Integrated Solutions for Infrastructure Development
Edited by Lau, H. H., Tang, F. E., Ng, C. K., and Singh, A.

ISBN: 978-0-9960437-3-1

ANALYTICAL STUDY ON PILED-RAFT FOUNDATION CONSIDERING NONLINEAR BEHAVIOR OF GIBSON SOIL

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Randolph (1994) was proposed simplified estimated equations to carried out the proportion of load between the components of piled-raft foundation. These equations are based on elastic theory. Therefore, Authors focus on the point of applicability for nonlinear behavior of soil. This paper is a part of study on behavior of piled-raft foundation under considering the nonlinear behavior of ground. Authors already discussed the effect of nonlinear behavior of soil on the equations by Randolph. In addition, as the extension of research, authors also discussed the applicability of these equations for irregular raft shape. However, foundations were rarely set in an ideal homogeneous single soil layer in our previous studies. Therefore, the applicability of these equations are discussed in case of inhomogeneous soil (Gibson soil) in this paper.

Keywords: Settlement stiffness, Loading share ratio, Gibson soil, Nonlinear analysis, Piled-raft foundation.

1 INTRODUCTION

The piled-raft foundation transfers load to the ground by the raft and the piles together and it was proposed in the 1970s. The key point that arises in the design of piled-raft foundation focus on the relative proportion of load carried out by raft and the piles separately. Then, this question is solved by Randolph (1994) and he pointed out methods which could carried out the proportion of load between the components. In the same paper, Randolph also proposed a method to estimate the settlement stiffness of piled-raft foundation. However, these methods were proposed based on elastic theory with homogeneous soil. The utilization of these methods is challenging because soil always exhibit nonlinear behavior even at low working loads in reality. Therefore, authors discuss the effect of nonlinear behavior of soil on the equations by Randolph. In addition, as the extension of research, authors also discussed the applicability of these equations to the raft with irregular shape. However, piles are rarely set in an ideal homogeneous single soil layer. Then, the following question arises. How about the applicability of these equations if inhomogeneous of soil is taken into account? Consequently, authors will discuss the applicability of these equations for inhomogeneous soil which has increasing stiffness with depth, and is known as the Gibson soil.

It is not realistic to do full scale tests for this research because it's costly. On the other hand, Numerical analysis satisfies our requirements and it could simulate complicated model and ground condition as we want. 3-D FEM (Finite Element Method) was adopted in this study. Soil has the characteristic of elastic-plastic material with Drucker-Prager failure criterion. Piled-Raft foundation is always used on soft ground to improve differential settlement. Then, we speculate that these equations which have a good feasibility on soft ground. However, it will be a thrill if they also give as a good applicability on hard ground and super-soft ground. Therefore, three different ground conditions are simulated in this study. More specifically, super-soft ground (case (A)), soft ground (case (B)) and hard-ground (case (C)).

2 GIBSON SOIL AND ESTIMATIMATED EQUATIONS

2.1 Gibson Soil

Gibson (1967) discusses an elastic ground layer in which the stiffness increases linearly with depth. Such a ground is described as nonhomogeneous and is known as Gibson soil, as shown in Figure1 (left side).

$$E=E_0+\lambda z \tag{1}$$

where, E_0 is surface stiffness of soil and λ is the rate of increase of the stiffness modulus with depth z. For the purpose of analysis, the ground system will be idealized as constant Possion`s ratio, its surface stiffness and adhesion are zero as shown Figure 1 (right side), the maximum stiffness is at the point reached rigid soil layer assumed as 2E and 2C.

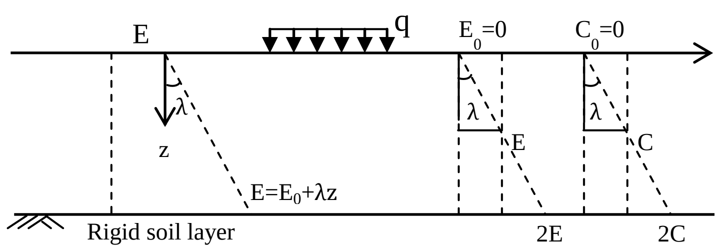

Figure 1. Gibson soil.

2.2 Estimated Equations

Estimated equations of settlement stiffness and loading share ratio of piled raft foundation proposed by Clancy and Randolph are shows as follows (Clancy and Randolph, 1996). Settlement stiffness is estimated by Equation (2).

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

where, 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 by Equation (3).

$$\frac{P_r}{P_p}=\frac{(1-\alpha_{rp})(k_r/k_p)}{1-\alpha_{rp}(k_r/k_p)} \tag{3}$$

where, P_p: shared load of friction pile group; P_r: shared load of the raft foundation.

$$\alpha_{rp}=1-\frac{\ln(n)}{\ln(2r_m/d_p)} \tag{4}$$

where, n is the ratio of equivalent circular raft diameter to pile diameter d_p, and $r_m = 2.5\rho L_p(1-\upsilon_s)$. L_p is the embedded length of a pile. ρ is a soil inhomogeneity factor varying from unity for homogeneous conditions to 0.5 in case of the stiffness is proportional to depth (Randolph, 1994).

3 ANALYTICAL MODEL

Three basic analysis models were set as below. Model ①: Raft foundation, Model ②: Pile group, Model ③: Piled-raft foundation as shown Figure 2.

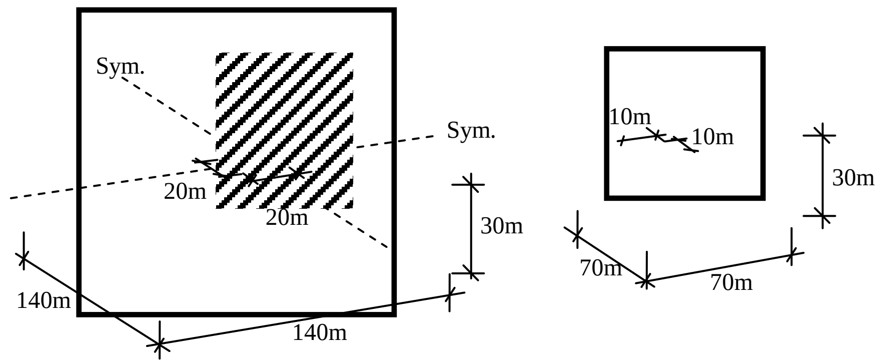

Figure 2. Analytical model.

Piles are assumed as elastic material made of concrete (diameter *d*=1m, length *l*=15m, 21m, 28m, Young's modulus E_c=2.1 × 10^7kN/m^2) and raft foundation is assumed to be rigid. The Drucker-Prager failure criterion with associated flow rule was used for the analytical model of ground. Poisson's ratio υ_s of ground was assumed 0.3. 1/4 model was analyzed by using the symmetry condition as shown in Figure 2. Figure 3 shows the FEM mesh of model. The soil properties of the analytical model are assumed by 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 equation of Osaki (AIJ, 2001). For the elastic modulus, and set the approximate value based on the empirical equation E = 1.4N (Mpa) (AIJ, 2001). For the adhesion *c*, it is the value of the order corresponding to the soft ground. Ground parameters are set as shown in Table1.

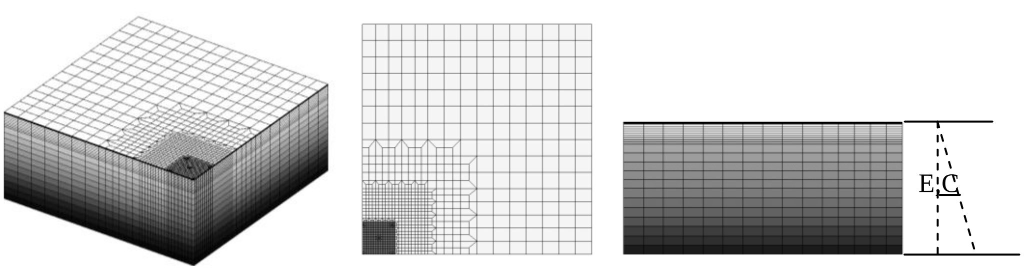

Figure 3. Mesh of analytical model.

Table 1. Ground Parameters.

	(A)	(B)	(C)
Es（kN/m^2）	10000	30000	150000
φ(deg.)	30	35	40
c（kN/m^2）	5	10	20

4 ANALYTICAL CASE

In consideration that the distribution range of k_r/k_p is very important when setting the analytical cases, the placements of pile are set as shown in Table 2. Number of pile is increased to be installed in the order of model (0) to (3), and piles length are increased on model (4) and (5). In other words, for the same ground conditions and loading conditions, k_p is increase and the value of k_r/k_p decreases from (0) to (5). Value of α_{rp} is determined by the placement of these piles. Total number of analytical case is 18 from (A)-(0) to (D)-(5).

Table 2. Pile arrangements.

	(0)	(1)	(2)	(3)	(4)	(5)
Pile spacing; s（m）	10	9	6	4.5	4.5	4.5
s/d	10	9	6	4.5	4.5	4.5
N×N	2×2	3×3	4×4	5×5	5×5	5×5
Pile length; L（m）	15 m	15 m	15 m	15 m	21 m	28 m
α_{rp}	0.26	0.38	0.47	0.54	0.58	0.61

5 ANALYTICAL RESULTS

5.1 Estimated Equation for the Settlement Stiffness

The secant settlement stiffness mentioned above (k_p, k_r, k_{pr}) are calculated to discuss the applicability of these estimated equations. The analytical results and the approximate solution from estimated equation (2) are compared by the relationships between the ratio k_r / k_p, and the ratio k_{pr} / k_r as shown in Figure 5.

As shown in Table 2, the range of α_{rp} in this analytical model is 0.26 to 0.61, two curves of approximate solution by the estimated equation (2) are also drawn (α_{rp} = 0.26 and α_{rp} = 0.61) in Figure 5 for comparison. Analytical results of first step (loading increments is very small) is seemed close to the initial elastic state, and it was considered as the first considering point (larger marked point in Figure 5 and Figure 6). Then analytical results were examined for every increment step of a settlement ratio; 0.01 (settlement/ pile diameter), and discussion range of settlement ratio was unified to 0.1 in this paper. Analytical results for homogeneous soil was shown as a comparison in Figure (5)-(a).

Pile group settlement stiffness k_p increase with increasing number of pile, therefore the value of k_r/k_p are reduced with in turns of case (0), (1), (2), (3) as the same with homogeneous soil case. Value of k_r/k_p is over 1 in case (A)-(1) with homogeneous soil, but it is below 1 for Gibson soil because its stiffness increases linearly with depth, then its surface stiffness is very small and lead to lacking of bearing capacity. All of the analytical results are distributed very close to the two curves obtained by the estimated equation (2) in Figure 5. It can be seen that good approximate results have been obtained regardless of elastic or non-linear regions.

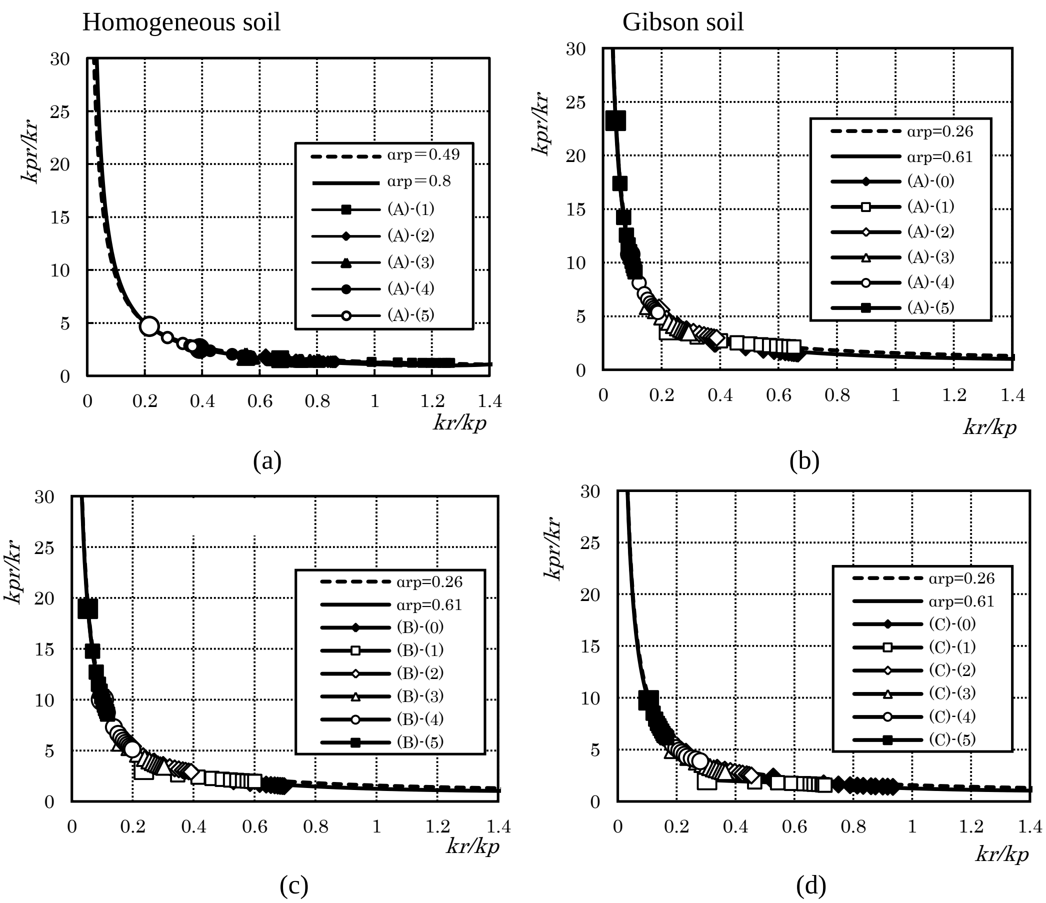

Figure 5. Compartion of analytical results and approximate solutions from estimated equation (2).

5.2 Estimated Equation for Loading Share Ratio

The analytical results and the approximate solutions from estimated equation (3) are compared by the relationships between the ratio k_r/k_p and the ratio of *Pr*/*Pp* as shown in Figure 6 with different ground condition. As described above, the estimated equation each analytical case, the analytical results are distributed close to the two curves obtained by the estimated equation (3) regardless of non-linear region or not. However, it seems large relative difference in case (0) of Gibson soil. Case (0) is an extreme model with number of pile for each ground conditions, it has many influential factors of difference. Furthermore, in fact it is necessary to examine the applicability of Piled-raft foundation.

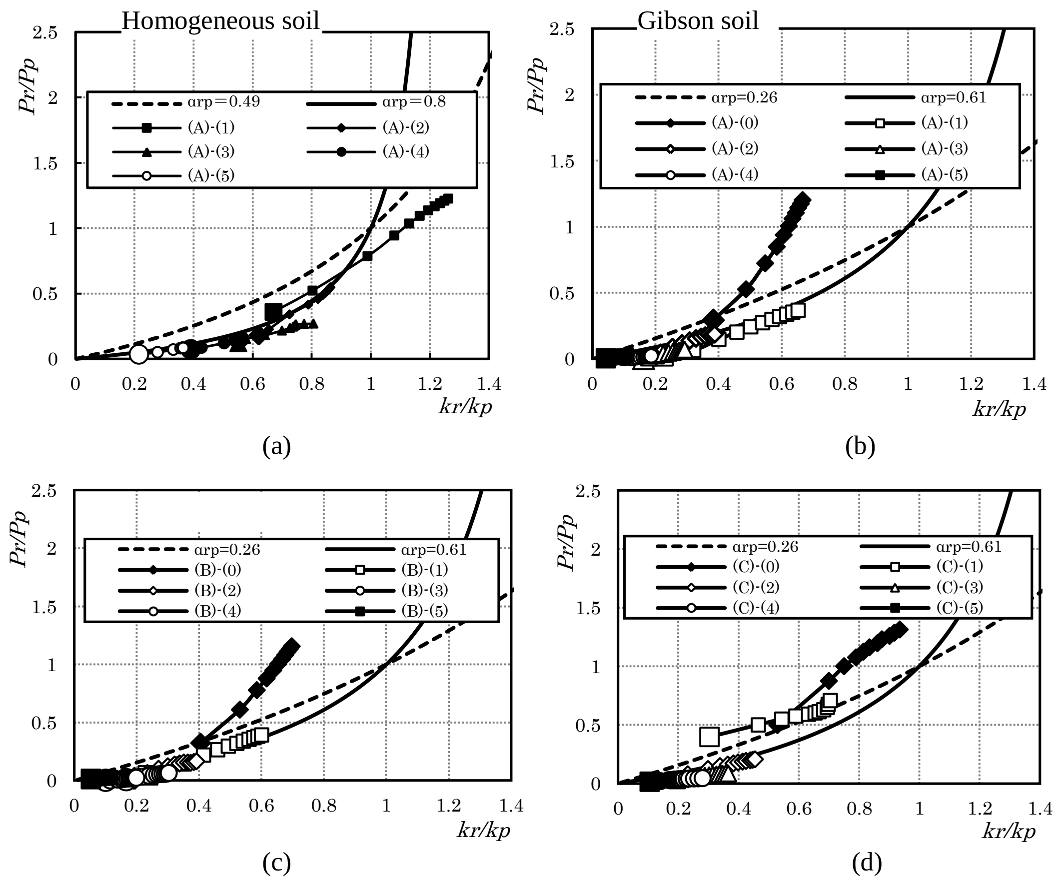

Figure 6. Compartion of analytical results and approximate solutions from estimated equation (3).

6 CONCLUSIONS

On the equations which estimate the settlement stiffness of the piled-raft foundation and the loading share ratio, it finds that most of analytical results are well in agreement with the results obtained by the estimating equation in each case under Gibson soil. There is almost no influence by a nonlinear behavior and the applicability of this estimating equation is very well also in a nonlinear domain (within the settlement ratio = 0.1). However, it shows some difference in the extreme case with fewest pile (case (0)) for the equation of the loading share ratio. It is necessary to examine the estimating equation for extreme case in the further.

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