

## Building frame-pile foundation-soil interactive analysis

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**Abstract.** The effect of soil-structure interaction on a simple single storeyed and two bay space frame resting on a pile group embedded in the cohesive soil (clay) with flexible cap is examined in this paper. For this purpose, a more rational approach is resorted to using the three dimensional finite element analysis with realistic assumptions. The members of the superstructure and substructure are discretized using 20 node isoparametric continuum elements while the interface between the soil and pile is modeled using 16 node isoparametric interface elements. Owing to viability in terms of computational resources and memory requirement, the approach of uncoupled analysis is generally preferred to coupled analysis of the system. However, an interactive analysis of the system is presented in this paper where the building frame and pile foundation are considered as a single compatible unit. This study is focused on the interaction between the pile cap and underlying soil. In the parametric study conducted using the coupled analysis, the effect of pile spacing in a pile group and configuration of the pile group is evaluated on the response of superstructure. The responses of the superstructure considered include the displacement at top of the frame and moments in the superstructure columns. The effect of soil-structure interaction is found to be quite significant for the type of foundation used in the study. The percentage variation in the values of displacement obtained using the coupled and uncoupled analysis is found in the range of 4-17 and that for the moment in the range of 3-10. A reasonable agreement is observed in the results obtained using either approach.

**Keywords:** soil-structure interaction; coupled analysis; uncoupled analysis; pile group; pile spacing; series arrangement; parallel arrangement; top displacement of frame and bending moment in columns.

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## 1. Introduction

The framed structures are normally analyzed with their bases considered to be either completely rigid or hinged. However, the foundation resting on deformable soils also undergoes deformation depending on the relative rigidities of the foundation, superstructure and soil. Interactive analysis is, therefore, necessary for the accurate assessment of the response of the superstructure. Numerous interactive analyses have been reported in many studies in the 1960's and 1970's such as Chameski (1956), Morris (1966), Lee and Brown (1972), King and Chandrasekaran (1974), Buragohain *et al.* (1977), and in few more recent studies such as Shriniwasraghavan and Sankaran (1983), Subbarao *et al.* (1985) and Deshmukh and Karmarkar (1991). While a majority of these analyses have been presented either for the interaction of frames with isolated footings or for the interaction of frames with raft foundation, few of them were focused on the interaction of frames with combined footings. In the meantime, much work is available on pile foundation (single as well as pile group), but comparatively little work, except Buragohain *et al.* (1985), was reported on the analysis of framed structures resting on pile foundations to account for the soil-structure interaction. A brief review of the literature on the prominent interaction analyses of framed structures and analyses of pile foundation is given in the subsequent section.

## 2. Brief review of literature

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

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

In the recent past also, much work was done on the quantification of the effect of soil-structure interaction on the behaviour of framed structures (Dasgupta *et al.* 1998, Mandal *et al.* 1999). Viladkar *et al.* (1991) used coupled finite-infinite element in the interactive studies of the framed structures and demonstrated the viability of application of such a technique in analysis. Similarly, an

interactive analysis was conducted by Noorzaei *et al.* (1991) for space frames resting on raft. Recently, Stavirdis (2002) presented a simplified interaction analysis of layered soil-structure interaction, and Hora (2006) the non-linear soil-structure interaction analysis of infilled building frames. While most of the above mentioned studies dealt with the interaction of frames with isolated footings or combined footings or raft foundation, only the study by Buragohain *et al.* (1977) is found to deal with the interaction analysis of frames on piles.

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

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

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

### 3. Significance and scope of the present work

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

Ingle and Chore (2007) reviewed the soil-structure interaction (SSI) analysis of framed structures and the soil-structure interaction problems related to pile foundations, and underscored the necessity of interactive analysis for building frames 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. Besides, Chore and Ingle (2008a) reported an interaction analysis on the space frame with pile foundations, thus, accounting for the SSI by the finite element method, wherein

foundation elements were modeled in the simplified manner as suggested by Desai *et al.* (1981).

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

In the study by Chore and Ingle (2008b), an uncoupled analysis (sub-structure approach) of the system of building frame and pile foundation was also presented. By this methodology, a building frame was analyzed separately considering the fixed column bases. Later, the pile foundations were worked out independently to get the equivalent stiffness of the foundation head. Further, they were used in the interaction analysis of the frame to evaluate the effect of SSI on the response of the frame. Such an analysis is computationally economical as compared to the coupled analysis, i.e., combined analysis in which the system of building frame and pile foundation along with sub-soil mass is considered as an integrated unit. Though the combined analysis is uneconomical in terms of computational resources and memory requirement, an effort is attempted herein for the interactive analysis of the building frame considering the system of a building frame- pile foundation-soil mass as a single unit. A group of three piles with two different arrangements (configurations) of piles therein, such as series or parallel arrangements, is considered. The effect of pile spacing on the top displacement and maximum moment in columns of the frame is studied. The results are compared with those existing in the literature.

#### 4. Idealizations in the proposed analysis

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

#### 5. Three dimensional formulation

##### 5.1 Continuum Element

The relation between the strains and nodal displacements is expressed as,

$$\{\varepsilon\}_e = [B]\{\delta\}_e \quad (1)$$

where  $\{\varepsilon\}_e$  is the strain vector,  $\{\delta\}_e$  is the vector of nodal displacements, and  $[B]$  is the strain displacement transformation matrix.

The stress-strain relation is given by,

$$\{\sigma\}_e = [D]\{\varepsilon\}_e \quad (2)$$

where,  $\{\sigma\}_e$  is the stress vector, and  $[D]$  is the constitutive relation matrix.

The stiffness matrix of an element is given as expressed as,

$$[K]_e = \int_V [B]^T [D] [B] dv \quad (3)$$

### 5.2 Interface Element

The relative displacements (strains) between the surface of the soil and structure will induce stresses on the interface elements. These relative displacements are given as,

$$\{\varepsilon\}_e = [B]_f \{\delta\}_e \quad (4)$$

where,  $[B]_f$  represents the strain displacement transformation matrix.

The element stiffness is obtained by the usual expression,

$$[K]_e = \int_S [B]_f^T [D]_f [B]_f ds \quad (5)$$

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

### 5.3 Equivalent Nodal Force Vector

The lateral or vertical force ( $F_H$  or  $F_V$ ), acting on the pile cap, is considered as uniformly distributed force over the pile cap. The intensity of this uniformly distributed force is,  $q = F / A$ , where  $A$  is the area of the pile-cap.

The equivalent nodal force vector,  $\{Q\}_e$ , is then expressed as,

$$\{Q\}_e = \int_A q [N]^T dA \quad (6)$$

where  $[N]$  represents the matrix of shape functions.

## 6. Method of analysis

The stiffness matrices for all elements are evaluated and assembled into global stiffness matrix,  $[A]$ , in skyline storage form. Similarly, the load vector is assembled in vector  $[B]$ . With the global stiffness matrix and load vector made available, the global equilibrium equations are formulated. The active column solution technique is used for the solution of the equilibrium equations of the system.

On the premise of aforementioned idealizations, a numerical procedure for the 3-D finite element analysis was programmed in Fortran 90, which was validated on some primary structures, such as cantilever beam, wherein the bending behaviour predicted by the program was found to be in close agreement with that obtained by theory. The program was also validated on single piles and few

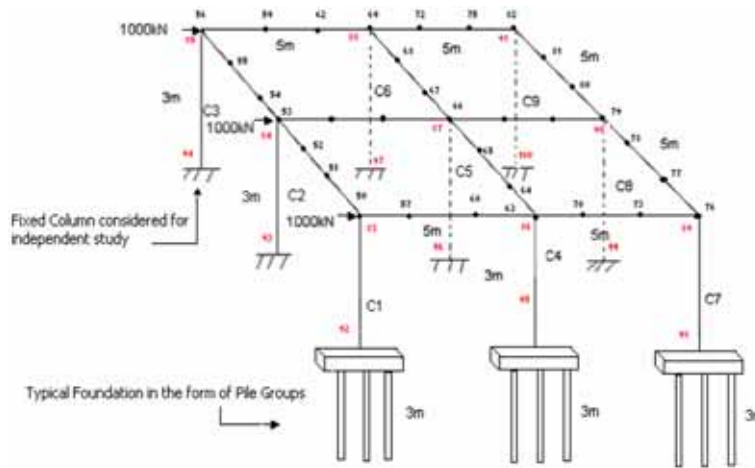


Fig. 1 (a) Typical building frame supported by group of three piles (Series configuration)

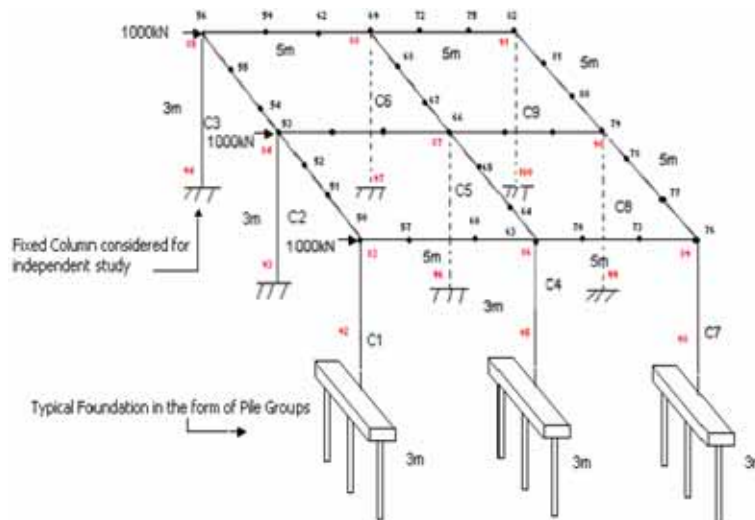


Fig. 1 (b) Typical building frame supported by groups of three piles (Parallel configuration)

cases of pile group, and then implemented for the analysis of the specific frame considered in this study.

## 7. Numerical problem

A three-dimensional single storeyed building frame resting on pile foundation comprising groups of three piles, as shown in Fig. 1 (a) and Fig. 1 (b), is considered for the study.

The frame, 3 m high, is 10 m × 10 m in plan with each bay of dimensions 5 m × 5 m. The slab, 200 mm thick, is provided at the top as well as at the floor level. The slab at top is supported by

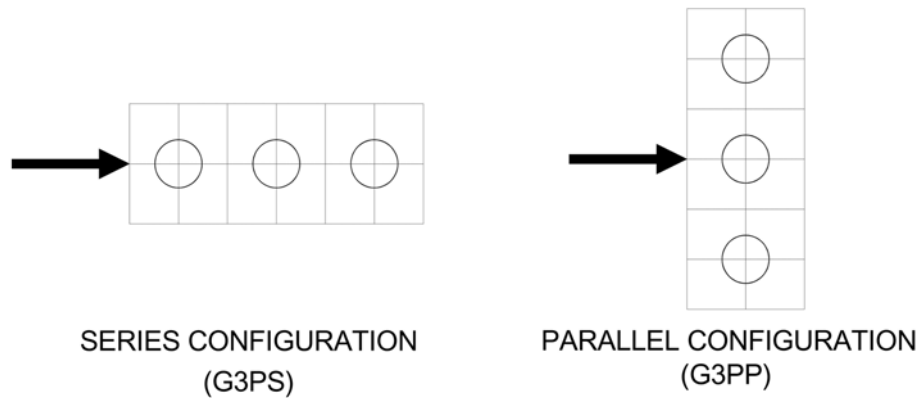


Fig. 2 Different configurations for three-pile groups considered in the present study

Table 1 Geometrical and material properties for pile and cap

Particulars	Corresponding Values
Pile Size/Diameter (D)	300 mm
Length of Pile (L)	3 m (3000 mm)
Concrete Grade used for Pile and Pile Cap	M- 40 (Characteristic Comp Strength: 40 MPa)
Young's Modulus of Pile and Cap ( $E_c$ )	$0.3605 \times 10^8$ kPa
Poisson's Ratio ( $\mu_c$ )	0.15

beams 300 mm wide and 400 mm deep. The beams rest on columns of size 300 mm  $\times$  300 mm. While dead load is considered according to unit weight of the materials of which the structural components of frame are made up for the purpose of the parametric study presented here, lateral loads of 1000 kN magnitude acting at three points on the frame, as shown in the Fig. 1, are also considered.

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

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

The value of the Young's modulus of elasticity and Poisson's ratio of the soil along with the interface properties are judiciously selected from the available literature [after Sawant and Dewaikar 2001).

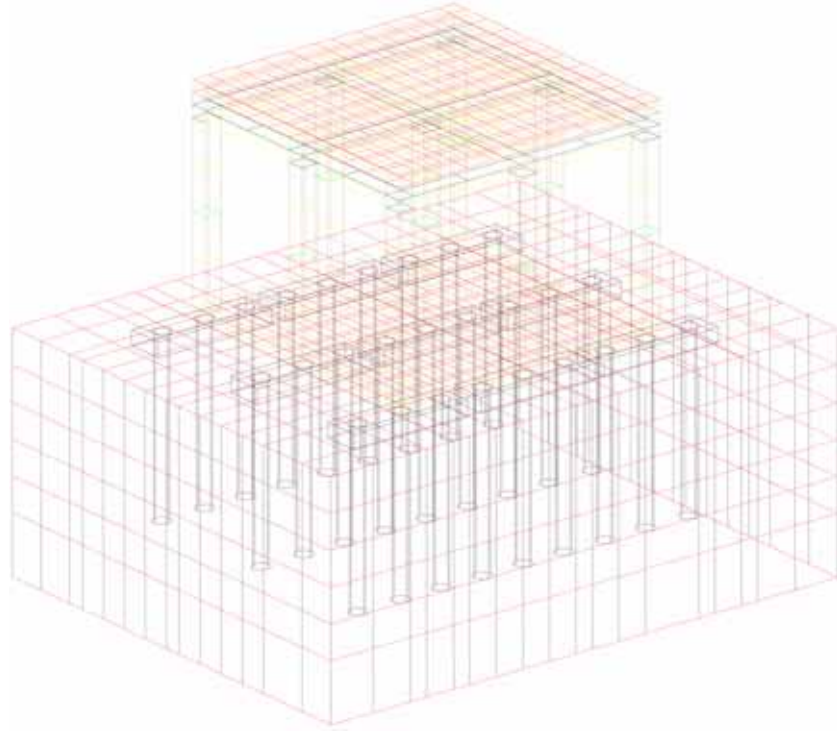


Fig. 3 Mathematical model of building frame-pile group- soil system considered for coupled analysis

- Young's modulus of elasticity ( $E_s$ ): 4267 kN/m<sup>2</sup>
- Poisson's ratio ( $\mu$ ): 0.45
- Stiffness of the interface in tangential direction ( $k_s$ ): 1000 kN/m<sup>3</sup>
- Stiffness of the interface in normal direction ( $k_n$ ): 1.0 E 06 kN/m<sup>3</sup>

## 8. Proposed analysis

Two analyses are reported in this paper: uncoupled analysis (analysis using sub-structure approach) and a combined, i.e., coupled analysis. For the uncoupled analysis, the pile foundation is worked out separately for unit lateral load and unit vertical load to get the equivalent stiffness in the horizontal direction ( $k_h$ ) and vertical direction ( $k_v$ ), which will be further used in the analysis of frame. In the coupled analysis, the system of the building frame and pile foundation along with the sub-soil mass is evaluated by considering it as a single compatible unit. The mathematical model of the building frame- pile group- soil system considered for the coupled analysis is shown in Fig. 3.

## 9. Results and discussion

In the parametric study conducted for the specific frame presented here, the responses of the



Table 2 Horizontal displacement at top of frame (mm)

Support Condition	Uncoupled Analysis		Coupled Analysis	
Fixed Base			38.20	
Pile Spacing 2D	89.53 (135.54)	84.54 (121.42)		
Pile Spacing 3D	82.53 (16.17)	79.33 (107.78)	86	88.80
Pile Spacing 4D	77.31 (102.49)	76.27 (99.76)	(125.13)	(132.46)
Pile Spacing 5D	73.49 (92.48)	74.23 (94.42)		

(Figures in parentheses indicate percentage increase in displacement owing to SSI)

Table 3 Percentage variation in displacements obtained using either approach

Condition of Support	G3PS	G3PP
Pile Spacing 2D	4.57	4.80
Pile Spacing 3D	4.03	10.67
Pile Spacing 4D	10.10	14.11
Pile Spacing 5D	14.55	16.41

superstructure considered for comparison include the horizontal displacement at top of the frame and the bending moment (BM) at the top, as well as at the bottom of the superstructure columns, in view of the fixed base and soil-structure interaction (SSI). Bending moments are computed using the moment-curvature relationship. The effect of the pile spacing in a group of three piles with the series and parallel arrangements of piles therein is evaluated on the response of superstructure and discussed in the following section. Further, the results of the coupled analysis are compared with those obtained for the same configurations of pile groups in a complete 3-D interaction analysis of the building frame- pile group –soil system using the uncoupled approach (Chore and Ingle 2008b).

### 9.1 Effect on horizontal displacement at top of frame

From the results of parametric study conducted on the specific building frame with pile foundation of different configurations, the top horizontal displacement is found to be comparatively less (38.2 mm) for the fixed column base condition and more when the effect of soil-structure interaction is taken into account. The displacements with pile spacing for both configurations of pile groups in respect of either analysis are given in Table 2. Similarly, the percentage variation in values of the displacements obtained using either approach is tabulated in Table 3.

The results, further, reveal that the percentage variation in the displacements obtained using the coupled analysis presented here and the uncoupled analysis is in the range of 4% - 14.5% in respect of the series arrangement and in the range of 5%-17% in respect of the parallel arrangement.

The difference in the percentage increase in the horizontal displacement obtained using the coupled analysis and uncoupled analysis procedure with respect to the displacement obtained in the context of fixed column bases is observed in the range of 9% - 32% for the series configuration and

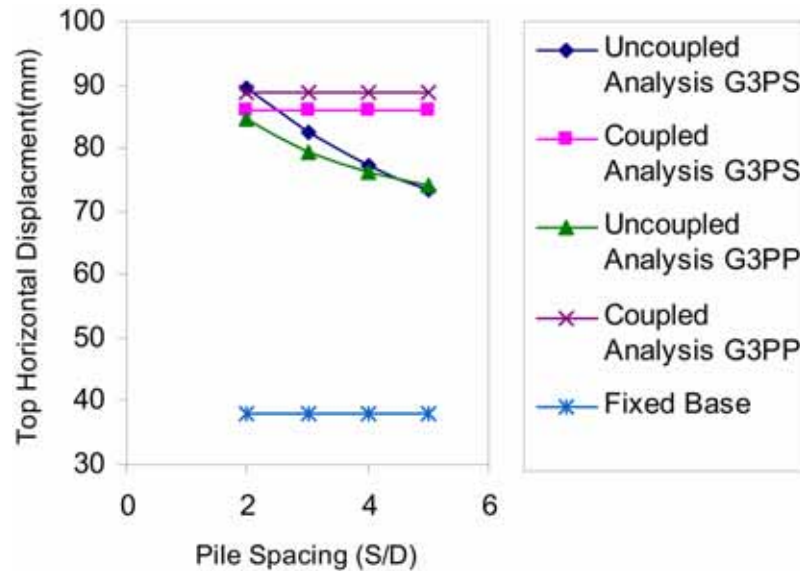


Fig. 4 horizontal displacements at top of frame

10% - 37% for the parallel configuration.

#### 9.1.1 Effect of pile spacing on top displacement

The trend in the displacement at the top of the building frame with pile spacing obtained in view of either analysis of the system is shown in Fig. 4.

From Fig. 4 it is observed that for the coupled analysis, the effect of pile spacing does not have appreciable effect on the displacement in respect of either arrangement, unlike the one observed for the uncoupled analysis where the displacement is found to decrease with the increase in pile spacing.

The trend of reduction in the displacement with the increase in pile spacing in the context of uncoupled analysis can be attributed to the overlapping of the stressed zones of the individual piles at closer spacing. When the piles are closer, the combined action of pile and that of pile cap is more rigid; and moreover, in three dimensional formulation, it reflects a block action. Owing to this, the displacement is observed to be higher for the spacing of 2D; and thereafter, it goes on decreasing. The difference between the displacements is further found to decrease with the increase in pile spacing.

In the uncoupled analysis, only three piles are considered in any arrangement whereas for the coupled analysis a total of 27 piles are considered in the area of  $11 \times 11$  m. They are closely spaced (9 piles in 11m) at least in one direction. Under such a circumstance, the individual spacing between the pile foundations under any column becomes insignificant, as in each row there are 9 piles at close distances. It will act like one unit block. The resistance offered by such a block will be independent of the individual spacing between the pile foundations.

#### 9.1.2 Effect of configuration on top displacement

In respect of the series configuration of the pile group, the displacement observed in respect of the coupled analysis is on the lesser side at closer pile spacing of 2D. However, for higher pile spacings

Table 4 Maximum moment (kN-m) in columns and corresponding percentage increase

Analysis	Positive Moment		Percentage Increase		Negative Moment		Percentage Increase	
Group of Two Piles (Series Configuration) [G2PS]								
Pile Spacing	2D	5D	2D	5D	2D	5D	2D	5D
Uncoupled Analysis	317.58	317.15	15.21	15.18	362.03	360.96	27.74	27.36
Coupled Analysis	305.12		10.29		344.22		21.45	
Group of Two Piles (Parallel Configuration) [G2PP]								
Pile Spacing	2D	5D	2D	5D	2D	5D	2D	5D
Uncoupled Analysis	317.55	317.22	15.21	15.08	362.06	361.11	27.75	27.41
Coupled Analysis	316.76		14.50		331.72		17.05	

Maximum B.M. for fixed base: 276.64 kN-m (Positive) and 283.42 kN-m (Negative)

such as 3D, 4D and 5D, the displacements obtained by the un-coupled analysis are on the lesser side. In respect of the parallel configuration, however, the displacements obtained using the coupled analysis procedure is on the higher side for all the pile spacings.

For the coupled analysis, the structural stiffness and stiffness imparted by the soil collectively support the load transferred by the superstructure. The structural stiffness for the series arrangement is always higher than that of the parallel arrangement and hence, the displacement is on the higher side in respect of the series arrangement of piles in a group.

However, for the uncoupled analysis with a single configuration of group of piles, the parallel configuration offers higher resistance since the stiffness offered by the supporting soil is more as a wider area is available for the development of passive resistance. But if there are three rows of piles with parallel configuration as in the coupled analysis, then the stiffness offered by the soil will be reduced due to overlapping of stress zones.

For the case of series arrangement, the overlapping of stresses is always there. But for single parallel configuration, the overlapping is not there. In such case, the series arrangement shows a stiffer behaviour owing to their high structural stiffness.

## 9.2 Effect of SSI on absolute maximum moment in columns

The effect of soil-structure interaction on the moment of superstructure columns is found to be significant using either the uncoupled or coupled analysis. The values of the absolute maximum positive and negative moments in the superstructure columns for both the configurations of pile groups considered in the present study in respect of either analysis is given in Table 4.

The effect of the SSI when evaluated using the coupled analysis is found to increase the absolute maximum positive moment in the superstructure column by 11% and the absolute maximum negative moment by 21.55% for pile groups of the series configuration. The corresponding increase is found to be 14% and 28% as reported by Chore and Ingle (2008b) using the uncoupled approach. The variation in the absolute maximum positive moment and negative moment obtained in either analysis, i.e., coupled analysis and uncoupled analysis, for the series configuration is 3% and 6%, respectively.

For the parallel configuration, the effect of the SSI is to increase the absolute maximum positive

moment in columns by 14.8% and the absolute maximum negative moment by 17.31% when the system is analyzed as one single compatible unit. The uncoupled analysis (Chore and Ingle 2008b) reveals the average increase in the positive moment by 15.15% and that in the negative moment by 27.58%. The variation in the absolute maximum positive moment and negative moment obtained in either analysis for the parallel configuration is 0.4% and 10%, respectively.

### *9.3 Effect of SSI on maximum moments in individual columns*

#### *9.3.1 Series configuration*

The hogging moment in the corner columns (C-1 and C-3) placed in the row on the extreme left hand side is found to increase by 12% whereas for the central column (C-2), it is found to increase by 15%. However, using the uncoupled analysis, the hogging moments in these columns are found to decrease in the range of 1-2%.

The hogging moment in the columns C-4 and C-6 is found to increase by 17%, whereas that in the central column (C-5) is to increase by 22%. The corresponding increase is found in the range of 22-27% in respect of the uncoupled analysis.

The hogging moment in the columns C-7 and C-9 is found to increase by 19% for the coupled analysis, whereas the corresponding increase using the uncoupled analysis is found to be 28%. Similarly, the hogging moment in column C-8 is found to increase by 10% as compared to 27% obtained in view of the analysis using the uncoupled approach.

The coupled analysis is found to decrease the positive moment in columns C-1 and C-2 by 31% and 13%, respectively. The corresponding decrease obtained using the uncoupled analysis is 38% and 18%, respectively.

The combined analysis, i.e., the coupled analysis, reveals a decrease in the positive moment in respect of column C-4 by 7%, whereas the corresponding decrease obtained using the proposed procedure is 5%. In respect of column C-5, the moment is found to increase by 11% and 15% respectively when using either approach.

In respect of the columns placed in the row on the extreme left hand side, the positive moment is found to decrease in the range of 12-28%, when the analysis is carried out treating the entire system as a single compatible unit. The corresponding decrease obtained in respect of the analysis attempted using the coupled approach is in the range of 7-29%.

#### *9.3.2 Parallel configuration*

The hogging moment in the corner columns (C-1 and C-3) placed in the row on the extreme left hand side is found to decrease by 3%, whereas for the central column, it is found to increase by 9.7%. In respect of the coupled analysis. However, for the uncoupled analysis, the hogging moments in these columns are found to decrease in the range of 0.9 -3%.

The hogging moment in the columns C-4 and C-6 is found to increase by 7%, whereas that in column C-5 is to increase by 17%. The corresponding increase is found in the range of 22-28% in respect of the uncoupled analysis.

The hogging moment in the columns C-7 and C-9 is found to increase by 32%, whereas the corresponding increase using the uncoupled analysis as reported by Chore and Ingle (2008b) is found to be 29%. Similarly, the hogging moment in column C-8 is found to increase by 25% as compared to 27% obtained by the uncoupled analysis.

The coupled analysis is found to decrease the positive moment in columns C-1 and C-2 by 29%

and 10%, respectively. The corresponding decrease obtained using the uncoupled analysis is 39% and 19%, respectively.

The combined analysis reveals a decrease in the positive moment in respect of column C-4 by 3%, whereas the corresponding decrease obtained using the uncoupled analysis is 5%. In respect of column C-5 the moment is found to increase by 15% when the analysis is carried out using either approach.

For the columns placed in the row on the extreme left hand side, the positive moment is found to decrease in the range of 7-25% when the analysis is carried out treating the entire system as a single compatible unit. The corresponding decrease obtained in respect of the analysis attempted using the uncoupled analysis is in the range of 7- 29%.

## **10. Conclusions**

A 3-D finite element interactive analysis of a single storeyed building frame supported on pile groups considering the system of frame and foundation as a single compatible unit (coupled analysis) is presented in this paper. The effect of the SSI on the response of the frame is examined here in respect of the coupled analysis vis-a-vis a 3-D interaction analysis attempted using the uncoupled (sub-structure) approach. Some of the broad conclusions deduced from the present parametric study are given below.

(i) The study carried out for a building frame resting on a group of three piles using the coupled analysis reveals the underestimation of the top deflection of the frame for the pile groups in series configuration at closer spacing of 2D by 4.5% and overestimation by 4% to 14.5% at higher spacings. As for the parallel configuration, the coupled analysis reveals an overestimation by 5% to 17% for the top displacement.

(ii) For the coupled analysis, the individual spacing between the piles for any pile group under any column becomes insignificant. Further, in the coupled analysis, the structural stiffness and stiffness imparted by the soil is always higher for pile groups in series configuration than in parallel arrangement. As a result, the displacements are on the higher side for the parallel arrangement.

(iii) The coupled analysis tends to underestimate the absolute maximum positive moment by 3% and negative moment by 6% for the pile groups in series arrangement. The absolute maximum positive moment as obtained in the context of the coupled analysis and the analysis attempted using the uncoupled approach is by and large same. However, the coupled analysis tends to underestimate the absolute maximum negative moment by 10%.

(iv) The increase or decrease in the moments (positive as well as negative) obtained for the individual columns using the coupled or uncoupled approach does not have significant effect for either configuration of pile groups.

From the parametric study of the building frame- pile group- soil system considering the system as the single compatible unit (coupled system) reported in the present paper, it is observed that the effect of soil- structure interaction is quite significant on the response of the building frame for the type of foundation used in the present study. However, such an analysis is computationally uneconomical. Moreover, the results obtained using the coupled analysis agrees fairly with those obtained using the uncoupled analysis which in turn is computationally viable.

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