Interaction and Multiscale Mechanics, Vol. 3, No. 1 (2010) 55-79
DOI: http://dx.doi.org/10.12989/imm.2010.3.1.055

Building frame - pile foundation - soil interaction analysis: a parametric study

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(Received January 15, 2009, Accepted February 3, 2010)

Abstract. The effect of soil-structure interaction on a single-storey, two-bay space frame resting on a pile group embedded in the cohesive soil (clay) with flexible cap is examined in this paper. For this purpose, a more rational approach is resorted to using the finite element analysis with realistic assumptions. Initially, a 3-D FEA is carried out independently for the frame on the premise of fixed column bases in which members of the superstructure are discretized using the 20-node isoparametric continuum elements. Later, a model is worked out separately for the pile foundation, by using the beam elements, plate elements and spring elements to model the pile, pile cap and soil, respectively. The stiffness obtained for the foundation is used in the interaction analysis of the frame to quantify the effect of soil-structure interaction on the response of the superstructure. In the parametric study using the sub-structure approach (uncoupled analysis), the effects of pile spacing, pile configuration, and pile diameter of the pile group on the response of superstructure are evaluated. The responses of the superstructure considered include the displacement at top of the frame and moments in the columns. The effect of soil-structure interaction is found to be quite significant for the type of foundation considered in the study. Fair agreement is observed between the results obtained herein using the simplified models for the pile foundation and those existing in the literature based on a complete three dimensional analysis of the building frame - pile foundation - soil system.

Keywords: foundation; frame; piles; simplified models; soil-structure interaction; superstructure.

1. Introduction

The framed structures are normally analyzed with their bases considered to be either completely rigid or hinged. However, the foundation resting on deformable soils also undergoes deformation depending on the relative rigidities of the foundation, superstructure and soil. Interactive analysis is, therefore, necessary for the accurate assessment of the response of the superstructure. Numerous interactive analyses have been reported in studies in the 1960-70's such as Chameski (1956), Morris

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(1966), Lee and Brown (1972), King and Chandrasekaran (1974), Buragohain *et al.* (1977), and in more recent studies such as Shriniwasraghavan and Sankaran (1983), Subbarao *et al.* (1985) and Deshmukh and Karmarkar (1991). While a majority of these analyses have been presented either for the interaction of frames with isolated footings or for the interaction of frames with raft foundation, few of them were focused on the interaction of frames with combined footings. In the meantime, much work is available on pile foundation (single as well as pile group), but comparatively little work, except Buragohain *et al.* (1977), was reported on the analysis of framed structures resting on pile foundations to account for the soil-structure interaction. The work reported by Buragohain *et al.* (1977) was based on simplified approach. Ingle and Chore (2007) emphasized the necessity of interaction analysis for building frames resting on pile foundation based on a more rational approach and realistic assumptions. Subsequently, Chore and Ingle (2008a, b) and Chore *et al.* (2009) presented interaction analysis of such a structural system. A brief review of the literature on the prominent interaction analyses of framed structures and analyses of pile foundation is given in the following section.

2. Brief review of literature

In the early 1960's, Mayerhof (1953) recognized the importance of superstructure – foundation - soil interaction. From then onwards, numerous studies have been carried out to quantify the effect of soil-structure interaction on the behaviour of framed structure. Chameski (1956) and Subbarao *et al.* (1985) considered the interaction effect in a very simplified manner and demonstrated that the force quantities should be revised to account for such an effect. Only a limited number of studies (Chameski 1956, Morris 1966, King and Chandrasekaran 1974) pointed out the necessity for evaluation of such an effect for multistoried space frames having more than three bays. Continuous efforts in improving the analytical techniques and availability of high speed computers gave rise to the powerful finite element method. In the literature, numerous finite element approaches are available for analyzing the interaction of plane frame-foundation-soil systems (Lee and Harrison 1970, Lee and Brown 1972, Deshmukh and Karamarkar 1991) and space frame-foundation-soil systems (Morris 1966, King and Chandrasekaran 1974, Shriniwasraghavan and Shankaran 1983). In the work by Subbarao *et al.* (1985), an interaction analysis of two dimensional as well as three dimensional frames was conducted. Buragohain *et al.* (1977) reported their analysis of building frames on pile foundation using the stiffness matrix method.

The behaviour of soil medium is often simulated using simplified models such as equivalent idealized stiffness elements, i.e., ideal springs and elastic continuum. While Lee and Harrison (1970) used the *Winkler* model, Mayerhof (1953) considered the soil medium as an elastic continuum. Both models were employed by Hain and Lee (1974) and Subbarao *et al.* (1985) in their comparative studies.

More recently, much work was done on the quantification of the effect of soil-structure interaction on the behaviour of framed structures (Dasgupta *et al.* 1998, Mandal *et al.* 1999). Viladkar *et al.* (1991) used coupled finite-infinite element in the interactive studies of framed structures and demonstrated the viability of application of such a technique in analysis. Similarly, an interactive analysis was conducted by Noorzaei *et al.* (1991) for space frames resting on raft. Recently, Stavirdis (2002) presented a simplified interaction analysis of layered soil-structure interaction, and Hora (2006) the non-linear soil-structure interaction analysis of infilled building frames. While most of the aforementioned studies dealt with the interaction of frames with isolated footings or combined footings or raft foundation, only the study by Buragohain *et al.* (1977) is found to deal with the interaction analysis of frames resting on piles.

In the latter category, three dimensional analysis of pile foundation requires substantial efforts. Depending upon the load applied at the foundation head, various approaches are available for analysis of the pile group. Even though a pile group may be subjected to axial loads, in the more often case, the combination of axial and lateral loads acting on the pile foundation can further complicate the analysis.

The approaches available for the analysis of axially loaded pile foundations include the Elastic Continuum Method (Poulos 1968, Butterfield and Banerjee 1971) and Load Transfer Method (Coyle and Reese 1966, Hazarika and Ramasamy 2000, Basarkar and Dewaikar 2005), while those for analyzing the laterally loaded pile foundations include the Elastic Approach (Spillers and Stoll 1964, Poulos 1971, Banerjee and Davis 1978) and Modulus of Subgrade Reaction Approach (Matlock and Reese 1956, Georgiadis and Butterfield 1982, Sawant *et al.* 1996, Wu *et al.* 1998).

With the advent of computers in the early seventies, more versatile finite element method (Desai and Abel 1974, Desai and Appel 1976, Sawant and Dewaikar 1999, Patil and Dewaikar 1999, Sawant and Dewaikar 2001, Ng and Zhang 2001, Krishnamoorthy *et al.* 2003, 2005, Dewaikar *et al.* 2007, Zhang 2009) has become popular for analyzing the problem of pile foundations in the context of linear and non-linear domains. Desai *et al.* (1981) presented a simplified finite element analysis for the soil-structure interaction problem, with consideration for the interaction of the pile cap and underlying soil. Along the same lines, such an effect was demonstrated to be significant in the analysis of pile groups along with the effect of socketted end condition in the studies by Chore and Sawant (2002, 2004).

3. Significance and scope of the present work

The above review of literature highlights extensive works on the interactive analysis of framed structures resting on either isolated footings or combined footings or on raft foundation. Except the work by Buragohain *et al.* (1977), hardly any work has been conducted on the framed structure supported by pile foundation. Buragohain *et al.* (1977) evaluated the space frames resting on pile foundation by the stiffness matrix method in order to quantify the effect of soil-structure interaction using simplified assumptions. In this study, the pile cap was considered to be rigid and with its stiffness ignored. The stiffness matrix for the entire pile group was derived by the principle of superposition using the rigid body transformation. The foundation stiffness matrix was then combined with the superstructure matrix for attempting the interactive analysis.

Ingle and Chore (2007) reviewed the soil-structure interaction (SSI) analysis of framed structures and the problems related to pile foundations, and underscored the necessity of interactive analysis for building frames resting on pile foundations by more rational approach and realistic assumptions. It was suggested that flexible pile caps along with their stiffness should be considered and the stiffness matrix for the sub-structure should be derived by considering the effect of all piles in each group.

However, the basic problem of the building frame is three dimensional in nature. Although a complex three-dimensional finite element approach, when adopted for the analysis, is quite expensive in terms of time and memory, it facilitates realistic modeling of all the parameters involved. Along these lines, Chore and Ingle (2008a) presented a methodology for the comprehensive analysis of building frames supported by pile groups embedded in soft marine clay using the 3-D finite element method. The effect of various foundation parameters, such as the configuration of the pile group, spacing and number of piles, and pile diameter, was evaluated on the response of the frame. The analysis also considered the interaction between pile cap and soil.

Besides, Chore and Ingle (2008b) reported an interaction analysis on the space frame with pile foundations using the finite element method, wherein the foundation elements were modeled in the simplified manner as suggested by Desai *et al.* (1981). The pile cap was idealized as two dimensional plate elements, the piles as one dimensional beam elements, and the soil as linearly elastic independent springs. In this way, the three dimensional pile foundation can be replaced by an assembly of one dimensional beam elements, two dimensional plate elements and equivalent springs. The memory requirement is about one tenth of that required by a three dimensional modeling, rendering it to rather easy to simulate the original complex problem.

In the studies by Chore and Ingle (2008a, b), an uncoupled analysis (sub-structure approach) of the system of building frame and pile foundation was presented. By this methodology, a building frame was analyzed separately with the assumption of fixed column bases. Later, equivalent stiffness was derived for the foundation head and used in the interaction analysis of the frame to include the SSI effect. More recently, Chore *et al.* (2009) presented an interaction analysis for the building frame resting on the pile group using a coupled approach, i.e., by considering the system of building frame - pile foundation - soil as a single combined unit. Although such an analysis is computationally uneconomical, fair agreement was observed between the results obtained using coupled and uncoupled approaches.

Using the uncoupled approach, a comprehensive interaction analysis of the building frame such as the one shown in Fig. 1 is presented in this paper with simplified models for the pile foundation, in a way similar to the work of Desai *et al.* (1981). Two groups of piles consisting of two piles and

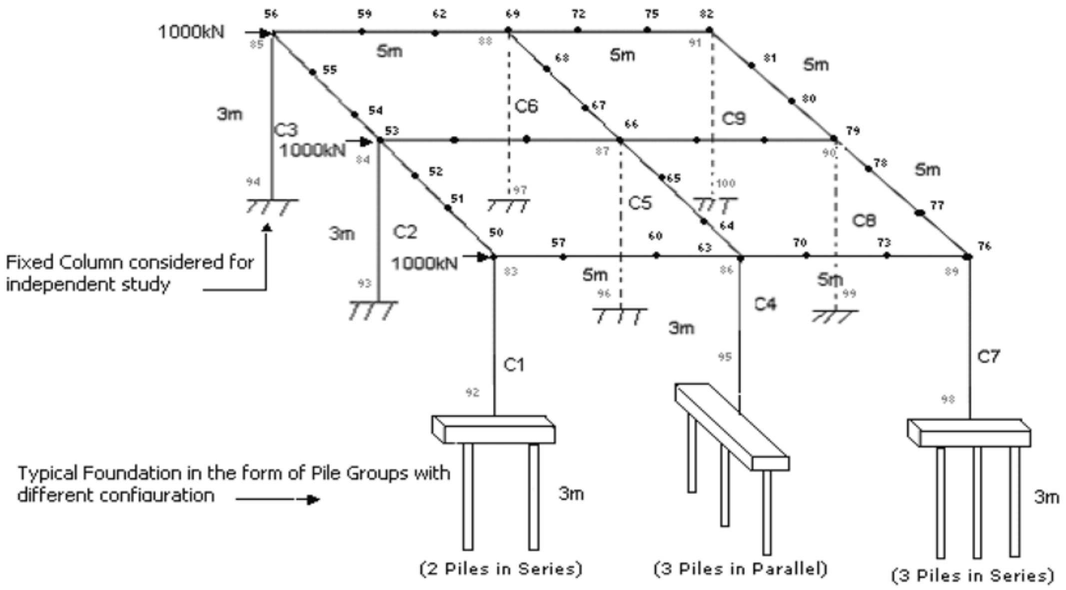


Fig. 1 Typical building frame supported by groups of piles

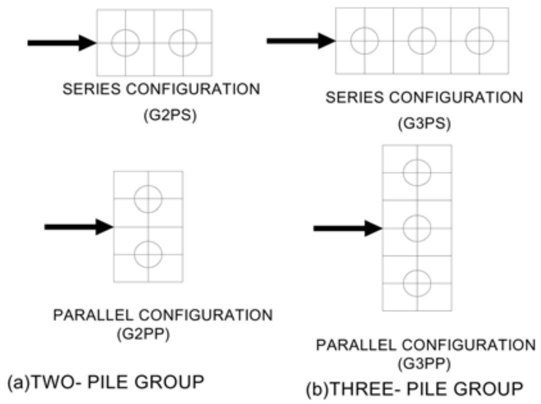


Fig. 2 Different configurations of the pile groups considered in the present study

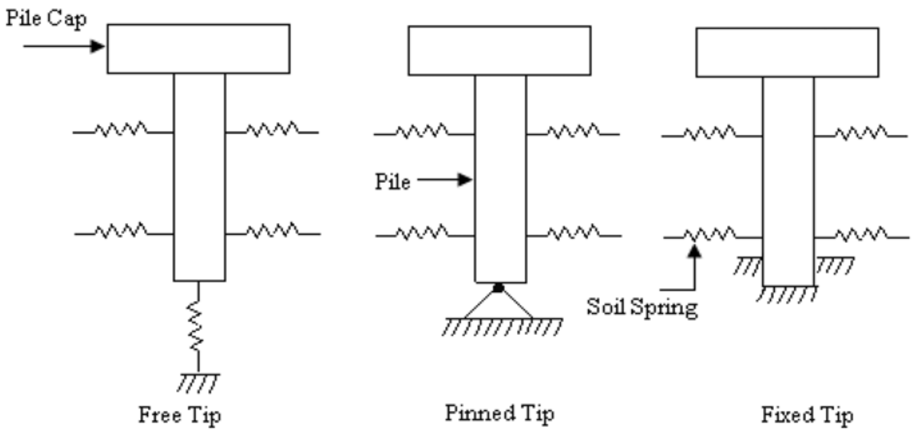


Fig. 3 Different end conditions assumed to prevail at the pile tip

three piles, respectively, with two different configurations, such as series or parallel arrangements of piles, are considered (Fig. 2). The effect of interaction between the piles and underlying soil is also included. In addition, three different end conditions that may prevail on the tip of the pile are considered (Fig. 3). The effects of pile spacing, pile configuration, and pile diameter on the top displacement of the frame and the maximum moment in columns of the frame, as well as variation of moments, is studied in the parametric study. The results are compared with those existing in the literature.

4. Modeling of the super- and sub-structures

The elements of the superstructure (beam, column and slab) and that of the substructure (pile and soil) are discretized into the 20-node iso-parametric continuum elements with three degrees of freedom at each node, i.e., with a displacement along each of the three directions X, Y and Z (Fig. 4). As for the substructure, i.e., pile foundation, simplified modeling approach, as the one suggested by Desai *et al.* (1981), is adopted. Namely, beam element, plate element and spring element are

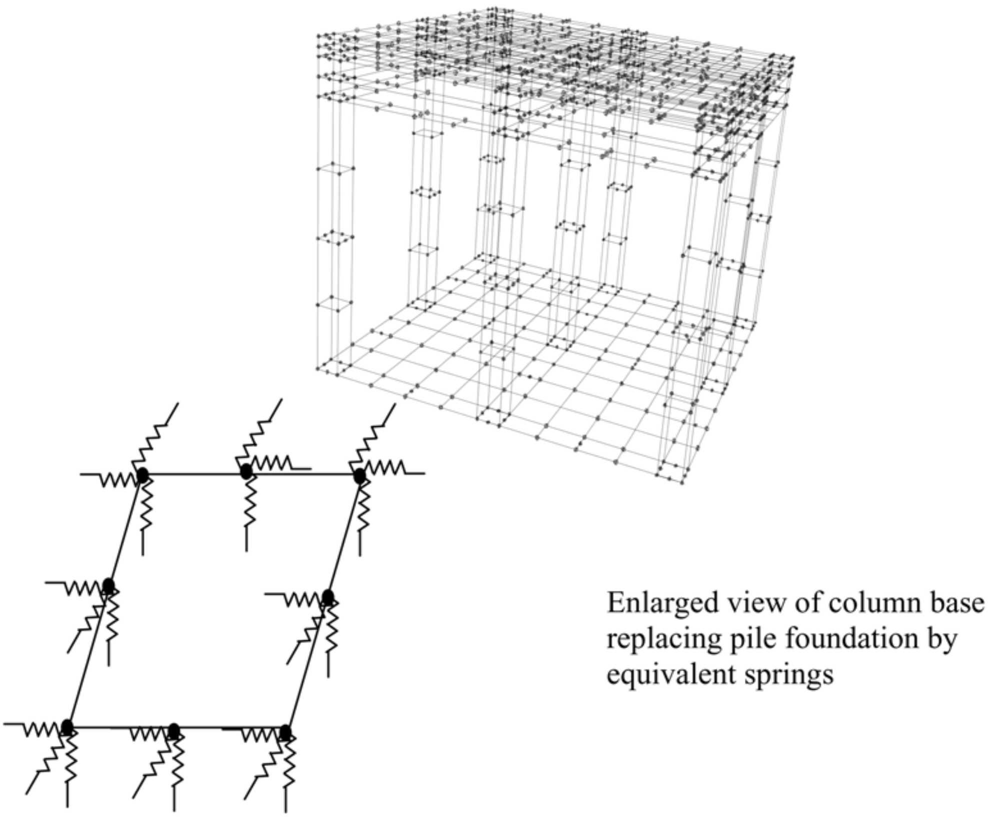


Fig. 4 Mathematical model of the building frame

used to simulate the pile, pile cap and underlying soil, respectively. The following is a brief description of the finite element formulation.

5. Finite element formulation

5.1 Formulation of three dimensional frame elements

The formulation employed in the present study for analyzing the building frame is briefly summarized below.

5.1.1 Continuum element

Relation between the strains and nodal displacements of an element can be expressed as

$$\{\varepsilon\}_e = [B][\delta]_e \tag{1}$$

where $\{\varepsilon\}_e$ is the strain vector, $\{\varepsilon\}_e$ is the vector of nodal displacements, and $[B]$ is the strain displacement transformation matrix. The stress-strain relation is given by

$$\{\sigma\}_e = [D][\varepsilon]_e \tag{2}$$

where $\{\sigma\}_e$ is the stress vector and $[D]$ is the constitutive relation matrix. The stiffness matrix of an element is given as

$$[K]_e = \int_V [B]^T[D][B]dv \tag{3}$$

where V denotes the volume of the element.

5.1.2 Interface element

The strains between the surface of soil and structure can induce stresses in the interface element. The strains can be expressed in terms of the relative displacements of the interface element as

$$\{\varepsilon\}_e = [B]_f[\delta]_e \tag{4}$$

where $[B]_f$ represents the strain displacement transformation matrix. The element stiffness can be computed by the following expression

$$[K]_e = \int_S [B]_f^T [D]_f [B]_f \, ds \tag{5}$$

where $[D]_f$ is the constitutive relation matrix for the interface element.

5.1.3 Equivalent nodal force vector

The lateral or vertical force (F_H or F_V) acting on the pile cap is considered as a uniformly distributed force over the area of action. The intensity of this uniformly distributed force is $q = F/A$, where A is the area of the pile cap. The equivalent nodal force vector, $\{Q)_e$, is then expressed as

$$\{Q\}_e = \int_A q[N]^T d\,A \tag{6}$$

where $[N]$ represents the shape function matrix.

5.1.4 Method of analysis

The stiffness matrices for all elements are computed and assembled into the global stiffness matrix, $[A]$, in skyline storage form. Similarly, the load vector is assembled in vector $[B]$. With these made available, the equilibrium equations are derived for the system. The Gauss elimination will then be employed to solve the equilibrium equations derived.

5.2 Formulation using simplified modeling for pile foundation

5.2.1 Beam element

The beam element has six degrees of freedom at each node, which includes the lateral displacement u and v, axial displacement w, and rotation about three axes. If the rotation about the z-axis is not considered, the number of degrees of freedom is reduced to 5, as indicated by the nodal displacement vector, $\{\delta\}_e$, given below

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

The stiffness matrix of the element $[k]_e$ is given as

$$[k]_e = \int_0^L [B]^T [D][B] dz \tag{7}$$

where $[B]$ is the strain-displacement transformation matrix and $[D]$ is the constitutive relation matrix for the beam element.

5.2.2 Spring element

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

$$\begin{Bmatrix} p_x \\ p_y \\ p_z \end{Bmatrix} = \begin{bmatrix} E_{sx} & 0 & 0 \\ 0 & E_{sy} & 0 \\ 0 & 0 & E_{sz} \end{bmatrix} \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} \tag{8}$$

where $\{E_{sx}$, E_{sy} and $E_{sz}\}$ are the soil subgrade reaction modulus at depth z. The soil support element stiffness matrix, $[K]_s$, can be obtained as

$$[K]_s = \int_0^L [N]^T \begin{bmatrix} E_{sx} & 0 & 0 \\ 0 & E_{sy} & 0 \\ 0 & 0 & E_{sz} \end{bmatrix} [N] dz \tag{9}$$

5.2.3 Plate element

The pile cap is modeled using the 4-node elements, as shown in Fig. 5. The lateral displacements u and v in the X and Y directions are included to account for the membrane effect, while to consider the bending effect, three degrees of freedom are included at each node, namely, the transverse displacement w, and rotations about the X and Y axes, θ_x and θ_y respectively. Together with two in-plane displacements, u and v, there is a total of 5 degrees of freedom at each node. The numbers of degrees of freedom for the beam element and plate element at each node are the same. Consequently, the requirement of inter-element compatibility between adjacent plate and beam elements is duly taken into account.

5.2.3 (a) Membrane effect

For the in-plane or membrane loadings, the plane stress idealization is considered. The nodal displacement vector, $\{\delta\}^T$, of the plate element is given by

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

And the element stiffness matrix, $[K]_{in}$, is given by

$$[k]_{in} = abh \int_{-1}^{1} \int_{-1}^{1} [B]^T [D][B] d\xi d\eta \tag{10}$$

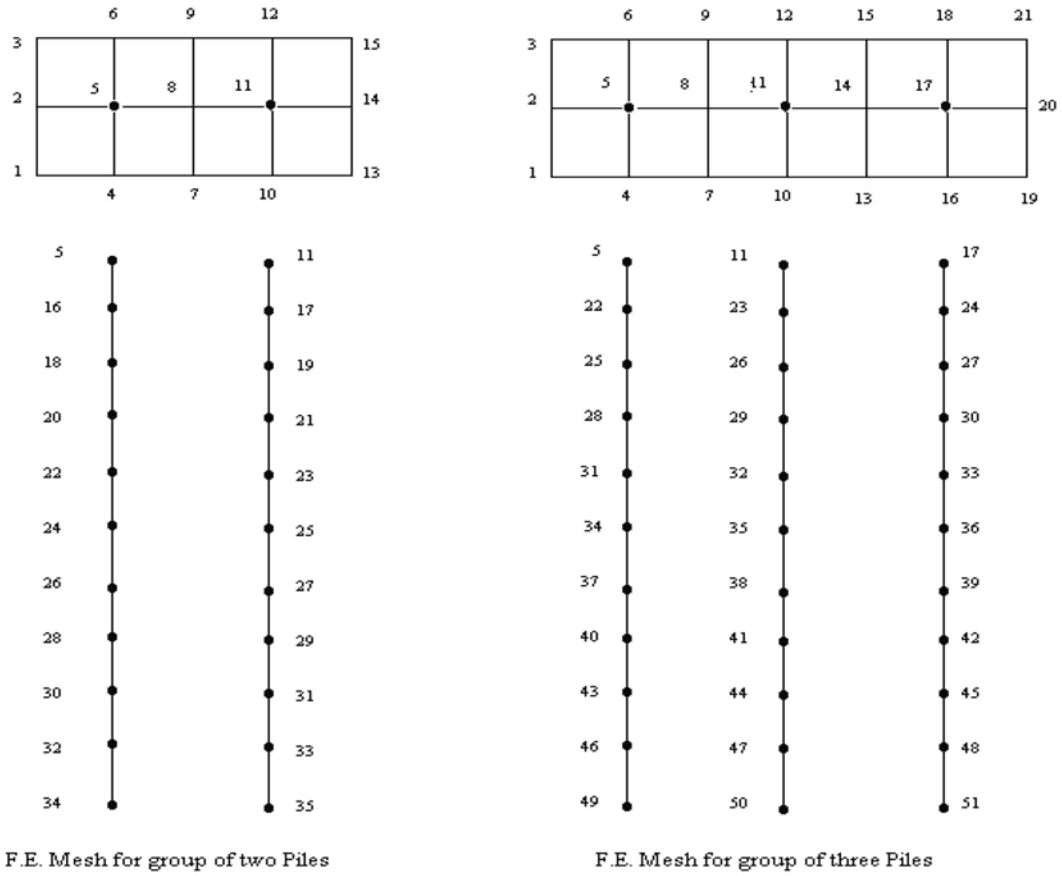


Fig. 5 Typical finite element mesh for the pile groups of two and three piles in series

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

5.2.3 (b) Bending Effect

The nodal displacement vector $\{\delta\}$ of the four-node pate element consists of 12 displacements, given as

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

The transverse displacement, w, is expressed in terms of polynomials in x and y

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

$$w = [P]\{\alpha\} \text{ and } [P] = [1\ x\ y\ x^2\ xy\ y^2\ x^3\ x^2y\ xy^2\ y^3\ x^3y\ xy^3] \tag{11}$$

where $\{\alpha\}$ is a vector consisting of 12 constants, α_1 to α_{12}. The rotations θ_x and θ_y are then given by

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

The constants α_1 to α_{12} can be evaluated by writing down 12 simultaneous equations for w, θ_x and θ_y at the 4 nodes by substituting their appropriate coordinates x and y. These twelve equations can be written as follows

$$\{\delta\} = [C]\{\alpha\} \tag{13}$$

where $[C]$ is a matrix defining the relationship between the displacements and constants α_i. The element stiffness matrix, $[K]_{bd}$, for plate bending can be written as

$$[K]_{bd} = \int_{-b}^{b}\int_{-a}^{a}[B]^T[D][B]dxdy \tag{14}$$

where $[B]$ is the strain-displacement transformation matrix for plate bending, and $[D]$ is the constitutive relation matrix. For uniformly distributed load q acting on the element, the load vector, $[F]$, can be obtained as

$$\{F\} = [C^{-1}]^T\int_{-b}^{b}\int_{-a}^{a}[P]^T q\,dxdy \tag{15}$$

5.2.4 Method of analysis

The stiffness matrices for the pile, soil and pile cap are assembled in the global stiffness matrix. With the global stiffness matrix and load vector made available, the overall equilibrium equations are established. Then, the Gauss elimination is employed to solve for the unknown nodal displacements.

Back Calculation of Internal Forces

After the nodal displacements are computed, the element stiffness matrix is recalled to obtain the internal forces $\{F\}_e$, (such as the axial force, shear force and bending moment) for each element.

$$\{F\}_e = [k]_e\{\delta\}_e \tag{16}$$

On the premise of aforementioned idealizations, a numerical procedure for the 3-D finite element analysis and another procedure using the simplified model were programmed in Fortran 90. It was validated on some benchmark structures, such as cantilever beams and frames, wherein the bending moments predicted by the program were found to agree well with those by theory. The program was also validated with the published results and then implemented for the analysis of the building frame considered in this study.

6. Numerical problem

A three-dimensional single storeyed building frame resting on pile foundation as shown in Fig. 1 is considered for the study. The frame, 3 m high, is 10 m × 10 m in plan with each bay of dimensions 5 m × 5 m. The slab, 200 mm thick, is provided at the top as well as at the floor level. The slab at the top is supported by beams, 300 mm wide and 400 mm deep, which in turn rest on

Table 1 Geometrical and material properties for the elements of the frame and foundation

Properties	Corresponding Values
Pile Size/Diameter (D)	300 mm, 400 mm, 500 mm and 600 mm
Length of Pile (L)	3 m (3000 mm)
Grade of Concrete used for the Frame Elements	M-20 (Characteristic Comp Strength: 20 MPa)
Young's Modulus of Elasticity for Frame Elements ($E_{c\ Frame}$)	0.25491×10^8 kPa
Grade of Concrete Grade used for Pile and Pile Cap	M-40 (Characteristic Comp Strength: 40 MPa)
Young's Modulus of Elasticity for Foundation Elements ($E_{c\ Foundation}$)	0.3605×10^8 kPa
Poisson's Ratio (μ_c)	0.15

columns of size 300 mm × 300 mm. While dead load is considered according to unit weight of the materials of which the structural components of the frame are made up for the parametric study presented here, a lateral load of 1000 kN is assumed to act at the three points of the frame, as shown in the Fig. 1.

The configurations of pile foundation considered in the present study include groups of two piles and three piles with series arrangement (G2PS and G3PS) and parallel arrangement (G2PP and G3PP), as shown in Fig. 2. All the piles in each group are assumed to be of friction type and are, further, assumed to be connected by a flexible cap.

The length of piles and thickness of the pile cap, along with the diameters considered in the parametric analysis, are listed in Table 1. The grade of concrete for the superstructure elements is assumed to be M-20 (according to Indian specification) corresponding to a characteristic compressive strength of 20 MPa. The grade of concrete used for the sub-structure elements is assumed to be M-40 corresponding to a characteristic compressive strength of 40 MPa. The corresponding Young's modulus of elasticity and Poisson's ratio are also given in Table 1. A soft marine clay type of soil (a cohesive soil) is considered in the analysis.

As for the soil, Young's modulus of elasticity and Poisson's ratio are selected from those available in the literature [*afte*r Sawant and Dewaikar 2001).

- Young's modulus of elasticity (E_s): 4267 kN/m^2
- Poisson's ratio (μ): 0.45

The proposed numerical procedure adopted in the analysis for analyzing the foundation requires the value of modulus of subgrade reaction. In absence of reliable data for 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 these considerations, the value of K_h is assumed to be 6667 kN/m^3.

The effect of various end conditions, such as free tip, pinned tip and fixed tip (Fig. 3), assumed to prevail at the tip of the piles, is evaluated on the response of the frame. The finite element model of the building frame based on the modeling idealizations described in the previous section is shown in Fig. 4. Typical finite element mesh for a group of two piles and three piles in series arrangement is shown in Fig. 5.

7. Results and discussion

An independent analysis is carried out for the pile foundation and the equivalent spring stiffness is calculated for both the horizontal and vertical directions; and further they are used in the interaction analysis. In the parametric study conducted for the specific frame presented here, the responses of the superstructure considered for comparison include the horizontal displacement at the top of the frame and the bending moment (BM) at the top, as well as at the bottom of the columns of the superstructure, for both fixed base and soil-structure interaction (SSI) cases. The effect of the pile spacing in the group of two and three piles with the series and parallel arrangements is evaluated on the response of superstructure using the three sub-models considered for the pile tip, as discussed in the following section. Further, the results are compared with those obtained in the interaction analysis of the building frame - pile group - soil system, where the pile foundation-soil system is modeled as a complete three dimensional system (Chore and Ingle 2008a).

7.1 Effect of SSI on displacement

The displacement at the top of the frame for various pile spacing with respect to different pile configurations and different pile tip conditions considered in the present study are indicated in Tables 2 (a) and (b).

From the results tabulated in Table 2, the effect of SSI appears to increase the top displacement in the range of 42% to 103%. The general trend observed for the horizontal displacement at top of the frame with pile spacing for all the configurations of the pile groups and all the pile diameters is that the horizontal displacement is higher at the closer spacing of 2D. The displacement decreases for larger pile spacing such as 3D, 4D and 5D. This trend in reduction in the displacement is attributed to the overlapping of the stressed zones of individual piles at closer spacing.

When the piles are closely spaced, stress bulbs around individual piles in a group overlap and this causes the loss of passive resistance leading to the large amount of deflections of the piles. As the spacing between the piles increases, the influence of the stress zone of one pile on another is reduced and the passive resistance offered by the surrounding soil mass is improved. This further leads to the reduction in deflections of the piles. The trend is same for all the three conditions considered to prevail at the pile tip.

The number of piles in a group also is found to have significant effect on the displacement. It is observed that for series configuration under the free tip condition, the top displacement of the frame reduces for all diameters with the increase in spacing and number of piles. Similar trend is observed for the group having piles with pinned tip and fixed tip. However, there is slight exception for the case of pinned tip condition with smaller diameter (300 mm) where the displacement at the larger spacing (5D) for the group of three piles is slightly higher as compared to that at the same spacing for the group of two piles. One similar exception is observed for the case with larger diameter and larger spacing under the fixed tip condition where for the 600 mm diameter pile, the displacement is the same for the groups of three and two piles. However, for the parallel configuration, the number of piles in the group does not have significant effect on the displacement for all end conditions assumed for the pile tip.

The effect of the configuration of pile group on the response of the superstructure is also significant. It is observed from the results that for the pile groups comprising of two as well as three piles, the displacements obtained for the parallel arrangement are on the higher side as compared to

Table 2 (a) Displacement (mm) at top of building frame for fixed base and SSI and corresponding percentage increase for group of two piles

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			
Fixed Base	38.18				38.18			
Free Tip								
2D	75.88 (98.95)	70.37 (84.31)	66.16 (73.28)	62.94 (64.85)	77.63 (103.32)	72.04 (88.69)	67.75 (77.45)	64.37 (68.60)
3D	72.86 (90.83)	67.45 (76.67)	63.53 (66.39)	60.68 (58.93)	75.68 (98.21)	69.95 (83.21)	65.69 (72.05)	62.46 (63.60)
4D	70.41 (84.42)	65.24 (70.87)	61.66 (61.50)	59.13 (54.87)	74.08 (94.02)	68.23 (78.71)	64.07 (67.81)	60.99 (59.74)
5D	68.48 (79.36)	63.59 (66.55)	60.30 (57.93)	58.02 (51.96)	72.54 (90.00)	66.78 (74.90)	62.74 (64.32)	59.80 (56.63)
Pinned Tip								
2D	73.53 (92.58)	68.86 (80.35)	65.42 (71.35)	62.65 (64.09)	77.63 (103.33)	72.04 (88.69)	67.74 (77.33)	64.36 (68.48)
3D	71.35 (86.88)	66.74 (74.80)	63.33 (65.87)	60.66 (58.88)	75.68 98.22	69.95 83.21	65.69 71.96	62.46 63.50
4D	69.48 (81.98)	64.97 (70.16)	61.64 (61.44)	59.11 (54.82)	74.00 (93.82)	68.23 (78.61)	64.07 (67.72)	60.99 (59.66)
5D	67.92 (77.90)	63.52 (66.37)	60.30 (57.93)	57.91 (51.68)	72.54 (90.00)	66.78 (74.82)	62.74 (64.24)	59.82 (56.60)
Fixed Tip								
2D	70.72 (85.13)	63.01 (64.94)	58.47 (53.06)	55.89 (46.31)	77.62 (103.19)	72.04 (88.59)	67.74 (77.33)	64.37 (68.60)
3D	68.79 (80.08)	61.84 (61.88)	57.74 (51.15)	55.35 (44.90)	75.68 (98.12)	69.95 (83.12)	65.69 (71.96)	62.47 (63.53)
4D	67.08 (75.60)	60.78 (59.11)	57.06 (49.37)	54.86 (43.62)	74.00 (93.72)	68.22 (78.59)	64.07 (67.72)	60.99 (59.66)
5D	65.65 (71.86)	59.85 (56.68)	56.46 (47.80)	54.41 (42.42)	72.54 (89.90)	66.78 (74.82)	62.75 (64.27)	59.82 (56.60)

Figures in bracket indicate percentage increase in displacement

those in the series arrangement for all diameters and for all end conditions assumed for the pile tip. When the simplified modeling is used, it is seen from the results that the series arrangement offers stiffer behaviour than the parallel arrangement. This can be due to the fact that the combined structural stiffness of the pile and pile cap in parallel arrangement is small as compared to that in series arrangement. For piles with short to medium lengths, this is a governing factor and the 3 m long pile considered in the present study falls under the category of short piles.

Further, it is observed that with increase in the diameter of piles, the displacement at the frame top decreases for any spacing within the configuration of pile group under consideration. This can be attributed to the increased stiffness of the pile group with higher diameters. Such a trend holds

Table 2 (b) Displacement (mm) at top of building frame for fixed base and SSI and corresponding percentage increase for group of three piles

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
	G3PS				G3PP			
Fixed Base	38.18				38.18			
	Free Tip							
2D	73.91 (93.48)	68.59 (79.55)	64.66 (69.26)	61.76 (61.68)	77.63 (103.22)	72.04 (88.58)	67.74 (77.33)	64.37 (68.51)
3D	71.52 (87.23)	66.21 (73.32)	62.57 (63.80)	60.02 (57.20)	76.80 (101.05)	70.66 (84.97)	66.15 (73.17)	62.76 (64.29)
4D	69.64 (82.30)	64.52 (68.90)	61.17 (60.13)	58.85 (54.05)	75.59 (97.87)	69.18 (81.10)	64.65 (69.24)	61.34 (60.58)
5D	68.24 (78.64)	63.52 (66.28)	60.13 (57.41)	57.95 (51.70)	74.30 (94.50)	67.78 (77.43)	63.30 (65.71)	60.11 (57.36)
	Pinned Tip							
2D	72.35 (89.39)	67.89 (77.72)	64.49 (68.82)	61.75 (61.65)	77.63 (103.22)	72.04 (88.58)	67.75 (77.36)	64.36 (68.48)
3D	70.77 (85.26)	66.11 (73.15)	62.56 (63.77)	59.85 (56.68)	76.80 (101.05)	70.66 (84.97)	66.16 (73.19)	62.78 (64.34)
4D	69.30 (81.41)	64.52 (68.90)	61.00 (59.68)	58.41 (52.91)	75.59 (97.87)	69.19 (81.13)	64.67 (69.29)	61.38 (60.68)
5D	68.07 (78.19)	63.25 (65.60)	59.81 (56.57)	57.35 (50.13)	74.29 (94.48)	67.79 (77.46)	63.35 (65.83)	60.21 (57.62)
	Fixed Tip							
2D	69.44 (81.78)	62.33 (63.17)	58.13 (52.17)	55.72 (45.86)	77.63 (103.22)	72.04 (88.58)	67.75 (77.36)	64.36 (68.48)
3D	67.96 (77.91)	61.41 (60.76)	57.58 (50.73)	55.32 (44.82)	76.80 (101.05)	70.66 (84.97)	66.16 (73.19)	62.77 (64.32)
4D	66.57 (74.27)	60.46 (58.27)	56.95 (49.08)	54.86 (43.61)	75.59 (97.87)	69.19 (81.13)	64.67 (69.29)	61.39 (60.71)
5D	65.44 (71.31)	59.65 (56.15)	55.00 (43.98)	54.42 (42.46)	74.30 (94.48)	67.81 (77.51)	63.36 (65.86)	60.22 (57.64)

good for all the pile configurations and for all the three conditions assumed for the pile tips.

7.1.1 Comparison with the published results (Chore and Ingle 2008a)

Chore and Ingle (2008a) presented a complete three-dimensional finite element analysis of the building frame supported on pile groups where the pile foundation was modeled using three dimensional idealizations. The pile, pile cap and soil was modeled as 20-node continuum elements and interface between the pile and soil was modeled as 16-node surface elements. In this paper the simplified approach is employed to model the foundation. The effect of SSI (free tip condition) is found to increase the top displacement in the range 42% to 103% in the present study whereas the corresponding increase reported by Chore and Ingle (2008a) is in the range of 55% to 165%.

Although the general trend of reduction in displacement with the increase in pile spacing, pile diameter and number of piles remains the same in either analysis, the arrangement of piles in a group has a significant effect in view of the approach employed in modeling the foundation. In the present study, the frame is found to be stiff in terms of the top displacement for the series arrangement of piles in a group, whereas the study by Chore and Ingle (2008a) indicated that the frame is stiff for the parallel arrangement; particularly for smaller pile diameters. In the 3-D analysis (Chore and Ingle 2008a), the soil is modeled as continuum and hence, more passive resistance is offered by the soil owing to larger area of soil, thereby leading to larger soil stiffness. The combined effect of piles and soil increases the stiffness of the parallel configuration and hence, the frame is found stiff for parallel arrangement.

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

7.2 Effect of SSI on moment in columns

The effect of soil-structure interaction on the bending moment at the top and bottom of the superstructure columns is evaluated in terms of the percentage increase (or decrease). The absolute maximum moments in columns obtained for the SSI case are compared with those of the case with the column bases fixed, to evaluate the effect of incorporating the SSI in analysis. Moreover, the trend of variation in moments with pile spacing is also studied for all configurations of the pile groups and for all the pile diameters and end conditions assumed for the pile tip. The absolute maximum positive and negative moments computed for the fixed column bases are 276 kN-m and 283 kN-m, respectively. The effect of SSI is found to increase the maximum positive moment in the range of 14-15% and the maximum negative moment in the range of 26-27%.

7.2.1 Effect of SSI on maximum moment in individual columns

For the group of two piles, a decrease of 1.4% is observed in the hogging moment at the top of column C-1 with 300 mm pile diameter, while at the top of all other columns, the moment is found to increase, with a maximum value of 28.15%. At the bottom of the superstructure columns, the maximum decrease in the moment is observed to be 38.4%, while the increase in moment is observed to be 15%. For the piles with 400 mm diameter, the maximum decrease in the moment at top of the superstructure columns is 0.9%, while the maximum increase by 27.97%. At the bottom, the maximum decrease is in the range of 38.21%, while the increase is observed to be 14.88%. For the piles with 500 mm diameter, the maximum decrease and increase in moment at the top of the column is found to be 0.3% and 27.75%, respectively, whereas at the bottom, it is observed to be 38% and 14.8%. For piles with larger diameters like 600 mm, the maximum decrease and increase in the hogging moment is observed to be 0.38% and 27.5% respectively, while at the bottom, the values are 37.65% and 14.68%.

For the group of three piles with 300 mm diameter, the maximum decrease and increase in the hogging moment in column is observed to be 1.67% and 28.20%, respectively, whereas at the bottom, the maximum decrease and increase in the sagging moment is 38.53% and 15.5% respectively. For next higher diameter of 400 mm piles, the maximum decrease in the hogging moment is 1.19% and the maximum increase is found to be 27.97%, whereas for the sagging moments, the maximum decrease and increase is 38.31% and 14.86%, respectively. For piles with 500 mm diameter, the maximum decrease and increase in the hogging moment is in the range of 0.53% and 27.75%, respectively, while these values are in the range of 38.03% and 14.8% for the positive moments. For piles with 600 mm diameter, however the hogging moment only increases, with the maximum being 27.50% higher. However, for the sagging moment, the maximum decrease and increase in the moment is 37.7% and 14.7%.

The effect of diameter is observed to be significant; particularly for the hogging moment induced in columns in the row on the left hand side of the frame for both pile groups with either configuration. For piles with 600 mm diameter, there is no decrease in the hogging moment. The effect of SSI on the moments in individual columns of the frame considered in the present study is observed to be less for the columns placed on the left hand side of the frame and more for those placed on the right hand side.

7.2.2 Effect of configuration on variation of moments versus pile spacing in columns

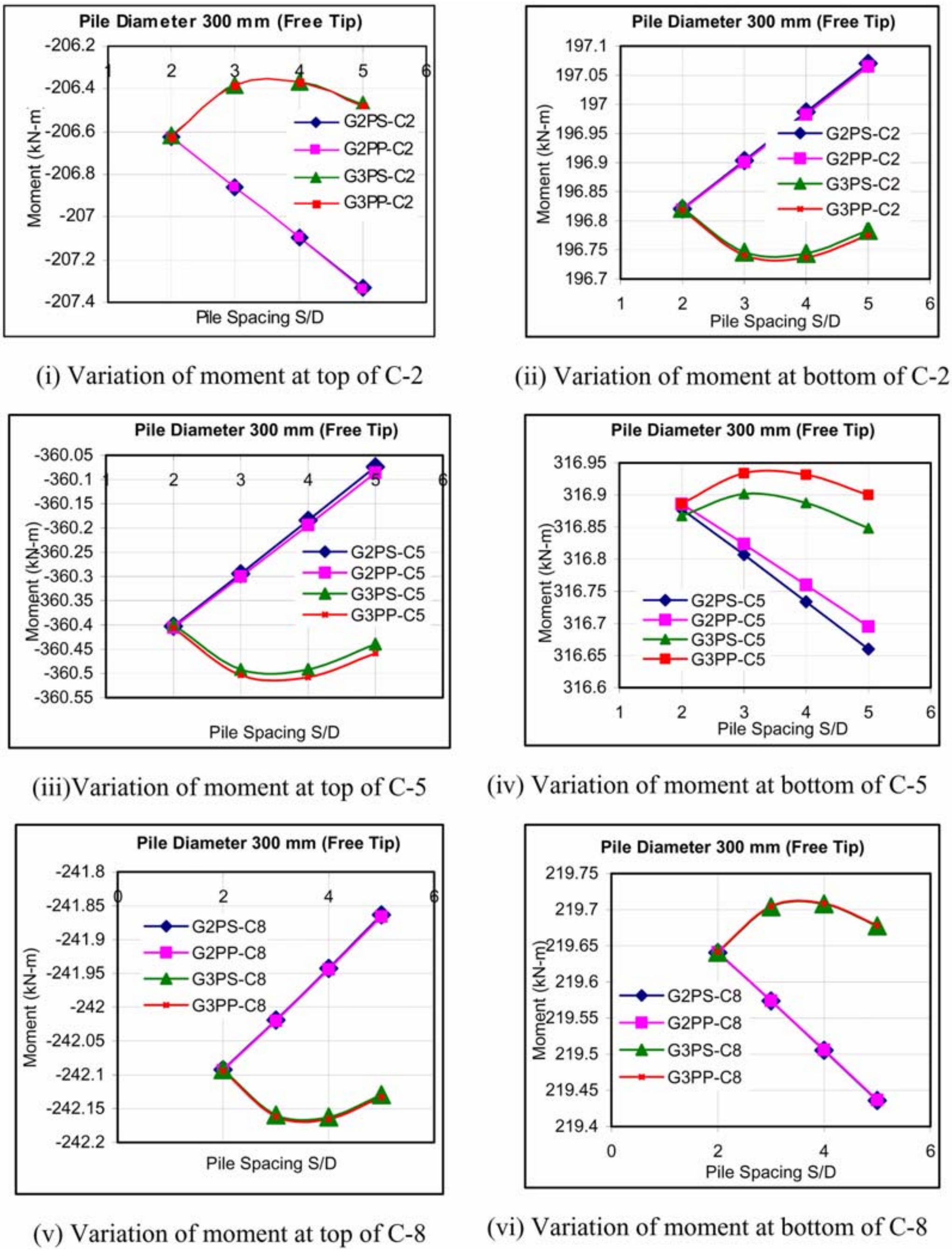
The variation of moment at the top and bottom of typical columns against the pile spacing for 300 mm pile diameter under all end conditions is shown in Figs. 6-8.

The effects of the configuration of pile groups and pile diameters therein are found to be significant on the variation of bending moment in columns with respect to pile spacing. The general trend observed pertaining to the variation of bending moment in columns irrespective of the configuration of pile groups is that for columns C-1, C-2 and C-3 in the row on the left hand side of the frame at the top, the bending moment increases on the negative side with increasing spacing and that at the bottom, the bending moment increases on the positive side. For the columns in the intermediate row (C-4, C-5 and C-6) and those in the row on the right hand side (C-7, C-8 and C-9), the trend of variation of bending moment is that at the top of these columns, it decreases on the negative side with increasing spacing and at the bottom, it decreases on the positive side with spacing.

This trend is observed for all the pile diameters considered for either configuration of the pile group of two piles. For the group of three piles with series and parallel configurations, the general trend of variation of moment with pile spacing for either arrangement of the group of two piles is observed for piles with larger diameters such as 500 and 600 mm with slight exceptions. For the moment at the bottom of columns C-7 and C-9, the moment follows the trend after the spacing of 4D. However, for piles with smaller diameters such as 300 (Fig. 6) and 400 mm, the trend is not stable with respect to the pile spacing.

For either arrangement of the group of three piles, the moment at the top of columns C-1, C-2 and C-3 placed on the left hand side of the frame is found to decrease on the negative side up to a spacing of 4D and increase at 5D. At the bottom of the corner columns (C-1 and C-3), the moment is found to decrease up to 3D and increase thereafter for next higher spacing. At the bottom of the central column (C-2), the moment decreases up to 4D and then increases at 5D.

At the top of the corner columns (C-4 and C-6) in the intermediate row, the moment increases on the negative side up to a spacing of 3D and decreases thereafter, for the G3PS while it decreases on the negative side up to 3D, slightly increases at 4D and again decreases for G3PP. However, at the



(i) Variation of moment at top of C-2

(ii) Variation of moment at bottom of C-2

(iii)Variation of moment at top of C-5

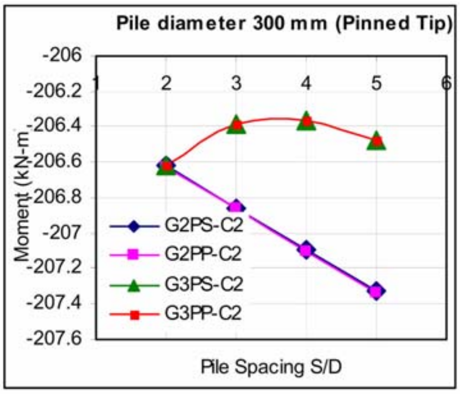
(iv) Variation of moment at bottom of C-5

(v) Variation of moment at top of C-8

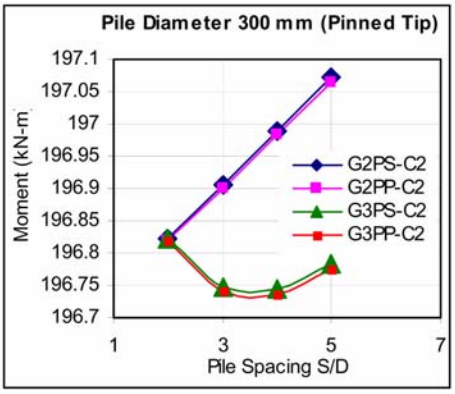
(vi) Variation of moment at bottom of C-8

Fig. 6 Effect of SSI on variation of moment versus pile spacing in columns for different configuration of pile groups (Free Tip)

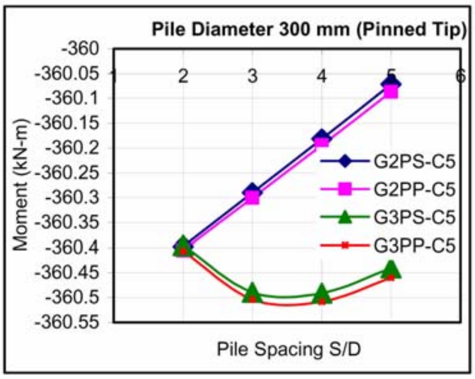
bottom of these columns, the moment is found to increase up to 3 D and thereafter increases for either configuration of the group of three piles. At the top of column C-5, the moment increases on



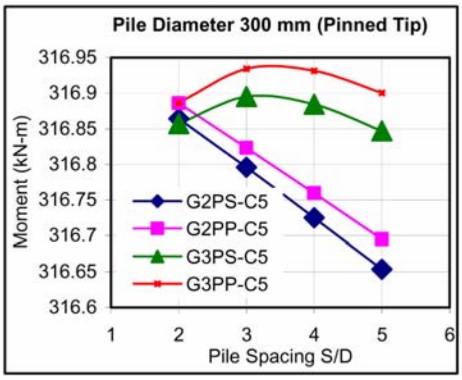
(i) Variation of moment at top of C-2



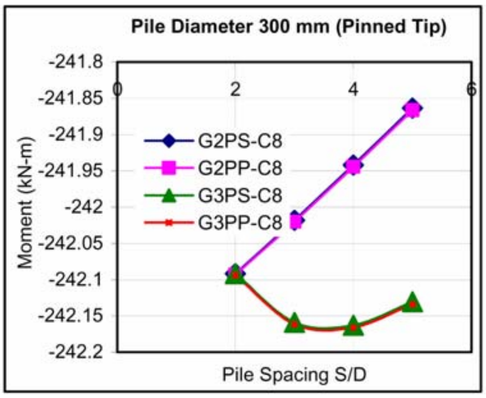
(ii) Variation of moment at bottom of C-2



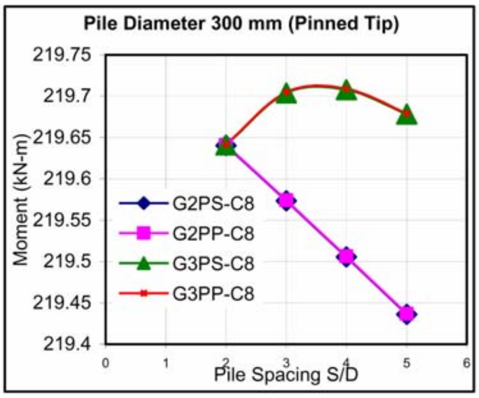
(iii) Variation of moment at top of C-5



(iv) Variation of moment at bottom of C-5



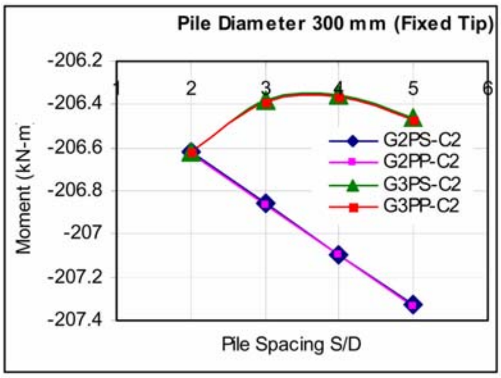
(v) Variation of moment at top of C-8



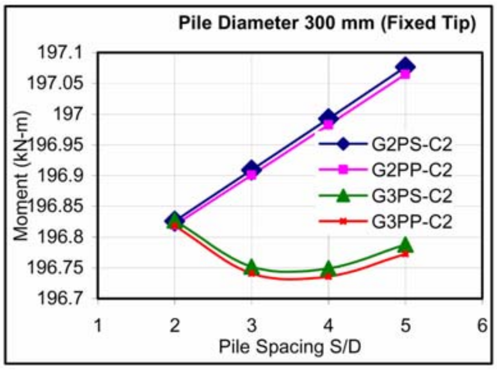
(vi) Variation of moment at bottom of C-8

Fig. 7 Effect of SSI on variation of moment versus pile spacing in columns for different configurations of pile groups (Pinned Tip)

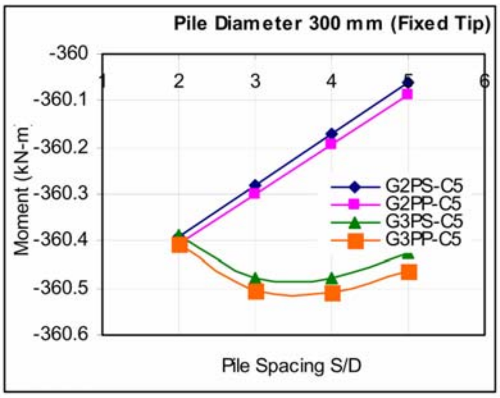
the negative side up to 3D, remains constant up to 4D and thereafter decreases for G3PS, whereas for G3PP, the moment increases on the negative side up to 4D and decreases thereafter. At the



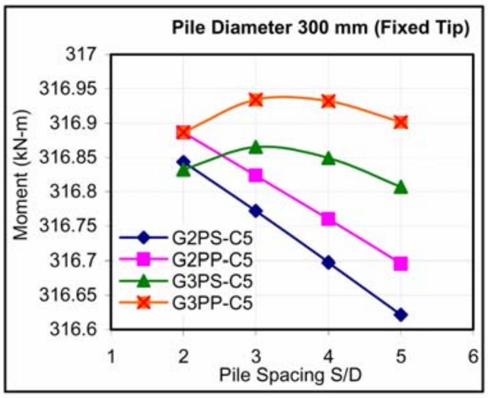
(i) Variation of moment at top of C-2



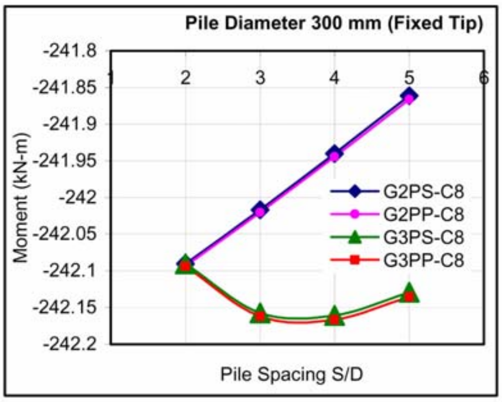
(ii) Variation of moment at bottom of C-2



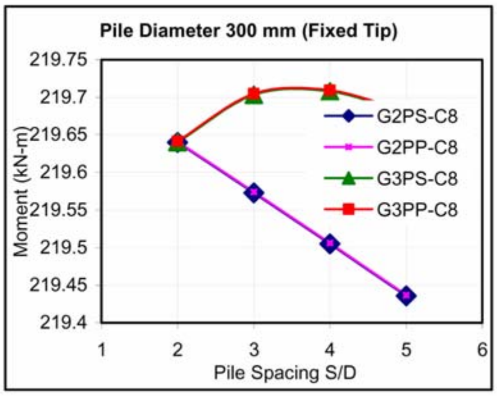
(iii) Variation of moment at top of C-5



(iv) Variation of moment at bottom of C-5



(v) Variation of moment at top of C-8



(vi) Variation of moment at bottom of C-8

Fig. 8 Effect of SSI on variation of moment versus pile spacing in columns for different configurations of pile groups (Fixed Tip)

bottom of this column (C-5), the trend of variation of moment is similar in either configuration to that observed for columns C-4 and C-6.

At the top of columns C-7, C-8 and C-9 on the right hand side of the frame, the moment is found to increase on the negative side up to 4D and decrease thereafter for G3PS and G3PP. At the bottom of columns C-7 and C-9, the moment is found to increase on the positive side for all spacing for G3PS. For columns C-7, C-8 and C-9 in respect of G3PP and column C-8 in respect of G3PS, the moment increases up to 4D and thereafter decreases.

For piles with 400 mm diameter, the trend of variation of moment with pile spacing is similar in either arrangement for G3PS and G3PP and falls in line with the general trend with few exceptions. At the top of columns C-1, C-2 and C-3, the moment follows the general trend at the spacing of 3D. At the bottom of column C-2, it assumes the general trend at the spacing of 3D. At the top of column C-5 and all the columns (C-7, C-8 and C-9), the moment assumes the general trend after the spacing of 3D.

For the series arrangement, the positive moment at the bottom of columns C-7 and C-9 follows the general trend as that for the spacing of 4D, while in column C-8, the corresponding spacing is 3D. For parallel arrangement, the moment follows the general trend of moment variation as that for the spacing of 3D.

The effect of the socketted end conditions, such as pinned tip and fixed tip, is also studied on the variation of moment in columns. The trend is almost similar to that observed for the corresponding pile groups and pile diameters under the free tip condition, with few exceptions as mentioned below.

For G2PS with pinned tip condition, the positive moment in columns C-7 and C-9 decreases up to 4D and then increases for larger pile diameters like 500 mm and 600 mm. For fixed tip condition, the moment at the bottom of columns with 400 mm diameter, i.e., columns C-7 and C-9, decreases up to 3D and thereafter increases. For piles with next larger diameters, such as columns C-7 and C-9 with 500 and 600 mm diameters, respectively, the moment at the bottom increases on the positive side for all the pile spacing.

For G3PS with pinned tip, the moment at the top of columns C-4 and C-6 with 400 mm diameter is constant up to 3D and then decreases on the negative side, while at the bottom of columns C-7 and C-9, the moment increases up to 4D and thereafter decreases slightly. The moment at the bottom of columns with the larger diameters such as 500 and 600 mm, i.e., in columns C-7 and C-9, increases on the positive side for all spacing.

For fixed tip conditions, there are few exceptions for piles with larger diameters, such as 400 and 500 mm, and to some extent 600 mm. For piles with 400 mm diameter, the moment at the bottom of columns C-7 and C-9 increases on the positive side for all spacing. For piles with 500 mm diameter, the moment at the bottom in columns C-1 and C-3 increases on the negative side up to 4D and thereafter decreases. At the top of columns C-4 and C-6, the moment decreases on the negative side up to 4D and thereafter increases. At the bottom of these columns, the moment decreases on the positive side up to 4D and then increases. At the bottom of column C-5, the moment decreases up to 4D and thereafter increases. At the bottom of columns C-7 and C-9, the moment increases up to 4D and thereafter decreases. For piles with 600 mm diameter, the moment at the bottom of columns C-7 and C-9 increases for all the spacing.

For G3PP with pinned tip, the moment at the top of the columns with 300 mm diameter (Fig.7) in the intermediate row (C-4, C-5 and C-6) increases on the negative side up to 4D; and decreases thereafter. For piles with 400 mm diameter, the moment at top of columns C-4 and C-6 increases on the negative side up to 3D and thereafter decreases. For fixed tip conditions, the moment at the bottom of column C-4 with 300 mm diameter increases on the negative side up to 4D and decreases, thereafter (Fig. 8). At the bottom of column C-5, the moment increases up to 4D and decreases thereafter. For piles with 400 mm diameter, i.e., columns C-4 and C-6, the moment at the top increases on the negative side up to 3D and decreases, thereafter.

7.2.3 Effect of number of piles in group on variation of moment in columns versus pile spacing

The effect of number of piles on moment variation in columns versus pile spacing is studied for the group of two piles and three piles with two arrangements (i.e., series and parallel). For the series configuration, the trend observed for the group of two piles (G2PS) for all the pile diameters can be observed in group of three piles (G3PS) except for piles with larger diameters such as 500 and 600 mm. For piles of 300 and 400 mm diameters in the group of three piles, the general trend of variation of moment as seen for the group of two piles exist in most of the columns with the spacing of 3D and 4D. This also holds good for the pinned tip and fixed tip conditions.

For parallel configuration, the trend of the variation of moment is similar at the top and bottom of all the columns in the group of two piles (G2PP) and those of three piles (G3PP) with larger diameters such as 500 and 600 mm. For piles with smaller diameters, such as 300 and 400 mm, the trend is stable in the group of two piles and similar to that observed for the group of two piles with series arrangement. Such a trend is not observed for piles with the same diameters in the group of three piles with parallel arrangement. The trend becomes stable for piles with either the spacing of 3D or 4D. This holds good for piles with pinned tip and fixed tip condition as well.

7.2.4 Comparison with the published results (Chore and Ingle 2008a)

The present study revealed the maximum increase in the positive moment to be 14 -15 % and in the negative moment to be 26-27% for the free tip condition. The corresponding values reported by Chore and Ingle (2008b) are 14 and 27.77%, respectively.

When the increase or decrease in the maximum moments in the individual columns are considered, the percentage decrease in the hogging moment as observed in the present study is in the range of 0.3-1.67 for columns placed on the left hand side of the frame. The corresponding decrease reported by Chore and Ingle (2008a) is in the range of 0.8-2.7. The hogging moment in the columns is found to increase in the range of 27.5-28.20% in the present study, whereas the corresponding increase reported by Chore and Ingle (2008a) is in the range of 21.2-28.9%. The maximum decrease in the positive moment as reported in the present study is in the range of 37.65 -38.53%, whereas Chore and Ingle (2008a) reported a corresponding decrease in the range of 37.4 - 38.8%. The present study revealed the maximum increase in the range of 14.68-15.5%, while Chore and Ingle (2008a) reported a corresponding increase in the range of 14.75-15.23%.

The trend of variation of moment versus pile spacing at the top and bottom of various superstructure columns as observed in the present study is compared with that reported by Chore and Ingle (2008a). In the present study, for the group of two piles the variation of moment is the same for both configurations G2PS and G2PP and this holds good for all the pile diameters. However, for the group of three piles with either configuration (G3PS and G3PP), the trend is not stable, unlike that observed for the group of two piles, particularly for piles with smaller diameters such as 300 and 400 mm. The trend is normal for this configuration at either at 3D or 4D spacing. The trend is stable for piles with larger diameters, such as 500 and 600 mm, with exception at the bottom of columns C-7 and C-9 where the moment follows the normal trend either at 3D or 4D spacing.

Chore and Ingle (2008a) revealed that the variation of moment follows the general trend after the spacing of 3D for piles with the smaller diameter of 300 mm and for few columns with 400 mm diameter in the group of two piles with series configuration. For piles with the next larger diameters, the trend of variation of moment in columns is found to be stable and similar to that observed for other configurations for all the pile diameters. The complete 3-D analysis further revealed that for pile group with more number of piles, the trend of variation of moment at the top and bottom of various columns was found to be stable and similar for either configurations for all the pile diameters, whereas for the pile group with less number of piles, the trend is not stable; particularly, for series configuration at smaller pile diameters. All the same, the trend observed for columns with spacing of 3D or 4D seems to be worthwhile.

8. Conclusions

Some of the significant findings emerging from the interaction analysis presented in this paper are summarized as follows:

1. The effect of SSI on the top displacement of the frame is quite significant. The displacement is less for fixed base condition and increases by 42 to 103% when the SSI effect is incorporated.
2. With the increase in pile spacing, the top displacement of the frame decreases. With the increase in the number of piles in a group under consideration, the displacement decreases.
3. The increase in the pile diameter reduces the displacement with spacing for a particular group. Further, the difference between the displacements is found to reduce with spacing for a particular group with the increase in pile diameter.
4. The arrangement of piles with respect to the direction of the lateral load acting on the frame along with the number of piles and pile diameter for a particular configuration is quite significant. Parallel configuration yields higher displacement than the series arrangement.
5. The effect of end conditions at the pile tip is also significant on the displacement. Though the displacements obtained for the pinned tip and fixed tip are less than those for the free tip, the end condition does not have appreciable effect for parallel configuration.
6. The effect of SSI is significant on bending moment also. The SSI is found to increase the maximum positive bending moment by 14.98 % and maximum negative bending moment by 27.20 % when compared with the absolute maximum bending moments calculated on the premise of fixed column bases.
7. The effect of soil-structure interaction is found to have significant effect on the moment in individual columns. The decrease in maximum hogging moment is observed to be in the range of 0.30-1.67%, while the increase in hogging moment is found in the range of 27.5-28.20%. The increase in the maximum positive moment is found to range between 14.68 and 15.5%, whereas the decrease in the maximum positive moment is in the range of 37.65-38.53%.
8. The hogging moment in columns in the leading row decreases while that in all other columns increases. The positive moment in the central column in the intermediate row increases and in all other columns decreases.
9. The effect of SSI is observed to be minimal for columns placed in the row on the left hand side, while for columns on the right hand side, it reaches the maximum.
10. The parameters like configuration of pile group, number of piles and diameter of pile, and end conditions for the pile tip have significant effects on the variation of bending moment in superstructure columns.

11. For free pile tip condition, the variation of bending moment at the top and bottom of various superstructure columns for group of two piles is the same for either configuration (G2PS and G2PP) and for all pile diameters. However, for the case of three-pile group with either configuration (G3PS and G3PP) the trend is not stable, unlike that observed for the two-pile group, particularly for piles with smaller diameters like 300 and 400 mm. The trend is normal for this configuration either at 3D or 4D spacing. The trend is stable for piles with larger diameters such as 500 and 600 mm, with exception at the bottom of columns C-7 and C-9 where the moment assumes the normal trend either at 3D or 4D spacing.

12. The variation of moment in columns for pinned tip and fixed tip is almost similar to that observed for free tip condition in the context of two-pile group. However, there are some exceptions for the three-pile group with 400 mm piles in series arrangement and few exceptions for 500 mm piles. For three-pile group with parallel arrangement, exceptions are observed for smaller pile diameter such as 300 and 400 mm.

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