Numerical modeling of pile groups under lateral loading in sand

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ABSTRACT
When soil stability is not suitable for shallow foundations, using of piles is a good replacement. Specially, in offshore structures pile groups are used and usually subject to lateral loading. Group interaction effects are very important and impressive in piles behaviour under lateral loading. Computer simulations of finite element modeling allow for in- depth studies into the complex pile–soil–pile interaction under lateral loading in deep foundation structures. In this paper the effect of piles head conditions on lateral behaviour of a 3×3 pile group in sand are investigated by means of numerical modeling. A three-dimensional finite element model was used to simulate the behaviour of piles and soil. In this model the material behaviour of the soil is described using an elastic-plastic constitutive model. Load-deflection curve and moment distribution were developed for each pile of free-head and fixed-head piles group. The piles head condition was found to be an effective parameter on piles behaviour under lateral loading in a group.

RÉSUMÉ
Lorsque la stabilité du sol n'est pas adapté pour les fondations superficielles, à l'aide de pieux est un bon remplacement. Spécialement, dans les structures offshore pile groupes sont utilisés et généralement soumise à un chargement latéral. Effets de l'interaction du groupe sont très importants et impressionnants dans le comportement des pieux sous chargement latéral. Simulations informatiques de la modélisation par éléments finis permettent des études approfondies dans le complexe de battage de l'interaction sol-pieu sous chargement latéral dans les structures de fondation profonde. Dans cet article l'effet des tas de conditions la tête sur le comportement latéral d'un groupe de 3× 3 pieux dans le sable sont étudiées au moyen de la modélisation numérique. Un modèle à éléments finis en trois dimensions a été utilisée pour simuler le comportement des pieux et le sol. Dans ce modèle, le comportement des matériaux du sol est décrit en utilisant un modèle de comportement élasto-plastique. Courbe charge-flèche et de la distribution moment ont été élaborés pour chaque pile de libre-tête et fixe la tête des pieux du groupe. L'état de la tête des pieux a été trouvé être un paramètre efficace sur le comportement des pieux sous chargement latéral dans un groupe.

1 INTRODUCTION

The lateral load capacity of pile foundation is critically significant in the design of deep foundation. Therefore, lateral loaded piles have received very extensive attention due to their common occurrence and usage in practice. Several methods for analyzing pile behaviour under such loads have been proposed. Developing a practical method while maintaining accuracy and precision in the prediction of capacity of pile foundation, has been becoming the challenge for most geotechnical engineers. Although fairly reliable methods have been developed for predicting the lateral resistance of single piles, methods for predicting the lateral resistance of pile groups are less developed. To study the pile groups' behaviour, only a couple of field tests have been carried out because of the large costs incurred. Most load tests were conducted for free-head piles. The behaviour of an individual pile in group is controlled to a major extent by its location within the group and its pile head fixity. Brown et al. (1988) were the first to propose the p-multiplier method. They conducted cyclic loading tests on nine closed-ended steel pipe piles. The piles were arranged in 3×3 pattern spaced at 3D in both directions. Another full-scale taste was conducted by Ruesta and Townsend (1997) on prestressed concrete piles. Two pile groups in a free-head condition and one in a fixed-head condition were arranged in 4 x 4 pattern spaced at 3D on centers in each direction. Rollins et al. (1998) performed tests on 3×3 steel pile group spaced at 2.8D with a pinned-head condition. The soil consisted of soft to medium-stiff clays overlaying dense sand. The p-multiplier approach was used to provide a match between computed and measured results. The p-multipliers were determined to be 0.6, 0.38, and 0.43 for the front, middle and back rows respectively. Ng et al. (2001) conducted series of full scale tests on three pile groups with large diameter bored piles. In the same year, Huang et al. (2001) studied the effect of pile installation on group interaction effect by conducting full scale tests on a group of driven piles and a group of drilled shafts. Rollins et al. (2005) conducted another full scale test on steel pipe piles in sand. Open ended piles were arranged in 3×3 pattern with the 3D space between center to center in both directions. They offer 0.8, 0.4 and 0.4 for p-multiplier respectively for lead, middle and trial rows. Full-scale cyclic lateral load tests were performed on pile groups in stiff clay spaced at 3.3, 4.4, and 5.65 pile diameters in the direction of loading with as many as five rows of piles by Rollins et al. (2006). According to their results, group effects decreased as pile spacing increased from 3.3 to 5.65D.

Together with these full scale tests, many centrifuge tests were conducted to study the group interaction effect in pile groups. McVay et al. (1995, 1998) performed a series of tests on pile groups in sand (3×3 to 3×7). Based on their tests, p-multiplier reduced from lead to trail row in a group except that in 3×4 to 7×3 groups, the trail row carry a little more load than its front row. The suggested p-multiplier for 3D spaced piles was 0.8, 0.4 and 0.3 (front to back row) for the 3×3 group, 0.8, 0.4, 0.3, 0.3 for the 4×3 group, and 0.8, 0.4, 0.3, 0.2, 0.3 for the 5×3 group, and 0.8, 0.4, 0.3, 0.2, . . . ,0.3 for all larger group size.

Besides these physical modelling, a few numerical simulations have been used to study the behaviour of pile groups under lateral loading. A three dimensional program was performed to approximate analyse of pile behaviour in group by defining non-linear behaviour for soil by Muqtadir and Desai (1986) and Shibata et al. (1988). Brown and Shie (1990, 1991), and Trochanis (1991) used 3D finite element method (FEM) to simulate the elastic-plastic soil and study the behaviour of piles and pile groups under lateral loading. Moreover, a series of models and field tests of free- or fixed-head pile groups have been analyzed by Adachai et al. (1994), Kimura et al. (1995), and Wakai et al. (1999) using 3D elastic-plastic FEM. Yang and Jeremic (2003) studied the group interaction effect in 3×3 and 4×3 group in sand by 3D elastic-plastic finite element modelling. Budiman and Ahn (2005) investigated the effect of piles caps on lateral behaviour of each pile in a 1×3 pile group in clay using 3D FEM.

In this paper, 3D finite element modeling used to simulate pile group behaviour under lateral loading in sand. Group interaction effect has been studied in two 3×3 pile groups, one with fixed-head condition and another with free-head condition. Load distribution in each row and each pile were examined and compared with centrifuge test result. P-y behaviour of individual piles was investigated. ABAQUS software was used to complete all the modelling and computations.

2 MODELLING

2.1 Centrifuge Test Description

McVay et al. (1998) conducted a series of centrifuge tests on 3×3 to 7×3 pile groups in sand under lateral static loading. The rectangular-shaped sample container was fabricated from aluminium alloy with an inside dimension of 0.254 m wide, 0.457 m long, and 0.305 high. The piles were spaced by three times the pile width and the pile caps (made of aluminium) were rigidly connected with the piles. The model square piles and pile cap were fabricated from solid square aluminium (alloy 6061) bars. Each individual pile is 9.5 mm wide and 304.8 mm long. To simulate the installing effects of field driven piles, the piles were driven in flight into sands by hydraulic equipment and tested at 45 g. The sands (artificially mixed by a number of different gradations) studied were at two different relative densities: a loose sand with relative density Dr = 36%, γ= 14,05 kN/m^3 and a medium dense sand with Dr = 55%, γ = 14,50 kN/m^3. The shear modulus G, Poisson's ratio v and friction angle φ are 8230 kN/m^2, 0.35, 34.58 for the loose sand and 8960 kN/m^2, 0.35, 37.18 for the medium dense sand.

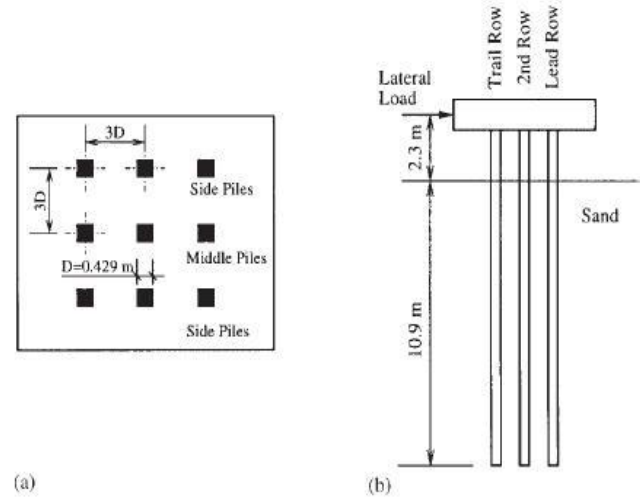


Figure 1. Layout of 3×3 pile group: (a) top view, (b) side view

2.2 Finite Element Modelling

Among these tests, 3×3 group were chosen to simulate using ABAQUS software to investigate interaction effects of groups. Figure 1 shows the layout of the pile group. Because of the symmetry of model in the load direction, only half of model is simulated. The finite element meshing of 3×3 group with cap is shown in Figure 2.

Soil and pile are modeled by 8 node brick elements. Each pile consists of 4 elements per cross section with elastic behavior corresponding to aluminium. The Young's modulus E and Poisson's ratio are 69 GPa and 0.35 for aluminium. The sides and bottom of model in each three coordinate direction have been fixed except symmetric boundary which is only fixed in Y direction.

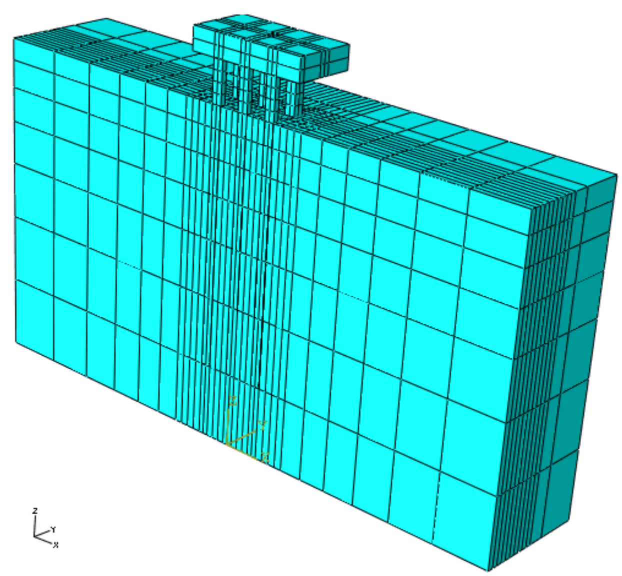


Figure 2. Finite element mesh for 3×3 pile group with cap

Soil was simulated by Mohr-Coulomb material model. All the mechanical parameters of dens sand are same with centrifuge test except Young's Modulus. The Young's Modulus was assumed to increase in depth. Equation 1 shows the distribution of E.

$$E = E_0(P/P_0)^{0.5} \quad [1]$$

Where E_0 is Young's Modulus at the atmospheric pressure, P is the mean effective normal stress, and P_0 is the atmospheric pressure. For the dense sand the E_0 is 17400 kPa as similar was also used by Yang and Jeremic (2003). The dilation angle of sand ψ is considered 2/3 φ according to references. The interface of soil and pile was simulated by frictional behaviour which allows separation between pile and soil.

3 SIMULATION RESULTS

3.1 Model Verification

In this section the results of piles behaviour in 3×3 group under lateral loading is presented. The results of pile group with cap are compared with those from the centrifuge studied by McVay et al. (1998).

3.1.1 Load Distribution

The static pushover tests were conducted to the pile head with the loading applied in X direction. In order to verification the results of this study with centrifuge results, load-deflection curves at piles head at 3×3 pile group for centrifuge model (McVay et al. 1998), numerical study of Yang and Jeremic (2003), and this study are plotted in Figure 3.

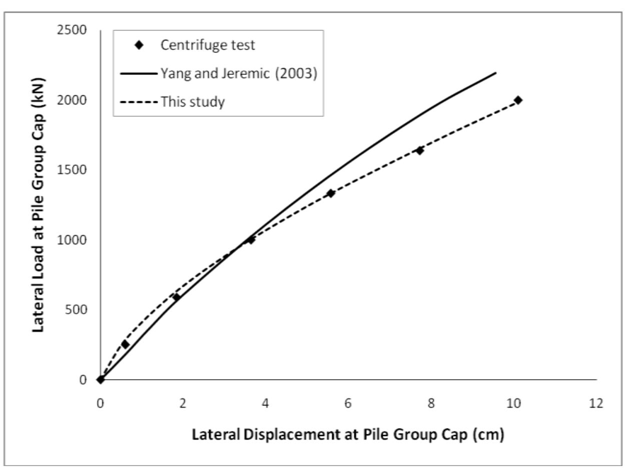


Figure 3. Comparison of load-deflection curve for 3×3 pile group with cap

It can be seen that this model have a good agreement with centrifuge results while Yang and Jeremic's model is stiffer than centrifuge result at large displacements.

The accuracy of finite element model also can be evaluated by load-deflection curve of each row in the group. Figure 4 is presented the load- deflection of each row of 3×3 pile group under lateral loading for both centrifuge testing and finite element model.

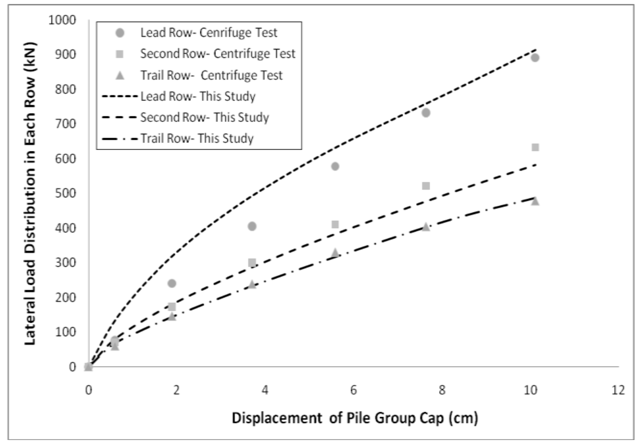


Figure 4. Variation of load taken by each row in the 3×3 pile group with cap

As it realized from Figure 4 there is good agreements between centrifuge tests and finite element model except in the lead row in small displacement the finite element model is a little stiffer than tests results. The load carried by individual piles in the group is a function of row location. The leading row piles carry more load than the middle and trailing row piles. This phenomenon is considered to be a result of overlapping shear zones since the piles are only spaced at 3 pile diameters. In addition, the back row piles actually carry slightly less load than the middle row piles.

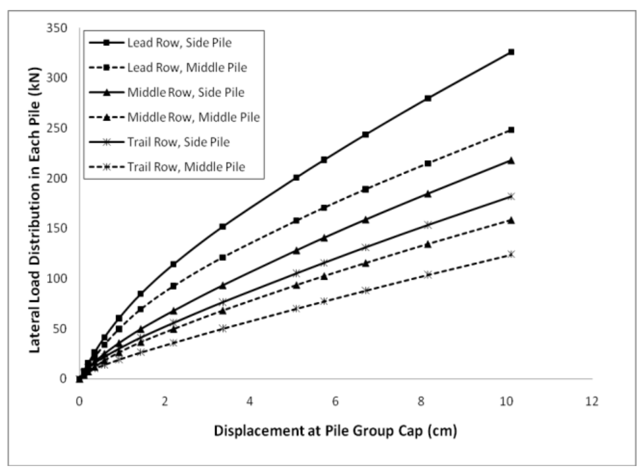


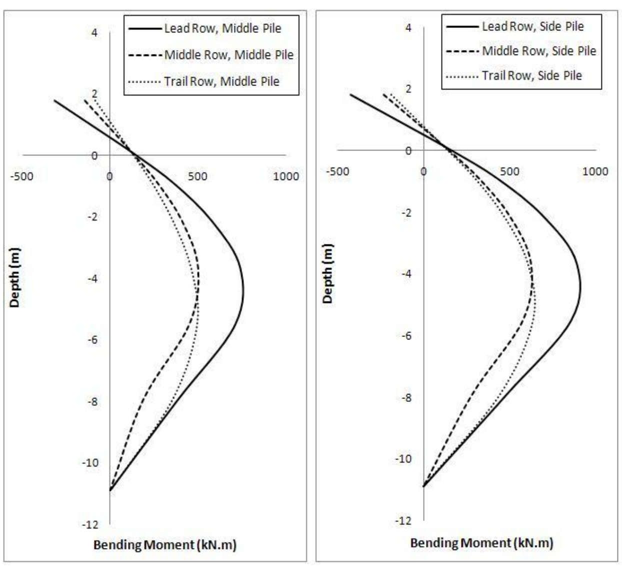
Figure 5. Variation of load taken by each pile in the 3×3 pile group with cap

The load carried by a pile in the group was also found to be a function of position within a given row which is also reported by Rollins et al. (2005). The variations of load distributions in each pile of 3×3 fixed-head group are illustrated in Figure 5. The middle pile carried the smallest load in all rows at a given displacement.

The width of passive wedge which forms in soil in front of a laterally loaded pile increases as the friction angle increases. Since sands generally have a higher friction angle than clays, the passive wedge would be wider in sands than in clays. As a result, more group interaction would be expected from adjacent piles within a row in sands than in clays. From a practical standpoint, the middle piles in a row would have the most interaction with adjacent piles and therefore, would be expected to carry less load than the outer piles.

3.1.2 Bending Moment

Bending moment versus depth curves at side and middle piles in each row for 3×3 pile group with cap under 2000 kN lateral load are presented in Figure 6. Like load distribution at piles, the moment along lead row piles is the maximum among piles in group. While the bending moment at leading row for both side and middle piles is considerably more than other ones, the middle and trail row piles have almost same moment distribution.



(a) (b)

Figure 6. Bending moment versus depth curves at lateral load of 2000 kN for piles in 3×3 group with cap, (a) middle piles, (b) side piles

Generally, the maximum bending moment location on a pile depends on the rotation of its head. If the pile head allowed rotating, then the maximum bending moment will occur below its head. This could occur for fixed-head pile groups if the cap is allowed to rotate sufficiently because of soft soils, long exposed lengths, etc. In this model based on McVay et al. (1998) and finite element results, the group attributed to a slightly rotation. Figure 7 shows deflection of pile and soil in pile direction, Z, under 2000 kN lateral load. As it mentioned before, using of frictional interaction between soil and piles allowed the piles to separate from soil. It cab be seen that the pile cap rotate slightly which cause the maximum bending moment did not occur at pile heads.

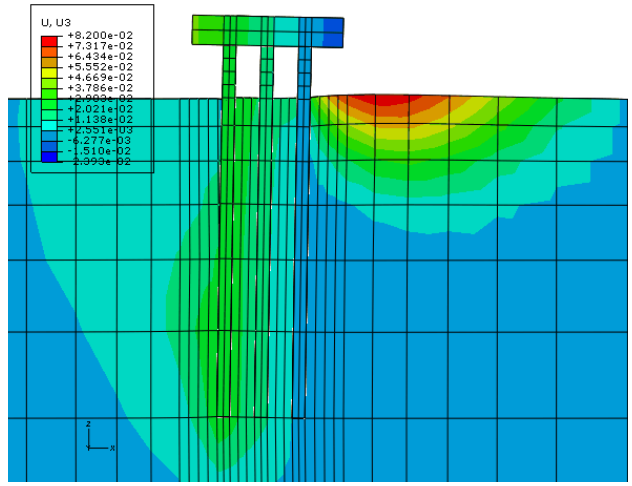


Figure 7. Model displacement in direction Z for 3×3 group under 2000 kN lateral loading

3.2 Free-head Pile Group

In order to study the effect of piles head condition on lateral behaviour of piles, another finite element model of 3×3 group without cap under lateral loading is performed. All the parameters used for modelling of soil and piles are same as group with cap.

3.2.1 Load Distribution

Figure 8 shows the load versus lateral deflection curves for both pile groups with and without cap.

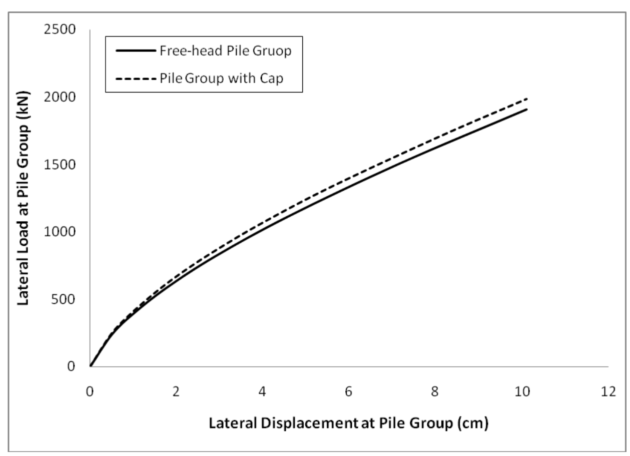


Figure 8. Comparison of load-deflection curve for 3×3 pile group with and without cap

As it expected, pile group without cap carry slightly less load than group with cap for a same deflection. This decrease in group capacity is not considerable. As the pile cap rotated under lateral loading, the pile group with cap did not behave as a completely fixed-head group. Therefore, the load capacity of pile group without cap is slightly less than group with cap.

Lateral load distribution for each row in free-head group is plotted in Figure 9. In this case also, the lead row carry maximum load in the group. This is because of shadowing effects of group which occur in group with and without cap. Figure 10 presents load distribution in each pile in 3×3 pile group without cap under lateral loading. The only difference between load distribution of 3×3 pile group with and without cap is the middle and trail rows piles in free-head group is carry same load while in the group with cap the middle row carry slightly more than trail row. Based on Figure 10, side and middle pile in middle and trail rows carry same load in free-head condition. This result is also reported by Rollins et al. (2005). They conducted a series of full scale tests on 3×3 steel pile group in sand under lateral loading with free-head condition, and resulted same load distribution for trail and middle row piles.

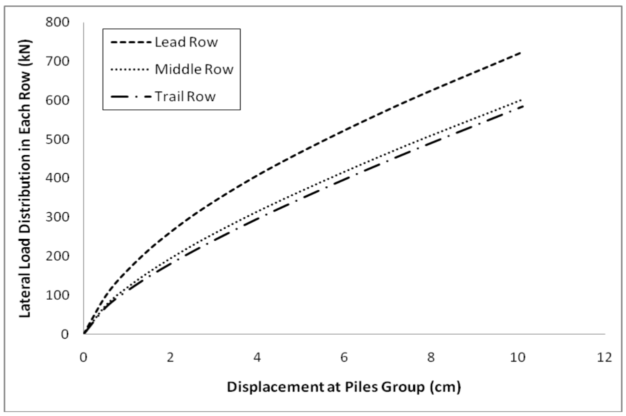


Figure 9. Variation of load taken by each row in the 3×3 pile group without cap

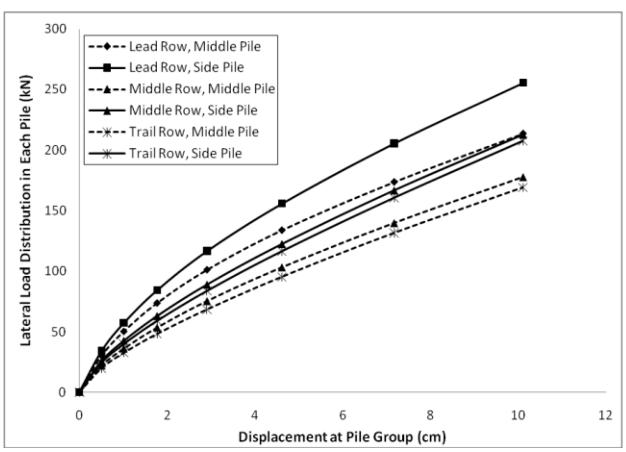
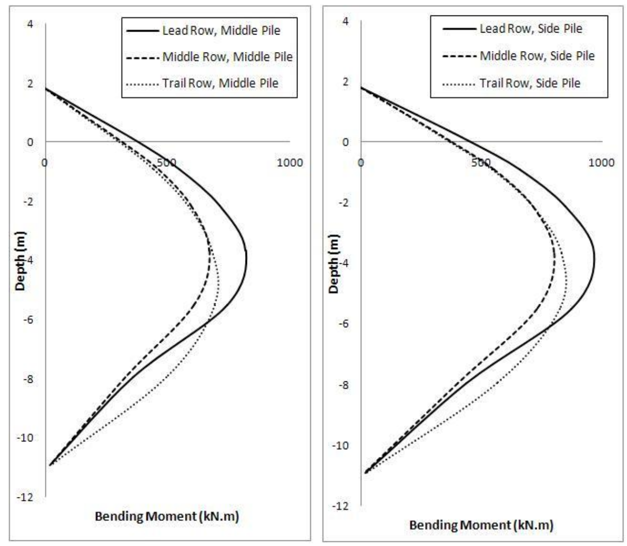


Figure 10. Variation of load taken by each pile in the 3×3 pile group without cap

3.2.2 Bending Moment

In free-head condition pile groups, the maximum bending moment on a pile under lateral loading always occur below the soil surface. Piles' heads can rotate and it makes the zero moment in pile heads. Bending moment versus depth curves at side and middle piles in each row for 3×3 pile group without cap under 2000 kN lateral load are presented in Figure 11. Maximum moment occurs at depth of 4 (m) below soil surface for lead and middle row piles and 5 (m) for trail row piles as same as group with cap. Maximum moment increased from it's among at pile group with cap for whole side and middle piles in three rows.



(a) (b)

Figure 11. Bending moment versus depth curves at lateral load of 1900 kN for piles in 3×3 group without cap, (a) middle piles, (b) side piles

4 CONCLUSION

This paper presents results from the finite element study on the interaction effects of pile groups founded in sands. The 3×3 pile groups with and without cap with 3diameter spaced were analysed in terms of bending moment and load distribution among individual piles. Comparison of results from FEM and centrifuge study shows that elasto-plastic finite element analysis can predict the behaviour of pile group with very good accuracy. Particularly, load distribution results for whole group and also each row from finite element analyses agree very well with that from centrifuge study.

It was shown that the load taken by each pile in the group is completely depends on its location in the group. The load taken by lead row is the maximum while the trail row piles carry the minimum load in 3×3 pile group with cap. In free-head group, the lead row carries the maximum load in the group, and the trail and middle row have same load distribution. Difference between side and middle piles in a row is decreased in free-head group comparing with group with cap. However, in all of three rows in with and without cap the side piles carry more load than middle piles.

Maximum bending moment in piles for both with and without cap groups occurred below the piles heads. This is expected from free-head group, but in group with cap the rotation of cap cause maximum moment did not occur at pile head.

Piles head condition of 3D spaced 3×3 pile group is effective on group behaviour under lateral loading. The influence of piles head on load distribution and moment versus depth curves is considerable. The most important effect of piles head is the difference of load distribution of piles comparing with group with cap. The difference between trail and middle row is very small in free-head group, but in group with cap they have a considerable different distribution.

Since FEM can capture the critical aspects of group effects, it could now be used to systematically study various pile group configurations at much smaller cost than actual load tests, and derive interaction factors for elastic and plastic loading levels that could be used in standard design practice.

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