Indian Geotechnical Journal, 38(4), 2008, 483-501

Interaction Analysis of Building Frame Supported on Pile Group

H. S. Chore* and Dr. R. K. Ingle**

Introduction

The framed structures are normally analyzed considering their bases to be either completely rigid or hinged. However, the foundation resting on deformable soil also undergoes deformation depending on the relative rigidities of the foundation, the superstructure and soil. Interactive analysis is, therefore, necessary for the correct assessment of the response of the superstructure. Such interactive analyses have been reported in many studies in the 1960's and 70's and in few studies in the recent past. While majority of these analyses report either interaction of frames with isolated footings or the interaction of frame with raft foundation, few of them report interaction of frame with combined footings. At the same time, much work is available on pile foundation (single as well as pile group). However, hardly any work has reported the analysis of framed structure resting on pile foundation, thus accounting for soil- structure interaction. Brief review of the literature on the prominent interaction analyses of framed structures and analyses of pile foundation is given in the subsequent sections.

Brief Review of Literature

In the early 1960's Mayerholf (1953) recognized the importance of superstructure- foundation- soil interaction and from then onwards, numerous studies have been made 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 are required to be revised. Only a limited number of studies [Chameski (1956), Morris (1966), King and Chandrasekaran (1974)] pointed out the necessity for evaluation of the effect of such interaction for multistoried space frame having more than three bays. Consistent efforts in improving the analytical techniques and availability of high speed computers gave rise to powerful finite element method. Available literature reports many finite element analyses into interaction of plain frame-foundation-soil system [Lee and Harrison (1970), Lee and Brown (1972), Deshmukh and Karamarkar (1991)] and interaction of space frame with foundation- soil system [Morris

* Research Scholar, Department of Applied Mechanics, Visvesvaraya National Institute of Technology, Nagpur- 440 011 (India), E-mail: hschore@rediffmail.com, hemantschore@yahoo.com

** Professor and Head, Department of Applied Mechanics, Visvesvaraya National Institute of Technology, Nagpur- 440 011 (India)

(1966), King and Chandrasekaran (1974), Shriniwasraghavan and Shankaran (1983)] while Subbarao et al (1985) attempted an interaction analysis of two dimensional as well as three dimensional frames. Buragohain et al (1977) reported analysis of frame on pile foundation using 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, Mayerholf (1953) considered the soil medium as elastic continuum. Hain and Lee (1970) and Subbarao et al (1985) carried out the comparative studies in which both the models were employed.

In the recent past also, much work was done on the quantification of the effect of the soil- structure interaction on the behaviour of framed structure [Dasgupta et al (1998) and Mandal et al (1999)]. Viladkar et al (1977) used coupled finite –infinite element in the interactive studies of the framed structures and demonstrated the viability of application of such technique in the analysis. On the similar lines, Noorzaei et al (1991) attempted an interactive analysis of space frame resting on raft. While Stavirdis (2002) reported simplified interaction analysis of layered soil- structure interaction, Hora (2006) reported non-linear soil- structure interaction analysis of infilled building frame. While most of the above mentioned studies deal with the interaction of frames with isolated footings or combined footings or raft foundation, only a study is found dealing with the interactive analysis of frame on pile [Buragohain et al (1981)].

In the latter category, analysis of three dimensional pile foundation in which response of the foundation head is considered itself requires major efforts. Depending upon the load applied at the foundation head, various approaches are available for analysis of the pile group. Even though pile group may be subjected to axial loads, in most of the cases combination of the axial and lateral load act on the pile foundation which further complicates the analysis.

The conventional approaches available for the analysis of axially loaded pile foundation are 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 approaches available for analyzing laterally loaded pile foundation include 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 and Dewaikar (1996)].

With the advent of computers in 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), Dewaikar et al (2007)] has become popular for analyzing the problem of pile foundation in the context of linear and non-linear analysis. Desai et al (1981) presented simplified finite element analysis for the soil-structure interaction problem and also pointed out the consideration of the interaction of pile cap and underlying soil. On the similar lines, significance of this interaction aspect in the analysis of pile group was demonstrated along with the effect of socketted end condition in another study [Chore and Sawant (2002) and Chore and Sawant (2004)].

Significance and Scope of the Present Work

Above review of literature highlights extensive work on the interaction analysis of framed structures resting on either isolated footings or combined footings or on raft foundation and points out hardly any work except that by Buragohain et al (1977) on the framed structure supported by pile foundation. They evaluated the space frames resting on pile foundation by stiffness matrix method in order to quantify the effect of soil-structure interaction by resorting to very simplified assumptions. Pile cap was considered rigid and stiffness of the pile cap was not considered. Stiffness matrix for the entire pile group was derived by the principle of superposition using rigid body transformation. Foundation stiffness matrix was then combined with the superstructure matrix for attempting the interactive analysis.

Ingle and Chore (2007) reviewed the soil-structure interaction analysis of framed structure and also soil-structure interaction problems related to pile foundation and underscored the necessity of interactive analysis of building frame on pile foundation by more rational approach and realistic assumptions. For this purpose, flexible pile cap along with its stiffness should be considered and stiffness matrix for the sub-structure should be derived at a time by considering the effect of all the piles in a group.

Pursuant to this, Chore and Ingle (2008) reported an interactive analysis on the space frame on pile foundation, thus, accounting for SSI using finite element analysis wherein foundation elements were modelled in the simplified manner as suggested by Desai et. al. (1981).

However, the basic problem of the building frame is three dimensional in nature. Even though complex three-dimensional finite element approach, which can be used for the analysis, is quite expensive in terms of time and memory, it facilitates realistic modeling of all the parameters. On this backdrop, a methodology for the comprehensive analysis of the building frame supported on pile group embedded in soft marine clay is presented in this paper by using 3-D finite element method. The effect of various foundation parameters like configuration of the pile group, spacing and number of piles along with the pile diameter is evaluated on the response of the frame. The analysis also takes into account the interaction between pile cap and soil.

Idealizations in the Proposed Analysis

The elements of the superstructure (beam, column and slab) and that of substructure (pile and soil) are discretized into a number of 20 noded iso-parametric continuum elements with three degrees of freedom at each node, i.e., displacement in three directions in X, Y and Z. The interface between pile and soil is modelled using 16 noded isoparametric surface elements as proposed by Buragohain and Shah (1977). These interface elements model friction and contact between pile and soil, and are thus, useful in simulating the mechanics of stress transfer along the interface. Figure 1 (a) shows the elements used in the study and Figure 1 (b) shows finite element model for typical group of two piles.

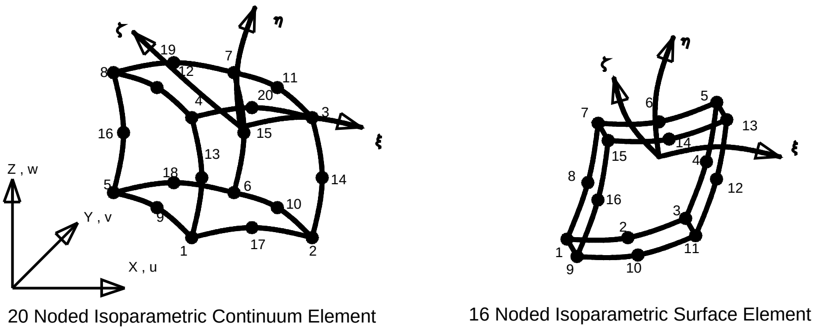


Fig. 1(a) Isoparametric Continuum and Interface Elements used in the Finite Element Formulation

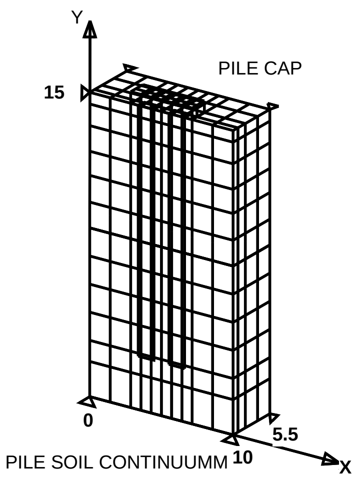


Fig. 1 (b) F.E. Model for Typical Pile Group Considered in the Study

Method of Analysis

The stiffness matrices for all elements were evaluated and assembled into global stiffness matrix in skyline storage form. Similarly, the load vector was assembled in vector form. The active column solution technique was used for the solution of equilibrium equations of the system.

On the premise of above mentioned idealizations, a numerical procedure of 3-D finite element analysis was programmed in Fortran 90 and it was validated on primary structures such as cantilever beam wherein bending behaviour predicted by the program was found to be in close agreement with that obtained using the theory of bending. The program was also validated on single pile and few cases of pile group; and then implemented for the analysis of specific frame considered in the problem.

Numerical Problem

A three-dimensional single storeyed building frame resting on pile foundation, as shown in Figure 2, is considered for the study. The frame, 3 m high is 10 m × 10 m in plan with each bay being, 5m × 5m. The slab, 200 mm thick, is provided at top as well as at the floor level. Slab at top is supported over 300 mm wide and 400 mm deep beams. The beams rest on 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 frame are made up for the purpose of the parametric study presented here, lateral loads as shown in the Figure 2 are also considered. Figure 3 shows the finite element model of the frame considered in the present study.

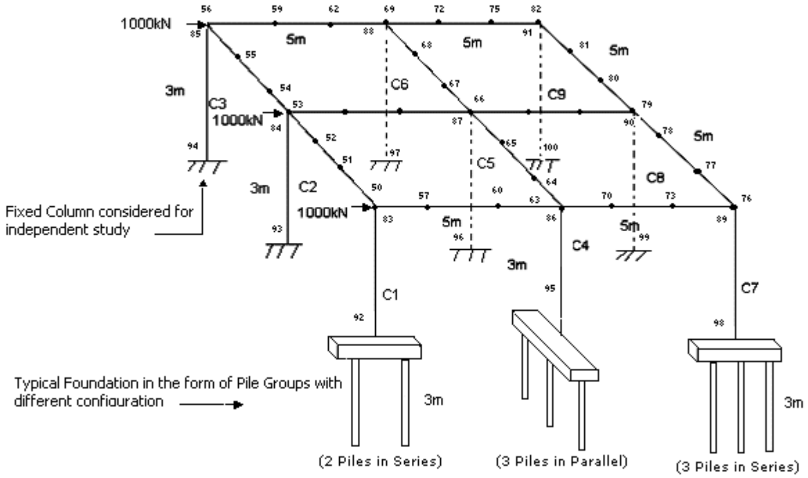


Fig. 2 Typical 3-D Building Frame Considered in the Study

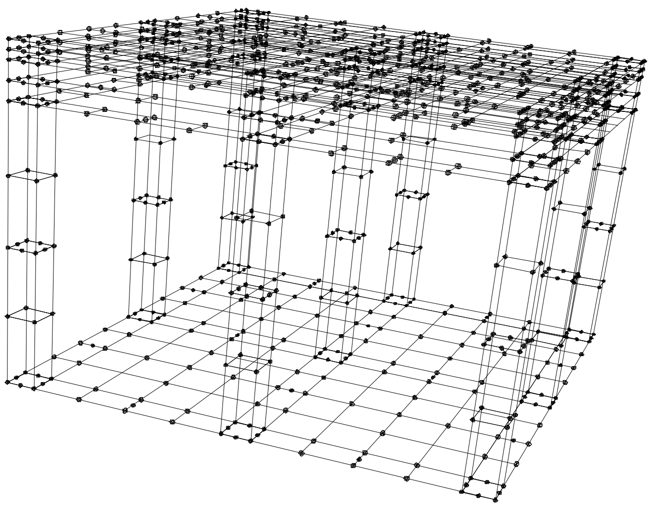


Fig. 3 Mathematical Model of the Building Frame

Two configurations of pile foundation considered in the present study include group of two piles and three piles with series and parallel arrangement (Figure 4). All the piles in a group which are friction piles are further connected by flexible pile cap. The particulars of the length of piles and thickness of the pile cap assumed for the purpose of parametric study along with different diameters considered in the analysis are given in Table 1 (a). The grade of concrete for superstructure elements is assumed to be M-20 and that for substructure elements, M-40. The corresponding values of young's modulus of elasticity and Poisson's ratio are also given in Table 1 (a). Cohesive soil (soft marine clay) is considered in the analysis. The properties of soil and interface are given in Table 1 (b). Initially, analysis for pile foundation was worked out separately for unit lateral load and unit vertical load to get equivalent stiffness in horizontal as well as vertical direction, i.e., k_h and k_v, for pile foundation which were further used in the analysis of frame.

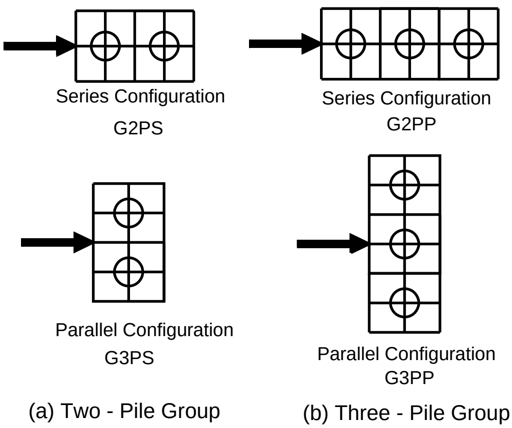


Fig. 4 Different Configurations of the Pile Group Considered in the Study

Table 1 (a) Geometrical and Material Properties for Pile and Cap

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 X 10^8 kPa
Poisson's Ratio (μ_c)	0.15

Table 1 (b) Properties of Soil and Interface
[After, Sawant and Dewaikar (2001)]

Soil	Interface
Young's Modulus of Soil (E_s)= 4267 kN/m^2 Poisson's Ratio (μ_s) = 0.45	Tangential Stiffness (k_s) = 1000 kN/m^3 Normal Stiffness (k_n) = 1.0 E 06 kN/m^3

Results and Discussions

In the parametric study conducted on a specific frame and presented here, response of the superstructure in the form of the parameters such as horizontal displacement at top of the frame and bending moment (BM) at top as well as bottom of the superstructure columns in view of the fixed base and soil-structure interaction (SSI) is considered for the purpose of comparison. Bending moments are computed using the moment-curvature relationship. Effect of pile spacing and configuration of the pile group along with number and diameter of piles is evaluated on the response of superstructure and discussed in the following section.

Effect of SSI on Horizontal Displacement at Top of Frame

From the results of parametric study conducted on a specific building frame with pile foundation of different configurations top horizontal displacement is found comparatively less (38.2 mm) for the fixed column base condition and more when the effect of soil-structure interaction is taken into account, the maximum values of top displacement being 101.47 mm and 95.14 mm, respectively at the minimum spacing of 2D in case of the group of two pile for either configuration (Refer Table 2). Incorporation of the aspect of SSI is found to increase the top displacement in the range of 55 to 165% when compared with the displacement obtained in view of the fixed base condition.

The general trend observed for all the configurations considered in the study in respect of all pile diameters and as evident from Table 2 is that the top displacement is more when the spacing between two piles is kept 2D and thereafter, decreases for higher spacing, i.e., 3D, 4D and 5D, in all the configurations. The general trend of reduction in displacement with increase in spacing could be attributed to the overlapping of the stressed zones of individual piles at closer spacing. When the piles are closer, combined action of pile and that of pile cap is more rigid; and moreover, in three-dimensional formulation, it reflects block action. Owing to this, displacement is observed more for spacing of 2D; and thereafter, it goes on decreasing.

It is further observed that with the increase in number of piles in a group of the identical configuration, displacement at the top of the frame decreases. More number of piles increases the stiffness of the pile group which further results in the reduction in displacement. With increase in diameter of the piles, displacement at top of the frame decreases for any spacing within the configuration of pile group under consideration owing to the increased stiffness of the pile group at higher diameter (Refer Figure 5).

Table 2 Top Displacement and Percentage Increase in Top Displacement with SSI

Configuration and pile dia	Top Displacement (mm)				Percentage Increase			
G2PS	2D	3D	4D	5D	2D	3D	4D	5D
300 mm	101.47	95.57	90.78	86.89	165.77	150.31	137.76	127.59
400 mm	90.37	84.51	80.02	76.51	136.70	121.34	109.59	100.39
500 mm	82.00	76.65	72.73	69.81	114.78	100.77	90.49	82.83
600 mm	75.80	71.17	67.92	65.61	98.53	86.40	77.91	71.85
G2PP	2D	3D	4D	5D	2D	3D	4D	5D
300 mm	95.14	88.90	84.67	81.56	149.18	132.86	121.77	113.63
400 mm	81.92	77.53	74.52	72.31	114.57	103.06	95.19	89.39
500 mm	74.52	71.14	68.82	67.10	95.19	86.33	80.24	75.74
600 mm	69.80	67.06	65.16	63.75	82.83	75.63	70.67	66.98
G3PS	2D	3D	4D	5D	2D	3D	4D	5D
300 mm	89.93	82.53	77.31	73.49	135.54	116.17	102.49	92.48
400 mm	79.62	72.91	68.53	65.62	108.53	90.96	79.49	71.86
500 mm	72.43	66.89	63.58	61.54	89.71	75.19	66.52	61.19
600 mm	67.63	63.27	60.83	59.39	77.15	65.72	59.33	55.56
G3PP	2D	3D	4D	5D	2D	3D	4D	5D
300 mm	84.54	79.33	76.27	74.23	121.42	107.78	99.76	94.42
400 mm	77.93	73.50	70.88	69.09	104.10	92.51	85.63	80.95
500 mm	73.12	69.32	67.03	65.43	91.51	81.56	75.56	71.37
600 mm	69.25	65.97	63.95	62.52	81.38	72.78	67.50	63.74

Effect of the configuration of pile group on response of the superstructure is quite significant. It is obvious from the results that for the pile group with series arrangement, displacements obtained are on higher side as compared to those obtained for the group having parallel arrangement for all diameters in respect of the group of two piles. In case of group of two piles, parallel arrangement offers stiffer behaviour than series arrangement. Piles in parallel arrangement offer more resistance as compared to the piles in series arrangement. This can be attributed to the larger area available for development of passive resistance. However, in respect of group of three piles at smaller pile diameter (300mm), displacements in series arrangement are on higher side than those in parallel arrangement for all spacing except that at 5D. At this spacing, trend is exactly opposite, i.e., displacement in parallel arrangement is more than that in series arrangement. At next higher diameter (400mm), displacement in series arrangement is more than that in parallel arrangement at the minimum spacing of 2D and thereafter, trend gets transformed in the reverse direction. For next two higher diameters (500mm and 600mm), displacements in parallel arrangement are on higher side as compared to that in series arrangement. At higher diameter (rigid piles) series arrangement exhibits more stiffer behaviour. This is because the combined structural stiffness of pile and pile cap in parallel arrangement is small as compared to that in series arrangement. For short to medium length piles, it is a governing factor. For long piles, different trend is possible where soil imparts considerable strength.

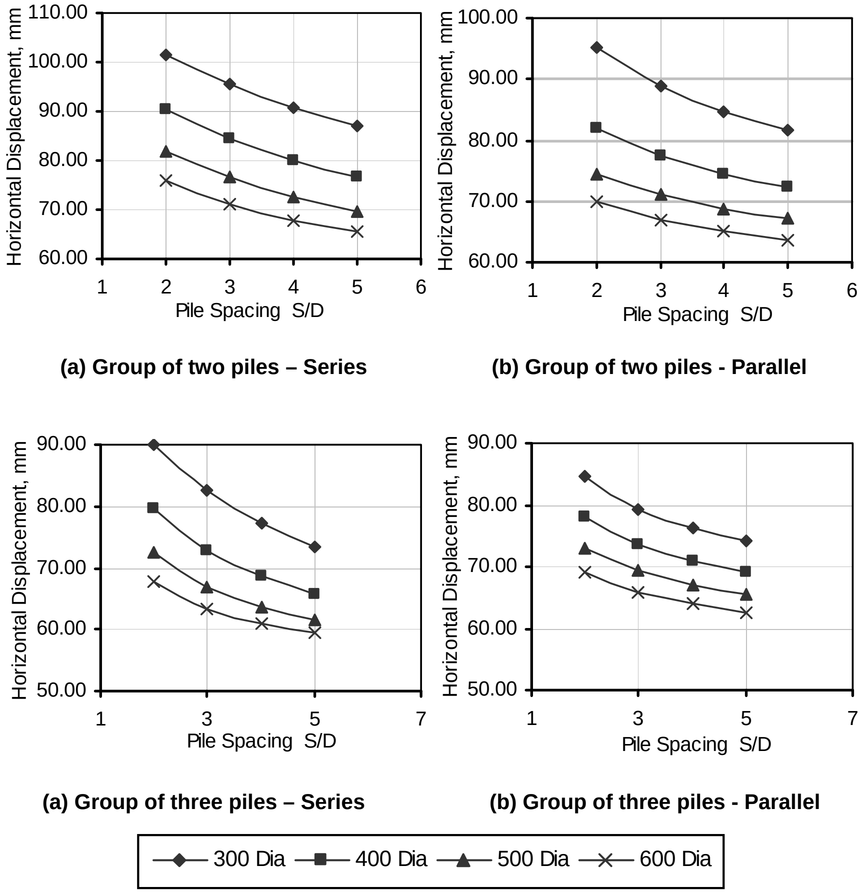


Fig. 5 Effect of Diameter on Displacement for Different Configurations (a), (b), (c) and (d)

Effect of SSI on B.M. in Superstructure Columns

Effect of SSI on B.M. in Superstructure Columns is found to be significant on the B.M. in superstructure columns. Effect on the columns placed on left hand side is minimum while that on right hand side, maximum. Table 3 (towards the end) shows the value of maximum positive B.M. and maximum negative B.M. in columns for various configurations. From this it is found that maximum positive moment increases by 14.01% and maximum negative moment increases by 27.77% owing to SSI. The variation of B.M. at top and bottom of various columns for spacing in respect of all the diameters considered in the study is shown in Figures 6-9.

Table 3 Maximum Positive and Negative Moments and Percentage Increase with SSI

	2D	3D	4D	5D	2D	3D	4D	5D
G2PS	Maximum Positive Moments (kN-m)				% increase in moments			
300 mm	314.25	317.22	317.52	317.57	14.01	15.09	15.19	15.21
400 mm	317.58	317.51	317.39	317.25	15.22	15.19	15.14	15.10
500 mm	317.38	317.18	316.97	316.77	15.14	15.07	14.99	14.92
600 mm	317.07	316.79	316.53	316.27	15.03	14.93	14.83	14.74
G2PS	Maximum Negative Moments (kN-m)				% increase in moments			
300 mm	-360.76	-362.13	-362.13	-362.01	27.29	27.77	27.77	27.73
400 mm	-361.96	-361.69	-361.42	-361.15	27.72	27.62	27.52	27.43
500 mm	-361.38	-360.99	-360.62	-360.26	27.51	27.37	27.24	27.11
600 mm	-361.38	-360.99	-360.62	-360.26	27.51	27.37	27.24	27.11
G2PP	Maximum Positive Moments (kN-m)				% increase in moments			
300 mm	317.56	317.56	317.48	317.38	15.21	15.21	15.18	15.14
400 mm	317.39	317.19	317.01	316.85	15.14	15.08	15.01	14.95
500 mm	316.99	316.73	316.50	316.29	15.00	14.91	14.82	14.75
600 mm	316.58	316.27	316.00	315.75	14.85	14.74	14.64	14.55
G2PP	Maximum Negative Moments (kN-m)				% increase in moments			
300 mm	-362.10	-361.87	-361.62	-361.39	27.76	27.68	27.60	27.51
400 mm	-361.40	-361.02	-360.68	-360.38	27.52	27.38	27.26	27.16
500 mm	-360.64	-360.17	-359.77	-359.42	27.25	27.08	26.94	26.82
600 mm	-359.90	-359.37	-358.92	-358.52	26.99	26.80	26.64	26.50
G3PS	Maximum Positive Moments (kN-m)				% increase in moments			
300 mm	317.58	317.49	317.33	317.15	15.21	15.18	15.13	15.06
400 mm	317.31	317.00	316.69	316.40	15.12	15.00	14.89	14.79
500 mm	317.31	317.00	316.69	316.40	15.12	15.00	14.89	14.79
600 mm	316.41	315.89	315.40	314.95	14.79	14.60	14.43	14.26
G3PS	Maximum Negative Moments (kN-m)				% increase in moments			
300 mm	-362.03	-361.68	-361.32	-360.96	27.74	27.61	27.49	27.36
400 mm	-361.24	-360.66	-360.13	-359.64	27.46	27.26	27.07	26.89
500 mm	-360.42	-359.69	-359.03	-358.41	27.17	26.91	26.68	26.46
600 mm	-359.63	-358.77	-358.01	-357.29	26.89	26.59	26.32	26.07

Table 3 Contd. Maximum Positive and Negative Moments and Percentage Increase with SSI

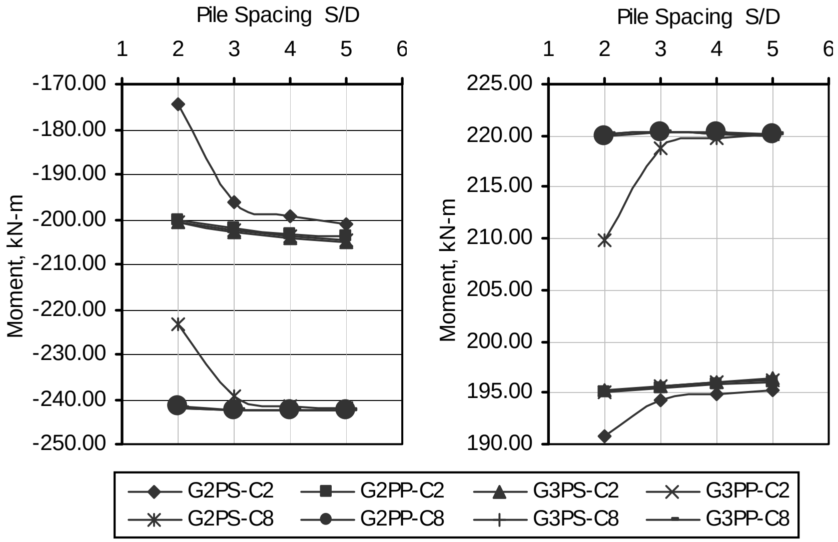
	2D	3D	4D	5D	2D	3D	4D	5D
G3PP	Maximum Positive Moments (kN-m)				% increase in moments			
300 mm	317.55	317.50	317.37	317.22	15.21	15.19	15.14	15.08
400 mm	317.34	317.07	316.82	316.57	15.13	15.03	14.94	14.85
500 mm	316.96	316.59	316.25	315.92	14.99	14.86	14.73	14.61
600 mm	316.56	316.11	315.69	315.28	14.84	14.68	14.53	14.38
G3PP	Maximum Negative Moments (kN-m)				% increase in moments			
300 mm	-362.06	-361.74	-361.42	-361.11	27.75	27.64	27.52	27.41
400 mm	-361.33	-360.81	-360.34	-359.89	27.49	27.31	27.14	26.98
500 mm	-360.58	-359.93	-359.34	-358.78	27.23	27.00	26.79	26.59
600 mm	-359.87	-359.11	-358.41	-357.74	26.98	26.71	26.46	26.23

Effect of configuration and diameter of pile therein is found to be significant on the trend of the variation of B.M. in columns with spacing. The general trend observed pertaining to the variation of B.M. in columns irrespective of the configuration of the pile group is that in various columns (C-1, C-2 and C-3) in the row on left hand side of the specific frame at top B.M. increases on negative side with spacing and that at bottom, increases on positive side. For the columns in the intermediate row (C-4, C-5 and C-6) and that in the row on right hand side (C-7, C-8 and C-9) the trend of variation of B.M. is that at top of these columns, B.M. decreases on negative side with spacing and at bottom, decreases on positive side with spacing.

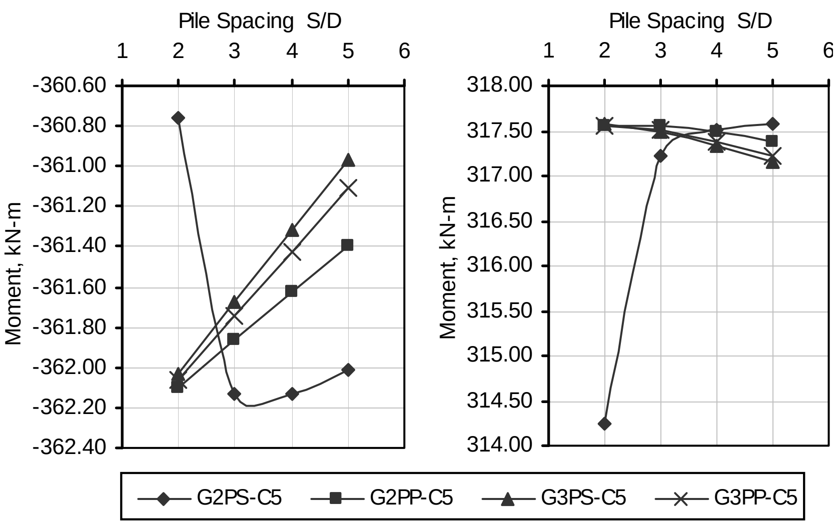
At higher diameter such as 500 mm and 600 mm, trend of variation of B.M. at top and bottom of various columns are similar in all the configurations, i.e., G2PS, G2PP, G3PS and G3PP. In respect of two pile group with series configuration (G2PS), variation of B.M. at top and bottom of few columns is not stable at smaller diameter. The B.M. either increases or decreases up to a spacing of 3D and follows reverse trend, for e.g., bottom of C-1 and C-3, top and bottom of all the columns in the intermediate row (C-4, C-5 and C-6). For the same configuration trend of variation of B.M. at top of C-1, C-3 and C-8 is not stable for next higher diameter (400 mm). B.M. at these columns assumes the trend observed at the same locations in other configurations at higher diameter after the spacing of 3D or 4D.

Similar exception is observed in case of group of two piles for series configuration as well as parallel configurations at top of C-1 and C-3 for 300 mm pile diameter where B.M. deviates up to 3D from the general trend observed at this location for higher diameters.

Effect of number of piles in a group under identical arrangement is also noteworthy. For the series configuration at smaller diameter (300 mm), trend of variation of B.M. is not similar in respect of two pile group (G2PS) and three pile group (G3PS) for most of the columns. The similarity is observed only for the B.M. at top and bottom of C-2.



(a) At top of columns C-2 and C-8 **(b) At bottom of columns C-2 and C-8**



(c) At top of column C-5 **(d) At bottom of column C-5**

Fig. 6 Effect of SSI on Variation of Moments at Top and Bottom of the Columns in Centre of the Frame (300 mm Pile Diameter)

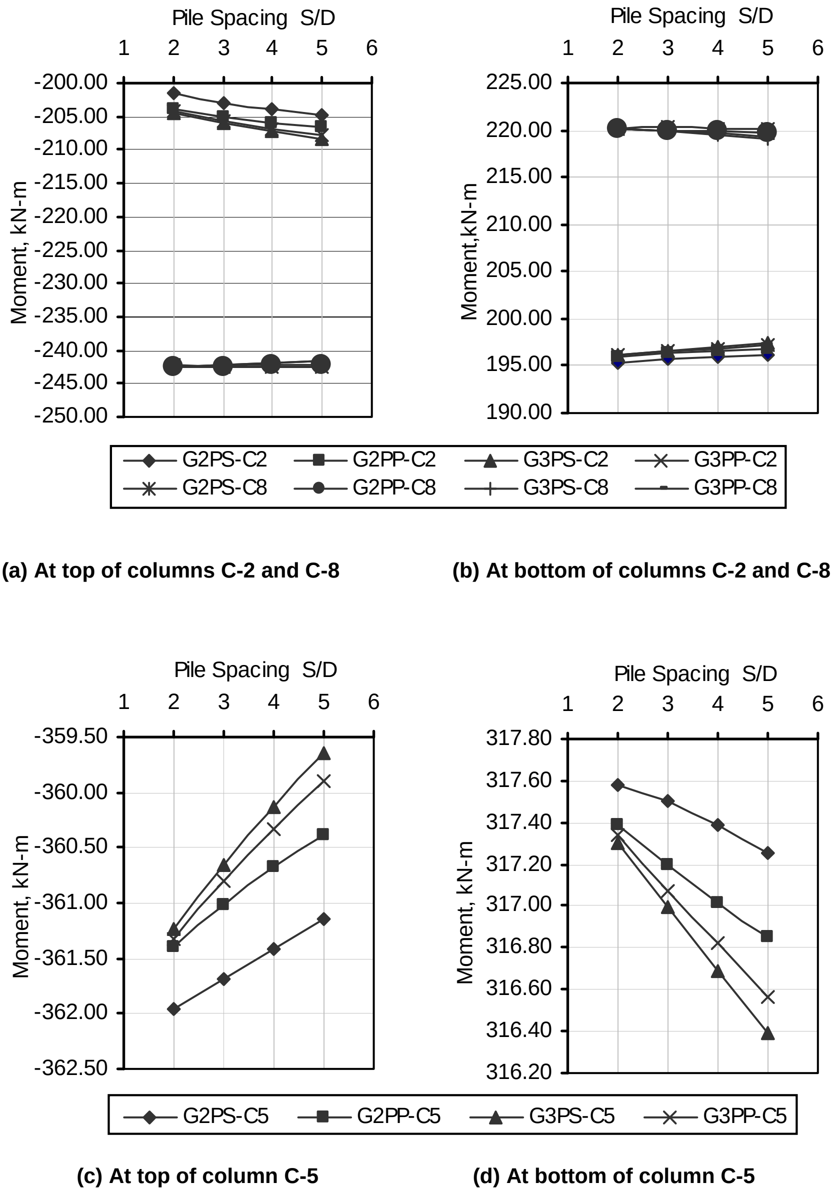
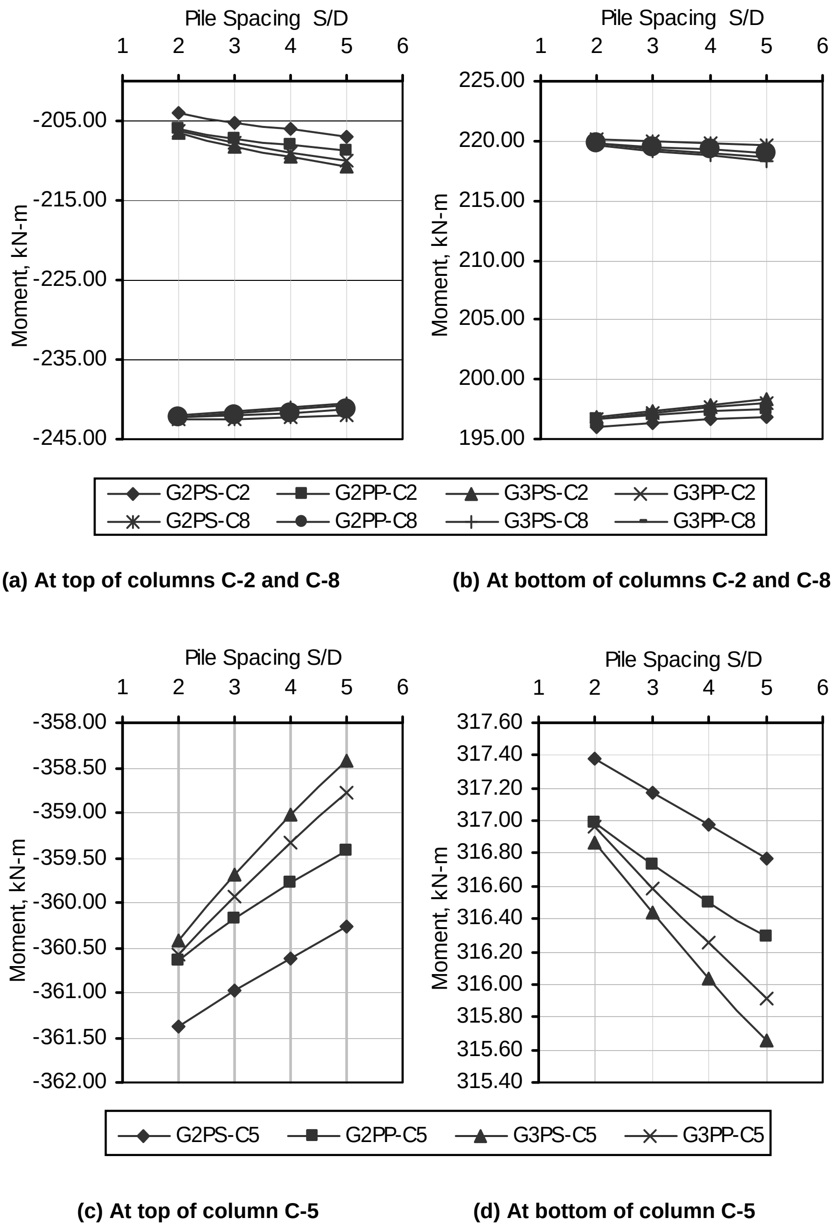


Fig. 7 Effect of SSI on Variation of Moments at Top and Bottom of the Columns in Centre of the Frame (400 mm Pile Diameter)



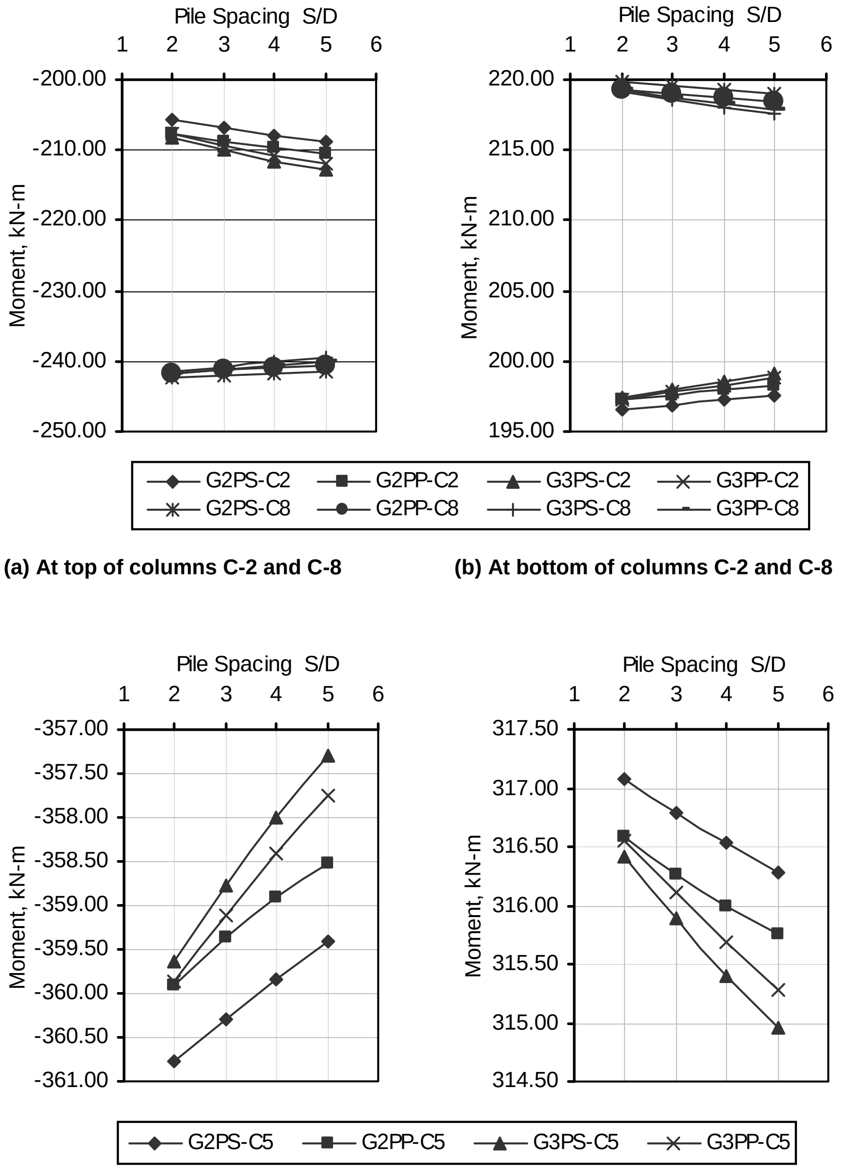
(a) At top of columns C-2 and C-8

(b) At bottom of columns C-2 and C-8

(c) At top of column C-5

(d) At bottom of column C-5

Fig. 8 Effect of SSI on Variation of Moments at Top and Bottom of the Columns in Centre of the Frame (500 mm Pile Diameter)



(a) At top of columns C-2 and C-8 **(b) At bottom of columns C-2 and C-8**

(c) At top of column C-5 **(d) At bottom of column C-5**

Fig. 9 Effect of SSI on Variation of Moments at Top and Bottom of the Columns in Centre the Frame (600 mm Pile Diameter)

Comparatively, the trend is found stable in case of three pile group with few exceptions such as at top of C-1 and C-3, B.M. decreases on negative side up to 3D and then, increases on negative side while at top of C-8, it increases on negative side at 3D, remains constant up to 4D and then decreases on negative side. However, in case of group of two piles at bottom of C-1, at top and bottom of C-4, C-5 and C-6, B.M. either increases or decreases (on negative or positive side) up to between 3D and 4D and then, trend gets transformed in the reverse direction. For remaining higher diameter (400 mm, 500 mm and 600 mm), trend of variation of B.M. at top and bottom of all the columns is similar in two pile group (G2PS) and three pile group (G3PS) with one exception in case of two pile group (G2PS) wherein at top of C-1 and C-3 where B.M. decreases on negative side up to 3D and thereafter, increases on negative side.

In case of parallel configuration, trend of variation of B.M. is similar at top and bottom of all the columns in the group of two piles (G2PP) and that of three piles (G3PP) for all the diameters unlike that observed in the series configuration particularly at smaller diameter. Moreover, trend of variation of B.M. is also found to be stable in either group, i.e., G2PP and G3PP, for parallel arrangement.

Summing up, for the group of three piles trend of variation of B.M. at top and bottom of all the columns is stable and almost similar in respect of either configuration for all the diameters with the exception at bottom of the corner columns in the row on right hand side (C-7 and C-9) for smaller pile diameter such as 300 mm.

When the trend of the variation of B.M. at top and bottom of various columns in respect of either configuration for two pile group is compared, parallel configuration yields stable and similar trend for all the diameters except at bottom of C-5 where B.M. remains constant up to a spacing of 4D and thereafter, assumes the general trend. However, this is negligible. But in case of series configuration, the general trend which is seen for all the diameters in parallel configuration is observed only at higher diameters such as 500mm and 600 mm and to some extent at 400mm pile diameter. At smaller diameter (300 mm), B.M. assumes the general trend seen for other diameters after a spacing of 3D and in few columns, although seldom, after the spacing of 4D.

Conclusions

From the comprehensive interactive analysis of the single storeyed building frame supported on pile groups comprising of two piles and three piles with series and parallel configuration, following broad conclusions can be arrived upon:

- Effect of soil- structure interaction on top displacement of the frame is quite significant. Displacement is less for fixed base condition and increases in the range of 55 to 165% when the aspect of SSI is incorporated.
- With increase in pile spacing displacement at top of the frame decreases. With increase in number of piles in a group under consideration displacement decreases. Increase in diameter reduces displacement with spacing for a particular group. Further, difference between the

displacements is found to reduce with spacing for a particular group with the increase in pile diameter.

> Arrangement of pile with respect to the direction of lateral load acting on the frame along with the number of pile and pile diameter for the particular configuration is quite significant. Top displacement is observed more in series configuration of two pile group than in parallel configuration for all the diameters. The trend although remains the same in respect three pile group at smaller diameter, parallel configuration yields higher displacement for higher diameter.

> Effect of soil- structure interaction is significant on B.M. Incorporation of the aspect of SSI is found to increase the maximum positive B.M. by 14.01% and maximum negative B.M. by 27.77%.

> The parameters like configuration of the pile group, number of piles and diameter of pile has a significant effect on the trend of the variation of B.M. in superstructure column. For the group of two piles with series configuration variation of B.M. in many columns assumes the general trend after the spacing of 3D at smaller diameter of 300 mm and in few columns in case of 400 mm pile diameter. At next higher diameters trend of variation of B.M. is found to be stable and similar as seen for other configurations for all the diameters.

> For pile group having more number of piles, trend of variation of B.M. at top and bottom of various columns is found to be stable and similar in either configuration for all diameters whereas in case of pile group having less number of piles, trend of variation of B.M. is not stable particularly in respect of series configuration at smaller pile diameter.

> It can be, thus, concluded that the effect of soil- structure interaction has been observed to be quite significant in the context of the foundation used for the specific building frame considered in the present study with the inference that various parameters of the pile foundation such as number, diameter and spacing of piles along with the arrangement of piles in a group affect the response of the superstructure considerably.

References

Basarkar, S.S. and Dewaikar, D.M. (2005): ‘Development of Load Transfer Model for Socketted Tubular Piles’, *Proc. Int. Geotechnical Conf., St. Petersburg,* Vol.I, pp 117-122

Buragohain, D.N. and Shah, V.L (1977): ‘Curved Interface Elements for Interaction Problems’, *Proc. Int. Symposium on Soil-Structure Interaction, Roorkee, India*, pp 197-202

Buragohain, D.N., Raghavan, N. and Chandrasekaran, V.S. (1977): ‘Interaction of Frames with Pile Foundation’, *Proc. Int. Symposium on Soil- Structure Interaction, Roorkee, India*, pp 109-115

Chameski, C. (1956): ‘Structural Rigidity in Calculating Settlements’, *Journal of Soil Mechanics and Foundation Engg., ASCE*, 82 (1), pp 1-9

Chore, H.S. and Sawant, V.A. (2002): 'Finite Element Analysis of Laterally Loaded Pile Group', *Proc. Indian Geotechnical Conf. (IGC-2002), Allahabad, India,* pp 545-548

Chore, H.S. and Sawant, V.A. (2004): 'Parametric Study of Socketted Pile Groups Subjected to Lateral Loads', *Proc. National Conf. on Hydraulics and Water Resources (HYDRO-2004), Nagpur, India*, pp 589-596

Chore, H.S. and Ingle, R.K. (2008): 'Interactive Analysis of Building Frame Supported on Pile Group Using Simplified F.E.Model', *Journal of Structural Engineering, SERC, Chennai,* Vol.34, No.6, pp 460-464

Coyle, H.M. and Reese, L.C. (1966): 'Load Transfer for Axially Loaded Pile in Clay', *Proc. ASCE,* 92(SM 2), pp 1-26

Dasgupta, S., Dutta, S.C. and Bhattacharya, G. (1998): 'Effect of Soil- Structure Interaction on Building Frames on Isolated Footings', *Journal of Structural Engg., India*, 26(2), pp 129-134

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,' *Proc. 2nd Int. Conf. On Numerical Methods in Geomechanics, Blacksburg,* Vol.I, pp 405-418

Desai, C.S., Kuppusamy, T., and Allameddine, A.R. (1981): 'Pile Cap- Pile Group- Soil Interaction', *Journal of Structural Engg. Division, ASCE*, 107(ST 5), pp817-834

Deshmukh, A.M. and Karmarkar, S.R. (1991): 'Interaction of Plane Frames with Soil', *Proc. Indian Geotechnical Conference, Surat, India*, Vol.I, pp 323-326

Dewaikar, D.M., Varghese, S.P., Sawant, V.A. and Chore, H.S. (2007): 'Non-linear 3-D FEA of Laterally Loaded Piles incorporating No-tension Behaviour of Soil', *Indian Geotechnical Journal,* 37 (3), pp 174-189

Georgiadis, M. and Butterfield, R. (1982): 'Laterally Loaded Pile Behaviour' *Journal of Geotechnical Engg., ASCE*, 108, pp 155-165

Hazarika, P.J. and Ramasamy, G. (2000): 'Response of Piles under Vertical Loading', *Indian Geotechnical Journal*, 30 (2), pp 73-91

Hora, M.(2006): 'Non-linear Interaction Analysis of Infilled Building Frame- Soil System', *Journal of Structural Engg., Chennai,* 33 (4), pp 309-318

Ingle, R.K. and Chore, H.S. (2007): 'Soil- Structure Interaction Analysis of Building Frames- An Overview', *Journal of Structural Engg., SERC, Chennai,* 34 (5), pp 201-209

King, G.J.W. and Chandrasekaran, V.S. (1974): 'Interactive Analysis of a Rafted Multistoreyed Space Frame Resting on an Inhomogeneous Clay Stratum', *Proc. Int. Conf. on Finite Element Methods, Australia*, pp 493-509

Lee, I.K. and Harrison, H.B. (1970): 'Structures and Foundation Interaction Theory', *Proc. ASCE,* 96(ST 2), pp 177-198

Lee, I.K. and Brown, P.T. (1972): ‘Structures and Foundation Interaction Analysis’, *Journal of Structural Engg. Division, ASCE,* 11, pp 2413-2431

Mandal, A., Moitra, D. and Dutta, S.C. (1999): ‘Soil- Structure Interaction on Building Frame: A Small Scale Model Study’, *International Journal of Structures, Roorkee, India,* 18(2), pp 92-107

Matlock, H. and Reese, L.C. (1956): ‘Foundation Analysis of Offshore Pile Supported Structures’, *Proc. Of 5th Int. Conf. On Soil Mechanics and Foundation Engg. Paris,* pp 91-97

Mayerholf, G. (1953): ‘Some Recent Foundation Research and its Application to Design’, *The Structural Engineer, 31 (6),* pp 151-167

Morris, D. (1966): ‘Interaction of Continuous Frames and Soil Media’, *Journal of Structural Engg. Division, ASCE,* 5, pp 13-43

Noorzaei, J., Viladkar, M.N. and Godbole, P.N. (1991): ‘Soil-Structure Interaction of Space Frame-Raft –Soil System: Parametric Study’, *Computers and Structures,* 40 (5), pp 1235-1241

Patil, M.A. and Dewaikar, D.M.(1999): ‘Three Dimensional Finite Element Analysis of Laterally Loaded Pile Group’, *Proc. Int. Conf. on Offshore and Nearshore Geotechnical Engg. (GEO Shore-1999), Panvel, India,* pp 315-320

Polous, H.G. (1968): ‘Analysis of Settlement of Pile’, *Geotechnique,* 18(4), pp 449-471

Poulos, H.G.(1971): ‘Behaviour of Laterally Loaded Piles: II- Group of Piles’, *Journal of Soil Mechanics Foundation Engg. Division, ACSE*, 97(5), pp 733-751

Sawant, V.A., Amin, N.B., Dewaikar, D.M.(1996): ‘Response of a Pile to Cyclic Lateral Loads Using Moment area Method’, *Indian Geotechnical Journal*, 26(4), pp 353-363

Sawant, V.A. and Dewaikar, D.M. (1999): ‘Analysis of Pile Groups subjected to Cyclic Lateral Loading’, *Indian Geotechnical Journal,* 29(3), pp 191-220

Sawant, V.A. and Dewaikar, D.M. (2001): ‘Geometrically Non-linear 3-D Finite Element Analysis of a Single Pile’, *Proc. Int. Conf. on Computer Methods and Advances in Geomechanics, Balkema, Rotterdam,* pp 1485-1487

Sriniwasraghavan, R. and Shankaran, K.S. (1983): ‘Settlement Analysis for Combined Effect of Superstructure-footings- Soil System’, *Journal of Institution of Engineers (India),* 6, pp 194-198

Stavirdis, L.T. (2002): ‘Simplified Analysis of Layered Soil-Structure Interaction’’ *Journal of Structural Engg., ASCE*, 128 (2), pp 224-230

Subbarao, K.S., Shrada Bai, H. and Raghunatham, B.V.(1985): ‘Interaction Analysis of Frames with Beam Footing’, *Proc. Indian Geotechnical Conference, Roorkee, India,* Vol.I, pp 389-395

Viladkar, M.N., Godbole, P.N., and Noorzaei, J. (1991): ‘Soil-Structure Interaction in Plane Frames using Coupled Finite-Infinite Elements’, *Computers and Structures,* 39 (5), pp 535-546