FEM analysis on the effect of the bearing layer thickness on the bearing characteristics of a pile group

Kyoto University Student Member ○Isabella Galarosa Martinez
Kyoto University Regular Member Yasuo Sawamura
Kyoto University Regular Member Ryunosuke Kido
Kyoto University Fellow Member Makoto Kimura

1. INTRODUCTION

End bearing pile foundations transfer the applied loads to an underlying bearing layer, made of rock or dense sand. While these dense sand layers may provide sufficient resistance, the thickness of these layers in some sites may be insufficient to meet the requirements of local codes. The piles may be required to be designed as friction piles, which may be more costly as they extend to greater depths to attain the required resistance. Therefore, investigating the effect of the bearing layer thickness on the bearing characteristics of a pile may result in a more optimized design of the piles.

As piles are often used in groups, the objective of the study is to conduct numerical analyses on a pile group supported by a dense sand layer of various thicknesses subjected to static loading. The joint effects of the group spacing and the bearing layer thickness were investigated.

2. METHODOLOGY

Soil-water coupled analysis using a Finite Difference (FD)-Finite Element Method (FEM) scheme was performed using the FEM code DBLEAVES (Ye *et al.*, 2007). To investigate the effects of the group spacing and the bearing layer thickness, two spacings (s) were considered: $s = 2.5D$ and $5.0D$. For the group with a spacing of $5.0D$, six (6) cases were conducted with various bearing layer thickness (H) values: $H = 1D$, $2D$, $3D$, $4D$, $5D$, and $8D$. For the group with a spacing of $2.5D$, the same cases were conducted, with an additional case corresponding to $H = 12D$. Simulations were also performed for a single pile. The tests are hereafter referred to as: Case-*s*-*H* (e.g., Case-2.5-1*D*).

Fig. 1 shows the analysis mesh for the two pile groups. Due to the geometric and loading symmetry, only one-fourth of the total area was modeled. For the bearing layer, Toyoura sand (D_r = 90%) was used, while the upper and lower clay layers were modeled based on Fujinomori clay (OCR = 2.5 and 1.65, respectively). For both soil materials, the subloading t_{ij} model was used, with the properties shown in Table 1 (Nakai and Hinokio, 2004). The water level is at ground level. The piles were modeled after a closed-ended hollow cylinder with a diameter of D = 1 m, using the framed beam model used by Danno and Kimura (2009) and Martinez *et al.* (2021). The properties of each pile are the same as that in the study of Martinez *et al.* (2021). The piles in the pile group were connected by a rigid footing, which was simplified using beam elements ($E = 1.39 \times 10^{11}$ kPa).

The initial stresses were calculated using the unit weight of each soil layer without the pile, with the initial stresses from pile installation assumed to be negligible. Displacement-controlled static load tests on the pile groups were simulated by applying a downward displacement of $0.1D$ to each pile head, with a loading rate of 0.01 mm/s.

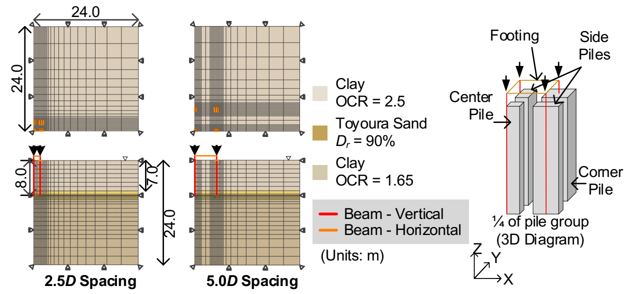

Fig. 1 FEM Mesh and Pile Group Diagram

Table 1. Subloading t_{ij} parameters

	Fujinomori clay	Toyoura sand
Principal stress ratio at failure R_{cs}	3.5	3.2
Poisson's ratio, ν	0.3	0.310
Static earth pressure coefficient, k_0	0.55	0.45
Stress-dilatancy relation parameter, β	1.5	2.0
Compression index, λ	0.09	0.07
Swelling index, κ	0.02	0.0045
a(ANN)	500	60
Permeability, k [m/s]	1.55×10^{-10} 3.00×10^{-10}	1.0×10^{-5}

3. RESULTS

3.1. Load distribution among piles

To investigate the group effect observed in pile groups with a relatively small spacing, the average pile head load was calculated, as shown in **Figure 2**. Regardless of the bearing layer thickness, the single pile results in the largest average pile head load values. The pile group with a spacing of $2.5D$ resulted in the lowest values, exhibiting the group effect. These results are consistent with those of Danno and Kimura (2009). Investigating the effect of the bearing layer thickness, the values of Case-5.0-1*D* are similar to that of a single pile. However, as the bearing layer thickness increases to $2D$ and $3D$, the difference with the single pile increases. When the bearing layer thickness is further increased to $8D$, this difference decreases.

To further investigate this tendency, the difference in the load-displacement curve values between the corner and the center pile, normalized by the total group capacity, is analyzed, as shown in **Fig. 3**. As the pile spacing decreases, the difference increases, which is consistent with the group effect. For the pile group with a spacing of $5.0D$, the difference increases when the bearing layer thickness increases from $1D$ to $3D$. When the bearing layer thickness is further increased, the values decrease.

Considering these observations, for the pile group with a spacing of $5.0D$ supported by a bearing layer with a thickness of $1D$, the piles act as individual piles,

Keywords: Pile group; thin bearing layer; FEM analysis; static loading; group effect
Contact address: C1-4-587 Kyoto University, Katsura Campus, Nishikyo-ku, Kyoto, 615-8540, TEL:075-383-3193

independent from each other. This may be attributed to the thin bearing layer which permits uneven settlement among the piles and consequently allows the piles to develop enough resistance independent of each other. As the bearing layer thickness increases up to a certain value (3*D* in this case), the increasing rigidity of the bearing layer restricts the piles to a more even settlement, concentrating the applied loads to the outer/corner piles. This restriction in the settlement, combined with the low resistance of the relatively thin bearing layer, results in the larger gap among the piles as the piles remain dependent on the shaft friction. When the bearing layer thickness is further increased, the higher resistance of the thick bearing layer results in more even load values among the piles despite the even settlement. In such case, the end bearing capacity prevails.

3.2. Soil displacement and excess pore water pressure distribution

Fig. 4 shows the vertical and horizontal displacement of the soil. For the pile group with $s = 2.5D$, the soil between the piles moves downward with the piles regardless of the bearing layer thickness. This results in lower frictional resistance along the pile shaft as no shearing occurs between the piles and this soil mass. This is consistent with the low average pile load values and large load difference between the center and corner piles. Furthermore, the section of the bearing layer underneath the pile group also moves downward with the pile group. However, the size of the soil mass that moves downward with the pile group decreases as the bearing layer thickness increases. For Case-2.5-8*D*, the soil mass moving downward is restricted to the upper clay layer, particularly that between the piles. On the other hand, for the pile group with a spacing of 5.0*D*, the displacement of the soil between the piles is significantly reduced, suggesting low interaction among the piles. This is consistent with the group effect discussed above.

Considering the horizontal displacement of the soil, the region exhibiting large horizontal displacement is located around the lower edge of the pile group. In particular, the region with large vertical displacement is observed to form a cone beneath the pile group, with the region of high horizontal displacement located around this cone. This reflects the radial shear zone surrounding the high-density cone discussed by previous studies such as Terzaghi (1941).

Fig. 5 shows the excess pore water pressure distribution. Regardless of the bearing layer thickness, the excess pore water pressure is concentrated in the underlying clay layer. However, as both the bearing layer thickness and the pile spacing increase, the excess pore water becomes more dispersed, and the values significantly decrease.

4. CONCLUSIONS

FEM analyses were conducted to investigate the joint effects of the pile group spacing and the bearing layer thickness. It can be concluded that the bearing layer thickness contributes to the group effect. In particular, when the bearing layer thickness is significantly smaller than the pile group width, the flexibility of the bearing layer permits even load distribution through uneven settlement. As the bearing layer thickness increases, the group effect becomes more apparent as the thicker bearing layer restricts pile settlement and as the piles remain dependent on shaft resistance. However, for sufficiently thick bearing layers, the end-bearing resistance prevails, resulting in even load distribution.

REFERENCES

Danno, K. and Kimura, M.: Evaluation of long-term displacements of pile foundation using coupled FEM and centrifuge model test, Soils and Foundations, Vol.49, No.6, pp.941-958, 2009.

Martinez, I. G., Kido, R., Sawamura, Y., and Kimura M.: FEM analysis on a pile suppoted by a thin sand layer subjected to static and cyclic axial loading, *Proceedings of the 23rd International Summer Symposium*, *JSCE*, 2021.

Nakai, T. and Hinokio, M.: A simple elastoplastic model for normally and over consolidated soils with unified material parameters, *Soils and Foundations*, Vol.44, No.2, pp.53-70, 2004.

Ye, B., Ye, G. L., Zhang, F., Yashima, A. 2007. Experiment and numerical simulation of repeated liquefaction-consolidation of sand, Soils and Foundations, 47(3), 547-558, 2007.

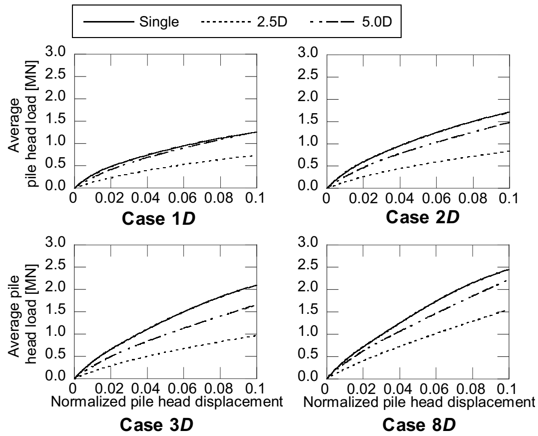

Fig. 2 Average Pile Head Load

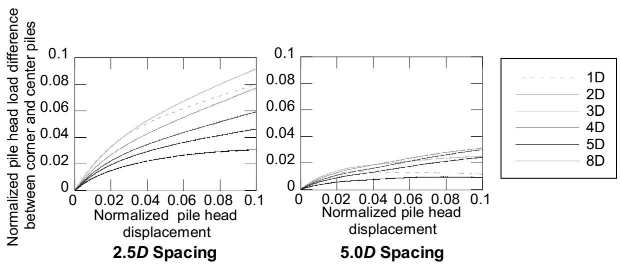

Fig. 3 Load Difference between Corner and Center Piles

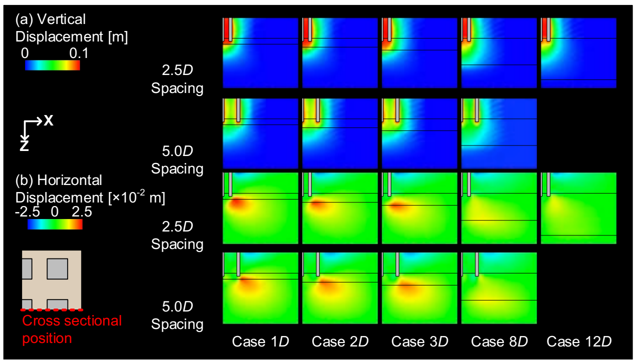

Fig. 4 Vertical and Horizontal Soil Displacement

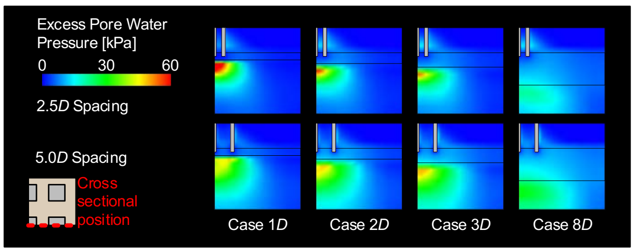

Fig. 5 Excess Pore Water Pressure Distribution