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Technical Note

Parametric study of pile groups subjected to lateral load

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1. Introduction

Pile foundations are generally preferred when heavy structural loads have to be transferred through weak subsoil to firm strata. Besides vertical loads, these foundations in some situations are subjected to a significant amount of lateral load. The lateral forces may be due to impact of ships during berthing and wave action in the case of off-shore structures. Pile supported foundations of earth retaining and transmission tower structures will also be subjected to lateral loads. Building frames supported by piled foundations exposed to wind forces also fall under the category of the structures/sub-structures subjected to lateral loads. The problem of laterally loaded piles or pile group involves particularly the complex soil-structure interaction between the piles and pile cap.

The conventional approaches available to analyze laterally loaded piles include the elastic continuum approach (Banerjee and Davis 1978) and the modulus of subgrade reaction approach (Reese and Matlock 1956, Geogiadis and Butterfield 1982). The last three decades have witnessed a tremendous growth in the numerical methods and it is now possible to obtain a more realistic and satisfactory solution for any soil- structure related problems. Among the numerical methods, the most versatile, prominent and successful procedure is the finite element method, which overcomes the drawbacks of the conventional approaches. Many studies reported in the literature include those by Desai and Appel (1976), Desai *et al.* (1981), Dewaikar *et al.* (2007).

In this paper, 3-D FEA of pile groups embedded in a homogeneous soil mass of soft marine clay and subjected to lateral load is presented. The analysis assumes linear elastic behaviour of the soil. It, further, takes into consideration the interaction between the pile cap and underlying soil, generally the most neglected parameter in the analysis of pile groups. The members of the pile foundation such as the pile and the soil are discretized using 20 node iso-parametric continuum elements. Three degrees of freedom are considered at each node, i.e., displacement in three directions in X, Y and Z. The interface between the pile and soil is modelled using 16 noded isoparametric surface elements as proposed by Buragohain and Shah (1978). In the proposed study,

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the effect of various parameters of the pile foundation such as spacing between the piles in a group, direction of the load, arrangement of piles in a group and diameter of piles is evaluated on the response of the foundation head. The response of the foundation head is considered in terms of the displacement at the top of the pile group and the bending moment in the piles.

2. Problem description

Two pile groups consisting of two and three piles respectively in the group having series and parallel configurations were considered for the purpose of the parametric study. When the direction of the loading is parallel to the line joining the piles, it is referred to as the series arrangement. On the other hand, if the lateral load is acting in a direction perpendicular to the line joining the piles, it is called as the parallel arrangement. The piles are connected at their heads by a pile cap of concrete. 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 to the pile cap. The properties of the materials (pile, soil and interface) are reported below.

Pile and Pile Cap	Young's Modulus 0.3605×10^8 kPa, Poisson's Ratio 0.15
Soil	Modulus of Elasticity (E_s) 4267 kPa, Poisson's Ratio (μ_s) 0.45
Interface Stiffness	Tangential Direction (k_s) 1000 kN/m^3, Normal Direction (k_n) 10^6 kN/m^3
Pile Diameter (mm)	300, 400, 500, and 600

3. Results and discussion

Displacement at the top of the pile group, and bending moment in the pile are considered for the purpose of comparison. The effect of the pile spacing, number of piles, arrangement of piles and the pile diameter is evaluated on the top displacements of the pile groups in the parametric study. The effect of the pile spacing on the horizontal displacement at the top of the pile group for various diameters considered in the study is presented in Table 1. For 300 mm diameter piles top-displacement is higher in the case of group of two piles with the series arrangement (G2PS) than those of the parallel arrangement (G2PP) for all spacings. A similar trend is observed in the case of the group of three piles (G3PS and G3PP) with the exception of higher pile spacing of 5D. At this spacing, displacement is observed to be higher in respect to the parallel arrangement. In general, displacement is found to reduce with pile spacing. The effect of arrangement of piles is complex. When the effect of pile configuration on displacements is compared, it is observed that at smaller pile diameter, displacements in the series arrangement are higher than those in the parallel arrangement. That is at smaller diameter (slender piles), the parallel arrangement offers a stiffer behavior than a series arrangement. But as the pile diameter increases, the trend goes in the reverse order. The displacements in the series arrangement are lower than those in the parallel arrangement at higher diameter. At higher diameter (rigid piles), the series arrangement exhibits a stiffer behavior. This is because the combined structural stiffness of the pile and pile cap in a parallel arrangement is small as compared to series arrangements. For short to medium length piles, it is a governing factor. For long piles, a different trend is possible where the soil stiffness imparts considerable strength. The trend is similar for the group of two and three piles with lower displacements at three pile arrangements.

Table 1 Displacement at top of the pile group

Pile Spacing	Horizontal Displacement (mm)				Vertical Displacement (mm)			
	2D	3D	4D	5D	2D	3D	4D	5D
Configuration	Pile Diameter 300 mm				Pile Diameter 400 mm			
G2PS	123.51	108.29	96.39	86.81	97.88	82.97	71.58	62.73
G2PP	110.24	94.58	84.05	76.40	90.60	77.96	69.45	63.23
G3PS	95.63	77.16	64.09	54.64	71.53	54.38	43.32	36.18
G3PP	78.98	66.92	60.25	56.09	78.98	66.92	60.25	56.09
	Pile Diameter 500 mm				Pile Diameter 600 mm			
G2PS	77.58	64.04	54.03	46.69	62.54	50.69	42.50	36.82
G2PP	75.65	65.12	58.00	52.78	63.26	54.39	48.38	43.95
G3PS	53.96	39.85	31.69	26.97	42.28	31.39	25.64	22.55
G3PP	55.34	46.40	41.28	37.88	46.38	38.71	34.24	31.20

Table 2 Comparison of Moments [kN-m] in G3PS and G3PP arrangement

	G3PS Dia. 300 mm				G3PS Dia. 400 mm			
Spacing	2D	3D	4D	5D	2D	3D	4D	5D
Front Pile	143	95	60	37	85	38	14	5
Central Pile	111	69	40	21	52	18	5	3
Rear Pile	141	94	59	37	85	39	14	5
	G3PS Dia. 500 mm				G3PS Dia. 600 mm			
Front Pile	39	10	5	3	17	8	6	4
Central Pile	15	5	4	3	7	6	5	4
Rear Pile	41	12	5	3	20	9	6	4
	G3PP Dia. 300 mm				G3PP Dia. 400 mm			
Central Pile	207	208	207	208	207	208	207	208
Corner Pile	227	220	227	220	227	220	227	220
	G3PP Dia. 500 mm				G3PP Dia. 600 mm			
Central Pile	161	161	161	161	161	161	161	161
Corner Pile	177	168	177	168	177	168	177	168

The bending moment is evaluated along the depth of the pile. It is observed that the maximum positive moment is decreasing with the increase in pile spacing and the pile diameter whereas the negative moment at the pile head is increasing with increase in pile spacing and pile diameter. The moments in the front and the rear pile are about the same in magnitude. The comparison of moments between the individual piles in the group of G3PS and G3PP are reported in Table 2.

In the G3PS arrangement, it is observed that the corner piles are subjected to higher positive bending moment. However, the fixing moment at the pile head is higher in the corner pile than that in the central pile at lower spacing. But at the higher spacing fixing moments in corner piles are smaller than that in the central pile. This indicates that a large portion of load is taken by corner piles than the central piles. For the G3PP configuration, it is observed that the maximum positive moment is decreasing with the increase in pile spacing, but the effect of spacing is marginal. Moments in the corner piles are 10% higher than the moments in the central piles. This again indicates that the larger portion of the load is shared by the corner piles. It is observed that for the piles in a series arrangement, the fixing moment at the pile head is increasing with the increase in pile spacing. Maximum positive bending moment is decreasing with the increase in the pile spacing. In case of the group of three piles, the moments in central pile are higher than in corner pile whereas in the group of two piles, moments in either pile are near about same.

4. Conclusions

From the three dimensional finite element analysis of a laterally loaded pile foundation embedded in soft marine clay, the following broad conclusions can be deduced:

- With the increase in pile spacing, resistance to lateral load increases. The capacity of a pile group increases with pile spacing and pile diameter.
- The arrangement of piles with respect to the direction of lateral load is an important factor. At smaller pile diameters capacity of the pile group is found to be higher in the parallel configuration than that in series configuration. However, at higher diameter capacity is found to be higher in the series configuration.
- The moment at the pile head increases with increase in pile spacing. In the group of three piles, the moments in the corner pile are higher than that in central pile.
- With the increase in pile spacing and pile diameter, a maximum positive moment is found to decrease whereas negative moment increases.

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