Structural Engineering and Mechanics, *Vol. 49, No. 1 (2014) 95-110*
DOI: http://dx.doi.org/10.12989/sem.2014.49.1.095

Non linear soil structure interaction of space frame-pile foundation-soil system

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

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

(Received July 21, 2013, Revised November 8, 2013, Accepted December 9, 2013)

Abstract. The study deals with physical modeling of space frame- pile foundation and soil system using finite element models. The superstructure frame is analyzed using complete three -dimensional finite element method where the component of the frame such as slab, beam and columns are descretized using 20 node isoparametric continuum elements. Initially, the frame is analyzed assuming the fixed column bases. Later the pile foundation is worked out separately wherein the simplified models of finite elements such as beam and plate element are used for pile and pile cap, respectively. The non-linear behaviour of soil mass is incorporated by idealizing the soil as non-linear springs using *p*-*y* curve along the lines similar to that by Georgiadis *et al*. (1992). For analysis of pile foundation, the non-linearity of soil via *p*-*y* curve approach is incorporated using the incremental approach. The interaction analysis is conducted for the parametric study. The non-linearity of soil is further incorporated using iterative approach, i.e., secant modulus approach, in the interaction analysis. The effect the various parameters of the pile foundation such as spacing in a group and configuration of the pile group is evaluated on the response of superstructure owing to non-linearity of the soil. The response included the displacement at the top of the frame and bending moment in columns. The non-linearity of soil increases the top displacement in the range of 7.8 %- 16.7%. However, its effect is found very marginal on the absolute maximum moment in columns. The hogging moment decreases by 0.005% while sagging moment increases by 0.02%.

Keywords: soil-structure interaction; non-linearity of soil; *p*-*y* curve; configuration of pile groups; 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.

*Corresponding author, Professor, E-mail: hschore@rediffmail.com
[a]Professor, E-mail: rkingle@rediffmail.com
[b]Associate Professor, E-mail: sawntfce@iitr.ernet.in

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

Interactive analysis is, therefore, necessary for the accurate assessment of the response of the superstructure. Numerous interactive analyses (Chameski 1956, Morris 1966, Lee and Harrison 1970, 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). 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), Reddy *et al*. (2011), Rajshekhar Swamy *et al*. (2011), Thangaraj and Illampurthy (2012). 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 a study by Buragohain *et al.* (1977) is found to deal with the interaction analysis of frames on piles.

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

2. Problem definition

Ingle and Chore (2007) reviewed the soil-structure interaction (SSI) analyses of framed structures and the soil-structure interaction problems related to pile foundations and underscored the necessity of such analysis for building frames resting on pile foundations by more rational approach and realistic assumptions. It was suggested that flexible pile caps along with their stiffness should be considered and the stiffness matrix for the sub-structure should be derived by considering the effect of all the piles in a group. Pursuant to this, Chore and Ingle (2008) presented a methodology for the comprehensive 3-D finite element analysis of the building frame supported on pile group (Fig. 1) embedded in soft marine clay. Chore and Ingle (2008) reported limited study on the interaction analysis of the system using simplified finite element models for substructure.

Further, Chore *et al.* (2010) reported the comprehensive interaction analysis of the system considered in the study (Chore and Ingle 2008) using simplified finite element models for the sub-structure part. In the either study, an uncoupled analysis of the system of building frame and pile foundation was presented. Chore *et al.* (2009) reported limited investigation on the coupled analysis of the system by considering the system of building frame and pile foundation as a single compatible unit. The studies reported recently (Chore and Ingle 2008, Chore *et al.* 2009, 2010) on building frame-pile foundation-soil system consider linearly elastic behaviour of soil. On this backdrop, the present work concerns with the interaction analysis of the building frame resting on pile foundation incorporating the non-linear behaviour of soil using the *p*-*y* curve approach along the lines similar to that reported by Georgiadis *et al.* (1992).

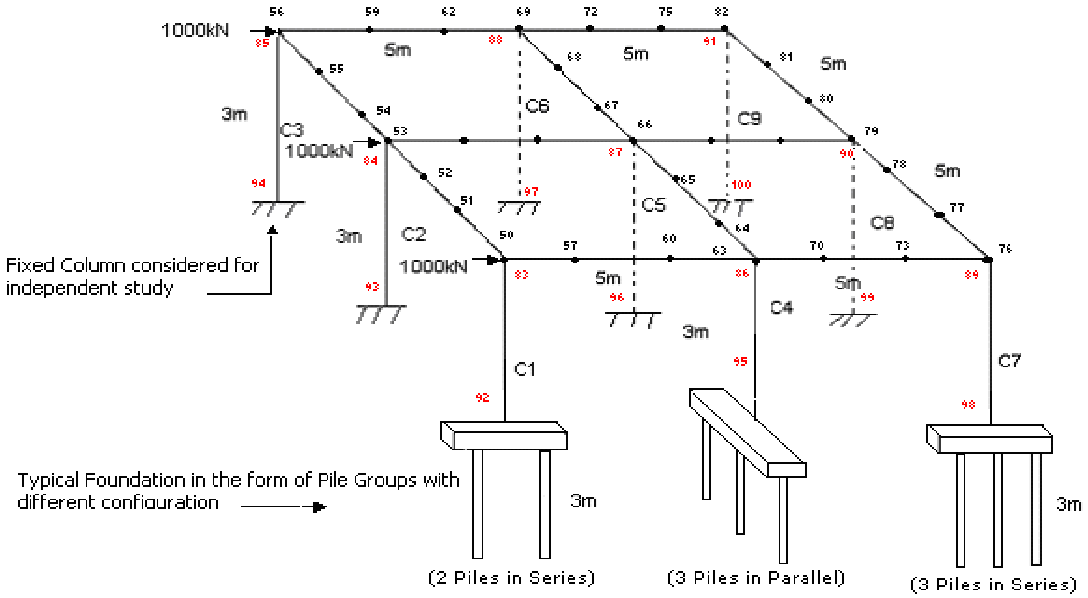


Fig. 1 Typical building frame supported by groups of piles (After Chore and Ingle 2008)

3. Mathematical modeling (formulation)

The interaction analysis is carried out using the finite element method. A building frame is analyzed separately considering the fixed column bases. Later, the pile foundations are worked out independently by considering the non-linear behaviour of soil using *p-y* curve approach to get the equivalent stiffness of the foundation head. Further, they are used in the interaction analysis to evaluate the effect of SSI on the response of the frame.

The elements of the superstructure (beam, column and slab) are discretized into 20 node iso-parametric continuum elements with three degrees of freedom at each node, i.e., displacement in three directions in X, Y and Z. For analyzing the substructure, i.e., pile foundation, more simplified finite element modeling approach, as suggested by Desai *et al.* (1981), is used here using well-known concepts in the theory of finite elements. A one dimensional beam element and two dimensional plate element are used for simulating pile and pile cap. However, for accounting the non-linear behaviour of soil, spring elements used for modeling the foundation soil as done in the study (2010) are modified using *p-y* curves developed by Georgiadis *et al.* (1992).

The mathematical model of the building frame and the various elements along with their degrees of freedom per node which have been employed in the mathematical modeling of pile foundation have already been presented elsewhere (Chore and Ingle 2008). The details of the formulations for analyzing the building frame using complete 3-D finite element formulation and pile foundation using simplified models have also been reported in the study (Chore *et al*. 2010). The Georgiadis' model (1992) used in the present study for *p-y* analysis of the pile foundation is described briefly in the subsequent section.

4. Georgiadis' model (1992)

Georgiadis *et al.* (1992) conducted a series of model tests on instrumented piles to study the pile response under static and cyclic lateral loads in soft clay. The results were analyzed to determine appropriate load-displacement relationship for the non-linear springs (*p*-*y* curves). For static loading the hyperbolic function, which is widely used in stress-strain soil problem was found to fit remarkably well to data points. This method approximates the empirical results much better than the empirical curve suggested by Matlock (1970). The main reason for this is the better approximation of initial stiffness of *p*-*y* curves (i.e., $dp/dy = k$ for $y = 0$).

$$p = \frac{y}{\left[\left(\frac{1}{k}\right) + \left(\frac{y}{p_u}\right)\right]} \tag{1}$$

Where K is the initial stiffness of the *p*-*y* curve and p_u is the ultimate soil resistance. The parameter K in Equation is a function of the basic elastic soil properties, diameter of pile and flexural stiffness.

Ultimate resistance of soil (p_u) is expressed as

$$p_u = N_P \, c_u \, d \tag{2}$$

N_P is non-dimensional coefficient, which increases with depth (x), 3 at ground level to a maximum value of 9 is given as

$$N_P = 3 + \left(\frac{\gamma x}{c_u}\right) + J\left(\frac{x}{d}\right) \tag{3}$$

Where c_u = un-drained cohesion of soil,
d = pile diameter,
γ = effective unit weight of the soil and
J = empirical constant = 0.14
x =depth of soil under consideration

It was found by Georgiadis *et al.* (1992) that Eq. (1) approximates test results much better than an empirical curve proposed by Matlock (1970). The main reason for this being the different initial stiffness of the two *p*-*y* curves. Eq. (1) corresponds to elastic soil properties ($dp/dy = k$, for y =0) while in Matlock's curve, the initial stiffness is infinite (dp/dy = infinity, for y =0). This infinite initial stiffness results in the erroneous pile response at the lower part of the pile while the soil resistance and displacements are small.

5. Analysis methodology

5.1 Methodology for accounting non-linearity of the soil

There are two approaches available for accounting non-linearity of soil using *p*-*y* concept. These approaches are incremental approach and iterative approach, i.e., secant modulus approach. The pile foundation is analyzed by resorting to the incremental approach and iterative approach is used in the interaction analysis.

In the incremental approach, the load is applied in equal increments ΔP. For each increment, linear analysis is carried out based on the tangent modulus dp/dy, and the incremental displacement Δy_i is obtained. For the first increment, soil stiffness is based on initial tangent modulus k, and in the successive increments it is function of pressure and displacement y_i at the previous increment.

$$\frac{dp}{dy} = \frac{k\left(1 - \dfrac{p}{p_u}\right)}{1 + \dfrac{ky}{p_u}} \tag{4}$$

After each increment, displacements due to that increment are added to the previous displacements to get the total displacements, y_i, due to total current load.

$$y_i = y_i + \Delta y_i$$

After computing the displacements, corresponding pressures and derivative are evaluated using above equations, which is used in next increment. The next increment is applied and again the procedure is repeated. Fig. 2 shows the schematic representation of the incremental approach and Fig. 3 illustrates the secant modulus approach schematically wherein iterative procedure is used to account for non-linear behaviour of soil.

In the iterative analysis, total load is analyzed repeatedly. The first iteration is carried out with initial tangent modulus (E_s) which depends on the type of soil. In the next iteration, the assumed value of E_s is revised so as to make it consistent with the evaluated deflection. The procedure is repeated until the calculated deflections between two successive analyses vary within a prescribed tolerance limits.

5.2 Non-linear analysis.

On the basis of the model of *'p-y'* curve developed by Georgiadis *et al.* (1992), a numerical procedure is programmed using FORTRAN 90. Accuracy of the proposed procedure is validated by comparing results obtained using this procedure with those obtained by earlier researchers. The pile foundation is worked out separately for the lateral or vertical force of 1000 kN to account for

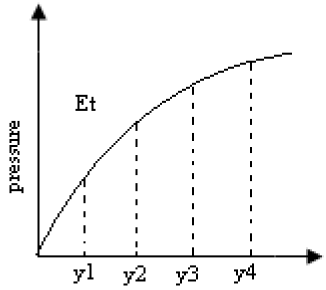


Fig. 2 Incremental approach

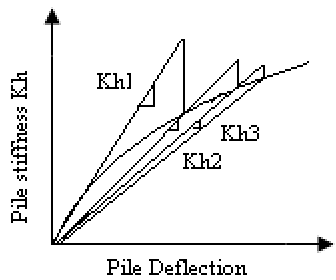


Fig. 3 Secant modulus approach

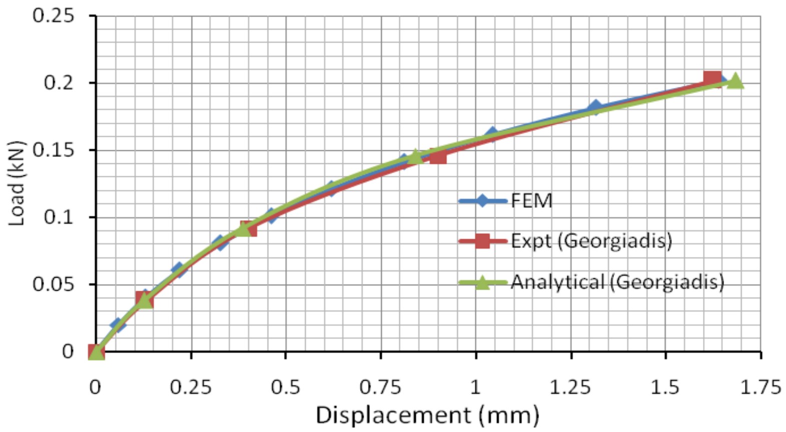


Fig. 4 Load-displacement relationship for the purpose of validation

the non-linear behaviour of soil using the concept of *p-y* curve. The equivalent stiffness in horizontal direction (K_h) and that in vertical direction (K_v) are calculated, which are further used in the interaction analysis.

6. Validation of the proposed procedure

The accuracy of the numerical procedure proposed to be employed in the analysis of sub-structure part in the context of the non-linear behaviour of soil using *p-y* curves is checked with the help of some of the work published by some of the previous researchers through two problems as given below.

6.1 Problem 1 (Georgiadis et al. 1992)

Georgiadis *et al.* (1992) carried out a series of model pile tests on an aluminium tubular pile of length 500 mm embedded in soft to medium clay (γ =17.2 kPa, undrained shear strength C_u = 28 kPa) for studying the non-linear response of the pile subjected to lateral loads in soft clay. Numerical analysis was performed wherein pile was treated as an elastic beam on non-linear springs making use of the concept of *p-y* curves.

Typical comparison by Georgiadis *et al.* (1992) between the measured and predicted pile responses indicates remarkably good agreement between the measurement and predictions. Fig. 4 shows the load -displacement relationship and Fig. 5 depicts the distribution of moments along the depth of pile, indicating the response reported by Georgiadis *et al.* (1992) and the response obtained using the numerical procedure proposed.

From Figs. 4 and 5, a close agreement is seen in the response reported by Georgiadis *et al.* (1992) and the response obtained by proposed numerical procedure. The variation observed in the response reported by Georgiadis *et al.* (1992) analytically and proposed procedure is in the range of 3% to 8 %. The variation in response reported experimentally and the one obtained by the procedure employed in the present investigation is in the range of 0.6% to 8%. This validates the accuracy of the proposed method.

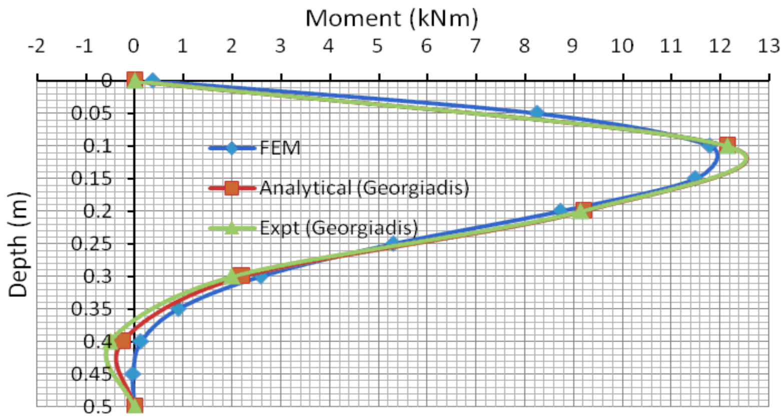


Fig. 5 Distribution of moment along the depth of pile

Table 1 Validation of the proposed procedure

Lateral Load (N)	Ground Line Deflection (mm)		
	Georgiadis *et al*. (1992)	Rajashree and Sundaravadivelu (1999)	Present FEM
202	0.88	0.77	0.84

6.2 Problem 2 (Rajashree and Sundaravadivelu 1999)

Rajashree and Sundaravadivelu (1999) described the computational procedure using finite element method for finding out the effect of aspect of soil-pile separation and degradation of soil on its non-linear behaviour adopting an incremental-iterative procedure. For the purpose of the analysis, pile was idealized as beam element and the soil by number elasto-plastic sub-element springs at each node. To verify the compatibility of the procedure, the comparison of the results in the context of the research work done earlier, by Georgiadis *et al*. (1992) was made basis.

The ground line deflection obtained at the lateral load of 202 N by Georgiadis *et al.* (1992), Rajashree and Sundaravadivelu (1999) and the proposed method used in the present study is given in Table 1. Quite a good agreement is observed in all the three results.

7. Parametric study

A three dimensional single storeyed building frame resting on pile foundation as shown in Fig. 1 is considered for the parametric study. The dimensions of the frame are indicated in the Fig. 1. The slab, 200 mm thick, is provided at top as well as at the floor level. The slab at the top is supported by beams, 300 mm wide and 400 mm deep, which in turn rest on the columns of size 300 mm × 300 mm. While dead load is considered according to unit weight of the materials of which the structural components of the frame are made up of, a lateral load of 1000 kN is assumed to act at the three points of the frame as indicated in Fig. 1. The configurations of pile foundation considered in the present study include group of two piles and three piles with series arrangement (G2PS and G3PS) and parallel arrangement (G2PP and G3PP), as shown in Fig. 6.

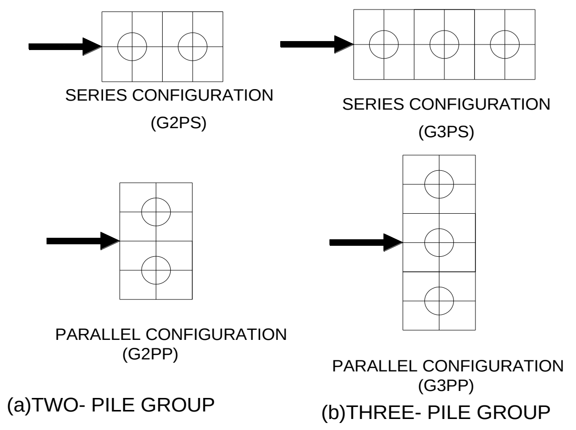


Fig. 6 Different configurations of the pile groups considered in the present study

Table 2 Geometrical and material properties for the elements of the frame and foundation

Properties	**Corresponding Values**
Pile diameter *(D)*	300 mm
Length of pile *(L)*	3 m (3000 mm)
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 pile and pile cap	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
Young's modulus of elasticity for soil (E_s)	4267 kPa
Poisson's ratio for soil (μ_s)	0.45
Modulus of subgrade reaction (K_h)	6667 kN/m^3

All the piles in each group are assumed to be of friction type. The properties of the materials considered in the studies reported previously (Chore and Ingle 2008, Chore *et al*. 2009, Chore *et al*. 2010) are used in the present investigation also and reported in Table 2.

In the parametric study conducted for the specific frame presented, the responses of the superstructure considered for comparison include the horizontal displacement at the top of the frame and the bending moment (BM) at top as well as at bottom of the columns of the superstructure, for both -fixed base and non-linear soil structure interaction cases. The effect of the pile spacing in the group of two and three piles with the series and parallel arrangements is evaluated on the response of the superstructure. Further, the results are compared with those obtained in the interaction analysis of the specific building (Chore *et al*. 2010) in which the soil was idealized to behave as the closely spaced linearly elastic independent springs.

Table 3 Horizontal displacement at top of the frame (mm)

Fixed base	38.18							
Pile spacing	Group of two piles							
	2D	*3D*	*4D*	*5D*	*2D*	*3D*	*4D*	*5D*
Analysis	Series arrangement				Parallel arrangement			
Non-Linear	88.02	81.87	77.40	74.09	90.55	85.47	81.69	78.73
Linear (Chore *et al.*2010)	75.88	72.86	70.41	68.48	77.63	75.68	74.08	72.54
	Group of three piles							
	Series arrangement				Parallel arrangement			
Non-Linear	85.60	80.20	76.34	73.59	90.56	86.56	83.18	80.34
Linear (Chore *et al.*2010)	75.88	72.86	70.41	68.48	77.63	75.68	74.08	72.54

Table 4 Percentage increase in displacement due to non-linearity of soil

Group of two piles							
2D	*3D*	*4D*	*5D*	*2D*	*3D*	*4D*	*5D*
Series arrangement				Parallel arrangement			
With respect to fixed base analysis							
130.54	114.43	102.72	94.05	137.17	123.86	113.96	106.21
With respect to the linear analysis (Chore et al. 2010)							
16.00	12.37	09.93	08.19	16.64	12.94	10.27	08.53
Group of three piles							
2D	*3D*	*4D*	*5D*	*2D*	*3D*	*4D*	*5D*
Series arrangement				Parallel arrangement			
With respect to fixed base analysis							
124.20	110.06	99.95	92.74	137.19	126.72	118.39	110.42
With respect to the linear analysis [35]							
15.82	12.14	09.62	07.84	16.66	12.71	10.04	08.13

8. Results and discussion

8.1 Effect on horizontal displacement at top of frame

The horizontal displacements at top of the in view of the non-linear behaviour of soil considered in the present investigation are given in Table 3. The horizontal displacement on the premise of the fixed column bases is worked out to be 38.18 mm. The percentage increase in the displacement due to non-linear behaviour of soil with respect to those obtained assuming the column bases to be fixed are shown in Table 4 for comparison. Similarly, percentage increase in the displacements obtained in the present study is further compared with those obtained linear analysis of the system (Chore *et al*. 2010) in Table 4.

Incorporation of the aspect of soil-structure interaction (SSI) is found to increase the top displacement. The maximum and minimum values of the top displacement obtained by considering SSI and accounting non-linear behaviour of soil are observed to be 90.60 mm and

73.60 mm, respectively. The effect of SSI is to increase the top displacement in the range of 92% to 137%. When the results of analysis presented here by considering non-linear behaviour of soil using *p-y* approach are compared with that obtained in the linear analysis of the system (Chore *et al*. 2010), the displacement is found to increase in the range of 7.8% to 16.7%.

The general trend pertaining to the reduction in displacement with increase in spacing as seen in the earlier studies reported in respect of the system of building frame considered in the present investigation holds good here as well. Because of the overlapping of the stressed zones of individual piles at closer spacing, displacement is observed to be more at 2D pile spacing and goes on reducing with increase in spacing.

The effect of number of piles in a group along with the arrangement of piles in a group is also significant. It is observed that with increase in number of piles in a group of piles in the context of series arrangement, displacement decreases. Further, the difference between the displacements obtained at the corresponding spacing in respect of the group of two and three piles with series arrangement is higher at the closer spacing of 2D. This difference is found to reduce with increase in spacing. However, exactly opposite trend is seen in case of parallel arrangement where displacements in a group of three piles are slightly on the higher side as compared to that in a group of two piles. Moreover, difference between the displacements at the corresponding spacing in respect of group of two and three piles for this arrangement is less at the closer spacing of 2D and is found to increase with spacing as against the trend seen in respect of series arrangement.

For a group of two piles and three piles, displacements obtained in respect of series arrangement are less as compared to that obtained in respect of parallel arrangement. This could be because the series arrangement offers stiffer behaviour. When the soil is modeled to behave as non-linear springs, structural stiffness of pile and pile cap is small in parallel arrangement as a result of which series arrangement offers stiffer behaviour. In case of short to medium length piles (as considered here), it is a governing factor.

8.2 Effect on B.M. in columns

The effect of SSI on B.M. at top and bottom of individual columns of the specific frame is evaluated in terms of the percentage increase or decrease in moments. The absolute maximum moments in columns obtained in view of SSI and those obtained considering the column bases to be fixed are compared. It is obvious that the effect of SSI on moments in superstructure columns is significant when the values of moments are calculated on the premise of fixed base approach. The effect on the columns placed on left hand side is less while that on right hand side, more.

The absolute maximum positive (sagging) and negative (hogging) moments in columns of the frame obtained considering the effect of SSI are shown in Table 5.

The corresponding change in moments with respect to the moments obtained considering fixed column bases is also shown in Table 4. The effect of SSI on B.M. in superstructure columns is found to be significant when the values of B.M. are calculated on the premise of fixed base. The absolute maximum positive and negative moments irrespective of the configurations of the group of pile are observed to be 317 kN-m and 361 kN-m when the effect of SSI is considered. However, when the moments are calculated on premise of the fixed column bases, these values are found to be 276 kN-m and 283 kN-m, respectively. When the effect of SSI is considered, absolute maximum positive moment is found to increase by 15% and that negative moment, in the range of 27-28 %.

Table 5 Absolute maximum moments in columns and percentage increase with SSI

Configuration of pile groups	Positive B.M.		% Increase		Negative B.M.		% Increase	
	2D	*5D*	*2D*	*5D*	*2D*	*5D*	*2D*	*5D*
G2PS	317	317	15	15	-360	-360	27	27
G2PP	317	317	15	15	-360	-360	27	27
G3PS	317	317	15	15	-360	-361	27	28
G3PP	317	317	15	15	-360	-361	27	28

8.2.1 Effect of SSI on maximum moment in each column

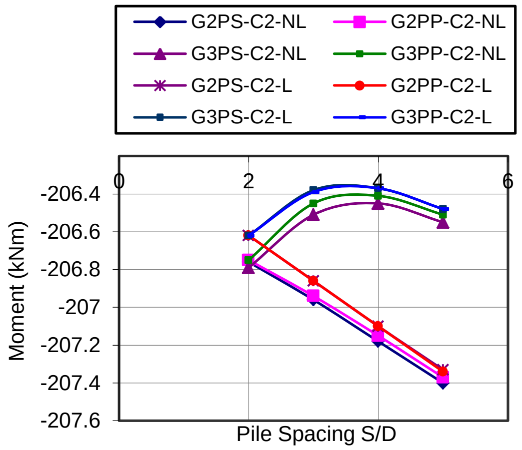
For the group of two piles, decrease in the hogging moment in columns [C-1 and C-3] placed in the corner on left hand side is observed to be 1.41% while hogging moment in all other columns [C-2, C-4 to C-9] is found to increase, the maximum value being 28.12% in column C-7 and minimum value being 0.38% in column C-2. Maximum decrease in the sagging moment is observed to be 38.47% in column C-1 while increase in the positive moment is observed to be 5.44% in column C-4. Similarly, for the group of three piles, maximum decrease and increase in the hogging moment is observed to be 1.73% and 28.18%, respectively in columns C-1 and C-7 whereas maximum decrease and increase in the positive moment are observed to be 38.47% and 14.97%, respectively in columns C-1 and C-5.

8.2.2 Effect of configuration on variation of moment with spacing

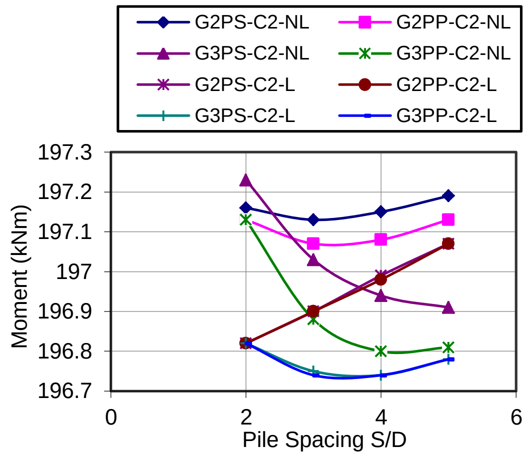
The effect of SSI on variation of moment in superstructure columns with spacing for all pile configurations is studied. The variation of moment in typical columns, i.e., central columns (C-2, C-5 and C-8) is shown in Fig. 7. The variation found for the similar columns as reported in the linear analysis (Chore *et al*. 2010) is also indicated in Fig. 7. The general trend observed pertaining to the variation of moment in columns in respect of pile group comprising of two piles in series arrangement (G2PS) is that in all the columns (C-1, C-2 and C-3) located in the row on left hand side of the specific frame, moment at top increases on negative side with spacing and that at bottom, increases on positive side with spacing. For the columns in the in the intermediate row (C-4, C-5 and C-6) and that in the row on the right hand side (C-7, C-8 and C-9), the trend of variation of moment is that at top, it decreases on negative side with spacing. However, at bottom of C-7 and C-9, moment increases with spacing and is same at the spacing of 4D and 5D while moment at bottom of C-8 decreases with spacing.

The trend of variation of moment with spacing for the pile group of two piles with parallel arrangement (G2PP) at top of all the columns and moment at bottom of C-4, C-5 and C-6 along with that at bottom of C-8 is similar to that observed in respect of group of two piles with series arrangement. The moment at the bottom of C-7 and C-9 is found to increase with spacing up to 4D and then decrease for next higher spacing of 5D.

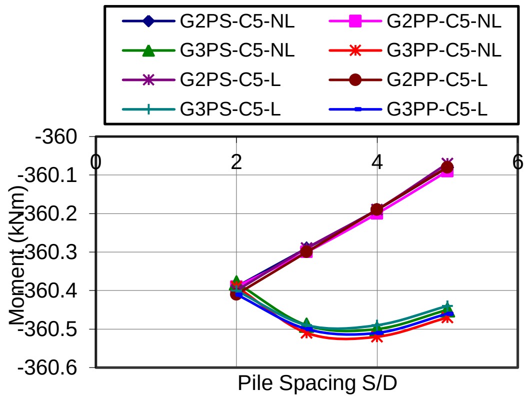
In respect of the group of three piles with series arrangement (G3PS), the moment at top of C-1, C-2 and C-3 decreases with spacing. The moment at top of C-4, C-5 and C-6 and also at top of C-7 and C-9 increases on negative side up to spacing of 4D and then decreases on negative side even though difference between the moments observed at 3D, 4D and 5D spacing is not that significant. At top of C-8, the moment increases on negative side up to 3D spacing and thereafter decreases on negative side gradually. As regarding positive moment, at bottom of C-1 and C-3 increases with spacing while at bottom of C-2, moment decreases with spacing. At bottom of C-4 and C-6, moment increases up to 3D, remains constant up to 4D and then decreases. At bottom of



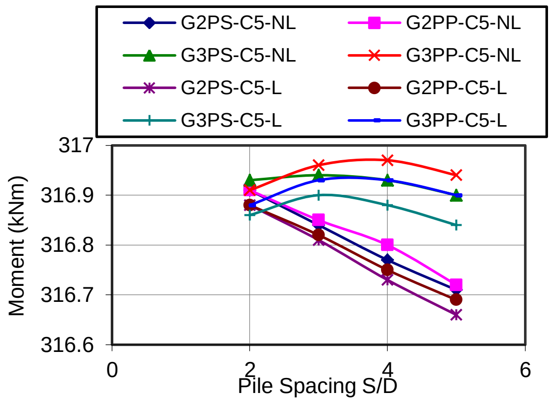
(a) Variation of moment at top of C-2



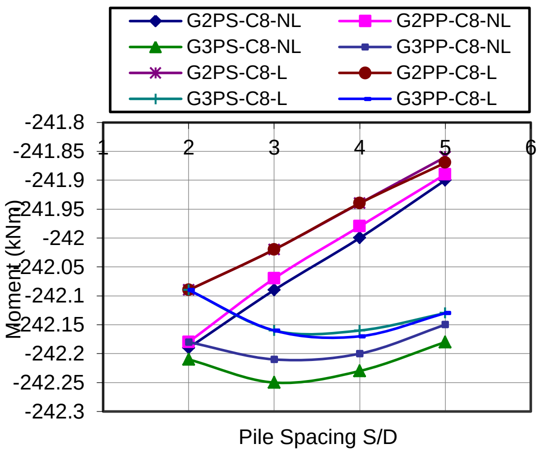
(b) Variation of moment at bottom of C-2



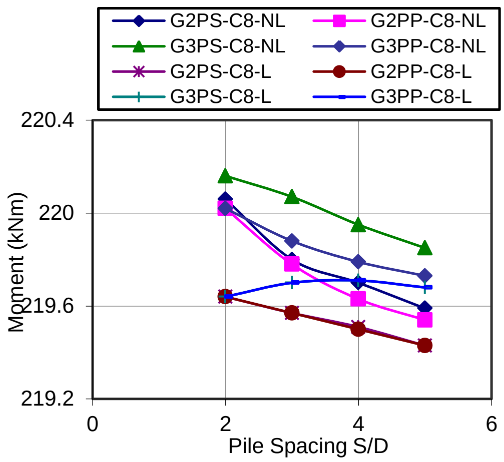
(c) Variation of moment at top of C-5



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



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



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

Fig. 7 Effect of SSI on variation of moment with spacing in typical columns for different configurations of pile groups

C-5, moment increases up to 3D and then decreases even though difference between the moments observed at the spacing of 2D, 3D and 4D is quite negligible. At bottom of C-7 and C-9 moment increases with spacing while that at C-8, moment decreases with spacing.

The variation of moment at top and bottom of the different columns of the frame in respect of the group of three piles with parallel arrangement is similar to that observed in respect of group of three piles with series configuration with few exceptions. At bottom of C-5, moment increases up to 4D and then decreases even though difference between the moments observed at 3D and 4D spacing is negligible. At bottom of C-7 and C-9, moment increases with spacing up to 4D and thereafter, remains constant up to next higher spacing of 5D. When the variation of moments in at top and bottom of the superstructure columns with pile spacing as observed in the present investigation is compared with that obtained by considering the linear elastic behaviour of soil (Chore *et al*. 2010), the variation is found by and large same.

In case of group of two piles (G2PS and G2PP), there is increase in the stiffness of pile foundation due to reduction in the overlapping of stresses zone. Due to this moments in the column C-5 and C-8 are decreasing with increase in spacing, whereas moments in the rear column C-2 are increasing. However in case of group of three piles (G3PS and G3PP), a little different trend is observed. In case of three pile group, at closer pile spacing structural stiffness of pile foundation is higher which may induce more fixity at the bottom of column. So observed trend is different than two pile case. However again at higher spacing trend is similar to two pile case owing to increase in the passive resistance offered by soil.

8.2.3 Comparison of absolute maximum moment with linear analysis

When the absolute maximum values of the hogging and sagging moments in the columns obtained in view of the non-linear analysis are compared with that obtained in view of the linear analysis (Chore *et al.* 2010), maximum decrease in hogging moment is 0.005% and maximum increase in sagging moment is observed to be 0.02%.

8.2.4 Effect of ultimate soil resistance P_u

It is clear from Eqs. (2) and (3) that P_u is directly proportional to undrained cohesion C_u. So to examine the impact of ultimate soil resistance on the response for a particular case of G2PS with spacing 3D, ratio $C_u/(K\ D)$ was varied as 0.005, 0.01, 0.02, 0.05 and 0.10. Fig. 8 depicts the improvement in the top-displacement with number of iterations for all the five cases. For the same case top displacement from linear analysis is 75.88 mm. For $C_u/(K\ D)$=0.005, top displacement from nonlinear analysis is 92.36 mm, whereas for $C_u/(K\ D)$=0.10 same is increased to 76.69 depicting almost linear behaviour. Table 6 summarizes top displacement and corresponding ratio with respect to linear analysis.

Table 6 Ratio of top displacement w.r.t. linear analysis

$C_u/(K\ D)$	Top Displacement (mm)	Ratio
0.005	92.362	1.217
0.010	84.268	1.111
0.020	80.028	1.055
0.050	77.515	1.022
0.100	76.693	1.011

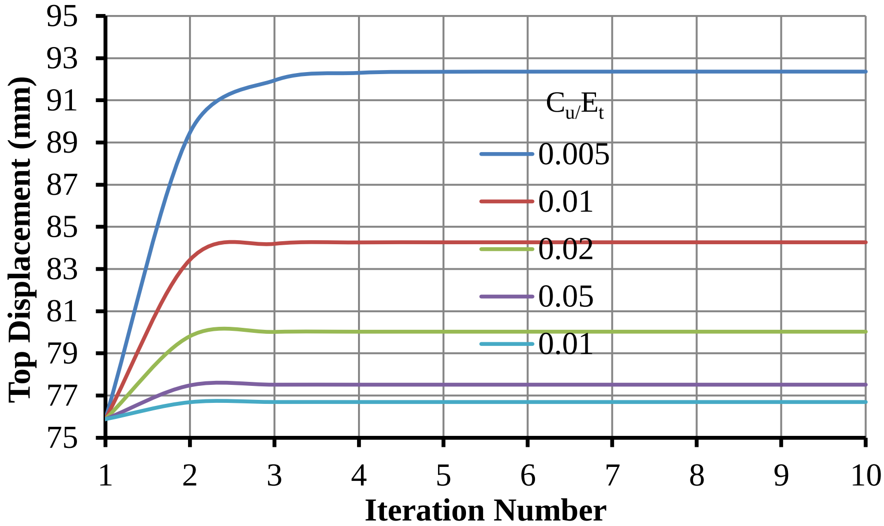


Fig. 8 Effect of ultimate soil resistance on top displacement

For smaller value of $C_u/(K\ D)$ top displacements are increased by 21% due to nonlinear behaviour of soil. However, with increase in the value of $C_u/(K\ D)$, effect of material nonlinearity is decreasing and approaching towards linear trend.

9. Conclusions

Some of the broad conclusions emerging from the present study are summarized below:

i. The effect of SSI on top horizontal displacement of the frame is significant and is to increase the same in the range of 92% to 137% in the context of non-linear behaviour of soil. The aspect of the nonlinearity of soil is found to increase the displacement in the range of 7.8% to 16.7% when compared with the linear behaviour of soil mass.

ii. With increase in number of spacing, top displacement decreases in respect of all the configurations considered in the study.

iii. Displacements for parallel configuration are on higher side as compared to that for the series configuration.

iv. Effect of soil-structure interaction is significant on B.M. in columns. The effect of SSI is to increase the absolute maximum positive moment by 15% and that negative moment, in the range of 27-28 %.

v. The maximum decrease and maximum increase in the hogging moment in column is observed to increase with increase in number of piles though increase is not that significant.

vi. The parameters like number of piles and configuration of the pile group have a significant effect on the variation of B.M. with pile spacing in columns.

vii. Inclusion of the aspect of non-linear behaviour of soil has very marginal effect on the maximum decrease and increase in the absolute maximum hogging moment and sagging moment when compared with the linear elastic behaviour of soil.

viii. For smaller value of P_u top displacements are increased by 21% due to nonlinear behaviour of soil. However, with increase in the value of P_u, effect of material nonlinearity is decreasing and approaching towards linear trend.

Hence, response of the building frame supported on pile foundation depends upon many parameters of the sub-structure system, i.e., pile foundation such as number and spacing of piles in a group along with their arrangement in the context of the direction of the load acting on the structure and position of the columns apart from the non-linear behaviour of soil. Incorporation of the aspect of non-linear behaviour of soil is found to have a significant effect on response of the frame.

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.

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

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.

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", *J. Soil Mech. Found. Eng*., ASCE, **82**(1), 1-9.

Chore, H.S. and Ingle, R.K. (2008), "Interaction analysis of building frame supported on pile group", *Indian 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*., SERC, **34**(6), 460-464.

Chore, H.S., Ingle, R.K. and Sawant, V.A. (2009), "Building frame- pile foundation- soil interactive analysis", *Interact. Multiscale 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. Multiscale 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", *Coupl. 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. Multiscale Mech*., **5**(1), 57-73.

Coyle, H.M. and Reese, L.C. (1966), "Load transfer for axially loaded pile in clay", *Proc. ASCE, 92 (SM-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. Multiscale 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*., SERC, **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 2nd International Conference on Numerical Methods in Geomechanics*, Blacksburg.
Desai, C.S., Kuppusamy, T. and Allameddine, A.R. (1981), "Pile cap- pile group- soil interaction", *J. Struct. Eng*., ASCE, **107**(ST -5), 817-834.
Deshmukh, A.M. and Karmarkar, S.R. (1991), "Interaction of plane frames with soil", *Proceedings of 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", *Indian Geotech. J.*, **36**(2).
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
Ingle, R.K. and Chore, H.S. (2007), "Soil- structure interaction analysis of building frames- an overview", *J. Struct. Eng.*, SERC, **34**(5), 201-209.
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 Int. Conf. Finite Element Methods*, Australia.
Krishnamoorthy, A. and Rao, N.B.S. (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*., **18**(2), 92-107.
Matlock, H. (1970), "Correlations for design of laterally loaded piles in soft clay", *Proceedings of 2nd Offshore Technology Conference*, Houston.
Matlock, H. and Reese, L.C. (1956), "Foundation analysis of offshore pile supported structures", *Proc. of the 5th International Conference on Soil Mechanics and Foundation Engineering*, 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. Geoenvir. 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. Found. Eng*., ACSE, **97**(5), 733-751.
Reddy, R.C. and Rao, G.T.D. (2011), "Experimental study of a modelled building frame supported by a pile group embedded in cohesionless soils", *Interact. Multiscale Mech*., **4**(4), 321-336.
Spiller, W.R. and Stoll, R.D. (1964), "Lateral response of piles", *J. Soil Mech. Found. Eng*., ASCE, **90**, 1-9.
Sriniwasraghavan, R. and Sankaran, K.S. "Settlement analysis for combined effect of superstructure-footings- soil system", *J. Inst. Eng*., **6**, 194-198
Subbarao, K.S., Shrada Bai, H. and Raghunatham, B.V. (1985), "Interaction analysis of frames with beam footing", *Proceedings of Indian Geotechnical Conference*, Roorkee, India.
Swamy, R.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. Multiscale Mech*., **4**(1), 65-83.
Thangaraj, D.D. and Illampurthy, K. (2010), "Parametric study on the performance of raft foundation with interaction of frame", *Elec. J. Geotech. Eng*., **15**(H), 861-878.
Thangaraj, D.D. and Illampurthy, K. (2012), "Numerical analysis of soil- mat foundation of space frame system", *Interact. Multiscale 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.