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# Non-linear Soil-structure Interaction Analysis of Framed Structure with Pile Foundation

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## ABSTRACT

*The study deals with physical modeling of a typical three storeyed building frame supported by pile foundation using three dimensional finite elements. The foundation comprises of pile group having four piles arrangement and embedded in cohesive soil mass. For the purpose of modeling, the elements of the superstructure frame such as beams, columns and slab; and that of the pile foundation such as pile and pile cap are descretized using twenty noded isoparametric continuum element. The interface between the pile and the soil is idealized using sixteen node isoparametric surface element. The more refined finite element mesh is used in the present study for modeling soil element as compared to the one used in the similar study reported in the literature (Chore and Ingle 2008). Three different elements are used for discretizing the soil. 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 superstructure and substructure (i.e., foundation) elements including that of soil. Further, the immediate behaviour of the soil is considered and total stresses in soil are considered. The parametric study is carried out for studying the effect of soil- structure interaction on response of the frame. The frame is analyzed initially without considering the effect of the foundation 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. The response of the frame included the displacement at each storey level of the frame along with the bending moments in columns. The effect of the soil- structure interaction is observed to be significant for the type of foundation and soil considered in the present study.*

***Keywords***

***Soil-structure interaction, pile groups, pile spacing, pile diameter, top displacement, bending moment, embedment depth ratio.***

## INTRODUCTION

In design practice the framed structures are normally analyzed with their bases considered to be either completely rigid or hinged. However, the foundation resting on deformable soils also undergoes deformation depending on the relative rigidities of the foundation, superstructure and soil. Interactive analysis is, therefore, necessary for the accurate assessment of the response of the superstructure. Numerous interactive analyses (Chameski 1956, Morris 1966, Lee and Brown 1972, King and Chandrasekaran 1974, Buragohain *et al.* 1977) have been reported in many studies in the 1960’s and 1970’sand 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; only the study by Buragohain *et al.* (1977) was found to deal with the interaction analysis of frames on piles until recent past.

The afore-mentioned work (Buragohain *et al.* 1977) was carried out using the stiffness matrix method and moreover, it was based on the simplified assumptions and relatively less realistic approach. Pointing out the lacunae in the interaction analysis of a framed structure resting on pile foundation presented by Buragohain *et al.* (1977), Chore and co-authors reported the methodology for the interaction analysis of a single storeyed building frame embedded in clayey soil on the rational approach and realistic assumptions. Many studies reported in the recent past related to the theme included Chore and Ingle (2008 a, b), Chore *et al*. (2009, 2010 a). Recently along similar lines, Reddy and Rao (2011) reported an experimental work on a model building frame supported by a pile group and compared the results analytically using finite element analysis.

Even numerous studies have been reported mostly recently that include those by Agrawal and Hora (2009, 2010), Thangaraj and Illampurthy (2010), Dalili *et al.* (2011), RajshekharSwamy *et al*. (2011); and Thangaraj and Illampurthy (2012). However, these studies were confined to the interaction analysis of frames or allied structure supported by isolated footings or raft foundation. On the backdrop of the relatively less work on the non-linear soil-structure interaction analyses of space frame-pile foundation- soil system, the interaction analysis of a three storeyed frame resting on pile foundation is reported in this investigation.

## MATHEMATICAL MODELING (FORMULATION)

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.

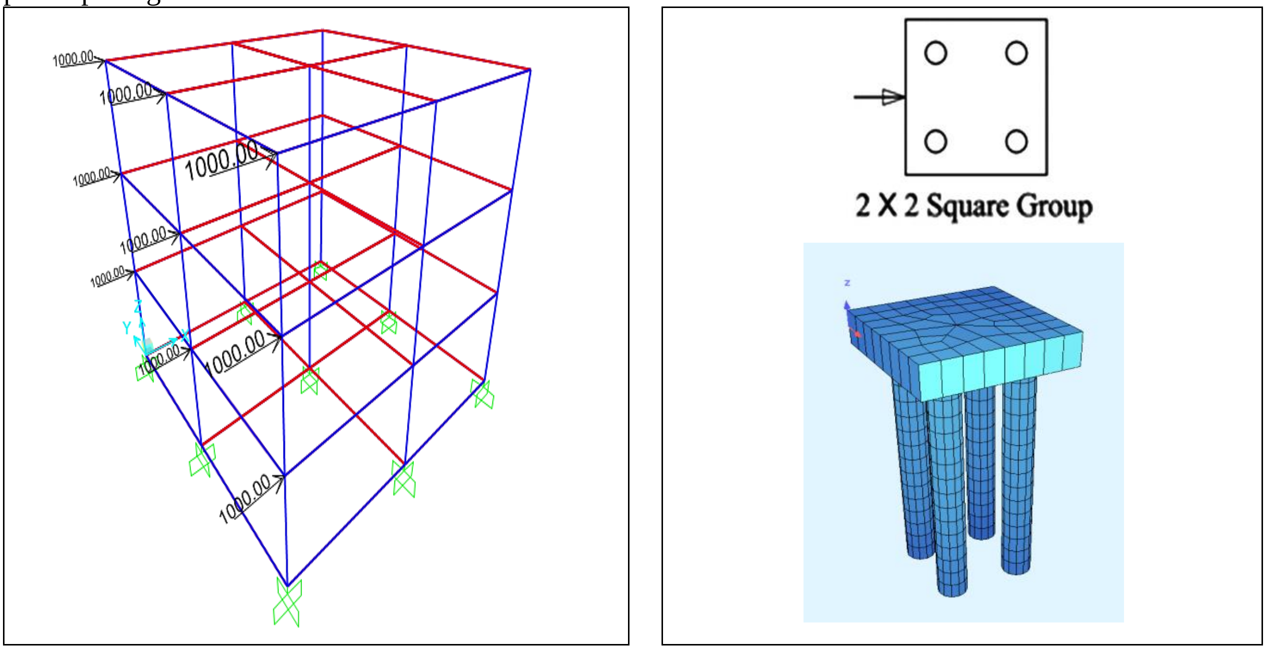
A full three dimensional geometric model of the sub-structure (pile foundation-soil system) is considered in the present study as against the half model for the sub-structure system considered in Chore and Ingle. The elements of the superstructure (beam, column and slab) and that of pile foundation (pile 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 nodediso-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.

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). 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.

## PROBLEM DESCRIPTION

A 3-D three storeyed building frame resting on pile foundation, as shown in Fig. 2, is considered for the study. The frame, 3 m high is 10 m × 10 m in plan with each bay being, 5m × 5m. The slab, 200 mm thick, is provided at top as well as at the floor level. Slab at the top of the first, second and third storey is supported over 300 mm wide and 400 mm deep beam. The beams are resting on columns of size 300 mm × 300 mm.While dead load is considered according to unit weight of the materials of which the structural components of the frame are made up for the parametric study presented here, a lateral load of 1000 kN is assumed to act at the joints of the frame, as shown in the Figure 1. The properties of the material for pile and pile cap are given in Table 1.




(a) Building frame in fixed position.　　(b) Typical pile group with four piles (2 × 2)

**Fig 1:** Building frame considered in the present study with fixed base and four piles

## RESULTS AND DISCUSSION

For the interaction analysis, a software programme Build-Frame is developed. The software program is developed using FORTRAN 90. After assessing the accuracy of the programme in the context of simple problems of structural engineering and soil- structural engineering 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 comparison include the horizontal displacement of the frame at each storey level and bending moment columns. The response is evaluated for two conditions- without considering the effect of SSI and another by considering the effect of SSI. Hence, two analyses are reported, non- interactive analysis (NIA) and the interactive analysis (IA). Further, the interactive analysis is carried out in the context of the linear and non-linear behavior of the soil.

**Table 1.** Pile and soil properties for parametric study

| **Soil properties** | **Corresponding Values** |
|---|---|
| Modulus of Elasticity, $E_s$ | 20000 kPa |
| Poisson's ratio, $\mu_s$ | 0.4 |
| Density, $\gamma_s$ | 18 kN/m$^3$ |
| Yield stress, $\sigma_y$ | 100 kPa |
| **Pile properties** | **Corresponding Values** |
| Modulus of Elasticity, $E_p$ | 25 GPa |
| Poisson's ratio, $\mu_p$ | 0.2 |
| Density, $\gamma_p$ | 25 kN/m$^3$ |
| Pile cap thickness, $t_p$ | 0.5 m |
| Pile diameter, $D$ | 1.0 m |
| $L/D$ ratio | 10 |
| $s/D$ ratio | 2, 3, 4, 5, 7 |
| **Interface element** | **Corresponding Values** |
| Normal stiffness, $k_n$ | $1.0 \times 10^6$ kN/m$^3$ |
| Tangential stiffness, $k_s$ | 1000 kN/m$^3$ |

### Effect of pile spacing on the storey displacement

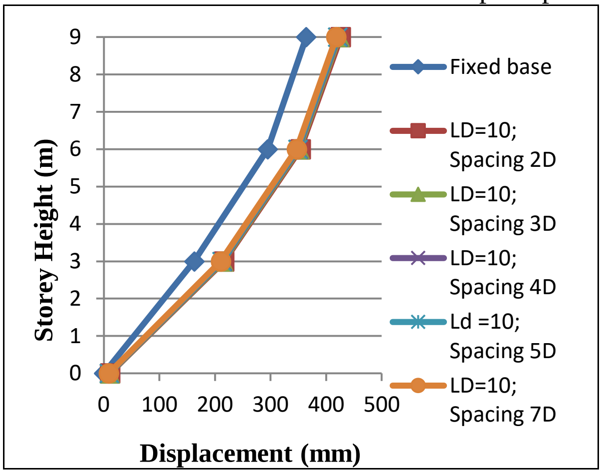
The displacements of frame at each storey level evaluated in respect of various pile spacing for fixed base condition and that for soil-structure interaction (SSI). The trend of horizontal displacement at each storey level of the frame with pile spacing in respect of $L/D$ = 10 considered in the study is shown in Table 2. The corresponding increase in displacement due to consideration of SSI is also shown in Table 2. The general trend observed for all the pile spacing considered in this investigation is that horizontal displacement at the storey level increases due to the effect of soil structure interaction (SSI) is considered.

**Table 2:** Effect of pile spacing on the storey displacement (mm) for $L/D$ = 10

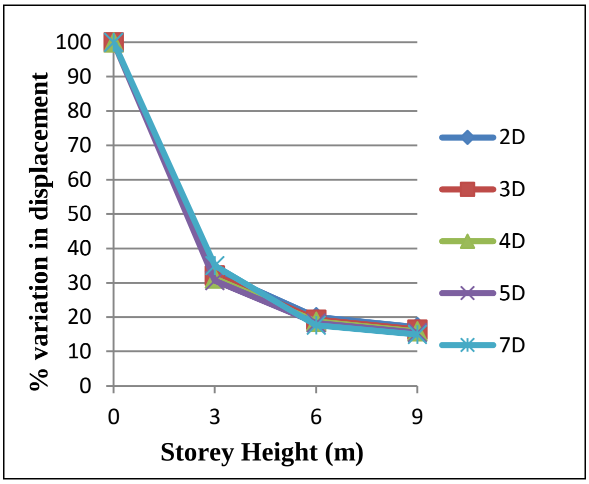
| Pile spacing | Storey Height (m) | 9.0 | 6.0 | 3.0 | 0.0 |
|---|---|---|---|---|---|
| | Fixed Base (NIA) Displacement (mm) | 363.99 | 294.9 | 162.53 | 0.0 |
| 2 D | % variation | 17.1 % | 20.03 % | 33.31 % | 100 % |
| 3 D | % variation | 16.4 % | 19.27 % | 32.16 % | 100 % |
| 4 D | % variation | 15.89 % | 18.71 % | 31.27 % | 100 % |
| 5 D | % variation | 15.51 % | 18.29 % | 30.6 % | 100 % |
| 7 D | % variation | 14.94 % | 17.65 % | 29.58 % | 100 % |

Variation in the storey displacement for different pile spacing (2D, 3D, 4D, 5D and 7D) is illustrated in Fig. 2 (a) w.r.t different pile spacing and Fig. 2 (b) w.r.t non-linear analysis for the case of 2×2 pile group, $E_s$ =

20000 kPa, *D* = 1.0m, *L*/*D* = 10. For pile spacing *L*/*D*=10 the top displacement is obtained to be 426.25 mm, 423.68 mm, 421.81 mm, 420.44 mm and 418.36 mm for pile spacing 2D, 3D, 4D, 5D and 7D. It is also observed that the effect of pile spacing reduces the displacement with increase in the pile spacing. As compared to fixed base analysis for pile spacing of 2*D* the percentage increase in displacement is obtained to be 17.10 % and it reduces to 14.94 % for pile spacing 7D.




(a) Effect of pile spacing on storey displacement for *L*/*D* = 10




(b) Percentage variation in storey displacement for non-linear analysis

**Fig.2** Effect of pile spacing on storey displacement for *L*/*D* = 10 and percentage variation in storey displacement for non-linear analysis

**Effect of non-linearity of soil on 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 percentage variation in storey the displacement obtained at the each storey level are indicated in Table 3 for embedment depth ratio of *L*/*D* = 10.

**Table: 3** Effect of pile spacing on the top displacement *L*/*D* = 10 (linear and Non-linear)

| Pile Spacing | Storey Height (m) | | | |
|---|---|---|---|---|
| | 9.0 | 6.0 | 3.0 | 0.0 |
| | % variation in displacement | | | |
| 2 D | 6.75 % | 9.71 % | 8.00 % | 3.65 % |
| 3 D | 5.99 % | 8.19 % | 6.47 % | 10.81 % |
| 4 D | 5.82 % | 7.68 % | 3.89 % | 20.98 % |
| 5 D | 5.52 % | 6.67 % | 3.33 % | 9.20 % |
| 7 D | 5.44 % | 6.22 % | 2.95 % | 6.11 % |

The general trend observed for all the pile spacing considered in the investigation in respect of embedment depth ratio is that horizontal displacement is more when the spacing between two piles is kept 2D and thereafter, decreases with higher spacing, i.e., 3D, 4D, 5D and 7D, in all the configurations 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 2D; and thereafter, it goes on decreasing. It may be further noted that although the difference between the displacements obtained for various spacing is slightly considerable in respect of group of two piles with series arrangement, the corresponding difference is too marginal for remaining groups.

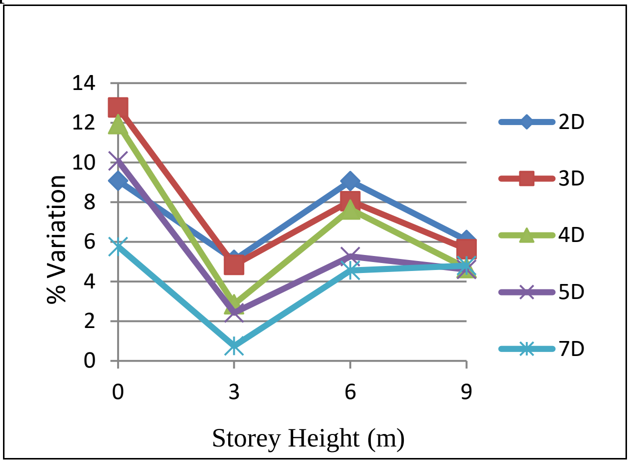



**Fig. 3** Effect of pile spacing on the displacement in terms of % variation (linear-Non linear)

The values of the displacements obtained in the present study are on higher side in respect of either condition- linear and non-linear with soil- structure interaction. The percentage variation in the top storey displacement obtained for embedment depth ration 20 in the present study is observed to be 6.09 %, 5.63 %, 4.60 %, 4.61% and 4.80 % for pile spacing 2D, 3D, 4D, 5D and 7D. Further, the percentage variation in the displacement for embedment depth ration 10 in the present study is observed to be 6.75 %, 5.99 %, 5.82 %, 5.52 % and 5.44 % for pile spacing 2D, 3D, 4D, 5D and 7D.

The trend of reduction in displacement with spacing although remains same, the reduction in displacement at higher spacing such as 3D onwards is too marginal in respect of both embedment ratio. The trend of percentage variation in the storey displacement at each storey level for different pile spacing is shown in fig.3.

### Effect of pile spacing on negative bending moments in columns

The absolute maximum positive (sagging) and negative (hogging) moments in columns of the frame, amongst those obtained for various spicing, in the individual columns with respect of either condition- linear and non-linear with soil- structure interaction for value of embedment depth ratios; *L/D* = 10 are reported in Table 4 and 5 at the lowest spacing between the piles (2D) and higher spacing (7D). The corresponding increase or decrease in maximum moments in individual columns as observed in the interactive analysis with respect to that observed in non-interactive analysis of the frame is also given in the Table. The effect of soil- structure interaction on corresponding percentage increase or decrease in maximum moments of the individual columns of the frame in respect of various configurations is discussed in the subsequent paragraphs.

**Table 4.** Effect of pile spacing on negative bending moments in column for *L/D* = 10

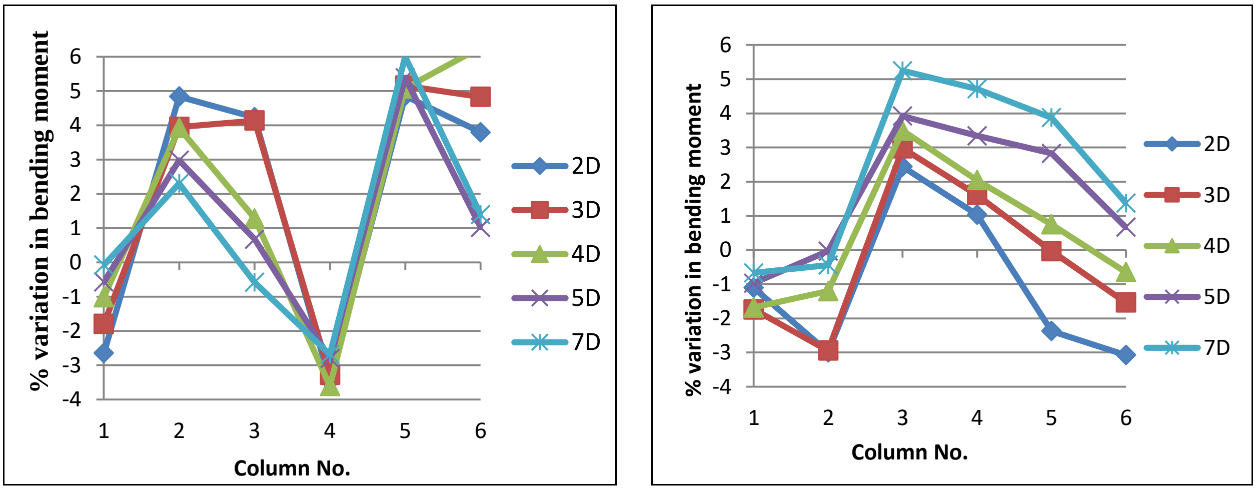
| Pile Spacing | Column | C-1 | C-2 | C-3 | C-4 | C-5 | C-6 |
|---|---|---|---|---|---|---|---|
| 2 D | % variation | -2.65 % | 4.84 % | 4.23 % | -3.47 % | 4.86 % | 3.80 % |
| 3 D | % variation | -1.80 % | 3.95 % | 4.14 % | -3.28 % | 5.16 % | 4.83 % |
| 4 D | % variation | -1.01 % | 3.92 % | 1.29 % | -3.61 % | 5.08 % | 6.28 % |
| 5 D | % variation | -0.57 % | 2.98 % | 0.67 % | -2.80 % | 5.39 % | 0.77 % |
| 7 D | % variation | -0.08 % | 2.31 % | -0.58 % | -2.68 % | 6.01 % | 1.23 % |

It is obvious from the results tabulated in Table 4 and 5 that the effect of soil- structure interaction on moments in individual columns is considerable when the values of moments are compared with those obtained without considering such interaction. 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.

**Table 5.** Effect of pile spacing on positive bending moments in column (sagging) for *L/D* = 10

| Pile Spacing | Column | C-1 | C-2 | C-3 | C-4 | C-5 | C-6 |
|---|---|---|---|---|---|---|---|
| 2 D | % variation | 1.09 % | 0.23 % | 2.36 % | 1.85 % | -0.40 % | 0.10 % |
| 3 D | % variation | -0.99 % | -2.37 % | 2.22 % | 0.62 % | 0.66 % | -1.41 % |
| 4 D | % variation | -2.07 % | -1.33 % | 2.33 % | 0.06 % | -0.11 % | -3.09 % |
| 5 D | % variation | -0.78 % | 0.34 % | 3.80 % | 3.33 % | 3.06 % | 1.07 % |
| 7 D | % variation | -0.40 % | 0.23 % | 5.87 % | 5.70 % | 4.31 % | 1.95 % |

The hogging moment in the central column (C-1) is found to decrease in the range of 0.08 to 2.65 % with the consideration of the effect of non-linear SSI. For the columns placed exterior of the same row, i.e., C-2, C-4 and C-6 the hogging moment is seen to be decreased in the range of 2.85 to 5.14 %. Fig. 5 shows variation of bending moment in columns for different pile spacing.




(a) % variation in negative bending moment (b) % variation in positive bending moment

**Fig.4** Percentage variation negative and positive bending moments in column for *L/D* = 10

In a nutshell, it is seen that the soil- structure interaction decreases negative moment in the columns placed in the leading row of the frame while increases the same in all the remaining columns. Along similar lines, the positive moment in all the columns of the frame decreases with the consideration of the effect of soil structure interaction; except that in the column (C-3) placed in the centre of the intermediate row where the moment increases.

## CONCLUSIONS

The broad conclusions emerging from the interaction analysis are given below.

- The effect of soil- structure interaction on each storey displacement of the frame is quite significant. Displacement is less for the conventional analysis, i.e., fixed base condition and increases in the range of 14.69 % to 33.25% when the effect of SSI is taken into consideration. The displacement at top of frame decreases with increase in pile spacing.
- The effect of soil- structure interaction is significant on B.M in columns. The soil- structure interaction analysis is found to decrease the absolute maximum positive bending moments in columns in the range of 2.85 to 5.14 %. and that negative bending moment is observed to be very marginal, 0.08-2.65% when compared with those obtained using conventional analysis.
- Effect of SSI in the columns placed on left hand side appears less and that in columns placed on the right hand side, the effect seems to be more. The pile spacing has a significant effect on the variation of bending moment in superstructure columns.
- The moment in the columns placed on the left exterior side of the frame increases with spacing on negative side whereas for all other columns decreases on negative side. Along similar lines, the positive moment increases with spacing for the columns placed on the left hand side and for remaining columns, it decreases with spacing by and large.

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