Coupled Systems Mechanics, *Vol. 7, No. 4 (2018) 455-483*
DOI: https://doi.org/10.12989/csm.2018.7.4.455

Interaction analysis of three storeyed building frame supported on pile foundation

S. A. Rasal[1a], H. S. Chore[*1] and V. A. Sawant[2b]

[1]Department of Civil Engineering, Datta Meghe College of Engineering, Sector-3, Airoli, Navi Mumbai-400708, India
[2]Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee-247667, India

(Received November 21, 2017, Revised February 7, 2018, Accepted February 8, 2018)

Abstract. The study deals with physical modeling of a typical three storeyed building frame supported by a pile group of four piles (2×2) embedded in cohesive soil mass using three dimensional finite element analysis. For the purpose of modeling, the elements such as beams, slabs and columns, of the superstructure frame; and that of the pile foundation such as pile and pile cap are descretized using twenty noded isoparametric continuum elements. The interface between the pile and the soil is idealized using sixteen node isoparametric surface element. The soil elements are modeled using eight nodes, nine nodes and twelve node continuum elements. The present study considers the linear elastic behaviour of the elements of superstructure and substructure (i.e., foundation). The soil is assumed to behave non-linear. The parametric study is carried out for studying the effect of soil- structure interaction on response of the frame on the premise of sub-structure approach. The frame is analyzed initially without considering the effect of the foundation (non-interaction analysis) and then, the pile foundation is evaluated independently to obtain the equivalent stiffness; and these values are used in the interaction analysis. The spacing between the piles in a group is varied to evaluate its effect on the interactive behaviour of frame in the context of two embedment depth ratios. The response of the frame included the horizontal displacement at the level of each storey, shear force in beams, axial force in columns along with the bending moments in beams and columns. The effect of the soil- structure interaction is observed to be significant for the configuration of the pile groups and in the context of non-linear behaviour of soil.

Keywords: soil-structure interaction; pile spacing; embedment depth; pile diameter; storey displacement; bending moment; shear force; axial force

1. Introduction

In the actual design practice, the superstructure frames 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,

∗Corresponding author, Professor, E-mail: hschore @rediffmail.com or chorehs@gmail.com
[a]Assistant Professor, E-mail: sarasal@rediffmail.com
[b]Associate Professor, E-mail: sawntfce@iitr.ac.in

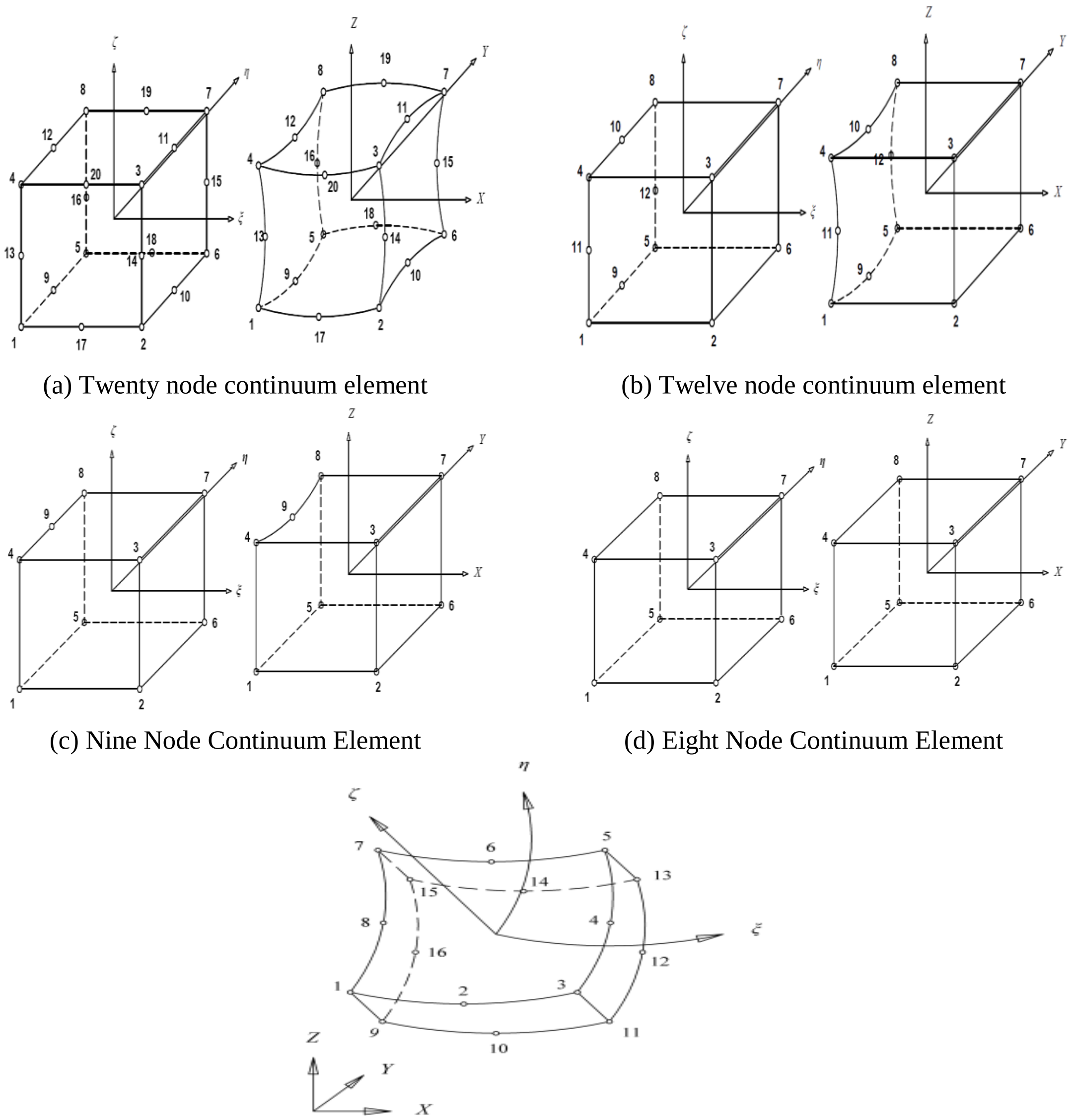
http://www.techno-press.org/?journal=csm&subpage=8 ISSN: 2234-2184 (Print), 2234-2192 (Online)

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 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; the only study reported by Buragohain *et al.* (1977) was found to deal with the interaction analysis of frames on piles until recent past. It was carried out using simplified assumptions and relatively less realistic approach.

Based on the lacunae in this study as is evident from the critical findings presented by Ingle and Chore (2007), Chore and co-authors (Chore and Ingle 2008, Chore *et al*. 2009, Chore and Sawant 2010, Chore *et al.* 2010, 2013) reported the methodology for the interaction analysis of a single storeyed building frame embedded in clayey soil on the rational approach and realistic assumptions. While most of the analyses were carried out using sub-structure approach, in some of the analysis the foundation (pile groups) was idealized as the completely three-dimensional model whereas in few, it was idealized using simplified finite element models. The building frame was, however, modeled as the complete 3-D model. Though, in most of these analyses, the linear elastic behavior of soil of soil was considered, a study (Chore *et al*. 2013) considered non-linear elastic behavior of soil wherein the non-linearity was incorporated p-y curve concept. Further, Chore and Sawant (2010) reported the analysis of the same frame using coupled approach and suggested that the sub-structure is more realistic. Chore (2013) reported the analysis of a single storeyed building frame supported on pile foundation, as done used in his earlier studies, using SAP-IV. Recently, Dode *et al.* (2014, 2015) reported the interaction analysis of the single storeyed building frame using more improved finite element model for the foundation, i.e., pile group and soil. Even numerous soil- structure interaction studies have been reported in the recent past that include those by Agrawal and Hora (2009, 2010), Thangaraj and Illampurthy (2010), Dalili *et al.* (2011), Rajshekhar Swamy *et al*. (2011), Thangaraj and Illampurthy (2012), Chore and Siddiqui (2015) and Varma *et al.* (2017). 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.* 2010b, Chore *et al.* 2012a, b) has become popular for analyzing the problem of pile foundations in the context of linear and non-linear analysis.

Based on the literature review, the present paper reports the interaction analysis of a three storeyed building frame resting upon the square pile group (2×2). The complete three-dimensional analysis incorporating non-linear behavior of soil is presented. The effect of embedment depth and



(a) Twenty node continuum element

(b) Twelve node continuum element

(c) Nine Node Continuum Element

(d) Eight Node Continuum Element

(e) Sixteen Node interface element

Fig. 1 Various elements used for modelling

spacing between the piles in a group is evaluated on the response of the typical building frame considered in the present study.

2. Mathematical modeling and analysis methodology

The interaction analysis of a three storeyed frame is carried out using three-dimensional finite element method. Initially; the frame is analyzed separately without considering the effect of foundation, i.e., considering the columns to be fixed at their bases. This analysis is referred to as the non-interactive analysis (NIA). Later, the pile foundations are worked out independently to get the equivalent stiffness of the foundation head. Further, they are used in the analysis of the frame to evaluate the effect of SSI on the response of the frame. The analysis carried out considering the effect of SSI is referred to as the interactive analysis (IA). The interactive analysis is carried out incorporating the linear and non-linear behavior of the soil media. The non-linearity of the soil is incorporated in the analysis using *von Mises* yield criterion. The study aims at bringing out the effect of the non-linearity of the soil media on the response of the super-structure.

A full three-dimensional geometric model of the sub-structure (pile foundation-soil system) is considered in the present study as against the half model for the sub-structure system considered in Chore and Ingle. The elements of the superstructure (beam, column and slab) and that of pile foundation (pile and pile cap) are discretized into 20 node iso-parametric continuum elements. On the other hand, soil elements are discretized using eight node, nine node and twelve node continuum elements. Further, three degrees of freedom at each node, i.e., displacement in three directions in X, Y and Z of these different elements, are considered in the present analysis. To ensure proper mechanics of stress transfer between soil and pile under lateral load, 16 noded iso-parametric surface elements is introduced at the interface of pile and soil. The normal and tangential stiffness of these elements are assumed in such a way that shearing at the soil and pile interface is allowed but separation of pile and soil node is not possible. All the elements used in the present analysis are shown in Fig. 1.

Since a 3-D geometric model is used to represent the soil-pile system, selection of the correct finite element to represent the medium is one of the very important aspects in finite element analysis. In the soil-pile system, two materials, viz. Soil and reinforced concrete are to be modelled. The either material show different behaviours when subjected to loading. The shear failure is predominant in soil whereas the bending failure is significant in reinforced concrete. Therefore, pile and pile cap along with the superstructure elements are modelled using twenty node continuum elements. This element has quadratic shape function which is well suited to model the medium with bending dominated deformation.

Eight node continuum elements are used to model the soil which has linear shape functions. These elements are suitable for the medium whose deformations are dominated by shear strength. To maintain the continuity of displacements between these two types of elements in the discretised soil-pile domain, two more elements were formulated, viz. Twelve node and nine node solid elements. The shape functions of these two elements were formulated by using degrading technique (Krishnamoorthy 2005). The shape functions are derived for these elements by degrading the twenty node solid elements. Twelve node elements are used at the junction where eight node and twenty node element meets. Further, nine node elements are used where twelve node element and twenty node element meets perpendicularly.

3. Problem description

A 3-D three storeyed building frame resting on pile foundation is considered for the study. The frame, 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. The slab at the top of the first, second and third storey is supported over 300 mm wide and 400 mm deep beams. The beams are resting on columns of size 300 mm×300 mm. The pile foundation comprises of the group of four piles (2×2). All the piles in each group are circular piles, connected by a 500 mm thick flexible pile cap. While dead

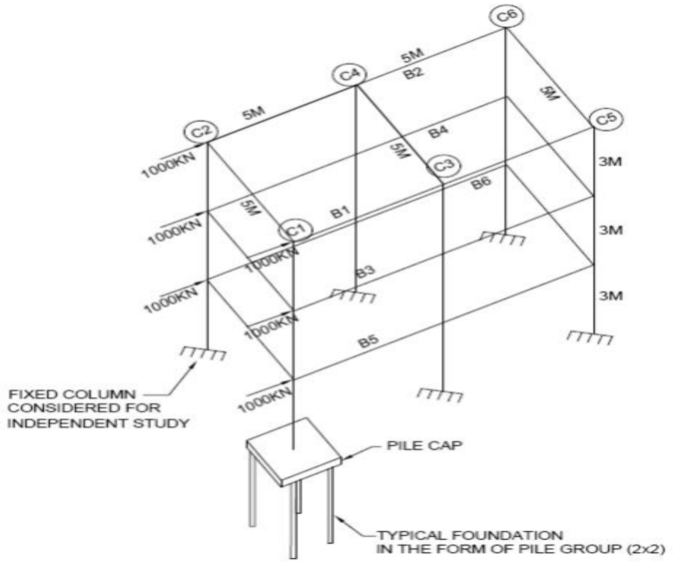


Fig. 2 Half geometrical model of building frame considered in the present study

Table 1 Pile and soil properties for parametric study

Soil properties	Corresponding Values
Modulus of Elasticity, E_s	20000 kPa
Poisson's ratio, μ_s	0.4
Density, γ_s	18 kN/m^3
Yield stress, σ_y	100 kPa
Pile properties	Corresponding Values
Modulus of Elasticity, E_p	25 GPa
Poisson's ratio, μ_p	0.2
Density, γ_p	25 kN/m^3
Pile cap thickness, t_p	0.5 m
Pile diameter, D	1.0 m
L/D ratio	10 and 20
s/D ratio	2, 3, 4, 5, 7
Interface element	Corresponding Values
Normal stiffness, k_n	1.0×10^6 kN/m^3
Tangential stiffness, k_s	1000 kN/m^3

load is considered according to the unit weight of the materials of which the structural components of frame are made up of, for the purpose of the parametric study presented here. The properties of the material for pile and pile cap are given in Table 1. Fig. 2 shows the half geometrical model of building frame with fixed column base and group of four piles.

The schematic of the group of four piles (2×2) considered in the present study is shown in Fig.

3. The discretized soil-pile domain for half 3-D geometrical model, which is used for the analysis of pile groups is also shown in Fig 3. The half geometrical model is used for the square configurations by taking advantage of the symmetry. Along the X and Y directions, the boundary is kept at 14*D* (*D* being the diameter of the pile) from the outermost pile of the pile group in each respective direction, as is apparent from Fig. 3. The position of the transmitting boundary is also shown by thick line, as is evident from the afore-mentioned figures. However, this boundary is meant to be used in the dynamic analysis and hence, is beyond the scope of the investigation reported herein. The details of the diameters of the pile and spacing between the piles in each group considered in the present study are 2*D*, 3*D*, 4*D*, 5*D* and 7*D*.

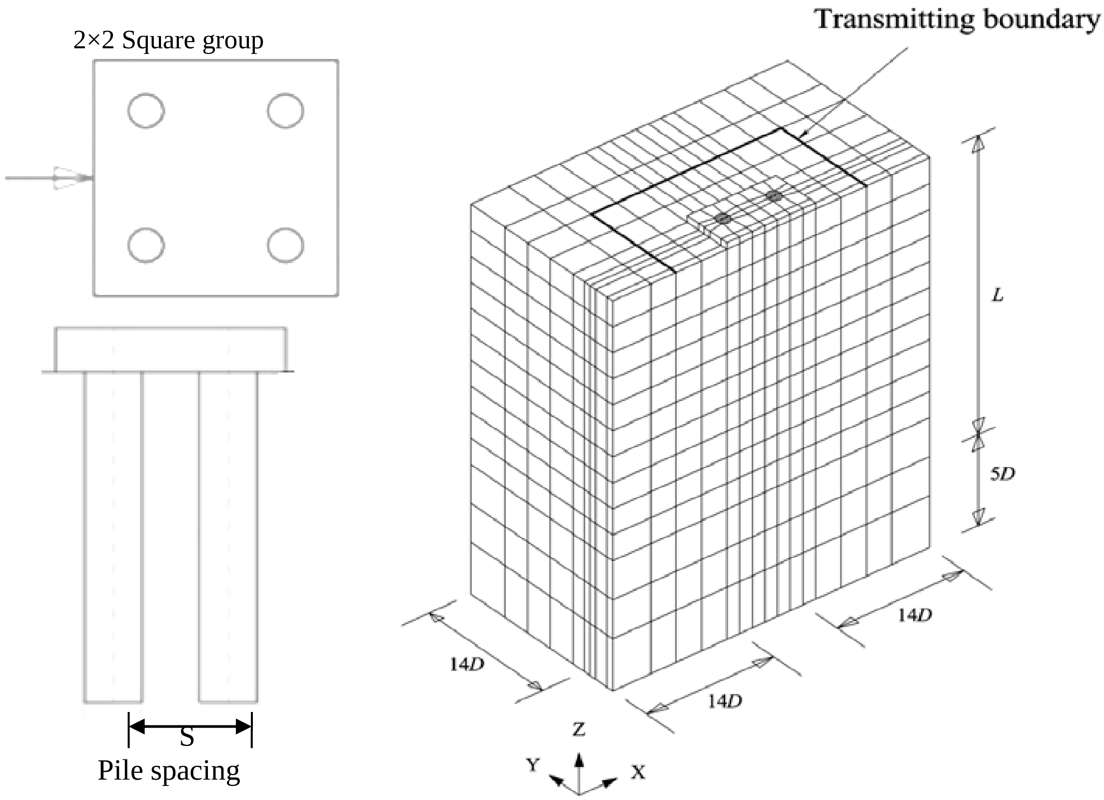


Fig. 3 Typical finite element mesh for a square group of four piles (2×2)

4. Results and discussion

For the interaction analysis, a software program Build-Frame is developed using FORTRAN 90. After assessing the accuracy of the program in the context of simple problems of structural engineering and soil-structure interaction and further, implementing it on the published work, the said program is used in the present study. 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 at the top of the frame corresponding to each storey, shear force in beams, bending moment in beams and columns along with the axial force in columns. The

Table 2 Effect of pile spacing on the storey displacement

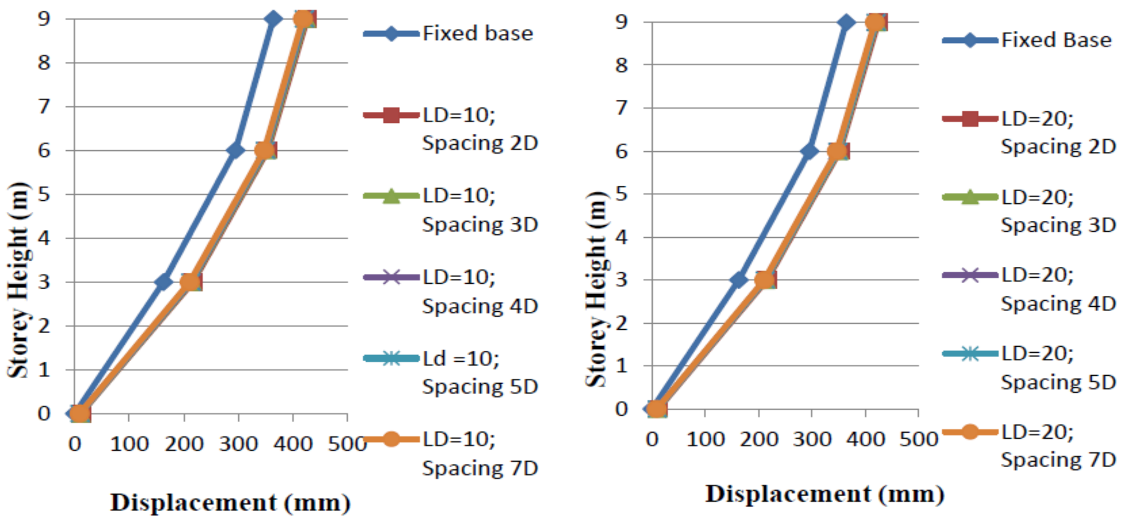
Pile spacing	Storey Height (m)	9.0	6.0	3.0	0.0
	Analysis	Displacement (mm)			
	Non-interactive	363.99	294.9	162.53	0.0
Embedment depth *L/D* = 10					
2*D*	Linear	17.1%	20.03%	33.31%	100%
	Nonlinear	6.75%	9.71%	8.00%	7.65%
3*D*	Linear	16.4%	19.27%	32.16%	100%
	Nonlinear	5.99%	8.19%	6.47%	10.81%
4*D*	Linear	15.89%	18.71%	31.27%	100%
	Nonlinear	5.82%	7.68%	3.89%	20.98%
5*D*	Linear	15.51%	18.29%	30.6%	100%
	Nonlinear	5.52%	6.67%	3.33%	9.20%
7*D*	Linear	14.94%	17.65%	29.58%	100%
	Nonlinear	5.44%	6.22%	2.95%	6.11%
Embedment depth *L/D* = 20					
2*D*	Linear	16.45%	19.39%	32.49%	100%
	Nonlinear	6.09%	9.06%	5.09%	9.08%
3*D*	Linear	15.65%	18.48%	31.0%	100%
	Nonlinear	5.63%	8.05%	4.83%	12.77%
4*D*	Linear	15.25%	18.03%	30.26%	100%
	Nonlinear	4.68%	7.63%	2.86%	12.94%
5*D*	Linear	15.32%	18.09%	30.31%	100%
	Nonlinear	4.61%	5.26%	2.42%	15.08%
7*D*	Linear	14.69%	17.39%	29.18%	100%
	Nonlinear	4.80%	4.56%	0.75%	5.76%

response is evaluated initially for two conditions- without considering the effect of SSI and another by considering it. Hence, two analyses are reported, non-interactive analysis (NIA) and the interactive analysis (IA). Further, the interactive analysis is extended to incorporate the non-linear behaviour of soil and the results obtained in the context of linear and non-linear behaviour of soil are compared.

4.1 Effect of pile spacing on the storey displacement

The values of the horizontal displacement obtained in respect of the non-interactive analysis at each storey level of the frame for two embedment depth ratios (*L*/*D*=10 and 20) considered in the study are shown in Table 2. The corresponding percentage increase in displacement due to consideration of SSI (linear-interactive w.r.t. non-interactive, i.e., fixed base, and further, non-linear-interactive w.r.t. linear-interactive) for different pile spacing considered in the present study is also indicated in the afore-mentioned table. Similarly, the variation in the storey displacement with storey height in respect of different pile spacing and embedment depth ratios considered in the present investigations is shown in Fig. 4. Further, the percentage variation in the displacement with storey height for different pile spacing and embedment depth ratio is also shown in Fig. 5.

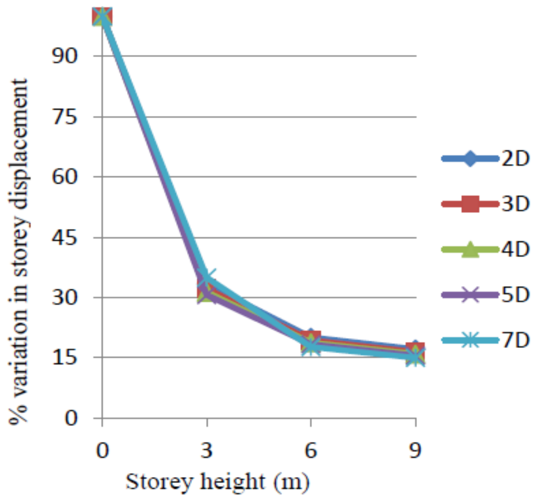
The general trend observed for all the pile spacing considered in this investigation is that horizontal displacement at each storey level increases due to the effect of soil structure interaction (SSI). It is seen that for *L/D*=10 the displacement at top of each storey is on higher side corresponding to different pile spacing considered in the present investigation when compared with the values of top displacement obtained for *L/D* = 20. The reduction in the displacement is attributed to the improved passive resistance of soil with higher embedment depth. Further, for any values of embedment depth, the displacement is found to decrease with increase in the spacing between the piles. The general trend observed for all the pile spacing considered in the investigation in respect of either embedment depth ratio is that horizontal displacement is more when the spacing between two piles is kept 2*D* and thereafter, decreases with higher spacing considered in present study. This 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 2*D*; and thereafter, it goes on decreasing.



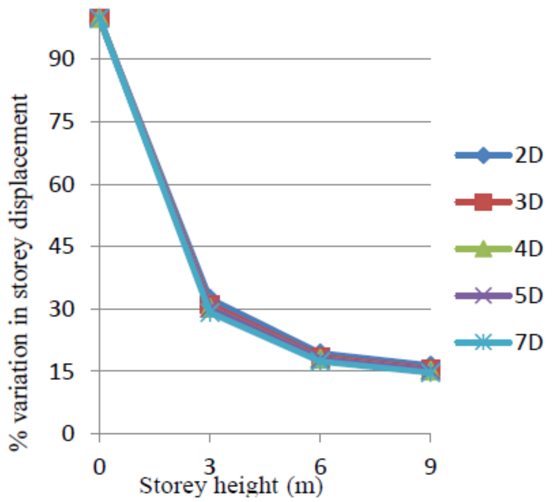
(a) Embedment depth *L/D* = 10 (b) Embedment depth *L/D* = 20

Fig. 4 Effect of pile spacing on storey displacement

Further, with increase in storey, the displacement at the top of each storey is found to increase. This holds good for either value of the embedment depths and for all values of pile spacing. The displacement is maximum at the top of the frame, i.e., third storey. The SSI is found to increase the percentage displacement in the range of 29.58-33.31, 17.65-20.3 and 14.9-17.1%, in respect of *L/D*=10. The corresponding increase in case of *L/D*=20 is in the range of 29.20-32.5, 17.4-19.40 and 14.70-16.45%, respectively. Further, it is seen that the increase in displacement due to consideration of SSI is prominent on the bottom storey for any pile spacing and with increase in the storey, the increase in displacement goes on decreasing.

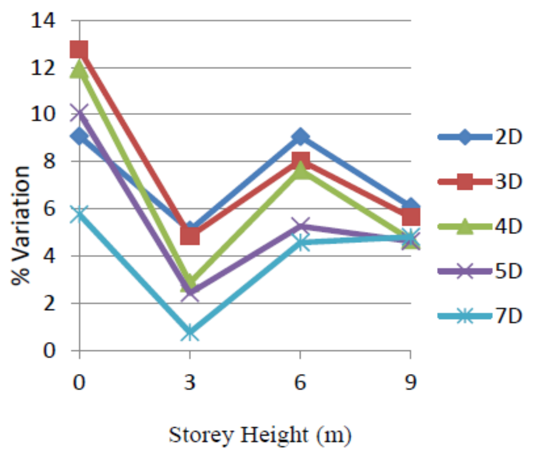


(a) Embedment depth *L/D* = 10

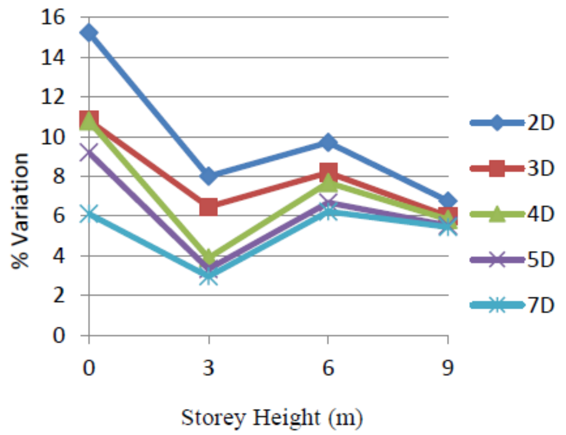


(b) Embedment depth *L/D* = 20

Fig. 5 Percentage variation in storey displacement for different pile spacing (linear)



(a) Embedment depth *L/D* = 10



(b) Embedment depth *L/D* = 20

Fig. 6 Effect of pile spacing on the displacement in terms of percentage variation (Non-linear)

4.1.1 Effect of non-linearity of soil on storey displacement

The analysis carried out in the context of linear behavior of soil is extended further to account for the non-linearity of the soil using *von Mises* yield criterion. The values of the displacement obtained at the each storey level with respect to non-linear behavior of soil are also indicated in Table 2 for two different values of embedment depth ratios.

The values of the displacements obtained in the present study are on a higher side in respect of non-linear soil-structure interaction in case of either embedment depths. For the embedment depth of 10, the percentage variation in displacement at top storey is observed to be in the range of 4.80-6.09, at second storey, 4.56-9.06 and at first storey, 0.75-5.09, respectively. Further, along similar lines, the displacement at top storey is observed to be 5.44-6.75%, at second storey the rage if observed to be 6.22-9.71% and 6.11-7.65% at first storey level for the higher embedment depth, i.e., 20. This clearly indicates that increase in embedment depth ratio of piles in a group enhances the stiffness of pile group and, therefore, decrease in displacement is observed.

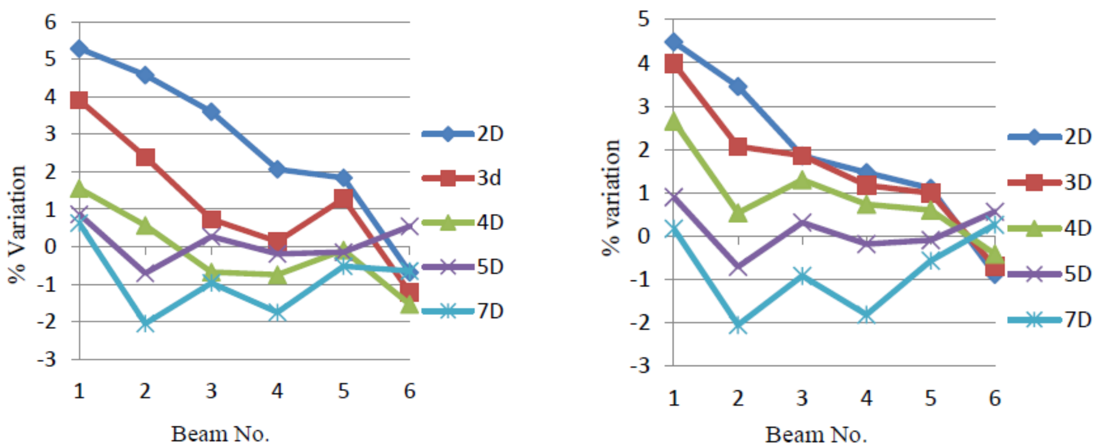
The trend of reduction in displacement with spacing although remains same, the reduction in displacement at higher spacing such as 3*D* onwards is too marginal in respect of both embedment ratio. The trend of percentage variation in the storey displacement is shown in Fig. 6.

It is seen from Table 2 that with the increase in *L/D* ratio, the displacement at each of the storey level of the frame is found to decrease. The embedment depth of a pile has a significant effect on the response of the frame. Passive resistance offered by the extended length of pile plays an important role on the interactive behavior of the pile-soil system. The decrease in the displacement at top of the frame with increase in embedment depth of piles is attributed to the improved zone of passive resistance.

4.2 Effect of pile spacing on bending moments in beams

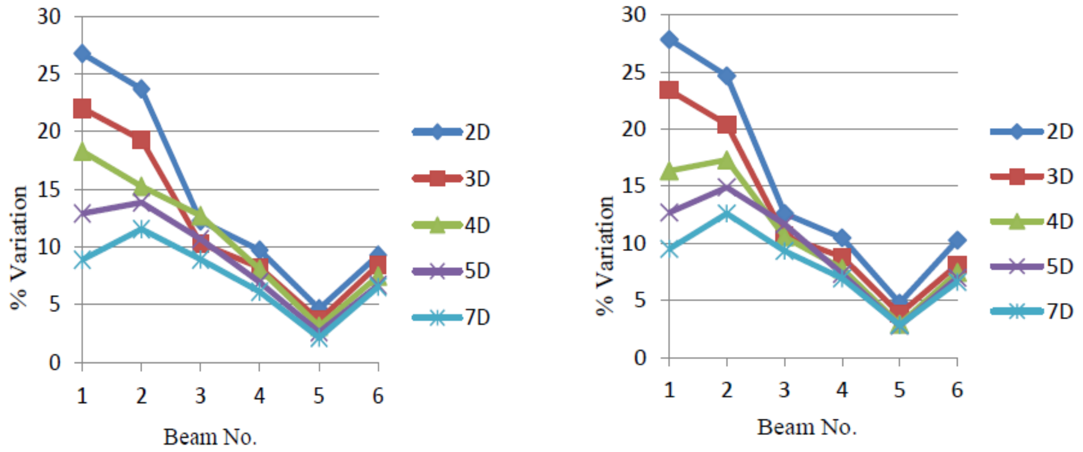
The values of maximum positive and negative bending moments obtained in view of non-interactive and interactive analysis (linear as well as non-linear) in respect of typical beams are reported in Tables 3 and 4. The corresponding increase or decrease in maximum positive and negative bending moments (B.M.) in the individual beams is also given in Tables 3 and 4. Fig. 7 shows trend of percentage variation in the positive bending moment for either embedment ratio. The trend of percentage variation in the negative bending moment in the beams for different pile spacing is shown in Fig. 8.

It is observed that the percentage increase in the moment in various beams is found to decrease with increase in spacing. The effect of SSI appears to be significant for the beams (B-1, B-3 and B-5) placed in the center as compared to that in beams (B-2, B-5 and B-6) placed on the external side. Further, the effect is more in beams placed in the first storey and gradually reduces with the storey. This is true in case of the beams placed in the center of the frame as well as on the external side. The afore-mentioned observations hold good for either embedment depth ratio considered in the present investigation.



(a) Embedment depth *L/D* = 10 (b) Embedment depth *L/D* = 20

Fig. 7 Percentage variation of positive bending moments in beams



(a) Embedment depth *L/D* = 10 (b) Embedment depth *L/D* = 20

Fig. 8 Percentage variation in negative bending moments in beams

Table 3 Effect of pile spacing on positive bending moments in beams

Pile spacing	Beam	B-1	B-2	B-3	B-4	B-5	B-6
	Analysis	Maximum positive bending moment (kN.m)					
	Non- interactive	199.68	290.11	529.24	676.23	861.78	1106.64
		Embedment depth *L/D* = 10					
2*D*	Linear	0.61%	-0.25%	2.01%	1.89%	5.44%	2.77%
	Nonlinear	5.29%	4.58%	3.60%	2.07%	1.84%	-0.68%
3*D*	Linear	0.50%	-0.22%	1.91%	1.19%	5.32%	2.73%
	Nonlinear	3.91%	2.39%	0.74%	0.15%	1.28%	-1.21%
4*D*	Linear	0.44%	-0.20%	1.84%	1.09%	5.24%	2.70%
	Nonlinear	1.56%	0.57%	-0.67%	-0.74%	-0.08%	-1.53%
5*D*	Linear	0.40 %	-0.18%	1.79%	0.89%	5.19%	2.68%
	Nonlinear	0.87%	-0.70%	0.28%	-0.18%	-0.13%	0.55%
7*D*	Linear	0.34%	-0.16%	1.72%	0.69%	5.10%	2.64%
	Nonlinear	0.63%	-2.04%	-0.96%	-1.74%	-0.51%	2.00%
		Embedment depth *L/D* = 20					
2*D*	Linear	0.45%	-0.20%	1.85%	1.98%	5.26%	2.70%
	Nonlinear	4.49%	3.45%	1.86%	1.47%	1.10%	-0.88%
3*D*	Linear	0.38%	-0.18%	1.77%	1.52%	5.16%	2.66%
	Nonlinear	3.99%	2.07%	1.86%	1.17%	0.99%	-0.71%
4*D*	Linear	0.34%	-0.16%	1.73%	0.89%	5.11%	2.64%
	Nonlinear	2.65%	0.54%	1.30%	0.73%	0.60%	-0.42%
5*D*	Linear	0.37%	-0.17%	1.76%	0.63%	5.15%	2.66%
	Nonlinear	0.90%	-0.71%	0.31%	-0.18%	-0.10%	0.57%
7*D*	Linear	0.30%	-0.14%	1.68%	0.29%	5.04%	2.61%
	Nonlinear	0.17%	-2.05%	-0.92%	-1.81%	-0.57%	2.03%

Table 4 Effect of pile spacing on negative bending moments in beams

Pile spacing	Beam	B-1	B-2	B-3	B-4	B-5	B-6
	Analysis	Maximum negative bending moment (kN.m)					
	Non-interactive	-145.66	-211.33	-491.26	-627.91	-818.83	-1048.26
Embedment depth *L/D* = 10							
2*D*	Linear	0.91%	-1.31%	-0.85%	-0.86%	4.70%	2.07%
	Nonlinear	27.84%	24.65%	12.61%	10.48%	4.78%	10.27%
3*D*	Linear	0.88%	-1.18%	-0.69%	-0.80%	4.64%	2.06%
	Nonlinear	23.39%	20.42%	10.64%	8.81%	3.83%	8.13%
4*D*	Linear	0.86%	-1.10%	-0.71%	-0.76%	4.59%	2.06%
	Nonlinear	16.34%	17.30%	10.54%	7.80%	2.92%	7.46%
5*D*	Linear	0.84%	-1.05%	-0.73%	-0.74%	4.56%	2.05%
	Nonlinear	12.68%	14.90%	11.68%	7.32%	2.79%	6.98%
7*D*	Linear	0.82%	-0.97%	-0.76%	-0.70%	4.50%	2.03%
	Nonlinear	9.50%	12.61%	9.32%	6.93%	2.84%	6.62%
Embedment depth *L/D* = 20							
2*D*	Linear	0.86%	-1.12%	-0.79%	-0.77%	4.60%	2.05%
	Nonlinear	26.75%	23.69%	12.26%	9.71%	4.65%	9.29%
3*D*	Linear	0.83%	-1.03%	-0.74%	-0.73%	4.54%	2.04%
	Nonlinear	22.02%	19.27%	10.30%	8.22%	3.66%	8.44%
4*D*	Linear	0.82%	-0.98%	-0.75%	-0.71%	4.50%	2.03%
	Nonlinear	14.88%	15.24%	12.72%	8.06%	3.12%	7.47%
5*D*	Linear	0.83%	-1.01%	-0.74%	-0.72%	4.53%	2.04%
	Nonlinear	10.17%	13.85%	10.68%	6.95%	2.62%	6.69%
7*D*	Linear	0.81%	-0.92%	-0.77%	-0.68%	4.46%	2.02%
	Nonlinear	8.90%	11.55%	8.93%	6.11%	2.13%	6.54%

The percentage increase in the maximum positive moment is observed to be 0.34-0.61% in the top beam B-1, placed in the center at top of the frame in case of embedment depth ratio of 10. In respect of beams B-3 and B-5, the corresponding increase is in the range of 1.72-2% and 5.1-5.44%. In respect of beam placed at the top on the external side (B-2), the moment is observed to decrease, the same being in the range of 0.16-0.25%. However, in case of beams B-4 and B-6, the increase in moment is observed to be in the range of 0.69-1.89% and 2.64-2.77%. For embedment depth ratio 20, the decrease in moment in beam B-2 is found to be in the range of 0.14-0.2% whereas the moment is found to increase in all other beams such as B-1, B-3, B-4, B-5 and B-6; the increase being in the range of 0.30-0.45%, 1.68-1.85%, 0.29-1.98%, 5-5.25% and 2.6-2.7%, respectively.

From Table 4, an increase is observed in the negative moment in respect of beams B-1, B-5 and B-6, range being 0.82-0.91%, 4.50-4.70% and 2-2.07%, respectively for embedment depth ratio 10. Further, when the variation of moment with pile spacing is considered in case of beam B-6, the effect seems to be marginal. However, in case of beams B-2, B-3, and B-4, the moment is found to decrease, the range being 0.97-1.3%, 0.76-0.85% and 0.7-0.86%, respectively, when the effect of

SSI is taken into consideration.

For higher embedment depth ratio (*L/D* = 20), the trend of increase and decrease in moment in various beams of the frame as seen in case of *L/D* = 10, remains same. In case of beams B-1, B-5 and B-6, the SSI is found to increase the moment in the range of 0.8-086, 4.46-4.6 and 2.02-2.05% respectively. Similarly, in case of beams B-2, B-3 and B-4, the decrease in moment is observed, it being in the range of 0.92-1.12, 0.77-0.79 and 0.68-0.77, respectively.

It is obvious from the values tabulated in Tables 3-4 that the effect of SSI is significant on moments in superstructure beams in the context of various pile spacing. The increase or decrease in moment seems to be on lesser side in respect of higher embedment depth. 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.

4.2.1 Effect of non-linearity of soil on bending moment in beams

From Table 3, the increase in positive moment in beam due to non-linearity goes on decreasing with increase in spacing in respect of beam B-1 in case of *L/D* ratio=10, the variation being in the range of 0.63-5.29%. The percentage variation in rest of the beams such as B-2, B-3, B-4, B-5 and B-6 is observed to be in the range of 0.70-4.58, 0.28-3.6, 0.15-2, 0.08-1.84 and 0.68-2, respectively. In respect of beams B-2, decrease in moment is observed at higher pile spacing such as 6*D* and 7*D*. In beam B-3 and B-4, the non-linear behaviour of soil is found to decrease the moment at the pile spacing of 4*D* and 7*D*. Similarly, the bending moment in beams B-4 and B-5 are found to be decreased at the higher pile spacing of 4*D*, 5*D* and 7*D*, respectively due to non-linearity of soil. In case of beam B-6, the moment is found to be decreased for the spacing of 2*D*, 3*D* and 4*D* whereas for next higher pile spacing (5*D* and 7*D*), the moment is found to be on higher side.

For higher embedment depth ratio (*L/D*=20), the increase moment in beam B-1(placed at top in the center) is found to decrease with increase in pile spacing, the increase being in the range of 0.17-4.5%. Similar trend is observed in remaining beams B-3 and B-5, placed at the second and first storey, respectively; except at the higher pile spacing such as 7*D* in case of beam B-3 and 5*D* and 7*D* in case of beams B-5, respectively. The increase in moment in beams B-3 and B-5 is observed to be in the range of 0.3-1.85 and 0.6-1.10%. The decrease in moment at higher pile spacing in these two beams, as mentioned earlier, is 0.92% and 0.1-0.6%.

As regards the moments in beam B-2, placed on the external side, the increase in moment is found to decrease with increase in spacing up to 4*D* due to non-linearity of the soil and at higher pile spacing (5*D* and 7*D*), decrease in moment is observed. The increase is found to be in the range of 0.5-3.45% while, decrease, 0.7-2.05%. Similar trend is seen pertaining to increase or decrease in moment due to non-linearity of soil with respect to spacing in case of beam B-4, the variation being 0.73-1.47% and 0.18-1.8%. In case of beam B-6, placed at the first storey on the external side of the frame, the trend opposite to that seen in case of beams, B-2 and B-4, placed at the top and second storey of the external side, is observed. The non-linearity of soil is found to decrease the moment at the spacing of 2*D*, 3*D* and 4*D* and thereafter, increase for subsequent higher pile spacing. The decrease in moment is observed in the range of 0.42-0.88% and increase, 0.57-2%.

It is seen that the effect of non-linearity is more in the beam at top placed in the center of the frame and goes on decreasing with decrease in the storey level. This is true in case of the beams placed in the centre of the frame as well as that on the external side of the frame. Further, with increase in embedment depth (*L/D* ratio), the increase or decrease in moment due to non-linear behaviour of soil reduces.

Table 5 Effect of pile spacing on positive bending moments in column

Pile spacing	Column	C-1	C-2	C-3	C-4	C-5	C-6
	Analysis	Maximum positive bending moment (kN.m)					
	Non- interactive	1017.65	1017.65	1017.65	1017.65	1017.65	1017.65
Embedment depth *L/D* = 10							
2*D*	Linear	-9.59%	-29.73%	7.95%	-10.78%	-12.54%	-31.64%
	Nonlinear	-1.10%	-3.00%	2.44%	1.04%	-2.37%	-3.07%
3*D*	Linear	-9.13%	-29.0%	7.54%	-10.87%	-11.99%	-30.86%
	Nonlinear	-1.74%	-2.94%	2.98%	1.61%	-0.03%	-1.54%
4*D*	Linear	-8.80%	-28.47%	7.24%	-10.94%	-11.59%	-30.29%
	Nonlinear	-1.68%	-1.20%	3.49%	2.04%	0.75%	-0.65%
5*D*	Linear	-8.55%	-28.06%	7.01%	-10.99%	-11.30%	-29.86%
	Nonlinear	-0.97%	-0.03%	3.92%	3.34%	2.83%	0.67%
7*D*	Linear	-8.14%	-27.39%	6.64%	-11.06%	-10.82%	-29.15%
	Nonlinear	-0.67%	-0.44%	5.25%	4.72%	3.87%	1.37%
Embedment depth *L/D* = 20							
2*D*	Linear	-9.62%	-29.76%	8.02%	-10.75%	-12.57%	-31.68%
	Nonlinear	-1.10%	-3.00%	2.44%	1.04%	-2.37%	-3.07%
3*D*	Linear	-9.16%	-29.04%	7.61%	-10.84%	-12.02%	-30.90%
	Nonlinear	-1.74%	-2.94%	2.98%	1.61%	-0.03%	-1.54%
4*D*	Linear	-8.82%	-28.50%	7.30%	-10.92%	-11.62%	-30.33%
	Nonlinear	-1.68%	-1.20%	3.49%	2.04%	0.75%	-0.65%
5*D*	Linear	-8.57%	-28.09%	7.07%	-10.97%	-11.32%	-29.90%
	Nonlinear	-0.97%	-0.03%	3.92%	3.34%	2.83%	0.67%
7*D*	Linear	-8.16%	-27.42%	6.69%	-10.05%	-10.84%	-29.18%
	Nonlinear	-0.67%	-0.44%	5.25%	4.72%	3.87%	1.37%

When the effect of non-linear behavior of soil is examined in the context of the embedment depth of 10 and for various pile spacing (Table 4), an increase in negative moment is observed in respect of all the beams (B-1, B-3 and B-5) placed in the center of the frame and this increase goes on decreasing with increase in pile spacing. The percentage variation of moment is observed to be in the range of 9.50-27.84, 9.3-12.6 and 2.8-4.8, respectively. Similarly, in case of beams (B-2, B-4 and B-6) placed on the external side of the frame, similar trend of increase in negative moment as seen in case of the beams placed in the centre, is observed. The percentage variation in these beams (B-2, B-4 and B-6) is observed to be 12.6-24.65, 6.9-10.5 and 6.6-10.3, respectively.

Further, in case of higher embedment depth (*L/D*=20), the non-linearity of the soil is found to increase the negative moment in all the beams, placed in the center as well as on the external side of the frame, the increase being in the range of 2.13-26.75%. Further, the increase is more at the lower pile spacing and goes on decreasing with increase in pile spacing. It is also seen that the increase in moment is more for the beams placed on the top (either in the center or on the external side of the frame) and goes on reducing at the second and first storey. Moreover, an increase in moment is more for the beams placed in the center as compared to that on the external side irrespective of the storey. The increase in embedment depth is found to decrease the increase in the negative moment.

The percentage increase in the support and mid span moment is observed in the top beam B-1 placed on central side is found to be 0.30% and 0.61%, respectively for the pile spacing of 7*D* and 2*D*. For beam B-2, the decrease in moment is observed to be 0.16% and 0.35% corresponding to *L/D*=10. Similarly, for *L/D*=20, the corresponding increase in moments at support in the B-1 placed on central side is found to be 0.30% and 0.45%, respectively, for the pile spacing of 7*D* and 2*D*.

4.2 Effect of pile spacing on bending moments in columns

The maximum values of positive and negative moments those obtained and either embedment depths (10 and 20) in the individual columns with respect to the non-interactive analysis (NIA) are presented in Tables 5 and 6. The corresponding increase or decrease in maximum moments in the individual columns as observed in the interactive analysis w.r.t. linear behaviour and further, interactive analysis incorporating non-linear behavior soil w.r.t. the linear interactive analysis, for two different embedment ratios is also given in the afore-mentioned tables. It is obvious from the results tabulated in Tables 5 and 6 that, the effect of SSI on moments in the superstructure columns of the frame is significant when the values of moments are compared with those calculated on the premise of fixed base approach (non-interactive analysis).

It is observed that the effect is less in respect of the columns (C-1, C-3 and C-5) placed in the center of the frame whereas it is more in respect of the columns (C-2, C-4 and C-6) placed on the external side of the frame. This is true in case of both the embedment depths considered in the present investigation. Further, the effect of SSI is to decrease the positive B.M. in all the columns of the frame except in case of column C-3 where the moment is observed to be increased with consideration of the effect of SSI in respect of either embedment depth.

The decrease in B.M. in the columns C-1, C-2, C-4, C-5 and C-6 is found to decrease with increase in spacing. Further, the increase in moment in case of column C-3 is also found to decrease with increase in spacing. This observation appears to be valid for the both the values of embedment depths with certain exception in respect of column C-4 for embedment depth of 20 where the decrease in moment is found to increase with spacing up to 5*D* and thereafter, at the last higher pile spacing, there is decrease in the moment. Further, when the values of decrease in moment in various columns (C-1, C-2, C-4, C-5 and C-6) in respect of both the embedment depths considered in the present investigation are compared, there is no significant difference observed; still the values observed for higher embedment depth is negligibly higher.

For both the embedment depth ratios, the percentage variation in positive B.M. is found to be in the range of range of 8.14-9.62, 27.39-29.76, 6.64-8.02, 10.05-10.78, 10.82-12.57 and 29.15-31.68, respectively in respect of all the six columns (C-1 to C-6).

As regards the negative B.M. (Table 6), the effect of SSI on negative moments in the superstructure columns of the frame is seen to be significant. It is observed that the effect of SSI is more in respect of the columns (C-1, C-3 and C-5) placed in the center of the frame whereas it is less in respect of the columns (C-2, C-4 and C-6) placed on the external side of the frame. This is true in case of both the embedment depths considered in the present investigation. Similarly, when the effect of SSI is considered in the columns placed in the leading row (columns placed in the left hand side of the frame), intermediate row (columns placed in the central row) and that in the trailing row (columns placed on the right hand side), the effect is more in case of the columns

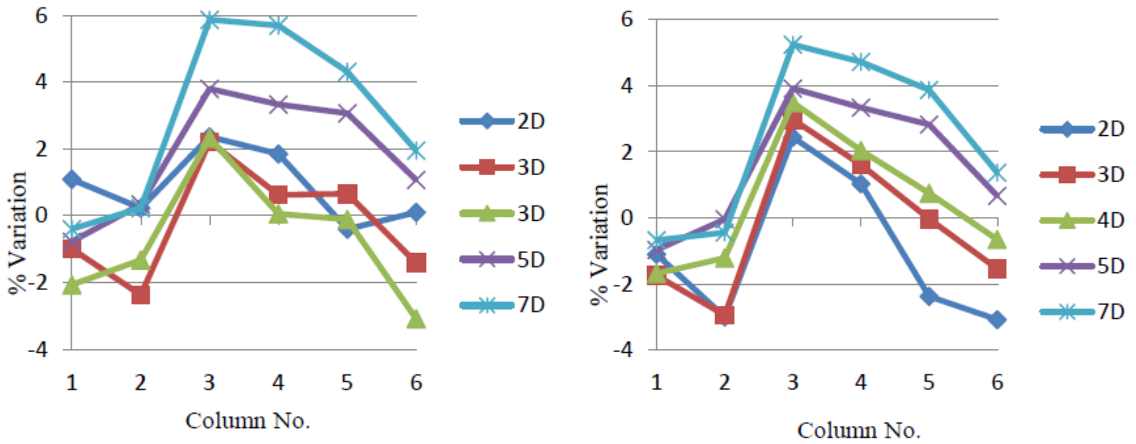
Table 6 Effect of pile spacing on negative bending moments in column

Pile spacing	Column	C-1	C-2	C-3	C-4	C-5	C-6
	Analysis	Maximum negative bending moment (kN.m)					
	Non-interactive	-769.29	-655.83	-1086.37	-989.50	-782.40	-674.37
Embedment depth $L/D = 10$							
2*D*	Linear	25.23%	20.66%	23.63%	18.17%	21.76%	18.11%
	Nonlinear	-2.65%	4.84%	4.23%	-3.47%	4.86%	3.80%
3*D*	Linear	24.77%	20.27%	23.08%	17.74%	21.37%	17.77%
	Nonlinear	-1.80%	3.95%	4.14%	-3.28%	5.16%	4.83%
4*D*	Linear	24.44%	19.98%	22.68%	17.41%	21.08%	17.52%
	Nonlinear	-1.01%	3.92%	1.29%	-3.61%	5.08%	6.28%
5*D*	Linear	24.19%	19.76%	22.37%	17.17%	20.86%	17.32%
	Nonlinear	-0.57%	2.98%	0.67%	-2.80%	5.39%	0.77%
7*D*	Linear	23.78%	19.40%	21.87%	16.76%	20.50%	17.00%
	Nonlinear	-0.08%	2.31%	-0.58%	-2.68%	6.01%	1.23%
Embedment depth $L/D = 20$							
2*D*	Linear	24.52%	20.05%	22.81%	17.52%	21.15%	17.58%
	Nonlinear	-2.09%	5.14%	4.51%	-3.43%	5.23%	3.70%
3*D*	Linear	24.09%	19.68%	22.29%	17.09%	20.77%	17.24%
	Nonlinear	-1.54%	4.15%	4.06%	-1.58%	4.62%	2.77%
4*D*	Linear	23.84%	19.45%	21.97%	16.84%	20.55%	17.04%
	Nonlinear	-0.95%	3.89%	1.61%	-2.88%	5.76%	1.64%
5*D*	Linear	24.01%	19.60%	22.16%	17.00%	20.70%	17.18%
	Nonlinear	-0.43%	2.99%	0.55%	-3.01%	5.62%	1.14%
7*D*	Linear	23.52%	19.17%	21.57%	16.52	20.27%	16.79%
	Nonlinear	0.34%	2.85%	-0.46%	-2.61%	6.00%	0.64%

placed in the leading row, followed by that in the central row and subsequently, trailing row. Further, the effect of SSI is to increase the negative bending moment in all the columns of the frame in respect of either embedment depth.

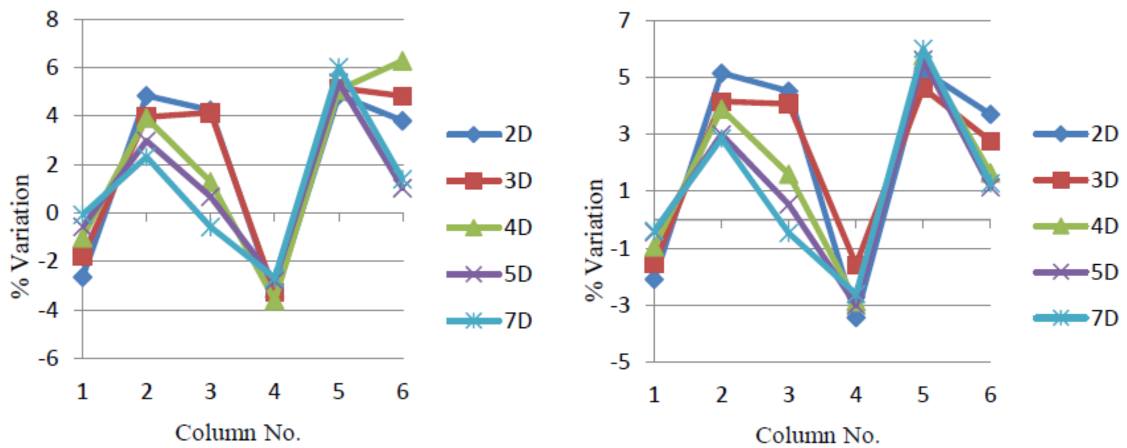
For the embedment depth ratio of 10, the increase in bending moment in all the columns of the frame due to SSI is found to reduce with increase in spacing. In respect of higher embedment depth ratio, the increase in bending moment due to consideration of the effect of SSI is found to reduce up to the pile spacing of 4*D*. Thereafter, it increases at the spacing of 5*D* and then, again decreases at next higher pile spacing of 7*D*. Further, when the values of increase in moment in various columns of the frame in respect of two embedment depths considered in the present investigation are compared, there is marginal difference observed with those observed for smaller embedment depth (L/D=10) being negligibly higher.

The percentage variation in the moments in columns C-1, C-2, C-3, C-4, C-5 and C-6 is found to be in the range of 23.52-25.23, 19.17-20.66, 21.57-23.63, 16.52-18.17, 20.27-21.76 and 16.79-18.11, respectively considering the variation obtained for both the embedment depths.



(a) Embedment depth *L/D* = 10 (b) Embedment depth *L/D* = 20

Fig. 9 Percentage variation positive bending moments in column



(a) Embedment depth *L/D* = 10 (b) Embedment depth *L/D* = 20

Fig. 10 Percentage variation negative bending moments in column

Figs. 9 and 10 show the percentage variation of positive and negative bending moment in the columns for different pile spacing and further, two different embedment depth ratios considered in the present investigation.

4.2.1 Effect of non-linearity of soil on bending moment in individual columns

The percentage increase or decrease in positive and negative moments in columns following the incorporation of non-linear behaviour of soil w.r.t. linear analysis is already indicated in Tables 5 and 6.

In respect of smaller embedment depth, the non-linearity of soil is found to decrease the positive B.M. in column C-1 for all the pile spacing considered in the present investigation, the variation being 0.67-1.1%. In column C-2, the moment is found to decrease up to the pile spacing of 4*D* and thereafter, increase. The percentage variation in moment due to non-linearity of soil in

Table 7 Effect of pile spacing on positive shear force in beams

Pile spacing	Beam	B-1	B-2	B-3	B-4	B-5	B-6
	Analysis	Maximum positive shear force (kN)					
	Non-interactive	245.53	419.51	328.80	574.77	467.25	814.66
Embedment depth *L/D* = 10							
2*D*	Linear	4.30%	1.57%	2.61%	0.64%	13.37%	9.35%
	Nonlinear	4.57%	-1.78%	1.48%	-1.49%	2.08%	0.45%
3*D*	Linear	4.25%	1.63%	2.59%	0.69%	13.17%	9.11%
	Nonlinear	3.99%	-2.08%	1.38%	-1.86%	1.94%	0.49%
4*D*	Linear	4.22%	1.67%	2.58%	0.73%	13.02%	8.93%
	Nonlinear	3.36%	-2.23%	1.42%	-2.06%	2.03%	0.60%
5*D*	Linear	4.20%	1.69%	2.58%	0.75%	12.91%	8.80%
	Nonlinear	2.56%	-2.63%	0.98%	-2.14%	1.93%	0.63%
7*D*	Linear	4.17%	1.73%	2.57%	0.78%	12.73%	8.57%
	Nonlinear	2.16%	-2.75%	0.82%	-2.31%	1.78%	1.16%
Embedment depth *L/D* = 20							
2*D*	Linear	4.23%	1.66%	2.58%	0.72%	13.05%	9.00%
	Nonlinear	3.82%	-1.77%	1.20%	-1.83%	2.13%	0.32%
3*D*	Linear	4.19%	1.71%	2.57%	0.75%	12.87%	8.77%
	Nonlinear	2.47%	-2.67%	1.76%	-2.05%	2.07%	0.42%
4*D*	Linear	4.17%	1.73%	2.56%	0.77%	12.76%	8.62%
	Nonlinear	1.64%	-3.61%	2.64%	-1.62%	2.02%	0.37%
5*D*	Linear	4.19%	1.71%	2.57%	0.76%	12.83%	8.71%
	Nonlinear	0.89%	-4.07%	3.56%	-1.37%	1.76%	0.38%
7*D*	Linear	4.15%	1.75%	2.56%	0.80%	12.62%	8.44%
	Nonlinear	0.22%	-4.60%	4.14%	-1.03%	1.77%	0.49%

column is in the range C-2, 0.03-3. In respect of column C-3 and C-4, the non-linearity of soil is found to increase the bending moment, the percentage variation being 2.44-5.25 and 1-4.72, respectively. In column C-5, at the closer spacing of 2*D*, the moment is found to be decreased by 2.4% and thereafter, increased for all the remaining spacing, the variation being in the range of 0.03-3.9%. In case of column C-6, the non-linearity of soil is found to decrease the bending moment up to the pile spacing of 3*D*; the variation is in the range of 1.5-3%. For all other higher pile spacing, the bending moment is found to increase due to non-linear SSI, the percentage variation being in the range of 0.65-1.37.

In respect of higher embedment depth, the non-linearity of soil is found to decrease the positive B.M. in column C-1 for all the pile spacing considered in the present investigation; the variation is in the range of 0.67-1.1%. In column C-2, the moment is found to decrease up to the pile spacing of 3*D* and thereafter, increase. The percentage variation in moment due to non-linearity of soil in column is in the range C-2, 0.03-3. In respect of column C-3 and C-4, the non-linearity of soil is found to increase the bending moment, the percentage variation being 2.44-5.25 and 1-4.72, respectively. In column C-5, at the closer spacing of 2*D*, the moment is found to be decreased by

2.37% and thereafter, increased for all the remaining spacing, the variation being in the range of 0.03-3.9%. In case of column C-6, the non-linearity of soil is found to decrease the bending moment at the closer pile spacing of 2*D* by 3%. For all other higher pile spacing, the bending moment is found to increase due to non-linear SSI, the percentage variation being in the range of 0.65-1.54.

As regards the effect of non-linearity of soil on negative bending moments in the columns, it is observed that the non-linearity decreases the moment in column C-1, placed in the centre in the leading row (i.e., on left hand side), the percentage variation being in the range of 0.08-2.65. Further, the variation goes on decreasing with increase in spacing. The effect of the interaction in the columns placed on left hand side (leading row C-1 and C-2) appears less and effect of SSI in columns placed in the intermediate row and right hand side (trailing row C-5 and C-6) the effect seems to be more. Further, the trend of variation in moments with pile spacing is studied for all configurations of the pile groups considered in this investigation.

It is observed that non-linear behavior of soil does not have appreciable effect on B.M. in columns of the frames for both the embedment depths considered in the present investigation. Moreover, when the difference in the percentage increase or decrease in moment is considered with respect to pile spacing and further, compared for both the embedment depths, it is found that the trend on increase or decrease in moment remains by and large same.

4.3 Effect of pile spacing on shear force in beams

The maximum values of positive and negative shear force obtained for various spacing in the individual beams with respect to the non-interactive analysis (NIA) and subsequent increase or decrease in the shear force due to linear and non-linear SSI for two embedment depths (10 and 20) considered in the present study are reported in Tables 7 and 8. The effect of SSI on corresponding percentage increase or decrease in maximum shear force as observed in individual beams of the frame is discussed in the subsequent paragraphs.

In case of smaller embedment depth, the maximum positive shear force in beams (B-1, B-3 and B-5) placed in the central row is found to increase in the range of 4.17-4.30%, 2.57-2.61% and 12.73-13.37%, respectively (Table 7). However, the increase is too small in respect of beams B-1 and B-3 as compared to that in B-5. As regards the increase in the maximum shear force in case of beams (B-2, B-4 and B-6) placed on the external side, it is found to be in the range of 1.57-1.73%, 0.64-0.78% and 8.57-9.35%, respectively. It is observed, further, that the increase in shear force in beams placed in the central row as well as that on the external side decreases with increases in pile spacing. The increase in shear force in beams placed on the first storey is comparatively higher as compared to that placed in the second and third storey, respectively.

Similarly, in respect of the embedment ratio 20, the increase in beams B-1, B-3 and B-5 is found to be in the range of 4.15-4.23%, 2.56-2.58% and 12.62-13.05%, respectively (Table 13). Corresponding increase in case of beams B-2, B-4 and B-6 is found to be in the range of 1.66-1.75%, 0.72-0.80% and 8.44-9.0%, respectively. The trend of increase in shear force in various beams placed at different storeys either in the central row or that on the external side, almost remains same as that in case of the embedment depth ratio of 20, barring few exceptions. In case of beams B-1, B-2, B-5 and B-6, the increase in the shear force decreases up to the pile spacing of 4D and thereafter increases at 5D; and thereafter, again decreases at next higher pile spacing considered in the study. However, the difference in the increase at any spacing is too small to be neglected.

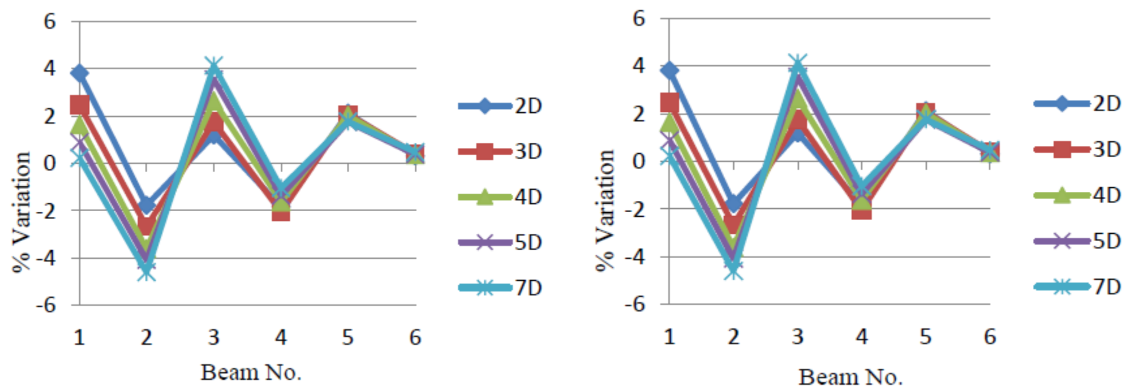
Table 8 Effect of pile spacing on negative shear force in beams

Pile spacing	Beam	B-1	B-2	B-3	B-4	B-5	B-6
	Analysis	Maximum negative shear force (kN)					
	Non-interactive	-248.49	-428.47	-330.32	-579.90	-463.88	-820.94
Embedment depth *L/D* = 10							
2*D*	Linear	-2.73%	-2.19%	-1.52%	-0.67%	11.06%	8.23%
	Nonlinear	3.31%	-1.67%	3.07%	-0.87%	0.58%	1.28%
3*D*	Linear	-2.83%	-2.16%	-1.56%	-0.63%	10.68%	7.99%
	Nonlinear	2.80%	-1.86%	2.47%	-0.69%	0.87%	0.34%
4*D*	Linear	-2.89%	-2.15%	-1.58%	-0.61%	10.40%	7.80%
	Nonlinear	2.66%	-1.95%	2.01%	-0.40%	0.95%	0.40%
5*D*	Linear	-2.94%	-2.14%	-1.60%	-0.60%	10.19%	7.66%
	Nonlinear	2.33%	-2.20%	1.56%	-0.24%	0.79%	0.53%
7*D*	Linear	-3.01%	-2.13%	-1.62%	-0.57%	9.84%	7.43%
	Nonlinear	1.82%	-1.75%	1.25%	-0.10%	1.09%	0.75%
Embedment depth *L/D* = 20							
2*D*	Linear	-2.88%	-2.15%	-1.58%	-0.62%	10.50%	7.87%
	Nonlinear	3.36%	-1.74%	3.05%	-0.92%	1.08%	0.34%
3*D*	Linear	-2.96%	-2.13%	-1.61%	-0.59%	10.14%	7.63%
	Nonlinear	3.08%	-1.17%	3.91%	-0.95%	2.00%	0.49%
4*D*	Linear	-3.00%	-2.13%	-1.63%	-0.58%	9.93%	7.48%
	Nonlinear	2.22%	-0.69%	4.29%	-0.96%	2.53%	0.60%
5*D*	Linear	-2.97%	-2.13%	-1.61%	-0.59%	10.05%	7.56%
	Nonlinear	1.87%	-0.32%	4.50%	-0.96%	2.80%	0.34%
7*D*	Linear	-3.04%	-2.12%	-1.64%	-0.56%	9.65%	7.29%
	Nonlinear	1.14%	-0.19%	4.95%	-0.98%	3.34%	0.53%

When the values of maximum positive shear force as obtained in different beams for the embedment depth ratios of 10 and 20 are compared, the increase in shear in all the beams is on higher side in respect of *L/D* ratio of 10.

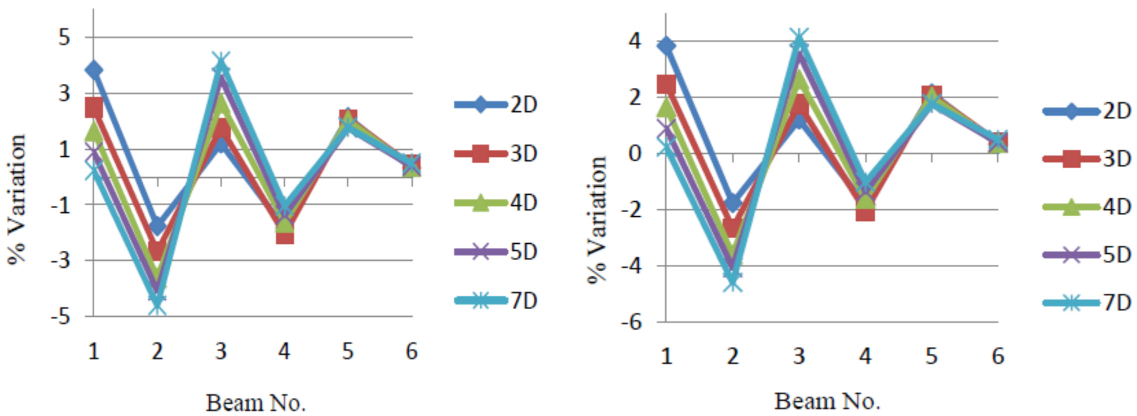
The maximum negative shear force (Table 8) in the beams B-1 and B-3, placed in the central row, is observed to decrease in the range of 2.73-3.01% and 1.52-1.62% whereas in case of beam B-5, the maximum shear force is found to increase in the range of 9.81-11.06% due to SSI in respect of embedment ratio of 10. The corresponding decrease in beams B-2 and B-4 is in the range of 2.13-2.19% and 0.57-0.67% while, increase in B-6, 7.43-8.23%. Further, the decrease in shear force in all the beams (B-1 to B-6) due to SSI is found to increase with the pile spacing. However, the increase in maximum shear force in case of beams placed at the level of ground storey is found to decrease with pile spacing. The increase effect of SSI is found to be significant in case of the shear force in beams placed at the level of first storey.

In respect of embedment ratio of 20, the decrease in the maximum values of the negative shear force in case of beams B-1 and B-3 is found to be in the range of 2.88-3.04% and 1.58-1.64% whereas in case of beam B-5, the shear force is found to increase in the range of 9.65-10.5%,



(a) Embedment depth *L/D* = 10 (b) Embedment depth *L/D* = 20

Fig. 11 Percentage variation positive shear force in beams for *L/D* = 10 and 20



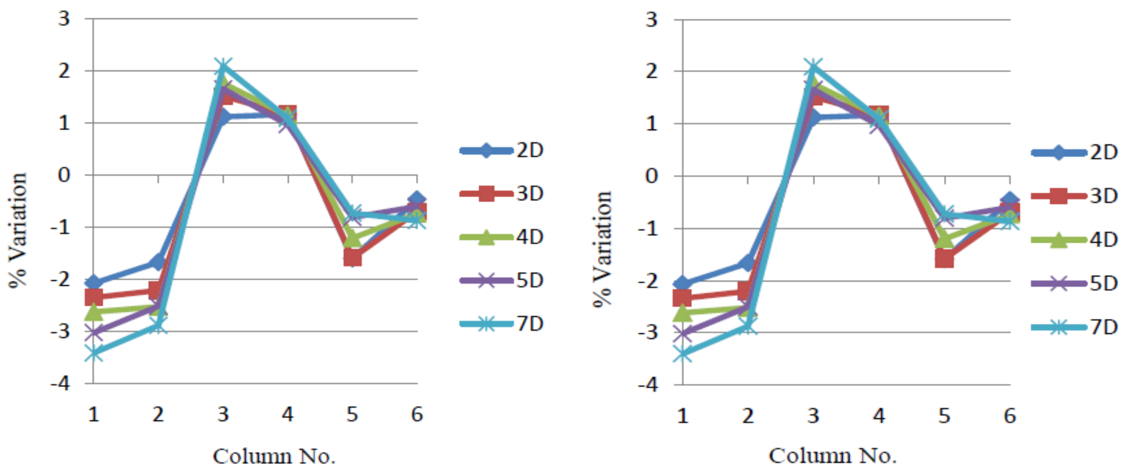
(a) Embedment depth *L/D* = 10 (b) Embedment depth *L/D* = 20

Fig. 12 Percentage variation negative shear force in beams

respectively (Table 8). Similarly, in case of beams B-2 and B-4, the shear force is found to decrease in the range of 2.12-2.15% and 0.56-0.62% whereas increase in the range of 7.29-7.87% in case of beam B-6.

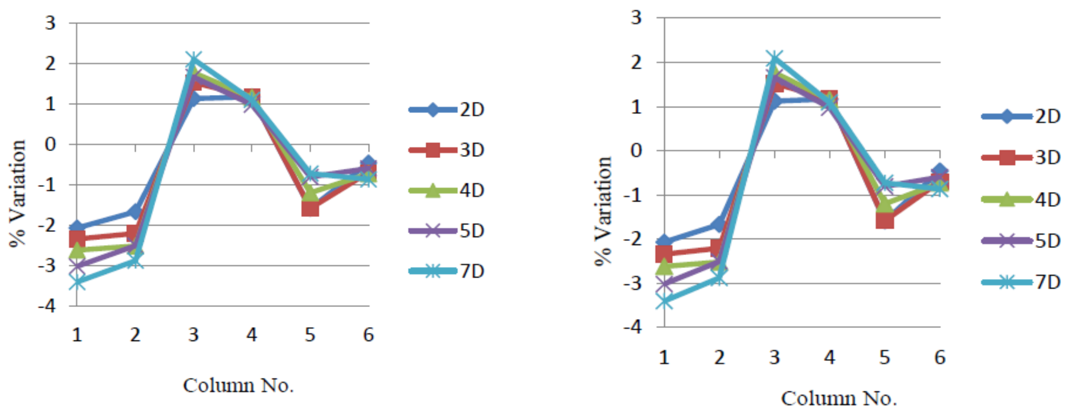
Further, in case of beams B-1 and B-3, the decrease in the shear force is found to increase up to the pile spacing of 4*D*, decrease at 5*D* and again increase at 7*D*. However, in case of beam B-5, the increase in the shear force is found to decrease up to 4*D* pile spacing, increase at 5*D* and again decrease at higher pile spacing. Similarly, in case of beams B-2 and B-5, the decrease in the shear force is found to decrease up to the pile spacing of 4*D*, increase at 5*D* and again decrease. In case of beam B-6, the increase in the shear force owing to the consideration of SSI is found to decrease up to 4*D* and thereafter, increase at pile spacing of 7*D* and again decrease at next higher pile spacing considered in the present investigation.

When the values of maximum negative shear force as obtained in different beams for the embedment depth ratios of 10 and 20 are compared, the decrease in shear in the beams placed at the level of second and top storey is on higher side in case of *L/D* ratio of 20 whereas, an increase



(a) Embedment depth *L/D* = 10 (b) Embedment depth *L/D* = 20

Fig. 13 Percentage variation maximum axial force in columns



(a) Embedment depth *L/D* = 10 (b) Embedment depth *L/D* = 20

Fig. 14 Percentage variation minimum axial force in columns

in shear in beams placed the level of first storey is on higher side in respect of embedment depth of 10. The percentage variation in maximum positive and negative shear in different beams due to non-linearity of soil in respect of either embedment depth ratio considered in the present study is shown in Figs. 11 and 12.

4.3.1 Effect of non-linearity of soil on shear force in beams

The increase or decrease in positive and negative shear force due to non-linear behaviour of soil w.r.t. the linear interactive analysis is indicated in Tables 7 and 8. The variation in the positive shear, due to non-linearity of the soil, in beams B-1, B-3 and B-6 is observed to be in the range of 2.16-4.57%, 0.82-1.48% and 1.78-2.08%, respectively, in respect of embedment depth ratio 10. The corresponding variation in beams B-2, B-4 and B-6 is in the range of 1.78-2.75%, 0.82-1.48% and 0.45-2.16%.

Table 9 Effect of pile spacing on maximum axial force in columns

Pile spacing	Column	C-1	C-2	C-3	C-4	C-5	C-6
	Analysis	Maximum axial force (kN)					
	Non-interactive	483.46	874.91	616.05	1150.90	487.89	487.89
Embedment depth *L/D* = 10							
2*D*	Linear	(5.74%)	(-8.98%)	(15.90%)	(3.15%)	(2.66%)	(62.00%)
	Nonlinear	(-2.15%)	(-1.30%)	(0.83%)	(1.01%)	(-1.60%)	(-0.89%)
3*D*	Linear	(5.80%)	(-8.71%)	(15.42%)	(2.89%)	(2.79%)	(62.56%)
	Nonlinear	(-1.97%)	(-1.64%)	(1.09%)	(1.20%)	(-2.04%)	(-1.34%)
4*D*	Linear	(5.84%)	(-8.51%)	(15.06%)	(2.70%)	(2.89%)	(62.98%)
	Nonlinear	(-1.83%)	(-1.99%)	(1.25%)	(1.28%)	(-2.33%)	(-1.73%)
5*D*	Linear	(5.87%)	(-8.36%)	(14.79%)	(2.55%)	(2.95%)	(63.29%)
	Nonlinear	(-1.64%)	(-2.34%)	(1.38%)	(1.60%)	(-2.45%)	(-1.96%)
7*D*	Linear	(5.92%)	(-8.11%)	(14.34%)	(2.32%)	(3.06%)	(63.81%)
	Nonlinear	(-1.59%)	(-2.70%)	(1.66%)	(1.83%)	(-2.58%)	(-2.28%)
Embedment depth *L/D* = 20							
2*D*	Linear	(5.82%)	(-8.62%)	(15.24%)	(2.80%)	(2.84%)	(62.76%)
	Nonlinear	(-2.07%)	(-1.67%)	(1.12%)	(1.17%)	(-1.59%)	(-0.46%)
3*D*	Linear	(5.8%)	(-8.36%)	(14.78%)	(2.55%)	(2.96%)	(63.30%)
	Nonlinear	(-2.34%)	(-2.21%)	(1.52%)	(1.17%)	(-1.59%)	(-0.70%)
4*D*	Linear	(5.90%)	(-8.20%)	(14.50%)	(2.40%)	(3.03%)	(63.63%)
	Nonlinear	(-2.62%)	(-2.52%)	(1.76%)	(1.15%)	(-1.20%)	(-0.73%)
5*D*	Linear	(5.89%)	(-8.27%)	(14.62%)	(2.46%)	(3.00%)	(63.49%)
	Nonlinear	(-3.02%)	(-2.51%)	(1.66%)	(0.97%)	(-0.81%)	(-0.60%)
7*D*	Linear	(5.94%)	(-7.98%)	(14.11%)	(2.19%)	(3.12%)	(64.07%)
	Nonlinear	(-3.41%)	(-2.88%)	(2.09%)	(1.09%)	(-0.73%)	(-0.87%)

The increase in shear force due to non-linearity of soil is found to reduce with pile spacing in case of beams B-1 and B-3 whereas in case of beam B-6, the opposite trend is observed. Here, the increase in shear force due to non-linearity increases with pile spacing. The decrease in the shear in beams B-2 and B-4 due to non-linearity of soil increases with pile spacing. On the contrary, the increase in shear in beam B-5 reduces with pile spacing up to 3*D*, increases at 4*D* and again reduces for next higher spacing.

For embedment depth ratio 20, the variation in the positive shear, due to non-linearity of the soil, in beams B-1, B-3 and B-6 is observed to be in the range of 0.22-3.82%, 1.2-4.14% and 0.32 - 0.49%, respectively. The corresponding variation in beams B-2, B-4 and B-6 is in the range of 1.77-4.60%, 1.03-1.83% and 1.77-2.13%. The trend of increase or decrease in shear force with pile spacing remains same as that observed in case of embedment depth ratio of 10.

As regards the maximum negative shear force, the variation in beams B-1, B-3 and B-5 due to non-linear soil-structure interaction is observed to be 1.82-3.11%, 1.25-3.07% and 0.58-1.09%, respectively. Similarly, the variation in B-2, B-4 and B-6 is observed to be in the range of 1.67-1.75%, 0.10-0.87% and 0.75-1.28%, respectively, in respect of the embedment depth of 10. The

Table 10 Effect of pile spacing on minimum axial force in columns

Pile spacing	Column	C-1	C-2	C-3	C-4	C-5	C-6
	Analysis	Minimum axial force (kN)					
	Non-interactive	150.73	233.52	246.87	435.70	163.50	269.68
Embedment depth *L/D* = 10							
2*D*	Linear	(5.91%)	(2.49%)	(0.79%)	(-0.25%)	(-3.29%)	(-3.78%)
	Nonlinear	(1.88%)	(-3.34%)	(3.62%)	(-2.07%)	(4.43%)	(-1.54%)
3*D*	Linear	(5.73%)	(2.51%)	(0.71%)	(-0.21%)	(-3.34%)	(-3.66%)
	Nonlinear	(1.43%)	(-2.95%)	(2.57%)	(-2.47%)	(3.40%)	(-1.63%)
4*D*	Linear	(5.62%)	(2.53%)	(0.66%)	(-0.19%)	(-3.37%)	(-3.58%)
	Nonlinear	(1.16%)	(-2.72%)	(2.54%)	(-2.65%)	(3.56%)	(-1.36%)
5*D*	Linear	(5.54%)	(2.55%)	(0.62%)	(-0.18%)	(-3.39%)	(-3.52%)
	Nonlinear	(0.98%)	(-2.56%)	(2.30%)	(-2.85%)	(2.63%)	(-1.11%)
7*D*	Linear	(5.43%)	(2.57%)	(0.57%)	(-0.16%)	(-3.42%)	(-3.44%)
	Nonlinear	(0.71%)	(-1.83%)	(2.23%)	(-3.05%)	(2.09%)	(-0.74%)
Embedment depth *L/D* = 20							
2*D*	Linear	(5.64%)	(2.53%)	(0.67%)	(-0.1%)	(-3.37%)	(-3.60%)
	Nonlinear	(2.10%)	(-3.50%)	(3.60%)	(-2.17%)	(4.31%)	(-1.76%)
3*D*	Linear	(5.51%)	(2.55%)	(0.61%)	(-0.17%)	(-3.40%)	(-3.50%)
	Nonlinear	(2.69%)	(-4.06%)	(3.25%)	(-2.43%)	(3.94%)	(-2.14%)
4*D*	Linear	(5.44%)	(2.56%)	(0.58%)	(-0.16%)	(-3.42%)	(-3.45%)
	Nonlinear	(4.17%)	(-4.12%)	(2.98%)	(-2.81%)	(3.66%)	(-2.80%)
5*D*	Linear	(5.49%)	(2.55%)	(0.60%)	(-0.17%)	(-3.41%)	(-3.49%)
	Nonlinear	(4.24%)	(-4.47%)	(2.35%)	(-3.04%)	(2.76%)	(-2.92%)
7*D*	Linear	(5.36%)	(2.58%)	(0.54%)	(-0.15%)	(-3.44%)	(-3.40%)
	Nonlinear	(4.98%)	(-5.14%)	(1.82%)	(-3.18%)	(2.01%)	(-2.98%)

corresponding variation in case of embedment depth of 20 is observed in the range of 1.14-3.36%, 3.05-4.95% and 1.08-3.34 (beams B-1, B-3 and B-5) and 0.19-1.74%, 0.92-0.98% and 0.34-0.53% (B-2, B-4 and B-6), respectively. The trend of increase or decrease in maximum negative shear force with pile spacing remains same as that seen in case of maximum positive shear force. This holds good for either embedment depth.

4.4 Effect of pile spacing on axial force in columns

The values of the maximum and minimum axial force those obtained for various spacing and either embedment depth (10 and 20) in the individual columns with respect to the non-interactive analysis (NIA) are indicated in Tables 9-10. The increase or decrease in axial forces due to interactive analysis in the context of both-the linear as well as non-linear behaviour of soil is also reported in the afore-mentioned tables. The percentage variation in maximum and minimum axial force in columns for *L/D* = 10 and 20 is shown in Figs. 13 and 14.

In case of embedment depth ratio of 10, the percentage increase in the maximum axial force in all the columns except C-2 is found to be in the range of 5.74-5.92, 14.34-15.90, 2.32-3.15, 2.66-3.06 and 62-63.81, respectively. However, in column C-2, the maximum axial force is found to decrease in the range of 8.11-8.98%. The increase in axial force in all the columns of the frame, except C-2, is found to increase with pile spacing. In case of C-2, the decrease in the axial force is found to reduce with pile spacing.

Along similar lines as that seen in the preceding case of embedment depth, the percentage increase in maximum axial force in all the columns of the frame except C-2 is observed to be in the range of 5.82-5.94, 14.11-15.24, 2.19-2.80, 2.84-3.12 and 62.76-64.07 in respect of higher embedment depth, i.e., 20. However, in case of column C-2, the maximum axial force is found to decrease in the range of 7.98-8.62%. As regards the increase or decrease in axial forces with pile spacing in various columns due to interactive analysis, the trend observed in case of lower embedment depth, i.e., L/D =10, holds good here in case of higher embedment depth.

When the results of maximum axial force in all the columns of the frame are compared vis-à-vis an embedment depth ratio, it is observed that the decrease in the axial force in column C-2 and increase that in C-3 is on lesser side in case of higher embedment depth ratio. The increase in axial force in all other columns is on higher side in respect of higher embedment depth ratio.

In respect of the embedment depth ratio of 10, the percentage increase in the minimum axial force in the columns C-1, C-2 and C-3 is found to vary in the range of 5.43-5.91, 2.49-2.57 and 0.57-0.79, respectively. However, in case of columns C-4, C-5 and C-6, the minimum axial force is observed to decrease in the range of 0.16-0.25, 3.29-3.42 and 3.44-3.78%, respectively. The increase in minimum axial force is found reduce with pile spacing in column C-1 and C-3. In case of column C-2, the increase in minimum axial force is found to reduce with pile spacing. Further, the decrease in minimum axial force is found to reduce in column C-4 and C-6 with pile spacing and in case of column C-5 decrease in minimum axial force is found to increase with pile spacing.

Along similar lines as that seen in the preceding case of embedment depth ratio, in respect of embedment depth of 20, an increase in minimum axial force in the columns C-1 to C-3 is observed in the range of 5.43-5.91, 2.49-2.57 and 0.57-0.79%, respectively and the percentage decrease in is observed in the columns C-4 to C-6 in the range of 0.16-0.25, 3.29-3.42 and 3.44-3.78, respectively. Further, the increase in force in case of columns C-1 and C-3 is found reduce with pile spacing. In case of column C-2, the increase is found to reduce with pile spacing. Further, the decrease in minimum force in column C-4 and C-6 is found to reduce with pile spacing and in column C-5, the decrease in force is found to increase with pile spacing.

4.3.1 Effect of non-linearity of soil on axial force in individual columns

The increase or decrease in the maximum and minimum axial forces in columns due to non-linearity of soil with respect to linear SSI analysis is indicated in Tables 9-10.

In respect of embedment depth ratio of 10, the percentage decrease in maximum axial force is found to be in the range of 1.59-2.15, 1.3-2.7, 1.6-2.58 and 0.89-2.28 in columns C-1, C-2, C-5 and C-6, respectively whereas in columns C-3 and C-4, the maximum axial force is found to increase in the range of 0.83-1.66 and 1.01-1.83%, respectively. Similar trend of increase or decrease in corresponding columns are observed in respect of the embedment depth ratio of 20, the percentage decrease in axial force being in the range of 2.07-3.41, 1.67-2.88, 0.73-1.59 and 0.46-0.87, respectively whereas percentage increase, 1.12-2.09 and 1.09-1.17, respectively.

The decrease in maximum axial force in column C-1 is found to reduce with pile spacing whereas the decrease in maximum axial force in C-2, C-5 and C-6 is found to increase with pile spacing in respect of embedment depth of 10. In case of column C-3 and C-4, the increase in the axial force is found to increase with pile spacing. For higher embedment depth of 20, the decrease in maximum force in columns C-1, C-2, C-5 and C-6 is found to reduce with pile spacing. In columns C-3 and C-4, increase in the axial force is found to increase with pile spacing.

As regards the minimum axial force, the non-linearity is found to be increased in columns C-1, C-3 and C-5 in respect of embedment depth of 10, the percentage increase being in the range of 0.71-1.88, 2.23-3.62 and 2.09-4.43, respectively. In columns C-2, C-4 and C-6, the decrease in the minimum axial force is observed in the range of 1.83-3.34, 2.07-3.05 and 0.74-1.54, respectively. The similar trend of increase or decrease in the minimum values of axial force in different columns is observed in respect of higher embedment depth ratio (L/D= 20), the percentage increase being in the range of 2.1-4.98, 1.82-3.60 and 2-4.3, respectively; and decrease being in the range of 3.5-5.14, 2.17-3.18 and 1.76-2.98, respectively

For embedment depth of 10, an increase in the minimum axial force is observed to increase with pile spacing in case of column C-1 and C-3 whereas in columns C-4 and C-6, the decrease in minimum axial force is found to reduce with pile spacing. In column C-2, the decrease in the minimum force is observed to increase with pile spacing. In column C-5, the increase in axial force is observed to reduce with pile spacing. Similar trend of increase or decrease in the values of minimum axial force in different columns of the frame with pile spacing is seen in respect of higher embedment depth.

5. Conclusions

Some of the broad conclusions emerging from the interaction analysis reported in the present investigations are given below.

• The effect of soil-structure interaction (SSI) is significant on the storey displacement. The linear SSI is found to increase the displacement in the range of 14.9-39.6%. The non-linearity of soil is found to increase the displacement in the range of 4.8-9% with respect to that obtained in the context of linear SSI.

• The displacement at each storey level decreases with pile spacing. The increase in displacement due to consideration of SSI is more on the bottom storey and with increase in storey, the displacement goes on decreasing.

• The passive resistance offered by the extended length of pile plays an important role on the interactive behaviour. The displacement at each storey level decreases with increase in embedment depth.

• The percentage variation in maximum positive and negative B.M. in beams is observed to be in the range of 0.18-2.5 and 9.5-27.84 due to consideration of linear SSI. Further, the non-linear SSI is found to vary the corresponding moments in the range of 0.17-5.19% and 2.13-26.75%, respectively. The effect of SSI is more on negative bending moment in beams in respect of both, linear and non-linear SSI as compared to that on positive moment.

• The effect is more in beams placed in the first storey and gradually reduces with the storey. The increase in moment is on higher side in respect of beams placed in the center as compared to that placed on the external side irrespective of the storey.

• The increase or decrease in moments in beams is on lesser side in respect of higher embedment depth ratio. With increase in embedment depth, the increase or decrease in moment due to non-linearity of soil reduces.

• The maximum positive and negative bending B.M. in columns is found to vary in the range of

8.14-29.76% and 16.52-25.23%, respectively due to linear SSI and further, the corresponding variation is in the range of 0.65-4.72% and 0.08-2.65%, respectively due to non-linear SSI.

• The effect of interaction in columns placed in leading row appears less as compared to that in columns placed in the intermediate and trailing row.

• As regards the effect of embedment depth on moment in columns, there is marginal difference in respect of linear SSI; although the variation is negligibly higher in case of smaller embedment depth. The non-linearity of soil does not seem to have an appreciable effect on B.M. in columns in respect of either embedment depth ratio.

• The maximum positive and negative shear force in beams is found to vary in the range of 0.64-13.37% and 0.57-10.50%, respectively due to linear SSI and 0.22-4.69% and 0.1-4.95%, respectively due to non-linear SSI.

•The increase in positive shear force in beams placed corresponding to first storey is comparatively higher than that in beams placed in the upper storey for smaller embedment depth whereas the decrease in maximum negative shear in beams placed at the level of second and top storeys is more in case of higher embedment depth, i.e., L/D=20.

• The trend of increase or decrease in maximum positive and negative shear force in beams with pile spacing in respect of non-linear soil structure interaction remains same in case of either embedment depth considered in the present investigation.

• The linear SSI varies the maximum and minimum axial force in columns in the range of 2.2-64% and 0.57-5.9%, respectively. The non-linearity of soil is found to vary the corresponding values in the range of 0.46-3.41% and 0.71-5.14%, respectively. The effect of non-linearity of soil does not have considerable effect on the axial force in columns.

• The increase in the axial force in columns C-6 (i.e., in the trailing row and external side) due to linear SSI is considerably on higher side in respect of all the pile spacing considered in the present study as compared to that in all other columns.

• Though the trend of variation in moments in beams and columns, shear force in beams and axial force in columns with pile spacing is stable in most of the cases, in few cases the trend is found to change at the pile spacing of 4D and 5D.

References

Agrawal, R. and Hora, M.S. (2009), “Coupled finite-infinite elements modeling of building frame-soil interaction system”, *ARPN J. Eng. Appl. Sci.*, **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 J. Eng. Appl. Sci.*, **5**(7), 75-87.

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

Basarkar, S.S. and Dewaikar, D.M. (2005), “Development of load transfer model for socketted tubular piles”, *Proceedings of the International Geotechnical Conference on Soil-Structure Interaction-Calculation Methods and Engineering Practice*, St. Petersburg, Russia.

Buragohain, D.N., Raghavan, N. and Chandrasekaran, V.S. (1977), “Interaction of frames with pile foundation”, *Proceedings of the International Symposium on Soil-Structure Interaction*, Roorkee, India.

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

Chameski, C. (1956), “Structural rigidity in calculating settlements”, *J. Soil Mech. Foundat. Eng.*, **82**(1), 1-9.

Chore, H.S. and Ingle, R.K. (2008), “Interaction analysis of building frame supported on pile group”, *Ind.*

Geotech. *J*., **38**(4), 483-501.
Chore, H.S. and Ingle, R.K. (2008), “Interactive analysis of building frame supported on pile group using a simplified F.E. model”, *J. Struct*. *Eng*., **34**(6), 460-464.
Chore, H.S., Ingle, R.K. and Sawant, V.A. (2009), “Building frame-pile foundation-soil interactive analysis”, *Interact*. *Multisc*. *Mech*., **l2**(4), 397-412.
Chore, H.S., Ingle, R.K. and Sawant, V.A. (2010), “Building frame-pile foundation-soil interaction analysis: A parametric study, *Interact*. *Multisc*. *Mech*., **3**(1), 55-80.
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. (2012), “Non-linear analysis of pile groups subjected to lateral loads using *p-y* curves”, *Interact*. *Multi-Scale Mech*., **5**(1), 57-73.
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.
Coyle, H.M. and Reese, L.C. (1966), “Load transfer for axially loaded pile in clay”, *Proc*. *ASCE*, **92**(2), 26-36.
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*. *Multisc*. *Mech*., **4**(1), 17-34.
Dasgupta, S., Dutta. S.C. and Bhattacharya, G. (1998), “Effect of soil-structure interaction on building frames on isolated footings”, *J. Struct*. *Eng*., **26**(2), 129-134.
Desai, C.S. and Abel, J.F. (1974), *Introduction to Finite Element Method*, CBS Publishers, New Delhi, India.
Desai, C.S. and Appel, G.C. (1976), “3-D analysis of laterally loaded structures”, *Proceedings of the 2nd International Conference on Numerical Methods in Geomechanics*, Blacksburg, U.S.A.
Desai, C.S., Kuppusamy, T. and Allameddine, A.R. (1981), “Pile cap-pile group-soil interaction”, *J. Struct*. *Eng*., **107**(5), 817-834.
Deshmukh, A.M. and Karmarkar, S.R. (1991), “Interaction of plane frames with soil”, *Proceedings of the Indian Geotechnical Conference*, 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”, *Ind*. *Geotech*. *J*., **36**(2).
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), 305-318.
Dode, P.A., Chore, H.S. and Agrawal, D.K. (2015), “Space frame-pile foundation-soil interaction analysis”, *J. Struct*. *Eng*., **42**(3), 246-255.
Georgiadis, M., Anagnostopoulos, C. and Saflekou, S. (1992), “Cyclic lateral loading of piles in soft clay”, *J. Geotech*. *Eng*., **23**(1), 47-60.
Hazarika, P.J. and Ramasamy, G. “Response of piles under vertical loading”, *Ind*. *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 International Conference on Finite Element Methods*, Australia.
Krishnamoorthy, A., Rao, N.B.S. and Rao, N. (2005), “Analysis of group of piles subjected to lateral loads”, *Ind*. *Geotech*. *J*., **35**(2), 154-175.
Lee, I.K. and Brown, P.T. (1972), “Structures and foundation interaction analysis”, *J. Struct*. *Eng*., **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*., **18**(2), 92-107.
Matlock, H. (1970), “Correlations for design of laterally loaded piles in soft clay”, *Proceedings of the 2nd Conference on Offshore Technology*, Houston, U.S.A.
Matlock, H. and Reese, L.C. (1956), “Foundation analysis of offshore pile supported structures”, *Proceedings of the 5th International Conference on Soil Mech. and Foundation Engineering*, Paris, France.

Morris, D. (1966), "Interaction of continuous frames and soil media", *J. Struct. Eng.*, **92**(5), 13-44.
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.*, **127**(6), 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. "Analysis of settlement of pile", *Geotech.*, **18**(4), 449-471.
Poulos, H.G. (1971), "Behaviour of laterally loaded piles: II-group of piles", *J. Soil Mech. Foundat. Eng.*, **97**(5), 733-751.
Rajsekar Swamy, 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. Multisc. Mech.*, **4**(1), 65-83.
Sawant, V.A. and Chore, H.S. (2009), "Building frame-pile foundation-soil interactive analysis using 3-D FEM", *J. Struct. Eng.*, **36**(6), 318-325.
Spiller, W.R. and Stoll, R.D. (1964), "Lateral response of piles", *J. Soil Mech. Foundat. Eng.*, **90**(6), 1-10.
Sriniwasraghavan, R. and Sankaran, K.S. (1983), "Settlement analysis for combined effect of superstructure-footings-soil system", *J. Inst. Eng.*, **6**, 194-198.
Subbarao, K.S., ShradaBai, H. and Raghunatham, B.V. (1985), "Interaction analysis of frames with beam footing", *Proceedings of the Indian Geotechnical Conference*, Roorkee, India.
Thangaraj, D.D. and Illampurthy, K. (2010), "Parametric study on the performance of raft foundation with interaction of frame", *Electr. J. Geotech. Eng.*, **15**, 861-878.
Thangaraj, D.D. and Illampurthy, K. (2012), "Numerical analysis of soil-mat foundation of space frame system", *Interact. Multisc. Mech.*, **5**(3), 267-285.
Verma, M., Sawant, V.A. and Chandaluri, V.K. (2017), "Effect of soil-structure interaction on response of G+3 building", *J. Struct. Eng.*, **44**(4), 307-318.
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.

CC