Jour. of the KGS, Vol. 21, No. 2. March 2005, pp. 47~55

Group Effects in Pile Group under Lateral Loading

수평력을 받는 군말뚝에서의 말뚝의 상호작용

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요 지

본 연구에서는 점토지반에서 수평력을 받는 군말뚝과 단말뚝의 수평저항력을 파악하기 위하여 유한요소 해석프로그램인 ABAQUS를 이용하여 수치해석을 행하였다. 수치해석은 말뚝직경(1.0, 0.5m), 말뚝길이(7, 10m) 그리고 두부조건(두부자유와 말뚝캡을 적용한 두부구속조건)을 변수로 하여 실시하였다. 수평력 작용시 선말뚝(leading pile)의 캡에 의한 영향과, 군말뚝내의 각각의 말뚝에 대한 수평저항력의 크기와 분포를 평가하기 위하여 1×3군말뚝을 사용하였다. 점토지반은 Cam-clay 모델을 사용하였고, 말뚝은 원형의 콘크리트로 탄성모델을 사용하여 3차원 해석을 수행하였다. 해석결과 말뚝캡의 크기는 단말뚝의 수평저항력에 영향을 미치는 것으로 나타났으며, 군말뚝내의 선말뚝은 군말뚝의 효과에 의해 수평저항력이 증가하면서 Brown이 제안한 *p*-multiplier 값이 1보다 크게 평가되었다.

Abstract

This paper describes the results for a numerical analysis of single piles and pile groups in clayey soils subjected to monotonous lateral loading using the ABAQUS finite element software. The investigated variables in this study include free head and embedded capped single piles, pile diameter (1.0 m, 0.5 m), pile length (7.0 m, 10.0 m), and pile groups. The 1×3 pile group was selected to investigate the individual pile and group lateral resistance, the distribution of the resistance among the piles, the effects of lateral stresses in front of and on the sides of the piles, and the effect of a cap on the lateral resistance of the leading pile. The soil was modeled using Cam-clay constitutive relationship and the pile was considered as a elastic circular concrete pile. The results show that the size of the cap influences lateral capacity of the single pile. The results also show that in pile groups, the pile-soil-pile interaction and the cap affect the resistance in the leading pile, and the *p*-multiplier for the leading pile of greater than 1.0 was able to be obtained.

Keywords : ABAQUS, Cam-clay, Clayey soil, Lateral loading, Pile groups, P-multiplier

1. Introduction

Numerous methods for analyzing pile behavior under lateral loads have been described in the literature, however, a practical method while maintaining accuracy and precision in the prediction of capacity of pile foundation has always been a challenge for geotechnical engineers.

A widely used method for lateral load design in a pile

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foundation is the *p-y* method. The development of this method was primarily based on the work of Matlock and Reese (1960) and their associates. Their subsequent work led to the development of user friendly computer programs. Reese and Van Impe (2001) give a comprehensive description of this method. This method is based on the Winkler's spring subgrade reaction approach, and it utilizes a beam-column on an elastic foundation with nonlinear springs to transfer the load from the pile to the soil. These springs represent the soil resistance at different depths and the lateral displacement of a horizontally loaded pile. For pile groups, Brown et al. (1987) proposed the *p-y* curve for a pile in a group by using p-multiplier. Individual piles in the group are assigned a multiplying factor corresponding to the capacity of a single pile, and the factored capacity for each individual pile provides to the cumulative group lateral capacity. Ashour et al. (2004) used a strain wedge model to analyze the lateral capacity of the pile group. The interaction of piles in the group is based on the overlapping passive wedge in front of piles, which is then transformed to an equivalent single modulus of subgrade reaction.

Most of full-scale load tests were conducted on free-head piles, but only a few load tests for fixed-head piles have been reported. In these tests, despite the fact that the piles and cap in a pile group are embedded in the soil layer, the influence of friction and adhesion resistance of cap with soils has not been sufficiently evaluated. To completely evaluate the lateral capacity of pile groups, the pile-soil-pile interaction, passive pressure on the pile cap, base friction, and side friction on the pile cap must be accounted for separately.

The *p*-multipliers have been typically obtained from a free-head pile, direct application of the capacity of a free head pile to the fixed-head pile group should be evaluated further, and this is due to the difference in their response under the loads. Rollins and Sparks (2002) performed the field tests for pile groups with cap to investigate the behavior of fixed-head pile groups, contribution of passive pressure, and base interface friction on the pile cap resistance, and then proposed the default *p*-multipliers, which were evaluated for single piles without caps.

To improve the understanding of fixed head pile behavior, pile-soil-pile interaction and the influence of a pile cap, a numerical analysis considering the above factors was performed for a pile group. The analysis was performed using the ABAQUS finite element program. To investigate the pile-soil-pile interaction, a 1×3 pile group was modeled. The *p*-multiplier was evaluated based on a fixed-head single pile. The variables employed in this study were the pile diameter of 0.5 m and 1.0 m, pile length of 7.0 m (short pile) and 10.0 m (long pile), the length of the cap size for a single pile, and the spacing of 3 diameters in a pile group.

2. Pile-Soil Models

In these analyses, the load was applied at the pile head for a free head pile and at the top of the cap for a fixed head pile and the pile group. The analysis was performed on one half of the model due to the geometric symmetry, and also to reduce the time of computation. The finite element model is shown in Figure 1. The concrete pile was modeled having linear elastic properties, while the soil in the inner-field region (around the pile and cap) was modeled as an elastoplastic material. The soil deformed elastically following the porous elastic theory, and plastically according to clay plasticity based on Cam-clay model. The soil in the far-field region was modeled as a porous elastic material and assumed to have an infinite boundary. The range of the inner-field region extended from the pile-soil interface to a distance of two times the length of the pile cap, and the far field boundary extended twice as far as the inner field boundary distance from the center of the pile. Interface elements between the concrete and soil had nodal points on the pile shaft separated from those nodal points to the adjacent soils elements to ensure independent movement between pile and soil elements, and allowing a gap to develop between soil and pile under tension. The interface friction between pile and soil element surfaces was simulated using the Coulomb friction model.

Boundary conditions along the symmetric plane were assumed to be on rollers which moved freely in the

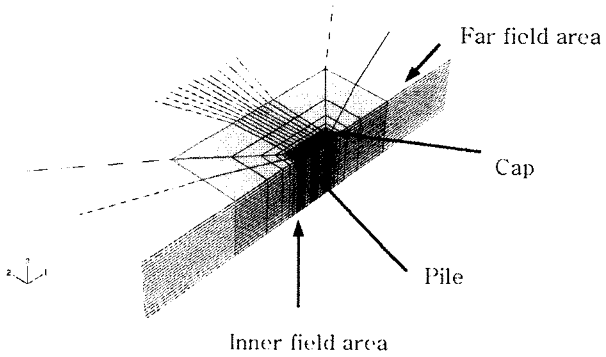


Fig. 1. Finite element model of pile group

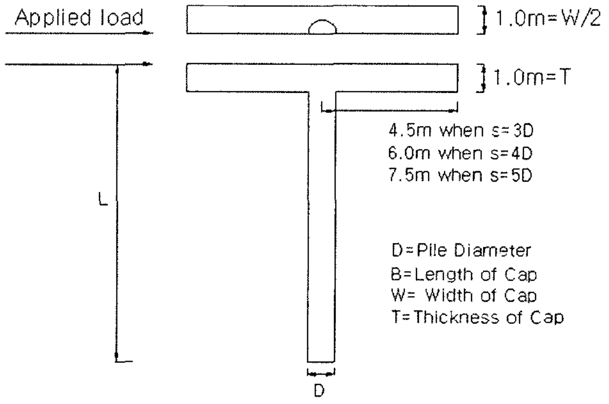


Fig. 2. Layout of single pile with cap

vertical plane. This plane was parallel to the direction of the applied horizontal load and restrained in the direction perpendicular to the symmetric plane. In the model, the pile tip was assumed to bear on two and four-meter thick layers of soil deposits for 7.0 m and 10.0 m piles, respectively. The variables used in the analysis were the typical values from the literature based on general field data.

Reduced-integration second-order 3-D solid (brick) elements were used to discretize both pile and soil medium. Bias elements were used in horizontal directions, so that the dimensions of the element varied with horizontal direction. In horizontal direction, finer elements were chosen around the center of the pile and became coarser with increasing horizontal distance away from the pile.

The layout for the single pile is shown in Figure 2. The dimensions of the concrete piles are shown in Table 1. The cap lengths were varied based on the assumed spacing in pile group. As shown in the figure, the cap length B is 9 m equivalent to the cap of a 1×3 pile group with a pile spacing of 3 diameters. The authors are aware of the extra length of the pile cap, which was used primarily to investigate their influence on lateral capacity.

Table 1. Dimensions of Pile and Cap for Single Pile

L [meter]	Diameter of pile (D) [meter]	Cap size B×W/2×T [meter]
7.0	1.0	9.0×1.0×1.0
&	&	12.0×1.0×1.0
10.0	0.5	15.0×1.0×1.0

In this study, soil parameters were selected from typical values in the reference and shown in Table 2.

3. Laterally Loaded Single Pile

Single piles with caps and without caps were modeled. The loads were applied until the pile head reached a deflection of 0.05-0.07 m. The result of the numerical analysis on the load-deflection response of large pile with a diameter of 1.0 m is shown in Figure 3.

The response in Figure 3 (a) shows that the single pile without a cap has the lowest lateral resistance, with deflection of 0.025 m. This pile exerts approximately 425 kN resistance. As expected, the single piles with cap at the same displacement of 0.025 m show higher resistance. The resistance of the pile with a cap containing spacing s = 3D exerts 1150 kN lateral resistance, and higher in piles with longer cap. The results also show that for a deflection of approximately 0.01 m, the three piles with cap show similar resistance. In comparison with the loads

Table 2. Summary of Input Data

Parameters	Values
Concrete pile:	
Modulus of elasticity, E	30.E9 Pa
Soil:	
Initial void ratio, e_0	0.7
Poisson's ratio, ν	0.25
Unit weight of soil, γ	19200 N/m^3
Internal friction angle of soil, ϕ	24°
Logarithmic plastic bulk modulus, K	0.174
Stress ratio at critical state, M	0.94

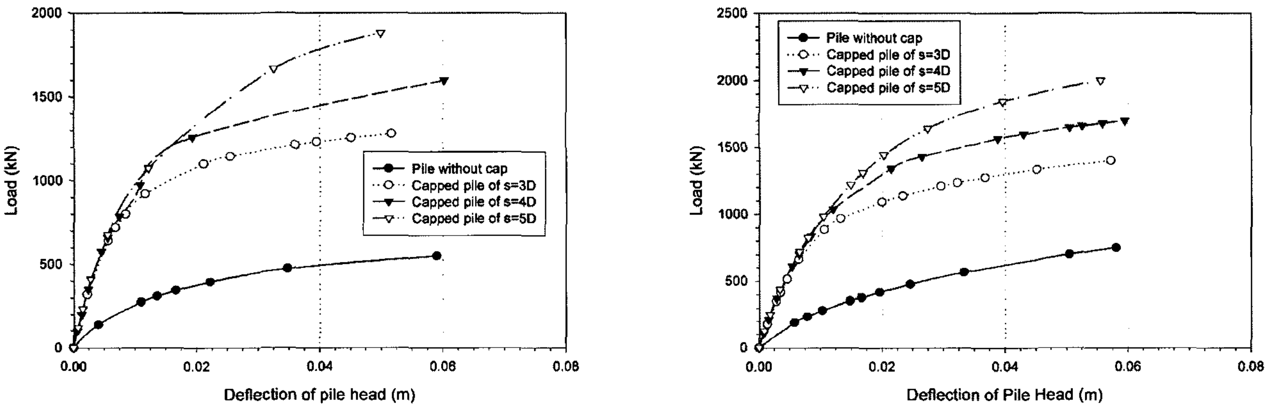
for uncapped piles, the capped piles with a spacing s = 3D is about 2.8 times greater than for the single pile without a cap at a deflection of 0.025 m. Subsequently, the resistance for the pile with a cap of s = 4D is about 80 kN greater than the pile with a cap of s = 3D, and the load of pile with a cap of s = 5D is about 180 kN greater than the pile with a cap of s = 4D. The results above clearly show the influence of the cap on lateral resistance of the pile. Moreover, the length of the cap also affects the lateral resistance.

Figure 3 (b) shows the response of piles with length L = 10 m. The trend in the response is similar to that of the shorter pile in Figure 3 (a). At 0.025 m displacement of the pile head, the resistances are 500 kN, 1150 kN, 1410 kN, and 1610 kN for pile without a cap, pile with a cap of s = 3D, s = 4D, and s = 5D, respectively. These values are greater than that of piles with a length of 7 m. The long single pile without a cap has approximately 18% greater resistance than the shorter pile.

Figure 4 (a) shows the load-deflection response of a short pile with diameter of D = 0.5 m. Comparing this with Figure 3 (a), the difference is the diameter of pile. The resistances at 0.025 m of pile head displacement are 160 kN, 342 kN, 460 kN, and 548 kN for the pile without a cap, and the pile with a cap of s = 3D, s = 4D, and s = 5D, respectively.

Based on the difference in pile diameter, the resistance of piles with D = 1 m is about 2.5-3.2 times greater than in piles with a diameter of D = 0.5 m. The difference is due to the diameters and the length of the cap. In general, the small diameter piles have lower capacity than the large diameter piles, and the piles without a cap have a lower capacity than the piles with a cap.

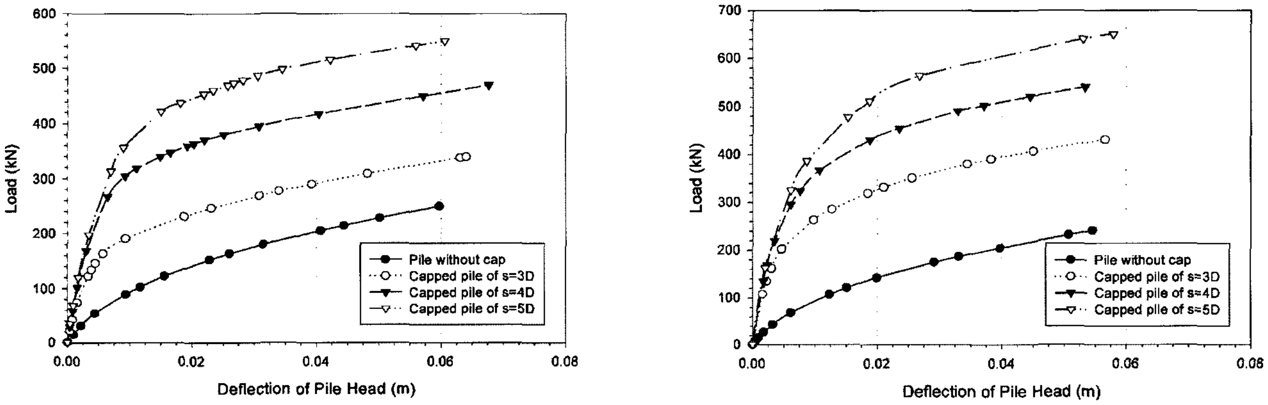
The direct contribution of a pile cap can be attributed



(a) Short pile length L=7 m

(b) Long pile length L=10 m

Fig. 3. Load versus deflection of single pile with diameter 1.0 m



(a) Short pile length L=7 m

(b) Long pile length L=10 m

Fig. 4. Load versus deflection of single pile with diameter 0.5 m

to several components: the passive resistance in front of cap face, the side and base friction resistance. For the passive resistance, it is proportional to the area in front of the cap, which is influenced by the diameter of the pile, while variation in cap length should not affect the passive resistance. The frictional resistance would be proportional to the contact area on the side and base of the cap, and the area is a function of cap length. By comparing the resistance in free head and fixed head piles of various cap lengths, the other indirect contribution to lateral resistance of pile caps can be identified. After isolating the contribution of passive resistance and friction resistance, the longer cap shows higher resistance. The indirect contribution to the resistance comes from the overhanging portion of the cap in front of pile, which affects the confining pressure of the soil. As the pile is displaced laterally due to loading, the cap tends to rotate (clockwise per load direction in Figure 2). As a result, the vertical stress in the soil in front of the pile and underneath the cap would also increase. The increase in the confining stress in the front of pile provides higher resistance to the lead pile.

4. Laterally Loaded Pile Group

The finite element model for the 1×3 pile group is as shown in Figure 1. In this analysis, the pile diameter was 1.0 m, the spacing was three times the diameter (s = 3D) and pile length was 7.0 m. The load was also applied on the same location as in the single pile. The schematic cross section for the pile group is shown in Figure 5.

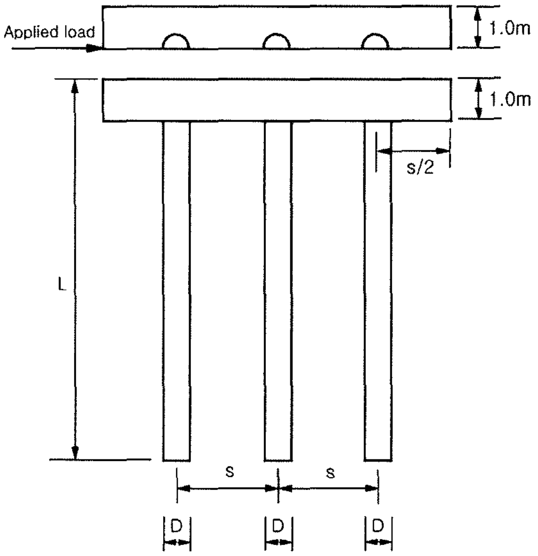


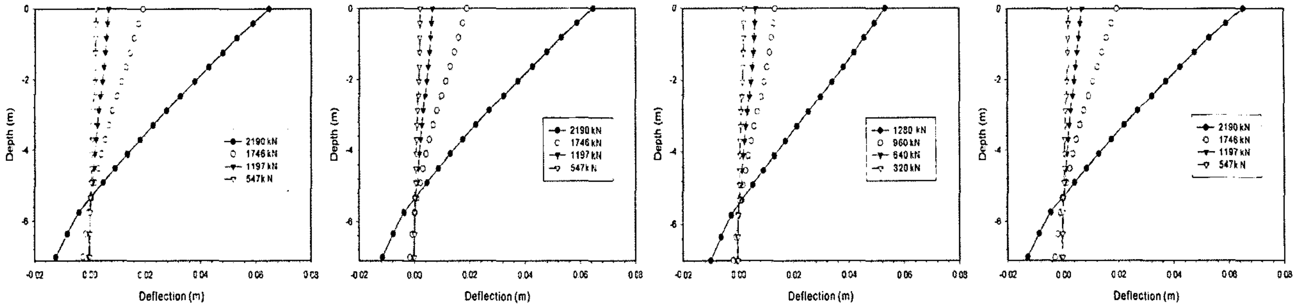
Fig. 5. Cross section pile group

The load-deflection response curves of the single pile with cap and from piles in groups are shown in Figure 6. The highest applied loads were 1280 kN and 2190 kN for the single pile and pile group, respectively. The applied load for the pile group was about 1.7 times higher than that of the single pile. The deflection curves shown here correspond to 25%, 50%, 75%, and 100% of the total applied load. It shows that the location of rotation points for the piles in the group are slightly higher than that for the single pile. This indicates a slight difference in the soil pressure distribution in front of the single pile and pile group. Within the group, the rotation points for trailing, middle, and leading piles are at the same elevation as expected in pile groups connected with a rigid cap. It was observed that the shapes of the deflection curves follow the shape for the conventional definition of a short pile. Also, the results also show that above the rotation point the soil stress in front of the piles is in compression, and below the rotation point the highest compression stress is behind the pile.

Figure 7 shows the *p-y* curves at depths of z = 0.43 m, z = 1.29 m and z = 2.15 m below the base of the cap, respectively. This depth of the observation points was related to the element thickness of the finite element mesh. In the figure, the soil resistance represents the value of soil pressure multiplied by the diameter of the pile per unit length of pile.

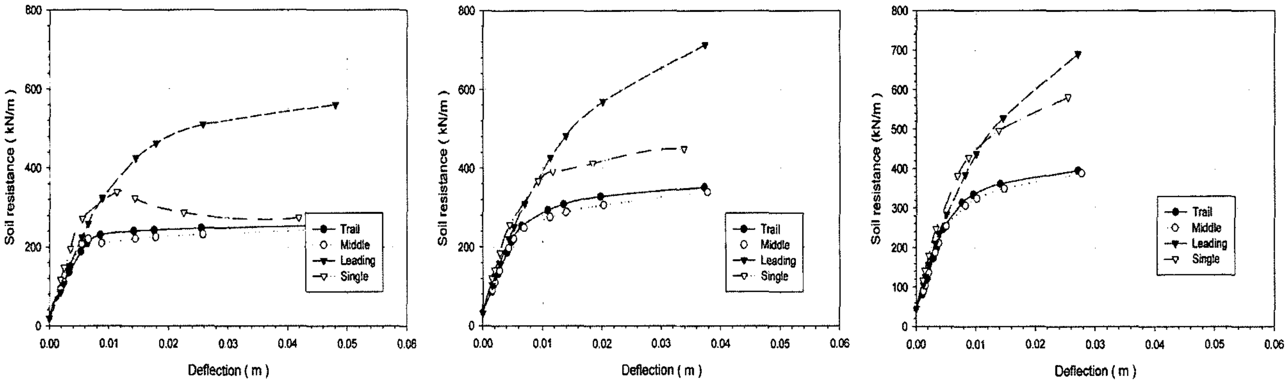
In Figure 7 (a), the leading pile shows the highest resistance, and the trailing and middle piles have almost the same resistance. Later in the analysis the result will suggest that the resistance of middle pile should be greater than the trailing pile. The figure shows that up to a deflection of about 0.005 m, the *p-y* response is linear and the soil resistance is about the same for all piles.

The peak resistance of the single pile is 340 kN/m at a deflection of 0.012 m and decreases with further deflection. The resistance of each pile in the group continues to increase with deflection. Comparing the response



(a) Single pile with cap (b) Trailing pile (c) Middle pile (d) Leading pile

Fig. 6. Deflection of pile



(a) At depth z=0.43 m (b) At depth z=1.29 m (c) At depth z=2.15 m

Fig. 7. *p-y* curve of short pile

behavior of the leading pile and the fixed head single pile, the single pile has reached its ultimate resistance while the leading pile is still gaining soil resistance with increasing deflection. This indicates that for the single pile, the soil in front of the pile has reached its ultimate lateral bearing capacity. While in the case of the leading pile, the soil has reached its lateral bearing capacity at a greater deflection. In addition, the curve of the leading pile follows closer to the general shear failure response. The response of middle and trailing pile are similar, but both do not show an ultimate value.

At a greater depth of z = 1.29 m in Figure 7 (b), the *p-y* response shows a general trend similar to those at z = 0.43 m, except that the single pile resistance does not have a discrete peak value. The linear portion of the curves is greater compared to the response at z = 0.43 m, and the soil resistance at z = 1.29 m is also greater than that at z = 0.43 m. The figure shows a soil resistance of 450 kN/m for the single pile, 710 kN/m for the leading pile, 340 kN/m for the middle pile, and 350 kN/m for the trailing pile. Figure 7 (c) shows the *p-y* response at z = 2.15 m. It shows that the soil resistance at a deeper location is greater than that of the shallower depth. However, the overall trend of the responses is similar to those of z = 1.29 m.

The *p*-multiplier is defined as the ratio of the soil resistance of a pile in group to the soil resistance of the single pile. The analysis below shows the *p*-multiplier of a pile for the three different depths. In general, the *p*-multiplier varies with depth; therefore, the *p*-multiplier obtained for each pile represents an averaged value from the three different depths. Table 3 shows the summary of *p*-multipliers for different depths. The averaged *p*-multipliers are 1.59, 0.75, and 0.77 for leading, middle, and trailing

Table 3. *p*-multipliers for short pile

Depth (z) [m]	Trailing pile	Middle pile	Leading pile
0.43	0.74	0.72	1.6
1.29	0.78	0.75	1.58
2.15	0.79	0.78	1.59
Average	0.77	0.75	1.59

pile respectively in comparison with the soil resistance of the single pile with a cap.

The analysis shows that the *p*-multiplier for the leading pile is greater than that found in literature, which is normally taken to be 1.0. The *p*-multiplier would have been greater if the resistance of the free head pile had been used. Another contributions to the higher resistance for the leading pile is due to the presence of the cap. As discussed previously in the case of single piles, the cap contributes to the lateral resistant not only due to the passive and the friction resistant of the cap, but also due to the increase of the vertical stress in soil below the overhanging portion of the cap.

The lateral soil pressure distribution for the piles under load is shown in Figure 8. It shows that at a depth of z = 4 m, the lateral soil pressures of the leading pile and single pile are the same. Above this point the soil pressure for the leading pile is higher than that for the single pile. Below z = 4 m, the soil pressure for the single pile is higher than that for the leading pile.

Examining the response of the leading pile and single pile in Figure 8, the location of maximum soil pressure for the leading pile is at approximately 2.5 m from the ground surface, while for the single pile is at approximately 4 m. Since there is only soil in the front of the piles, the shift in the location of the maximum soil pressure should be caused by the factor other than the pile itself. The difference in conditions between these two piles may be attributed to the length of the cap overhang. The overhang in the single pile is 4 m, and in the case of the leading pile is only 1 m. As described earlier, the front end of the cap exerts vertical pressure to the soil as it tends to rotate under load, and the region covered by this pressure is much smaller in front of the leading pile than the single pile. However, for the same lateral displacement, the short overhanging cap in pile group would undergo a greater rotation than the longer overhanging cap in the single pile. As a result, the confining pressure directly below the overhanging area of a pile group would increase higher than that of the area in front of the single pile. Moreover, since the contact area (overhanging cap area) in the front of the pile group is smaller than the area in the single pile, the distribution of the stress from a larger area would extend deeper, resulting in the higher lateral stress response for the single pile.

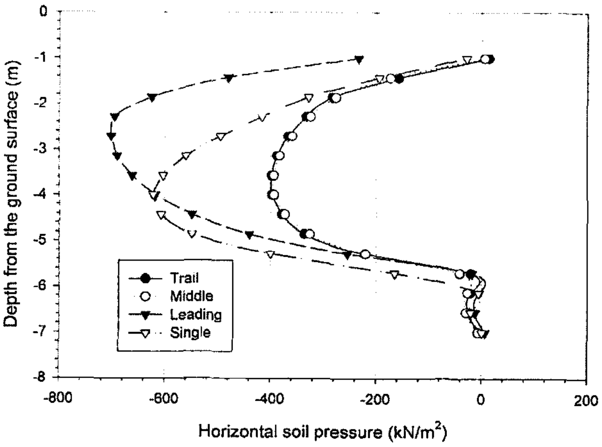
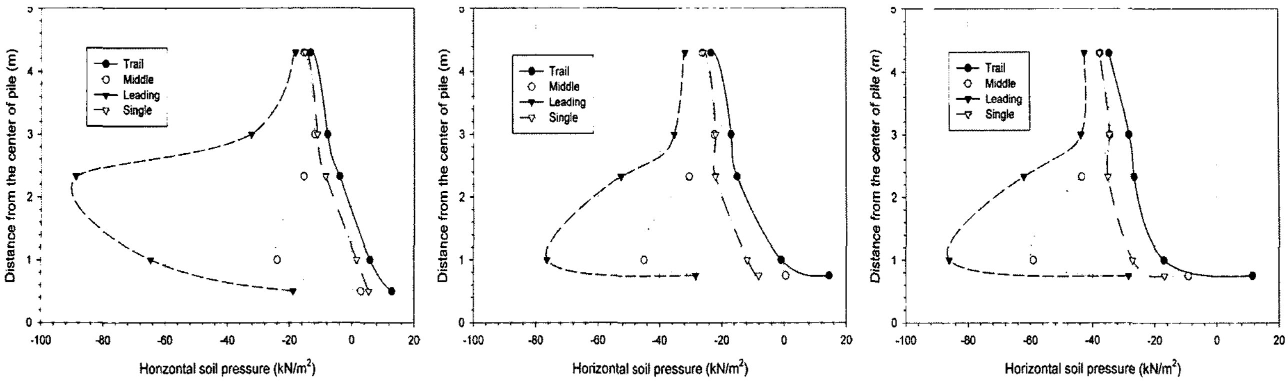


Fig. 8. Lateral soil pressure in front of piles at final loading

The lateral resistance of a pile in a group was also analyzed with consideration of lateral soil pressure exerted on both sides of the pile. Figure 9 shows the top view of lateral soil pressure distribution on the side of each pile. In this figure, the soil pressure is acting on a transversal vertical plane, which passes through the center of each pile, and these planes are perpendicular to the direction of the loading. Figure 9 (a) shows the distribution of the lateral soil pressure along the level of z = 0.49 m from a point next to the pile to a distance of about 4 m from the pile. It shows that at this depth and for the applied load, the soil pressures adjacent to the trailing, the middle, and the single pile are in the tension region (in ABAQUS, a positive sign). In contrast, the soil pressure adjacent to the leading pile is in the compression region. The figure clearly shows the shadow effect on the lateral stress in soil around the piles. Considering the stress level, the lateral stress for the leading pile initially increases then decreases, for an increasing distance from the pile. The highest lateral stress of 90 kN/m^2 occurs at a point of about 2.3 m away from the center of the pile.

Beyond this distance, the lateral stress starts to decrease with increasing distance away from pile. For the middle pile, except at the point adjacent to the pile, the middle



(a) At depth 0.43 m (b) At depth 1.29 m (c) At depth 2.15 m

Fig. 9. Lateral soil pressure on transversal plane

pile shows a similar response to the leading pile with lower stress level. The trailing pile shows a greater tension zone but the stress gradually changes to compression as the distance from the pile increases. The stress along the single pile is similar to that of the trailing pile. The horizontal stress of all piles appears to converge to a common value at a distance about 3.0 m from the pile indicating the zone of stress influence.

Figure 9 (b) shows the lateral soil pressures along the level of z = 1.29 m. At this level, the trailing pile still shows a tension zone adjacent to the pile. Also at this level, the soil pressures adjacent to the middle and leading pile are in the compression region. In contrast, the soil pressures at greater depth z = 2.15 m as shown in Figure 9 (c) for all piles are in the compression region except for the trailing pile. The maximum lateral stresses at z = 1.29 m and z = 2.15 m are located at about 1.0 m from the center of the pile, which is closer than in z = 0.43 m. The lateral stress starts to converge at a distance of 2.8 m, which is closer than at z = 0.43 m. At depth z = 2.15 m, the response of the leading pile shows slight increase in the maximum soil pressure.

An influence of higher stress in leading pile can be analyzed as follows; considering the qN_q term in the conventional bearing capacity formula, this term represents the contribution for the surcharge, where q and N_q are the overburden and the bearing capacity factors, respectively. Applying the same principle to the lateral capacity of the pile, the stresses on both sides of the leading pile can be treated as the additional lateral surcharge contributing to its lateral capacity. With the increase of the lateral stress on both sides of the pile, the pile capacity would also increase. It is also believed to be the reason for obtaining a p-multiplier greater than 1.0 for the leading pile.

5. Conclusions

The capacity of the single pile with a cap can be significantly greater than that of the free head single pile. The increase of the capacity due to the cap is not only from the passive resistance and the skin resistance of the cap, but also from the vertical confinement provided by the cap. The cap contributes to an increase of vertical stress in the front of the pile, which in turn increases the resistance of the soil due to the increase in the confining stress.

The p-multiplier for the leading pile in a group is found to be greater than 1.0. In the pile group, the distribution of the resistance among the piles is not uniform. The leading pile has the highest soil resistance, while the middle and trailing piles have lower soil resistances. The shadow effect benefits the leading pile.

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(received on Jan. 10, 2005, accepted on Mar. 26, 2005)