Effect of Piles on Response of Raft Foundations

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ABSTRACT

A raft foundation transmits load directly to the ground. The introduction of piles can enhance the load carrying capacity for a given permissible settlement of the plain raft. Both the raft and the piles can then share and transmit superstructure column loads simultaneously to the soil. The location of the piles can be planned to reduce the bending moment and shear in the raft, as well as the contact pressure and local settlement below any column. The objective of this study is to understand the response of the foundation system when piles are added to a load bearing raft. The load ratio shared by the piles is initially high and decreases with settlement to reach a constant value. The settlement of the raft-piles system is obtained for different numbers of piles. A parametric analysis is also carried out for controlling the differential settlement.

1 INTRODUCTION

Piles can be introduced below raft when it becomes necessary to reduce settlement or to improve the bearing capacity. A geotechnical assessment for design of such a raft-piles foundation system therefore needs to consider not only the capacity of the raft and the pile elements, but their combined capacity and interaction under serviceability loading. Several different methods of analysis have been developed in order to predict the behaviour of such foundation systems.

Cooke (1986) conducted model tests to bring together information on some design aspects of unpiled rafts, free standing piles and piled rafts of various sizes. Model test results showed that no significant reduction in settlement was achieved by adding more piles and thereby decreasing pile spacing below 4 to 6 diameter. Randolph (1994) developed new numerical and analytical approaches to allow design studies for pile groups and piled raft foundations to focus on the settlement issue rather than the capacity. Design principles were introduced based on conventional approach, creep piling and differential settlement control.

Gandhi & Maharaj (1996) analyzed the effect of raft rigidity on the differential settlement and the effect of size of raft by finite element method, by considering the soil as linear elastic material. It was found that if raft thickness is 3 to 4 times the pile diameter, the differential settlement is negligible. The percentage load shared by piles can be increased by providing stiffer piles. Poulos (2001) presented three different stages of design consideration of piled raft foundation. In the first stage, the effects of the number of piles on load capacity and settlement is assessed via an approximate analysis. The second stage is a more detailed examination to assess where piles are required and to obtain some indication of the piling requirements. The third is a detailed design phase in which a more refined analysis is employed to confirm the optimum number and location of the piles, and to obtain essential information for the structural design of the foundation system.

Prakoso & Kulhawy (2001) analyzed piled rafts using simplified linear elastic and nonlinear plane strain finite element models to develop an approximate design methodology for reducing both average and differential displacement. Liang et al. (2003) extended the concept of piled raft to a new type of foundation named composite piled raft to mobilize shallow soil bearing capacity by introducing a cushion of sand-gravel and to make it participate in the interaction of piled raft sufficiently where soil profile contains soft clays.

Sanctis & Mandolini (2006) proposed a simple criterion to evaluate the ultimate vertical load of a piled raft from the separate ultimate capacities of its components (the raft and the pile group) based on experimental evidence and three dimensional finite-element analyses. The proportion of the load taken by the raft at failure is typically less than unity, depending on the pile layout and geometry.
The ultimate capacity of the piled raft is at least 80% of the sum of the ultimate capacities of the separate components.

In this study, the load sharing between the raft and the piles is first calculated, and this is followed by a determination of the required thickness of the raft. The differential settlement response of the raft-piles system is then obtained through a parametric analysis.

2. ANALYSIS OF RAFT

In order to implement the method, a raft as shown in Figure 1 has been analyzed. The problem involves a raft foundation on a uniform soil layer of finite depth. The total superstructure load is 16,000 kN from 16 columns at 4 m c/c spacing. The raft is square in shape, and data of the raft and soil are:

**Raft Data**
- Width of raft, $B$: 14 m
- Young's modulus, $E_r$: 20 GPa
- Poisson's ratio of raft, $v_r$: 0.2

**Soil Data**
- Young's modulus of soil, $E_s$: 25 MPa
- Poisson's ratio of soil, $v_s$: 0.383
- Undrained shear strength, $C_u$: 32.92 kN/m$^2$

The soil is considered as a continuum, and the interaction between the raft and the soil is computed through the use of elasticity theory. Table 1 presents the settlement of the raft for gradual increase in structural loading. The required raft thickness determined from bending moment and shear stress considerations are also shown in the table.

<table>
<thead>
<tr>
<th>Total load (kN)</th>
<th>Settlement (mm)</th>
<th>Required raft thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>28.1</td>
<td>0.705</td>
</tr>
<tr>
<td>5000</td>
<td>53.5</td>
<td>1.032</td>
</tr>
<tr>
<td>7500</td>
<td>74.7</td>
<td>1.286</td>
</tr>
<tr>
<td>10000</td>
<td>93.4</td>
<td>1.502</td>
</tr>
<tr>
<td>12500</td>
<td>110.1</td>
<td>1.691</td>
</tr>
<tr>
<td>15000</td>
<td>130</td>
<td>1.861</td>
</tr>
<tr>
<td>16000</td>
<td>134</td>
<td>1.93</td>
</tr>
</tbody>
</table>

3. ANALYSIS OF RAFT WITH PILES

The raft shown in Figure 1 is then converted into a raft-piles system by adding piles of 0.5 m diameter, with other data as follows:

**Pile Data**
- Young's modulus of pile, $E_p$: 20 GPa
- Length of piles, $L_p$: 11 m
- Spacing of piles, $s$: 4 m

Initially, only 16 no. of piles are considered directly below the columns. The computed load-settlement relationship is shown in Figure 2. In the analysis, the total applied load is increased to 48,000 kN, which is three times the actual structural load. The total capacity of the piles is fully mobilized at 9,636 kN when the total applied load reaches a magnitude of 15,127 kN, as indicated by $V_A$ in the figure. Beyond this point, the stiffness of the foundation system is that of the raft alone, and this holds till the ultimate load capacity of the raft-pile system is reached.

The analysis is then extended by varying the no. of piles. The numbers of piles considered are 6, 10, 16, 20
4. PARAMETRIC STUDY

The response of raft-piles system depends on several parameters. The parameters can include dimensions of raft; pile diameter, length and spacing; Young’s modulus of raft, pile and soil; and Poisson’s ratio of raft and soil. It is necessary to consider a set of non-dimensional parameters to obtain a framework for differential settlement control. A study was carried out to examine the influence of parameters as summarized in Table 3, for minimizing differential settlement. Only a group of piles is considered in the middle portion of the raft with the central pile located below the centre of the raft. The pile diameter, pile length $L_p$ and pile spacing $s$ are chosen as variables. Half the width of the raft is represented as $b$. An equivalent circular radius $a_{eq}$ is taken for a square or rectangular raft. Step calculations are required as non-linear behaviour is considered.

### Table 3: Range of Parameters

<table>
<thead>
<tr>
<th>$E_p/E_s$</th>
<th>100, 500, 1000, 3000, 10000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_p/a_{eq}$</td>
<td>1.39, 2, 3, 4</td>
</tr>
<tr>
<td>$\nu_s$</td>
<td>0.10, 0.30, 0.50</td>
</tr>
<tr>
<td>$s/b$</td>
<td>0.3, 0.4, 0.5, 0.57</td>
</tr>
</tbody>
</table>

### Influence of Pile Spacing

The centre mid-side differential settlement is normalized by the average settlement of the raft, and is represented by $\delta w^*$. The ratio of combined pile capacity to total applied load is designated as $1/Pt^*$. Figure 5 shows the differential settlements for cases with different pile spacings ranging from 2.1 to 4.0 m. It can be noted that the differential settlement remains constant during the early elastic stages of loading where $1/Pt^*$ is greater than 2.25 to 2.5, but after the early stage it increases as the piles start to develop their full capacity. There is a tendency for the differential settlement to decrease as the piles are more closely placed within the central portion of the raft.

### Influence of Pile Compressibility

In the analyses, the pile-soil stiffness ratio $E_p/E_s$ is varied from 100 to 10,000. The pile support is optimized by varying the pile radius from 0.08 m to 0.60 m while keeping the same equivalent pier-raft stiffness ratio $K_{pr}$. In this condition, the equivalent pier modulus and diameter are

![Fig. 5: Effect of Pile Spacing on Differential Settlement](image)

![Fig. 6: Effect of Pile Compressibility on Differential Settlement](image)
kept constant, as are the number and length of the piles. The total pile capacity changes as the pile radius is varied. As such, the ultimate unit shaft friction of pile is kept constant in all the cases. The effect of varying pile compressibility on the differential settlement is shown in Figure 6. It can be noted that as for a higher \(E_p/E_s\) value at the same \(1/P_t^*\) ratio, the differential settlement is found to be greater.

**Influence of Poisson’s Ratio of Soil**

The effect of the Poisson’s ratio of the soil on the differential settlement is studied by keeping a constant equivalent pier-raft stiffness ratio of 1.92, while adjusting the pile radius between 0.191 m and 0.328 m. The raft thickness is changed to keep the raft-soil stiffness ratio constant. The pile length is kept unchanged. The results are shown in Figure 7. It can be observed that the differential settlement shows a tendency to rise as Poisson’s ratio increases.

![Fig. 7: Effect of Poisson’s Ratio on Differential Settlement](image)

**Influence of Pile Length**

The effect of pile length on the differential settlement is examined by performing analyses. The \(L/a_e\) ratio is varied from 1.39 to 4.0. The equivalent pier-raft stiffness ratio is kept constant at 1.92 by adjusting the pile radius from 0.168 m to 0.184 m. The pile spacing is set at \(s/b = 0.57\) in all the cases with the number of piles maintained as 16. The calculated results are depicted in Figure 8. It can be noted that even if the pile length is increased significantly, the differential settlement reduces only slightly.

![Fig. 8: Effect of Pile Length on Differential Settlement](image)

5. CONCLUSIONS

From economical considerations, the average and differential settlement of a raft should be controlled to an acceptable level and not suppressed completely. The settlement of the raft-piles system can be reduced by providing a small number of piles mainly in the central portion of the raft. The required raft thickness in the raft-piles system is found to be less in comparison to that of the raft alone. In the initial stage of loading, load sharing between the raft and piles depends on the relative stiffness between them. If the relative stiffness is kept unchanged, pile length affects differential settlement only marginally. The combined pile capacity should be designed for the range of 50 to 75% of the total structural load.

**REFERENCES**


