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Soil –structure interaction analysis of a building frame supported on piled raft

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Abstract. The study deals with physical modeling of a typical building frame resting on pile raft foundation and embedded in cohesive soil mass using finite element based software ETABS. Both- the elements of superstructure and substructure (i.e., foundation) including soil is assumed to remain in elastic state at all the time. The raft is modelled as a thin plate and the pile and soils are treated as interactive springs. Both- the resistance of the piles as well as that of raft base - are incorporated into the model. Interactions between raft-soil-pile are computed. The proposed method makes it possible to solve the problems of uniformly and large non-uniformly arranged piled rafts in a time saving way using finite element based software ETABS. The effect of the various parameters of the pile raft foundation such as thickness of raft and pile diameter is evaluated on the response of superstructure. The response included the displacement at the top of the frame and bending moment in columns. The soil-structure interaction effect is found to increase displacement and increase the absolute maximum positive and negative moments. The effect of the soil- structure interaction is observed to be significant for the type of foundation and soil considered in the present study.

Keywords: soil-structure interaction; piled raft; raft thickness; pile diameter; top displacement; bending moment

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 (Chameski 1956, Morris 1966, Lee and Brown 1972, King and Chandrasekaran 1974, Buragohain *et al.* 1977) have been reported in many studies in the 1960's and 1970's and few in recent studies (Shriniwasraghavan and Sankaran 1983, Subbarao *et al.* 1985, Deshmukh and Karmarkar 1991, Viladkar *et al*. 1991, Noorzaei *et al*. 1991, Dasgupta *et*

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al. 1998, Mandal *et al.*1999). While most of the above mentioned studies dealt with the quantification of the effect of interaction of frames with isolated footings or combined footings or raft foundation in the context of supporting sub-soil either analytically or experimentally; only the study by Buragohain *et al.* (1977) was found to deal with the interaction analysis of frames on piles until recent past.

The afore-mentioned work (Buragohain *et al.* 1977) was carried out using the stiffness matrix method and moreover, it was based on the simplified assumptions and relatively less realistic approach. Pointing out the lacunae in the interaction analysis of a framed structure resting on pile foundation presented by Buragohain *et al.* (1977), Chore and co-authors reported the methodology for the interaction analysis of a single storeyed building frames embedded in clayey soil on the rational approach and realistic assumptions. Many studies reported in the recent past related to the theme included Chore and Ingle (2008 a, b), Sawant and Chore (2010), Chore *et al*. (2009 and 2010), Chore (2013), Chore *et al.* (2014) and Dode *et al.* (2014, 2015) along with Fatahi *et al.* (2014). Although most of the analyses used sub-structure method (uncoupled approach), few of them used coupled approach where the structure and foundation were considered to be a single compatible unit. However, the investigations underscored that the sub-structure approach is preferred in such interaction analysis owing to simplicity in the method, less memory requirement on part of the computational resources and not much variation in the results obtained using sub-structure method and coupled approach. Recently along similar lines, Reddy and Rao (2011) reported an experimental work on a model building frame supported by a pile group and compared the results analytically using finite element analysis.

Even numerous studies have been reported mostly recently that include those by Agrawal and Hora (2009, 2010), Thangaraj and Illampurthy (2010), Dalili *et al.* (2011), Swamy Rajshekhar *et al*. (2011), Thangaraj and Illampurthy (2012). However, these studies were confined to the interaction analysis of frames or allied structure supported by isolated footings or raft foundation.

In the meantime, much work is available in the literature on axially loaded as well as laterally loaded single pile and pile groups. The approaches available for the analysis of axially loaded pile foundations include the elastic continuum method (Polous 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 continuum approach (Spiller and Stoll 1964, Polous 1971, Banerjee and Davis 1978) and modulus of subgrade reaction approach (Matlock and Reese 1956, Matlock 1970, Georgiadis *et al*. 1992, Dewaikar and Patil 2006). With the advent of computers in the early seventies, more versatile finite element method (Desai and Abel 1974, Desai and Appel 1976, Desai *et al.* 1981, Ng and Zhang 2001, Krishnamoorthy *et al.* 2005, Chore *et al.* 2010, 2012 a, b) has become popular for analyzing the problem of pile foundations in the context of linear and non-linear analysis.

The review of literature indicates that relatively lesser work is reported in respect of building frames supported by piled raft foundation. In view of this, the interaction analysis of the building frame resting on pile raft is presented here.

2. Idealizations made in the mathematical modeling

The elements of the superstructure (beam, column and slab) and that of the substructure (pile, raft and soil) are modeled using simplified modeling approach using a standard computer software ETABS. The slab and raft in the frame is idealized as the two-dimensional plate element, beams and columns of the frame along with pile are idealized as one dimensional beam element. The raft takes the load from super structure and transfers it to pile as well as soil; the part load will be taken by raft and part that by pile. In this method, the Pile is modeled beneath raft with the line spring or point spring representing the surrounding soil and the soil beneath the raft is represented by spring of equivalent stiffness. Fig. 1 indicates the structural idealization for piled raft with supporting sub-soil.

3. Numerical problem

A 3-D three storeyed building frame resting on pile raft foundation, as shown in the Fig. 2, is considered for the study. Full height of the frame is 9 m, each storey, 3 m high is 10 m × 10 m in plan with each bay being, 5 m × 5 m. 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 beam. The beams are resting on columns of size 300 mm × 300 mm and piles are provided under each column.

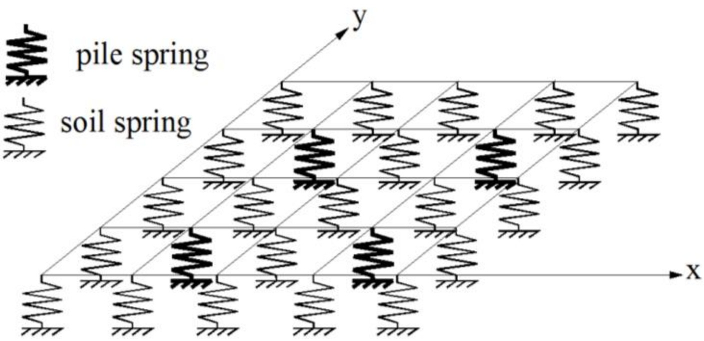

Fig. 1 Structural idealization for piled raft and supporting soil

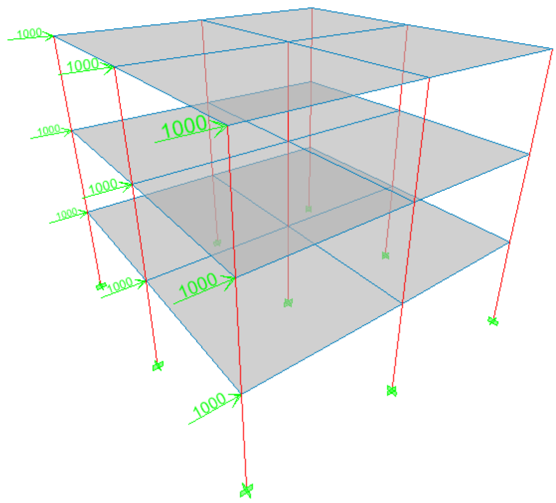

Fig. 2 Typical building frame with fixed base considered in the present investigation

Table 1 Material properties for the elements of the frame and foundation

Properties	**Corresponding Values**
Pile diameter in mm *(D)*	200, 300, 400, 500 and 600
Raft thickness (mm)	200, 300, 400 and 500
Raft dimension	12 m × 12 m
$^{L}/_{D}$ (Constant)	10
Grade of concrete used for frame elements	M-20 (as per Indian Specification) Characteristic compressive strength: 20 MPa
Young's modulus of elasticity for frame elements ($E_{c\ Frame}$)	0.25491×10^{8} kPa
Grade of concrete used for foundation	M-40 (as per Indian Specification) Characteristic compressive strength: 40 MPa
Young's modulus of elasticity for foundation ($E_{c\ Foundation}$)	0.3605×10^{8} kPa
Poisson's ratio for concrete (μ_c)	0.15
Modulus of Subgrade Reaction (K_h)	4267 kPa

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, a lateral load of 1000 kN is assumed to act at the joints of the frame, as shown in the Fig. 2. The properties of the material for piled raft are given in Table 1.

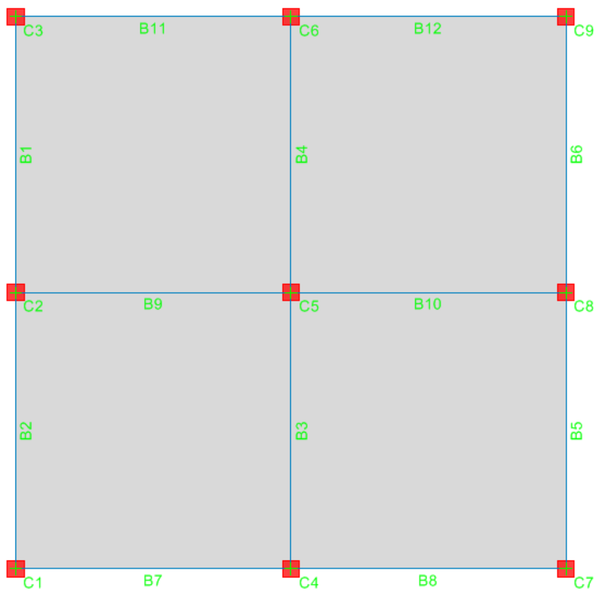

Fig. 3 Particulars of the frame (plan) showing the element numbering for various components of the frame [Top slab]

4. Parametric study

The building frame is analyzed in ETABS software. The analytical modeling of the frame resting on the fixed base and subsequently, on the pile-raft foundation is indicated in Figs. 4 and 5. The displacement at the corresponding storey and moments developed in beams and columns of the frame obtained in view of the fixed column bases condition are considered for the sake of comparison. Further, the effect of pile diameter and raft thickness is evaluated on the response of displacement and moment developed in piled-raft.

Following aspects are considered in the analysis:

- The diameter of pile is varied (200 mm, 300 mm, 400 mm, 500 mm and 600 mm) with constant embedment depth ratio (L/D) = 10 for the modulus of subgrade reaction (K_h) to be 4267 kN/m^3.
- The thickness of raft is varied (200 mm, 300 mm, 400 mm and 500 mm) with constant material properties for all diameter of pile.

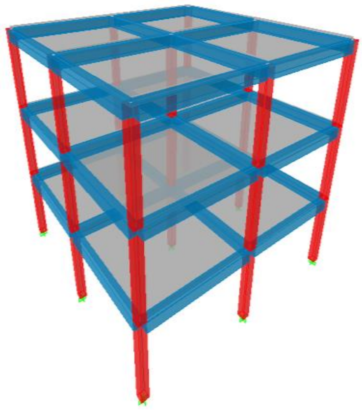

Fig. 4 Mathematical model of frame assuming fixed column bases using ETABS

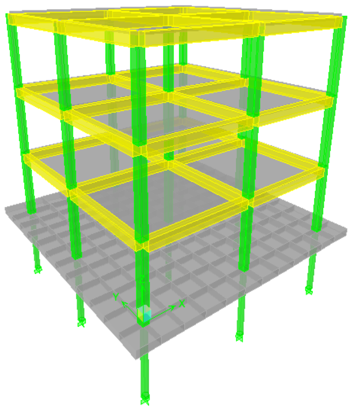

Fig. 5 Mathematical model of frame with piled-raft using ETABS

5. Results and discussion

In the parametric study conducted for the specific frame presented here, the response of the superstructure considered for the purpose of comparison includes the horizontal displacement of the frame at the storey level as well as moment in superstructure columns, i.e., at top and bottom thereof, for both fixed base and soil- structure interaction condition on the premise of piled raft foundation. Similarly, the moment in the flexural members such as beams is also considered in view of the fixed base condition of the columns and considering the effect of soil- structure interaction.

5.1 Effect of pile diameter and raft thickness

This section describes the effect of the soil- structure interaction on storey displacement of the frame and moments in superstructure columns in view of the various pile diameters with constant ratio of embedment depth and a constant value of the modulus of subgrade reaction of soil.

5.1.1 Effect on displacement of frame

The displacements of frame at each storey level evaluated in respect of various pile diameters for fixed base condition and that for soil-structure interaction (SSI) in view of only 200 mm thick raft thickness is shown in Table 2. The corresponding increase in displacement due to consideration of SSI is also shown in Table 2. The storey wise variation of displacement in view of the consideration of piled raft (SSI) is indicated in Fig. 6.

The general trend observed for all the pile diameters considered in this investigation is that horizontal displacement at the storey level increases due to the effect of soil structure interaction (SSI) is considered.

Table 2 Values of displacements (mm) and increase therein due to SSI for 200 mm thick raft base

Storey Height in m	Fixed Base Displacement (mm)	D = 200 mm Displacement (% increase)	D = 300 mm Displacement (% increase)	D = 400 mm Displacement (% increase)	D = 500 mm Displacement (% increase)	D = 600 mm Displacement (% increase)
9	9.71	28.63 (194.85)	26.36 (171.47)	24.25 (149.74)	23.69 (143.98)	23.29 (139.86)
6	8.39	27.14 (223.48)	25.17 (200.00)	23.32 (177.95)	22.55 (168.77)	22.40 (166.98)
3	4.62	22.74 (392.21)	20.43 (342.21)	18.78 (306.49)	18.33 (296.75)	18.16 (293.07)
0	0.0	8.30 (100)	7.04 (100)	6.15 (100)	5.89 (100)	5.49 (100)

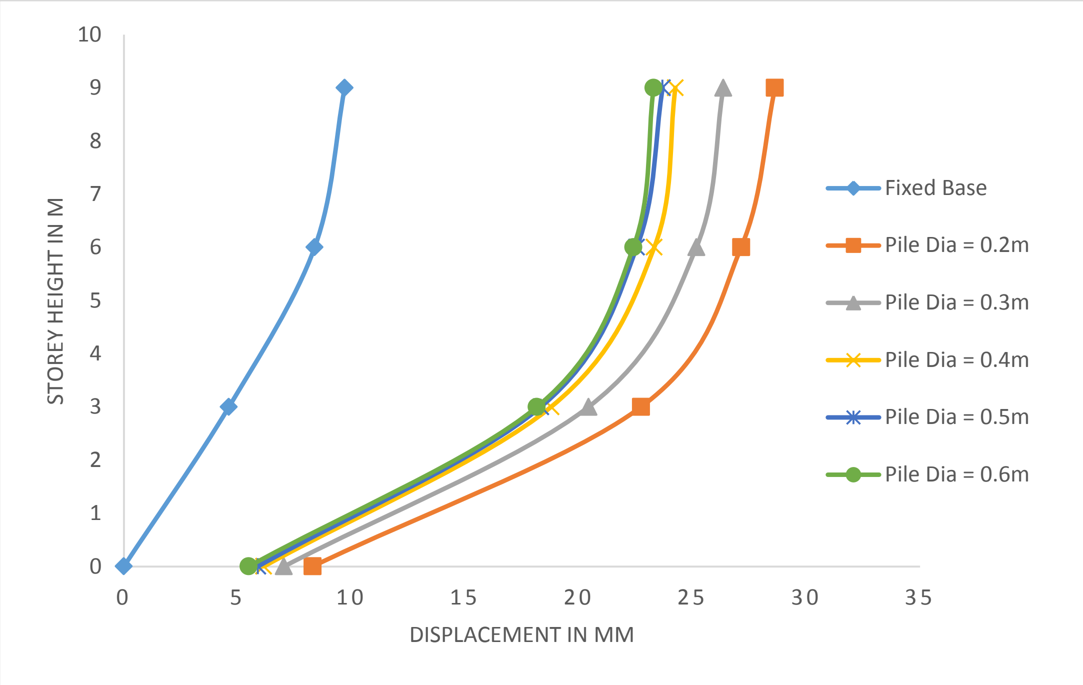

Fig. 6 Effect of pile diameter on displacement

For 200 mm pile diameter, the percentage increase in displacement is found to be 392%, 223% and 195% at top of the subsequent storeyes due to incorporation of the effect of SSI (piled raft base). The corresponding increase is observed to be 342%, 200% and 171% for 300 mm pile diameter; and 306%, 178% and 150% for 400 mm pile diameter; and 297%, 169% and 144% for 500 mm pile diameter. In respect of 600 mm pile diameter, the corresponding increase is found to be 293%, 167% and 140%.

With increase in the pile diameter, it is observed that the displacement at each storey decreases, especially in respect of 200 mm pile diameter. Although the trend remains same for all other pile diameters considered in the study, not much difference is observed between the displacements at corresponding storey obtained in respect of higher pile diameters such as 300 mm, 400 mm, 500 mm and 600 mm. The increase in diameter of the pile increases the stiffness of the sub-structure (i.e., foundation) and therefore, the displacement decreases.

Moreover, with increase in storeyes, the displacement is found to decrease when the effect of piled raft is considered. The displacements obtained at the second storey are found to decrease by 70% on an average as compared to that obtained at the first storey in respect of all the pile diameters. Similarly, the displacements obtained at the third (top) storey is observed to be less by 17% when compared with the displacements obtained at the second storey.

The above discussion is especially for the analysis carried out with 200 mm thick raft base. Further, the displacement gets reduced with the increase in the thickness of the raft.

5.1.2 Effect on moments in superstructure columns

The effect of pile diameter on increase or decrease in maximum moment in the individual columns of the frame is reported in Table 3-8. The effect of pile diameter on corresponding percentage increase or decrease in maximum moments of the individual columns at various storeys for various diameters of pile is discussed below.

Further, percentage increase or decrease in moments at supports and span of individual beams of the frame due to incorporation of the effect of pile diameter in the analysis is also evaluated. It is obvious from the values tabulated in Table 3-8, that the effect of pile diameter on moments in superstructure columns is significant when the values of moments are calculated on the premise of fixed base approach and that, soil- structure interaction (SSI).

Table 3 Values of moments (kN-m) and variation therein due to SSI in column 'C-1' and 'C-3' (Corner column in the leading row)

Storey Height in m	Fixed base	200 mm thick raft base				
		D = 200 mm	D = 300 mm	D = 400 mm	D = 500 mm	D = 600 mm
	Moment kN-m	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)
9	1.60	1.78 (11.25) (+*I*)	1.78 (11.25) (+*I*)	1.76 (10.00) (+*I*)	1.76 (10.00) (+*I*)	1.74 (8.75) (+*I*)
6	-11.27	-11.46 (1.69) (-*I*)	-11.46 (1.69) (-*I*)	-11.46 (1.69) (-*I*)	-11.46 (1.69) (-*I*)	-11.46 (1.69) (-*I*)
3	-22.70	-48.00 (111.45) (-*I*)	-47.60 (109.69) (-*I*)	-46.90 (106.61) (-*I*)	-46.00 (102.64) (-*I*)	-46.00 (102.64) (-*I*)
0	-36.26	-15.80 (-56.43) (-*D*)	-15.80 (-56.43) (-*D*)	-19.00 (-47.6) (-*D*)	-19.50 (46.22) (-*D*)	-19.50 (46.22) (-*D*)

Note: (*I*) increase in moment, (*D*) decrease in moment

Table 4 Values of moments (kN-m) and variation therein due to SSI in column 'C-4'and 'C-6' (Corner column in the intermediate row)

Storey Height in m	Fixed base	200mm thick raft base				
		D = 200 mm	D = 300 mm	D = 400 mm	D = 500 mm	D = 600 mm
	Moment kN-m	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)
9	8.97	-9.96 (11.04) (+*D*)	-9.96 (11.04) (+*D*)	-9.96 (11.04) (+*D*)	-9.96 (11.04) (+*D*)	-9.96 (11.04) (+*D*)
6	-17.23	-22.60 (31.17) (-*I*)	-22.44 (30.24) (-*I*)	-22.23 (29.02) (-*I*)	-22.20 (28.85) (-*I*)	-22.20 (28.85) (-*I*)
3	-31.50	-52.40 (66.35) (-*I*)	-51.40 (63.17) (-*I*)	-49.70 (57.78) (-*I*)	-48.20 (53.02) (-*I*)	-48.20 (53.02) (-*I*)
0	-38.15	-15.60 (-59.11) (-*D*)	-16.10 (-57.80) (-*D*)	-17.75 (-53.47) (-*D*)	-18.38 (-51.82) (-*D*)	-18.53 (-51.43) (-*D*)

Table 5 Values of moments (kN-m) and variation therein due to SSI in column 'C-7' and 'C-9' (Corner column in the trailing row)

Storey Height in m	Fixed base	200 mm thick raft base				
		D = 200 mm	D = 300 mm	D = 400 mm	D = 500 mm	D = 600 mm
	Moment kN-m	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)
9	-13.85	-14.55 (5.05) (-*I*)	-14.52 (4.84) (-*I*)	-14.49 (4.62) (-*I*)	-14.60 (4.33) (-*I*)	-14.42 (4.12) (-*I*)
6	-22.36	-23.87 (6.75) (-*I*)	-23.83 (6.57) (-*I*)	-23.78 (6.35) (-*I*)	-23.72 (6.04) (-*I*)	-23.67 (5.86) (-*I*)
3	-32.15	-56.95 (77.14) (-*I*)	-56.13 (74.59) (-*I*)	-55.28 (71.94) (-*I*)	-54.90 (70.76) (-*I*)	-54.35 (69.05) (-*I*)
0	-41.35	-16.10 (-61.06) (-*D*)	-16.90 (-59.12) (-*D*)	-18.10 (-56.23) (-*D*)	-19.75 (-52.24) (-*D*)	-19.87 (-51.95) (-*D*)

Note: (*I*) increase in moment, (*D*) decrease in moment

Table 6 Values of moments (kN-m) and variation therein due to SSI in column 'C-2' (Central column in the leading row)

Storey Height in m	Fixed base	200 mm thick raft base				
		D = 200 mm	D = 300 mm	D = 400 mm	D = 500 mm	D = 600 mm
	Moment kN-m	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)
9	7.51	13.47 (79.57) (+*I*)	12.94 (72.50) (+*I*)	12.29 (63.82) (+*I*)	12.07 (60.72) (+*I*)	11.93 (58.85) (+*I*)
6	-9.66	-6.72 (-30.43) (-*D*)	-7.00 (-27.54) (-*D*)	-7.33 (24.12) (-*D*)	-7.56 (21.74) (-*D*)	-7.62 (21.12) (-*D*)
3	-24.12	-51.40 (113.10) (-*I*)	-48.64 (101.66) (-*I*)	-48.49 (101.04) (-*I*)	48.36 (100.5) (-*I*)	48.32 (100.33) (-*I*)
0	-38.13	-16.50 (-56.73) (-*D*)	-17.70 (-53.58) (-*D*)	-18.95 (-50.30) (-*D*)	-19.39 (-49.15) (-*D*)	-19.63 (-48.52) (-*D*)

The effect of soil- structure interaction is significant on B.M. The soil- structure interaction analysis is found to increase the absolute maximum positive B.M. in the range of 8.75- 79.57 % and that negative B.M., 1.69- 111.45 % when compared with those obtained using conventional analysis. Similarly the decrease in the absolute positive bending moment is seen to be in respect of all diameters 11.04% and that, negative moment in the range of 46.22- 70.55%.

Table 7 Values of moments (kN-m) and variation therein due to SSI in column 'C-5' (Central column in the intermediate row)

Storey Height in m	Fixed base	200 mm thick raft base				
		D = 200 mm	D = 300 mm	D = 400 mm	D = 500 mm	D = 600 mm
	Moment kN-m	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)
9	-12.78	-12.55 (-1.80) (-*D*)	-12.60 (1.40) (-*D*)	-12.66 (0.94) (-*D*)	12.58 (-1.56) (-*D*)	12.58 (-1.56) (-*D*)
6	-31.90	-37.80 (18.50) (-*I*)	-37.10 (16.30) (-*I*)	-36.90 (15.67) (-*I*)	-19.71 (-38.21) (-*I*)	-17.83 (-44.11) (-*I*)
3	-44.38	-71.25 (60.55) (-*I*)	-69.38 (56.33) (-*I*)	-66.88 (50.70) (-*I*)	-55.28 (-24.56) (-*I*)	-49.35 (-11.20) (-*I*)
0	-48.55	-14.30 (-70.55) (-*D*)	-15.70 (-67.66) (-*D*)	-16.95 (-65.09) (-*D*)	-19.05 (-60.76) (-*D*)	-19.93 (-58.95) (-*D*)

Note: (*I*) increase in moment, (*D*) decrease in moment

Table 8 Values of moments (kN-m) and variation therein due to SSI in column 'C-8' (Central column in the trailing row)

Storey Height in m	Fixed base	200 mm thick raft base				
		D = 200 mm	D = 300 mm	D = 400 mm	D = 500 mm	D = 600 mm
	Moment kN-m	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)
9	-22.83	-28.77 (26.02) (-*I*)	-28.28 (23.87) (-*I*)	-27.68 (21.24) (-*I*)	-27.48 (20.37) (-*I*)	-27.42 (20.11) (-*I*)
6	-30.98	-38.75 (25.08) (-*I*)	-38.26 (23.50) (-*I*)	-37.85 (22.18) (-*I*)	-37.60 (21.37) (-*I*)	-36.90 (19.11) (-*I*)
3	-40.60	-66.90 (64.77) (-*I*)	-63.55 (56.53) (-*I*)	-62.55 (54.06) (-*I*)	-62.25 (53.32) (-*I*)	-62.25 (53.32) (-*I*)
0	-46.35	-14.88 (-67.90) (-*D*)	-15.98 (-65.52) (-*D*)	-17.20 (-62.89) (-*D*)	-19.07 (-58.86) (-*D*)	-19.00 (-59.00) (-*D*)

When increase or decrease in the maximum moments in individual columns placed on the left hand side, i.e., column C-1 (and C-3) are considered for different diameters, the increase in sagging moment is observed in the range of 8.75- 11.25% at top storey. At second storey, the hogging moment increases by 1.69% and subsequently, for the first storey, the increase in hogging moment is found in the range of 102.64- 111.45%. However, the hogging moment decreases at the bottom, the decrease being in the range of 46.22- 56.43. Therefore, at the bottom of column C-1 (and C-3), the decrease in hogging moment is observed and for the next two storeyes, hogging moment tends to increase and at the top storey, the sagging (positive) moment increases.

For column C-2, for different diameters of the piles, the increase in the sagging moment at the top storey is observed to be in the range of 58.85- 79.57 %. Thereafter, at second storey the decrease in hogging moment is observed in the range of 21.12- 30.43% and subsequently, at first storey the increase in the hogging moment is observed in the range of 100.33- 113.10%. At bottom, the decrease in the hogging moment is observed in the range of 48.52- 56.73%. Hence, the decrease in hogging moment is seen at bottom and second storey and increase in it, at first storey. However, the sagging moment is found to increase at the topmost storey.

The percentage decrease in the sagging moment at the top in the column C-4 (and C-6) is found to be 11.04% for all pile diameters. Similarly, at second storey the increase in hogging moment is observed in the range of 28.85- 31.17% and the corresponding increase at first storey is observed in the range of 53.02- 66.35%. At bottom of this column the decrease the hogging moment is observed, the range being 51.43 to 59.11%. Hence, the hogging moment decreases at first and second storey and decreases at bottom. However, the sagging moment decreases at the topmost storey.

Further for column C-7 (and C-9), the percentage increase in hogging moment is observed in the range of 4.12- 5.05, 5.86- 6.75, 69.05- 77.14 at top, second and first storey respectively, while percentage decrease in the hogging moment is observed in the range of 51.95- 61.06 at the bottom. The decrease in hogging moment is observed at the bottom and for rest of storeys, the increase in hogging (negative) moment is observed. For column C-8, the increase in the hogging moment is observed in the range of 53.32-64.77, 19.11- 25.08 and 20.11- 26.02% at first, second and top storey respectively. Similarly at the bottom, percentage decrease in the hogging moment is observed in the range of 59.00- 67.90. The decrease in the hogging moment is observed at the bottom and increase is observed for rest of the storeys.

The moment at top of columns placed in the leading row (C-1, C-2) and intermediate row (C-4, C-5) is found to be positive and in the trailing row (C-7, C-8 and C-9) it is found as negative, whereas for all the columns decrease in the moment at bottom is observed. Along similar lines, the positive moment decreases in the columns with increase in the pile diameters.

Effect of pile diameter in the columns C-1, C-4 and C-7 placed in front row of the frame appears less in comparison with the columns C-2 and C-8 placed in the middle row of the frame except central column C-5and in which the moment appears less.

However, the trend of variation of negative moment in columns has certain exceptions, such as in respect of column C-7 (placed in the trailing row) moments are increases at the each storey and decreases at the junction of pile and column; but in respect of columns C-2 (placed in leading row at the center), the increase in positive moments is observed, decrease in negative moment at top second storey, increase in negative moment and decrease in negative moment is observed at the bottom. For this column, the trend is exactly opposite. Also, in case of column C-5 decrease in negative moment is observed at bottom and top storey, while increase in moment is observed for first and second storey.

5.1.3 Effect on moments in superstructure beams

The effect of pile diameter on increase or decrease in maximum moments in the beams at supports and at the mid span of the frame is reported in Tables 9 and 10. The effect of pile diameter on corresponding percentage increase or decrease in support and mid span moments in the beams in respect of various diameters of pile is discussed below. Further, percentage increase or decrease in moments at end and mid span of individual beams of the frame due to incorporation of the effect of pile diameter in the analysis is also evaluated.

The percentage increase in the support and mid span moment is observed in the top beam B-7 and B-8 placed on external side is 231.63- 528.94 and 169.47- 915.88, respectively for the pile diameter 200 mm. For pile diameter 300 mm, the increase in moment is observed in the range of 204.62- 476.61 at support and 150-983.34 at mid span. Similarly for the pile diameters 400,500 and 600 mm the moments at support is observed as 183.89- 428.22, 167.94- 391.93 and 156.78- 367.74 while at mid span the moment is observed as 136.17- 891.67, 123.50- 816.67 and 111.98- 750.

Further, the percentage increase in the support and span moments is observed in the beam B-9-B-10 placed on internal side is 202.05- 218.25 and 144.54- 342.54 respectively for the pile diameter 200 mm. For pile diameter 300 mm, the increase in moment is observed in the range of 178.92- 194.20 at support and 127.73- 305.87 at mid span. Similarly, for higher pile diameters such as 400, 500 and 600 mm the moments at support is observed as 160.92- 175.81, 146.78- 161.67 and 136.5- 150.35 while at mid span the moment is observed as 115.13- 276.52, 105.04- 254.50 and 99.16- 234.96.

Table 9 Values of moments (kN-m) and variation therein due to SSI in the corner beams

Beam	Moment kN-m	Fixed base	Pile diameter (D) in mm				
			200	300	400	500	600
		Moment kN-m	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)
Beam-7 S.F	Support	17.90	40.7 (127.37) (+*I*)	38.10 (112.84) (+*I*)	36.60 (101.11) (+*I*)	35.50 (98.32) (+*I*)	34.80 (94.41) (+*I*)
	Span	22.60	48.4 (114.15) (+*I*)	45.50 (101.32) (+*I*)	43.90 (94.24) (+*I*)	42.80 (89.38) (+*I*)	42.20 (86.73) (+*I*)
Beam-8 S.F	Support	15.50	11.6 (-25.16)(+*D*)	11.80 (-23.87) (+*D*)	12.80 (-17.41) (+*D*)	13.70 (-11.61) (+*D*)	13.00 (-16.13) (+*D*)
	Span	13.40	7.1 (-47.01)(+*D*)	7.59 (-43.35) (+*D*)	8.59 (-35.89) (+*D*)	9.52 (-28.95) (+*D*)	8.62 (-35.67) (+*D*)
Beam-7 F.F	Support	10.90	26.4 (142.20) (+*I*)	24.60 (125.68) (+*I*)	23.30 (113.76) (+*I*)	22.30 (104.88) (+*I*)	21.80 (100.00) (+*I*)
	Span	13.10	28.3 (116.03) (+*I*)	26.50 (102.27) (+*I*)	25.20 (92.36) (+*I*)	24.20 (84.73) (+*I*)	23.60 (80.15) (+*I*)
Beam-8 F.F	Support	5.94	-6.86 (15.48) (+*D*)	-5.52 (-7.07) (+*D*)	-4.41 (-25.75) (+*D*)	-3.50 (-41.07) (+*D*)	-2.92 (-50.84) (+*D*)
	Span	5.77	-6.65 (15.25) (+*D*)	-5.35 (-7.85) (+*D*)	-4.25 (-26.34) (+*D*)	-3.34 (-42.11) (+*D*)	-2.54 (-55.98) (+*D*)
Beam-7 G.F	Support	6.27	20.80 (231.63) (+*I*)	19.10 (204.62) (+*I*)	17.80 (183.89) (+*I*)	16.80 (167.94) (+*I*)	16.10 (156.78) (+*I*)
	Span	8.68	23.40 (169.47) (+*I*)	21.70 (150.00) (+*I*)	20.50 (136.17) (+*I*)	19.40 (123.50) (+*I*)	18.40 (111.98) (+*I*)
Beam-8 G.F	Support	-2.48	-15.60 (528.94) (-*I*)	-14.30 (476.61) (-*I*)	-13.10 (428.22) (-*I*)	-12.20 (391.93) (-*I*)	-11.60 (367.74) (-*I*)
	Span	-1.20	-14.30 (915.88) (-*I*)	-13.00 (983.34) (-*I*)	-11.90 (891.67) (-*I*)	-11.00 (816.67) (-*I*)	-10.20 (750.00) (-*I*)

Note: (I) increase in moment, (D) decrease in moment, S.F = Second floor, F.F =First floor, G.F = Ground

Table 10 Values of moments (kN-m) and variation therein due to SSI in intermediate beams

Beam	Moment kN-m	Fixed base	Pile diameter (D) in mm				
			200	300	400	500	600
		Moment kN-m	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)	Moment (% increase /decrease)
Beam-9 S.F	Support	14.90	36.1 (142.28) (+*I*)	33.60 (125.50) (+*I*)	32.10 (115.44)(+*I*)	30.90 (107.38)(+*I*)	30.00 (101.34)(+*I*)
	Span	21.00	46.4 (120.95) (+*I*)	43.40 (106.67) (+*I*)	41.70 (98.57) (+*I*)	40.50 (92.86) (+*I*)	39.60 (88.57) (+*I*)
Beam-10 S.F	Support	8.49	-0.76 (108.94)(+*D*)	0.03 (-1.0) (+*D*)	1.22 (85.63)(+*D*)	2.30 (-72.91)(+*D*)	3.05 (64.08)(+*D*)
	Span	7.41	-2.85 (138.46)(+*D*)	-1.93 (126.04)(+*D*)	-0.80 (110.8)(+*D*)	0.19 (97.48)(+*D*)	0.69 (90.69)(+*D*)
Beam-9 F.F	Support	10.40	26.5 (154.80)(+*I*)	24.60 (136.54) (+*I*)	23.20 (123.07)(+*I*)	22.20 (113.46)(+*I*)	21.70 (108.65)(+*I*)
	Span	13.80	30.5 (121.01)(+*I*)	28.60 (107.24) (+*I*)	27.10 (96.38) (+*I*)	26.00 (88.41)(+*I*)	25.70 (86.23)(+*I*)
Beam-10 F.F	Support	1.69	-12 (-810)(+*D*)	-10.60 (-727.2)(+*D*)	-9.34 (652.6)(+*D*)	-8.35 (-594.0)(+*D*)	-8.12 (-380.5)(+*D*)
	Span	2.32	-10.4 (-348.2)(+*D*)	-9.08 (-291.3)(+*D*)	-7.94 (242.2)(+*D*)	-7.00 (201.7)(+*D*)	-6.36 (174.2)(+*D*)
Beam-9 G.F	Support	7.78	23.50 (202.05)(+*I*)	21.70 (178.92) (+*I*)	20.30 (160.92)(+*I*)	19.20 (146.78)(+*I*)	18.40 (136.50)(+*I*)
	Span	11.90	29.10 (144.54)(+*I*)	27.10 (127.73) (+*I*)	25.60 (115.13)(+*I*)	24.40 (105.04)(+*I*)	23.70 (99.16)(+*I*)
Beam-10 G.F	Support	-7.07	-22.50 (218.25) (-*I*)	-20.80 (194.20) (-*I*)	-19.50 (175.81) (-*I*)	-18.50 (161.67) (-*I*)	-17.70 (150.35) (-*I*)
	Span	-4.09	-18.10 (342.54) (-*I*)	-16.60 (305.87) (-*I*)	-15.40 (276.52) (-*I*)	-14.50 (254.52) (-*I*)	-13.70 (234.96) (-*I*)

Note: (*I*) increase in moment, (*D*) decrease in moment, S.F = Second floor, F.F =First floor, G.F = Ground

It is obvious from the values tabulated in Tables 9 and 10 that the effect of pile diameter on moments in superstructure beams is significant when the values of moments are calculated on the premise of fixed base approach and that, soil- structure interaction (SSI). The effect of pile diameter in the moments of beams placed on external side appears less and effect of pile diameter in beams placed on intermediate the effect seems to be more. Further, the percentage increase in the support and span moments in the superstructure beam in front row of the frame is observed to be decrease, subsequently, from top to bottom storey.

5.1.4 Effect on displacement of piled raft

In the parametric study conducted for the specific frame presented here, the response of the substructure includes the displacement of the piled-raft. This section describes the effect of varying pile diameter and raft thickness on displacement of piled-raft.

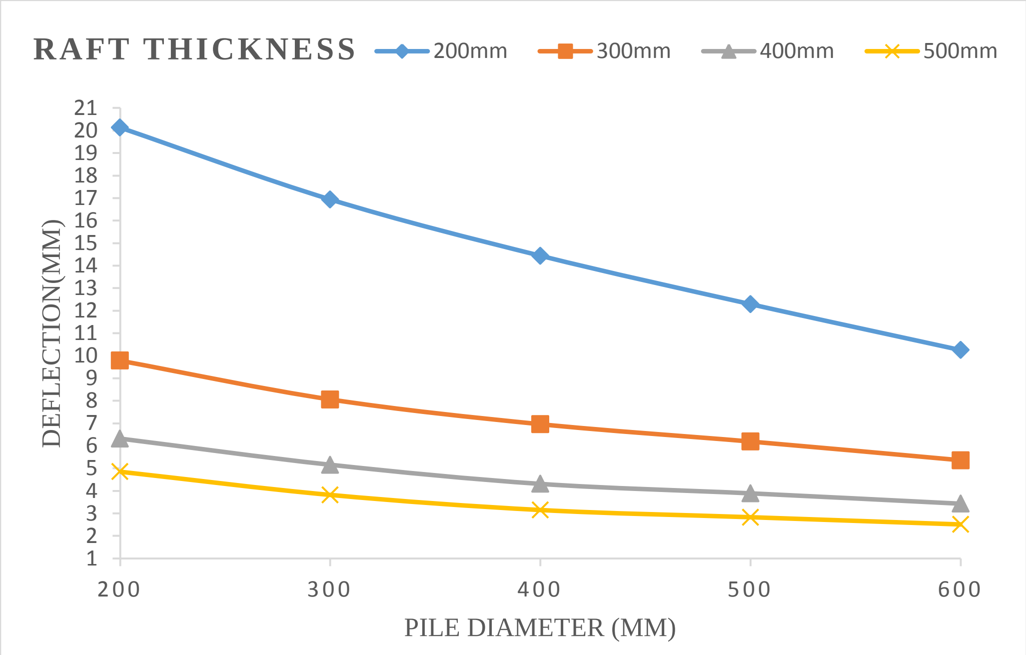

Fig. 7 Variation in maximum displacement for piled raft foundation

Fig. 7 shows the variation in maximum displacements for various pile diameters in respect different thicknesses of the raft considered in the present study. It is seen that with increase in the raft thickness, displacement in each pile decreases, especially in respect of 200 mm raft thickness. Although the trend remains same for other values of the raft thickness, much difference is observed between the displacements at corresponding pile diameter obtained in respect of higher raft thicknesses such as 300 mm, 400 mm and 500 mm. The increase in raft thickness increases the stiffness of the sub-structure, i.e., foundation and therefore, the displacement decreases. Moreover, with increase in the pile diameter, the displacement is found to be decrease.

For 200 mm pile diameter, displacement is found to be decrease 51.42%, 35.38% and 23.26% for 300mm, 400mm and 500mm raft thickness respectively. The decrease in the displacement is observed to be 52.42%, 35.98% and 25.97% for 300 mm pile diameter respectively; and 51.81%, 38.07% and 26.91% for 400 mm pile diameter respectively; and 49.63%, 37.16% and 27.25%for 500 mm pile diameter respectively. In respect of 600 mm pile diameter, the corresponding decrease is found to be 47.71%, 36.07% and 26.82%, respectively.

5.1.5 Effect in the moment of piled raft

In the parametric study conducted for the specific frame presented here, the response of the substructure considered for moment of the piled-raft. This section describes the effect of varying pile diameter and raft thickness in the moment of piled-raft.

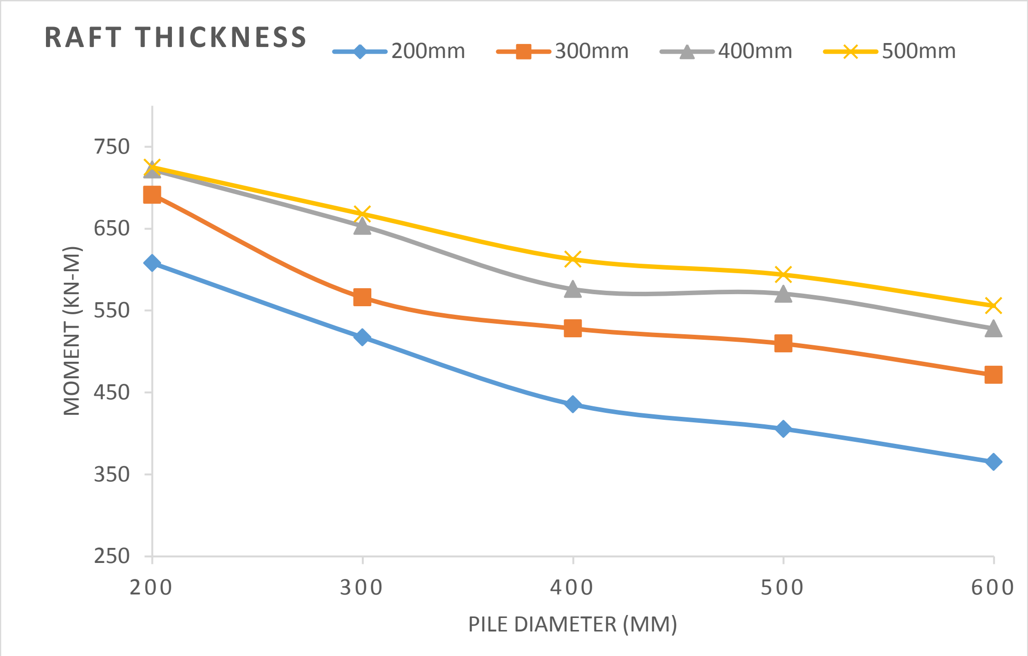

Fig. 8 Variation in maximum moment for piled raft foundation

Fig. 8 shows the variation in maximum moments in piled-raft foundations for different pile diameters in respect of various values of raft thicknesses. With increase in the raft thickness, it is observed that the moment increases especially in respect of 200 mm raft thickness. Although the trend remains same for other raft thickness considered in the study, not much difference is observed between the moment at corresponding pile diameter obtained in respect of higher raft thicknesses such as 300 mm, 400 mm and 500 mm. Moreover, with increase in the pile diameter, the moment is found to be decrease. Substantial reduction in maximum moments is observed in case of piled-raft configurations with increase in the pile diameter but substantial increment in maximum moments are observed with increase in the raft thickness. It is seen from Fig. 8 that as the diameter of pile increases the moments in the raft decreases. Further, the maximum moments are found to increase with increase in the raft thickness.

6. Conclusions

The broad conclusions emerging from the interaction analysis of the typical building frame are given below.

- The displacement is found to be more at the top storey and less at the bottom storey. The interactive analysis with respect to piled raft foundation is found to increase the displacement at base and top by 100% and 42%, respectively.

- The interaction analysis is found to yield 1-5% variation in moments in beams and columns of the frame. The moments are on higher side at the bottom with respect to non-interactive analysis. The moments are more in the middle columns than those placed at the edges in either analyses- non-interactive and interactive analysis.
- The substantial reduction in the values of maximum deflections is observed in case of piled-raft configurations with increase in raft thickness. The deflection in piled raft is found to decrease by 25% to 50% with increase in the raft thickness.
- The increase in pile diameter of the foundation results in decrease in the settlement of pile. The increase in raft thickness also results in decrease in settlement of pile.
- With the increase in the pile diameter, there is a decrease in moments in the raft and further, there is an increase in the maximum moments with the increase in the raft thickness.

References

Agrawal, R. and Hora, M.S. (2009), "Coupled finite- infinite elements modeling of building frame- soil interaction system", *ARPN Jl. Eng. App. Sc.*, **4**(10), 47-54.

Agrawal, R. and Hora, M.S. (2010), "Effect of differential settlements on non-linear interaction behaviour of plane frame-soil system", *ARPN Jl. Eng. App. Sc*., **5**(7), 75-87.

Basarkar, S.S. and Dewaikar, D.M. (2005), "Development of load transfer model for socketted tubular piles", *Proceedings of the Int. Geotech. Conf. Soil- Struct. Interaction- Calculation Meth. and Eng. Practice, St. Petersburg, May*.

Buragohain, D.N., Raghavan N. and Chandrasekaran, V.S. (1977), "Interaction of frames with pile foundation", *Proceedings of the Int. Symp. Soil- Structure Interaction, Roorkee*, India.

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

Butterfield, R. and Banerjee, P.K. (1971), "The problem of pile group and pile cap interaction", *Geotechnique*, **21**(2), 135-142

Chameski, C. (1956), "Structural rigidity in calculating settlements", *Jl. Soil Mech. Foundation Eng. - ASCE*, **82**(1), 1-9.

Chore, H.S. and Ingle, R.K. (2008a), "Interaction analysis of building frame supported on pile group", *Indian Geotech. Jl.*, **38**(4), 483-501.

Chore, H.S. and Ingle, R.K. (2008 b), "Interactive analysis of building frame supported on pile group using a simplified F.E. model", *Jl. Struct. Eng. (JoSE), SERC, Chennai (India)*, **34**(6), 460-464.

Chore, H.S., Ingle, R.K. and Sawant, V.A. (2009), "Building frame- pile foundation- soil interactive analysis", *Interact. Multis. Mech.*, **2**(4), 397-412.

Chore, H.S., Ingle, R.K. and Sawant, V.A. (2010), "Parametric study of pile groups subjected to lateral loads", *Struct. Eng. Mech.*, **26**(2), 243-246.

Chore, H.S., Ingle, R.K. and Sawant, V.A. (2010), "Building frame- pile foundation- soil interaction analysis: A parametric study", *Interact. Multis. Mech.*, **3**(1), 55-80.

Chore, H.S., Ingle, R.K. and Sawant, V.A. (2012), "Parametric study of laterally loaded pile groups using simplified F.E. models", *Coupled Syst. Mech.*, **1**(1), 1-18.

Chore, H.S., Ingle, R.K. and Sawant, V.A. (2012), "Non-linear analysis of pile groups subjected to lateral loads using p-y Curves", *Interact. Multis. Mech.*, **5**(1), 57-73.

Chore, H.S. (2013), "Interactive analysis of a building frame resting on pile foundation", *Coupled Syst. Mech.*, **3**(4), 367-384.

Chore, H.S., Ingle, R.K. and Sawant, V.A. (2014),"Non-linear soil- structure interaction of space frame- pile foundation-soil system: A parametric study", *Struct. Eng. Mech.*, **49** (1), 95-110.

Dode, P.A., Chore, H.S. and Agrawal, D.K. (2014), "Interaction analysis of a building frame supported on pile groups", *Coupled Syst.Mech.*, **3**(3), 305-305.

Dode, P.A., Chore, H.S. and Agrawal, D.K. (2015), "Space frame- pile foundation- soil interaction analysis", *J. Struct. Eng. - ASCE*, **42**(3), 78-87.

Coyle, H.M. and Reese, L.C. (1966), "Load transfer for axially loaded pile in clay", *Proc. ASCE,* **92**(2), 1-26.

Dalili, M., Alkarami, A., Noorzaei, J., Paknahad, M., Jaafar, M.S. and Huat, B. (2011), "Numerical simulation of soil- structure interaction in framed and shear wall structures", *Interact. Multis. Mech.*, **4**(1), 17-34.

Dasgupta, S., Dutta, S.C. and G. Bhattacharya (1998), "Effect of soil- structure interaction on building frames on isolated footings", *J. Struct. Eng. (JoSE), SERC, Chennai (India),* **26**(2), 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", *Proceedings of the 2nd Int. Conf. Numerical Meth. Geomech., Blacksburg*.

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

Deshmukh, A.M. and Karmarkar, S.R. (1991), "Interaction of plane frames with soil", *Proceedings of the Indian Geot. Conf., Surat, India*.

Dewaikar. D.M. and Patil, P.A. (2006), "Analysis of a laterally loaded pile in cohesion-less soil under static and cyclic loading", *Indian Geot. J.*, **36**(2),

Fatahi, B., Tabatabaiefar, H.R. and Samali, B. (2014), "Soil- structure interaction versus site effect for seismic design of tall buildings on soft soil", *Geomech. Eng*., **6**(3), 293-320.

Georgiadis, M., Anagnostopoulos, C. and Saflekou, S. (1992), "Cyclic lateral loading of piles in soft clay", *J. Geotech. Eng. - SEAGS*, **23**, 47- 60.

Hazarika, P.J. and Ramasamy, G. (2000), "Response of piles under vertical loading", *Indian Geotech. J.*, **30**(2), 73-91.

King, G.J.W. and Chandrasekaran, V.S. (1974), "Interactive analysis of a rafted multi-storeyed space frame resting on an inhomogeneous clay stratum", *Proceedings of the Int. Conf. Finite Element Meth.*, Australia.

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

Lee, I.K. and Brown, P.T. (1972), "Structures and foundation interaction analysis", *J. Struct. Eng. - ASCE*, **11**, 2413-2431.

Mandal, A., Moitra, D. and Dutta, S.C. (1999), "Soil- structure interaction on building frame: A small scale model study", *Int. J. Struct., Roorkee (India)*, **18**(2), 92-107.

Matlock, H. (1970), "Correlations for design of laterally loaded piles in soft clay", *Proceedings of the 2nd Offshore Tech. Conf.*, Houston.

Matlock. H. and Reese, L.C. (1956), "Foundation analysis of offshore pile supported structures", *Proceedings of the 5th Int. Conf. Soil Mech. Foundation Eng.*, Paris.

Morris, D. (1966), "Interaction of continuous frames and soil media", *J. Struct. Eng. - ASCE*, **5**, 13-43.

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

Noorzaei, J., Viladkar, M.N. and Godbole, P.N. (1991), "Soil-structure interaction of space frame-raft –soil system: Parametric study", *Comput. Struct*., **40**(5), 235-1241.

Polous, H.G. (1968), "Analysis of settlement of pile", *Geotechnique*, **18**(4), 449-471.

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

Reddy, Ravikumar C. and Rao, Gunneswara T.D. (2011), "Experimental study of a modelled building frame supported by a pile group embedded in cohesionless soils", *Interact. Multis. Mech*., **4**(4), 321-336.

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

Sriniwasraghavan, R. and Sankaran, K.S. (1983), "Settlement analysis for combined effect of superstructure-

footings- soil system", *J. Instt. Engineers (India),* **6**, 194-198.
Subbarao, K.S., Shrada Bai, H. and Raghunatham, B.V. (1985), "Interaction analysis of frames with beam footing", *Proceedings of the Indian Geotech. Conf., Roorkee*, India.
Swamy, Rajshekhar H.M., Krishnammorthy, A., Prabhakara, D.L. and Bhavikatti, S.S. (2011), "Evaluation of the influence of interface elements for structure- isolated footing- soil interaction analysis", *Interact. Multis.Mech*., **5**(3), 65-83.
Thangaraj, D.D. and Illampurthy, K. (2010), "Parametric study on the performance of raft foundation with interaction of frame", *Electronic J. Geotech. Eng*., **15**, 861-878.
Thangaraj, D.D. and Illampurthy, K. (2012), "Numerical analysis of soil- mat foundation of space frame system", *Interact. Multis. Mech*., **5**(3), 267-284.
Viladkar, M.N., Godbole, P.N. and Noorzaei, J. (1991), "Soil-structure interaction in plane frames using coupled finite-infinite elements", *Comput. Struct*., **39**(5), 535-546.