3-D NUMERICAL ANALYSIS OF CONSOLIDATION EFFECT ON PILED RAFT FOUNDATION IN BANGKOK SUBSOIL CONDITION

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ABSTRACT: This study focused on the investigation of influencing factors on behaviour of piled raft foundation in Bangkok subsoil. To evaluate the possibility of implementing this system in Bangkok subsoil condition, this research performed the consolidation analysis of piled raft foundation systems for low-rise (8-storey) and high-rise (25-storey) buildings with basement levels in clay soil, using coupled three-dimensional (3D) mechanical and hydraulic numerical model. The soils are modelled with Hardening Soil model and Mohr-Coulomb model. Evaluations of piled raft foundation, i.e., the load sharing ratio of piles, settlement behaviours in the foundation system are performed. The parametric study on the effect of raft depth, and load carried by piles of piled raft was done. The consolidation had a strong influence on the load carried by piles of the piled raft foundation in Bangkok. The load shared by piles can increase by up to 12% and 6% for low rise and high-rise buildings, respectively due to the consolidation effect. Therefore, the design of the piled raft foundation system in Bangkok subsoil essentially consider the consolidation effect.

Keywords: 3-D-FEM, Bangkok subsoil, Consolidation, piled rafts, Piled-raft load sharing, Softs soil

1. INTRODUCTION

In Bangkok, there are many building projects constructed on soft soil. As the subsoil of this area consists 13-16 m thick soft clay and stiff clay interspersed with sand [1], the pile foundation must be used to transfer the load to stiff soil layers. Normally, the design and construction of foundation system on soft ground have posed various problems to geotechnical engineers, such as consolidation, excessive settlement, negative skin friction and bearing capacity failure. To avoid these problems, the structure of foundation in this area are relatively expensive.

In Thailand, the designers prefer to consider the pile group to support a structure [2]. The pile groups mostly focus on pile capacity and group settlement without considering the presence of the raft or mat. In fact the foundations are built using concrete and their bottom surfaces are attached to the soil beneath. Therefore, in most cases end up with overdesign of the foundation. Typically, new office or residential buildings require 2 or more basements (depth10-20m.) for utilizing as a car park space. Meanwhile, the foundation has constructed in deeper level. This means that the mat foundations is placed on the stiff soil. Therefore, the soil bearing capacity are increasing at the bottom of the mat foundations. In recent years, the foundation engineers tend to combine these two separate systems (between shallow foundations (rafts) and deep foundations (piles)). Such a foundation system is referred to as piled raft foundation.

Recent years, the “Piled Raft Foundations” (PRF) have been widely accepted as one of the most economical methods of foundation systems [3], [4]. Thus, the piled raft systems have been used extensively in many parts of the world e.g. England [5], Japan [6], Germany [7], [9], [10]. The application of piled rafts on soft ground is becoming a significant issue in foundation design. A few successful applications and analysis of piled rafts on soft ground have been reported [8]–[13]. However, the behaviour of piled raft foundation supporting the structure in clay soil was found that the long-term effect (consolidation) increases the load carried by piles and decreases raft contact pressure [5]. This means that the effect of consolidation in clay has influence on piled raft foundation system. Previous studies on numerical analysis of piled raft foundation in Bangkok subsoil condition indicated the potential of using PRF in Bangkok subsoil [2], [14]. However, they considered only short term behaviour.

To pay special attention to the consolidation effect, a coupled three-dimensional (3D) mechanical and hydraulic numerical model is used to analysis the behaviour of piled raft in Bangkok subsoil. The model considers the dissipation of excess pore water pressure in saturated clays. Two different building sizes, i.e., low-rise (8-storey) and high-rise (25-storey) buildings with basements are considered in this study to evaluate the potential of using the piled raft system in Bangkok subsoil condition. The main factor to be investigated its influence is the level of raft under long-term condition.
2. PILED RAFT WITH CONSOLIDATION

The PRF is a complex design of foundation that combines the bearing effect of both foundation elements (piles and raft) [11]. In Bangkok subsoil condition the characteristics of soft soils are high compressibility, low shear strength and high water content.

The consolidation is a procedure by which soils decrease in volume. Generally, it is the process in which reduction in volume takes place by eviction of water under long term static loads. When the consolidation settlement occurs, the soil at the bottom of the raft are deformed. Therefore, the consolidation may have a strong influence on the load carried by raft, which consequently affect the load carried by piles. In this study, only the settlement due to consolidation is of interest. The value of incremental of consolidation settlement $\Delta S_{end}$ is defined as shown in Fig.1.

![Fig. 1 Concept of piled raft foundation with consolidation.](image)

Both, piles and raft are considered in the load distribution process:

$$P_{tot} = P_p + P_r$$  \hspace{1cm} (1)

where $P_{tot}$ = total load of the building; $P_p$ = load carried by the pile group; $P_r$ = load carried by the raft.

The bearing behaviour of the piled raft is commonly described by the piled raft coefficient or the load sharing ratio of piles $\alpha_{pr}$ which is defined by the ratio between the sum of load carried by pile and the total load of the building:

$$\alpha_{pr} = \frac{\sum R_{pile,i}}{R_{tot}}$$  \hspace{1cm} (2)

where $\alpha_{pr}$ = the load sharing ratio of piles; $\sum R_{pile,i}$ = the amount of the pile loads; $R_{tot}$ = total load of the structure. $\alpha_{PG}$ = the load sharing ratio of pile group.

For the pile group concept which does not take the advantage of raft into consideration, the $\alpha_{PG}$ is therefore equal 1 and defined in this study as

$$\alpha_{PG} = 1$$  \hspace{1cm} (3)

$$\alpha_{\Delta} = \alpha_{final} - \alpha_{initial}$$  \hspace{1cm} (4)

The effect of consolidation settlement is considered in load sharing ratio of pile. As mentioned previously $\alpha_{final}$ = the load sharing ratio of pile at end of settlement; $\alpha_{initial}$ = the load sharing ratio of pile before consolidation.

3. NUMERICAL MODELING OF PILED RAFT FOUNDATION ANALYSIS

3.1 Reference Case

A parametric study was considering 9 × 9 m, and 1 m thick raft with 9 piles. The low-rise (8-storey) and high-rise (25-storey) buildings with basements are considered in this study. Both Low-Rise-Piled Raft (LR-PR) and High Rise-Piled Raft (HR-PR) having identical characteristics as shown in Fig.2 (a) and 2 (b), respectively.

The pile foundation in this study was designed following the pile group concept with a safety factor (FS) of 2.3 for each single pile, which is the current design in engineering practice. The raft level is varied from 0 to 10 m below the ground level. The bored piles have 1 m diameter (d) being arranged in the foundation with the spacing of 3 m. The level of pile tip is at 23 (1st stiff clay layer) and 36 m (2nd sand layer) below the ground surface for low-rise and high-rise buildings, respectively. Summary of the analysis cases is shown in Table 1.

3.1.1 Applied Load

Uniformly Distributed Loads (UDL) is used in this analysis. The weight of the structure and designed load were computed.
These UDL are applied on top surface of the raft in analysis of PRF. The basement is considered to apply the load of 50 ton per level. The total applied loads on each foundation are listed in Table 1.

Table 1  Summary of piled raft foundation of numerical analysis conducted

<table>
<thead>
<tr>
<th>Building</th>
<th>Pile spacing</th>
<th>Pile tip level (m)</th>
<th>Raft level (m)</th>
<th>Total load (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-rise</td>
<td>3d*</td>
<td>23**</td>
<td>0</td>
<td>140</td>
</tr>
<tr>
<td>8-storey</td>
<td>4</td>
<td>146</td>
<td>8</td>
<td>152</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>158</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-rise</td>
<td>3d*</td>
<td>36**</td>
<td>0</td>
<td>350</td>
</tr>
<tr>
<td>25-storey</td>
<td>4</td>
<td>356</td>
<td>8</td>
<td>362</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>368</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* d (pile diameter): 1 m.
** f: floating pile in clay; e: end bearing in sand layer.

3.1.2 SUBSOIL CONDITION

The subsoil profile in this study are referred from that in the north of Bangkok. The generalized profiles of the stratified soil at the considered location are shown in Fig. 4 (a). The top 2.0 m thick layer is the weathered crust, -which is underlain by 6.0 m thick soft to medium clay layer. A medium clay layer is found at the depth of 8.0 m from the surface. Below the medium clay is stiff clay; the thickness is about 15m. The first sand layer is generally found at a depth of 25 to 30m. Below the upper first sand layer, there is stiff clay and further down alternating layers of dense sand and hard clay. The ground water table is below the ground surface at 1.5 m [14], [15]. The pore water pressure condition in Bangkok soft clay are hydrostatic from 1m below ground surface. Then the piezo-metric changed to drawdown near middle of clay layer as shown in Fig.4 (a) [22]. The piezo-metric drawdown pressure was considered in this study.
The geometry of the problem and FE mesh simulation of the piled raft foundation are shown in Fig.3 and Fig.4 (b). The 3D-FEA using PLAXIS 3D version 2013 was carried out in this study. A coupled mechanical and hydraulic model was used for the consolidation analysis. The 3D model included a rigorous treatment of the soil and raft which were represented by volume elements. The piles are modelled as embedded piles in which the pile is assumed to be a slender beam element. The boundary conditions adopted for analysis are displacement restraints with roller supports applied on all vertical sides and pin supports applied to the base of the mesh. The layer surface (upper and bottom side) is allowed to drain while the other sides are kept undrained by imposing closed consolidation boundary conditions.

### 3.2.1 Constitutive Models and Parameters

The soft clay, medium clay and first stiff clay layers were modelled with Hardening Soil Model with small strain [14]–[16]. The 1st-2nd sand, 2nd stiff clay and hard clay layers were modelled with Mohr–Coulomb model. The soil properties used in the analysis are mostly determined from comparing local investigated data with comprehensive in situ tests of MRT projects [17] and previous laboratory tests from Asian Institute of Technology (AIT) [18]–[20]. Table 2 summarizes the material parameters used in the analysis.

### Table 2
Constitutive models and model parameters used in analyses

<table>
<thead>
<tr>
<th>Material</th>
<th>Material behaviour</th>
<th>Model</th>
<th>$\gamma_1$ (kN/m$^3$)</th>
<th>$C_r$ (kPa)</th>
<th>$\phi$ (°)</th>
<th>$E_{s}E'$ (kPa)</th>
<th>$E_{ref}$ (kPa)</th>
<th>$G_{r}r_{eq}$ (kPa)</th>
<th>$k_{eq}$ (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weathered clay</td>
<td>Undrained</td>
<td>HSS</td>
<td>0.2</td>
<td>17</td>
<td>40</td>
<td>6000</td>
<td>7000</td>
<td>32380</td>
<td>8954</td>
</tr>
<tr>
<td>Soft clay</td>
<td>Undrained</td>
<td>HSS</td>
<td>8-10</td>
<td>19</td>
<td>0</td>
<td>23</td>
<td>10300</td>
<td>39090</td>
<td>22380</td>
</tr>
<tr>
<td>Medium clay</td>
<td>Undrained</td>
<td>HSS</td>
<td>10-25</td>
<td>23</td>
<td>0</td>
<td>26</td>
<td>25400</td>
<td>83900</td>
<td>32270</td>
</tr>
<tr>
<td>1st stff clay</td>
<td>Undrained</td>
<td>MCM</td>
<td>1</td>
<td>25-28</td>
<td>20</td>
<td>36</td>
<td>85800</td>
<td>1.6</td>
<td>0.3</td>
</tr>
<tr>
<td>2nd stff clay</td>
<td>Undrained</td>
<td>MCM</td>
<td>28-35</td>
<td>192</td>
<td>20</td>
<td>37</td>
<td>96000</td>
<td>2.5 x 10$^5$</td>
<td>0.3</td>
</tr>
<tr>
<td>Hard clay</td>
<td>Undrained</td>
<td>MCM</td>
<td>35-46</td>
<td>223</td>
<td>20</td>
<td>111500</td>
<td>2.5 x 10$^5$</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subsoil</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weathered clay</td>
<td>0.2</td>
</tr>
<tr>
<td>Soft clay</td>
<td>8-10</td>
</tr>
<tr>
<td>Medium clay</td>
<td>10-25</td>
</tr>
<tr>
<td>1st stff clay</td>
<td>1</td>
</tr>
<tr>
<td>2nd stff clay</td>
<td>28-35</td>
</tr>
<tr>
<td>Hard clay</td>
<td>46-60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Foundation</th>
<th>Model</th>
<th>Depth (m)</th>
<th>General characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bored Pile</td>
<td>LEM</td>
<td>6-8</td>
<td>Non-porous</td>
</tr>
<tr>
<td>Raft</td>
<td>LEM</td>
<td>24</td>
<td>Non-porous</td>
</tr>
</tbody>
</table>

### 4. COMPUTED RESULTS

#### 4.1 Effect of the Load Sharing Ratio of Piles against Time with Differential Raft Level

Fig.5 shows the load sharing ratio of piles for different raft levels below the ground surface and time for both building types. The analysis results show that when the raft was placed on deeper soil layer, the load sharing ratio of pile has been decreased significantly. For subsoil condition and problem characteristics in this study, before consolidation, the load sharing ratio of pile reduces from 95% to 80% and 98% to 91% with increasing raft levels (0-10 m.) for the low-rise and high-rise buildings, respectively.

At the end of consolidation, the load sharing ratio of pile increases 2% to 12% and 1% to 6% with increasing raft levels (0-10 m.) for the low-rise and high-rise buildings respectively. Significant changes of load sharing by raft are obviously observed. This leads to the long-term load sharing by piles of 92% to 98% and 97% to 99% for the low-rise and high-rise buildings respectively. This means that the consolidation has a strong influence on the load carried by piles of the PRF in Bangkok subsoil.

HSS: Hardening Soil model with small strain; MCM: Mohr-Coulomb model; LEM: Linear Elastic Model
increase from 8.6 to 10.4 mm, with increasing $\alpha_A$ from 3% to 12% when increasing raft (0-10 m). For the case of high-rise building, the $\Delta S_{end}$ increase from 8.6 to 10.4 mm, with increasing $\alpha_A$ from 1% to 6.5% with increasing raft level.

5. CONCLUSION

This article presents the results of numerical analysis of the PRF in the subsoil condition of north Bangkok, using 3-D FEM to investigate the effect of raft level on load shared by piles in Bangkok subsoil condition and paying special attention to the consolidation effect.

Fig. 7 Incremental settlement at end of consolidation $\Delta S_{end}$ versus the load sharing ratio of, $\alpha_A$

The analysis result in terms of load shared by piles with consolidation effect for the PRF case in this study in Bangkok subsoil condition can be summarized as follows:

- The consolidation had a strong influence on the load carried by piles of piled raft foundation in Bangkok. The load shared by piles can increase by up to 12% and 6% for low rise and high-rise buildings, respectively. Therefore, the design of the piled raft foundation system in Bangkok subsoil should consider the consolidation.

- The incremental consolidation settlement $\Delta S_{end}$ has significant influence on the incremental load sharing ratio of piles $\alpha_A$. The incremental load sharing ratio of pile in consolidation process ($\alpha_A$) increase with increasing incremental consolidation settlement $\Delta S_{end}$.

Since the pile foundation was designed using the pile group concept with high FS. The raft is not

Fig. 6 Variation of load sharing ratio of piles versus raft level of different building types

Fig. 5 Load sharing ratio of piles ($\alpha_{ap}$) versus Time and raft level of different building types
considered in the design of which the FS of the pile can be smaller. Higher efficiency of the system can be expected. Further study with less FS of pile should be done, to confirm effectiveness of PRF.

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7. REFERENCES


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