001), Krishnamurthy *et al.* (2003, 2005) , Dewaikar *et al.* (2007), Zhang (2009), Chore *et al.* (2010).

Among the many above-mentioned studies, a study reported by Desai *et al*. (1981) proposed simplified procedure which used beam column, plate and linear spring elements for simulating piles, pile-cap and soil, respectively. One of the limitations of this type of analysis was that pile-cap should be fairly thin so that it can be used as a thin plate.

2. Scope of the present work

Based on above review of literature, it is aimed to use finite element formulation using simplified procedure suggested by Desai *et al.* (1981) for the analysis of pile group subjected to lateral load. The basic problem of laterally loaded pile group is three dimensional in nature. The analysis of such problem using complete three dimensional finite element methods would be expensive in terms of computational resources as it requires more time and memory. The procedure suggested by Desai *et al.* (1981) using simplified models can replace the complete three dimensional system of pile group by one dimensional beam column element, two dimensional plate element and spring elements. The memory requirement is nearly one tenth of actual three dimensional formulations. In this manner, more complex problems can be handled with significant accuracy.

The pile groups, in the present investigation, are considered to have been embedded in homogeneous cohesive soil. The analysis assumes linear elastic behaviour of soil. The analysis, further, takes into consideration the interaction between the pile cap and underlying soil, generally the most neglected parameter in the analysis of pile group. In the proposed study, the effect of various parameters of the pile foundation such as spacing between the piles in a group, direction of the load, arrangement of piles in a group and diameter of piles is evaluated on the response of the foundation head. The response of the foundation head is considered in terms of the displacement at top of the pile group and bending moment in piles. The results obtained using simplified procedure in the present investigation is compared further with the results available in the published literature (Chore *et al.* 2010).

3. Finite element formulation

3.1 Formulation using simplified modeling for pile foundation

3.1.1 Beam element

Beam element has six degrees of freedom at each node, which includes lateral displacement u and

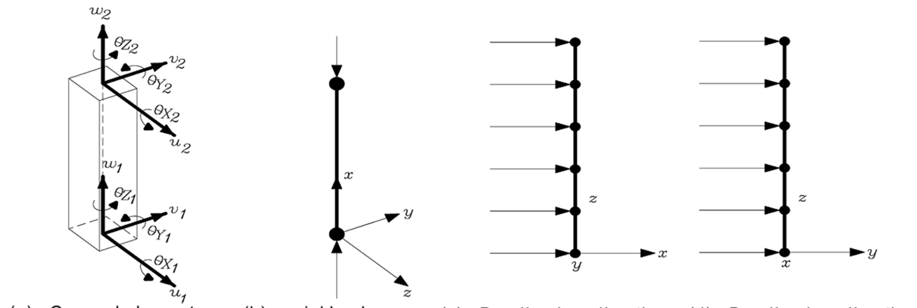


Fig. 1 General beam-column element Desai *et al.* (1981)

v, axial displacement w, and rotation about three axes (Fig. 1).

If rotation about z-axis is not considered the degrees of freedom are reduced to 5. Nodal displacement vector, $\{\delta\}_e$

$$\{\delta\}_e^T = \{u_1 v_1 w_1 \theta_{x1} \theta_{y1} u_2 v_2 w_2 \theta_{x2} \theta_{y2}\}$$

Stiffness matrix of the element $[k]_e$, is given by the expression

$$[k]_e = \int_0^L [B]^T [D][B] dz \tag{1}$$

Where, $[B]$ is Strain-displacement transformation matrix and $[D]$ is constitutive relation matrix for beam element.

3.1.2 Spring element

Soil support at various nodes of beam element is simulated by using a series of equivalent and independent elastic springs in three directions (X, Y, and Z). Soil stiffness can be found out using principle of virtual work. A virtual displacement $\{\Delta\delta\}$ is applied to the spring system and by equating internal work done to external work, soil stiffness can be worked out. Soil reactions at any point $\{p_x$, p_y and $p_z\}$ within the element are given by

$$\begin{Bmatrix} p_x \\ p_y \\ p_z \end{Bmatrix} = \begin{bmatrix} E_{sx} & 0 & 0 \\ 0 & E_{sy} & 0 \\ 0 & 0 & E_{sz} \end{bmatrix} \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} \tag{2}$$

$\{E_{sx}$, E_{sy} and $E_{sz}\}$ are soil subgrade reaction modulus at depth z.

Soil support element stiffness matrix, $[K]_s$, can be obtained as

$$[K]_s = \int_0^L [N]^T \begin{bmatrix} E_{sx} & 0 & 0 \\ 0 & E_{sy} & 0 \\ 0 & 0 & E_{sz} \end{bmatrix} [N] dz \tag{3}$$

3.1.3 Plate element

Pile cap (Fig. 2) is modeled using 4 node elements. Lateral displacements u and v in X and Y

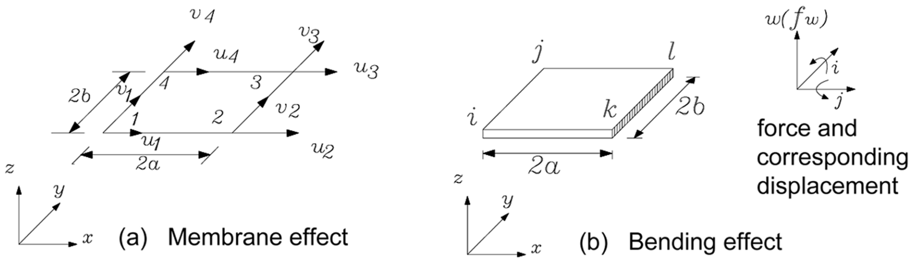


Fig. 2 A schematic of general plate element Zienkiewicz (1977)

directions are considered in membrane effect, while to consider bending aspect, the three degrees of freedom are considered at each node, namely the transverse displacement *w*, and the rotations about *X* and *Y* axis, θ_x and θ_y respectively. Together with two inplane displacements, *u* and *v*, there are total 5 degrees of freedom at each node. The number of degrees of freedom, for beam element and plate element are same. Consequently, the requirement of inter element compatibility between adjacent plate and beam elements can be taken care of.

3.1.4 Membrane effects

For the inplane or membrane loading the plane stress idealization is considered. The nodal displacement vector, $\{\delta\}^T$, given by

$$\{\delta\}^T = \{u_1, v_1, u_2, v_2, u_3, v_3, u_4, v_4\}$$

Element stiffness matrix, $[k]_{in}$, is given by

$$[k]_{in} = abh \int_{-1}^{1}\int_{-1}^{1}[B]^T[D][B]d\xi d\eta \tag{4}$$

Where, $[B]$, is strain-displacement transformation matrix, $[D]$, is constitutive relation matrix, and, h represents thickness of the element. Integration is carried out numerically with respect to ξ and η, using Gauss quadrature.

3.1.5 Bending effects

The nodal displacement vector $\{\delta\}$ consists of 12 displacements given as

$$\{\delta\}^T = \{\delta_1\ \delta_2\ \delta_3\ \delta_4\}\ and\ \{\delta_i\}^T = \{w_1\ \theta_{xi}\ \theta_{yi}\}$$

Transverse displacement, *w*, is expressed in terms of polynomial in x and y

$$w = \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 x^2 + \alpha_5 xy + \alpha_6 y^2 + \alpha_7 x^3 + \alpha_8 x^2 y + \alpha_9 xy^2 + \alpha_{10} y^3 + \alpha_{11} x^3 y + \alpha_{12} xy^3$$

$$w = [P]\{\alpha\}\ and\ [P] = [1\ x\ y\ x^2\ xy\ y^2\ x^3\ x^2y\ xy^2\ y^3\ x^3y\ xy^3] \tag{5}$$

$\{\alpha\}$ is matrix of constants, α_1 to α_{12}.

Rotations θ_x and θ_y are then given by

$$\theta_x = \frac{\partial w}{\partial y} = \alpha_3 + \alpha_5 x + 2\alpha_6 y + \alpha_8 x^2 + 2\alpha_9 xy + 3\alpha_{10} y^2 + \alpha_{11} x^3 + 3\alpha_{12} xy^2$$
$$\theta_y = \frac{\partial w}{\partial x} = \alpha_2 + 2\alpha_4 x + \alpha_5 y + 3\alpha_7 x^2 + 2\alpha_8 xy + \alpha_9 y^2 + 3\alpha_{11} x^2 y + \alpha_{12} y^3 \tag{6}$$

The constants, α_1 to α_{12} can be evaluated by writing down 12 simultaneous equations for w, θ_x and θ_y at 4 nodes by substituting appropriate values of coordinates x and y. These twelve equations can be written in following way

$$\{\delta\} = [C]\{\alpha\} \tag{7}$$

where, $[C]$, is a matrix defining relationship between displacements and constants α_i.

Element stiffness matrix, $[K]_{bd}$, for plate bending can be written as

$$[K]_{bd} = \int_{-b}^{b}\int_{-a}^{a}[B]^T[D][B]dxdy \tag{8}$$

Where, $[B]$ is Strain-displacement transformation matrix plate bending, $[D]$, is constitutive relation matrix.

For uniformly distributed load acting q on the element, load vector, $[F]$, can be obtained as

$$\{F\} = [C^{-1}]^T\int_{-b}^{b}\int_{-a}^{a}[P]^T q dxdy \tag{9}$$

3.1.6 Method of analysis

Stiffness matrices for pile, soil and pile cap are assembled in global stiffness matrix. From assembled global stiffness matrix and known load vector, overall equilibrium equations are formulated. The resulting equations are solved for unknown nodal displacements by Gauss elimination.

Back Calculation of Internal Forces-

After computation of nodal displacements stiffness matrix of each element is recalled to get the internal forces $\{F\}_e$, (such as axial force, shear force and bending moment) within the element.

$$\{F\}_e = [k]_e\{\delta\}_e \tag{10}$$

Based on the aforementioned idealizations, a numerical procedure for the finite element analysis using simplified model were programmed in Fortran 90. It was validated on some primary structures, such as cantilever beams and other similar structures wherein the bending behaviour predicted by the program was found to be in close agreement with that obtained by theory. The program was also validated with the published work and then implemented for the analysis of the pile groups considered in this study.

4. Problem description

The two pile groups consisting of two and three piles respectively in the group are considered. Further, different configurations (series and parallel arrangement of piles in the group) are considered

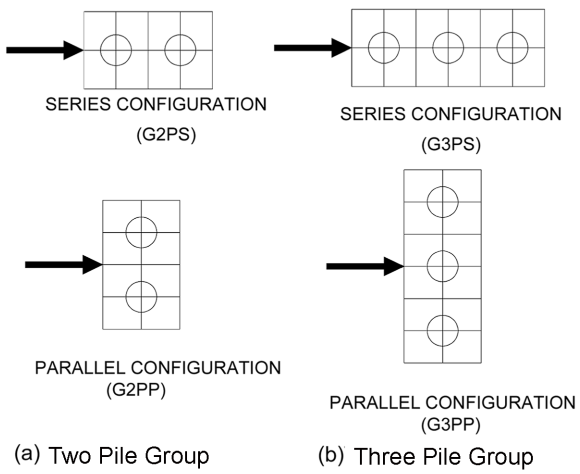


Fig. 3 Different configurations considered in the study

Table 1 Material properties

Particulars	Corresponding values
Pile Size/Diameter *(D)*	300 mm, 400 mm, 500 mm and 600 mm
Length of Pile *(L)*	3 m (3000 mm)
Concrete Grade used for Pile and Pile Cap	M- 40
Young's Modulus of Pile and Pile Cap(E_c)	0.3605×10^8 kPa
Poisson's Ratio for Concrete (μ_c)	0.15

for each pile group. In each case, the spacing between the piles is varied from 2*D* to 5*D*. When the direction of loading is parallel to the line joining piles, it is referred to as the series arrangement. On the other hand, if the lateral loading is acting in a direction perpendicular to the line joining piles, it is called as the parallel arrangement. Further, the piles are connected at their heads pile cap of concrete. The pile group is considered to have been embedded in cohesive soil. Fig. 3 shows various configurations of pile groups considered for the parametric study.

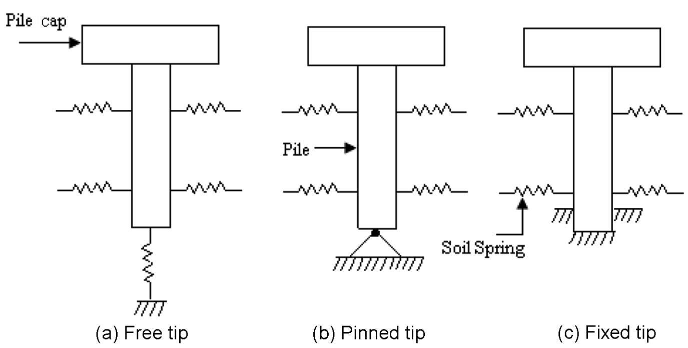


Fig. 4 Different end conditions assumed to prevail at the pile tip

The properties of the material are given in Table 1. The proposed numerical procedure adopted in the analysis for analyzing the foundation requires the value of modulus of subgrade reaction. In absence of the reliable value of this modulus, it is required to be judiciously selected. IS: 2911-1979 has suggested the range of 3200-6500 kN/m^3 for the values of K_h. Moreover, Tomlinson (1977) suggested the relationship between K_h and E_s to be $K_h = 1.66\, E_{s.}$ Hence, based on this, the value of K_h is assumed to be 6667 kN/m^3.

The effect of end conditions assumed to prevail at the pile tip is also evaluated on response pile groups. In view of this, three end conditions are assumed namely: (*i*) Free tip, (*ii*) Pinned tip and (*iii*) Fixed tip, as indicated in Fig. 4.

5. Results and discussion

The analysis is carried out for the lateral or vertical force (F_H or F_V), of 1000 kN applied on top of the pile group. Displacement at top of the pile group and bending moments developed in the pile in case of lateral loading are considered for comparison.

5.1 Effect on displacement

The effect of pile spacing, number of piles and arrangement of pile and diameter of pile on displacements at top of the pile group is evaluated and presented in Table 2. The typical variation in horizontal displacements with pile spacing at top of the pile group for 300 mm pile diameter is indicated in Fig. 5.

For a given configuration, the top horizontal displacements are observed to decrease with increase in pile spacing and pile diameter. The results indicate that with increase in spacing, there is increase in the resistance to lateral loads. When the piles are closely spaced, stress bulbs around individual piles in a group overlap and this causes loss of passive resistance leading to a large amount of deflections of piles. As the spacing between the piles increases, the influence of the stress zone of one pile on the other pile gets reduced and the passive resistance offered by the surrounding soil

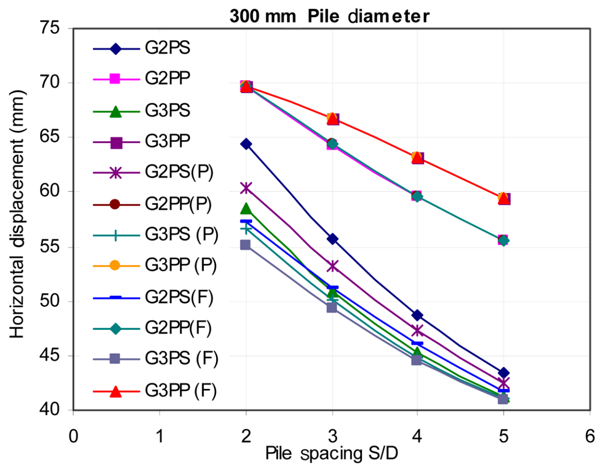


Fig. 5 Effect of pile spacing on horizonral displacement (300 mm Pile diameter)

Table 2 Displacement at top of pile group (mm)

Pile spacing	300 mm Dia	400 mm Dia	500 mm Dia	600 mm Dia	300 mm Dia	400 mm Dia	500 mm Dia	600 mm Dia
	G2PS				G2PP			
	Free tip							
2*D*	64.41	49.07	37.73	29.36	69.65	54.09	42.47	33.36
3*D*	55.75	40.93	30.63	23.49	64.23	48.42	37.11	28.84
4*D*	48.78	34.87	25.73	19.68	59.58	43.82	32.94	25.24
5*D*	43.39	30.45	22.30	17.11	55.57	40.02	29.62	22.44
	Pinned tip							
2*D*	60.36	46.05	36.06	28.67	69.65	54.09	42.47	33.63
3*D*	53.22	39.56	30.19	23.45	64.43	48.42	37.11	28.84
4*D*	47.26	34.36	25.69	19.63	59.58	43.82	32.94	25.24
5*D*	42.48	30.31	22.31	16.86	55.57	40.02	29.62	22.44
	Fixed tip							
2*D*	57.33	44.56	35.51	28.50	69.65	54.09	42.47	33.63
3*D*	51.23	38.80	30.01	23.43	64.23	48.42	37.11	28.84
4*D*	46.00	34.04	25.68	19.61	59.58	43.82	32.94	25.24
5*D*	41.70	30.21	22.30	16.74	55.57	40.02	29.62	22.40
	300 mm Dia	400 mm Dia	500 mm Dia	600 mm Dia	300 mm Dia	400 mm Dia	500 mm Dia	600 mm Dia
	G3PS				G3PP			
	Free tip							
2*D*	58.51	43.75	33.22	25.81	69.66	54.09	42.48	33.64
3*D*	50.92	36.56	27.25	21.15	66.76	49.89	37.97	29.36
4*D*	45.27	31.77	23.59	18.41	63.12	45.76	34.03	25.87
5*D*	41.25	28.55	21.20	16.59	59.42	42.03	30.70	23.05
	Pinned tip							
2*D*	56.69	42.76	32.94	25.80	69.66	54.09	42.48	33.64
3*D*	50.09	36.41	27.24	20.91	66.76	49.89	37.97	29.36
4*D*	44.90	31.77	23.40	17.87	63.12	45.76	34.03	25.87
5*D*	41.07	28.52	20.84	15.93	59.42	42.03	30.70	23.05
	Fixed tip							
2*D*	55.15	42.12	32.82	25.80	69.66	54.09	42.48	33.64
3*D*	49.37	36.31	27.21	20.68	66.76	49.89	37.97	29.36
4*D*	44.57	31.77	23.15	17.22	63.12	45.76	34.03	25.87
5*D*	40.92	28.45	20.33	14.94	59.41	42.03	30.70	23.05

mass gets improved which leads to the reduction in pile deflections. The trend is same for all the three conditions considered to prevail at the pile tip.

The effect of end conditions at the pile tip is also found to be significant on the displacement at the top of the pile groups. In series configuration, for group of two and three piles, displacements obtained for free tip conditions are on higher side than that obtained for pinned tip condition and socketed condition yields lesser displacement. In socketed condition, rotation as well as displacement of the pile at the tip is assumed to be restrained and hence, displacements at the top are found to be lesser than what is obtained with respect to pinned tip condition where even though displacement at the tip of the pile is prevented, rotation is allowed. In the free tip condition, displacement as well as rotation is allowed at the pile tip and as such, displacements are higher as compared to the displacements obtained in the context of other two conditions. However, for parallel configuration, top displacements are same for all the three conditions assumed to prevail at the tip of the pile.

The effect of number of piles in a group is also observed to be significant on response of the pile groups. It is found that for the series configuration, the displacement is more in case of the group of two piles as compared to that in the group of three piles in respect of all the three end conditions assumed to prevail at the pile tip. However, for parallel configuration, slightly opposite trend is observed. The displacements in the group of three piles are slightly higher than that obtained in the group of two piles. Normally, with the increase in the number of piles in the group under identical arrangement, displacement reduces for either configuration and as evident from the analysis of piles using 3-D modeling. However, when the soil is modeled as discrete springs as is being done here, it can not model the effect of soil appropriately and therefore, such trend is observed.

The effect of arrangement of piles is complex. Displacements in the parallel arrangement are observed to be higher as compared to the displacements obtained with respect to series configuration for both the group of two and three piles in the context of all the three conditions assumed to prevail at the tip of the pile and for all diameters. It is attributed to the less structural stiffness of pile and pile cap in the parallel arrangement than that in series arrangement.

5.1.1 Comparison with the published results (Chore et al. 2010)

Chore *et al*. (2010) presented the complete three- dimensional finite element analysis of pile groups where the pile foundation was modeled using three dimensional idealizations. The pile, pile cap and the soil was modeled as 20 node continuum element and interface between the pile and soil was modeled as 16 node surface elements. In the present investigation, simplified approach is employed while modeling the foundation.

Although the generalized trend of reduction in displacement with the increase in pile spacing, pile diameter and number of pile remains same in respect of either analysis, the arrangement of piles in a group is found to have a significant effect on the response in view of the approach employed for modeling the foundation. In the present study, response of the pile groups in terms of top displacement is found stiff for series arrangement of piles in a group whereas in the analysis reported by Chore *et al.* (2010) the response of the pile groups is observed to be stiff for parallel configuration; particularly at the smaller pile diameters. In *3-D* analysis (Chore *et al.* 2010), the soil is modeled as continuum and hence, more passive resistance is offered by the soil owing to larger area of soil and thus, increased soil stiffness. The combined effect of pile and soil increases stiffness of the parallel configuration and hence, response is found stiff for parallel arrangement.

In the simplified analysis reported here, soil is modeled as discrete independent springs which are independent of the area of soil zone as a result of which appropriate modeling of the passive resistance of soil is not possible. The soil offers nearly the same stiffness for either configuration and combined stiffness of the pile- soil system is less in the context of parallel arrangement and hence, response of the series arrangement is found to be stiffer. Apart from this possibility, in the simplified analysis presented here, the pile cap should be fairly thin whereas the pile cap considered in the present investigation is thick. Moreover, the formulation using simplified models for the foundation does not consider the torsional degrees of freedom. These could be the reasons for deviation in the trend of the response. Long piles could change the trend of the response.

Table 3 Capacity of the pile groups (kN)

Free tip condition of pile								
Dia (mm)	300	400	500	600	300	400	500	600
Spacing	Two piles' group (series) [G2PS]				Two piles' group (parallel)[G2PP]			
2*D*	466	815	1325	2043	431	740	1177	1799
3*D*	538	977	1632	2554	467	826	1348	2081
4*D*	615	1147	1943	3049	504	913	1518	2377
5*D*	691	1314	2242	3507	540	1000	1688	2674
Spacing	Three piles' group (series) [G3PS]				Three piles' group (parallel)[G3PP]			
2*D*	513	914	1505	2325	431	740	1177	1784
3*D*	589	1094	1835	2837	449	802	1317	2044
4*D*	663	1259	2119	3259	475	874	1469	2319
5*D*	727	1400	2359	3616	505	952	1628	2603
Pinned tip condition of pile								
Dia (mm)	300	400	500	600	300	400	500	600
Spacing	Two piles' group (series) [G2PS]				Two piles' group (parallel)[G2PP]			
2*D*	497	869	1387	2093	431	740	1177	1784
3*D*	564	1011	1656	2559	466	826	1347	2080
4*D*	635	1164	1946	3057	504	913	1518	2377
5*D*	706	1320	2241	3559	540	1000	1688	2674
Spacing	Three piles' group (series) [G3PS]				Three piles' group (parallel)[G3PP]			
2*D*	529	935	1518	2326	431	740	1177	1784
3*D*	599	1099	1836	2869	449	802	1317	2044
4*D*	668	1259	2137	3358	475	874	1469	2319
5*D*	730	1403	2399	3766	505	952	1629	2603
Fixed tip condition of pile								
Dia (mm)	300	400	500	600	300	400	500	600
Spacing	Two piles' group (series) [G2PS]				Two piles' group (parallel)[G2PP]			
2*D*	523	898	1408	2105	431	740	1177	1784
3*D*	586	1031	1666	2561	467	826	1347	2080
4*D*	652	1175	1947	3060	504	913	1518	2377
5*D*	719	1324	2242	3584	540	1000	1688	2679
Spacing	Three piles' group (series) [G3PS]				Three piles' group (parallel)[G3PP]			
2*D*	544	950	1523	2326	431	740	1177	1784
3*D*	608	1102	1838	2901	449	802	1317	2044
4*D*	673	1259	2160	3484	475	874	1469	2319
5*D*	733	1406	2459	4016	505	952	1629	2603

5.2 Capacity of pile group

The effect of spacing between the piles is evaluated on capacity of the pile group. The capacity of pile group is considered as the load corresponding to 10% of the pile diameter. The capacity for different pile diameters is shown Table 3. From Table 3, it is observed that capacity is increasing with increase in pile spacing and pile diameter. The capacity of the pile group is on higher side for series configuration in respect of group of two piles and three piles. Further, capacity of the pile group is observed to be more for socketed condition followed by pin condition in respect of all configurations. The capacity of pile group is lesser for free tip condition.

5.3 Effect on moments in pile

The bending moments developed in piles in pile groups is evaluated. Maximum moments in piles are found out and variation of moments along depth of pile is also studied.

5.3.1 Variation of moment in pile

The variation of B.M. along depth of pile in the group of two and three piles in respect of series and parallel configurations for different diameters and end conditions considered in the study is

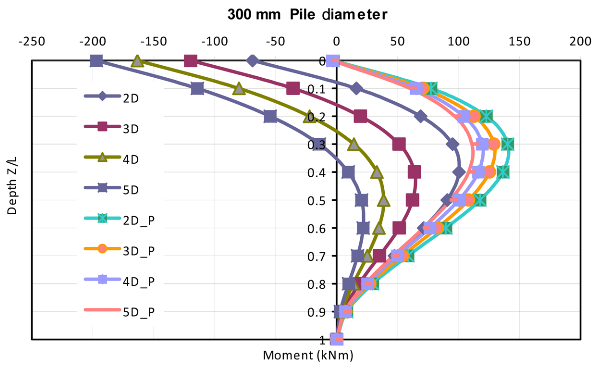


Fig. 6 Variation of moment along depth of piles in group of two piles

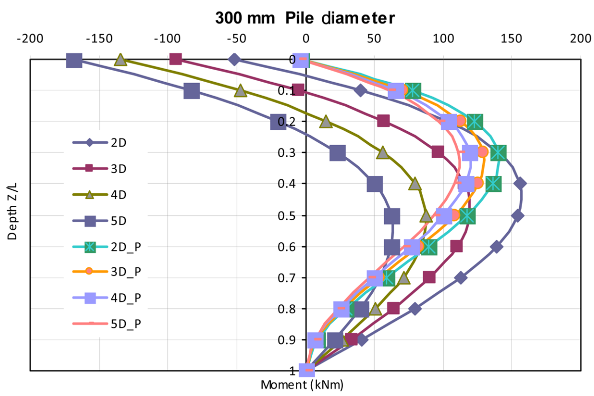


Fig. 7 Variation of moment along depth of piles in group of two piles (Fixed tip)

reported in the subsequent section.

(a) Group of two piles

Figs. 6 and 7 indicates a typical variation of moments along pile depth for the group of two piles in respect of 300 mm pile diameter for free tip condition and fixed tip condition. Similarly, the fixing moments in group of two piles with series arrangement are indicated in Table 4. The maximum positive moments in piles in respect of group of two piles (parallel configuration) are indicated in Table 5.

The maximum positive B.M. is found to decrease with increase in pile spacing and pile diameter in respect of either configuration whereas the negative moment is found to increase with increase in pile spacing and pile diameter. Maximum negative moments in the front pile and rear pile are same in case of series and parallel arrangement when pile tip is assumed to be free and fixed. However, the moments in the front pile and rear pile are found to be different for the pinned pile tip.

Table 4 Fixing moment, i.e., max. negative moment in pile (kN-m) [G2PS]

Pile diameter	Pile spacing 2*D*	Pile spacing 3*D*	Pile spacing 4*D*	Pile spacing 5*D*
	Free tip condition			
300 mm	−69	−120	−163	−197
400 mm	−95	−154	−202	−236
500 mm	−120	−182	−226	−253
600 mm	−142	−200	−235	−252
	Fixed tip condition			
300 mm	−52	−94	−134	−168
400 mm	−66	−119	−169	−213
500 mm	−87	−151	−212	−265
600 mm	−111	−186	−257	−315
	Pinned tip condition			
300 mm (Front)	4	−56	−109	−152
(Rear)	−122	−155	−186	−211
400 mm (Front)	55	−43	−128	−194
(Rear)	−206	−220	−236	−251
500 mm (Front)	48	−85	−195	−276
(Rear)	−238	−234	−239	−245
600 mm (Front)	−5	−161	−281	−364
(Rear)	−230	−219	−220	−224

Table 5 Max. positive moment in the pile (kN-m) [G2PP]

Pile diameter	Pile spacing 2*D*	Pile spacing 3*D*	Pile spacing 4*D*	Pile spacing 5*D*
	Free / Fixed/ tip condition			
300 mm	140	129	119	111
400 mm	112	100	90	81
500 mm	86	74	64	57
600 mm	64	53	45	39

(b) Group of three piles

Fig. 8 illustrates the typical variation of moment along depth of the piles in respect of a pile group of 300 mm pile diameter with reference to free pile tip. The values of fixing (hogging moments) and positive moments in piles of the various pile groups considered in the present investigations are shown in Tables 6 and 7.

In case of series configuration, it is observed that the fixing moments in the corner and central piles are found to increase with increase in spacing and increase in diameter whereas maximum positive moments are found to decrease with increase in spacing and diameter in respect of other two conditions assumed to prevail at the pile tip.The difference in the moment between the spacing of 2*D* and 5*D* is further found to decrease with increase in the diameter. Further, difference between the B.M. for corner and central piles is too marginal in respect of free tip and fixed tip. However, the difference is significant in case of pinned tip condition.

For series configuration, negative moments in the central pile are higher than the corner piles for free tip condition. For pile with free tip, difference is in the range of 1.4% to 9% with higher difference at higher spacing and higher diameter. For fixed tip condition, increase in the moment in central pile is up to 55% with higher difference at higher spacing and higher diameter. In respect of pinned tip, the difference is up to 175%; but the difference is reducing with spacing and diameter.

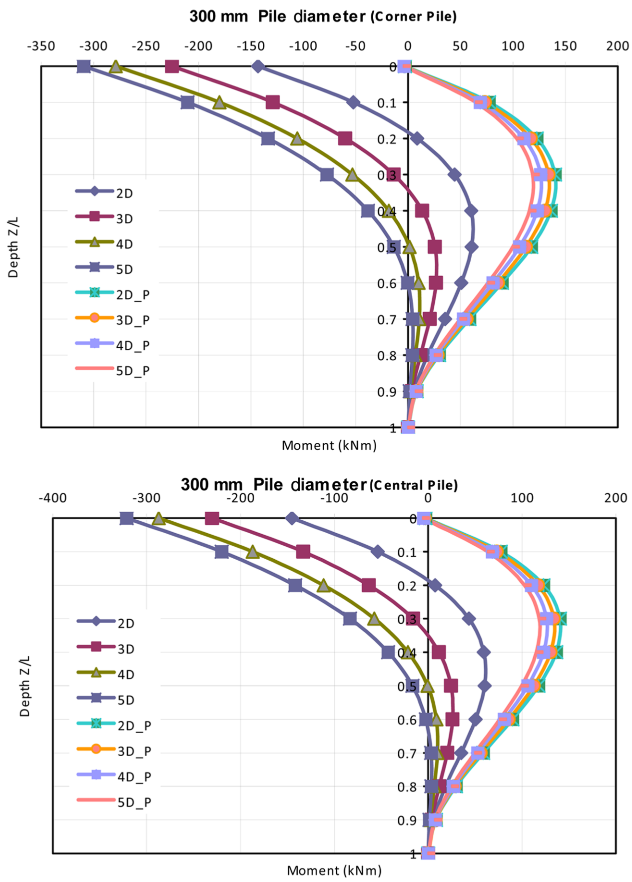


Fig. 8 Variation of moment along depth of pile (Group of three piles)

Table 6 Fixing moments, i.e., max. negative moment in pile (kN-m) [G3PS]

Pile diameter	Pile spacing 2*D*	Pile spacing 3*D*	Pile spacing 4*D*	Pile spacing 5*D*
	Free tip condition			
300 mm (Corner)	–143	–225	–279	–310
(Central)	–145	–230	–287	–322
300 mm (Corner)	–187	–276	–327	–351
(Central)	–191	–286	–344	–375
300 mm (Corner)	–221	–301	–339	–351
(Central)	–227	–316	–361	–380
300 mm (Corner)	–243	–307	–328	–327
(Central)	–251	–323	–352	–358
	Pinned tip condition			
300 mm (Corner)	–62	–164	–235	–278
(Central)	–170	–242	–293	–325
400 mm (Corner)	–39	–212	–322	–383
(Central)	–239	–301	–345	–370
500 mm (Corner)	–99	–328	–454	–510
(Central)	–265	–310	–342	–360
600 mm (Corner)	–215	–463	–573	–605
(Central)	–258	–292	–317	–329
	Fixed tip condition			
300 mm (Front)	–90	–179	–242	–282
(Rear)	–90	–182	–250	–294
400 mm (Front)	–105	–232	–320	–372
(Rear)	–102	–245	–352	–423
500 mm (Front)	–157	–307	–403	–455
(Rear)	–161	–359	–506	–601
600 mm (Front)	–219	–373	–462	–505
(Rear)	–252	–501	–678	–786

Table 7 Max. positive moment in pile (kN-m) [G3PP]

Pile diameter	Pile spacing2*D*	Pile spacing 3*D*	Pile spacing 4*D*	Pile spacing 5*D*
	Free / Pinned/ Fixed tip condition			
300 mm (Corner)	140	134	126	119
(Central)	140	134	126	118
400 mm (Corner)	113	103	94	85
(Central)	113	103	93	84
500 mm (Corner)	86	75	66	59
(Central)	86	74	65	58
600 mm (Corner)	64	54	45	39
(Central)	64	53	44	38

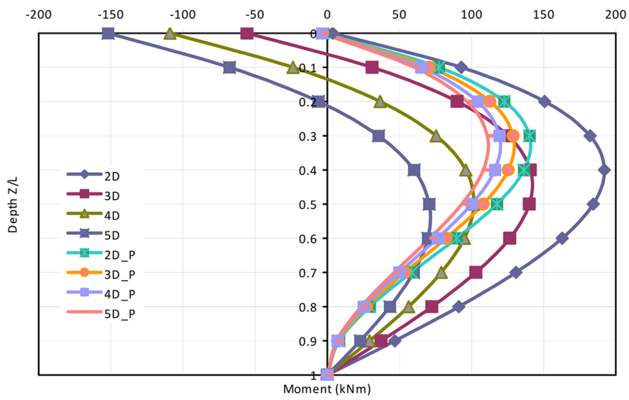
Incase of parallel configuration, maximum positive moments are found to decrease with increase in spacing and diameter. Further, the moments are same for all end conditions assumed to prevail at tip of the piles.

5.3.2 Effect of number of piles in group on moment

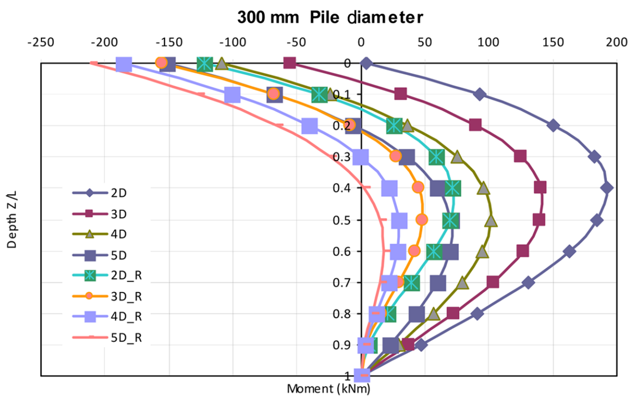
In respect of pile groups having series arrangement of piles and for piles with free tip, fixing moments, i.e., maximum negative moments, in the corner pile are higher in the group of three piles as compared to that in group of two piles. The difference is in the range of 30% to 100%. The difference is decreasing with increase in spacing and diameter. In case of fixed tip condition, the difference is in the range of 60 to 100% and it is reducing with higher spacing. In case of pinned tip condition, the moments are found to increase by 66% to 390% in corner pile and the difference is reducing with spacing. In case of parallel configuration, the fixing moments are same for all the three cases. For this arrangement, slight increase in positive B.M. is observed for the group of three piles with maximum increase being 7% at the spacing of 5*D*. Further, difference in moment is found to increase with spacing, but decrease with diameter.

5.3.3 Comparison of the moments

The typical variation in B.M. along the depth of pile for different pile spacing and 300 mm pile



(a) Comparison of moments for series and parallel configuration



(b) Comparison of moments in front and rear pile (series configuration)

Fig. 9 Comparison of the variation of moment along depth in group of two piles (300 mm pile diameter) [Pinned tip] diameter in respect of pinned tip condition is presented in Fig. 9. It is observed that maximum positive B.M. is decreasing with increase in pile spacing and pile diameter whereas the negative moment at pile head is increasing with increase in pile spacing and pile diameter. The moments in front pile and rear pile are observed to be same for free and fixed tip condition whereas for pinned tip condition, the moments in rear and front pile are different. In case of rear pile, fixing moments are found considerably higher than that in front piles and the difference between the fixing moments is reducing at higher spacing. Fixing moments in the pile with free tip is higher than that in piles with fixed tip and pinned tip. When effect of diameter is considered, it is observed that maximum positive moment is decreasing with increase in pile diameter. Fixing moment in the pile with free tip is higher than that in pile with fixed tip and pinned tip.

5.3.4 Comparison with published results (Chore et al. 2010)

The maximum positive moments are found to decrease while fixing moments are found to increase in pile spacing and pile diameter in the present study and in the study reported by Chore *et al.* (2010). Similarly, in respect of group of two piles, load shared by both the piles is almost similar in the context of the present investigation and the one reported by Chore *et al.* (2010). The investigation reported by Chore *et al.* (2010) indicates that in respect of group of three piles large portion of the load is shared by the corner piles. However, in the present investigation, for parallel configuration at closer spacing of 2*D* central pile shares more load; but at higher spacing such as 3*D* onwards corner pile is found to have shared large portion of the load.

6. Conclusions

Following are the broad conclusions emerging from the analysis reported in the present study:

- With increase in pile spacing and pile diameter top displacement of the pile group decreases which further, increases the resistance to lateral loads.
- Effect of number of piles along with the configuration is quite important. For group of two piles with series configuration, displacements are on higher side as compared to that for group of three piles.
- Effect of arrangement of pile in a group particularly with respect to the direction of lateral load is an important factor.
- Effect of end condition at tip of the pile is also significant on displacement of the pile group. Displacements are on higher side for free tip condition and fixed tip condition yields lower displacement.
- The capacity of the pile group is found to increase with pile spacing and pile diameter. The capacity of the pile group is found to be higher in the series configuration than that in parallel configuration. Capacity of the pile group is observed to be highest for fixed condition and lowest for free tip condition.
- Maximum positive B.M. decreases whereas negative moment increases with increase in pile spacing and pile diameter.
- While fixing moments in front pile and rear pile are same in respect of the group of two piles in the context of free tip and fixed tip of the pile, they differ for pinned tip.
- Fixing moments in corner piles are higher in the group of three piles as compared to that in group of two piles. The difference is more for free tip condition followed by fixed tip and

pinned tip with difference getting reduced.

References

Banerjee, P.K. and Davis, T.G. (1978), "The behaviour of axially and laterally loaded single piles embedded in non-homogeneous soils", *Geotechnique*, **28**(3), 309-326.

Bransby, M.F. and Springman, S. (1999), "Selection of load transfer functions for passive lateral loading of pile groups", *Comput. Geotech*., **24**, 155-184.

Chore, H.S., Ingle, R.K. and Sawant, V.A. (2010), "Parametric study of pile groups subjected to lateral load", *Struct. Eng. Mech*., **36**(2), 243-246.

Desai, C.S. (1974), "Numerical design and analysis of piles in sands", *J. Geotech. Eng.- ASCE*, **100**(6), 613-635.

Desai, C.S. and Abel, J.F. (1974*), Introduction to finite element method*, CBS Publishers, New Delhi.

Desai, C.S. and Appel, G.C. (1976), "3-D Analysis of laterally loaded structures", *Proceedings of the 2nd Int. Conf. on Numerical Methods in Geomechanics*, Blacksburg.

Desai, C.S., Kuppusamy, T. and Alameddine, A.R. (1981), "Pile cap- Pile group- Soil interaction", *J. Struct. Eng. - ASCE*, **107**(5), 817-834.

Dewaikar, D.M., Verghese, S., Sawant, V.A. and Chore, H.S. (2007), "Non-linear 3-D FEA of laterally loaded pile group incorporating no-tension behaviour of soil", *Indian Geotech. J*., **37**(3), 174-189.

Georgiadis, M. and Butterfield, R. (1982). "Laterally loaded pile behaviour", *J. Geotech. Eng - ASCE*, **108**(1), 155-165.

IS 2911 (Part I) (1979), *Code of practice for design and construction of pile foundations (First Revision)*, Bureau of Indian Standards (BIS), New Delhi (India).

Krishnamoorthy, Rao, N.B.S. and Anil, D.S. (2003), "Non-linear analysis of group of piles", *Indian Geotech. J*., **33**(4), 375-395.

Krishnamoorthy, Rao, N.B.S. and Rao, Nitin (2005), "Analysis of group of piles subjected to lateral loads", *Indian Geotech. J*., **35**(2), 154-175.

Kuhlemeyer, R.L. (1979), "Static and dynamic laterally loaded floating piles", *J. Geotech. Eng. - ASCE*, **105**(2), 289-304.

Narsimha Rao, S. and Ramkrishna, V.G.S.T. (1996), "Behaviour of pile supported dolphins in marine clay under lateral loading", *J. Geotech. Eng. - ASCE*, **122**(8), 607-612.

Ng, C.W.W. and Zhang, L.M. (2001), "Three dimensional analysis of performance of laterally loaded sleeved piles in sloping ground", *J. Geotech. Geoenviron*., **127**(6), 499-509.

Poulos, H.G. (1971), "Behaviour of laterally loaded piles-I: single piles", *J. Soil Mech. Eng.- ASCE*, **97**(5), 711-731.

Poulos, H.G. (1971), "Behaviour of laterally loaded piles-II: pile group", *J. Soil Mech. Eng.- ASCE*, **97**(5), 733-751.

Reese, L.C. and Matlock, H. (1956). "Non dimensional solutions for laterally loaded piles with soil modulus proportional to depth", *Proceedings of the 8th Texas Conf. On Soil Mechanics and Foundation Engineering*, University of Texas, Austin.

Sawant, V.A., Dewaikar, D.M. and Karthikanand, P.K. (1996), "Analysis of a pile subjected to cyclic lateral loading", *Proceedings of the International Conference in Ocean Engineering*, COE'96, IIT Madras.

Sawant, V.A. and Dewaikar, D.M. (2001), "Geometrically non-linear 3-D finite element analysis of a single pile", *Proceedings of the Int. Conf. on Computer Methods and Advances in Geomechanics*, Balkema, Rotterdam.

Spiller, W.R. and Stoll, R.D. (1964), "Lateral response of piles", *J. Soil Mech. Eng.- ASCE*, **90**, 1-9.

Tomlinson, M.J. (1977), *Pile design and construction practice*, A View Point Publications, London

Yegian, M. and Wright, S.G. (1973), "Lateral soil resistance- displacement relationships for pile foundations in soft clays", *Proceedings of the 5th Annual Offshore Technology Conference*, Houston, Texas.

Zaman, M.M., Najjar, Y.M. and Muqtadir, A. (1993), "Effects of cap thickness and pile inclination on the response of a pile group by a three dimensional non-linear finite element analysis", *Comput. Geotech*., **15**(2), 65-86.

Zhang, L. (2009), "Non-linear analysis of laterally loaded rigid piles in cohesionless soil", *Comput. Geotech.*, **36**(5), 718-729.

Zienkiewicz, O.C. (1977), *The finite element method*, Mc-Graw Hill Book, Co., New York.