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Analysis of Piled Raft Foundation Behavior Considering Raft-Pile-Soil Interaction

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***Abstract*— This study developed an approximate hybrid method of analysis to be used for the practical design of piled raft foundations considering pile-soil, raft-soil, pile-soil-pile and raft-soil-pile interactions. In the presented method of analysis, the settlements of the system are estimated satisfying the compatibility of two separate models which are the flexible raft model consisting of 2-dimensional finite elements supported by springs representing soils and piles, and the group-pile model embedded in layers of soil having different properties.**

***Keywords*— piled raft; nonlinear behavior; layered soil; interaction**

I. Introduction

Traditional piled foundation design methods assume all loads were supported by the piles and ignore the load sharing effect by the raft. However, Cooke et al. (1981) and Cooke (1986) mentioned that up to 30% of the total building load can be supported by the raft based on their laboratory test results. Poulos and Davis (1980) and Randolph (1983, 1994) proposed simplified analytical methods using composite stiffness of the raft and piles. These methods are useful for rough and prompt estimation of the average settlement of a foundation, although they cannot estimate the differential settlement of a foundation.

Approximate methods were developed using the raft divided into strip (Poulos, 1991; Brown and Weisner, 1975) or rectangular (Poulos, 1994; Clancy and Randolph, 1993; Franke et al., 1994; Yamashita et al., 1993) elements on springs with stiffness of soil and piles. For more rigorous analysis, Hain and Lee (1978), and Shinha (1997) proposed analytical methods combining the boundary element method and the finite element method assuming the raft divided into a number of rectangular elements.

Those approximate methods introduced above perform only linear analysis of piles embedded in layered soil. Three-dimensional finite element method is known to be the most accurate method for estimating the settlement of a piled raft foundation. However, 3-dimensional modeling requires a large amount of time and effort and it is not practical to use 3-dimensional analysis during design process. Therefore, this study proposes an approximate analytical method that can adequately predict non-linear behavior of piles embedded in layered soils considering structure to structure and structure to soil interactions.

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II. Methods of Analysis

The developed analysis program is comprised of two models, which are flexible raft model consisting of 2-dimensional finite elements supported by springs representing soils and piles, and the group-pile model embedded in layers of soil having different properties. The settlements of the system are estimated satisfying the compatibility of the two separate models.

The behavior of a raft is analyzed by FEM using 8 nodes rectangular elements. Each node is supported by a soil spring with stiffness given in (1). It should be noted that the stiffness of soil spring at each node varies depending on the stiffness of raft and the interaction between the raft and soil. Fig. 1 shows how the stiffness of soil spring is calculated using the intelligent soil spring method (Cracknell, 2000).

$$k_s = \frac{q_s}{w_s} \, . \qquad (1)$$

where, q_s = subgrade reaction; and w_s = settlement at an arbitrary nodal point.

The relationships between unit base and shaft resistance and settlement of a pile used in this analysis are shown in (2) and (3) respectively, which are similar to the load-settlement curves proposed by Kondner (1963). The initial normal and shear stiffness in (2) and (3) can be estimated using the method proposed by Randolph and Wroth (1978).

$$q_{pb} = \frac{w_p}{\dfrac{1}{k_{pb}} + \dfrac{w_p}{q_{pba}}} \qquad (2)$$

$$q_{ps}(i) = \frac{w_p}{\dfrac{1}{k_{ps}(i)} + \dfrac{w_p}{q_{psa}(i)}} \qquad (3)$$

where, w_p = vertical displacement at pile base; q_{pb} = base resistance; k_{pb} = initial normal stiffness at pile base; q_{pba} = maximum unit base resistance = q_{pbu}/R_f; q_{pbu} = ultimate unit base resistance; $q_{ps}(i)$ = unit shaft resistance of pile element (i); $k_{ps}(i)$ = initial shear stiffness at shaft of pile element (i); $q_{psa}(i)$ = maximum unit shaft resistance of pile element (i) = $q_{psu}(i)/R_f$; $q_{psu}(i)$ = ultimate unit shaft resistance of pile element (i); and R_f = failure ratio.

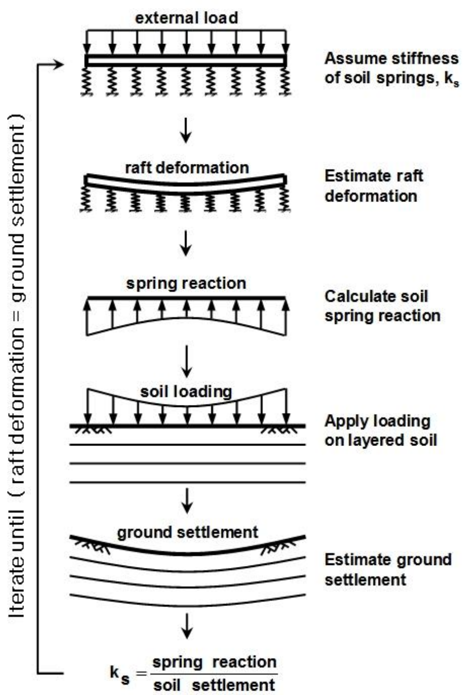


Figure 1. Estimation of stiffness of soil springs

Due to influence by adjacent piles, a pile in group piles shows larger settlement (equation (4)) than the single pile settlement which can be estimated using the method proposed by Randolph and Wroth (1978)..

$$w_p(i,j) = \frac{\tau_s(j) r_p(j)}{G_s} \ln\left(\frac{r_m(j)}{r_{i,j}}\right) \tag{4}$$

where, $w_p(i)$ = total settlement of pile(i); $w_p(i,i)$ = net settlement of pile(i) due to the load on pile(i); $w_p(i,j)$ = additional settlement of pile(i) due to the load on pile(j); $r_m(i)$ = radius influence of pile (i); $r_p(i)$ = radius of pile (i); and $r_{i,j}$ = distance between pile i and pile j.

In actual condition slip at the interface between a pile and soil takes place and generally pile settlement is larger than the settlement of ground surface around the pile. A variable, R_s given in (5) is introduced and the settlement of each pile in group piles can be estimated as (6). In order to simplify the calculation, it is assumed that the slip $w_{slip}(i)$ is proportional to the pile settlement $w_p(i,i)$, and thus the variable R_s has constant value for all piles in a foundation system. The value of R_s could be roughly estimated from literature review and numerical analysis.

$$R_s = \frac{w_p(i,i) - w_{slip}(i)}{w_p(i,i)} \tag{5}$$

where, $w_p(i,i)$ = net settlement of pile(i) due to the load on pile(i); and w_{slip} = slip at the interface between pile (i) and soil.

$$\begin{Bmatrix} w_p(1) \\ w_p(2) \\ \vdots \\ w_p(n) \end{Bmatrix} = \begin{bmatrix} \frac{r_p(1)}{R_s}\ln\left(\frac{r_m(1)}{r_p(1)}\right) & r_p(2)\ln\left(\frac{r_m(2)}{r_{1,2}}\right) & \cdots & r_p(n)\ln\left(\frac{r_m(n)}{r_{1,n}}\right) \\ r_p(1)\ln\left(\frac{r_m(1)}{r_{2,1}}\right) & \frac{r_p(2)}{R_s}\ln\left(\frac{r_m(2)}{r_p(2)}\right) & \cdots & r_p(n)\ln\left(\frac{r_m(n)}{r_{2,n}}\right) \\ \vdots & \vdots & \ddots & \vdots \\ r_p(1)\ln\left(\frac{r_m(1)}{r_{n,1}}\right) & r_p(2)\ln\left(\frac{r_m(2)}{r_{n,2}}\right) & \cdots & \frac{r_p(n)}{R_s}\ln\left(\frac{r_m(n)}{r_p(n)}\right) \end{bmatrix} \begin{Bmatrix} \Gamma(1) \\ \Gamma(2) \\ \vdots \\ \Gamma(n) \end{Bmatrix} \tag{6}$$

The settlement distribution of group piles, $\{\mathbf{w_p}\}$ is known because it should be same with the raft settlement for the given pile stiffness, and the matrix $\{\mathbf{\Gamma}\}$ can be obtained. Once the matrix $\{\mathbf{\Gamma}\}$ is obtained, the net settlement $w_p(i,i)$ due to the load on pile(i) can be estimated (7).

$$w_p(i,i) = \Gamma(i) r_p(i) \ln\left(\frac{r_m(i)}{r_p(i)}\right) \tag{7}$$

The reaction of a pile is related to the relative displacement of a pile with respect to surrounding ground movement. The raft settlement causes additional ground movement around a pile and the relative displacement of the pile would be reduced. Thus the raft settlement consequently induces decrease of reaction of piles as if the stiffnesses of piles are reduced.

The ground settlement due to shaft stress around piles causes ground surface settlement underneath the raft, and it seems like the stiffness of soil springs supporting raft is reduced. The total ground settlement of the raft can be obtained by summing up the raft settlement due to the load and the ground surface settlement influenced by settlement of piles.

The load on the raft causes effective stress increase around piles, and the hardening of ground due to effective stress increase should be taken into account in analyzing the behavior of piled raft foundation system. The ultimate unit resistance of piles (q_{psu} and q_{pbu}) should be re-estimated using the increased effective vertical stress, and the unit base resistance-settlement curve needs to be revised during iteration process.

III. Verification Problems

A computer program incorporating the proposed analytical method was developed and the adequacy of analysis was compared with the analysis result of Plaxis 3D Foundation Version 1.5 (Brinkgreve and Broere, 2006). Plaxis 3D program is based on 3-dimensional finite element method and its versatility and adequacy for both foundation design and research were verified by many engineers. Because the settlement of foundation system is the main factor controlling the design of piled raft foundation, the predicted settlements of various foundation systems were compared. Fig. 2 shows the dimension of piled raft foundation supported by 9 piles and soil properties of a verification problem.

The constitutive models used in Plaxis 3D analysis were Hardening-soil model for soil and linear-elastic model for the raft and piles. The interface between piles and soil in Plaxis

3D were simulated with elements of fictitious thickness showing elasto-plastic behavior based on Coulomb's failure criteria. The elastic modulus of soil was assumed to increase with depth and estimated using the similar method proposed by Schmertmann and Hartmann (1978).

Two more numerical programs incorporating the linear-elastic approximate method are used for the purpose of comparison. "PILE+R" numerical program was developed by Hyundai Institute of Construction Technology (1999) and it simulates the piled raft foundation using the plate bending finite element model supported by elastic soil and pile springs. "FEAR 8.1" numerical program incorporates the Finite Layer method proposed by Chow and Small (2005).

Fig. 3 shows the maximum and differential settlement increase with load increase on a piled raft foundation. It is found that the proposed analysis could adequately estimate the maximum settlement under both low and high loading because the present study considers the nonlinear behavior of piles. The proposed method overestimates the differential settlement under medium to high loading because the proposed method does not consider the shear failure of ground near the edge of the raft.

Fig. 4 shows the behavior of each component in the piled raft foundation system. Fig. 4(a) shows the maximum settlement change with increase of load shared by the raft, and Fig. 4(b) shows the maximum settlement change with increase of part of load supported by piles. The proposed method predicts maximum settlement very similar to the value estimated by 3-dimensional finite element method, and Fig. 4 proves the merit of nonlinear analysis for pile behavior.

The % load shared by piles with increase of maximum settlement is shown in Fig. 5. The linear-elastic approximate methods assume constant load sharing regardless of settlement increase, but the proposed nonlinear analysis method augments the load shared by piles as the settlement increases and predicts the % load sharing of piles similarly to the 3-dimensional finite element method.

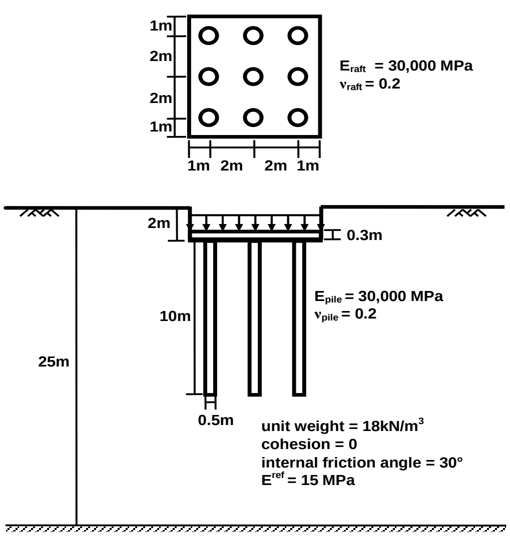
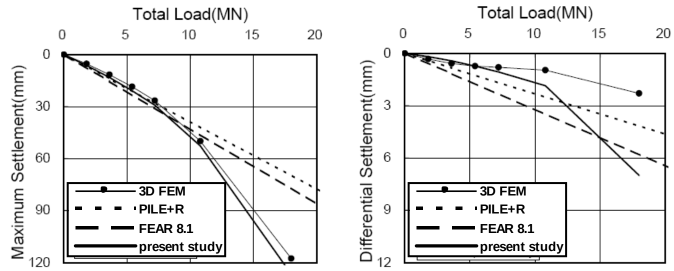
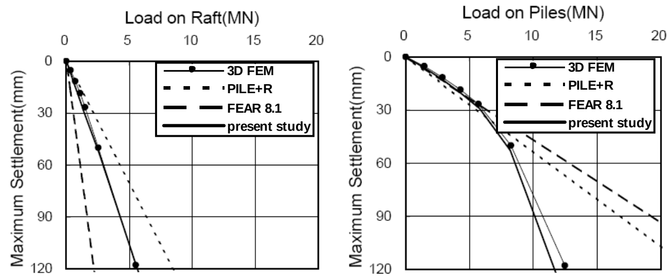


Figure 2. Verification problem



(a) Maximum Settlement (b) Differential Settlement

Figure 3. Maximum and differential settlement estimation



(a) Raft (b) Piles

Figure 4. Maximum settlement change with increase of load shared by each component

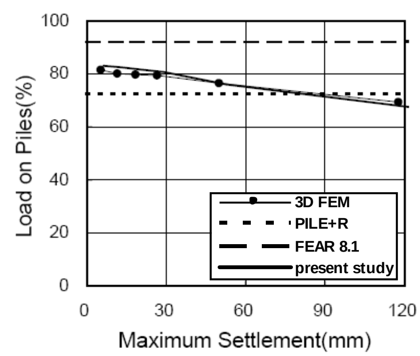
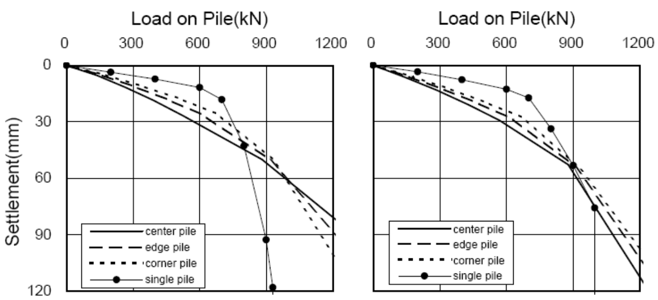


Figure 5. Percent load shared by piles with increase of maximum settlement of foundation

Fig. 6 shows settlement of piles in a piled raft foundation with increase of loading and the settlement-load relationship was compared with single pile case. It should be noted that the load shared by each pile in a piled raft foundation is different, although the load shared by each pile seems to be not much different in this example due to relatively small size of foundation. Compared with the single pile case, it is found that the proposed method could adequately take into account the pile-soil-pile interaction (equation (4)) and ground hardening due to raft settlement. However, the proposed method generally underestimates the effect of ground hardening under large loading condition.



(a) 3-Dimensional FEM (b) Proposed Method

Figure 6. Load-settlement curves of piles in piled raft

IV. Conclusion

This study developed an approximate hybrid method of analysis to be used for the practical design of piled raft foundations considering interactions between pile and soil, raft and soil, pile and pile, and raft and pile. Compared with the analysis results of rigorous 3-dimensional finite element program and approximate linear analysis programs, the capability and adequacy of the proposed approximate nonlinear analysis method was verified in analyzing the behavior of piled raft foundations on multi-layered soil.

It was found that if large stress is applied on piles bigger than yielding stress the linear analysis methods make considerable error in estimating maximum and differential settlement, although the error is relatively small before yielding. Since the piles in a piled raft foundation reduce the total settlement as well as increase the total bearing capacity, it is found to be very important to estimate accurately the nonlinear behavior of piles after yielding for the economic design of piled raft foundation. The developed computer program on the basis of the proposed approximate method could estimate the nonlinear behavior of a piled raft adequately and can be used in design phase without tremendous effort and costs which might be required in 3-dimensional numerical analyses.

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