

ANALYTICAL STUDY OF PILED-RAFT FOUNDATIONS CONSIDERING PLAN GEOMETRY AND NONLINEAR BEHAVIOR OF GROUND

HARUYUKI YAMAMOTO and HE HUANG

Graduate School for IDEC of Hiroshima University, Hiroshima, Japan

The piled-raft foundation transfers loading to the ground by the raft and the piles together. It was proposed in the 1970s and is widely used for controlling settlement. Simplified estimate equations are used for the primary design. Equations by Randolph can presume the settlement stiffness of the piled-raft foundation and the loading share ratio from the settlement stiffness of raft and pile foundation. Raft foundations not only have regular shapes as squares, they also have some particular shape like triangular or L-plan. Therefore, different shape plans are discussed in this paper to verify the applicability of these equations. Also, these equations are proposed based on a theory of elasticity. However, the ground has nonlinear behavior even under small loading levels, so estimating the applicability of these equations when the ground behaves nonlinearly is necessary.

Keywords: Settlement stiffness, Loading share ratio, Nonlinear analysis, Elasticity.

1 INTRODUCTION

A piled-raft foundation is a combination of pile foundation and raft foundation, sharing the loading from the upper structure. It was proposed in the 1970s (Burland *et al.* 1978), and is widely used to control differential settlement. Many studies on the behavior of piled-raft foundation have been made, e.g., settlement behavior of the building supported by the piled-raft foundation (Sahara *et al.* 2002), the behavior of piled-raft foundation in multilayer ground (Ta *et al.* 1998), etc. Some analysis methods included the boundary element method (BEM) (Yamashita *et al.* 1987), 3-dimensional finite-element method (FEM), and hybrid method. Randolph proposed a simple estimation equation of piled-raft foundation behavior from settlement stiffness of raft and pile group. These equations have been proposed on the basis of the elasticity theory, and many studies have been made with regard to the application in the elastic range. However, since the ground shows non-linear behavior even if under a small initial loading level, elastic regions are not strictly present. Therefore, it is necessary to consider the effects of this non-linear behavior when using this estimation equation.

It was not realistic to do full-scale tests for this research due to cost. However, advanced analytical accuracy, complicated foundation conditions, and mechanical characteristics of the ground are well simulated by developing numerical-analysis techniques, such as finite-element analysis. In this study, a model analysis used the 3-dimensional finite-element method with elastic-plastic theory. Analyses were carried

out with elastic-plastic elements which were applied the Drucker-Prager failure criterion of the ground with associated flow rule. Further, raft foundations have regular shapes like square and particular shapes like triangular. Therefore, four different shape plans were assumed to be square, rectangular, triangular and circular. The combined stiffness and loading share ratio were calculated by Randolph's estimating equation according to the analytical results. However, all rigidity defined in this paper was the secant stiffness.

2 ESTIMATED EQUATIONS

Estimation equation of settlement stiffness and loading share ratio of piled-raft foundation proposed by Clancy and Randolph are as follows (Clancy *et al.* 1996). Settlement stiffness is estimated by Eq. (1).

$$\frac{k_{pr}}{k_r} = \frac{1 + (1 - 2\alpha_{rp})(k_r/k_p)}{\{1 - \alpha_{rp}^2(k_r/k_p)\}(k_r/k_p)} \quad (1)$$

Here, k_{pr} : settlement stiffness of piled-raft foundation; k_p : settlement stiffness of friction pile group foundation; k_r : settlement stiffness of raft foundation; α_{rp} : influence coefficient of pile group for the raft foundation. Pile group and raft foundation loading share ratio is estimated Eq. (2).

$$\frac{P_r}{P_p} = \frac{(1 - \alpha_{rp})(k_r/k_p)}{1 - \alpha_{rp}(k_r/k_p)} \quad (2)$$

Here, P_p : shaved load of friction pile group; P_r : shaved load of the raft foundation.

3 ANALYTICAL MODEL

Based on the model shown in Figure 1, three basic analysis models were set as below. Model 1: raft foundation; Model 2: pile group; Model 3: piled-raft foundation. The pile was assumed to be elastic material made of concrete (diameter $d = 1\text{m}$, length $l = 15\text{m}$, Young's modulus $E_c = 2.1 \times 10^7 \text{kN/m}^2$) and raft foundation to be rigid.

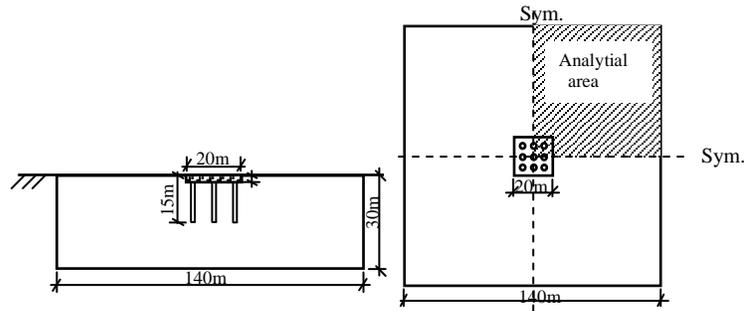


Figure 1. Analytical model (Square piled-raft foundation).

The Drucker-Prager criteria with associated flow rule was used for the ground. Poisson's ratio ν_s of ground was assumed to be 0.3. 1/4 model (1/2 model used for

triangular raft) was analyzed by using the symmetry condition as shown in Figure 1 (an example of raft foundation of square shape plane). Figure 2 shows the divided elements of models. The soil properties of the analysis model were assumed to be three parameters of elastic modulus E_s , the internal friction angle ϕ and adhesion c . Assuming a normal consolidation sand ground with N value of about 20, the internal friction angle ϕ of the ground was set by the Osaki equation. For the elastic modulus, the approximate value was set based on the empirical equation $E = 1.4N$ (Mpa) (AIJ 2001). For adhesion c , it was the value of the order corresponding to the soft ground.

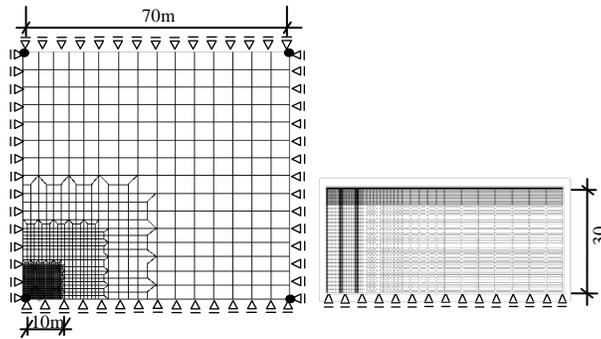


Figure 2. Mesh of analytical model.

4 ANALYTICAL CASE

When setting the analytical cases, the distribution range of k_r/k_p is important to perform preliminary studies, so the placement of pile was set as per Table 1. The pile number was increased to be installed in the order of Models 1, 2 and 3. Thus, for the same ground and loading conditions, the model order k_p is increased, and the value of k_r/k_p decreases from (1) to (3). The value of α_{rp} determined by the placement of these piles. The total case number is 12 from (A)-(1) to (D)-(3). Figure 3 shows the relationship between k_r/k_p (stiffness ratio of pile and raft foundation) and k_{pp}/k_r (stiffness ratio of piled-raft and raft foundation), and P_r/P_p (loading share ratio) based on Eqs. 1 and 2.

Table 1. Analytical case.

| Raft foundation | Pile number | | |
|--------------------------------|-------------|-----|------|
| | (1) | (2) | (3) |
| (A) square (20m×20m) | 9 | 16 | 25 |
| (B) rectangular(20m×60m) | 27 | 48 | 75 |
| (C) triangular (h×b = 20m×20m) | 4 | 7 | 13 |
| (D) circular (r = 10m) | 7 | 11 | 19 |
| α_{rp} | 0.4 | 0.5 | 0.62 |
| | 9 | 6 | |

5 VERIFICATION OF ANALYTICAL ACCURACY AND TREATMENT METHOD OF ANALYTICAL RESULTS

Because the FEM analysis method with incremental analysis includes some approximation conditions, the ultimate bearing capacity of ground, immediate settlement under raft foundation, and elastic settlement under pile foundation were computed to evaluate the validity of the calculation results. Analytical accuracy from these verification-created models was found to be generally satisfactory (a more detailed description is omitted due to space concerns).

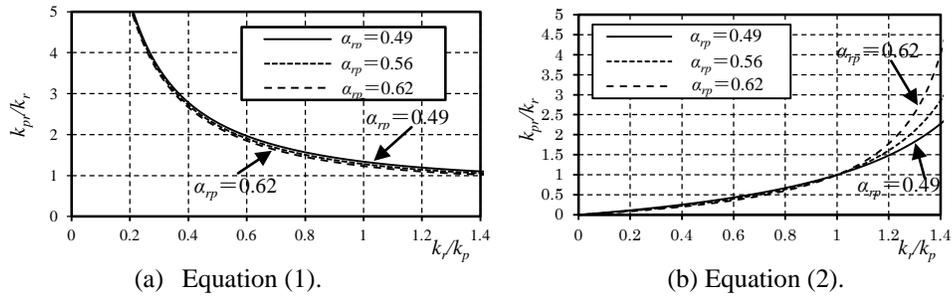


Figure 3. Estimated equations.

The calculation method of settlement stiffness is illustrated by the analytical case of the pile foundation of (B) – (1) (see Figure 4). Settlement stiffness of pile group (k_p) represents a gradient of a straight line connecting the point and the origin on the settlement curve corresponding to the settlement (secant modulus). To calculate the settlement stiffness (k_r , k_{pr}), the same calculation method was used for the analytical result of raft foundation and piled-raft foundation.

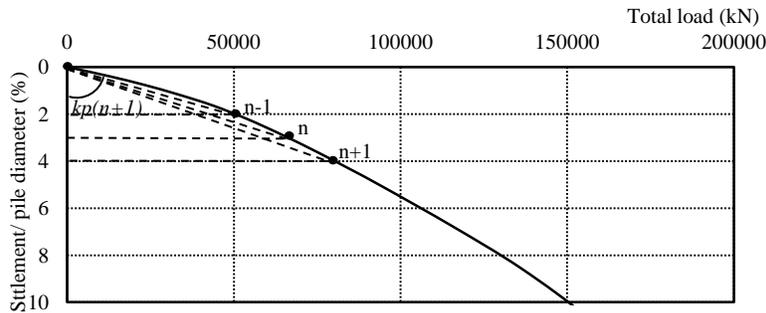


Figure 4. The calculation method of settlement stiffness.

6 DISCUSSION OF THE ANALYTICAL RESULTS

6.1 Estimated Equation (1) for the Settlement Stiffness

Using the settlement stiffness calculated from the slope of the secant mentioned above (k_p , k_r , k_{pr}) enables a discussion of the applicability of these estimate equations. The analytical results and the approximate solution from estimated Eq. (1) are compared

with the relationship between two ratios, as shown in Figure 5 with different raft foundation shape planes. One is the ratio of raft foundation settlement stiffness k_r and pile group settlement stiffness k_p , and another is the ratio of piled-raft foundation settlement stiffness k_{pr} and raft foundation settlement stiffness k_r . As shown in Table 1, the range of α_{rp} in the analysis model is 0.49 to 0.62, three curves of approximate solution by the estimated Equ. (1) are also drawn ($\alpha_{rp} = 0.49$, $\alpha_{rp} = 0.56$ and $\alpha_{rp} = 0.62$) in Figure 5 for comparison.

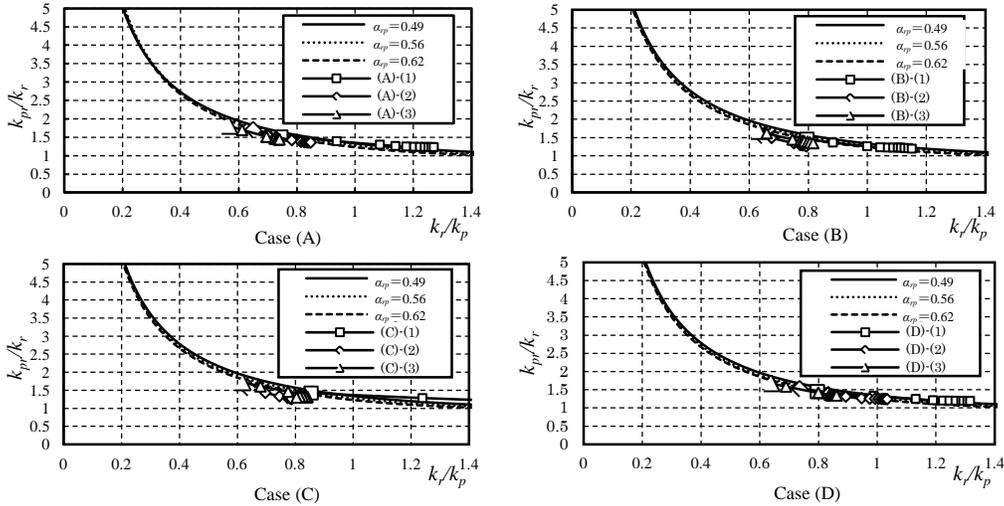


Figure 5. Comparison of analytical results and approximate solution from estimated Eq. (1).

The analytical results of the first step (loading increments being very small) seems close to the initial elastic state, and it was considered as the first considering point (see the larger marked point in Figure 5 and Figure 6). Then analytical results were investigated for every increment step of a settlement ratio (settlement/pile diameter) increasing by 0.01. Pile group settlement stiffness k_p increased with the increasing number of pile, therefore the value of k_r/k_p was reduced with the in turns of cases 1, 2, and 3. All analytical results were distributed close to the three curves obtained by the estimated Eq. (1) in Figure 5. Good approximate results were obtained regardless of elastic and non-linear regions.

6.2 Estimated Eq. (2) for Loading Share Ratio

The analytical results and the approximate solution from estimated Eq. (2) were compared with the relationship between two ratios as per Figure 6, with different raft foundation shape planes. One is the ratio of raft foundation settlement stiffness k_r and pile group settlement stiffness k_p , and another is the ratio of pile group shaved load P_p and raft foundation shaved load P_r . As described above, the estimated Eq. (2) has been proposed on the basis of the elasticity theory, so if the value of k_r/k_p is 1, the shaved load of raft foundation and pile group is the same (at the point (1, 1)). In each

analytical case, the analytical results are distributed close to the three curves obtained by the estimated Eq. (2) regardless of when it reaches a non-linear region or not. However, it seems to be large relative error in case (C) of triangular raft foundation. Triangular shape raft foundation model with $h \times b = 20\text{m} \times 20\text{m}$ but not equilateral triangular was used in this paper.

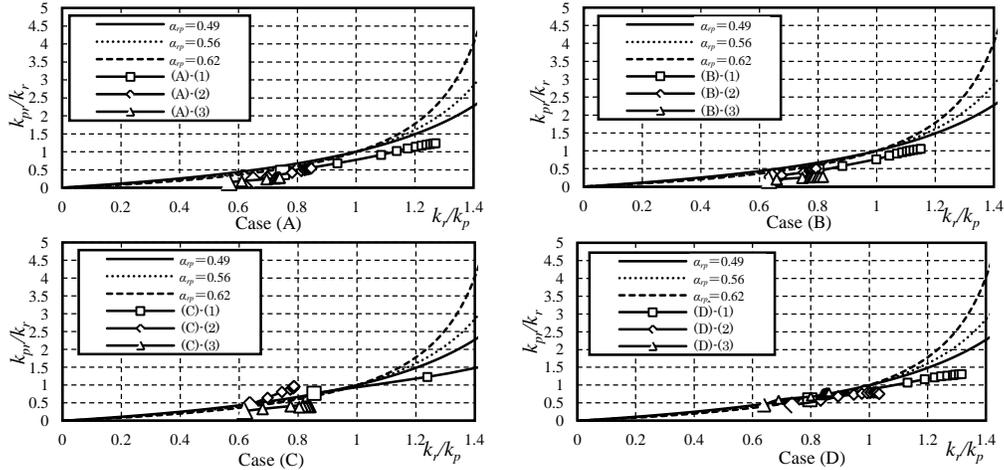


Figure 5. Comparison of analytical results and approximate solution from estimated Eq. (2).

7 CONCLUSION

For equations that presume the settlement stiffness of the piled-raft foundation and the loading share ratio, they find that the analytical results are well in agreement with the results obtained by the estimated equation in each case under all ground conditions in this case study. There is almost no influence by a nonlinear behavior of the ground, and the applicability of these estimated equations is very good in a nonlinear domain (within the settlement ratio = 0.1).

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