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Interactive analysis of a building fame resting on pile foundation

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Abstract. The study deals with the physical modeling of a typical single storeyed building frame resting on pile foundation and embedded in cohesive soil mass using the finite element based software SAP-IV. Two groups of piles comprising two and three piles, with series and parallel arrangement thereof, are considered. The slab provided at top and bottom of the frame along with the pile cap is idealized as four noded and two dimensional thin shell elements. The beams and columns of the frame, and piles are modeled using two noded one dimensional beam-column element. The soil is modeled using closely spaced discrete linear springs. A parametric study is carried out to investigate the effect of various parameters of the pile foundation, such as spacing in a group and number of piles in a group, on the response of superstructure. The response considered includes the displacement at the top of the frame and bending moment in columns. The soil-structure interaction effect is found to increase the displacement in the range of 38 -133% and to increase the absolute maximum positive and negative moments in the column in the range of 2-12% and 2-11%. The effect of the soil- structure interaction is observed to be significant for the type of foundation and soil considered in this study. The results obtained are compared further with those of Chore *et al.* (2010), wherein different idealizations were used for modeling the superstructure frame and sub-structure elements (foundation). While fair agreement is observed in the results in either study, the trend of the results obtained in both studies is also same.

Keywords: soil-structure interaction; pile groups; pile spacing; top displacement; bending moment

1. Introduction

Framed structures are normally analyzed with their bases considered to be either completely rigid or hinged. However, their 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 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 1960-70's and a 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

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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.

The afore-mentioned work (Buragohain *et al*. 1977) was carried out using the stiffness matrix method. Moreover, it was based on simplified assumptions and a relatively less realistic approach. Pointing out the lacunae in Buragohain's *et al*. (1977) interaction analysis of a framed structure resting on pile foundation, Chore and co-authors presented the interaction analysis of a single storeyed building frames embedded in clayey soil using a more rational approach with realistic assumptions. Many studies reported in the recent past related to the theme included Chore and Ingle (2008a,b), Chore *et al*. (2009, 2010a). Although most of the analyses used the sub-structure method (uncoupled approach), few of them used coupled approach where the structure and foundation were considered to be a single compatible unit. However, these investigations underscored that the sub-structure approach is preferred in such interaction analysis owing to simplicity in the method, less memory requirement on the part of computational resources, and no much variation in the results obtained using the sub-structure method and coupled approach. Recently, along similar lines, Reddy and Rao (2011) reported an experimental work on a model building frame supported by a pile group and compared the results analytically using the finite element analysis.

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

In the meantime, much work is available in the literature on axially loaded as well as laterally loaded single pile and pile groups. The approaches available for the analysis of axially loaded pile foundations include the elastic continuum method (Polous 1968 and Butterfield and Banerjee 1971) and load transfer method (Coyle and Reese 1966, Hazarika and Ramasamy 2000, Basarkar and Dewaikar 2005), while those for analyzing the laterally loaded pile foundations include the elastic continuum approach (Spiller and Stoll 1964, Polous 1971, Banerjee and Davis 1978) and modulus of subgrade reaction approach (Matlock and Reese 1956, Matlock 1970, Georgiadis *et al*. 1992, Dewaikar and Patil 2006). With the advent of computers in the early seventies, more versatile finite element method (Desai and Abel 1974, Desai and Appel 1976, Desai *et al*. 1981, Ng and Zhang 2001, Krishnamoorthy *et al*. 2005, Chore *et al*. 2010b, Chore *et al*. 2012a,b) has become popular for analyzing the problem of pile foundations in the context of linear and non-linear analysis

On the backdrop of the considerable work of the interaction analyses of space frame-pile foundation-soil system reported in the recent past, the interaction analysis of a single storeyed frame resting on pile foundation as available in the literature (Chore *et al*. 2010a) is reported in this investigation using finite element based software SAP-IV as against the one carried out by *Chore et al*. (2010a) wherein a numerical procedure, developed based on the complete 3-D modeling of the frame and simplified modeling for substructure, was programmed into FORTRAN-90. While the interaction analysis reported in the published literature (Chore *et al*., 2010a) was carried out using the sub-structure approach, the present work aims at reporting the coupled analysis of the same system.

2. Problem description

A three-dimensional single storeyed building frame resting on the pile foundation, as shown in Fig. 1 (Chore *et al*. 2010a), is considered for the study. The frame, 3 m high is 10 m × 10 m in plan with each bay of 5 m × 5 m. The slab, 200 mm thick, is provided at the top as well as at the floor level. The slab at the top is supported by 300 mm wide and 400 mm deep beams. The beams are resting on square columns of size 300 mm.

Two different pile groups comprising two and three piles each in a group with series and parallel arrangement of piles therein are considered. In addition, the pile foundation comprising a single pile is also considered, which was not considered in the study by Chore *et al*. (2010a). All the piles in a group are connected by 500 mm thick pile cap. The concrete of M- 20 grade is assumed for the superstructure elements and that of M-40, for the substructure elements.

While the 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, the lateral loads shown in the Fig. 1 are also considered. The properties of the material for the piles and pile caps are given in Table 1.

Fig. 2 and Table 2 show the particulars of the various configurations of the pile groups considered in the parametric study.

The thickness of the pile cap is considered to be 300 mm and the spacing between the piles is varied as 2D, 3D, 4D and 5D.

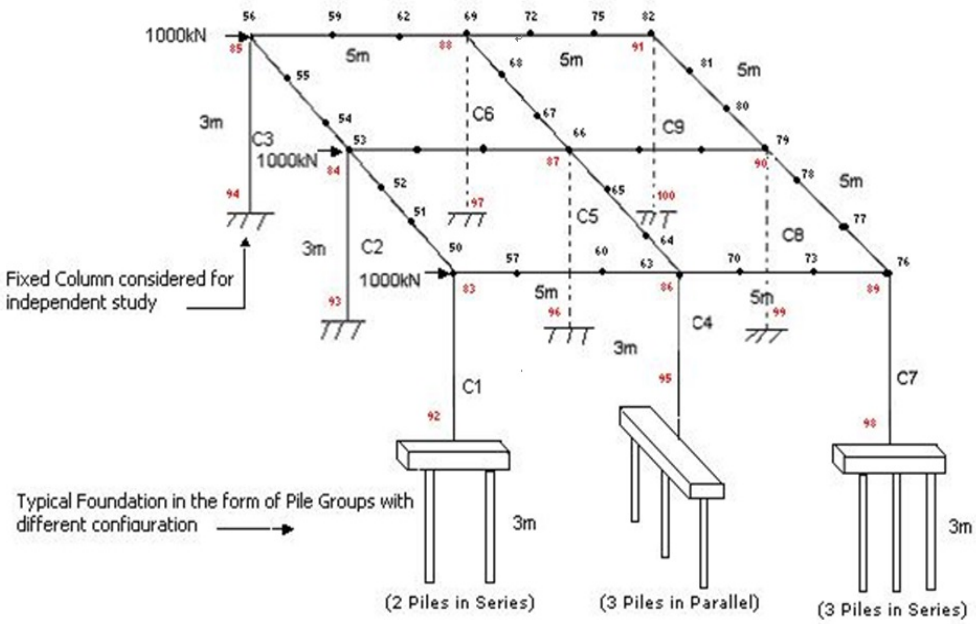


Fig. 1 Typical building frame (After Chore *et al*. 2010a)

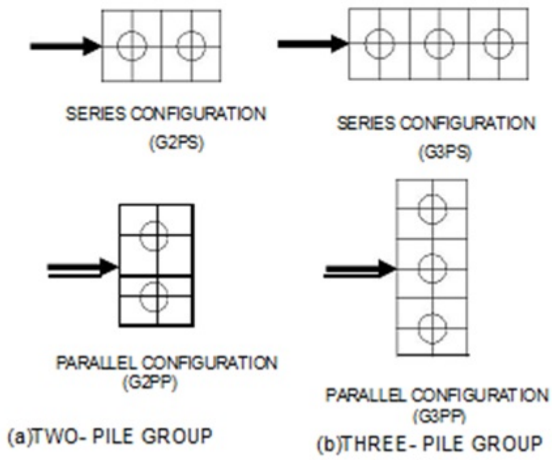


Fig. 2 Different configurations of piles

Table 1 Material properties

Particulars	Corresponding values
Pile size/ Diameter	300 mm
Length of pile	3 m (3000 mm)
Concrete grade used for superstructure elements	M-20
Young's modulus for superstructure elements	0.25491×10^8 kPa
Concrete grade used for Sub-structure elements	M- 40
Young's modulus of Sub-structure elements	0.3605×10^8 kPa
Poisson's ratio for concrete	0.15

Table 2 Configurations of pile groups

Sr. No.	Particulars of the pile groups
1.	Single Pile
2.	Two piles (Series arrangement) [G2PS]
3.	Two piles (Parallel arrangement) [G2PP]
4.	Three piles (Series arrangement) [G3PS]
5.	Three piles (Parallel arrangement) [G3PP]

3. Modeling idealizations for analysis in SAP- 2000

The interaction analysis reported herein envisages use of the finite element based software SAP-2000. For this purpose, the slabs provided at the top as well as at the bottom of the superstructure frame are modeled using four noded two dimensional thin shell elements; beams and columns are modeled using two noded one dimensional beam-column elements. Further, similar analogy is applied for modeling the sub-structure elements such as the pile caps and piles. The soil is simulated using closely spaced discrete linear springs.

Fig. 3 shows the schematic of the mathematical model of the building frame with fixed column bases. Further, Figs. 4-8 show the solid mathematical model as well as schematic of the finite

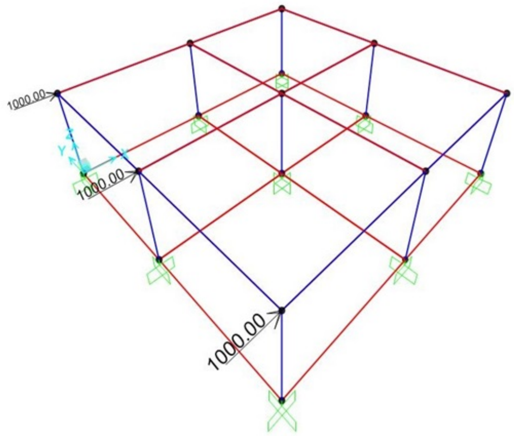
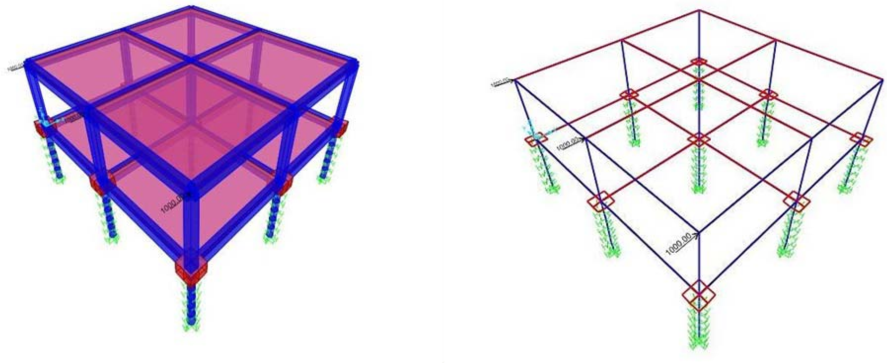
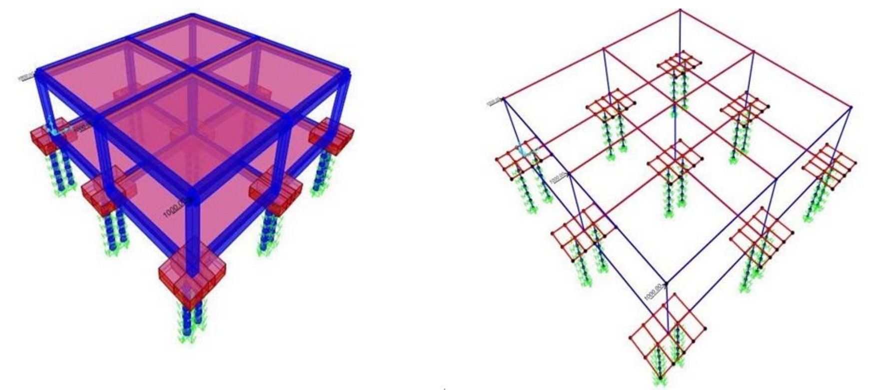


Fig. 3 Finite element model of the building frame



(a) Extruded 3-D model (b) Schematic of F.E. model

Fig. 4 Mathematical model for a frame with single pile foundation



(a) Extruded 3-D model (b) Schematic of F.E. model

Fig. 5 Mathematical model for a frame with two piles (series arrangement)

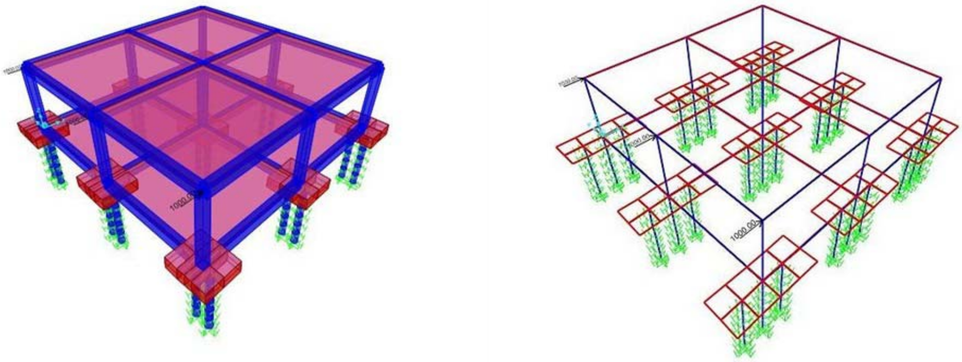


Fig. 6 Mathematical model for a frame with two piles (parallel arrangement)

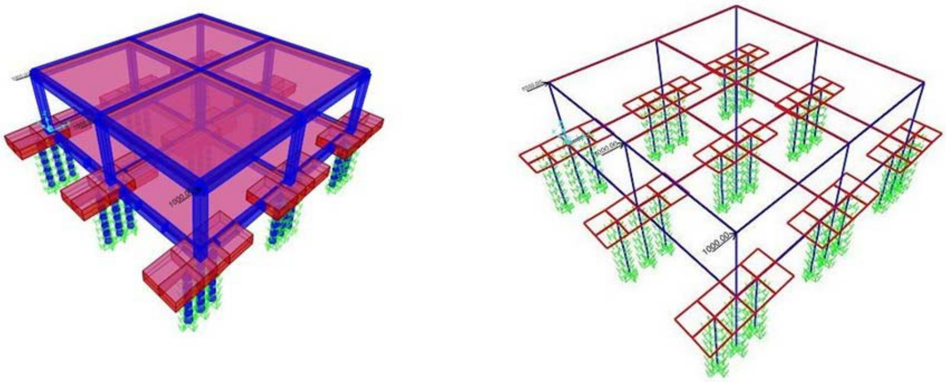


Fig. 7 Mathematical model for a frame with three piles (series arrangement)

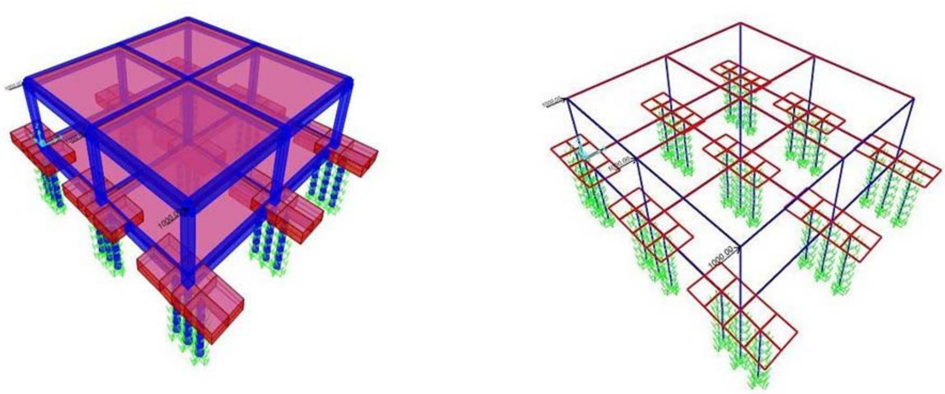


Fig. 8 Mathematical model for a frame with three piles (parallel arrangement)

element model of the building frame with different arrangement of pile foundations. The spring constant (k_s) as required in the analysis of SAP-2000 is calculated using the relation given by Bowles (1988) in the context of the value of the modulus of subgrade reaction listed in Table 1.

4. Results and discussion

The building frame modeled using the afore-mentioned idealizations is analyzed to evaluate the displacement at the top of the frame and bending moment in columns. The results obtained are discussed in the sub-sequent sections.

4.1 Effect of SSI on displacement at top of frame

The displacements evaluated at the top of the frame in respect of various pile configurations and different pile spacings are listed in Table 3.

From the results of parametric study conducted on a specific building frame with pile foundation of different configurations, it is observed that the top displacement is very less (58.3 mm) when the column bases are fixed and increases when the effect of soil-structure interaction is taken into account. For a single pile configuration, the maximum displacement at the top is 136.1 mm. The soil structure interaction is found to increase the displacement by 133.45%.

The maximum values of the displacement at the top of the frame are found to be 95.9 and 101.8 mm at the minimum spacing of 2D for groups of two piles with series and parallel arrangement, respectively. The corresponding values at the higher pile spacing of 5D are observed to be 91.2 mm and 101.5 mm, respectively. Incorporation of the aspect of soil-structure interaction is found to increase the top displacement in the range of 56.43 to 74.62% when compared with the displacement obtained for the fixed base for the same groups of two piles.

For group of three piles, the top displacement is observed to be 81.2 and 91 mm at the closer spacing of 2D in respect of series and parallel arrangement, respectively. The corresponding values of displacement at higher displacement of 5D are found to be 80.2 and 90.7 mm, respectively. The soil-structure interaction is found to increase the displacement in the range of 37.57 to 56.09%.

Table 3 Top displacement and percentage increase in top displacement with SSI

	Top displacement (mm)				**Percentage increase**			
Pile Spacing	2D	3D	4D	5D	2D	3D	4D	5D
Single Pile	136.1				133.45			
G2PS	95.9	93.3	92	91.2	64.50	60.03	57.80	56.43
G2PP	101.8	101.6	101.5	101.5	74.61	74.27	74.10	74.10
G3PS	81.2	80.5	80.3	80.2	39.28	38.08	37.74	37.56
G3PP	91	90.8	90.7	90.7	56.09	55.75	55.57	55.57

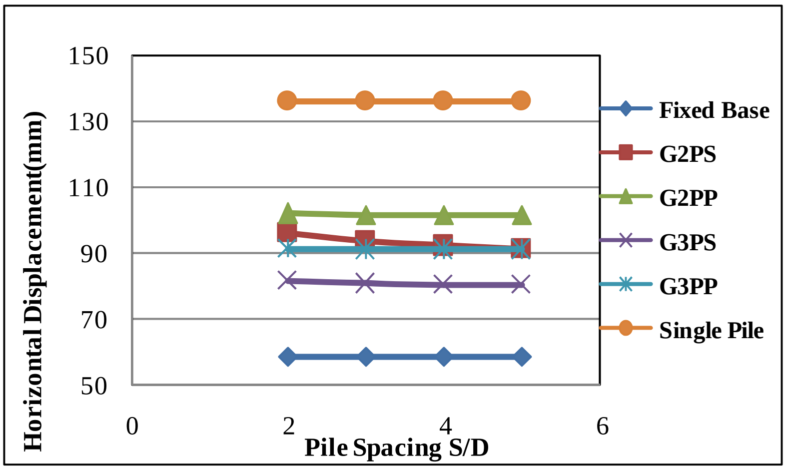


Fig. 9 Effect of pile spacing on horizontal displacement at top of frame

4.1.1 Effect of pile spacing

The trend of horizontal displacement at the top of frame with pile spacing in respect of all pile diameters of all configurations of the pile group is shown in Fig. 9.

The general trend observed for all the configurations considered with respect to the pile diameter is that the horizontal displacement is higher when the spacing between two piles is kept 2D and thereafter, decreasing with higher spacing, i.e., 3D, 4D and 5D, in all the configurations considered. This trend of reduction in displacement with the increase in spacing can be attributed to the overlapping of the stressed zones of individual piles at closer spacing. When the piles are closer, combined action of the pile and pile cap is more rigid; and moreover, in three-dimensional formulation, it reflects the block action. Owing to this, the displacement is observed higher 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 groups of two piles with series arrangement, the corresponding difference is rather marginal for the remaining groups.

4.1.2 Effect of pile spacing

Effect of the configuration of pile group on the response of the superstructure is quite prominent. It is obvious from the results that for the parallel arrangement, the displacements obtained are on the high side compared to the series arrangement in respect of groups of two piles.

The series arrangement exhibits stiffer behaviour than parallel arrangement. This is because the combined structural stiffness of pile and pile cap in parallel arrangement is small as compared to that in series arrangement. For short to medium length piles, it can be a governing factor. The piles used in the present study falls under the category of short piles. For longer piles, different trend is possible where soil imparts considerable strength.

4.1.3 Effect of number of piles

It is observed from Table 3 that with the increase in number of piles in a group of identical configuration, the displacement at the top of the frame decreases. Larger number of piles increases the stiffness of the pile group, which further results in reduction in the displacement.

4.1.4 Comparison with the published results (Chore et al. 2010a)

The values of the displacements obtained in the present study are compared with those available in Chore *et al*. (2010a) in Table 4.

The percentage increase in the displacements at the top of the frame is compared with those obtained by Chore *et al*. (2010a) in Table 5.

When compared with those of Chore *et al*. (2010a), the values of the displacements obtained in the present study are on the high side in respect of either condition with fixed column bases or with soil-structure interaction. The displacement obtained in the present study is found to underestimate that obtained by Chore *et al*. (2010a) by 52.7% for the condition of fixed column bases.

Along similar lines, in respect of the group of two piles, the increase in displacement with respect to that by Chore *et al*. (2010a) is observed in the range of 26.38 – 39.92%. Further, the increase is found to be on the high side for the parallel arrangement of piles for the case of groups with two piles. Similarly, the corresponding increase is found in the range of 9.86 – 22%. Again the increase is on the high side in respect of parallel configuration for groups of three piles.

The trend of reduction in displacement with spacing although remains the same, the reduction in displacement for higher spacing such as 3D onwards is too marginal for groups with two piles (series arrangement) and either arrangement of groups with three piles as against that observed for the displacements available in Chore *et al*. (2010a).

The difference in the results obtained and those of Chore *et al*. (2010a) is attributed to the variations in modeling idealizations resorted to in the either analysis. The present study deals with the coupled analysis of the system of superstructure and sub-structure, whereas the analysis reported by Chore *et al*. (2010a) follows the un-coupled (i.e., sub-structure) approach, in which the frame is analyzed on the presumption of fixed column bases, the foundation is worked out separately and thereafter, the stiffness of the foundation is provided at the column bases to get the response due to interactive behaviour.

Moreover, while the frame was treated as the space structure, the elements of the superstructure

Table 4 Top displacements (in mm)

Pile spacing	Present study				Chore *et al*. (2010)			
	2D	*3D*	*4D*	*5D*	*2D*	*3D*	*4D*	*5D*
Fixed	58.3				38.18			
G2PS	95.9	93.3	92	91.2	75.88	72.86	70.41	68.48
G2PP	101.8	101.6	101.5	101.5	77.63	75.68	74.08	72.54
G3PS	81.2	80.5	80.3	80.2	73.91	71.52	69.64	68.24
G3PP	91	90.8	90.7	90.7	77.63	76.80	75.59	74.30

Table 5 Percentage increase in SSI with respect to those by Chore *et al*. (2010a)

Pile spacing	Present study			
	2D	*3D*	*4D*	*5D*
Fixed	58.3			
G2PS	26.38	28.05	30.66	33.17
G2PP	31.13	34.25	37.01	39.92
G3PS	9.86	12.56	15.31	17.53
G3PP	17.22	18.23	20	22.07

were modeled using 20 noded isoparametric continuum elements in a similar study by Chore *et al*. (2010a). The latter was further resorted to the use of a simplified approach for modeling the sub-structure, in that the pile cap was idealized as the two dimensional plate element and the pile by one dimensional beam column element, whereas the behaviour was idealized using closely spaced discrete independent springs.

On the contrary, the present study uses more simplified idealizations for modeling the superstructure frame. The slabs at the top as well as the bottom are idealized using four noded two dimensional thin shell elements, and the beams and columns using two noded one dimensional beam column elements as against the complete 3-D idealization of the space frame with 20 noded isparametric continuum elements in the study by Chore *et al*. (2010a). Further, the behaviour of the pile cap was considered flexible in the aforementioned study, whereas the pile cap in the present study seems to be rigid. Further, there may be slight variation in the dimensions of the pile cap in either analysis. These can be some of the reasons for different trends in the results obtained in either analysis, although the superstructure frame and other details remain the same. All the trend of the results for the displacement at the top of the frame remains the same by and large.

4.2 Effect of SSI on B.M. in superstructure columns

The effect of soil-structure interaction (SSI) on the bending moment at the top and bottom of superstructure columns of the specific frame is evaluated, with the percentage increase or decrease calculated. The absolute maximum moments in columns obtained in view of SSI and those obtained considering the column bases to be fixed are compared.

The absolute maximum positive (sagging) and negative (hogging) moments in columns of the frame obtained considering the effect of SSI are shown in Table 6 at the lowest spacing between the

Table 6 Max. positive and negative bending moments (kN-m) and increase with SSI

Positive B.M.		% increase		Negative B.M.		% increase	
2D	5D	2D	5D	2D	5D	2D	5D
Group of two piles (Series configuration) [G2PS]							
582.26 (317)	564.1 (317)	3.26 (15)	0.043 (15)	-589.7 (-361)	-569.58 (-360)	5.25 (28)	1.65 (27)
Group of two piles (Parallel configuration) [G2PP]							
591.61 (317)	621.83 (317)	4.92 (15)	10.28 (15)	-587.51 (-361)	-621.14 (-360)	4.85 (28)	10.86 (27)
Group of three piles (Series configuration) [G3PS]							
568.61 (317)	563.04 (317)	0.84 (15)	-0.14 (15)	-571.51 (-360)	-567.03 (-360)	2.00 (27)	1.20 (27)
Group of three piles (Parallel configuration) [G3PP]							
614.31 (317)	613.61 (317)	8.95 (15)	8.82 (15)	-617.37 (-360)	-615.36 (-360)	10.18 (27)	9.82 (27)

piles (2D) and higher spacing (5D). The corresponding change in moments with respect to the moments obtained considering the fixed column bases is also listed in Table 6. In the present study, the values of the absolute maximum positive and negative moments for the fixed column base condition are 563.86 (sagging) and 560.31 kN-m (hogging), whereas these values as obtained in the analysis presented by Chore *et al*. (2010a) are 276 (sagging) and 283 kN-m (hogging).

From this, it is apparent that the sagging moment in the present study is on the high side by 104%, whereas the hogging moment by 98%. The values of the absolute maximum positive and negative moments with respect to the fixed base condition and SSI condition corresponding to lowest spacing and higher spacing between the piles (i.e., 2D and 5D) as obtained by Chore *et al*. (2010a) are also given in Table 6 in parentheses.

From the values listed in Table 6, the effect of SSI is found to increase the maximum positive moment in columns in the range of 2-12% with respect to the absolute maximum positive moment obtained for the fixed base condition. The corresponding increase in the maximum negative moment in columns is found to be in the range of 2-11.

In contrast, the effect of SSI, as observed by Chore *et al*. (2010a), was to increase the maximum positive moment in the range of 14-15% with respect to the absolute maximum positive moment. The corresponding increase in the maximum hogging moment was found in the range of 26-27%. Thus, the moments in the present study is found to be underestimated by 3-12% and 6- 24% compared with those of Chore *et al*. (2010a).

Table 7 Maximum moment and percentage increase in columns for single piles

Column	Moment for fixed base	Moment for flexible base	Percentage difference
C-1(T)	-429.5	-436.37	1.60
C-2 (T)	-471.89	-406.62	-13.83
C-4(T)	-536.9	-599.42	-12.83
C-5 (T)	-560.32	-642.61	14.69
C-7 (T)	-429.69	-429.31	-0.09
C-8 (T)	-473.59	-500.91	5.77
C-1 (B)	499.54	407.3	-18.47
C-2 (B)	520.1	472.3	-9.19054
C-4(B)	552.02	593.94	-8.19
C-5 (B)	563.86	639.75	13.46
C-7 (B)	479.84	407.57	-15.06
C-8 (B)	520.18	475.36	-8.62

4.2.1 Effect of SSI on maximum moment in individual columns

4.2.1.1 Groups of single piles

As for groups of single piles, the hogging moment in all the columns is found to be varying. For the corner columns (C-1 and C-3), the hogging moment is found to increase by 1.59%, while for column C-2 the hogging moment is found to decrease by 13.83%. The percentage increase in bending moment at the top of the central column C-5 is 14.68%, whereas for column C-7 it is negligible. The sagging moment in the columns shows a decrease ranging from 8.2 to 18.47% in all the columns except for column C-5, which shows an increase of 13.45%.

4.2.1.2 Groups of two piles (G2PS and G2PP)

As for groups of two piles with either configuration, the hogging moment in all the columns is found to increase. For the series arrangement, in corner columns (C-1 and C-3), the hogging moment is found to increase by 1.58%, while in column C-2 the increase is 2.11%. The corresponding values observed for the parallel configuration are 5.6 and 3.5%, respectively. The increase in hogging moment in the columns placed in the row on the left hand side is observed to be on the high side for the parallel configuration.

Table 8 Maximum moment and percentage increase in columns for groups of two piles

Column	Moment for fixed Base	Maximum moment	Percentage difference	Maximum moment	Percentage difference
		Series configuration		*Parallel configuration*	
C-1(T)	-429.05	-435.81	1.58	-452.9	5.56
C-2 (T)	-471.89	-481.88	2.12	-488.14	3.44
C-4 (T)	-536.9	-559.59	4.23	-587.5	9.42
C-5 (T)	-560.32	-582.26	3.92	-623.09	11.20
C-7 (T)	-429.69	-489.81	13.99	-457.22	6.41
C-8 (T)	-473.59	-513.74	8.48	-490.65	3.60
C-1 (B)	499.54	490.8	-1.75	430.82	-13.76
C-2 (B)	520.1	512.81	-1.40	475.82	-8.51
C-4 (B)	552.02	560.21	1.48	593.52	7.52
C-5 (B)	563.86	589.7	4.58	622.66	10.43
C-7 (B)	497.84	437.51	-12.12	432.19	-13.18
C-8 (B)	520.18	484.85	-6.79	478.63	-8.00

In respect of either configuration, the positive moment in columns C-4 and C-5 increase in the range of 1.48 - 7.5% and 4.58 - 10.43%, respectively. The positive moment in all other columns is found to decrease, the minimum decrease being in the range of 1.74%- 8% and the maximum in the range of 12.12 - 13.76%.

The hogging moment in all other columns, i.e., C-4 to C-9 increases; the increase being in the range of 4.3 -14% for the series configuration with an exception of C-5, which shows an increase of 3.9%. The hogging moment in the columns C-4 to C-9 for the parallel configuration shows an increase ranging from 3.6 to 11.2%. Further, when the increase in hogging moment in columns in the centre and that on the right hand side in the context of groups of two piles are compared, it is observed that, the increase is slightly on the high side for the series configuration than for the parallel arrangement.

For the series arrangement, the percentage decrease in the sagging moment in columns C-1 and C-3 is found to be 1.75%. The decrease in column C-2 is found to be 1.41%. The positive moment is found to decrease by 12.2% for column C-7. The decrease is observed to be 6.8% for column C-8.

In respect of parallel configuration, the positive moment is found to decrease by 13.76% for columns C-1 and C-3, and 8.5% for column C-2. The decrease in columns C-7 and C-9 placed on the right hand side is found to be 13.19%, while that in column C-8 is 7.99%.

As for the positive moments of various configurations, the percent decrease for the columns placed on left hand side of the frame is observed to be slightly on the high side for series configuration. The decrease and increase for the columns placed in the intermediate (central) side of the frame are on the high side for parallel configuration, though the difference is negligible.

4.2.1.3 Group of three piles (G3PS and G3PP)

For groups of three piles with either configuration, the hogging moment in all the columns is found to increase. For series arrangement, in corner columns (C-1 and C-3), the hogging moment is found to increase by 0.79% while in column C-2 it is 0.85%. The corresponding values for parallel configuration are 1.6 and 3.13%. The increase in hogging moment in the columns placed in the row on the left hand side is observed to be on the high side for parallel configuration.

The hogging moment in all other columns, i.e., C-4 to C-9, increases; the increase being in the range of 3.18 - 14.5% for either arrangement. Further, when the configurations for groups of three piles are compared, it is observed that the increase in the hogging moment for columns in the centre and those on the right hand side is found to be almost same for both configurations.

For either configuration, the positive moment in column C-5 increases by 1.36%. The positive moment in all other columns is found to decrease, the minimum decrease being 0.92% and maximum being 12.89%.

For the series and parallel arrangements, the percentage decrease in the sagging moment in columns C-1 and C-3 is found to be 1.24 and 12.12, respectively. The decrease in column C-2 is found to be 0.92% for series configuration and 8.07% for parallel configuration. For columns C-4 and C-6, the corresponding decrease is found to be 1.02% for series configuration, while there is an increase of 6.03% for parallel configuration. The positive moment is found to decrease by 12.89 and 8.03% for columns C-7 and C-8, respectively, for series arrangement, and the corresponding decrease for parallel arrangement is observed to be 11.78 and 7.62%.

As for positive moments of either configuration, the decrease for the columns placed on the left hand side of the frame is observed to be almost same. The decrease and increase in moment for the columns placed in the intermediate (central) side of the frame is almost same. Along similar lines, the percentage decrease in columns C-7 and C-8 is almost the same for either configuration.

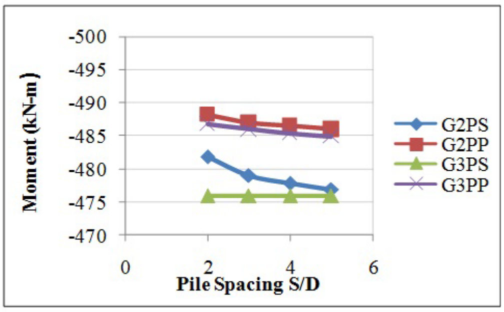
Table 9 Maximum moment and percentage increase in columns for groups of three piles

Column	Moment for fixed base	Maximum moment	Percentage difference	Maximum moment	Percentage difference
		Series configuration		*Parallel configuration*	
C-1(T)	-429.05	-432.48	0.80	-435.91	1.60
C-2 (T)	-471.89	-475.92	0.85	-486.7	3.14
C-4 (T)	-536.9	-553.99	3.18	-582.6	8.51
C-5 (T)	-560.32	-568.61	1.48	-617.37	10.18
C-7 (T)	-429.69	-491.98	14.50	-437.8	1.89
C-8 (T)	-473.59	-515.73	8.90	-489.12	3.28
C-1 (B)	499.54	493.31	-1.25	439	-12.12
C-2 (B)	520.1	515.29	-0.92	478.14	-8.07
C-4 (B)	552.02	546.42	-1.01	585.86	6.13
C-5 (B)	563.86	571.51	1.36	614.3	8.95
C-7 (B)	497.84	433.67	-12.89	439.21	-11.78
C-8 (B)	520.18	478.41	-8.03	480.54	-7.62

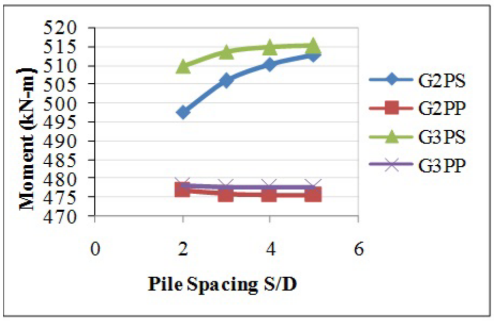
4.2.2 Effect of arrangement of piles on bending moment for columns with various spacings

The variation of bending moment at the top and bottom of few typical columns (C-2, C-5 and C-8) for various spacings for both configurations is shown in Fig. 10. Similarly, the values of bending moment for various spacings at the top and bottom of all the columns are shown in Appendix.

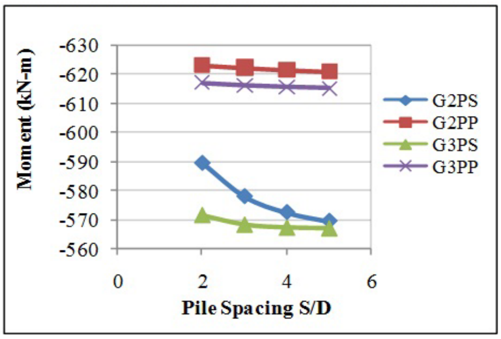
For groups of two piles with series arrangement, the bending moment (i.e., hogging moment) at the top of corner columns, (C-1, C-2 and C-3) placed on the left hand side of the frame decreases on the negative side with increasing spacing and that at the bottom, increases. For all other columns of the frame, i.e., columns in the interior (C-4, C-5 and C-6) and those on the right hand side (C-7, C-8 and C-9), the moment at the top of the columns decreases on the negative side with increasing spacing. Similarly, the moment at the bottom of the columns decreases with increasing spacing. Almost similar trend is observed for groups of two piles with parallel arrangement with certain exceptions. For columns placed on the right hand side of the frame, the bending moment at the bottom of columns C-7, C-8 and C-9 decreases on the negative side with increasing spacing, unlike that for series arrangement.



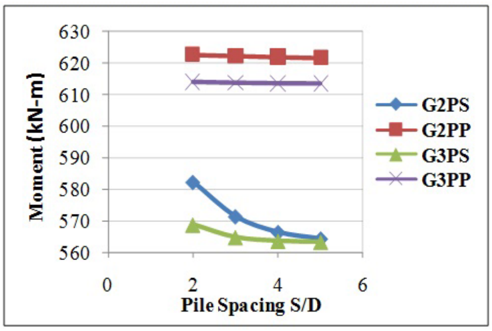
(a) Variation of hogging moment vs. spacing at top of column C-2



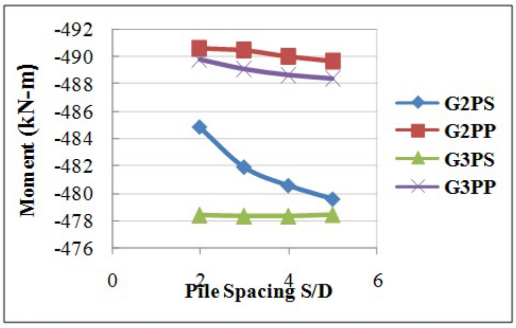
(b) Variation of sagging moment vs. spacing at bottom of column C-2



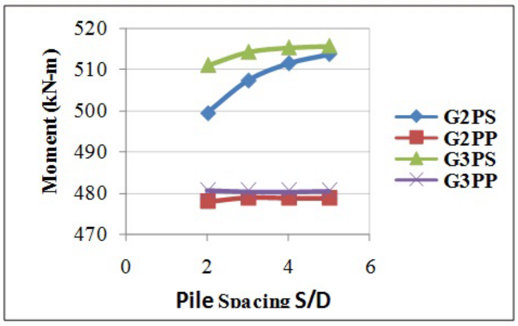
(c) Variation of hogging moment vs. spacing at top of column C-5



(d) Variation of sagging moment vs. spacing at bottom of column C-5



(e) Variation of hogging moment vs. spacing at top of column C-8



(f) Variation of hogging moment vs. spacing at bottom of column C-8

Fig. 10 Variation of moment at top and bottom of typical columns of the frame

For groups of three piles with series arrangement, the bending moment at the bottom of columns C-1, C-2 and C-3 remains more or less the same, whereas at the top goes on increasing. For columns in the centre the bending moment at top goes on decreasing on the negative side, while at the bottom goes on decreasing. For columns C-7 and C-9, the moment at the bottom increases with increasing spacing, whereas for column C-8, the moment decreases with increasing spacing. However, for parallel arrangement with three pile groups, the bending moment at the top goes on decreasing on the negative side, whereas at the top remains constant more or less.

4.2.3 Effect of number of piles on bending moment for columns with various pile spacings

The effect of number of piles in a pile group is studied concerning the variation of moment in columns with various pile spacings for either configuration. For series configuration, the trend of variation in moment for either group is almost same for groups of two piles and three piles, except that at the bottom of the columns placed on the either side of the frame. While the moment at the bottom of columns C-2 and C-8 increases with increasing pile spacing for groups of two piles and three piles, it decreases in all other cases. For parallel configuration, the trend of variation of bending moment is similar at the top and bottom of all the columns for groups of two piles (G2PP) and those of three piles (G3PP).

5. Conclusions

The following conclusions are drawn from the numerical studies conducted in this paper:

(1) The effect of soil-structure interaction on the top displacement of the frame is quite significant. The displacement at the top of frame increases by 133% when the effect of SSI is taken into account for pile foundation comprising a single pile.

(2) The increase in the displacement is observed to be in the range of 38-75% when the effect of SSI is taken into account for groups with two and three piles. This indicates that increasing the number of piles can result in decrease of the displacement.

(3) The displacement at the top of the frame decreases with the increase in pile spacing for all configurations of pile groups.

(4) The arrangement of piles with respect to the direction of the lateral load acting on the frame and the number of piles for particular configuration is significant factors to be considered in design.

(5) With increasing number of piles in a group under identical arrangement, the displacement decreases, due to enhancement of the stiffness of the pile groups.

(6) The effect of soil-structure interaction is significant on bending moment, which can result in variation of the maximum positive and negative moments in the range of 0-15 and 8-18%, respectively for the case of single piles.

(7) The increase in the absolute maximum positive and negative moment in columns is observed to be in the range of 2-12 and 2-11% when compared with those obtained using the conventional analysis.

(8) For either configuration, the increase in the maximum (hogging) moment is observed in the range of 1.58- 5.56% for columns placed on the left hand side (leading rows in the context of lateral load) of the frame. The hogging moment in all other columns (C-4 to C-9) increases in the range of 4-14 %. The positive moment in the central column C-5 increases in the range of 4.6-10.4 %. And the positive moment in column C-4 increases in the range of 1.5-7.52%.

(9) For columns with identical arrangement, the percentage difference in moments of columns is marginal for groups of two piles, whereas such difference for groups of three piles is considerably negligible.

(10) The effect of SSI seems to be less for columns placed in the leading row and more for columns placed in the trailing row.

A comparison of the results obtained in the present analysis with those of Chore *et al*. (2010a) exhibits fair agreement. Further, the trend in the response obtained in either study is also same by and large. The difference in the values of the response can be attributed to the different axioms followed in either study. All the same, the effect of soil-structure interaction is shown to be prominent on the response of the specific building frame considered and the type of foundation used in the present study.

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