Settlement analysis for piled raft foundations

Phung Duc Long

i) Director, Long GeoDesign, Hanoi, Vietnam (phung.long@gmail.com).

ABSTRACT

During the last few decades, the quick growth of cities all over the world led to a rapid increase in the number and height of high-rise and super high-rise buildings, even in unfavourable subsoil conditions. Piled raft foundation concept, in which piles only for reducing the settlement, not for carrying the whole load from the superstructure, has been successfully applied for many projects. This design philosophy has also been increasingly applied for high-rise buildings. In this paper the result from the Author’s experimental study, which strongly supports the concept of settlement-reducers are reviewed. The experimental results are surprisingly in good agreement with case histories many years later. Applications of the proposed simplified design method in combination with FEM in design of piled-raft foundations for high-rises are also discussed.

Keywords: Pile foundation, piled raft, FEM, field model test, simplified method.

1. INTRODUCTION

Piled raft foundations become recently more and more accepted in many countries. In conventional pile foundations, the piles are commonly designed with an assumption that the entire load from the superstructure is taken by piles, and the raft does not take any load. In reality however the raft can take a considerable part of load. According to most standards, the piles must be designed with a safety factor of 2 to 3. This design requirement results in more and longer piles, and therefore the pile foundation is considerably conservative and expensive. Conversely, the settlement of the pile foundations is unnecessarily small. The conventional pile is commonly used for high-rises worldwide, especially in the US and South East Asia. Foundations are predominantly founded on large-diameter bored piles, barrettes or diaphragm wall, which are in most cases driven deeply into the ground to reach bearing layers.

In the past decades, there has been an increasing recognition that the use of piles to reduce the raft settlements and its differential settlements can lead to considerable economy without compromising the safety and performance of the foundation. The concept of piled raft foundations (PRF), where piles are only designed to reduce the settlement, not to take the full load from superstructure, is more and more accepted.

Various methods of analysis of piled raft foundations have also been developed, but there appears to be only limited information on the comparative performance of these methods in predicting the foundation settlement behaviour. In the design practice, simplified methods are needed, especially for the conceptual design. Many simplified analytical methods have also been suggested. However, they are still complicated, and computer programs need to be developed for the methods. Unfortunately, such programs are not commercially available (Poulos, 2011). Besides, most of these methods are based on theory of elasticity, which is not suitable for the piled footings with complicated pile-soil-raft interaction (Phung, 1993).

A systematic experimental field model study was carried out by the Author for piled groups in non-cohesive soil. The study clarified the complicated interaction between the piles, the pile cap and the surrounding soil. The experimental results can be used as a base for a simplified method, which can be easily used for the design practice. This method can be used in combination with FEM for design of piled raft foundations, with a desired settlement. In this paper the experimental results are summarized, and a case study, in which concept design of a pile raft foundation for a high-rise building, is presented. The design is carried out using the proposed simplified method in combination of FEM analysis, with a required settlement of 20mm. This approach is quite useful and effective for practical design.

2. CASE HISTORIES OF PILED-RAFT AND PILE FOUNDATIONS

During the last few decades, the quick growth of cities all over the world led to a rapid increase in the number and height of high-rise and super high-rise buildings, even in unfavourable subsoil conditions. Piled raft foundation concept has been successfully applied for many projects, which are shown in Table 1. Some of the well-known conventional pile foundations are also presented in the table for comparison.

From Table 1, a clear connection can be seen between the settlement and the load carried by piles: the larger the load taken by piles, the smaller the settlement occurs. In fact the settlement (maximum value, differential settlement and its pattern) can be controlled by changing the number of piles, their length as well as their layout. It can be also noted that some foundations were designed as a pile foundation, but they acted as a combined piled-raft-foundation, i.e. the raft can take some part of building load.
Petronas Tower in Kuala Lumpur is a good example. The foundation was designed as a conventional pile foundation. However, a certain part of the total load was still taken by the raft. According to the measurement, 15% of the dead load was taken by the raft when the structure reached the height of 34 stories. ICC Tower in Hong Kong is another example. The foundation was also designed as a conventional pile foundation; however the Author’s analysis indicated that a major part, up to 30% of the total load, could be carried by the raft, Phung (2002).

3. FIELD MODEL TESTS AND SIMPLIFIED ANALYSIS METHOD

In order to create a better understanding of the load-transfer mechanism and of the load-settlement behaviour of a piled footing in non-cohesive soil, especially the settlement-reducing effect of the piles, three extensive series of field large-scale model tests were performed by the Author (Phung, 1993). In each series, four separate tests on a shallow footing/cap alone, a single pile, a free-standing pile group, and a piled footing with cap in contact with soil were performed under equal soil conditions and with equal geometry. All pile groups were square and consisted of 3 piles, one central and 4 corner piles, with a centre-to-centre pile spacing of 4b, 6b and 8b for test series No.1, 2 and 3 respectively. The soil relative density in the three test series was different. Comparison of the results from the tests on free-standing pile groups with those on single pile shows the pile-soil-pile interaction, while comparison of the results on piled footings with those on free-standing pile groups and on unpiled footings (cap alone) shows the pile-soil-cap interaction.

The results from all the three test series show the same tendency. Comparison of the results from the separate tests in Test series T2 is shown in Fig. 1. In this figure, we can see that the load taken by cap in the piled footing test, the curve T2F-Cap, is very close to the load taken by cap in the test on footing alone, T2C-Cap. This means that the load-settlement curve of the cap in a piled footing is very similar to, and can therefore be estimated as, that of the unpiled footing under the same load. The load taken by piles in the piled footing, T2F-Piles, is however much larger than the load taken by piles in the free-standing pile groups, T2G-Piles. The increase is due to the cap-soil contact pressure. From these conclusions, a simplified design procedure for piled footings in sand can be carried out with the steps below:

1) Estimating the load taken by the unpiled footing/raft at a required settlement. This load is equal to that taken by the raft in the piled footing $P_{cap}$.

2) Estimating the load taken by the piles:

$$P_{piles} = P_{total} - P_{cap}$$

where, $P_{total}$ is the total applied load.

3) Estimating the number of piles: as the piles are very close to failure state, the number of piles can be calculated as:

$$n = P_{piles} / P_s$$

where, $P_s$ is ultimate capacity of a single pile.

![Figure 1. Test series T2 - Comparison of tests](image-url)
The number of piles can then be estimated by dividing the load taken by piles $P_{piles}$ to the bearing capacity of a single pile, which can be taken as the creep load or even the failure load of a single pile. Creep load is the load, at which significant creep starts to occur, typically 90% of the ultimate load capacity. There is an extreme case, in which the full load capacity of the piles is utilized, i.e. piles operate at 100% of their ultimate load capacity. Even in this 100% extreme case, the design is still on the safe side because under the raft contact pressure the pile shaft capacity is considerably increased. This simplified design method is good enough for the concept design phase. Poulos & Makarchian (1996) also used this method to estimate the settlement of the model footing in their study and found a fair agreement with the test results.

4. CASE STUDY

In the last few decades, there has been considerable development of methods for calculating settlement of free-standing pile groups and piled footings. However, most of the methods are based on the theory of elasticity. From the above-mentioned experimental study, the Author had drawn conclusions different from those obtained from the studies basing on theory of elasticity. For example, the comparisons of settlement of a piled footing with that of a free-standing pile group show that due to the contribution of the cap, the increase in stiffness of the piles footing, as compared with the corresponding free-standing pile groups, is considerable. This conclusion is contrary to that drawn in most of the theoretical studies basing on the theory of elasticity (Butterfield & Banerjee, 1971; Poulos & Davis, 1980; and Randolph, 1983).

In practice, a simplified and less time-consuming method should first be used for the conceptual design, especially for a feasible foundation option study. The detailed design of piled raft foundation for high-rises should later be done by numerical analyses using FEM or explicit finite difference codes. Foundation design using FEM is now becoming a must for high-rise buildings especially when they become higher and heavier, with more complex configurations. This can recently be realized due to faster computers and more advanced commercial programs, 2D or 3D, available. The most common codes are: PLAXIS 2D or 3D, FLAC 2D or 3D, ABAQUS, and DIANNA and Midas GTS, etc.

4.1 Project

In this section a pile foundation for a large high-rise building is studied as a case study. The foundation was designed by the project engineers as conventional pile foundation, i.e. the piles would take the full load from superstructure. Piled raft is studied by the Author as an alternative option with a much smaller number of piles used as settlement reducers. The piled raft is designed using FEM in combination with the simplified method proposed in Section 3. The FE analysis is carried out using Plaxis 3D in this study and mainly concerns to the settlement behaviour. As an illustration, a settlement of 20mm is required.

The studied project is Datum Jelatek, located about 4 km from central Kuala Lumpur, Malaysia. The development has a 12-floor podium consisting of retail, office and car park bay floors, and four multi-storey residential towers with a number of stories varying between 41 and 47, Fig. 3. The development has three levels of underground basement for parking vehicles and retail. A circular-shaped bridge connects the four towers together at level 24. The podium distributed load is about 167 kPa, while the distributed loads in Tower A, Tower B, Tower C, and Tower D respectively on top of the podium, $q_A = 470.4$ kPa, $q_B = 475.9$ kPa, $q_C = 505.4$ kPa, $q_D = 458.4$ kPa.

The layout of the conventional pile foundation designed by the project engineers is shown in Fig. 4, in which 387 piles are used, including 67 piles with a diameter of 0.9 m, 110 piles 1.2 m, and 210 piles 1.5 m. With a large number of piles, conventional pile foundations are often too safe and have too small settlements (Phung, 2011).

4.2 Soil conditions and 3D model

The soil condition at the site is complicated. In order to avoid the unnecessary complication for a conceptual design, it is assumed that the soil profile is even with data from the borehole B12-2, 70m deep. The soil consists two layers: 1) Silty sand, 22m thick, and 2) Gravelly sand, 38m thick.
Table 2. Material parameters for soil layers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sily sand</th>
<th>Gravelly Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_{\text{unsat}} ) [kN/m³]</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>( \gamma_{\text{sat}} ) [kN/m³]</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>( \varphi ) [°]</td>
<td>35</td>
<td>42</td>
</tr>
<tr>
<td>C [kPa]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( \psi ) [°]</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>( \nu_{\text{rg}} ) [-]</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>( E_{\text{50,ref}} ) [kPa]</td>
<td>60,000</td>
<td>100,000</td>
</tr>
<tr>
<td>( E_{\text{40,ref}} ) [kPa]</td>
<td>60,000</td>
<td>100,000</td>
</tr>
<tr>
<td>( E_{\text{ur,ref}} ) [kPa]</td>
<td>180,000</td>
<td>300,000</td>
</tr>
<tr>
<td>m [-]</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>( p_{\text{ref}} ) [kPa]</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>( K_{\text{nc}} ) [-]</td>
<td>Automatic</td>
<td>Automatic</td>
</tr>
<tr>
<td>( R_{\text{f}} ) [-]</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>( \sigma_{\text{Tens.}} ) [kPa]</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The Hardening Soil model (HS) is used to model the soil behavior. The material parameters are summarized in Table 2. Calculations are carried out as drained analysis; as a result the final settlements are obtained.

### 4.3 FE analysis of unpiled raft

Plaxis 3D was first used to predict the load can be taken by the unpiled raft at a settlement of 20mm. The building was considered to be stiff. In order to avoid unnecessary complicated modeling of the excavation and basement construction process, the basement was simulated as a volume with a unit weight being estimated as the total weight of the basement dividing to the depth of the basement, i.e. about 6kN/m³. Non-porous linear elastic volume elements were used for modeling the raft, whose bottom is located at -12.0m under the ground surface. The analysis was done with increasing podium load, to establish the load settlement curve for the raft alone, and to find out the load that the raft can take so that the settlement would not be over 20mm. Because the full excavation phases are not modeled in this study, it is not easy to define the load at 20mm settlement. In this study, it is therefore reasonable to accept the full podium load, i.e. 167 kPa, being taken by the raft. The construction process was simulated with the phases:

1. Generation of initial stresses;
2. Activation of raft by changing raft material;
3. Loading on raft (100, 200, 300, 400, 500 kPa).

### 4.4 FE analysis of piled raft

The simplified approach showed in Section 2 is used to estimate the number of piles. The load taken by the piles is calculated according to equation (1). In the analysis of the raft alone, it is concluded that the full podium load can be taken by the raft. This means that the total load for each tower above the podium can be directly used for defining the number of piles under each tower. The piles will be then arranged directly under the towers. Pile with 1.5m diameter is chosen. In the piled-raft concept, piles have to work as friction piles, and therefore they have not to socket to the limestone layer. The pile base is therefore decided to be located at a level of 2m above the limestone, i.e. -58m, and the pile length is 46 m. According to the study done by a local consultant, an ultimate load of 20,000 kN can be accepted for such a pile. As a result, 16 piles are needed for each tower A and D, and 21 piles are needed for each tower B and C; or a total of 74 piles are used for the four towers, see the pile layout in Fig. 6.

Diaphragm wall, DW, with a thickness of 0.8m being constructed on the foundation perimeter, can act as a bearing component. In the Plaxis 3D model, piles are modeled as embedded pile elements, and DW plate elements. Loads from the superstructure are simulated as distributed load in the four tower areas. The 3D FE piled-raft model is shown in Figures 7 and 8. The construction was simulated with the following phases:

1. Generation of initial stresses,
2. Basement construction in one stage,
3. Podium loading \( q_0 \) over the raft/podium;
4. Tower loading, \( q_A \), \( q_B \), \( q_C \), and \( q_D \).

Figure 5. Settlement of the raft alone at \( q_0 = 300 \text{kPa} \)

Figure 6. Piled raft foundation - Pile layout

Figure 7. Plaxis 3D piled raft foundation model

1247
4.5 Analysis results

From the output results, the maximum settlement of the piled-raft system is 18 mm, which satisfies the 20mm-criterion mentioned in Section 3.1. The maximum differential settlement is about 8mm. The settlement of the ground surface is shown in Figure 9, while the settlement contours at two cross-sections one along x-x axis and another along y-y axis, through the raft center, are showed in Figure 10. The vertical contact pressure distributed under the raft bottom is shown in Figure 11. The main purpose of this study is the settlement of the piled raft foundation, and therefore other obtained results are not discussed here.

With an acceptably small settlement less than 20mm, the number of piles is reduced considerably. The number of piles used for the piled raft option in this study, even plus the additional piles for reducing large bending moments and shear forces in the raft, is much smaller than that used in the conventional pile option. If the accepted settlement is higher, more piles can be saved.

5. CONCLUSIONS

Piled-raft foundation, in which piles are designed to reduce the settlement, not to take the full load from superstructure, is an effective foundation method for high-rise buildings. However, predicting the settlement for piled-rafs is a difficult task for geotechnical engineers due to the complex pile-cap-soil interaction. Most of the available prediction methods are not suitable for piled-raft foundations as they are based on the theory of elasticity. The simplified method, proposed in this paper, basing on the experimental study performed by the Author can be used easily for the conceptual design of a piled raft foundation. This method can be used more effectively if it is used in combination with FEM method to predict the settlement behavior of piled raft foundations. The analysis for the case study carried out by the Author for a large high-rise project presented in this paper is a clear illustration for the design practice for piled-raft foundations. Applying piled raft foundation method, a large number of piles can be saved in comparison to the traditional conventional pile foundation. Unfortunately, the concept has not been accepted in many countries.

6. REFERENCES


