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ANALYSIS OF A BUILDING FRAME CONSIDERING SOIL STRUCTURE INTERACTION

Raksha Khare[1] And Dr.H.S.Chore[2]
[1]*Department of Civil Engineering A.P.Shah Institute of Technology,Thane (MS)*
[2]*Department of Civill engineering ,Datta Meghe College of Engineering,Airoli (MS)*

Abstract - The study deals with the physical modeling of a typical four (G+3) building frame resting on pile foundation and embedded in cohesive soil mass using the finite element based software Etabs . Two groups of piles comprising two and three piles, with series and parallel arrangement thereof, are considered The slab of the frame is idealized as three dimensional four-noded shell elements. Beams and columns of the superstructure frame are idealized as three dimensional two-noded beam elements. Pile of the sub-structure is idealized as three dimensional six-noded beam elements.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 effect of the soil- structure interaction is observed to be significant for the type of foundation and soil considered in this study.

Keywords— Soil-structure interaction; pile groups; pile spacing; top displacement; bending moment.

I. 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 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 (2008 a,b), Chore *et al*. (2009, 2010 a). 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); 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.

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 and Hazarika and Ramasamy 2000, Basarkar and Dewaikar 2005), while those for analyzing the laterally loaded pile foundations include the elastic continuum approach (Spiller and Stoll 1964, Polous 1971, Banerjee and Davis 1978) and modulus of subgrade reaction approach (Matlock and Reese 1956, Matlock 1970, Georgiadis *et al*. 1992, Dewaikar and Patil 2006). With the advent of computers in the early seventies, more versatile finite element method (Desai and Abel 1974, Desai and Appel 1976, Desai *et al.* 1981, Ng and Zhang 2001, Krishnamoorthy *et al.* 2005, Chore *et al.* 2010 b; Chore *et al.* 2012 a and 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 four storeyed frame resting on pile foundation is reported in this investigation using finite element based software ETABS.

II. PROBLEM DESCRIPTION

A four storeyed (G+3) space frame resting on pile foundation as shown in Fig 1 is considered for the purpose of the parametric study. Figure 2 shows the arrangement of column and beams. The frame, 9 m high, is 10 m × 10 m in plan with each bay of dimension 5m × 5m. The height of each storey is 3 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 beams, 300 mm wide and 400 mm deep, which in turn rest on columns of size 300 mm × 300 mm.

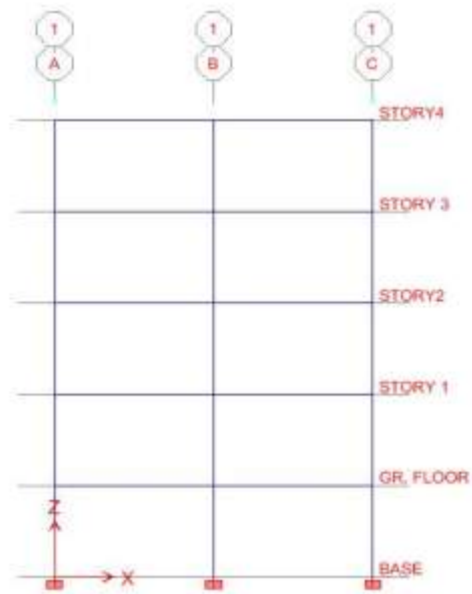

Figure 1: Typical building frame.

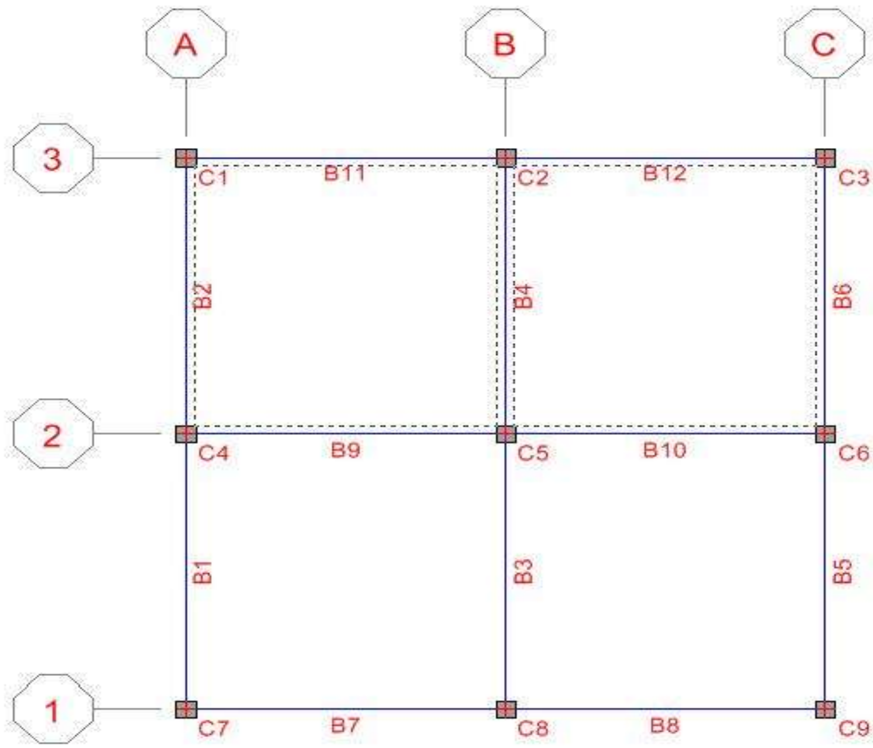

Figure 2: Plan view showing beam and column postion

Two different pile groups comprising two and three piles each in a group with series and parallel arrangement of piles therein are considered. 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 properties of the material for the piles and pile caps are given in Table 1.

Table 1 Material properties

Properties	**Corresponding Values**
Grade of Concrete used for the Frame Elements	M-20
Young's Modulus of Elasticity for Frame Elements (E_c Frame)	0.25491×10^8kPa
Young's Modulus of Elasticity for Foundation Elements (E_c Foundation)	0.3605×10^8kPa
Poisson's Ratio (μ_c)	0.15
Young's modulus of elasticity (E_s)	4267 kN/m^2
Poisson's ratio (μ_s)	0.45

Figure 3 and Table 2 show the particulars of the various configurations of the pile groups considered in the parametric study.

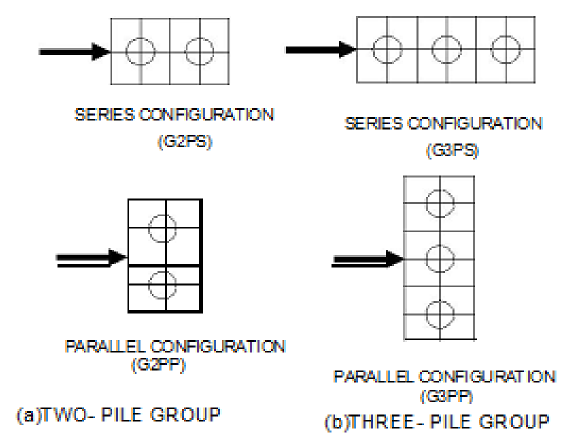

Figure 3. Different configurations of piles.

Table 2 Configurations of pile groups

Sr. No.	**Particulars of the Pile Group**	Cap	Spacing
1	Two Piles (Series Arrangement) [G2PS]	500 mm	2D, 3D, 4D, 5D
2	Two Piles (Parallel Arrangement) [G2PP]	500 mm	2D, 3D, 4D, 5D
3	Three Piles (Series Arrangement) [G3PS]	500 mm	2D, 3D, 4D, 5D
4	Three Piles(Parallel Arrangement) [G3PP]	500 mm	2D, 3D, 4D, 5D

Modeling idealization for analysis in Etabs

The interaction analysis reported herein envisages use of the finite element based software Etabs. For this purpose, The slab of the frame is idealized as three dimensional four-nodded shell elements. Beams and columns of the superstructure frame are idealized as three dimensional two-nodded beam elements. Pile of the sub-structure is idealized as three dimensional six-nodded beam elements.

Figure 4 shows the schematic of the mathematical model of the building frame with fixed column bases. Further, Figures 5-8 show the schematic and extruded view model of the building frame with different arrangement of pile foundations.

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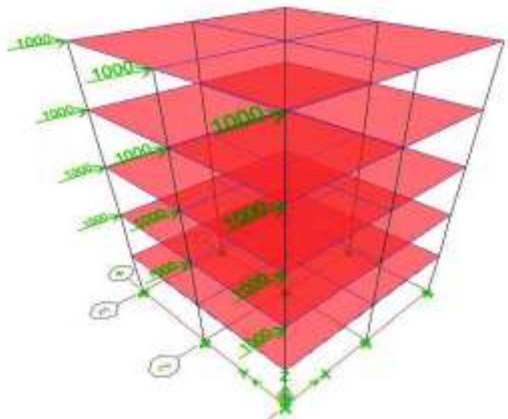
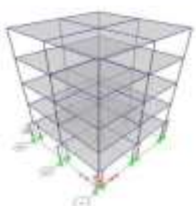
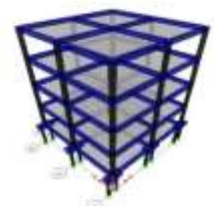
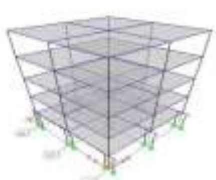
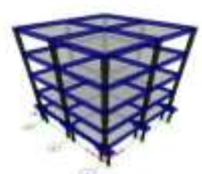
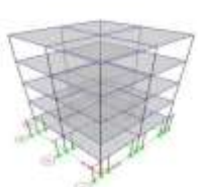


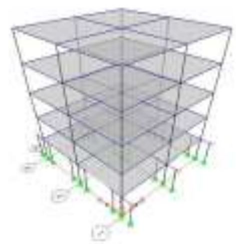
Figure 4. Schematic model of the building frame in fixed position **.**

	
(a) Schematic model for group of two piles (Series arrangement)	**(b)** Extruded model
Figure 5. Mathematical model for a frame with group of two piles (Series arrangement)	

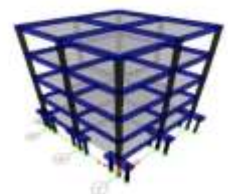
	
(a) Schematic model for group of two piles (parallel arrangement)	**(b)** Extruded model
Figure 6. Mathematical model for a frame with two piles (parallel arrangement)	
	

(a) Schematic model for group of three piles (Series arrangement)	**(b)** Extruded model

Figure 7. Mathematical model for a frame with three piles (Series arrangement)



(a) Schematic model for group of three piles (Parallel arrangement)



(b) Extruded model

Figure 8. Mathematical model for a frame with three piles (Parallel arrangement)

IV. 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 spacing are listed in Table 4-7.

Table 4 Values of displacements (mm) for (G2PS) with corresponding increase due to SSI

Storey Height (m)	Fixed Base	Soil-Structure Interaction				Percentage increase due to SSI			
		2D	3D	4D	5D	2D	3D	4D	5D
12	408.68	528.68	516.12	509.62	509.62	29.36	26.28	24.69	23.89
9	328.61	448.86	436.23	429.52	429.52	36.59	32.75	30.71	29.69
6	213.23	253.47	280.93	274.53	274.53	37.63	31.75	28.75	27.1
3	115.28	108.93	183.26	180.38	180.37	63.88	58.97	56.47	55.03
0	0	60.97	58.76	54.23	52.34	100	100	100	100

Table 5: Values of displacements (mm) for (G2PP) with corresponding increase due to SSI

Storey Height (m)	Fixed Base	Soil-Structure Interaction				Percentage increase due to SSI			
		2D	3D	4D	5D	2D	3D	4D	5D
12	408.68	528.68	541.65	540.67	539.86	32.79	32.53	32.29	32.09
9	328.61	448.86	462.78	461.03	459.76	40.77	40.83	40.28	39.91
6	213.23	253.47	305.82	304.82	303.82	43.88	43.42	42.95	42.48
3	115.28	108.93	187.85	187.21	187.02	64.382	62.95	62.39	62.21
0	0	60.97	66.82	63.03	62.99	100	100	100	100

Table 6: Values of displacements (mm) for (G3PS) with corresponding increase due to SSI

Storey Height (m)	Fixed Base	Soil-Structure Interaction				Percentage increase due to SSI			
		2D	3D	4D	5D	2D	3D	4D	5D
12	408.68	542.75	482.6	480.81	480.31	19.45	18.086	17.65	17.54
9	328.61	463.21	402.7	400.87	400.36	24.28	22.55	21.99	21.82
6	213.23	306.8	278.02	276.08	275.41	28.33	30.38	29.48	29.165
3	115.28	189.54	156.78	155.52	155.03	38.28	35.99	34.91	34.45
0	0	67.37	50.63	29.84	29.12	100.00	100.00	100.00	100.00

Table 7: Values of displacements (mm) for (G3PP) with corresponding increase due to SSI

Storey Height (m)	Fixed Base	Soil-Structure Interaction				Percentage increase due to SSI			
		2D	3D	4D	5D	2D	3D	4D	5D
12	408.685	494.23	493.88	492.4	488.24	20.93	20.84	20.48	19.45
9	328.61	410	411.02	410.67	408.45	24.77	25.07	24.97	24.28
6	213.23	253.55	254.83	254.34	253.62	18.91	19.52	19.28	18.94
3	115.28	187.98	187.67	187.76	187.93	63.07	62.79	62.87	63.023
0	0	88.98	88.13	86.90	82.87	100.00	100.00	100.00	100.00

The maximum values of the displacement at top of the frame are found to be 528.628 mm, 516.1 mm, 509.62 mm and 506.35 mm at the minimum spacing of 2D, 3D, 4D and 5D for the group of two piles with series arrangement, respectively. With the effect of soil-structure interaction, it is found to increase the top displacement in the range of 26.28 %- 29.82 % ,when compared with the displacement obtained in view of the fixed base condition in respect of group of two piles in series arrangement.

The maximum values of the displacement at ground floor level of the frame are found to be 60.970 mm, 58.76 mm,54.23 mm and 52.34 mm at the minimum spacing of 2D, 3D, 4D and 5D for the group of two piles with series arrangement, respectively

The maximum values of the displacement at top of the frame are found to be 542.7 mm 541.65 mm, 540.67 mm, 539.86 mm at the minimum spacing of 2D, 3D, 4D and 5D for the group of two piles with parallel arrangement, respectively. Incorporation of the aspect of soil-structure interaction is found to increase the top displacement in the range of 24.12 % to 24.23 % when compared with the displacement obtained in view of the fixed base condition in respect of group of two piles in parallel arrangement.

The maximum values of the displacement at ground floor level of the frame are found to be 162.3 mm,66.82 mm, 68.9 mm, 69.99 mm at the minimum spacing of 2D, 3D, 4D and 5D for the group of two piles with parallel arrangement, respectively.

4.1.2 Effect of configuration of the pile group

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.

4.2.1 Effect of SSI on maximum moment in individual columns

The effect of SSI on the increase or decrease in the maximum moment of individual columns of the frame is given in Tables below for various configurations. Further, the percentage increase or decrease in the moments from the top to bottom of individual columns of the frame due to incorporation of the SSI effect in the analysis is also evaluated. From this, the extent of the SSI effect on columns placed on the left and right hand side of the frame is studied, with the corresponding increase or decrease in the moments of individual columns listed in Tables 8-19.

It is obvious from the results tabulated in the aforementioned tables that the effect of SSI on the moments in superstructure columns is significant when compared with the case of fixed base columns. The effect of SSI appears to be less for the columns on the left hand side, and more for those on the right hand side. Further, the trend of variation in moments with pile spacing is studied for all configurations of the pile groups considered in this investigation.

Table 8: Values of moments (kN-m) and % variation in column No.4

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G2PS)				Soil-Structure Interaction (G2PP)			
		2D	3D	4D	5D	2D	3D	4D	5D
12	-452.56	-438.13 (0.02%)	-457.21 (-4.54%)	-(457.12 (-4.52%)	-457.91 (-4.70%)	-437.27 (-0.13%)	-437.02 (-0.11%)	-436.78 (-0.08%)	-436.42 (-0.01%)
9	-942.45	-936.33 (-0.64%)	-935.34 (-0.75%)	-935.05 (-0.78%)	-933.49 (-0.95%)	-393.89 (0.05%)	-393.76 (0.04%)	-393.55 (0.07 %)	-393.26 (0.12%)
6	-762.74	-756.67 (-0.79%)	-755.52 (-0.94%)	-754.9 (-1.03%)	754.81 (-2.55%)	-938.08 (0.12%)	-938.33 (0.18%)	-937.97 (-0.20%)	-937.60 (0.22%)
3	1523.88	1566.13 (2.42%)	1528.25 (0.28%)	1545.74 (1.43%)	924.17 (-39.35%)	-762.37 (-0.06%)	-762.76 (-1.60%)	-762.54 (-1.65%)	-762.27 (-1.67%)
0	- 1020.0	-1008.3 (1.16%)	-991.79 (-2.76%)	-982.41 (-3.68%)	-981.46 (-3.96%0	1257.09 -(5.93%)	1236.81 (-5.00%)	1237.49 (-5.02%)	1237.57 (-5.04%)

Table 9: Values of moments(kN-m) and % variation in column No.5

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G2PS)				Soil-Structure Interaction (G2PP)			
		2D	3D	4D	5D	2D	3D	4D	5D
12	-682.81	-638.7 (6.02%)	-638.59 (-6.09%)	-638.53 (-6.94%)	-638.52 (-6.96%)	-679.14 (-0.23%)	-679.08 (-0.23%)	-678.92 (-0.26%)	-678.698 (-0.29%)
9	-525.79	-497.46 (29.06%)	-497.38 (-1.20%)	-497.13 (-1.23%)	-519.13 (1.23%)	-519.75 (-1.16%)	-519.70 (-1.17%)	-519.57 (-1.12%)	-519.406 (-1.18%)
6	- 1387.34	-1377.8 (-0.68%)	-1378 (-0.68%)	-1377.7 (-0.69%)	-977.06 (-0.69%)	-1374.10 (2.10%)	-1373.56 (2.02%)	-1373.23 (2.001%)	-1372.887 (1.97%)
3	-997.31	-1016.4 (1.92%)	-1015.4 (1.92%)	-1014.8 (1.75%)	678.45 (1.75%)	-1021.37 (0.97%)	-1021.6 (0.99%)	-1021.48 (0.974%)	-1021.265 (0.95%)
0	1763.00 2	1726.92 (-2.04%)	1722.66 (-2.28%)	1724.56 (-2.18%)	1723.96 (-2.54%)	1791.02 (-9.87%)	1798.28 (-10.51)	1800.1 (-10.39)	1801.607 9-10.30)

Table 10: Values of moments (kN-m) and % variation in column No.6

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G2PS)				Soil-Structure Interaction (G2PP)			
		2D	3D	4D	5D	2D	3D	4D	5D
12	-452.88	-454.58 (-0.373%)	-450.81 (-0.45%)	-450.71 (-0.46%)	1377.31 (-3.19%)	-532.81 (1.11%)	-532.97 (1.11%)	-588.35 (3.52%)	-588.79 (3.59%)
9	-947.39	-948.71 (-0.138%)	-944.92 (-0.26%)	-944.89 (-7.26%)	-1014.3 (-5.76%)	-573.53 (1.29%)	-573.55 (1.9%)	-477.07 (1.75%)	-477.41 (1.82%)
6	-782.60	-822.19 (-4.814%)	-763.16 (-2.48%)	-762.71 (-2.54%)	1727.11 (-9.99%)	-486.66 (4.99%)	-484.2 (4.99%)	1192.60 (8.63%)	1192.96 (8.66%)
3	-1502.8	-1532.2 (1.95%)	-1532 (1.93%)	-1549.2 (3.088%)	-1552.9 (2.44%)	1467.62 (5.30%)	1467.87 (5.30%)	-917.19 (0.02%)	-917.46 (0.05%)
0	1300	1013.38 (2.06%)	996.79 (-3.67%)	987.482 (-4.56%)	988.72 (-4.45%)	1136.88 (-2.78%)	1136.86 (-2.78%)	1766.40 (-7.39%)	1767.26 (-7.34%)

Table 11: Values of moments (kN-m) and % variation in column No.7

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G2PS)				Soil-Structure Interaction (G2PP)			
		2D	3D	4D	5D	2D	3D	4D	5D
12	-346.65	-344.33 (-0.66%)	-344.36 (-0.66%)	-344.31- (0.67%)	-344.12 (-0.72%)	-343.66 (-0.13%)	-343.69 (-0.11%)	-343.85 (-0.08%)	-344.05 (-0.01%)
9	-739.24	-736.04 (-0.43%)	-736.9- (0.32%)	-737.56 (-0.22%)	-738.9 (-0.05%)	-733.31 (0.05%)	-733.22 (0.04%)	-733.49 (0.07%)	-733.79 (0.12%)
6	-668.22	-647.51 (-3.09%)	-646.9 (-3.35%)	-646.55- (3.24%)	945.00 (-1.42%)	-652.004 (0.12%)	-652.42 (0.18%)	-652.54 (-0.20%)	-652.68 (0.22%)
3	1423.08	1460.56 (4.86%)	1492.3 (4.86%)	1507.77 (5.95%)	1500.9 (5.46%)	-1224.24 (0.056%)	-1204.1 (-1.60%)	-1203.66 (-1.65%)	-1203.36 (-1.67%)
0	-918.19	-909.86 (-0.908%)	-892.15- (2.83%)	-882.48- (3.88%)	-762.5 (-16.9%)	1018.11 (-5.935)	1027.14 (-5.00%)	1026.26 (-5.02%)	1026.75 (-5.04%)

Table 12: Values of moments (kN-m) and % variation in column No.8

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G2PS)				Soil-Structure Interaction (G2PP)			
		2D	3D	4D`	5D	2D	3D	4D	5D
12	- 587.464	-586.48 (-0.16%)	-586.36 (-0.18%)	-586.37 (-0.18%)	-1558 (0.52%)	-587.71 (3.41%)	-588.03 (3.47%)	-588.35 (3.52%)	-588.79 (3.59%)
9	-482.32	-475.99 (-1.31%)	-475.94 (-1.32%)	-475.94 (-1.32%)	287.87 (-0.57%)	-476.61 (1.65%)	-476.82 (1.70%)	-477.07 (1.75%)	-477.41 (1.82%)
6	-1304.3	-1206.9 (-7.46%)	-1209.3 (-7.28%)	-1209.9 (-7.24%)	-982.28 (-24.6%)	1193.56 (8.70%)	1192.32 (8.61%)	1192.60 (8.63%)	1192.96 (8.66%)
3	-898.1	-914.02 (1.77%)	-913.7 (1.74%)	-913.35 (1.69%)	-944.22 (5.13%)	-916.73 (-0.02%)	-916.99 (0.001%)	-917.19 (0.02%)	-917.46 (0.05%)
0	1300	1229.66 (-5.418%)	1200.33 (-7.66%)	1186.3 (-8.74%)	1244.05 (-4.30%)	1759.11 (-7.84%)	1766.07 (-7.41%)	1766.40 -(7.39%)	1767.26 (-7.34%)

Table 13: Values of moments (kN-m) and % variation in column No.9

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G2PS)				Soil-Structure Interaction (G2PP)			
		2D	3D	4D	5D	2D	3D	4D	5D

12	-354.67	-355.78 (0.311%)	-355.93 (-0.21%)	-356.04 (-0.17%)	-356.18 (-0.13%)	-353.21 (1.47%)	-353.18 (-0.42%)	-354.26 (-0.40%)	-353.36 (-0.37%)
9	-752.37	-743.36 (0.138%)	-744.41 (-1.05%)	-745.26 (-0.94%)	-745.91 (-0.85%)	-738.16 (0.78%)	-738.38 (0.81%)	-738.99 (0.89%)	-739.29 (0.93%0
6	-673.91	-653.17 (0.186%)	-652.66 (-3.15%)	-652.43 (-3.18%)	-652.37 (-3.19%)	`-657.43 (5.8%)	-657.46 (5.86%0	-657.59 (5.88%)	-657.68 (5.89%)
3	- 1423.82	-1464.1 (2.82%)	-1495.4 (5.02%)	-1510.6 (6.09%)	-1518.3 (6.63%)	1243.55 (9.47%)	1242.97 (9.43%)	1240.25 (9.23%)	1239.25 (9.15%)
0	-928.92	-913.98 (-1.60%)	-896.23 (-3.51%)	886.59 (-4.55%)	-881.2 (-5.14%)	-1026.68 (-6.07%)	-1026.14 (-6.13%)	-1024.76 (-6.27%)	-1024.33 -(6.31%)

Table 14: Values of moments (kN-m) and % variation in column No.4

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G3PS)				Soil-Structure Interaction (G3PP)			
		2D	3D	4D	5D	2D	3D	4D	5D
12	-452.56	-451.82 (0.16)	-451.69 (-0.19)	-451.50 (-0.23)	-438.33 (-0.27)	-394.16 (-0.20)	-394.04 (-0.24)	-393.91 (-0.27)	-393.77 (-0.30)
9	-942.45	-994.18 (5.20)	-994.03 (5.19)	-993.87 (5.17)	-993.72 (5.16)	-762.43 (0.88)	-762.35 (0.87)	-762.03 (0.83)	-761.86 (0.81)
6	-762.74	-785.56 (2.90)	-784.98 (2.83)	-775.56 (1.65)	-773.55 (1.39)	-1131.81 (0.91)	-1131.09 (0.85)	-1133.03 (1.02)	-1133.05 (1.02)
3	1,524	1545.04 (1.38)	1543.51 (1.28)	1554.23 (1.98)	1554.06 (0.19)	-762.43 (2.56)	-762.35 (2.55)	-762.03 (2.51)	-761.86 (2.49)
0	1020	997.87 (2.21)	994.94 (2.51)	1001.3 (1.86)	100 (6.93)	1275.67 (-4.12)	1273.81 (-4.27)	1278.44 (-3.90)	1278.99 (-3.85)

Table 15: Values of moments (kN-m) and % variation in column No.5

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G3PS)				Soil-Structure Interaction (G3PP)			
		2D	3D	4D	5D	2D	3D	4D	5D
12	-682.81	-678.71 (-0.603)	-678.66 (-0.61)	-678.66 (-0.62)	-678.5 (-0.63)	-678.98 (-0.57)	-679.02 (-0.57)	-678.98 (-0.57)	-678.98 (-0.58)
9	-525.79	-529.47 (0.69)	-529.38 (0.68)	-527.35 (0.29)	-526.29 (0.09)	-519.75 (-7.63)	-519.78 (-7.62)	-519.75 (-7.63)	-519.75 (-7.64)
6	-1387.3	-1462.46 (5.41)	-1452.41 (4.69)	-1449.74 (4.50)	-1442.46 (3.97)	-1377.06 (-4.96)	-1376.94 (-4.97)	-1376.54 (-5.00)	-1376.54 (-5.01)
3	-997.31	-1014.87 (1.73)	-1014.26 (1.67)	-1014.26 (1.64)	-1013.93 (1.63)	-1022.47 (2.32)	-1022.43 (2.32)	-1022.25 (2.30)	-1022.25 (2.29)
0	1763	1729.69 (-1.91)	1733.43 (-1.70)	1733.43 (-1.62)	1735.003 (-1.61)	1498.00 (1.00)	1498.18 (1.01)	1500.35 (1.157)	1500.35 (1.190)

Table 16: Values of moments (kN-m) and % variation in column No.6

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G3PS)				Soil-Structure Interaction (G3PP)			
		2D	3D	4D	5D	2D	3D	4D	5D
12	-452.88	-450.80 (0.46)	-450.92 (0.43)	-450.92 (0.41)	-451.01 (0.39)	-449.75 (1.117)	-449.94 (1.159)	-449.94 (1.19)	-450.10 (1.22)
9	-947.39	-943.13 (0.45)	-943.23 (0.44)	-943.23 (0.43)	-943.32 (0.42)	-945.07 (1.296)	-945.28 (1.318)	-945.28 (1.27)	-944.86 (1.27)
6	-782.61	-762.25 (2.67)	-761.90 (2.71)	-761.90 (2.72)	-761.82 (2.72)	-769.62 (4.994)	-769.73 (5.008)	-769.73 (4.99)	-769.65 (5.00)
3	1502.82	1553.97	1566.85	1566.85	1570.94	-1280.85	-1280.81	-1280.81	-1284.04

		(3.29)	(4.08)	(4.33)	(4.40)	(5.304)	(5.301)	(5.54)	(5.59)
0	1034.76	1020.02 (-1.39)	1022.02 (-1.202)	1025.308 (-0.90)	1034.76 (-0.61)	1136.88 (-2.783)	1136.86 (-2.784)	1136.86 (-2.63)	1138.50 (-2.61)

Table 17: Values of moments (kN-m) and % variation in column No.7

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G3PS)				Soil-Structure Interaction (G3PP)			
		2D	3D	4D	5D	2D	3D	4D	5D
12	-346.65	-344.46 (-0.63)	-344.40 (-0.63)	-344.32 (-0.674)	-344.269 (-0.69)	-344.07 (2.89)	-343.79 (2.81)	-343.64 (2.77)	-343.53 (2.74)
9	-739.24	-744.319 (0.68)	-744.249 (0.67)	-744.18 (0.664)	-744.13 (0.65)	-731.27 (2.50)	-730.99 (2.46)	-731.65 (2.55)	731.76 (2.42)
6	-668.22	-738.249 (9.48)	-738.91 (9.56)	-739.09 (9.589)	-739.08 (9.58)	-652.01 (4.29)	-651.80 (4.26)	-651.85 (4.27)	-651.81 (4.26)
3	1423.09	1502.03 (5.25)	1513.44 (5.97)	1516.97 (6.189)	1517.98 (6.25)	1239.01 (0.51)	1239.72 (0.56)	1235.35 (0.21)	1234.19 (0.12)
0	-918.19	-882.54 (-4.04)	-874.50 (-4.99)	-871.86 (-5.314)	-871.19 (-5.3)	-1022.49 (-6.89)	-1022.14 (-6.92)	-1020.27 (-7.12)	-1019.70 (-7.18)

Table 18: Values of moments (kN-m) and % variation in column No.8

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G3PS)				Soil-Structure Interaction (G3PP)			
		2D	3D	4D	5D	2D	3D	4D	5D
12	-587.46	-587.32 (1.65)	-587.13 (1.61)	-587.13 (1.63)	-587.20 (1.63)	-586.23 (-0.209)	-586.28 (-0.202)	-586.28 (-0.19)	-586.36 (-0.18)
9	-452.77	-451.53 (-0.27)	-456.38 (-0.30)	-456.38 (-0.29)	-456.41 (-0.31)	-475.859 (-1.36)	-475.865 (-1.35)	-475.86 (-1.35)	-475.92 (-1.34)
6	-1124.3	-1197.33 (6.09)	-1196.9 (6.067)	-1196.9 (6.06)	-1196.89 (6.05)	-1210.23 (-7.77)	-1210.504 (-7.74)	-1210.50 (-7.74)	-1210.69 (-7.73)
3	-838.34	-917.91 (8.66)	-917.71 (8.64)	-917.71 (8.64)	-917.68 (8.64)	-913.47 (1.684)	-913.138 (1.64)	-913.138 (1.63)	-913.05 (1.63)
0	1441.08	1491.60 (3.50)	1494.72 (3.71)	1525.48 (5.85)	1535.48 (6.55)	-1185.9 (20.92)	-1175.036 (21.063)	-1175.03 (2.10)	-1170.7 (2.11)

Table 19: Values of moments (kN-m) and % variation in column No.9

Storey Height (m)	Fixed Base moment	Soil-Structure Interaction (G3PS)				Soil-Structure Interaction (G3PP)			
		2D	3D	4D	5D	2D	3D	4D	5D
12	-354.67	-353.61 (0.26)	-353.71 (0.29)	-353.83 (-0.23)	-353.9 (-0.20)	-353.21 (0.41)	-353.18 (0.42)	-353.18 (0.401)	-353.26 (0.37)
9	-752.37	-752.82 (0.06)	-752.98 (0.08)	-752.49 (0.01)	-752.59 (0.029)	-738.16 (0.78)	-738.38 (0.81)	-738.38 (0.89)	-738.99 (0.93)
6	-673.91	745.368 (19.040)	746.22 (19.30)	746.61 (0.08)	746.78 (0.081)	-657.43 (5.85)	-657.46 (5.86)	-657.46 (5.88)	-657.59 (5.89)
3	-1423.8	-1504.62 (5.37)	-1515.85 (6.07)	-1519.32 (6.28)	-1520.3 (6.34)	1243.55 (9.47)	1242.97 (9.43)	1242.97 (9.23)	1240.25 (9.15)
0	-928.92	-886.311 (-4.80)	-878.316 (-5.76)	-875.75 (-6.070)	-875.16 (-6.14)	-1026.68 (-6.07)	-1026.14 (-6.13)	-1026.14 (-6.27)	-1024.76 (-6.31)

4.2.1.1 Effect of configuration of pile

Series arrangement (G2PS)

When the configuration of pile is considered ,significant variation is observed.for group of two pile in series arrangement, B.M. (i.e., hogging moment) at top of corner columns, (C-1, C-4 and C-7) placed on left hand side of the frame decreases on negative side with spacing and that at the bottom, varies according to pile spacing. For all other columns of the frame, i.e., columns in the interior (C-2, C-5 and C-8) and that placed on the right hand side (C-3, C-6 and C-9), the moment at top decreases on negative side with spacing. Similarly, the moment at bottom of the columns decreases with an increase spacing.

Parallel arrangement (G2PP)

For group of two pile in parallel arrangement the moment at the bottom (i.e., sagging moment) shows the same trend for all columns. The sagging moment decreases with an increase in spacing but increases for the last case with a spacing of 5D. The moment at the top (i.e., hogging moment) shows the same trend on the negative side.

Effect of number of piles on variation of B.M. in columns with pile spacing

The effect of number of piles in a pile group is studied on the variation of moment in columns with pile spacing and for either arrangement, i.e., series as well as parallel arrangement.

Series arrangement (G2PS)

When compared the trend of variation of moment in columns for the group of two piles and three piles under identical arrangement (series arrangement), the trend of variation in moment in respect of either group is almost same. The moments at the bottom decrease initially with an increase in spacing and later increase again for the final case of pile spacing. The moments at the top vary over a wide range but show a similar trend for all the columns.

Parallel arrangement (G2PP)

For parallel arrangement, trend of variation of B.M. is similar at top and bottom of all the columns in the group of two piles in series

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

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

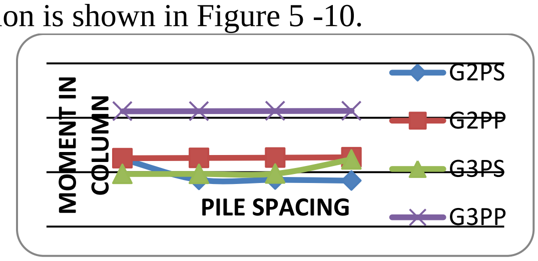


Figure 5: variation of moment with spacing at the top At the bottom of column C-4

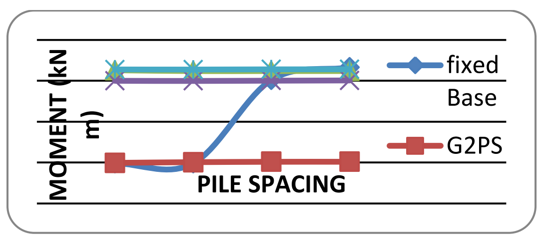


Figure 6: Variation of moment with spacing column C-4

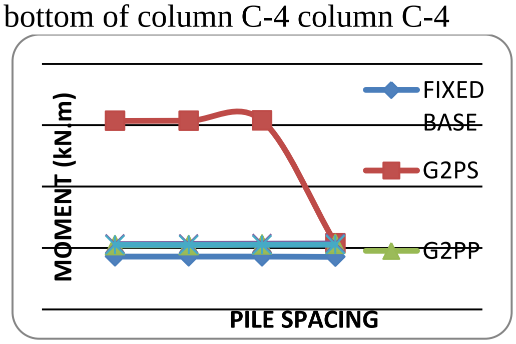


Figure 7: Variation of moment with spacing at the top at bottom column C-5

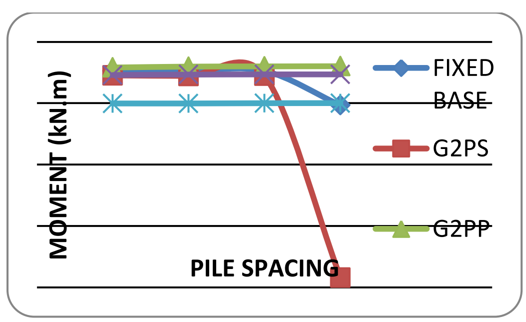


Figure 8: Variation of moment with spacing of column C-5

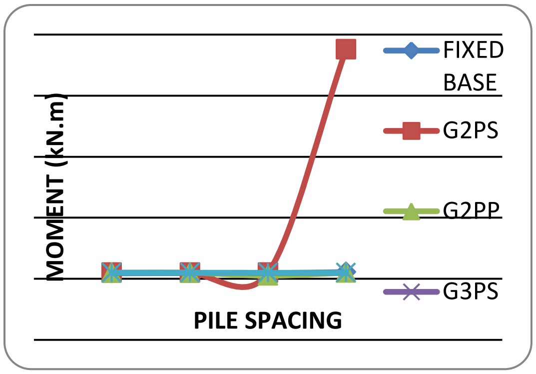


Figure 9: Variation of moment with spacing at the at bottom of column C-6

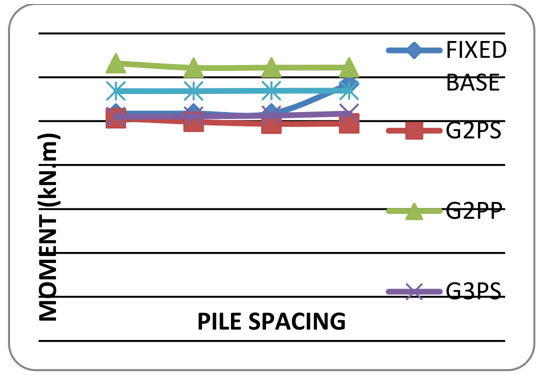


Figure 10: Variation of moment with top spacing of column C-6

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.

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 spacing's

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).

V. CONCLUSIONS

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

Some of the major findings observed from the parametric study in the preceding chapter are summarized below.

1. The consideration of the soil-structure interaction on top displacement of the frame is significant .Displacement at top is less for fixed base condition and increases when SSI is taken into account by 39 % -80 %

2. The various parameters considered like arrangement of pile,spacing has a noteable effect on variation of Bending moment in superstructure column.By increasing the spacing between individual pile in a group ,the displacement at top of frame decreases.The same is observed with increase in number of piles.
3. The effect of the soil- structure interaction in the columns placed in the leading row seems to be less and that in the columns placed on the right hand side, the effect appears to be more.
4. The moment at top of columns placed on the left hand 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 .Considering the percentage increase and decrease in columns ,it is negligible for three piles and higher for two piles.
5. The hogging moment in all the columns increases and sagging, i.e., positive moment in all the columns decreases, except that in respect of column C-5 where the moment increases.
6. The response of the building frame is found to be stiffer for the parallel arrangement of the piles in a group for the group of two piles. However, the response is observed exactly opposite, with increase in number of piles in a group. When the building frame is supported by a group of three piles, the response is stiffer for series arrangement of piles in a group.
7. The direction of applied load has a considerable effect on the displacement. When load is applied along the direction of pile in a group ,the displacement reduces because mere lateral stiffness is developed. Similarly when load is applied in other direction ,the displacement increases ..For group of two piles and three piles in series the displacement is less as compared to the parallel arrangement. On the other hand the displacement is lesser for three pile in series as compared to two pile in series.
8. The various parameters considered like arrangement of pile, spacing of pile has a considerable effect effect on variation of bending moment in superstructure column. When columns are placed in leading row, the SSI effect is less than that in trailing row. For all columns the negative moment increases and positive moment decreases.
9. Displacement obtained is on higher side for parallel arrangement as compared to the series for group of two pile. On the contrary, for group of three pile in parallel ,the displacement is higher when compared to this series arrangement. For three pile in series arrangement the displacement are less when compared to two pile in series
10. For group of two piles in parallel, moments in the front and the rear pile are near about the same. In respect of group of two piles, the maximum positive bending moment is found to decrease with increase in pile spacing..
11. Similar trend is observed as in case of group of two piles with series arrangement when maximum positive moments and the negative moments at the pile head in the individual piles are considered.
12. The maximum positive B.M. is decreasing with increase in pile spacing but the effect of spacing is marginal. However, the positive bending moment are increasing with increase in pile diameter considerably. The moments in the corner piles are on higher side as compared to that in central piles which indicates that the corner piles shares the larger proportion of load.

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