Coupled Systems Mechanics, *Vol. 3, No. 3 (2014) 305-318*
DOI: http://dx.doi.org/10.12989/csm.2014.3.3.305

Interaction analysis of a building frame supported on pile groups

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(Received October 23, 2013, Revised November 1, 2013, Accepted November 11, 2013)

Abstract. The study deals with the physical modeling of a typical building frame resting on pile foundation and embedded in cohesive soil mass using complete three-dimensional finite element analysis. Two different pile groups comprising four piles (2 × 2) and nine piles (3 × 3) are considered. Further, three different pile diameters along with the various pile spacings are considered. The elements of the superstructure frame and those of the pile foundation are descretized using twenty-node isoparametric continuum elements. The interface between the pile and pile and soil is idealized using sixteen-node isoparametric surface elements. The current study is an improved version of finite element modeling for the soil elements compared to the one reported in the literature (Chore and Ingle 2008). The soil elements are discretized using eight-, nine- and twelve-node continuum elements. Both the elements of superstructure and substructure (i.e., foundation) including soil are assumed to remain in the elastic state at all the time. The interaction analysis is carried out using sub-structure approach in the parametric study. The total stress analysis is carried out considering the immediate behaviour of the soil. The effect of various parameters of the pile foundation such as spacing in a group and number piles in a group, along with pile diameter, is evaluated on the response of superstructure. The response includes the displacement at the top of the frame and bending moment in columns. The soil-structure interaction effect is found to increase displacement in the range of 58 -152% and increase the absolute maximum positive and negative moments in the column in the range of 14-15% and 26-28%, respectively. The effect of the soil- structure interaction is observed to be significant for the configuration of the pile groups and the soil considered in the present study.

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

1. Introduction

Framed structures are normally analyzed with their bases considered to be either completely

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http://www.techno-press.org/?journal=csm&subpage=7 ISSN: 2234-2184 (Print), 2234-2192 (Online)

rigid or hinged. However, the foundation resting on deformable soils also undergoes deformation depending on the relative rigidities of the foundation, superstructure and soil. Interactive analysis is, therefore, necessary for an accurate assessment of the response of the superstructure. Numerous interactive analyses have been reported in many studies in the 1960's and 1970's (Chameski 1956, Morris 1966, Lee and Harrison 1970, Lee and Brown 1972, King and Chandrasekaran 1974, Buragohain *et al*. 1977) and some in the recent past (Shriniwasraghavan and Sankaran 1983, Subbarao *et al*. 1985, Deshmukh and Karmarkar 1991, Viladkar *et al*. 1991, Noorzaei *et al*. 1991, Dasgupta *et al*. 1998, Mandal *et al*. 1999). While most of the above mentioned studies dealt with the quantification of the effect of interaction of frames with isolated footings or combined footings or raft foundation in the context of supporting sub-soil either analytically or experimentally, only the study by Buragohain *et al*. (1977) was found to deal with the interaction analysis of frames on piles until the recent past.

The afore-mentioned work (Buragohain *et al*. 1977) was carried out using the stiffness matrix method and moreover, it was based on the simplified assumptions and relatively less realistic approach. Pointing out the lacunae in the interaction analysis of a framed structure resting on pile foundation presented by Buragohain *et al*. (1977), Chore and co-authors reported the methodology for the interaction analysis of a single storeyed building frames embedded in clayey soil by a rational approach and realistic assumptions. Many studies have been reported in the recent past related to the theme, including Chore and Ingle (2008), Chore *et al*. (2009, 2010).

The analyses by Chore and Ingle (2008) and Chore *et al*. (2010) used the sub-structure method (uncoupled approach) in which the building frame was analyzed separately on the assumption of fixed column bases. Similarly the pile groups were analyzed independently to get the equivalent stiffness of the foundation head, which were used in the interaction analyses to examine the effect of soil-structure interaction on the response of the frame. While a complete three dimensional finite element modeling was resorted for the frame (superstructure) in which all the components (slab, beams and columns) were modeled with 20-node isoparametric continuum elements in either study (Chore and Ingle 2008 and Chore *et al*. 2010), different approaches of modeling the pile foundation (sub-structure) were used in these studies. A complete three dimensional modeling was resorted in the study (Chore and Ingle 2008) in which pile, pile cap and soil were modeled using 20-node isoparametric continuum elements, while 16-node isoparametric interface elements were also used between the pile and soil. On the contrary, simplified modeling approach was used in another study (Chore *et al*. 2010) for modeling the foundation elements, with the pile idealized as one dimensional two-node beam element, pile cap as two dimensional four-node plate element and the soil as closely spaced discrete independent springs.

Chore *et al*. (2009) used a coupled approach where the structure and foundation were considered to be a single compatible unit and a complete three dimensional analysis was carried out based on the idealizations made in a study (Chore and Ingle 2008). However, this study indicated that the sub-structure approach is preferred in such an interaction analysis owing to its simplicity, less memory required on part of the computational resources and no much variation in the results obtained between the two approaches.

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 with those obtained by the finite element analysis. Recently, numerous studies have been reported, 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), 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*. (2010, 2012 a, b)] has become popular for analyzing the problem of pile foundations in the context of linear and non-linear analysis

2. Significance of the present study

On the backdrop of the considerable work on the interaction analyses of space frame-pile foundation-soil system in the recent past, the interaction analysis of a single storeyed frame resting on pile foundation as reported by Chore and Ingle (2008) is presented in this study based on slightly different idealizations for sub-structure and more improved algorithm. Further, the full model of the pile foundation is used in the present study as against the one used by Chore and Ingle (2008). It should be noted that a more refined 3-D finite element mesh is employed for pile foundation, wherein soil elements are discretised using three different elements, i.e., eight-, nine- and twelve-node continuum elements, as compared to the mesh employed in Chore and Ingle (2008). The previous study discretised the soil mass using twenty-node continuum elements. Further, the piles that were modeled by Chore and Ingle (2008) were square for simplicity in modeling. However, while considering their effect, they were treated as circular piles of a diameter equivalent to the size of the square piles.

Along the lines similar to that considered by Chore and Ingle (2008), the structural behaviour of the pile cap is assumed to be flexible in the present investigation. The stiffness of the pile cap is considered and the stiffness matrix for the sub-structure is derived by considering the effect of all the piles in a group. Moreover, the behaviour of elements of the superstructure and sub-structure including soil is considered to be linearly elastic. The total stress analysis is carried out with the immediate behaviour of the soil taken into account.

Further, in the parametric study by Chore and Ingle (2008), no consideration was made for the groups of four and nine piles. In contrast, the present investigation considers the same building frame as in the literature with a similar model of the superstructure frame with variations in the modeling idealization of the sub-structure, unlike that used in the literature, along with a parametric study presented of the group of four piles (2 × 2) and (3 × 3).

3. Particulars of the idealization made in mathematical modeling

The modeling idealization for various components of the superstructure frame remains same as that of Chore and Ingle (2008), as already mentioned in the *Introduction*.

A full three dimensional geometric model of the sub-structure (pile foundation-soil system) is considered in the present study as against the half model for the sub-structure system considered in Chore and Ingle (2008). Further, the elements of the superstructure (beam, column and slab) and those of the pile foundation (pile and pile cap) are discretized into 20-node iso-parametric continuum elements. On the other hand, soil elements are discretised using eight-, nine- and twelve- node continuum elements. Further, for these elements, three degrees of freedom at each node, i.e., displacement in each of the three directions X, Y and Z are considered. To ensure proper mechanics of stress transfer between soil and pile under the lateral load, 16-node iso-parametric surface elements is introduced at the interface. The normal and tangential stiffness of these elements are assumed in such a way that shearing at the soil and pile interface is allowed, but gapping will be restricted.

Since a 3-D geometric model is used to represent the soil-pile system, selection of correct finite elements to represent the medium is one of the very important aspects in analysis. In the soil-pile system, the two materials, viz. soil and reinforced concrete, are to be modelled. Either of the two materials shows different behaviours when subjected to loadings. The failure of the soil is dominated by its shear characteristics, whereas flexure dominated failure is shown by the reinforced concrete. Therefore, the pile and pile cap along with the superstructure elements are modelled using twenty-node continuum elements. This element has quadratic shape functions that are well suited for modelling media with bending dominated deformation.

Eight-node continuum elements are used to model the soil which has linear shape functions. These elements are suitable for the medium whose deformations are dominated by shear strength. To maintain the continuity of displacements between the two types of elements in the discretised soil- pile domain, two more elements were formulated, viz. twelve- and nine-node solid elements. The shape functions of these two elements were formulated using the degrading technique (Krishnamoorthy, 2010). The shape functions are derived for these elements by degrading the twenty-node solid elements. Twelve-node elements are used at the junction where eight- and twenty-node elements meet. Further, nine-node elements are used where twelve- and twenty-node elements meet perpendicularly.

4. Numerical problem

A 3-D single storeyed building frame resting on pile foundation, as shown in Fig. 1, is considered in the study. The frame, 3 m high, is 10 m × 10 m in plan with each bay being 5 m × 5 m. The slab, 200 mm thick, is provided at top as well as at the floor level. The slab at top is supported by 300 mm wide and 400 mm deep beams, which are resting on columns of size 300 mm × 300 mm.

However, two different pile groups comprising four (2 × 2) and nine piles (3 × 3) in each group are considered in the present study (Fig. 2), which were not considered in Chore and Ingle (2008). All the piles in each group are circular piles, connected by a 500 mm thick flexible pile cap. While dead load is considered according to unit weight of the materials of which the structural components of frame are made up for the purpose of the parametric study presented here, lateral load as shown in Fig. 1 are also considered. The properties of the material for pile and pile cap are given in Table 1.

Fig. 3 shows the finite element model of the building frame with the modeling idealizations mentioned in the preceding section. Half geometrical model is used for square configurations by

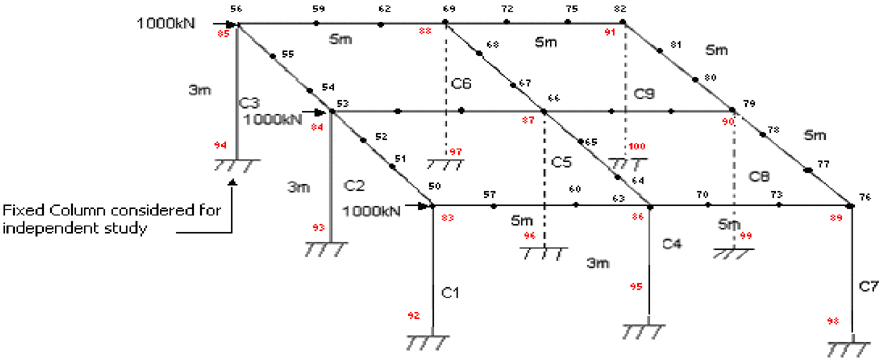
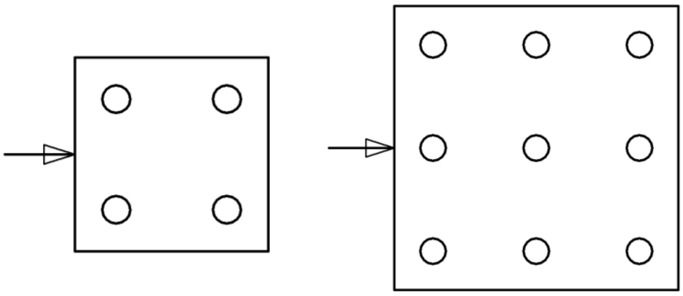


Fig. 1 Typical building frame considered in the study (After Chore and Ingle 2008)


2 X 2 Square Group

3 X 3 Square Group

Fig. 2 Different pile groups considered in the study

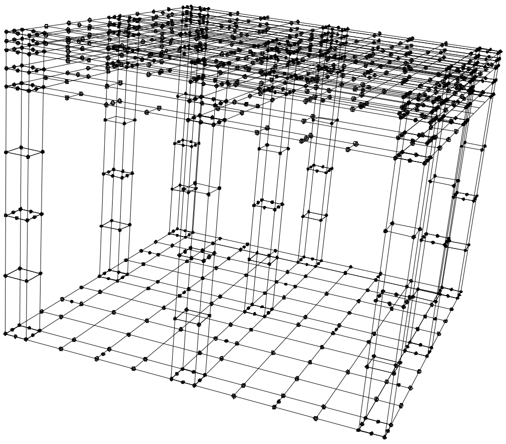


Fig. 3 Mathematical model of the building frame (After Chore and Ingle 2008)

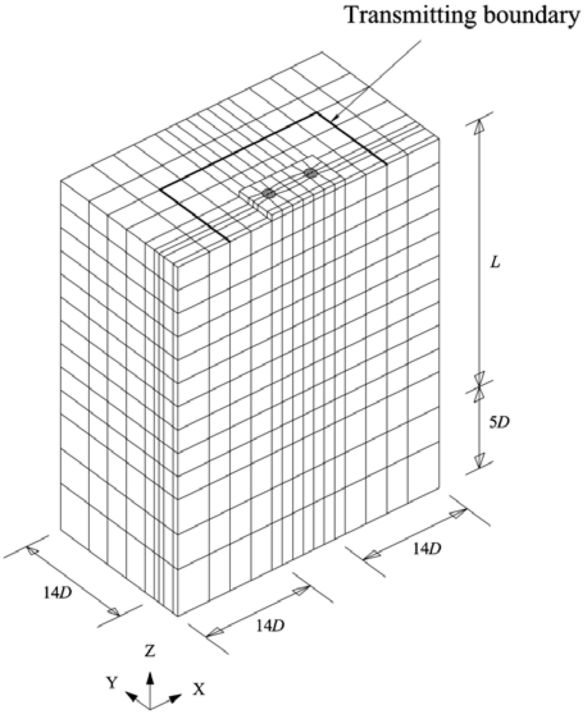


Fig. 4 Typical finite element mesh for a square group of four piles (2 × 2)

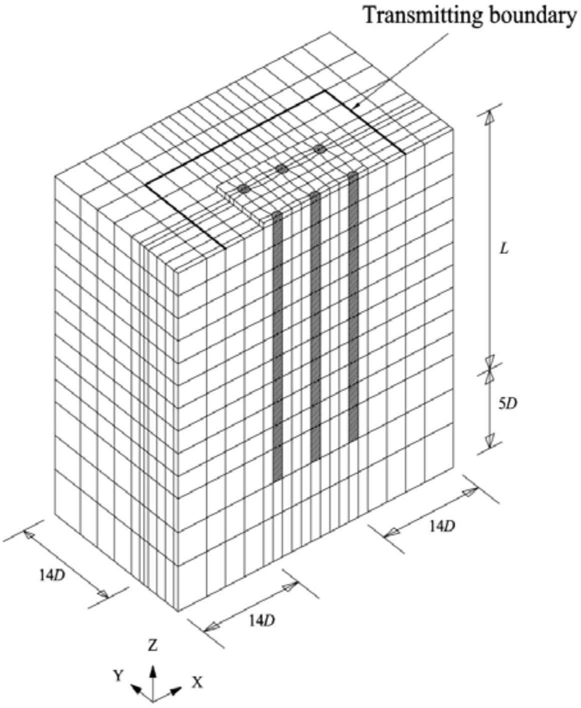


Fig. 5 Typical finite element mesh for a square group of nine piles (3 × 3)

Table 1 Geometrical and material properties for the elements of the frame and foundation

Properties	Corresponding Values
Pile diameter *(D)*	300 mm
Length of pile *(L)*	3 m (3000 mm)
Thickness of pile cap	500 mm
Grade of concrete used for frame elements	M-20 (as per Indian Specification) Characteristic compressive strength: 20 MPa
Young's modulus of elasticity for frame elements ($E_{c\ Frame}$)	0.25491×10^8 kPa
Grade of concrete used for pile and pile cap	M-40 (as per Indian Specification) Characteristic compressive strength: 40 MPa
Young's modulus of elasticity for foundation ($E_{c\ Foundation}$)	0.3605×10^8 kPa
Poisson's ratio for concrete (μ_c)	0.15
Young's modulus of elasticity for soil (E_s)	4267 kPa
Poisson's ratio for soil (μ_s)	0.45
Interface stiffness in tangential direction (k_s)	1000 kN/m^3
Interface stiffness in normal direction (k_n)	1×10^6 kN/m^3

Table 2 Particulars of pile diameters and spacing for different configurations

Four piles square group (2 × 2)	
300 mm pile diameter	3D, 4D, 5D and 6D
400 mm pile diameter	3D, 4D and 5D
500 mm pile diameter	3D and 4D
Nine piles square group (3 × 3)	
300 mm pile diameter	3D, 4D, 5D and 6D
400 mm pile diameter	3D, 4D and 5D
500 mm pile diameter	3D and 4D

taking advantage of the symmetry. The discretised soil-pile domain for the half 3-D geometrical model, which is used for the analysis of two pile groups, i.e., group of four (2 × 2) and nine piles (3 × 3), is shown in Figs. 4 and 5, respectively. Along the X and Y directions, the boundary is kept at 14D (D being the diameter of the pile) from the outermost pile of the pile group in each respective direction, as is apparent from Figs. 4 and 5. The position of the transmitting boundary is also shown by thick line, as is evident from the afore-mentioned figures. However, this boundary is meant to be used in the dynamic analysis and hence, is beyond the scope of the investigation reported herein.

The details of the diameters of the pile and spacing between the piles in each group considered in the present study are given in Table 2.

5. Results and discussion

To analyze the pile foundation separately, a software program Pile_Routine was used. The analysis of the pile foundation is carried out for the lateral or vertical force (F_H or F_V) of magnitude of 1000 kN applied on pile cap. The equivalent stiffness, k_h and k_v, are calculated and are further used in the interaction analysis of the frame structure. For the interaction analysis, a software programme Build_Frame is developed. The software programs are developed using FORTRAN 90.

After assessing the accuracy of the programme in the context of simple problems of structural engineering and soil-structural engineering and further, implementing it on the published work, the said program is used in the present study. In the parametric study conducted for the specific frame presented here, the response of the superstructure considered for comparison include the horizontal displacement of the frame at top of the frame, for both fixed base and soil-structure interaction (SSI) cases along with the bending moment in columns.

5.1 Effect of SSI on displacement at top of frame

The displacements of the frame evaluated for various arrangements of piles group is shown in Table 3. From the results of parametric study conducted on a specific building frame with pile foundation of different configurations as mentioned in the preceding section, it is observed that top displacement is very less (38.18 mm) when the column bases are assumed to be fixed and increases when the effect of soil-structure interaction is taken into account.

The maximum values of the displacement at top of the frame are found to be 96.3 and 75 mm at the minimum spacing of 3D for the group of four and nine piles, respectively for 300 mm pile diameter. The corresponding values at the higher pile spacing of 6D are observed to be 78.50 and 62.60 mm, respectively. Incorporation of the soil-structure interaction is found to increase the top displacement in the range of 105.6 to 152.22 % for the group of four piles when compared with the displacement for the fixed base condition. The corresponding increase for group of nine piles is found to be in the range of 64 to 96.44%.

For next higher pile diameter such as 400 mm, the displacement at the spacing of 3D and 5D is observed to be 83.8 and 73.50 mm, with the increase therein to the tune of 92.5-119.5% due to SSI for the group of four piles. For the group of nine piles, the corresponding displacements are observed to be 67.80 and 60.70 mm. The SSI is found to increase the displacement in the range of 59 – 77.6%.

For 500 mm pile diameters, the displacement at the spacing of 3D and 4D is found to be 76.20 and 71.40 mm for the group of four piles, and 63.6 and 60.30 mm for the group of nine piles. The corresponding increase is observed to be in the range of 87- 99.6 % and 60.30- 63.60 %.

The general trend observed for either pile group considered in the investigation for all pile diameters is that horizontal displacement is higher when the spacing between two piles is kept 3D and thereafter, decreases with higher spacing for various values of pile diameters considered in respective configurations. 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, the combined action of the pile and pile cap appears to be more rigid, similar to the block action. Owing to this, the displacement is observed to be higher for lower spacing of 3D; and thereafter, it goes on decreasing for higher spacing.

The effect of the number of piles in each group on the response of displacement at top of the superstructure is quite prominent. When the building frame is founded on a group of four piles (2 ×

), the displacement at any spacing and for any pile diameter is on higher side as compared to that for the group of nine piles.

For 300 mm pile diameter, the displacement is observed to be 55.78 and 41.64% less for the group of nine piles than that for the group of four piles at the lowest spacing of 3D and higher spacing of 6D. Similarly, for 400 mm pile diameter, the displacement is less than 41.91 and 33.53% for the group of nine piles than that for the group of four piles at the spacing of 3D and 5D, respectively. Further, along similar lines, the displacement is less than 33 and 29% at the spacing of 3D and 4D for 500 mm pile diameter for nine piles' group when compared with that obtained for four piles' group. This clearly indicates that increase in number of piles in a group enhances the stiffness of pile group and therefore, decrease in displacement is observed.

5.2 Effect of SSI on bending moment in superstructure columns

The effect of soil-structure interaction (SSI) on bending moment (B.M.) at top and bottom of superstructure columns of the specific frame is evaluated. The percentage increase or decrease in moments in columns of the frame is evaluated. The absolute maximum moments in columns obtained in view of SSI and those obtained for the fixed base are compared. The absolute maximum positive (sagging) and negative (hogging) moments in columns of the frame obtained considering the SSI are shown in Table 4.6. The corresponding change in moments with respect to the moments obtained for the fixed bases is also shown in Table 4.

From the values tabulated in Table 4, the effect of SSI is found to increase the maximum positive moment in columns in the range of 14.42 - 15.22 % with respect to absolute maximum positive moment obtained for fixed base condition. The corresponding increase in maximum negative moment in columns is found to be in the range of 26.29- 27.76%.

5.2.1 Effect of SSI on maximum moment in individual columns

The values of moments for the fixed column base condition and a particular type of foundation are reported in Table 5. The corresponding increase or decrease in the maximum moments in individual columns of the frame due to SSI is also given in brackets in the table. From this, the extent of the effect of SSI on columns placed on left and right hand side of the frame can be found. The effect of SSI on the percentage increase or decrease in the maximum moments of individual columns for various configurations is discussed in the subsequent paragraphs.

It is obvious from the results tabulated in Table 5 that the effect of SSI on moments in superstructure columns is significant when the values of moments are calculated on the premise of fixed base approach. The effect of SSI in the columns placed on left hand side (leading row) appears to be less and the effect of SSI in columns placed in the intermediate row and right hand side (trailing row) seems to be higher. Further, the trend of variation in moments with pile spacing is studied for all configurations of the pile groups considered in this investigation.

5.2.1.1 Group of four piles (2 × 2)

For a group of four piles (2 × 2), the hogging moment at top of the columns (C-1 and C-3) placed in the corner of the leading row is found to decrease in the range of 1.30- 2.32% with consideration of the SSI effect. For the column placed in the center of the same row, i.e., C-2, the hogging moment is seen to decrease in the range of 0.1 to 1% for the 300 and 400 mm pile diameters, less variation being for the 400 mm pile diameter. However, for the 500 mm pile diameter, the hogging moment is observed to increase by 0.5% for the column C-2.

Subsequently, for all remaining columns placed in the intermediate row and trailing row (C-4 to C-9), the hogging moment at top is found to increase for all the pile diameters considered in the present investigation, the increase being in the range of 21.5- 28.9%. For the column C-4, the increase in hogging moment for the lower pile diameter (300 mm) is found to be 22.1% and reduces to 21.6% for the higher pile diameter such as 500 mm. Further, for the column C-5, the increase in moment is observed to be in the range of 27.23- 27.76%, the higher percentage variation being for lower pile diameter considered in the study. Similarly, for the hogging moments at top of the columns C-7 and C-8, it is found to increase in the range of 28.25-28.9% and 26.85-27.05%, respectively. For the variation in hogging moment for these two columns, the variation is observed to be slightly higher for the lower pile diameter as compared with that for the higher pile diameter.

The sagging moment is found to develop at the bottom of all the columns. The moments in the columns (C-1 and C-2) placed in the leading row and the column (C-4) in the intermediate row is found to decrease with consideration of the SSI, the extent of decrease being higher for column C-1 followed by C-2 and then, C-4. The variation is observed to be in the range of 38.4 - 38.8% and 18.6 - 19% for columns C-1 (i.e., C-3) and C-2, respectively, the variation being on the higher side or lower values of pile diameter considered in the present study. Further, for column C-4, the variation is seen to be in the range of 5.1-5.4%. However, for lower pile diameters, the variation is less.

For column C-5 placed at the centre of the intermediate row, the moment is found to increase in the range of 15-15.22%, with higher variation in the context of 300 mm pile diameter (lower pile diameter). On the contrary, the moment in all the columns placed in the trailing row (C-7 and C-8), is found to decrease, with the decrease in the range of 29-29.35% and 16.25-16.45%. For these columns, the decrease is found to be on the higher side for larger pile diameter considered in the present investigation.

In the nutshell, the effect of SSI is found to decrease the negative moment in the columns placed in the leading row of the frame with few exceptions as observed for column C-2 at 500 mm pile diameter; and to increase the negative moment in all the remaining columns. Along similar lines, the positive moment in all the columns of the frame is found to decrease with the consideration of the effect of SSI; except for the column (C-5) placed in at the centre of the intermediate row where the moment increases.

5.2.1.3 Group of nine piles (3 × 3)

For this pile group, the hogging moment at top of all the columns of the frame is found to increase unlike that for the previous configuration, i.e., group of four piles where the moment in all the columns placed in the leading row (C-1 to C-3) decreases. The percentage increase in hogging moment is found in the range of 0.21- 28.26%.

The effect of SSI is found to increase the hogging moment in column C-1 (and C-3) in the range of 0.2- 1.65% and in column C-2 with 2.12- 3.60%. However, the variation is found to increase with pile diameter unlike the pile group comprising four piles (2 × 2) for similar columns where the variation goes on decreasing with the increase in pile diameter.

For the columns placed at the corners and centers of the intermediate row, viz., C-4 and C-5, the percentage increase is found to be in the range of 20.7- 21.6 and 26.3- 27.25%, respectively. Here, the variation is found to decrease with the increase in pile diameter and the trend is observed to be same as that for the group of four piles (2 × 2) for the corresponding columns. Further, for the columns placed at the corner and center of the leading row, i.e., C-7 and C-8, the moment is found to increase in the range of 26.82 -28.26% and 25.75- 26.86%, respectively. Here, also the variation is found to decrease with the increase in pile diameter.

At bottom of all the columns, the sagging moment (i.e., hogging moment) is found to develop. The moment for all the columns of the frame except C-5 is found to decrease with the consideration of SSI. The SSI is found to increase the moment in column C-5. The percentage decrease for the columns placed in the leading row (C-1 and C-2) is found to be in the range of 37.24- 37.82 and 17.69-18.10 %, respectively. The percentage decrease in positive moment in column C-4 is found in the range of 5.42- 5.78. However, the moment is found to increase in the range of 14.43-15%. Further, for the columns placed in the trailing row, i.e., C-7 and C-8, the percentage decrease in moment is observed in the range of 29.33-29.5 and 16.43- 17.11.

Moreover, it is seen that the variation in positive moment decreases with the increase in pile diameter for the columns in the leading row (C-1 to C-3), increases with pile diameter for column C-4 and again, decreases with pile diameter for column C-5. The variation in moment for all the columns in the trailing row (C-7 to C-9) increase with pile diameter.

Nevertheless, the variation in increase or decrease in either the hogging or sagging moment at top and bottom of the columns with pile diameter is too marginal to be approximated.

5.2.2 Effect of configuration on variation of bending moment in columns with pile spacing

The variation of bending moment at top and bottom of the typical columns for spacing for all configurations considered in study is shown in Figs. 6 - 7.

The general trend of variation of moment at the top and bottom of the superstructure columns with pile spacing is almost similar in either pile group, i.e., group of four piles (2 × 2) and nine piles (3 × 3) for all the pile diameters considered for the respective groups and respective pile spacing therein; with few exceptions. It is observed that the bending moment (i.e., hogging moment) at top of corner columns, (C-1, C-2 and C-3) placed on left hand side of the frame (i.e., leading row) increases on negative side with spacing and that at the bottom, increases. For all other columns of the frame, i.e., columns in the intermediate row (C-4, C-5 and C-6) and that placed on the right hand side (C-7, C-8 and C-9), the moment at top decreases on negative side with spacing. Similarly, the moment at bottom of the columns decreases with spacing.

However, there are few exceptions. For group of four piles (2 × 2) of 300 mm diameter, at top of column C-1, the moment initially decreases on negative side up to spacing of 4D and thereafter, resumes the general trend, i.e., increases for the next higher spacing. Similarly, at the top of column C-8, the hogging moment at top increases on negative side up to the spacing of 5D and thereafter, decreases unlike the general trend of reduction with pile spacing. Further, for the same column, the moment at bottom is found to increase with pile spacing up to the spacing of 5D and thereafter, decreases.

For group of nine piles (3 × 3) of 400 mm diameter, the hogging moment at top of column C-8 is found to increase on the negative side up to the pile spacing of 4D and thereafter, decreases at 5D. Further, for piles of 500 mm diameter, the moment at bottom of column C-7 is same for either pile spacing considered in the present study.

Although the trend of variation for hogging or sagging moments in columns remains the same regardless of pile spacings or pile diameters for both pile groups considered and, even if few exceptions are observed for piles of smaller diameters for the group of four piles and for piles of intermediate diameters for the group of nine piles, the difference in the moments is too small to be noted.

6. Conclusions

The conclusions emerging from the interaction analysis of the typical building frame are given as follows:

- The effect of soil-structure interaction on top displacement of the frame is quite significant. Displacement is less for the conventional analysis, i.e., fixed base condition, and increases in the range of 58 -152 % when the effect of SSI is taken into account.
- The displacement at top of frame decreases with the increase in pile spacing.
- The effect of number of piles in a group is also significant on the displacement at the top of the frame. The displacement is less for the group having a higher number of piles since it enhances the stiffness of the pile group.
- The SST effect is significant on bending moment. The SSI analysis is found to increase the absolute maximum positive bending moment in the range of 14- 15 % and the negative bending moment in the range of 26 – 28 %, compared with those obtained using the conventional analysis.
- The SSI effect on columns placed on the left hand side appears to be less and that on columns placed on the right hand side to be more.
- The SSI is found to increase the hogging moment in individual columns of the frame for either pile group and for all the pile diameters considered, except for the group of four piles where the moment is found to decrease initially in columns placed on the left hand side of the frame.
- The positive bending moment decreases due to SSI in all the columns of the frame, except for column C-5, placed in the centre of the intermediate (central) row where the moment increases.
- The effect of pile diameter on the increase or decrease in moments due to SSI is too marginal.
- As regards the variation of bending moment with respect to pile spacing and pile diameter for either pile group, the hogging moment in columns placed in the leading row increases on the negative side and the sagging moment increases. For all other columns, i.e., placed in the intermediate row and trailing row, the hogging moment decreases on the negative side and the sagging moment decreases.
- There are very few exceptions in the trend of variation of moment in columns with various spacings, but they are too marginal to deserve noting.

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