EFFECT OF CUSHION ON COMPOSITE PILED–RAFT FOUNDATION

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ABSTRACT
In order to mobilize shallow soil to participate in the interaction of piled raft foundation sufficiently, the concept of piled raft has been modified to new type of foundation named composite piled raft. In the system of composite piled raft, the short piles made of flexible materials were used to strengthen the shallow soft soil, while the long piles made of relatively rigid materials were used to reduce the settlements and the cushion beneath the raft was used to redistribute and adjust the stress ratio of piles to subsoil. Finite element method was applied to study the behavior of this new type of foundation subjected to vertical load. This paper focuses on general effect of cushion on properties of composite piled raft foundation system such as axial stresses on piles, superimposed stress on subsoil and settlements of piles and subsoil.

KEYWORDS Piles, Raft, Foundation, Analysis.

1. INTRODUCTION
In earlier foundation design, it is customary to consider first the use of shallow foundation such as a raft (possibly after some ground-improvement methodology performed). If it is not adequate, deep foundation such as a fully piled foundation is used instead. In the former, it is assumed that load of superstructure is transmitted to the underlying ground directly by the raft. In the latter, the entire design loads are assumed to be carried by the piles. In recent decades, another alternative intermediate between shallow and deep foundation, what is called piled raft foundation or settlement reducing piles foundation, has been recognized by civil engineers. The concept of piled raft foundation was firstly proposed by Davis and Poulos in 1972, since then it has been described by many authors, including Burland et al. (1977), Cooke (1986), Chow (1987), Randolph (1994), Horikoshi and Randolph (1996), Ta and Small (1996), Kim et al. (2001), Poulos (2001), and many others. Now the piled raft concept has been used extensively in Europe and Asia. In this concept, piles are provided to control settlement rather than carry the entire load. Piled raft foundation has been proved to be an economical way to improve the serviceability of foundation performance by reducing settlement to acceptable levels. The favorable application of piled raft occurs when the raft has adequate loading capacities, but the settlement or differential settlement exceed allowable values. Conversely, the unfavorable situations for piled raft include soil profiles containing soft clays near the surface, soft compressible layers at relatively shallow depths and some others. In the unfavorable cases, the raft might not be able to provide significant loading capacity, or long-term settlement of the compressible underlying layers might reduce the contribution of raft to the long-term stiffness of foundation. However, most of economically developed cities, especially in Shanghai Economic Circle of China, are located in coastal areas. In these areas, the piled raft concept is unfavorable as mentioned above because building construction often meets with deep deposit soft soil. In order to take advantage of piled raft foundation, civil engineers have developed many methods to practice it in China [10]. Based on the engineering practices, Fa-Yun Liang, Long-Zhu Chen and Xu-Guang Shi (2003) have developed the concept of piled raft foundation to long-short composite piled raft foundation with intermediate cushion (For short as ‘‘composite piled raft’’) as is shown schematically in Figure 1. In this new type of foundation, short piles made of relatively flexible materials such as soil–cement columns or sand–gravel columns (also called sand–stone columns in China), etc. are applied to improve the bearing capacity of shallow natural subsoil; the long piles made of relatively rigid materials such as reinforced concrete are embedded in deep stiff clay or other bearing stratum to reduce the settlement; and the cushion made of sand–gravel between the raft and piles plays an important role in mobilizing the bearing capacity of subsoil and modifying load transfer mechanism of piles. The advantages of different ground-improvement methodologies may be used fully.

Fig. 1. Sketch of composite piled raft foundation
Many theories concerning the analysis of piled raft foundation have been proposed by various researchers [1]. However, most of them do not
incorporate the effect of cushion in the analysis and all the piles have the equal length. Composite piled raft is so complex that the analytical approach cannot be used to deal with. But it is well known that the finite element method is very versatile for studying complex problems. This paper presents general effect of cushion on properties of composite piled raft foundation, which includes effect of axial stresses on piles, superimposed stresses on subsoil and settlement of piles and subsoil.

2. METHOD OF ANALYSIS
2.1. Model for numerical analysis

The geometry of composite piled raft analyzed in present study is illustrated in Fig.2. The analysis method refers to three-dimension finite element method proposed by Ottaviani [12]. It is implemented via a computer program Midas GTS (a universal computer program for finite element analysis developed by MIDAS Information Technology Co., Ltd). Because most foundation is in elastic state under common working load conditions, the raft, cushion, piles and subsoil are all assumed to be weightless linearly elastic media. No relative displacements are allowed at the interfaces between the piles and subsoil. The piles have been given as square section for dividing element grids conveniently. The side width of piles, the spacing between the piles and the raft dimensions have been kept constant with values chosen among the widely used in practice. In the analysis, the long piles and raft are made of concrete; the short piles and cushion are made of sand–gravel. To simplify the analysis, let the side width of long and short piles be equal, \( d_1 = d_2 = d = 0.45 \text{m} \). Considering that the spacing between short piles is usually small, let \( s=d \), where “s” is the net spacing between adjacent piles (shown in Fig. 2). Compared with the subsoil, the raft is assumed relatively rigid with elastic modulus \( E_c = 3 \times 10^4 \text{MPa} \), Poisson’s ratio \( \mu_c=0.2 \), side width \( B = 6d = 2.7 \text{m} \) and thickness \( h=0.5 \text{m} \). In this paper, these values are used unless otherwise specified. The elastic moduli and Poisson’s ratios of long piles, short piles, subsoil and cushion are listed in Table 1.

### Table 1: Parameters of materials for analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>Long piles</th>
<th>Short piles</th>
<th>Subsoil</th>
<th>Cushion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus/Mpa</td>
<td>( E_{p1} = (1–3) \times 10^4 \text{MPa} )</td>
<td>( E_{p2} = 100–2500 \text{MPa} )</td>
<td>( E_s = 5 \times 10^6 \text{MPa} )</td>
<td>( E_m = 10–80 \text{MPa} )</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>( \mu_{p1}=0.2 )</td>
<td>( \mu_{p2}=0.3 )</td>
<td>( \mu_c=0.35 )</td>
<td>( \mu_m=0.3 )</td>
</tr>
</tbody>
</table>

Fig. 3 shows three-dimensional finite element model which incorporates piles, cushion and raft. A maximum number of 6493 nodes and 5496 elements are employed to represent the model analyzed. The concerned geometric domain and element grid are determined on the base of trial calculation method. The criteria for them are listed as follows:

1. The calculated results of stresses and displacements distribution do not change apparently with the further expansion of concerned domain (in case the boundary has to be expanded).
2. The size of elements in the zones of high stress gradient should be as small as possible while the size of elements around the domain boundary could be larger.

### 2.2. Non-dimensional parameters for numerical study

The main influencing factors include material parameters of piles, cushion, subsoil and the length of piles and the spaces of piles and others. In order to simplify the analysis and summarize the rules from the calculating results, several dimensionless parameters are introduced below:

a. \( k_1 = E_{p1}/E_s \), which is the elastic modulus ratio of long piles to subsoil;

b. \( k_2 = E_{p2}/E_s \), which is the elastic modulus ratio of short piles to subsoil;

c. \( k_3 = E_m/E_s \), which is the elastic modulus ratio of cushion to subsoil.

Fig. 3. Finite element schematic of composite piled raft system
3. EFFECTS OF CUSHION ON THE PROPERTIES OF COMPOSITE PILED RAFT

Practice shows that sand–gravel cushion between the raft and piles can adjust the load-sharing ratios of piles and subsoil, and enhance the strength of subsoil among piles. Some researchers have studied the effects of cushion on the properties of raft foundation [11,15], while studies on effects of cushion on composite piled raft system has been carried out recently [16,17].

3.1. General effects of cushion on the properties of composite piled raft.

Some rules can be drawn out from Figs. 4, 5, 6 and 7.

1. The axial stress of long piles in composite piled raft foundation with cushion are smaller than that of foundation without cushion, while the axial stress of short piles in composite piled raft foundation with cushion are larger than that of foundation without cushion. Thus it shows that cushion can adjust the load-sharing ratios evenly among piles and help to make better use of the bearing capacities of short piles.

2. In composite piled raft foundation without cushion, the maximum axial stress occurs at the head of piles and axial stress of piles decreases along the depth. However, these properties have changed after installed cushion between piles and raft. Compared with the foundation without cushion, the maximum axial stress of piles shifts lower from the head of piles to a certain depth. It is because that the load undertaken by subsoil increases under the adjustment of cushion and the displacements of subsoil are larger than that of piles in a range of certain depth along piles shaft (shown in Fig. 7). And then the negative friction is generated by the relatively larger settlement of shallow subsoil. However, when the depth is lower than the certain depth, the displacements of piles are larger than that of subsoil with the further increasing of depth, and the friction along piles will become positive and then the axial stress of piles decreases with the depth again.

3. The change of superimposed stress of subsoil mainly occurs in the shallow subsoil, though the load-sharing ratio of subsoil is improved after cushion installed. It is the result of deformation compatibility among long piles,

In calculation, \( \delta = 0.3 \) m, \( E_m = 80 \) MPa (equivalent to \( k_3 = 16 \)), \( \mu = 0.3 \), \( E_s = 5 \) MPa, \( k_1 = 2000-3000 \), \( k_2 = 40 \), \( L_1 = 54d = 24.3 \) m, \( L_2 = 26d = 11.7 \) m, and other parameters are the same as the above. When the uniform load acted on the raft is \( p = 100 \) kPa, the mean axial stress in each pile and the mean vertical superimposed stress of soil among piles varied with depth are shown in Figs. 4, 5 and 6.

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Fig 4: Results for axial stress of long pile \( k_1 = 2000 \) and 3000.

Fig 5: Results for axial stress of short pile \( k_1 = 2000 \) and 3000.

Fig 6: Results for superimposed stress of soil for \( k_1 = 3000 \).

Fig 7: Results for settlement of piles and subsoil for composite pile with cushion and \( k_1 = 3000 \).

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3. The change of superimposed stress of subsoil mainly occurs in the shallow subsoil, though the load-sharing ratio of subsoil is improved after cushion installed. It is the result of deformation compatibility among long piles,
short piles and subsoil. Thus it can be seen that the bearing capacities of shallow subsoil can be better used through appropriate application of cushion technique, especially for ground containing hard crust in shallow layers.

4. SUMMARIES AND CONCLUSIONS

In order to apply conventional piled raft to the unfavorable situations, the concept of composite piled raft has been developed which incorporates effect of unequal length and moduli of piles as well as the action of cushion in consideration. In this new type of foundation, the short piles are used to strengthen the shallow soft soil, the long piles are used to reduce the settlement and the cushion is used to redistribute and adjust the settlement and the stress ratio of piles to subsoil. The advantages of different ground-improvement methodology were thus made good use. Three-dimensional finite element method was used to analyze it. The main factors influencing the bearing capacities and settlement behavior of the foundation are investigated. Based on the parametric study presented in this paper, the following conclusions are drawn out:

1. As far as influences of elastic modulus and length of piles are concerned, increasing lengths of long piles has much more obvious effects on reducing settlement of foundation than improving the elastic modulus of short piles.

2. Cushion can adjust the load-sharing ratios evenly among piles and help to make better use of the bearing capacities of short piles. Compared with the foundation without cushion, the maximum axial stress shifts lower from the head of piles to a certain depth. And the bearing capacities of shallow subsoil can be better used through appropriately applied cushion technique, especially for ground containing hard crust in shallow layers.

REFERENCES