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Effect of interaction between pile cap and underlying soil on response of building frame

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Abstract

The effect of the interaction between the pile cap and the soil underlying it is presented in this paper for a single-storey, two-bay space frame resting on a pile group embedded in the cohesive soil with flexible cap. For this purpose, a more rational approach is resorted to using the finite element analysis with realistic assumptions. Initially, an independent 3-D finite element analysis is carried out for the frame assuming the column bases to be fixed using 20 noded continuum element for the elements of the superstructure. Later, a model is worked out separately for the pile foundation, by using the beam elements, plate elements and spring elements to model the pile, pile cap and soil, respectively. The stiffness obtained for the foundation is used in the interaction analysis of the frame to quantify the effect of soil-structure interaction on the response of the superstructure. The effects of pile spacing and pile configuration are evaluated on the response of superstructure through a parametric study. The responses of the superstructure considered include the displacement at top of the frame and moments in the columns. The analysis does not consider the interaction between the pile cap and soil underlying it. Further, the results are compared with those existing in the literature based on a similar approach for modeling foundation elements and where the aspect of interaction between the cap and underlying soil is considered (Chore et al. (2010). The effect of interaction between the cap and soil is found to be significant.
data.

Keywords: Foundation, Frame, Piles, Simplified Models, Soil-Structure Interaction, Superstructure

1. Introduction

The framed structures are normally analyzed with their bases considered to be either completely rigid or hinged. However, the foundation resting on deformable soils also undergoes deformation depending on the relative rigidities of the foundation, superstructure and soil. Interactive analysis is, therefore, necessary for the accurate assessment of the response of the superstructure. Numerous interactive analyses have been reported in the 1960-70’s studies such as Chameski (1956), Morris (1966), Lee and Harrison (1970), Lee and Brown (1972), King and Chandrasekaran (1974), Buragohain *et al.* (1977), and in more recent studies such as Shriniwasraghavan and Sankaran (1983), Subbarao *et al*. (1985), Deshmukh and Karmarkar (1991) and Dasgupta *et al*. (1998). While a majority of these analyses have been presented either for the interaction of frames with isolated footings or for the interaction of frames with raft foundation, few of them were focused on the interaction of frames with combined footings. In the meantime, much work is available on pile foundation (single as well as pile group), but comparatively little work, except Buragohain *et al.* (1977), was reported on the analysis of framed structures resting on pile foundations to account for the soil-structure interaction. The work reported by Buragohain et al (1977) was based on simplified approach. Ingle and Chore (2007) emphasized the necessity of interaction analysis for building frames resting on pile foundation based on a more rational approach and realistic assumptions. Pursuant to this, Chore and Ingle (2008 a and b) and Chore *et al.* (2009, 2010 a) presented interaction analysis of such a structural system (Fig.1).

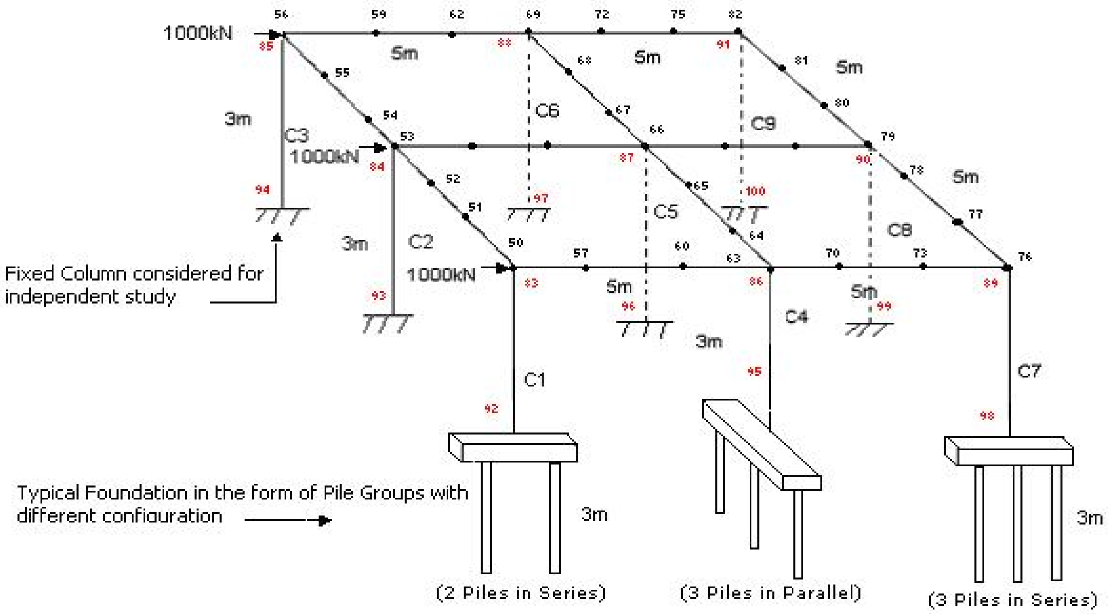


Fig. 1. Typical building frame supported by groups of piles

The various approaches available for analyzing the pile foundation are based on the application of the load at the foundation head. Even though a pile group may be subjected to axial loads, in the more often case, the combination of axial and lateral loads acting on the pile foundation can further complicate the analysis. The approaches available for the analysis of axially loaded pile foundations include the Elastic Continuum Method (Poulos 1968; Butterfield and Banerjee 1971) and Load Transfer Method (Coyle and Reese 1966; Hazarika and Ramasamy 2000), while those for analyzing the laterally loaded pile foundations include the Elastic Approach (Spillers and Stoll 1964; Poulos 1971) and Modulus of Subgrade Reaction Approach (Matlock and Reese 1956; Georgiadis and Butterfield 1982; Sawant *et al.* 1996). With the advent of computers in the early seventies, more versatile finite element method (Desai and Abel 1974; Desai *et al.* 1981; Sawant and Dewaikar 1999; Sawant and Dewaikar 2001; Ng and Zhang 2001; Krishnamoorthy *et al.* 2003; Dewaikar *et al.* 2007, Chore *et al*. 2010, b and Chore *et al*. 2012 a, b) has become popular for analyzing the problem of pile foundations in the context of linear and non-linear domains.

2. Scope of the Work

The comprehensive interaction analysis of the system of building frame (Fig.1) reported by Chore *et al.* (2010, a) was based on simplified approach (Desai *et al.* 1981) resorted to for modeling the elements of pile foundation. However, the analysis (Chore *et al.* 2010, a) considered the interaction between the pile cap and the soil underlying it. On this backdrop, the present study is aimed at evaluating the response of the frame in view of the pile foundation by ignoring the interaction between the cap and the underlying soil. Further, the results are compared with those obtained by considering this aspect (Chore *et al*. 2010, a).

Two groups of piles consisting of two piles and three piles, respectively, with two different configurations, such as series or parallel arrangements of piles, are considered (Fig. 2). All the piles in each group are assumed to be of friction type and are, further, assumed to be connected by a flexible cap. In addition, three different end conditions that may prevail on the tip of the pile are considered (Fig. 3). The effects of pile spacing and configuration of the pile group on the top displacement of the frame and the maximum moment in columns of the frame, as well as variation of moments, is studied in the parametric study.

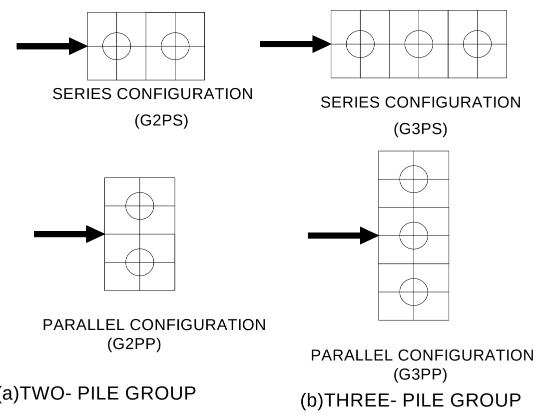


Fig. 2. Different configurations of the pile groups considered in the present study

3. Modeling of the Super- and Sub-Structures

The elements of the superstructure (beam, column and slab) and that of the substructure (pile and soil) are discretized into 20 noded iso-parametric continuum elements with three degrees of freedom at each node, i.e., with a displacement along each of the three directions X, Y and Z. As for the substructure, i.e., pile foundation, simplified modeling approach, as the one suggested by Desai et al (1981), is adopted. Namely, beam element, plate element and spring element are used to simulate the pile, pile cap and underlying soil, respectively. The finite element formulation employed in the analyses is presented elsewhere (Chore *et al*. 2010, a).

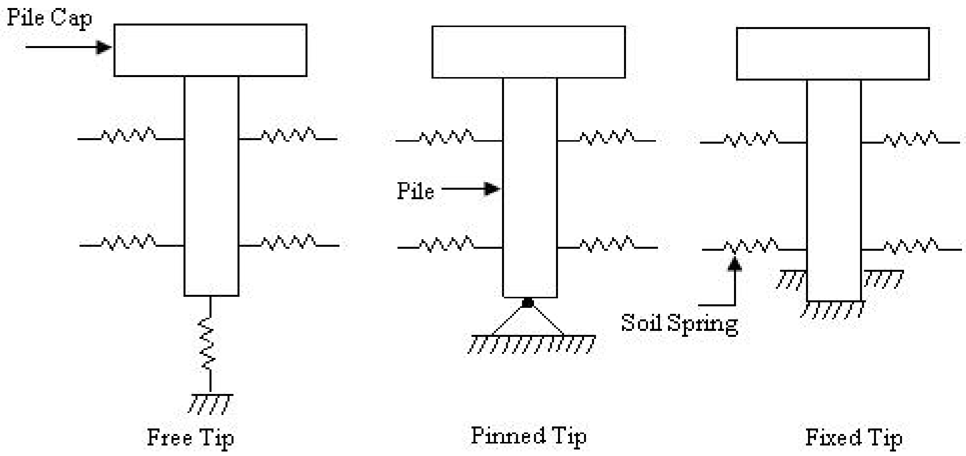


Fig. 3. Different end conditions assumed to prevail at the pile tip

Table 1
Geometrical and material properties for the elements of the frame and foundation
(After Chore *et al.*, 2010)

Properties	Corresponding Values
Grade of Concrete used for the Frame Elements	M-20 (Characteristic Comp Strength: 20 MPa)
Young's Modulus of Elasticity for Frame Elements ($E_{c\ Frame}$)	0.25491×10^8 kPa
Grade of Concrete Grade used for Pile and Pile Cap	M-40 (Characteristic Comp Strength: 40 MPa)
Young's Modulus of Elasticity for Foundation Elements ($E_{c\ Foundation}$)	0.3605×10^8 kPa
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
Modulus of subgrade reaction (K_h)	6667 kN/m^3

4. Numerical Problem

A three-dimensional single storeyed building frame resting on pile foundation as shown in Fig. 1 is considered for the study. The frame, 3 m high, is 10 m × 10 m in plan with each bay of dimensions 5m × 5m. 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. While dead load is considered according to unit weight of the materials of which the structural components of the frame are made up for the parametric study presented here, a lateral load of 1000 kN is assumed to act at the three points of the frame, as shown in the Fig. 1. The length of piles considered in the parametric study is 3 m, thickness of the pile cap is 500 mm and the diameter of pile considered is 300 mm. The properties of the concrete for the superstructure elements and sub-structure element (according to Indian specification) are given in Table 1. The corresponding Young's modulus of elasticity and Poisson's ratio are also given in Table 1. A soft cohesive soil is considered in the analysis.

5. Results and discussion

An independent analysis is carried out for the pile foundation and the equivalent spring stiffness is calculated for both the horizontal and vertical directions; and further they are used in the interaction analysis. In the parametric study conducted for the specific frame presented here, the responses of the superstructure considered for the comparison include the horizontal displacement at the top of the frame and the bending moment (BM) at the top, as well as at the bottom of the columns of the superstructure, for both fixed base and soil-structure interaction (SSI) cases. The effect of the pile spacing in the group of two and three piles with the series and parallel arrangements is evaluated on the response of superstructure using the three sub-models considered for the pile tip, as discussed in the following section. Further, the results are compared with those obtained in the interaction analysis (Chore *et. al.*, 2010, a) where the pile foundation-soil system was modeled using simplified models and further, the interaction between the pile cap and soil underlying it was also considered.

5.1 Effect of SSI on displacement

The displacement at the top of the frame for various pile spacing with respect to different pile configurations and different pile tip conditions considered in the present study without considering the interaction aspect of cap and soil are indicated in Tables 2- 4. The values of the displacements obtained by considering this interaction aspect as reported by Chore *et al.* (2010, a) are also indicated in these Tables.

Table 2
Displacements at top frame (Free tip)

Spacing	Top Displacement (mm)				Percentage Increase			
	2D	3D	4D	5D	2D	3D	4D	5D
Group of Two Piles (Series Arrangement) [G2PS]								
Without Interaction	86.54	83.53	80.72	78.40	126.54	118.66	111.30	105.23
Chore *et al.* (2010)	75.88	72.86	70.41	68.48	98.64	90.37	84.32	79.26
Group of Two Piles (Parallel Arrangement) [G2PP]								
Without Interaction	90.05	90.04	90.03	90.02	135.73	135.73	135.73	135.73
Chore *et al.* (2010)	77.63	75.68	74.08	72.54	103.22	98.11	93.93	89.90
Group of Three Piles (Series Arrangement) [G3PS]								
Without Interaction	82.74	80.53	78.67	77.38	116.60	110.80	105.95	102.57
Chore *et al.* (2010)	73.91	71.52	69.64	68.24	93.48	87.23	82.30	78.64
Group of Three Piles (Parallel Arrangement) [G3PP]								
Without Interaction	90.05	92.73	94.48	95.68	135.73	142.75	147.33	150.47
Chore *et al.* (2010)	77.63	76.80	75.59	74.30	103.22	101.05	97.88	94.50
Displacement at Top of Frame on the premise of Fixed Column Base =38.20 mm								

From the results it is observed that when the interaction aspect between pile cap and soil is not considered, displacements at top of the frame increase in the range of 105% to 127% in respect of free tip condition, 101% to 114% in respect of pinned tip condition and 88 % to 11% in respect of fixed tip condition for the group of two piles with series arrangement (G2PS). However, for parallel arrangement (G2PP), the increase is found to be around 136% for all the end conditions assumed to prevail at the pile tip.

Table 3
Displacements at top frame (Pinned tip)

Spacing	Top Displacement (mm)				Percentage Increase			
	2D	3D	4D	5D	2D	3D	4D	5D
Group of Two Piles (Series Arrangement) [G2PS]								
Without Interaction	81.60	80.00	78.34	76.84	113.61	109.42	105.08	101.15
Chore *et al.* (2010)	73.53	71.35	69.48	67.92	92.50	86.78	81.88	77.80
Group of Two Piles (Parallel Arrangement) [G2PP]								
Without Interaction	90.05	90.04	90.03	90.02	135.73	135.73	135.73	135.73
Chore *et al.* (2010)	77.63	75.68	74.00	72.54	103.22	98.12	93.72	89.90
Group of Three Piles (Series Arrangement) [G3PS]								
Without Interaction	79.55	78.80	77.76	76.89	108.24	106.28	103.56	101.28
Chore *et al.* (2010)	72.35	70.77	69.30	68.07	89.40	85.26	81.41	78.19
Group of Three Piles (Parallel Arrangement) [G3PP]								
Without Interaction	90.05	92.73	94.48	95.68	135.73	142.75	147.33	150.47
Chore *et al.* (2010)	77.63	76.80	75.59	74.29	103.22	101.05	97.88	94.50
Displacement at Top of Frame on the premise of Fixed Column Base =38.20 mm								

Table 4
Displacements at top frame (Pinned tip)

Spacing	Top Displacement (mm)				Percentage Increase			
	2D	3D	4D	5D	2D	3D	4D	5D
Group of Two Piles (Series Arrangement) [G2PS]								
Without Interaction	76.54	74.98	73.37	71.90	100.37	96.28	92.07	88.22
Chore *et al.* (2010)	70.72	68.79	67.08	65.65	85.13	80.08	75.60	71.86
Group of Two Piles (Parallel Arrangement) [G2PP]								
Without Interaction	90.05	90.04	90.03	90.02	135.73	135.73	135.73	135.73
Chore *et al.* (2010)	77.62	75.68	74.00	72.54	103.22	98.12	93.72	89.90
Group of Three Piles (Series Arrangement) [G3PS]								
Without Interaction	74.55	73.53	72.33	71.35	95.16	92.49	89.34	86.78
Chore *et al.* (2010)	69.44	67.96	66.57	65.44	81.78	77.91	74.26	71.31
Group of Three Piles (Parallel Arrangement) [G3PP]								
Without Interaction	90.05	92.73	94.48	95.68	135.73	142.75	147.33	150.47
Chore *et al.* (2010)	77.63	76.80	75.59	74.30	103.22	101.05	97.88	94.50
Displacement at Top of Frame on the premise of Fixed Column Base =38.20 mm								

From the results it is observed that when the interaction aspect between pile cap and soil is not considered, displacements at top of the frame increase in the range of 105% to 127% in respect of free tip condition, 101% to 114% in respect of pinned tip condition and 88 % to 11% in respect of fixed tip condition for the group of two piles with series arrangement (G2PS). However, for parallel arrangement (G2PP), the increase is found to be around 136% for all the end conditions assumed to prevail at the pile tip.

On the contrary to this, the corresponding increase reported in the interaction analysis by Chore *et al.* (2010, a), which considered the interaction between the cap and soil, is in the range of 79 % to 99% for the group of two piles with series arrangement (G2PS) in the context of free tip condition, 78 % to 93% and 72 % to 85% in respect of pinned tip as well as fixed tip condition. The increase for the pile group comprising two piles with parallel arrangement is same (90 % to 103%) in respect of all the three end conditions. For the group of three piles with series arrangement, the increase is found to be in the range of 102% to 117%, 101% to 108% and 86% to 95% in respect of free tip, pinned tip and fixed tip conditions of the piles as against the corresponding increase being in the range of 79 % to 93%, 78% to 89% and 71% to 81% obtained for the respective end conditions, reported by Chore et al (2010). For the parallel arrangement, the corresponding increase is in the range of 135% to 150% as against the increase observed in the range of 94% to 103% for all the three end conditions (Chore *et al.*, 2010 a).

The displacements are found to be on the higher side when analysis is carried out without considering the interaction aspect between pile cap and underlying soil as compared to the displacements obtained in view of the consideration of this aspect as reported by Chore *et al.* (2010, a). The interaction between the pile cap and underlying soil increases the stiffness of the pile group and further, results in reduction in top displacement of the frame. The effect of number of piles and arrangement of piles in a group, particularly in the context of the lateral load, is found to be significant on the response of the frame. The displacements are found to reduce with spacing for either pile group with series arrangement and the trend is similar to the one reported in the literature (Chore *et al.*, 2010 a). However, different trend of displacement with spacing is observed in respect of the parallel arrangement for either pile group.

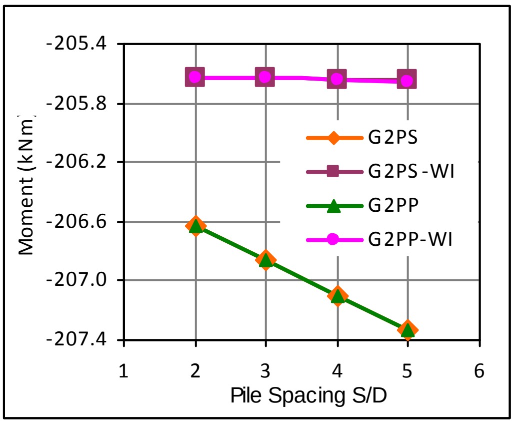
While displacement is found to be constant with spacing for a group of two piles, displacement is found to increase with spacing in respect of group of three piles with parallel arrangement. In the simplified analysis, the soil is modeled as discrete independent springs, which are independent of the area of the soil zone. As a result, appropriate modeling of the passive resistance of the soil is not possible. The soil offers nearly the same stiffness for either configuration and the combined stiffness of the pile-soil system is less in the context of parallel arrangement and hence, the response of the series arrangement is found to be stiffer. For piles with short to medium lengths, this is a governing factor and the 3 m long pile considered in the present study falls under the category of short piles. Further, when the interaction between pile cap and soil is not considered, pile element and cap element might act separately as a results of which such trend in displacement could be obtained.

For the series arrangement, displacements obtained at any spacing are higher in case of group of two piles than that of three piles. The trend of the displacement with spacing as observed when the analysis is carried out by considering the interaction between pile cap and soil holds good here as well. The displacements are on higher side when obtained in view of fixed tip condition, followed by that obtained in view of pinned tip condition. The displacements obtained in view of the fixed tip condition are less than that obtained in view of pinned tip condition.

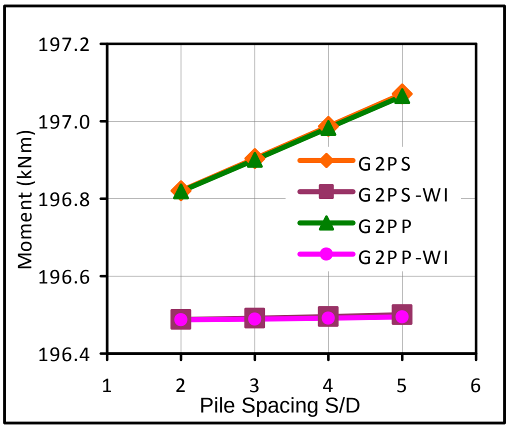
5.2 Effect of SSI on moment in columns

The effect of soil-structure interaction on the bending moment at the top and bottom of the superstructure columns is evaluated in terms of the percentage increase (or decrease). The absolute maximum moments in columns obtained for the SSI case are compared with those of the case with the column bases fixed, to evaluate the effect of incorporating the SSI in analysis. Moreover, the trend of variation in moments with pile spacing is also studied for all configurations of the pile groups and for all the pile diameters and end conditions assumed for the pile tip. The increase in absolute maximum positive and negative moment in columns is found to be 15 % and 27%. The corresponding increase found in the interaction analysis (Chore *et al.*, 2010 a) which considered the interaction between cap and soil is also in the similar range and hence, the aspect of the interaction between cap and soil does not seem to have significant effect on the absolute maximum moments.

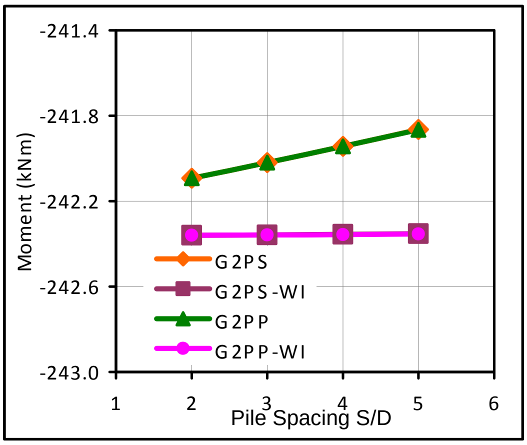
5.2.1 Effect of configuration on variation of moments versus pile spacing in columns



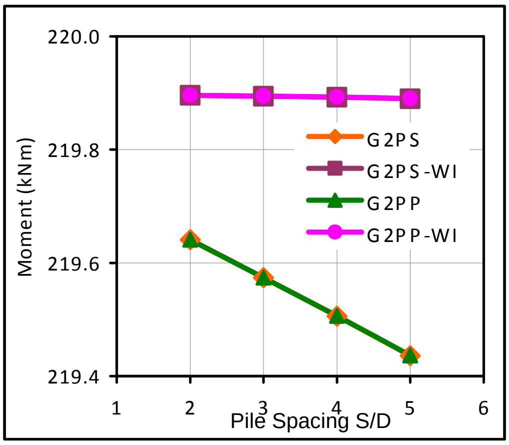
(a) Variation of moment at top of C-2



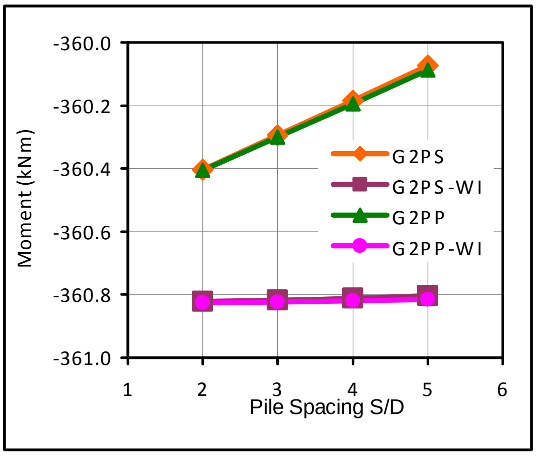
(b) Variation of moment at bottom of C-2



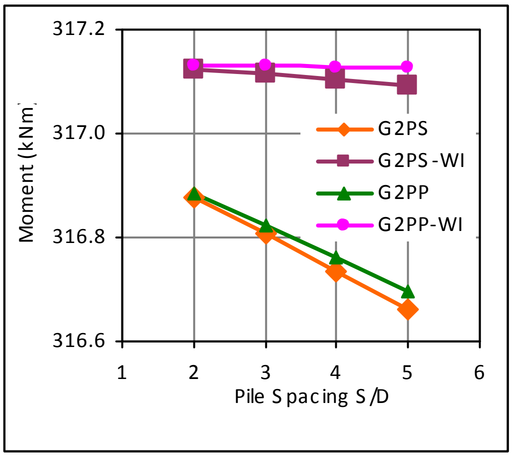
(c) Variation of moment at top of C-8



(d) Variation of moment at bottom of C-8

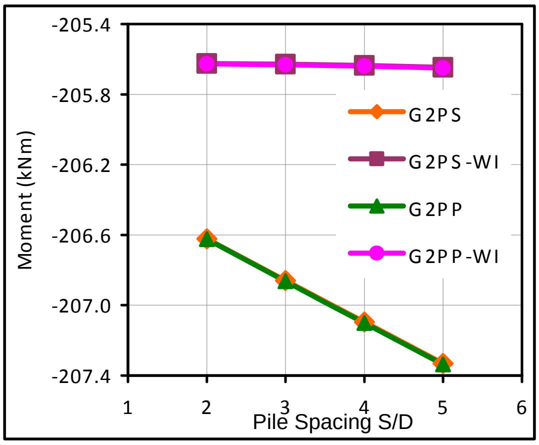


(e) Variation of moment at top of C-5

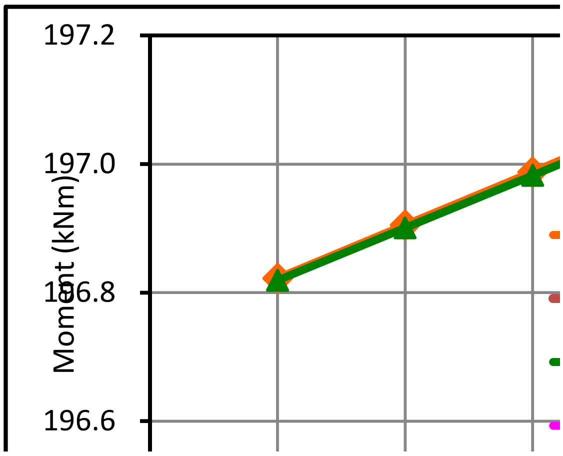


(f) Variation of moment at bottom of C-5

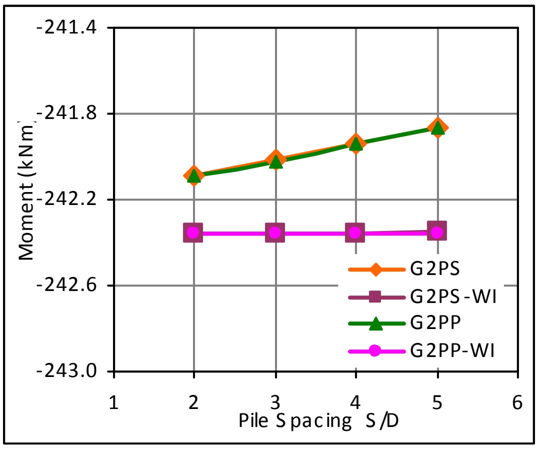
Fig. 4. Variation of moments with spacing in group of two piles [Free Tip]



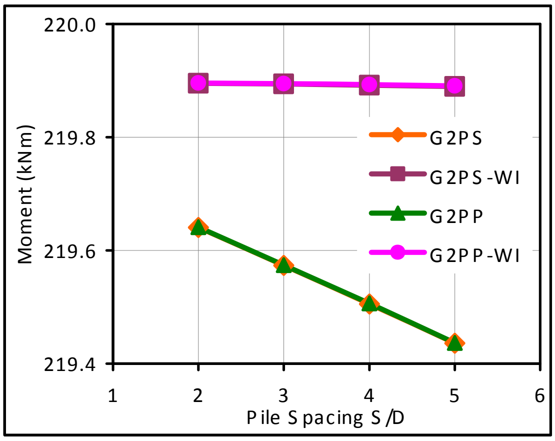
(a) Variation of moment at top of C-2



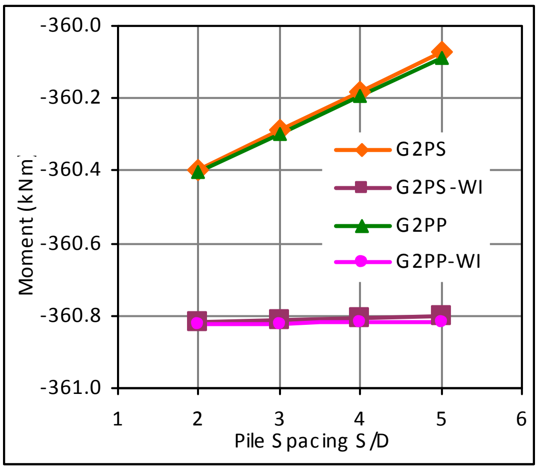
(b) Variation of moment at bottom of C-2



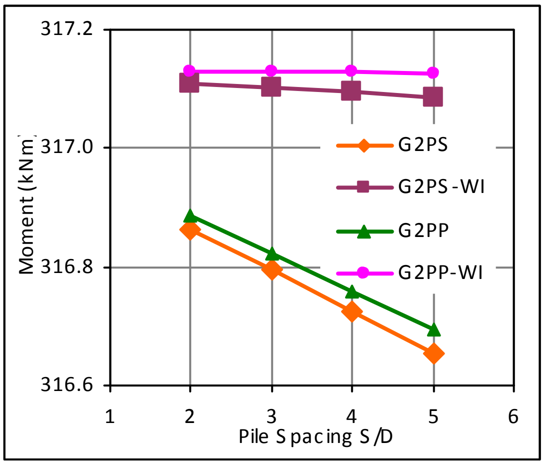
(c) Variation of moment at top of C-8



(d) Variation of moment at bottom of C-8

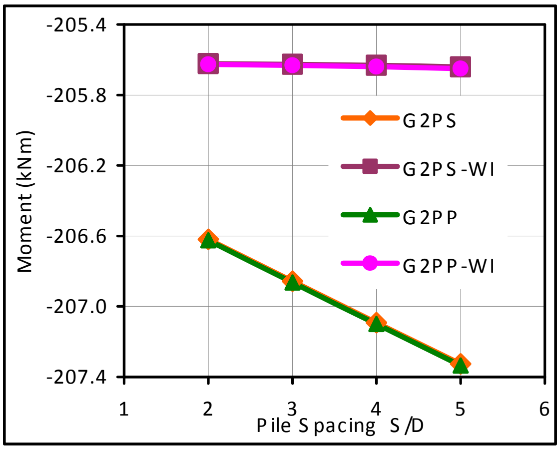


(e) Variation of moment at top of C-5

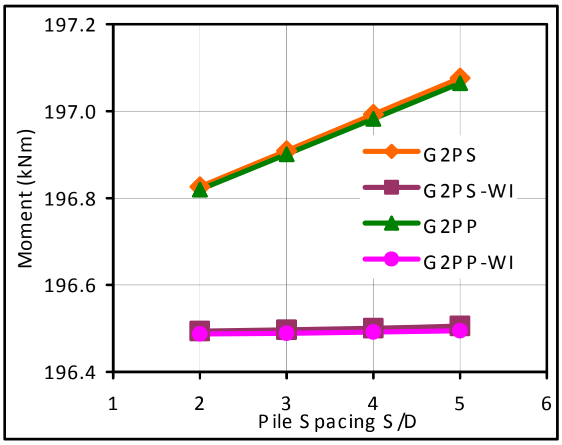


(f) Variation of moment at bottom of C-5

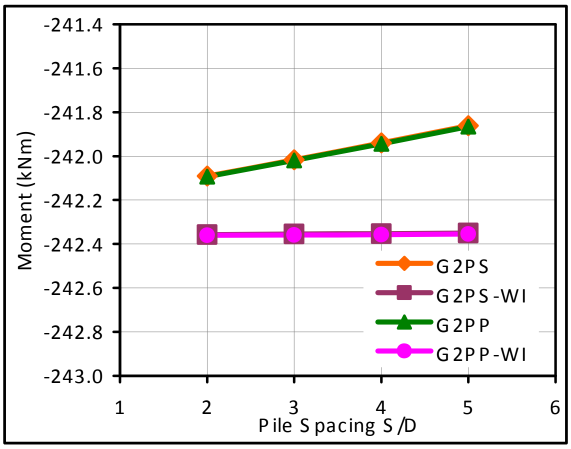
Fig. 5. Variation of moments with spacing in group of two piles [Pinned Tip]



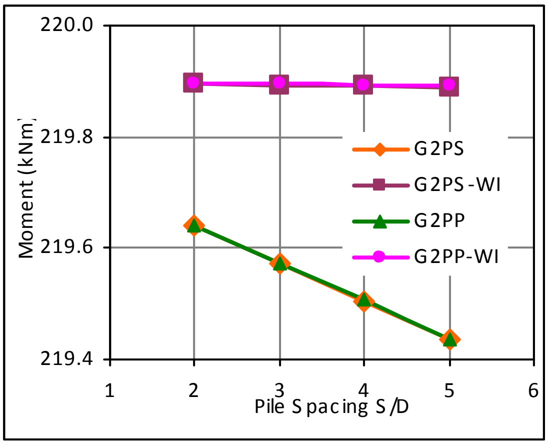
(a) Variation of moment at top of C-2



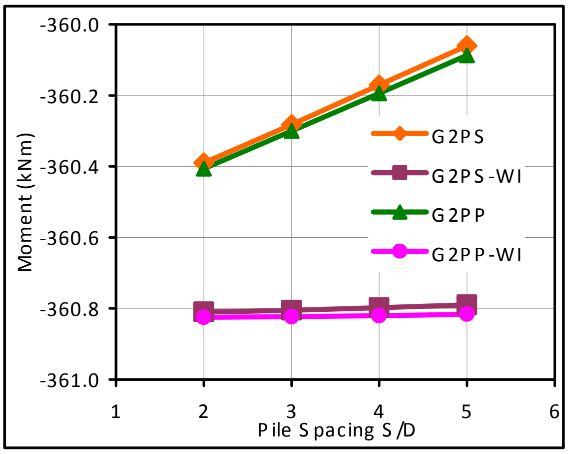
(b) Variation of moment at bottom of C-2



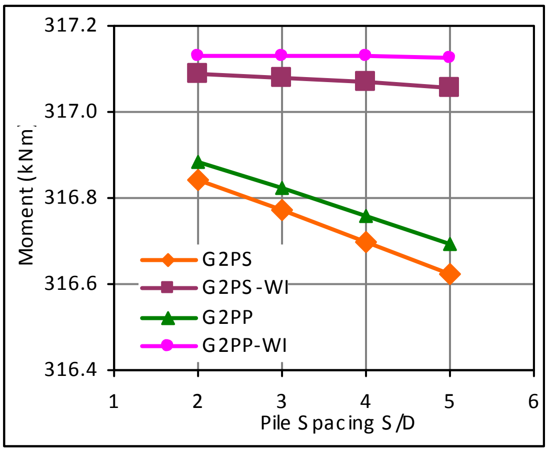
(c) Variation of moment at top of C-8



(d) Variation of moment at bottom of C-8

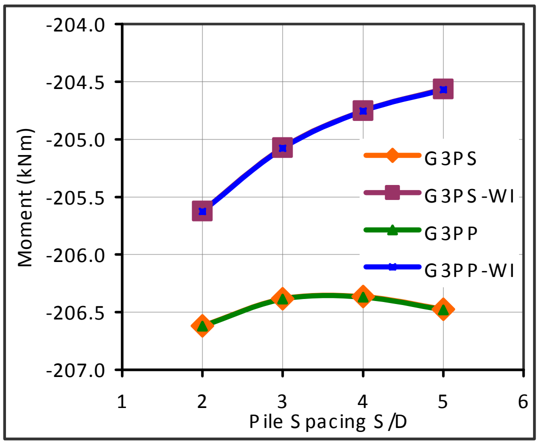


(e) Variation of moment at top of C-5

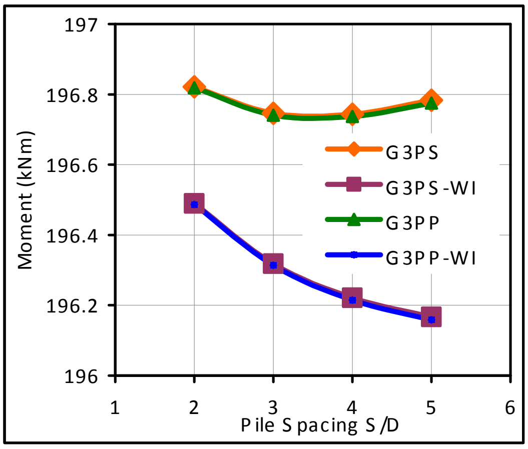


(f) Variation of moment at bottom of C-5

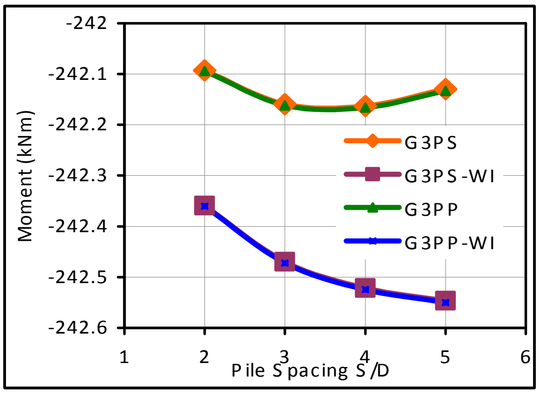
Fig. 6. Variation of moments with spacing in group of two piles [Fixed Tip]



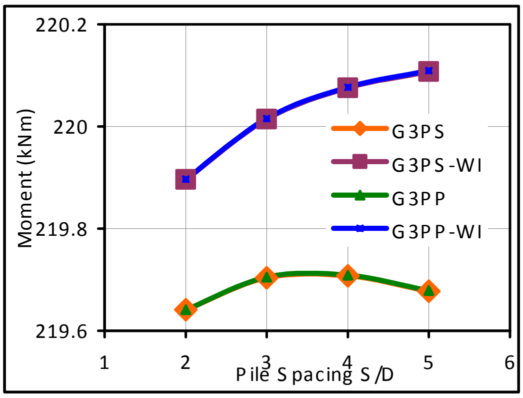
(a) Variation of moment at top of C-2



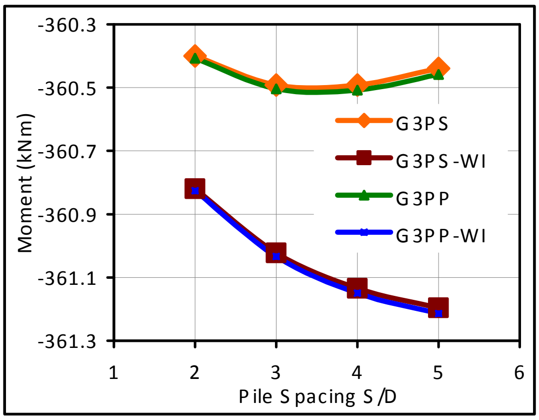
(b) Variation of moment at bottom of C-2



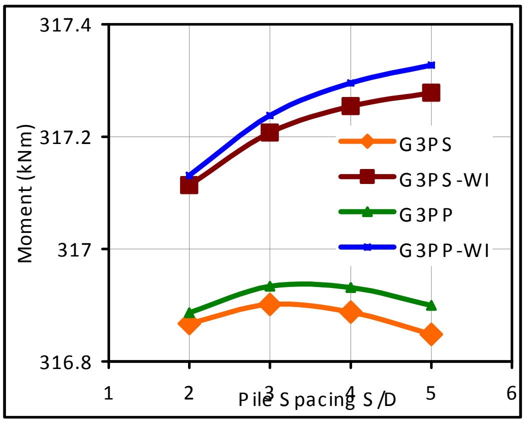
(c) Variation of moment at top of C-8



(d) Variation of moment at bottom of C-8

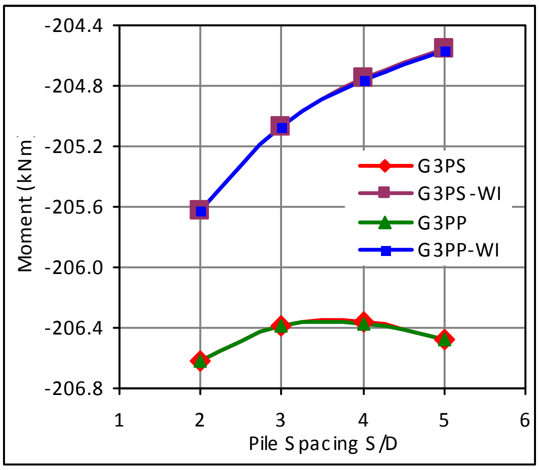


(e) Variation of moment at top of C-5

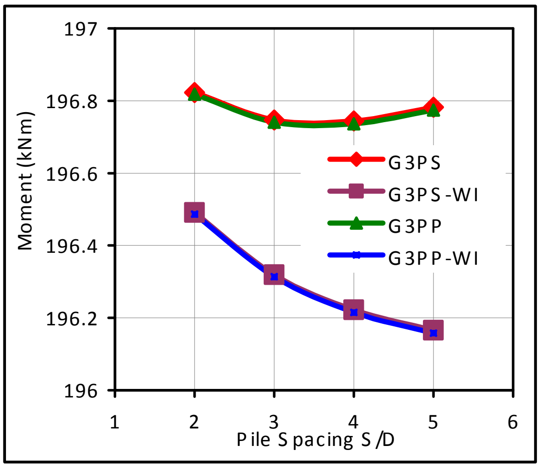


(f) Variation of moment at bottom of C-5

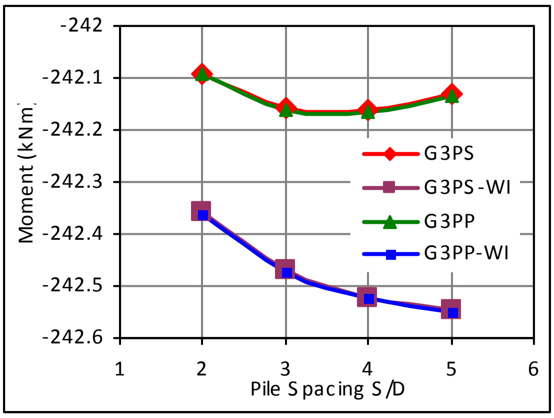
Fig. 7. Variation of moments with spacing in group of three piles [Free Tip]



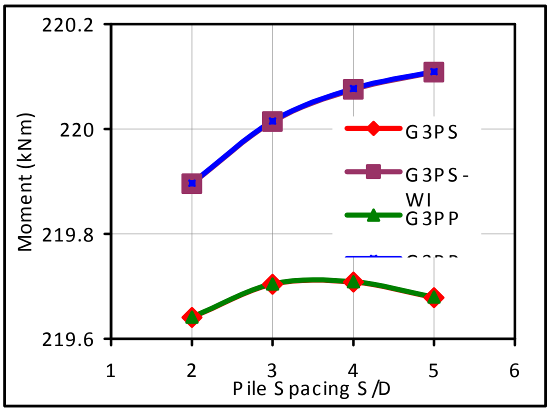
(a) Variation of moment at top of C-2



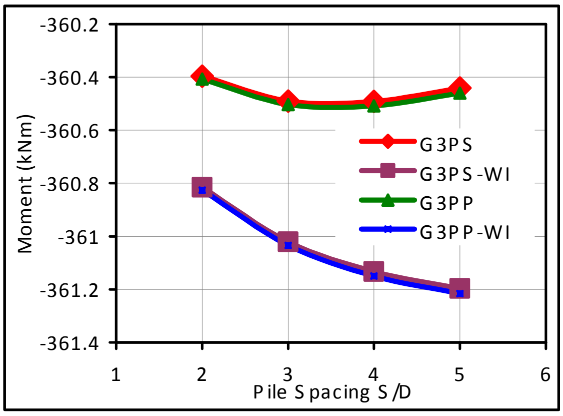
(b) Variation of moment at bottom of C-2



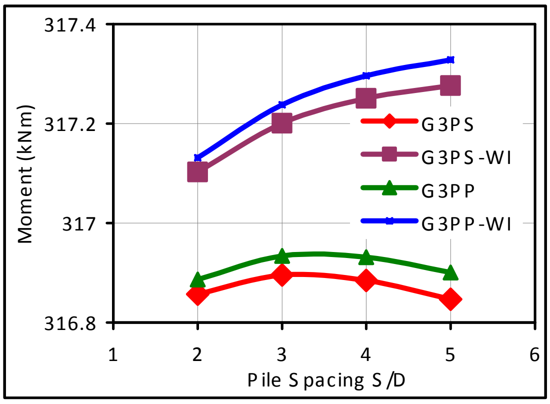
(c) Variation of moment at top of C-8



(d) Variation of moment at bottom of C-8

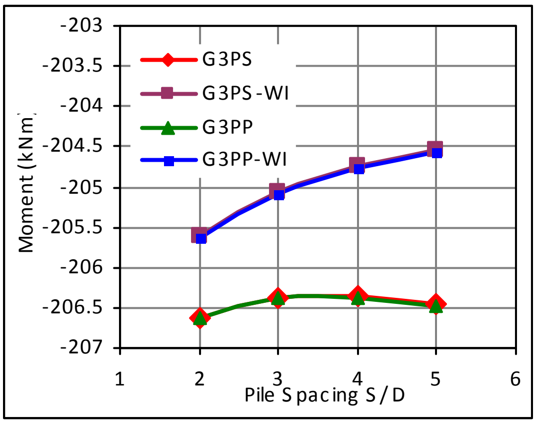


(e) Variation of moment at top of C-5

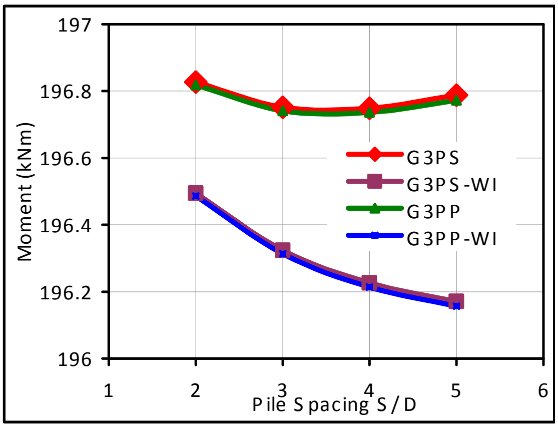


(f) Variation of moment at bottom of C-5

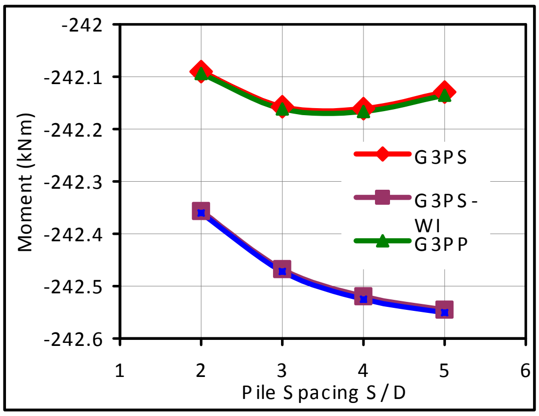
Fig. 8. Variation of moments with spacing in group of three piles [Pinned Tip]



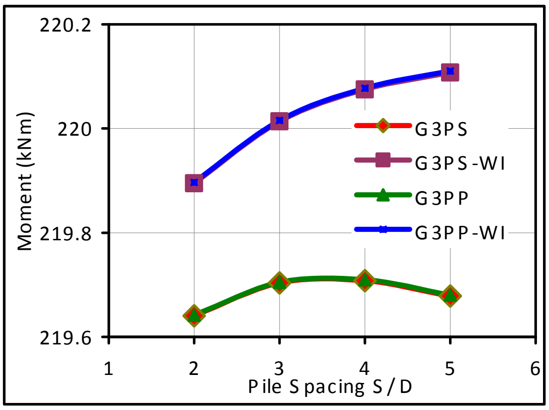
(a) Variation of moment at top of C-2



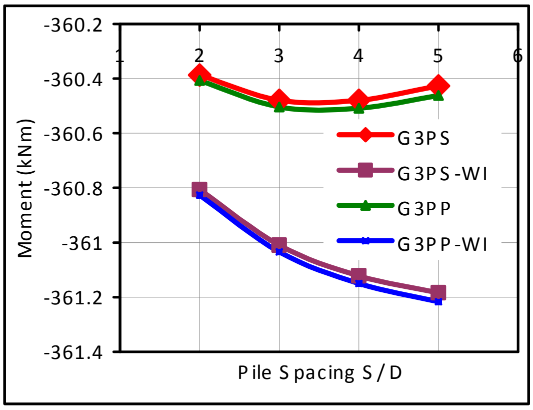
(b) Variation of moment at bottom of C-2



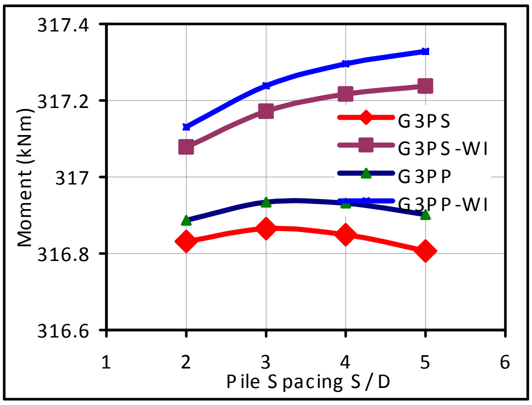
(c) Variation of moment at top of C-8



(d) Variation of moment at bottom of C-8



(e) Variation of moment at top of C-5



(f) Variation of moment at bottom of C-5

Fig. 9. Variation of moments with spacing group of three piles [Fixed Tip]

The variation of moment at the top and bottom of typical columns in the context of the analysis presented here for all the end conditions is shown in Fig. 4-9 and discussed in the subsequent section.

The general trend observed pertaining to the variation of bending moment in columns irrespective of the configuration of pile groups is that for columns C-1, C-2 and C-3 in the row on the left hand side of the frame at the top, the bending moment increases on the negative side with increasing spacing and that at the bottom, the bending moment increases on the positive side. For the columns in the intermediate row (C-4, C-5 and C-6) and those in the row on the right hand side (C-7, C-8 and C-9), the trend of variation of bending moment is that at the top of these columns, it decreases on the negative side with increasing spacing and at the bottom, it decreases on the positive side with spacing.

5.2.1.1 Group of two piles

When the values of moment with pile spacing in superstructure columns obtained by ignoring the interaction between the pile cap and the soil underlying it in the context of either arrangement are compared with those obtained considering this aspect (Chore *et al.* 2010 a), it is observed that the trend regarding increase or decrease in moment almost remains same except that in case of corner columns C-7 and C-9 for pile group with series configuration where moment increases for all the spacing unlike that observed in respect of the same configuration where interaction between cap and soil is taken into account(Chore *et al.* 2010 a).

Such exceptional results could be attributed to the lack of precise interaction between two piles in a group, particularly in the rear row, in this analysis where soil is modeled as the spring. Further, it may be noted that the interaction between cap and soil is neglected. However, difference between the values of moment obtained corresponding to different spacing is observed to be marginal as compared to that obtained with respect to the analysis carried out by considering this interaction aspect (Chore *et al*., 2010 a). The trend of variation of moment with spacing in superstructure columns observed as above in the context of the analysis carried out without considering the interaction of pile cap and soil in respect of free tip condition holds well in respect of remaining two end conditions.

5.2.1.2 Group of three piles

In case of the group of three piles with either arrangement and in respect of all the end conditions assumed to prevail at the pile tip, trend of variation of moment with spacing in columns although remains same; but exactly opposite to the one observed in general and in many cases seen previously in various analyses attempted in this investigation. For the columns in the row on left hand side, moment at top decreases on negative side and that at bottom decreases on negative side. For the remaining columns, i.e., columns placed in the intermediate row and the row on right hand side, moment at top increases on negative side and that at bottom increases on positive side.

6. Conclusions

A comprehensive analysis of single storeyed and two bayed building frame supported on pile group is analyzed using simplified modeling for the foundation elements. Following are the broad conclusions emerging from the independent analysis:

i. Incorporation and exclusion of the aspect of interaction between pile cap and soil underlying it in the analysis has the significant effect on the response in terms of displacement at top of the frame though its effect on absolute maximum moments in the individual columns is almost negligible.
ii. Exclusion of this aspect from the analysis yields higher displacement in either configuration for both the pile groups. Further, trend of displacement with spacing in case of the group of the piles with parallel arrangement is also exactly opposite to that observed normally as for this group displacement is found to increase with spacing.

iii. When interaction between cap and soil is not considered, variation of moment in columns with spacing in respect of the group of two piles is similar to that observed when this aspect is modeled in the analysis. But in respect of the group of three piles, the trend is exactly opposite.

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