Interactive Analysis of Building Frames with Different Shapes Supported on Pile Foundation

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***Abstract*- In the analysis of two building frames having square and rectangular shape resting on pile foundation, the effect of soil-structure interaction is examined in this paper. Two seven storeyed (G+6) building frames comprising of two and three bays and columns are supported by piles which are assumed to be embedded in cohesive soil mass. The finite element-based software ETABS is used for analysis. The effect of different pile diameter, pile spacings and different soil parameters on the response of superstructure evaluated for two different shapes of building (square and rectangle). The response of storey is considered in terms of bending moment of column & axial force in column for square and rectangular frame.**

***Index Terms*- Frame, pile, bending moment in column, axial force in column, soil subgrade reaction, square and rectangular shape of building, soil structure interaction.**

I. INTRODUCTION

With advent of massive construction on soft soils the soil structure analysis problem has become an important feature of structural engineering. Fixity is assumed at the base of the foundation as per conventional design. It neglects the flexibility of the foundation and the compressibility of the sub-soil. For the realistic solution, it is essential that the superstructure- foundation- soil interaction be considered as one compatible unit. Soil Structure Interaction(SSI) is, therefore, necessary for the accurate assessment of the response of the superstructure. Several researchers on topic of Soil Structure Interaction(SSI) have been reported in the 1960-70s studies such as Chameski [1], Morris [2], Lee and Harrison [3], King and Chandrasekaran [4], Deshmukh and Karmarkar [5] and Dasgupta et al. [6].Buragohain et al. [7], and in more recent studies such as Subbarao et al. [8]. Though the majority of these analyses have been presented either for the interaction of frames with raft foundation or for the interaction of frames with isolated footings, whereas only few of them were focused on the interaction of frames with combined footings.

Soil structure interaction evaluates the collective response of the structure, the foundation, soil underlying and soil surrounding the foundation to a specied ground motion. Finite element method can handle complex boundary conditions or complicated soil layers. Buragohain et al. [7] work was based on simplified approach. The necessity of interaction analysis for building frames resting on pile foundation based on a more rational approach and realistic assumptions was reported by Ingle and Chore [10] emphasized the necessity of interaction analysis for building frames resting on pile foundation based on a more rational approach and realistic assumptions and subsequently Chore [11] reported the interaction analysis of a single storeyed building frame having two bays and supported on the group of piles. In accordance to this, Chore and co-authors [12, 13, 14, 15, 16 and17] reported the interaction analyses for the building frame resting on pile foundation which included the coupled and uncoupled approaches. 3-D finite element idealizations were made for building frame and the sub-structure was idealized using 3-D as well as simplified idealizations based on the theory postulated by Desai et al. [18] which considered linear as well as non-linear behavior of the soil. Analysis of four storeyed building frame having two bays is reported in the present study. The effect of varying diameter of piles with Soil- structure Interaction (SSI) effects is evaluated on the displacement of the frame.

II. REVIEW OF LITERATURE

Many researchers have studied the importance of considering soil-structure interaction in a very simplified manner resorting to different approaches. Some of the prominent literature available on interaction analysis of building frames with different foundation systems.

Chameski. C (1956) 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. 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

A study by Buragohain*et al.* (1977) reported the analysis of the 3-D building frame supported on pile foundation in a very simplified manner and underscored the necessity of interactive analysis. Although considerable work was available in the literature on the analyses of building frames resting either on isolated footings or mat foundation to study the effect of soil- structure interaction, much less work was reported on the analyses of frames resting on pile foundation until recently.

Further, pointing out limited work carried out on the interaction analysis of pile supported building frames (Ingle and Chore, 2007), comprehensive interaction analyses of such system were reported (Chore and Ingle, 2008, Chore *et al.* 2009, 2010 and 2011; Sawant and Chore 2010) based on more rational approach and realistic assumptions.

Ingle and Chore (2007) reported the comprehensive review of the soil- structure interaction analyses of framed structures resting on various types of foundations and various approaches. The reviewhighlighted relatively much lesser work having been carried out on the interaction analyses of building frame supported on pile foundation, except that by Buragohain *et al.* (1977) and underscored the necessity of the analysis of such a system based on the rational approach and realistic assumptions.

Based on this, interaction analyses of the system of building frame supported on pile foundation were reported recently [Chore and Ingle (2008), Chore *et al.* (2009, 2010), Sawant and Chore (2010)]. In all these analyses, more rational approach based on the realistic assumptions as pointed out in the review study by Ingle and Chore (2007) was resorted to. The flexible pile cap was assumed, and its stiffness was also considered. Moreover, stiffness matrix for the entire pile group was derived at a time by considering the effect of all the piles in a group at a time as against the one followed by Buragohain *et al.* (1977). The work reported by Buragohain *et al.* (1977) considered only one configuration of pile group. However, the studies reported by Chore and co-authors considered different configurations of the pile group.

S.A.Rasal *et al.* (2010) examined the effect of soil structure interaction on response of the three storeyed building frame supported on pile foundation. For the purpose of the analysis, simplified idealizations made in the theory of finite elements. The effect of different pile diameters is evaluated on the response of superstructure through a parametric study. The response of the superstructure considered includes the displacement of the frame. The general trend observed for all the pile diameters considered in this investigation is that horizontal displacement is on higher side when the effect of soil structure interaction (SSI) is considered. The increase in diameter of the pile increases the stiffness of the sub-structure (i.e., foundation) and therefore, the displacement decreases. Moreover, with increase in storeys, the displacement is found to decrease when the effect of SSI is considered.

S. A. Rasal *et al*. [26, 27, 28, 29, 30 and 31] presented the study which deals with physical modeling of a typical three storeyed building frame supported by a pile group of four piles (2x2) embedded in cohesive soil mass using three-dimensional finite element analysis. The parametric study is carried out for studying the effect of soil- structure interaction on response of the frame on the premise of sub-structure approach. The frame is analyzed initially without considering the effect of the foundation (non-interaction analysis) and then, the pile foundation is evaluated independently to obtain the equivalent stiffness; and these values are used in the interaction analysis. The effect of the soil- structure interaction is observed to be significant for the configuration of the pile groups and in the context of non-linear behaviour of soil.

S. A. Rasal *et al*. study dealt with mathematical modeling of a typical three storeyed building frame supported by a pile group of four piles (2×2) embedded in soft marine clay, a cohesive type of soil mass, using three-dimensional finite element analysis. For the purpose of modeling, the elements suchas beams, slabs and columns, of the superstructure frame; and that of the pile foundation such as pile and pile cap are discretised using twenty noded isoparametric continuum elements. They concluded that the effect of SSI is significant on the storey displacement, the displacement at each storey level decreases with increase in the embedment depth ratio. The passive resistance offered by the extended length of pile plays an important role on the interactive behaviour.The increase or decrease in moments in beams is on lesser side in respect of higher embedment depth ratio. As regards the effect of embedment depth on moment in columns, there is marginal difference in respect of linear SSI; although the variation is negligibly higher in case of smaller embedment depth.

The study by S. A. Rasal *et al*. 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. 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 response of the frame included the displacement at each storey level of the frame along with the bending moments in columns. The effect of soil- structure interaction on each storey displacement of the frame is quite significant. 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 and that negative bending moment is observed to be very marginal 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.

S.A. Rasal *et al.* (2017), examined a typical three storeyed building frame supported by piled-raft foundation using three dimensional finite elements. The foundation embedded in cohesive soil mass. 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, piled-raft foundation is evaluated independently to obtain the equivalent stiffness; and these values are used in the interaction analysis. The response is evaluated for three conditions- without considering the effect of SSI and another by considering the effect of SSI. The effect of soil- structure interaction on each storey displacement of the frame is quite significant. Displacement is less for the conventional analysis and increases when nonlinearity of soil is considered. The effect of soil-structure interaction is significant on B.M. The percentage increase in the maximum positive moment is observed in the columns placed in the middle row of the frame.

III. MODELLING THE SUPER-STRUCTURE AND SUB-STRUCTURE

By using finite element-based software ETABS, the superstructure of the two frames square and rectangular along with supporting system are modeled. The Beams and Columns of the building frame are idealized as three dimensional two-noded beam elements. The slab of building frame is idealized as three dimensional four-noded shell elements. Whereas in substructure, piles are idealized as three dimensional six-noded beam elements.

IV. DESCRIPTION OF NUMERICAL PROBLEM

Both 3-Dimensional building frames of seven stories (G+6) resting on pile foundation as shown in Figure 1 and Figure 2 are considered for study. The square frame, 20m high is 10m × 10 m in plan with each bay measuring 5m × 5m. The rectangular frame, 20m high is 10m × 15 m in plan with each bay measuring 5m × 5m, height of each storey is 3m for both the frames, the slab being 200 mm thick supported by 230 mm wide and 460 mm deep beam. Beams are resting on columns of size 300 mm × 300mm. The unit weight of material of which structural components are made up of is considered for dead load. 1000 kN lateral load is assumed to act at joints of both the frames as shown in Figure 1 and Figure 2 at the 21 nodes excluding the fixed support condition.

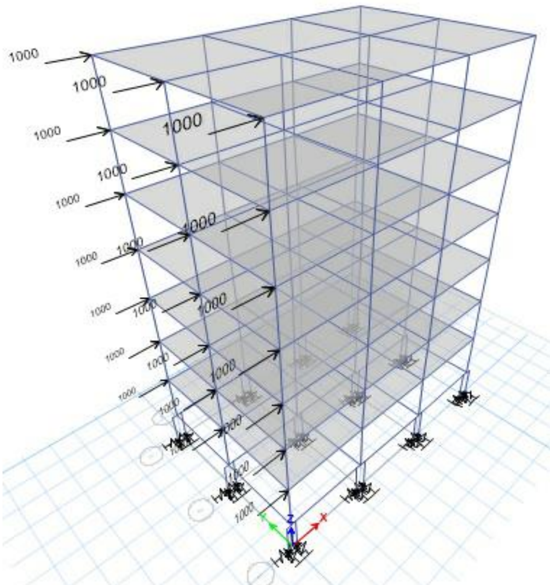

Figure 1. Square Building Frame considered for study

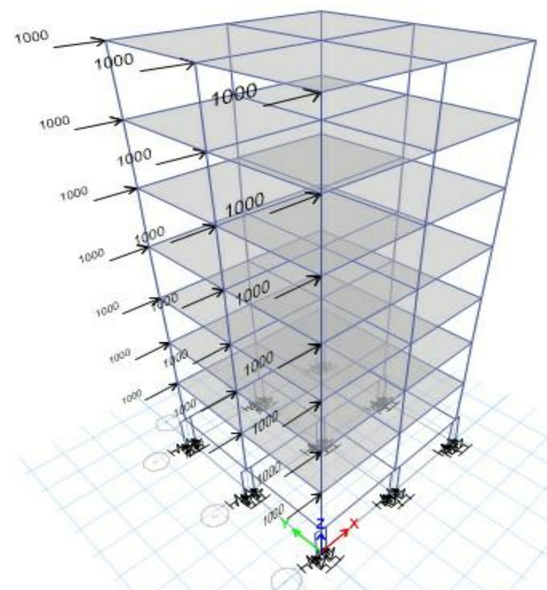

Figure 2. Rectangular Building Frame considered for study

For parametric study, arrangement of columns & beams of Square frame and rectangular frame are shown in Figure 3 and Figure 4.

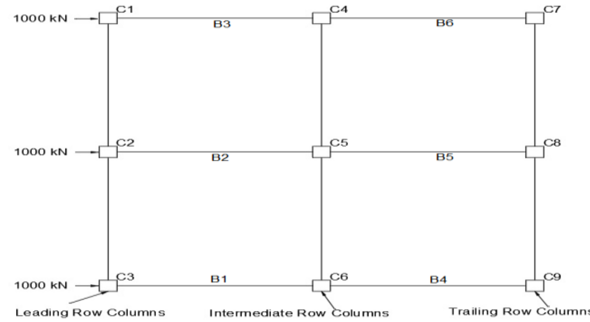

Figure 3. Arrangement of columns & beams of Square frame

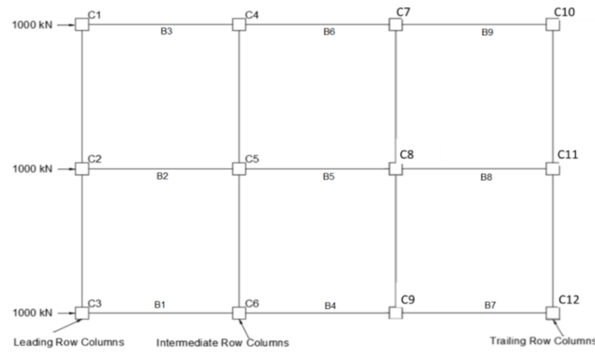

Figure 4. Arrangement of columns & beams of Rectangular frame

For parametric study, various pile arrangements are considered. The properties according to Indian specification for concrete of super-structure and sub-structure elements are listed below in Table I.

TABLE I. MATERIAL PROPERTIES

Material Properties	Corresponding Values
Grade of Concrete for the Frame Elements	M-40 (Characteristic Comp. Strength- 40MPa)
Young's Modulus of Elasticity for Frame Elements	0.3×10^8 kPa
Grade of Concrete used for Pile	M-40
Young's modulus of Elasticity For Foundation Elements	0.3×10^8 kPa
Poisson's ratio (μc) for Concrete	0.18
Poisson's ratio (μs) for Steel	0.3
Modulus of subgrade reaction (Kh)	6667 kN/m^3, 13000 kN/m^3 , 20000 kN/m^3

Pile group comprising of two piles in series, two piles in parallel, three piles in series and three piles in parallel formation as shown in Figure 5, considered for present study.

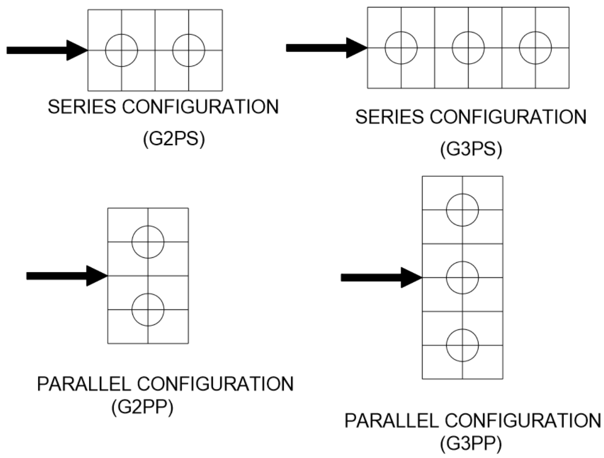

Fig. 5 Particulars of the various configurations of pile groups considered for the parametric study

A) Comparison of Bending Moment in column of square and rectangular frame:

The effect on bending moment of central column of intermediate row C5 due to different pile arrangement like G2PS, G2PP, G3PS and G3PP with single pile having fixed base for square and rectangular frame is explained below.

Group of two piles [G2PS and G2PP]- The values of bending moments in kN-m for column C5for square and rectangular frame with Group of two piles in series and group of two piles in parallel with fixed base are explained in Table II and Table III

From the values tabulated in Table II, the effect of SSI is found to decrease the moments at top storey in columns of square & rectangular frame by 2.03% & 2.17% respectively with respect to absolute maximum positive moment obtained in view of fixed base condition. The corresponding increase in maximum moments in columns is found to be in the range of 2.04 % and 2.28 % for columns of square & rectangular frames respectively. From the values tabulated in Table III, the effect of SSI is found to decrease the moments at top storey in columns of square & rectangular frame by 1.11% & 1.57% respectively with respect to absolute maximum positive moment obtained in view of fixed base condition. The corresponding increase in maximum moments in columns is found to be in the range of 2.10 % and 2.02 % for columns of square & rectangular frames respectively.

TABLE II: VALUES OF MOMENTS (KN-M) AND CORRESPONDING INCREASE THEREIN DUE TO SSI FOR VARIOUS PILE SPACING IN COLUMN C5 HAVINGSERIES ARRANGEMENT

Storey Height (m)	Moment for fixed base (kN-m)	Square		Rectangular	
		Moment (kN-m)	% Variation	Moment (kN-m)	% Variation
20	-478.90	-469.36	-2.03	-468.69	-2.17
17	-514.63	-507.89	-1.33	-504.48	-2.01
14	-587.78	-574.21	-2.36	-573.46	-2.49
11	-682.81	-638.7	-6.02	-638.59	-6.09
8	-525.79	-497.46	-5.69	-497.38	-5.71
5	-1387.4	-1377.8	-0.68	-1378	-0.68
2	-997.31	-1016.4	1.92	-1015.4	1.92
0	1763.2	1726.2	-2.04	1722.6	-2.28

TABLE III : VALUES OF MOMENTS (KN-M) AND CORRESPONDING INCREASE THEREIN DUE TO SSI FOR VARIOUS PILE SPACING IN COLUMN C5 HAVING PARALLEL ARRANGEMENT

Storey Height (m)	Moment for fixed base (kN-m)	Square		Rectangular	
		Moment (kN-m)	% Variation	Moment (kN-m)	% Variation
20	-525.91	-520.13	-1.11	-517.74	-1.57
17	-587.52	-584.12	-0.58	-580.42	-1.22
14	-624.36	-620.24	-0.66	-618.75	-0.91
11	-682.81	-679.14	-0.23	-679.08	-0.23
8	-525.79	-519.75	-1.16	-519.70	-1.17
5	-1387.3	-1374.1	-2.10	-1373.5	-2.02
2	-997.31	-1021.3	0.97	-1021.6	0.99
0	1763.00	1791.02	-9.87	1798.28	-10.51

The values of bending moments in kN-m for column C5 for square and rectangular frame with Group of two piles in series and group of two piles in parallel with fixed base are explained in table II and III in view of fixed base condition. The corresponding increase in maximum moments in columns is found to be in the range of 28.06% and 27.34 % for columns of square & rectangular frames respectively.

Group of Three Piles [G3PS and G3PP]

The values of bending moments in kN-m for column C5 for square and rectangular frame with Group of three piles in series and group of three piles in parallel with fixed base are explained in Table IV. From the values tabulated in Table IV, the effect of SSI is found to decrease the moments at top storey in columns of square & rectangular frame by 1.27% & 1.77% respectively with respect to absolute maximum positive moment obtained in view of fixed base condition. The corresponding increase in maximum moments in columns is found to be in the range of 1.91% and 1.70 % for columns of square & rectangular frames respectively.

From the values tabulated in Table IV, the effect of SSI is found to decrease the moments at top storey in columns of square & rectangular frame by -0.69% & 1.01% respectively with respect to absolute maximum positive moment obtained in view of fixed base condition. The corresponding increase in maximum moments in columns is found to be in the range of 4.96% and 4.97 % for columns of square & rectangular frames respectively.

TABLE IV: VALUES OF MOMENTS (KN-M) AND CORRESPONDING INCREASE THEREIN DUE TO SSI IN COLUMN C5 HAVING SERIES ARRANGEMENT AND PARALLEL ARRANGEMENT

Storey Height	Moment fixed base	Square		Rectangular		Square		Rectangular	
(m)	(kN-m)	Moment (kN-m)	% Variation	Moment (kN-m)	Moment (kN-m)	Moment (kN-m)	% Variation	Moment (kN-m)	% Variation
20	-521.21	-517.63	-0.69	-507.78	-507.78	-507.78	-1.27	-505.56	-1.77
17	-541.17	-537.42	-0.67	-534.25	-534.25	-534.25	-1.52	-532.31	-1.88
14	-624.65	-617.42	-1.17	-618.26	-618.26	-618.26	-0.50	-617.48	-0.62
11	-682.91	-678.98	-0.57	-678.71	-678.71	-678.71	-0.603	-678.66	-0.61
8	-559.43	-519.75	-7.63	-529.47	-529.47	-529.47	0.69	-529.38	0.68
5	-1445.4	-1377.06	-4.96	-1462.46	-1462.46	-1462.46	5.41	-1452.41	4.69
2	-998.68	-1022.47	2.32	-1014.87	-1014.87	-1014.87	1.73	-1014.26	1.67
0	1482.99	1498.00	1.00	1729.69	1729.69	1729.69	-1.91	1733.43	-1.70

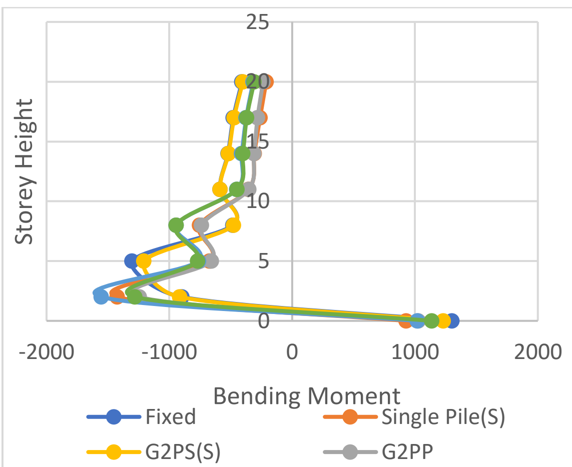

Figure 6 : Variation in BM of C5 for square frame

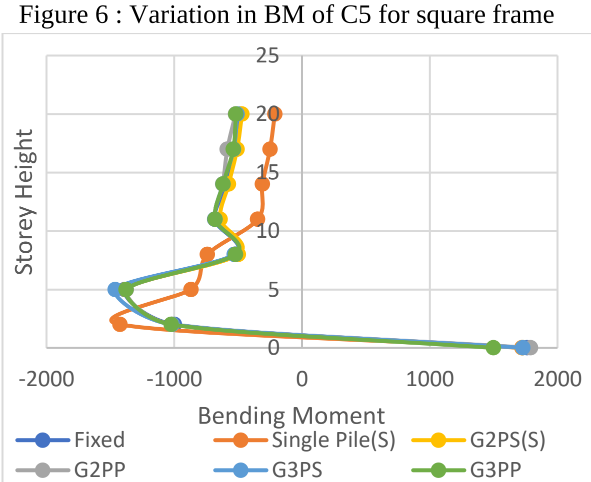

Figure 7: Variation in BM of C5 for Rectangular Frame

B) Comparison of Axial force of column C5 Central column in intermediate row of Square and Rectangular Frames is shown in Table V by providing single pile, Group of two piles in series, Group of two piles in parallel , Group of three piles in series, Group of three piles in parallel.

TABLE V- COMPARISON OF A.F. (KN) OF COLUMN C5 FOR SQUARE AND RECTANGULAR FRAMES FOR VARIOUS PILE ARRANGEMENTS.

Pile Arrangement	A.F. (kN) Of Square Frame	A.F. (kN) Of Rectangular Frame
Fixed Base	2823.60	2769.81 (-1.91%)
Single	2758.06	2689.03(-2.50 %)
G2PS	2740.63	2643.78 (-3.53 %)
G2PP	2700.48	2616.20 (-3.12 %)
G3PS	2710.5	2632.88 (-2.87 %)
G3PP	2769.36	2660.91 (-3.92 %)

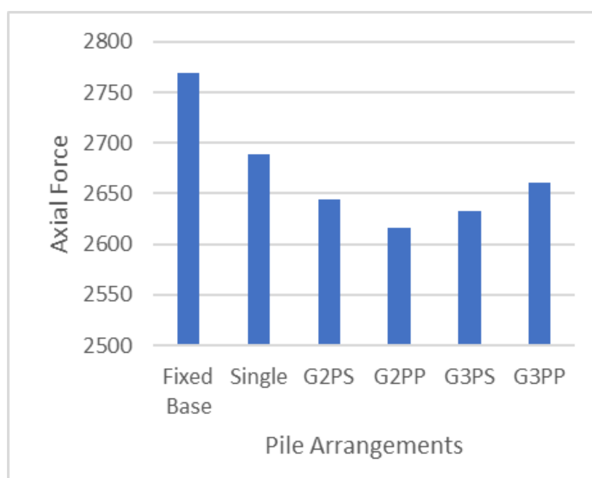

Figure 8 Variation in Axial Force in C5 of Rectangular frame.

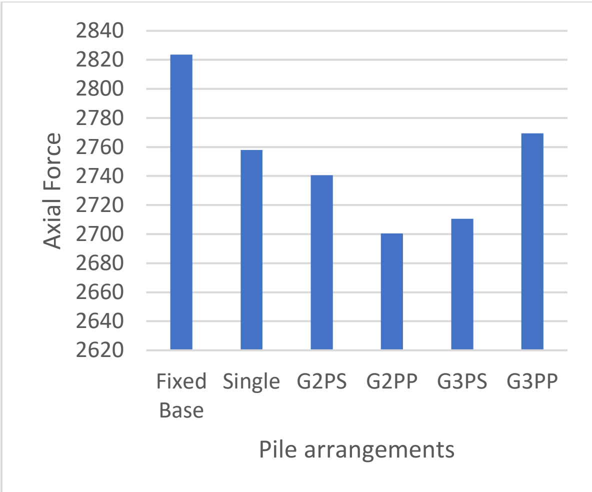

Figure 9 Variation in Axial Force in C5 of Square Frame.

Maximum Axial force in columns for fixed base support for square frame is 2823.60 kN and for rectangular frame is 2769.81 kN which has reduction in percentage is 1.91%

For Interaction analysis of building frame with single pile support system, the maximum axial force for square frame is 2758.06 kN and for rectangular frame is 2689.03 kN which has reduction in percentage is 2.50 %

For Interaction analysis of building frame with group of 3 piles in parallel, the maximum axial force for square frame is 2769.36 kN and for rectangular frame is 2660.91 kN which has reduction in percentage is 3.92 %

V. RESULTS AND DISCUSSION

Major finding concluded from parametric study and interaction analysis of square and rectangular building frame which are summarized below,

1. Bending moment in central column of square frame is found more than rectangular frame.
2. The percentage decrease in Bending moment of Central column in the intermediate row for rectangular frame as compared to the square frame for various pile arrangement is ranges from 2% to 4 %.
3. The percentage decrease in Axial force of central column in the intermediate row for rectangular frame as compared to the square frame for various pile arrangement is ranges from 2% to 6 %.
4. Soil Structure Interaction is found to be significant in respect of shape of building frame considered for present study.

VI. CONCLUSION

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

1. The bending moment at top of frame decreases for rectangular shape frame as compared to square shape frame for Non-Interactive and also for Interactive analysis for any combination.
2. The general trend observed for all the pile diameters considered in this investigation is that bending moment is on higher side when the effect of soil structure interaction (SSI) is considered for square & rectangular shape of frame.
3. It's also observed that with increase in number of storeys, the bending moment decreases.
4. The values of Axial force in column for fixed base, single pile support system, piles in series and piles in parallel decreases in rectangular frame as compared to square frame.

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