Analysis of group effect for laterally loaded piles in clay using two practical methods

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ABSTRACT

Lateral load bearing capacity of piles within a closely spaced group is less than the capacity of piles when they are used as single piles for the same average load. Therefore, the 'group effect' may have significant influence on design of piles and structures. Analysis of piles for offshore platforms are commonly carried out through interactive analysis of pile, soil and structure using non-linear load transfer data to represent the soil behaviour. Group effect with respect to lateral load is generally incorporated by using 'P' and 'Y' factors (multipliers) to modify the p-y data used for the interactive analysis. Two methods, one by Focht and Koch (1973) and the other by Hariharan and Kumarasamy (1982) have, generally, been applied to determine these factors for analysis of pile groups for fixed offshore platforms in the Indian offshore. It was of interest to examine the relative performance of the methods in a commonly encountered offshore soil condition. Two groups of piles (fixed-headed) having 2-pile and 4-pile configurations embedded in normally consolidated clay were analysed. It was found from analysis of these pile groups that the difference of results from the two methods were insignificant for practical purposes.

Keywords: pile; offshore; group; lateral.

1 INTRODUCTION

Open-ended steel tubular piles are used as foundation for offshore jacket platforms. Analysis of piles subjected to lateral loading should incorporate group effect if piles are closely spaced in a group since the average load carrying capacity of individual piles reduces when piles are in groups. Thus, group effect has influence on stresses and deflections of the pile as well as in the design of the structure. The effect may be significant depending on many factors - primarily, the pile geometry, spacing between piles, number of piles in a group, orientation of piles in the group, loading direction, soil condition and magnitude of load. Recommended practice API RP 2GEO (2011, with addendum, 2014) which is widely followed by the offshore industry, prescribes that group effect for lateral loading needs to be considered in the design of pile groups when the centre to centre spacing between piles is less than eight times the pile diameter.

Analysis of offshore piles is generally carried out using non-linear lateral load-displacement (p-y) data to simulate the soil behaviour with respect to lateral loading. The method by Focht and Koch (1973), with modification by Reese et al. (1984), subsequently described as FK method in this paper, is also recommended for assessment of the group effect for offshore piles by API RP 2GEO. FK method has been used in case of some platforms in the Indian offshore. Another method by Hariharan and Kumarasamy (1982) has also been used in case of many offshore platforms in Indian offshore (subsequently described as HK method in this paper).

Analyses were performed for comparison of the results of the two methods on two different pile groups. Normally consolidated clay was selected for the analysis. Lateral loads were selected to cover elastic to plastic range of displacements for the piles.

2 SOIL AND PILE DATA

There are many sites in offshore where the soil profile consists of very soft to soft clays near the seafloor and shear strength gradually increases with depth below the seafloor. Such a representative soil profile used for the analysis is presented in Table 1. Non-linear lateral load-displacement data (p-y) were generated for the analysis using Matlock (1970) as recommended by API RP 2GEO (2011, with addendum, 2014).

Open-ended, steel tubular piles were considered for the analysis. Piles in the group were long piles with

Table 1. Relevant soil properties used for the analysis

Layer	Depth m	s_u (kPa)	γ' (kN/m^3)	ε_{50} %
1	0-10	2.0-21.6	5.5	1.5
2	10-50	21.6-100	7.5	1.0

Note: s_u = undrained shear strength of clay; ε_{50} = strain at 50% of peak shear strength; γ' = Effective unit weight of soil.

Outer diameter 1 m and wall thickness 25 mm arranged with centre to centre spacing as 3 times the pile diameter along 0 and 90 degrees. The configurations of the pile groups and load directions considered are shown in Figure 1.

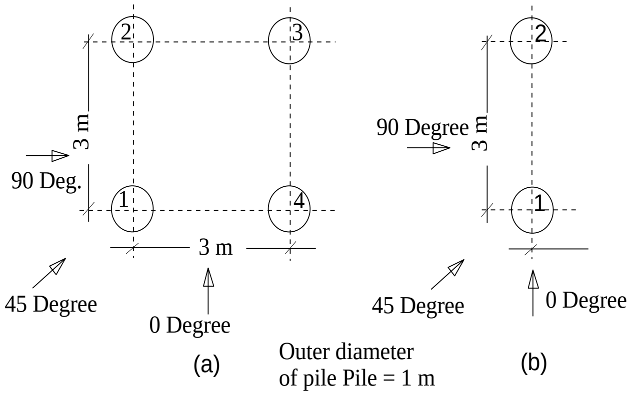

Fig. 1. Geometry of groups: (a) 4-pile group, (b) 2-pile group

3 METHODS

It may be mentioned that both the methods use 'P' and 'Y' factors (multipliers) for modification of p-y data to analyze piles for group effect in lateral loading. Brief description of the methods follows.

3.1 Focht and Koch method

It is also termed as a 'hybrid' or 'p-y Poulos' method where both elastic and plastic behaviour of soil, in response to lateral loading, are taken into account. The displacement of piles in the group as per the method is described by the Eq. (1).

$$Y_g = y_s + y_g \tag{1}$$

where y_s = displacement of piles computed using p-y data without considering group effect and y_g = displacement due to group interaction, calculated through Poulos (1971a) and Poulos (1971b) elastic procedure modified as per the method. A relative stiffness factor (R) is introduced in the method as per Eq. (2). For calculating the displacement of a single pile, the pile is considered as fixed-headed in this approach.

$$\rho_k = \overline{\rho_F} \sum_{\substack{j=1 \\ j\neq k}}^{m} \left(H_j \alpha_{\rho_{Fkj}} + RH_k \right) \tag{2}$$

where ρ_k = horizontal movement of pile 'k' in the group of m piles; $\overline{\rho_F}$ = horizontal movement of a single pile per unit applied load with elastic approach as per Poulos (1971a); H_k = horizontal load in pile 'k'; H_j = horizontal load in pile 'j'; R = relative stiffness factor, i.e. pile head lateral displacement by p-y method divided by that with elastic method; $\alpha_{\rho Fkj}$ = interaction factor related to piles 'k' and 'j' with corresponding spacing and angle as per Poulos. In brief, the method can be summarized as follows:

- p-y approach for deriving lateral displacement of a fixed-headed single pile.
- Poulos' (1971a) and Poulos' (1971b) approach (modified as per the method) are followed to compute lateral displacement of a single pile and additional displacement of piles due to group effect using Poulos' interaction factors.
- N+1 simultaneous equations (N is the no. of piles in the group) are formed.
- Solution of the equations results in the lateral displacement of the pile group and distribution of loads in individual piles
- Group effect is finally taken into account in the interactive analysis (using p-y approach) with 'P' and 'Y' multipliers to modify the p-y input data which match the lateral deflection of the pile group calculated in the preceding step.

According to the Focht and Koch (1973), value of 'P' factor in the range of 0.7 to 1.0 is appropriate for offshore conditions. The 'Y' factor required for the analysis of the group is determined by matching the displacement of a single pile computed using p-y analysis, with the group displacement computed through solution of the simultaneous equations as mentioned earlier. An interpolated value of 'Y' factor that matches the pile group displacement is finally chosen and the pile solution for the group effect is carried out using p-y data modified with the 'Y' and 'P' multipliers.

3.2 Hariharan and Kumarasamy method

Method prescribed by Hariharan and Kumarasamy (1982) is a relatively simpler approach for taking into account the group effect of piles subjected to static lateral loads. Consideration of group effect by this method is consistent with the p-y approach for analysis of laterally loaded piles and carried out in a similar way as in FK method i.e. by using 'P' and 'Y' multipliers to modify the data of p-y used for interactive analysis.

Based on elastic calculation, the multipliers 'P' and 'Y' are obtained from Eqs. (3) and (4). Equation (3) shows the stress ratio that is less than 1.0 due to the stress influence from the other piles on a given pile in a group of N no. of piles. Similarly, Eq. (4) shows the ratio of displacement larger than unity due to group action.

$$P_i = \sigma_{x0} \Big/ \left(\sigma_{x0} + \sum_{\substack{j=1 \\ i\neq i}}^{N} \sigma_{xij} \right) \tag{3}$$

$$Y_i = \left(\mathrm{d} + \sum_{\substack{j=1 \\ i\neq i}}^{N} x_{ij} \right) \Big/ d \tag{4}$$

where σ_{x0} = stress at periphery of pile in x direction; σ_{xij} and x_{ij} are interactive stresses and displacements; N = no. of piles in the group and d = incremental displacement of pile.

Developers of the method show that the P and Y multipliers can be calculated on the basis of pile configuration and direction of loading only.

4 ANALYSIS

Non-linear p-y data were generated at every 1 m depth interval as per Matlock (1970). Initially, soil-pile interactive analysis for a single pile was carried out without incorporating group effect. Analysis was also carried out with modified p-y data applying P and Y factors as per the FK and HK methods to account for the group effect. As per Method-FK, the pile head is to be considered as fixed to derive the 'P' and 'Y' factors. It is also observed that most of the offshore jacket structures supported by multiple piles spread over an area at the base of the jacket are, in general, very highly restrained against rotation. Therefore, pile head was considered as fixed against rotation in the analysis.

Y factors calculated using HK and FK methods are shown in Fig. 2. P factors were calculated as 0.78 and 0.65 for the 2-pile and 4-pile groups respectively, following HK method. It may be noted that the P and Y factors derived from the HK method remain the same for a pile group irrespective of the value of lateral loads. Therefore, two sets of P and Y values are applicable for the method for the two pile groups. In the analyses presented in the paper, same 'P' factors as calculated using HK method have been used with both the methods. Since using an arbitrary value of P (within 0.7 to 1.0) in Focht method eventually produces the same amplification of displacement for a group (only causing corresponding changes in Y), P values in HK and FK methods are kept the same to make a better comparison of corresponding Y values and other results.

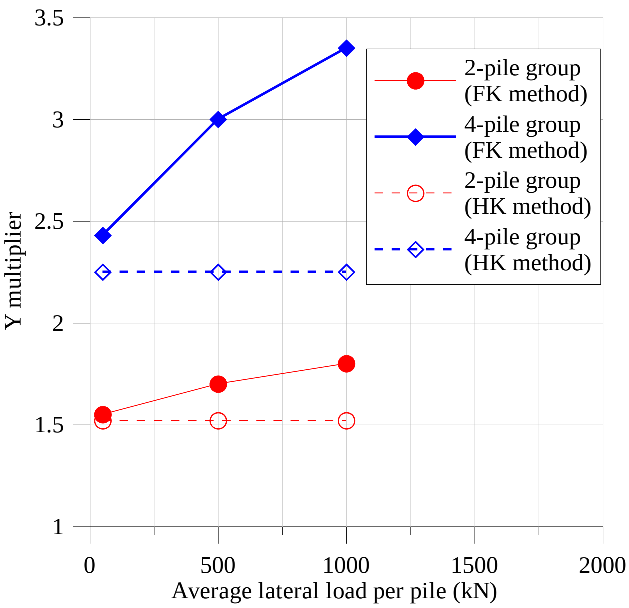

Fig. 2. Y factors for modification of p-y data.

Regarding loading direction, in case of a 2-pile group, the group effect is maximum when the loading direction is in line with (at zero degree with the axis connecting) the piles. In case of the 4-pile group the most onerous loading direction is 45 degree as shown in Figure 1. Results of maximum group effects are presented in the paper.

Comparison of results from the methods were made for a loading (lateral) range to cover both elastic and plastic displacements of soil. Therefore, lateral loads 50 kN, 500 kN and 1000 kN were applied for both the pile groups.

For the considered pile geometry and soil condition, the displacement for a single pile applying the p-y data was calculated as 3.12 mm, 51.6 mm and 156.5 mm for lateral loads of 50 kN, 500kN and 1000 kN respectively.

5 RESULTS AND DISCUSSION

The results of amplification of maximum displacement and bending moments in piles (at pile head) are presented in Table 3, 4 and 5 for values of average lateral load per pile as 50 kN, 500 kN and 1000 kN respectively. Factor R for FK method was considered as 1.0.

Table 3. Comparative results for average load 50 kN per pile

Method	Piles in group	Load per Pile (kN)	Displacement amplification	Max.. B.M amplification
HK	4	50	2.08	1.29
FK	4	50	2.17	1.31
HK	2	50	1.48	1.15
FK	2	50	1.50	1.15

Table 4. Comparative results for average load 500 kN per pile

Method	Piles in group	Load per Pile (kN)	Displacement amplification	Max. B.M. amplification
HK	4	500	1.97	1.26
FK	4	500	2.19	1.30
HK	2	500	1.45	1.14
FK	2	500	1.51	1.15

Table 5. Comparative results for average load 1000 kN per pile

Method	Piles in group	Load per Pile (kN)	Displacement amplification	Max. B.M amplification
HK	4	1000	1.93	1.25
FK	4	1000	2.21	1.30
HK	2	1000	1.44	1.13
FK	2	1000	1.51	1.15

Summary of comparative results from the two methods for lateral loading range of 50 kN to 1000 kN per pile is presented in Table 6.

Table 6. Summary of Comparative results from FK method with respect to HK method

Piles In group	% increase of maximum displacement in pile	% increase of maximum bending moment in pile
2	1.3 – 4.9	0.6 – 1.4
4	4.5 – 14.1	1.6 – 4.3

Displacement of piles with respect to different average lateral loads per pile are shown in Fig. 3 and

Fig. 4. It is observed from the analysis that differences in displacements for practical loads (generally, loads causing displacement of less than 10% of diameter) is insignificant. Differences further reduce in case of resulting maximum bending moments.

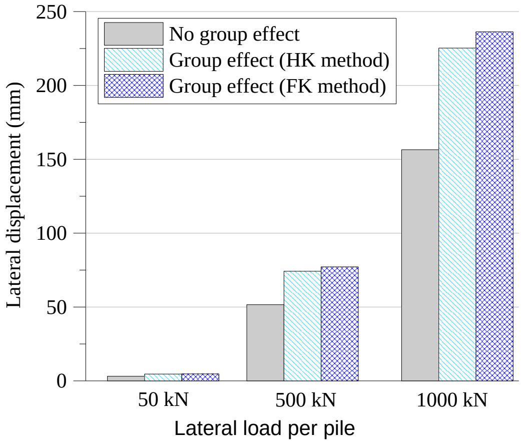

Fig. 3. Comparison of pile displacements with respect to average load per pile the 2-pile group.

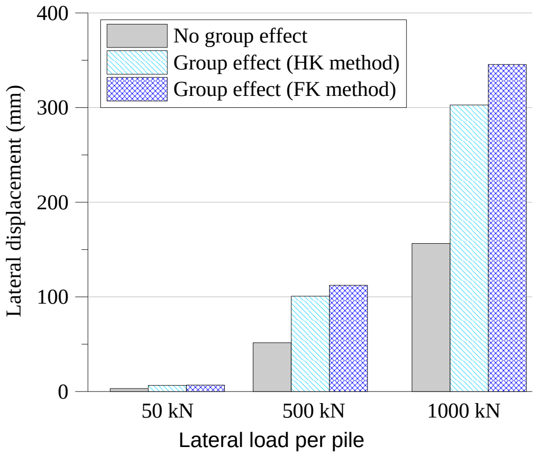

Fig. 4. Comparison of pile displacements with respect to average load per pile for the 4-pile group.

6 CONCLUSION

A comparative analysis on group effect in piles with respect to lateral loading has been presented for piles in normally consolidated clay using two practical methods used for actual design.

Compared with HK method, amplification of displacement using FK method (with R = 1) was higher by 1.3% to 4.9% for the 2-pile group. In case of the 4-pile group, the values were 4.5% to 14.1% higher for the applied range of loads. Amplification of maximum bending moment increased by 0.6% to 1.4% and 1.6% to 4.3% for the 2-pile and 4-pile groups respectively. Differences in results are observed to be marginal for practical loading conditions.

Earlier, analysis by the authors on a two pile group from an actual design case from a site having a mixed soil profile with soft clay, stiff clay and sand occurring near seafloor, showed above-mentioned parameters as significantly higher as per FK method (with R as 1.0) when compared to result from HK method.

Based on the present study, authors opine that considering limitations of both the methods, any of these methods can be practically used for analysis of laterally loaded typical pile groups for offshore piles without appreciable difference in results when following conditions are fulfilled:

a) Soil condition in the zone of significance near the seafloor is normally consolidated clay.
b) Pile heads are fixed or nearly fixed against rotation.
c) Interactive analysis is carried out using p-y data as per method of Matlock (1970)
d) Pile groups have 2 to 4 piles in one group.

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REFERENCES

American Petroleum Institute (2011, addendum 2014) Geotechnical and Foundation design Considerations, API RP 2GEO. 1st edition, API, Washington, DC.

Focht, J. A. and Koch, K. H. (1973). Rational Analysis of the Lateral Performance of Offshore Pile Groups, Proceedings from the 5th Annual Offshore Technology Conference, OTC 1896, Houston, Texas.

Hariharan, M. and Kumarasamy, K. (1982) Analysis of pile groups subjected to lateral loads, Proceedings, 3rd International Conference on Behaviour of Offshore Structures, Vol. 2, Hemisphere Publishing Corp., Washington, D. C., pp. 383-390.

Poulos, H. G. (1971a) Behavior of Laterally Loaded Piles: I - Single Piles, Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 97, No. SM5, pp. 711-731.

Poulos, H. G. (1971b) Behavior of Laterally Loaded Piles: II - Pile Groups, Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 97, No. SM5, pp. 733-751.

Mahanta, R., Ghanekar, R. K. and Nayak, B. (2017) Comparison of Two Common Methods for Analysis of Group Effect for Laterally Loaded Offshore Piles, Indian Geotechnical Conference, Guwahati, India.

Reese, L. C., Wright, S. G. and Aurora, R. P. (1984) Analysis of a Pile Group under Lateral Loading, Laterally Loaded Deep Foundations: Analysis and Performance, ASTM, STP 835, pp. 56–71.