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AN ESTIMATING METHOD FOR LATERAL BEHAVIOR OF PILED-RAFT FOUNDATION

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Some simplified design methods were proposed to predict behavior of lateral loaded piled-raft foundations on homogenous soil. One of them is the cone model method. However, only one average solution of pile behavior can be given by this method. It can't evaluate the location factors of piles. Therefore, this paper describes a new simplified method to predict behavior of lateral loaded piled raft foundations covering the location factor of piles. At first, ground surface displacement is derived theoretically by Cerutti's solution, then assuming that the raft foundation has rigid stiffness, these displacements are the same to calculation lateral loading distribution. Second, the ground displacement where pile placed could be estimated under calculated lateral loading. Third, the piles behavior are evaluated based on these lateral ground displacements. In addition, 3-D FEM numerical analysis were performed to compared with these solutions.

Keywords: Numerical analysis, Interaction, Shear force, Bending moment, FEM, Ground displacement.

1 INTRODUCTION

Since the piled-raft foundation was proposed, a lot of research on the vertical bearing capacity has been done and published. Simple calculation methods used for designing piled-raft foundations have also been verified. However, there are many unknown points for the horizontal resistance of the pile in comparison with the issue of vertical bearing capacity, and also no simply method to calculate the sharing rate of the horizontal bearing capacity of the pile, especially at the primary design. Currently, cone method as an approximation method for calculating pile section force of piled-raft foundation (Ishii *et al.* 2003).

In this method, horizontal displacement occurs in the ground just below the raft due to friction on the bottom of the raft and acts on the pile via the soil-pile spring. Although this method can evaluate the sharing load between piles and rafts considerably easily, but only average pile stress is calculated and the difference in stress on each position of the pile can't be expressed. Therefore, in this study, we propose a simple estimating method that can express the difference of the pile stress with consideration for the position of the pile.

2 SIMPLY ESTIMATING METHOD

In this study, ground displacement due to lateral load acting on raft is calculated by the following assumptions. First, for interaction, consider only raft-to-pile influences. Second, the ground is assumed to be a linear elastic. Third, the raft foundation is rigid. Based on these assumptions, actual procedure of this simple estimating method is shown as follows.

2.1 Surface Shear Stress and Ground Displacement

The same horizontal displacement occurs on the ground surface under raft, as the raft foundation is rigid. The shear stress distribution on the ground surface under raft can be obtained by using the solution (Kanai *et al.*1968) of horizontal displacement, when a lateral concentrated load acts on the surface of the semi-infinite elastic ground (solution to the surface shear stress is obtained by integrating this basic solution). The ground horizontal displacement at an arbitrary point is calculated by Eq. (1), when the central lateral load acting position is the point of origin.

$$u_x = \frac{Q}{4\pi G}\cdot\frac{1}{R}\cdot\left[\frac{x^2}{R^2}+1+\frac{(1-2\nu)R}{R+z}\left\{1-\frac{x^2}{R(R+z)}\right\}\right] \quad (1)$$

Here, u_x is ground horizontal displacement in direction-x, Q is the horizontal load in direction-x, G is shear coefficient of the ground, ν is Poisson's ratio, and R is distance from the loading point to the calculation point. x and z are coordinates of the calculation point, z is zero, when calculation point is on the ground surface.

2.2 Response Analysis of Piles

As the cone method, the horizontal sharing force, stress, and displacement of the pile are calculated by using the response displacement method. As shown in Figure 1, the ground displacement at the pile position is calculated from the surface shear stress acting under raft obtained by the Eq. (1), this displacement of the ground is applied to the pile via the ground spring, and the lateral force of pile is calculated in consideration for the displacement of the pile head is equal to the raft foundation displacement. Then, we can calculate the stress and displacement distribution of the pile. The spring between the pile and the ground is given by Eq. (2) (Kishida and Nakai 1979).

$$k_{h0}B = 1.3\frac{E_s}{1-\nu^2}\sqrt[12]{\frac{E_sB^4}{E_pI_p}} \quad (2)$$

Here, k_{h0} is the coefficient of subgrade reaction, B is pile diameter, E_pI_p is the bending stiffness of pile, E_s is the ground stiffness. The total force of surface shear stress under raft and the horizontal sharing force of all the piles acts as the lateral load on the piled-raft foundation.

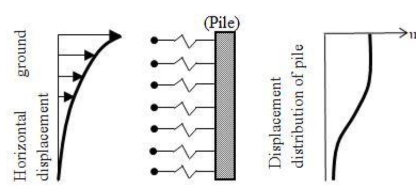

Figure 1. Pile deformation due to ground deformation.

3 VERIFICATION OF ACCURACY BY COMPARISION WITH FEM ANALYSIS

The validity of the proposed estimating method was verified by comparing it with the FEM analysis. As shown in Figure 2, the FEM analysis was performed on a square raft foundation with equally spaced piles in a homogeneous semi-infinite elastic ground.

The piles were assumed to be a cast-in-place concrete pile (pile diameter d = 1000 mm). Pile, raft, and ground were analyzed as elastic material. The symmetric condition was used to make the half model of the analytical region. The ground properties of the analytical model are expressed by the elastic modulus E. Three different ground models were set as shown in Table 1. In order to examine the influence of the ground conditions, we choice the case of very soft ground (Case A), the case of soft ground (Case B) and the case of the rigid ground (Case C).

9, 16, and 25 piles with equal intervals arranged under the prescribed raft foundation (20 m × 20 m) as shown in Table 2 and Figure 2 in order to verify the influence of the pile group interaction. A list of analysis cases is shown in Table 3 (9 cases) by combining Table 1 and 2.

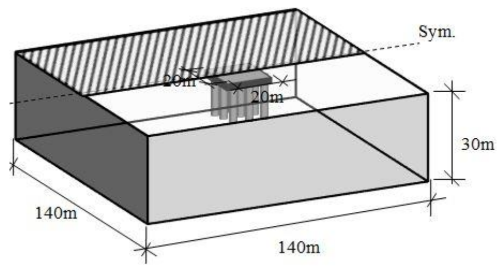

Figure 2. Analytical model.

Table 1. Ground characteristics.

	(A)	**(B)**	**(C)**
E(kN/m^2)	10000	30000	150000

Table 2. Pile arrangement.

	(1)	**(2)**	**(3)**
Pile space s(m)	9	6	4.5
s/d	9	6	4.5
N×N	3×3	4×4	5×5
Pile length L(m)	15 m	15 m	15 m

Table 3. Analytical cases.

	(1)	**(2)**	**(3)**
(A)	A-1	A-2	A-3
(B)	B-1	B-2	B-3
(C)	C-1	C-2	C-3

4 COMPARISION RESULTS

From the characteristics of the pile arrangements, it is predicted that the shear force and bending moment of the pile placed at the corner of the raft are the largest, and the cross-section force of the pile arranged at the center of the raft is the smallest. The calculation results by this simplified estimating method and the FEM analysis were compared on the pile arranged at the ⓐ and ⓑ in Figure 3 (under unit force Q=1kN).

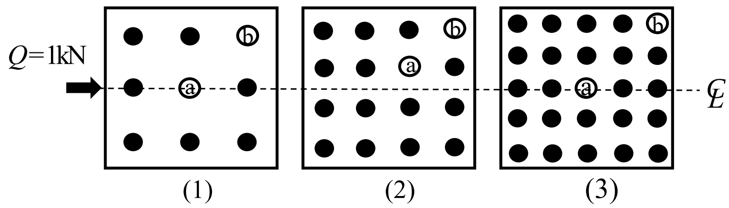

Figure 3. Pile arrangements.

Figure 4 shows the distribution of pile displacement calculated from these two methods in case of A-1 and C-3 as an example (The legend of "FEM" in Figure 4-8 indicates the results of FEM analysis and "Analysis "indicates the results of this simplified estimating method). Regardless of the rigidity of the ground, the results of both methods are in good agreement for both the central pile and the corner pile. These results demonstrate the validity of this simply estimating method in pile deformation. Figure 5 shows the comparison results of shear force and bending moment of the pile in case A-1.

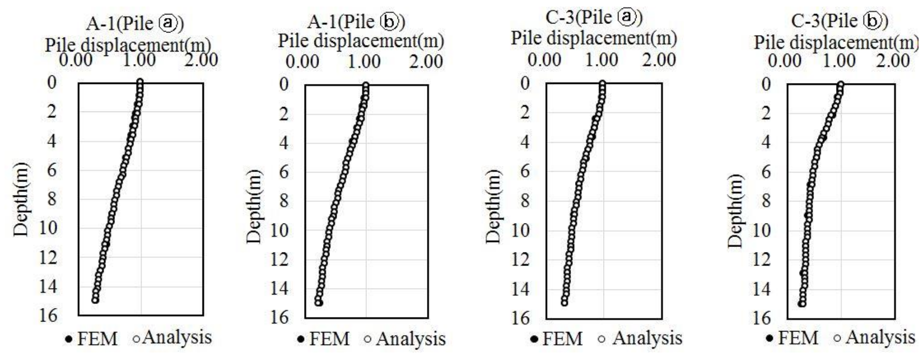

Figure 4. Distribution of pile displacement (case A-1 and C-3).

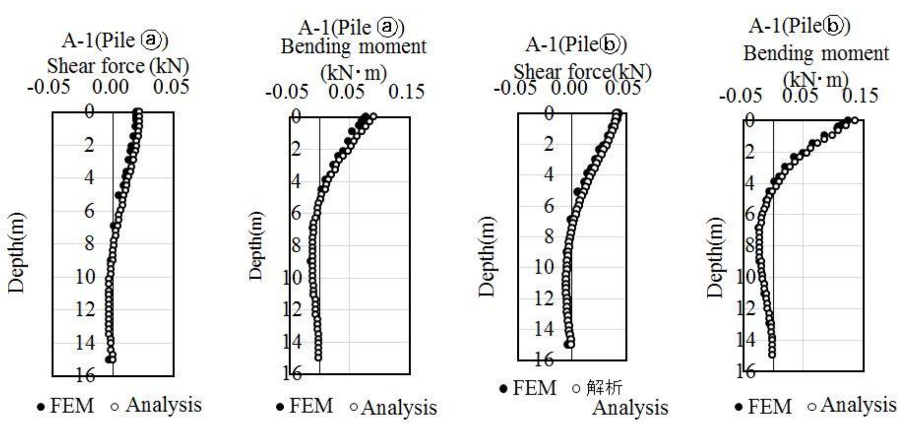

Figure 5. Comparison results of shear force and bending moment (caseA-1).

For shear force and bending moment of the central pile, the simply estimating method which does not considering the influence of interaction between piles shows a slightly larger results than FEM analytical results. Although there is a tendency to overestimate somewhat, it is considered that the cross-section forces of pile calculated by this proposed simply estimating method are on the safe side. A slight difference is seen also in the comparison results of the corner pile, but it is comparatively well matched. In addition, both results are in good agreement with the depth and the maximum points of the underground bending moment.

Figure 6 shows the comparison results of shear force and bending moment of pile in case C-1. The FEM and the simply estimating method results are in good agreement with each other in the case of the ground C which has a high rigidity. In other words, the simply estimating method tends to overestimate slightly on the shear force and the bending moment of the pile in calculation with the higher rigidity of the ground. It is thought that the deformation of the pile is restrained in the higher rigidity of ground and the influence of the interaction between the pile and the pile is reduced.

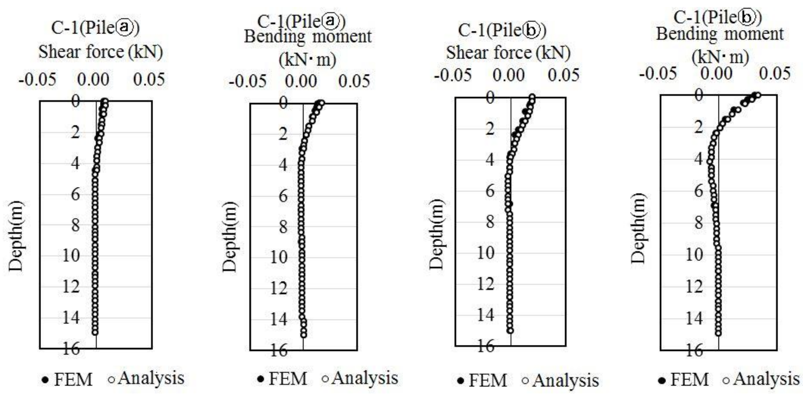

Figure 6. Comparison results of shear force and bending moment (case C-1).

Figure 7 and 8 shows a comparison of the shear force and the bending moment of the pile in Case A-2 and Case A-3 which has a large number of piles in order to examine the influence of pile-pile interaction.

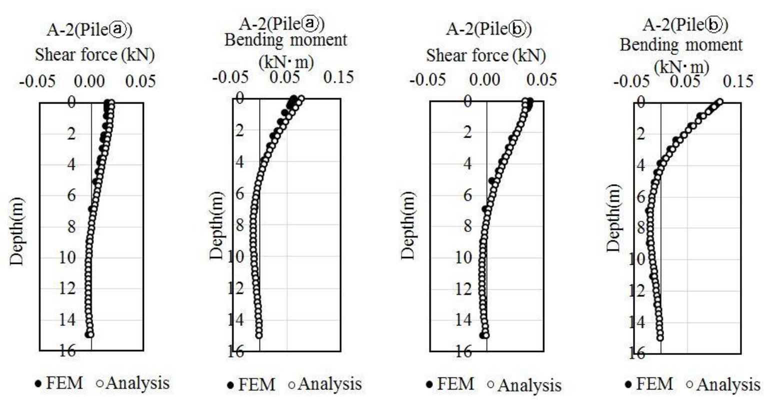

Figure 7. Comparison results of shear force and bending moment of pile (case A-2).

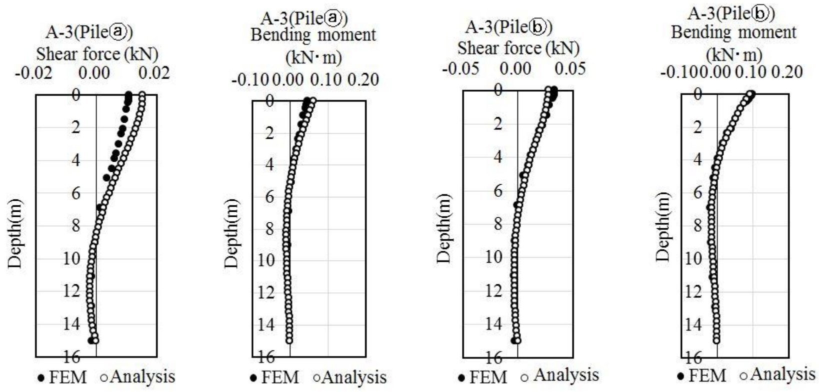

Figure 8. Comparison results of shear force and bending moment of pile (case A-3).

In both cases, there was no significant difference on shear force and bending moment for corner pile. However, in case A-2, the shear force of the central pile by this method was overestimated with 20% over of FEM analysis result. In case A-3, this overvaluation is increased to 30%. It is considered that the influence of the interaction between the piles becomes larger when the pile spacing is narrow. In other words, the cross-section forces of pile at the corner of raft are larger than that of the reference pile and it is necessary to design by the conventional method with an appropriate safety factor. However, it has possibility that the actual pile head cross-section force of the central pile may smaller than the value by this simply estimating method, and it leads the safe side.

5 CONCLUSION

In this study, we proposed a simple estimating method on the behavior of piled raft foundation under lateral force. The results by proposed estimating method are in good agreement with the results by FEM, and the validity of this simplified estimating method was verified. In order to apply to the actual case, it is necessary to verify the correspondence to the nonlinear behavior of the ground and multilayered ground. In particular, the nonlinear behavior of the ground appears strongly with increasing load. Therefore, the study about load level is required for the more rational design of piled-raft foundation. They are the subjects in the future.

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