PILED RAFT

by

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✓ As compared to a full pile solution, pile assisted raft has a major advantage of substantial reduction in number of piles, which in turn results in savings of cost and time.

✓ It also to some extent removes uncertainties associated with bored piles and driven cast in-situ piles.
Design Philosophy of Piled Rafts

Conventional Pile Design Method
- Disregards the capacity of Pile caps/Rafts
- Increased number of piles or length of piles
- Very small allowable settlement
- Pile factor of safety (FS ≈ 2)

Piled Raft Design Method
- Raft is the main bearing element
- Design for full utilization of pile capacity (FS ≥ 1)
- Piles are Settlement reducers
- Consideration of the optimal location of piles to
decrease the differential settlement and bending moment of raft.

Concept of Piled Raft:

- A very good reference

Fig. 1 Load settlement curves for piles and Raft on cohesion-less soils (sands & non plastic silts)

Schematic Model of Burj Dubai

- World’s tallest building.
- 160 storey high rise tower.
Steps involved in Piled Raft Design

Step 1:
The safe bearing capacity of raft from shear consideration is checked so that raft can transfer the load to soil without failure. The settlement criterion is also checked. Commonly the safe bearing capacity (SBC) of raft on cohesionless soils (sands and non-plastic silts) is very high.

- For Raft size 20 m x 20 m, SBC will be in the range of 75 to 125 t/m²

Step 2:
The settlements of raft are calculated assuming first that there are no piles. If the settlements are < 75 mm, then a raft foundation will suffice.

Step 3:
If the settlements are > 75 mm, then piles are provided to act as settlement reducers. The number of piles is estimated so that the settlements of the piled raft foundation system are less than 75 mm. The ultimate capacity of the pile is used in design.
Steps involved in Piled Raft Design

Step 4:

➢ The load shared by the piles and the raft are estimated.

The load coming on the raft will be shared by raft (directly transferring to soil layer below) and the piles (transferring the load to soil through skin friction and end bearing). The load sharing depends on relative stiffness of piles and soil support to the raft.

Step 5: The settlements due to load on piles are estimated
Step 6:
The settlements of the raft due to the load shared by the raft are estimated.

Total settlement of the piled raft = Raft contribution + Pile contribution

This should be < 75 mm for cohesionless soils

< 100 mm for cohesive soils

Subgrade modulus of raft \((k)\) = \(\frac{\text{Gross bearing pressure on Raft}^{***}}{\text{Total raft settlement (Without piles)}}\)

*** More appropriate would be to use net bearing pressure. But in the structural Analysis of the raft gross bearing pressure (actual loading from superstructure) is used.

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Current Practice Method 1

Plate Load Test

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**Recommended values in literature**

Most often used reference is *Foundation Analysis and Design* book by Joseph E Bowles

<table>
<thead>
<tr>
<th>Soil</th>
<th>$E_s$ (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (Normally consolidated)</td>
<td>500(N+15)</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>300 (N+6)</td>
</tr>
<tr>
<td>Clayey sand</td>
<td>320 (N+15)</td>
</tr>
</tbody>
</table>
Realistic estimation of subgrade modulus:

- Estimate settlements considering all soil layers up to 1.5 times the actual raft width.
- Calculate the k value as ratio of actual bearing on the raft to the calculated settlement.
- Structural designer to use this value for structural design of the raft.

Structural analysis of the Piled Raft:

Pu – Pile Ultimate Capacity

Pile Spring (Ps) up to 4 to 6 cm settlement, $Ps = (Ps / 4$ to 6) in kg/cm.

If the settlements exceeds 4 to 6 cm, replace springs with Pu.
Drawbacks of Current Practice:

- In a plate load test, dimensions of the plate are much smaller than actual raft size.

- Hence k value obtained from plate load test does not take into account settlement contribution of all the soil layers up to 1.5 times width of the raft.

- This may lead to over estimation of subgrade modulus leading to under-design of the raft (unsafe).

- For eg. for a raft size 30 x 60 m, thickness = 2.5 m, analysis was done for 2 cases with \( k = 1 \text{ kg/cm}^3 \) and \( k = 0.5 \text{ kg/cm}^3 \). In the 2nd case, moments were higher by 20%, resulting in 20% higher reinforcement steel or 10% thicker raft.

Predicting the Settlements on cohesionless soils

\[
S = H \left( \frac{\Delta \sigma_z}{E_s} \right)
\]

- \( S \) = Settlement
- \( H \) = Thickness of the layer
- \( \Delta \sigma_z \) = Pressure increase @ middle of the layer (obtained from stress distribution curves)
- \( E_s \) = Soil Modulus

\( E_s \) is determined by correlating

- (a) With SPT N value
- (b) Static cone penetration value
- (c) Footing / Plate load test (at shallow depth only)
Soil Modulus (Es) Vs SPT N
After Schultze and Muhs:

- This curve gives relation only up to a N value of 50.
- For N > 50, we used the following procedure:
  - Linear extrapolation of slope between N = 40 and 50
  - \( Es = (Es \text{ for } N = 50) + [(N - 50) \times 87.5] \) in t/m²
  - I have been using this graph for last 40 years
  - For N = 40, \( E_s = 730 \text{ kgf/cm}^2 \)

Soil Modulus (Es or Ev) Vs SPT N
As per IS – 8009, 1976 (Reaffirmed 1998):

- This curve gives relation only up to a N value of 60.
- For \( N = 40 \) and \( P_0 = 0 \), Ev is 800 kgf/cm²
- For \( N = 40 \) and \( P_0 = 1.5 \text{ kgf/cm}^2 \), Ev is 400 kgf/cm² (For ~ 10 m of soil)

(Remarks: The reduction in Ev value with overburden pressure is difficult to explain.)
Predicting the settlements on cohesionless soils

As per IS – 8009, Part 1, 1976 (Reaffirmed1998):

(a). Method based on standard penetration test (SPT):

- The observed SPT N values are first corrected for overburden and dilatancy.
- The average of the corrected SPT N values between the level of the base of the foundation and a depth equal to 1.5 to 2 times the width of foundation below the base is calculated.
- Settlement of a footing of width B under unit intensity of pressure can be read from Fig. 9.

- One can read settlements per unit pressure as a function of width of footing and N values.
- Curves become asymptotic after a width of 3 to 4 m.
- This cannot certainly be applied for bigger rafts.
Determination of Soil Modulus (Es)

Based on plate load tests (As per IS – 2950, Part 1, 1981 (Reaffirmed 1998):

\[ E_s = q B \left( \frac{1-\mu^2}{s} \right) I_w \]

- \( E_s \) = Modulus of elasticity (Soil modulus)
- \( q \) = Intensity of contact pressure
- \( B \) = Least lateral dimension of test plate
- \( S \) = Settlement
- \( \mu \) = Poisson’s ratio
- \( I_w \) = Influence factor, = 0.82 for a square plate

Field determination of Es based on footing load test conducted at “Delhi International Airport (DIAL)”:

1st Footing load test:

Soil type = Sandy silt
SPT N = 50
Size of footing = 1.5 m x 1.5 m
For \( q = 40 \text{ t/m}^2 \) = 4 Kg/cm²,
Settlement (S) = 4 mm

\[ E_s = 4 \times 150 \left( \frac{1-0.3^2}{0.4} \right) \times 0.82 \]

= 1119 Kg/cm²

As per Shultze and Muhs for SPT N = 50
Es = 800 Kg/cm²

Ratio = 1119/800 = 1.4
Results from DIAL Project:
2\textsuperscript{nd} Footing load test:
Type of soil = Clayey silt with fine sand
SPT N = 22
Size of footing = 1.5 m x 1.5 m
q = 38 t/m\textsuperscript{2} = 3.8 Kg/cm\textsuperscript{2}
Settlement (S) = 5.4 mm

\[ E_s = 3.8 \times 150 \left( \frac{1-0.32^2}{0.54} \right) \times 0.82 \]
\[ = 787 \text{ Kg/cm}\textsuperscript{2} \]

As per Shultz and Muhs for SPT N = 22
Es = 530 Kg/cm\textsuperscript{2}
Ratio = \frac{787}{530} = 1.48

<table>
<thead>
<tr>
<th>S. No</th>
<th>SPT N</th>
<th>Es as per Bowles book</th>
<th>Es as per IS Code</th>
<th>Es as per Schultze and Muhs</th>
<th>From Footing Load test at DIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>325</td>
<td>820***</td>
<td>800</td>
<td>1119</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>185</td>
<td>710***</td>
<td>530</td>
<td>787</td>
</tr>
</tbody>
</table>

Note: All Es values are in kg/cm\textsuperscript{2} (multiply by 100 for Kpa)
Es values calculated from Bowles book are for corrected N values.
***However, for the same N value at a depth of 8 m, the Es value would be only 400 kg/cm\textsuperscript{2} as per IS.

+++ However, for the same N value at a depth of 8 m, the Es value would be only 320 kg/cm\textsuperscript{2} as per IS.
Permissible settlements:

**As per IS – 1904, 1986 (Reaffirmed 1995):**

For spread foundation resting on Sand and Hard clay

<table>
<thead>
<tr>
<th>Type of structure</th>
<th>Maximum settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Isolated foundation</td>
</tr>
<tr>
<td>For reinforced concrete structures</td>
<td>50</td>
</tr>
</tbody>
</table>

Details of piled raft foundation of the buildings in Germany (Katzenbach, et al., 2000)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Messe Torhaus</th>
<th>Messeturm</th>
<th>DG-Bank (Westendstrasse 1)</th>
<th>American Express</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Height above ground surface (m)</td>
<td>130</td>
<td>256.5</td>
<td>208</td>
<td>74.7</td>
</tr>
<tr>
<td>Basement floors</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Foundation area (m²)</td>
<td>2 x 430</td>
<td>3457</td>
<td>2940</td>
<td>3570</td>
</tr>
<tr>
<td>Foundation level below GL (m)</td>
<td>-3</td>
<td>-14</td>
<td>-12.0/-14.0</td>
<td>-14</td>
</tr>
<tr>
<td>Raft thickness (m)</td>
<td>2.5</td>
<td>3.0-6.0</td>
<td>3.0-4.5</td>
<td>2</td>
</tr>
<tr>
<td>Number of piles</td>
<td>2 x 42</td>
<td>64</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>Observed pile load (MN)</td>
<td>1.7-6.9</td>
<td>5.8-20.1</td>
<td>9.2-14.9</td>
<td>2.7-5.1</td>
</tr>
<tr>
<td>Observed Max. settlements (mm)</td>
<td>150</td>
<td>144</td>
<td>110</td>
<td>55</td>
</tr>
</tbody>
</table>
Settlement of the piled raft foundation of the Burj Dubai:

- 160 storey high rise tower
- Founded on 3.7 m thick raft supported on bored piles (1.5 m diameter, 50 m long).
- Estimated total settlement is 45 mm to 75 mm.
- Settlements under dead load (February 2008) 43 mm.
- Extrapolated to full load is 55 mm to 60 mm
- Predicted final settlement is 70 to 75 mm
**Examples in Delhi Region – Settlements of Rafts**

1. **DIAL – Terminal 3 on Raft**
   - Settlements measured and reported as not significant.

2. **Sector 58, Gurgaon**
   - **Structure**: Residential building 2B+30 floor on Raft.
     - Frame completed
   - Dead load settlements = 26 mm
   - Estimated total settlement = 40 mm

- Settlements observations are being carried out for about 6 structures
- One structure in Noida is fully instrumented, where load on the piles, reactions of the base raft and the settlements are being measured.
- For one more structure in Noida, pile loads and settlements are planned to be observed.
We need number of settlement observations:

Method:

- Any precision leveling will be O.K
- Fix plates on the floor or to the columns (basement is ideal), ground floor level is also adequate.

Execution: The following points are crucial in particular for Rafts and Pile assisted rafts:

1. Flooding of the excavation from surface water during monsoon to be avoided. This can be done by proper bunding and sand bagging around the excavation and providing surface drainage away from the excavation.
2. The last 50cm of the excavation should be done just prior to placement of the mud mat.
3. The excavated surface should be thoroughly compacted:
   - For Rafts: Heavy duty vibratory roller or plate vibrator
   - For Pile assisted Rafts: Heavy duty plate vibrator which passes in between the piles

4. Flooding should not be used for compaction.

5. For dust control, if required water sprinkling can be done.

6. Desirable to place 125 mm thick soling stones on the compacted surface. The soling stones should be well compacted.

7. The mud mat for the raft will come on the soling stones.

In case of high Ground Water Table (GWT):

1. Prior to the excavation, GWT has to be lowered to 1 m below the bottom of the excavation. This level has to be maintained till the foundations are cast.

2. The ground water lowering has to be done by a specialist contractor. This is especially difficult in case of Silts, Sandy silts and Silty sands.

3. There must be 100 % standby power for the dewatering system to ensure that the GWT is below the bottom of the excavation at all times.
## PROJECTS NEAR DELHI:

<table>
<thead>
<tr>
<th>Sector</th>
<th>Area</th>
<th>Number of storeys</th>
<th>Ground Water Table (m)</th>
<th>Foundation Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>103</td>
<td>Gurgaon</td>
<td>1B + S + 14</td>
<td>2</td>
<td>Raft Foundations</td>
</tr>
<tr>
<td>68</td>
<td>Gurgaon</td>
<td>1B + G+ 13 to 25</td>
<td>21</td>
<td>Raft Foundations</td>
</tr>
<tr>
<td>86</td>
<td>Gurgaon</td>
<td>1B + G+ 13 to 17</td>
<td>28</td>
<td>Raft Foundations</td>
</tr>
<tr>
<td>16 B</td>
<td>Gurgaon</td>
<td>3B + G+ 17 to 39</td>
<td>11</td>
<td>Pile Assisted Raft, Raft Foundations</td>
</tr>
<tr>
<td>67</td>
<td>Gurgaon</td>
<td>2B + G+ 18 to 33</td>
<td>20</td>
<td>Raft Foundations</td>
</tr>
<tr>
<td>62</td>
<td>Gurgaon</td>
<td>3B + G+ 29 to 37</td>
<td>8</td>
<td>Pile Assisted Raft Foundations</td>
</tr>
<tr>
<td>102</td>
<td>Gurgaon</td>
<td>1B + G+ 26</td>
<td>1.5</td>
<td>Pile Foundations</td>
</tr>
<tr>
<td>128</td>
<td>Noida</td>
<td>2B + G+ 35 to 38</td>
<td>8</td>
<td>Pile Assisted Raft Foundations</td>
</tr>
</tbody>
</table>

Contd... 37

<table>
<thead>
<tr>
<th>Sector</th>
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<th>Number of storeys</th>
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<th>Foundation Recommendations</th>
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</thead>
<tbody>
<tr>
<td>16</td>
<td>Noida</td>
<td>G + 22 to 34</td>
<td>18</td>
<td>Pile Assisted Raft, Raft Foundations</td>
</tr>
<tr>
<td>Gwalpahari</td>
<td>Gurgaon</td>
<td>3B + G+ 17</td>
<td>21</td>
<td>Raft Foundations</td>
</tr>
<tr>
<td>48</td>
<td>Gurgaon</td>
<td>2B + G+ 34</td>
<td>21</td>
<td>Pile Assisted Raft Foundations</td>
</tr>
<tr>
<td>58</td>
<td>Gurgaon</td>
<td>2B + G+ 23 to 30</td>
<td>7</td>
<td>Raft Foundations</td>
</tr>
<tr>
<td>Gwalpahari</td>
<td>Gurgaon</td>
<td>2B + G+ 28</td>
<td>Not met</td>
<td>Raft Foundations</td>
</tr>
</tbody>
</table>

Contd... 38
The take aways from this presentation:

✓ Piled raft is very effective and economic solution in most situations for high rise towers and heavily loaded structures.

✓ Reduction in number of piles being between 50 to 75% resulting in savings of cost and time.

✓ We need to improve on estimation of soil moduli in case of cohesion-less soils and over consolidated clays.

✓ We should carry out many systematic settlement observations on all types of structures to improve our predictions.

✓ Lastly and most importantly, our geo-technical investigation practices have to reach global standards at the earliest.

ACKNOWLEDGEMENT:

We wish to express our sincere thanks to:


✓ L&T Construction team at DIAL for carrying out the tests and sharing the information.

Contd...
Katzenbach R, Arslan V and Moorman ch (2000 b), piled raft foundation
Projects in Germany, Design application of raft foundations, Ed,
by J.A. Hersley Telford Ltd. PP 323-391

All our Clients and many others who are in the process of executing the foundations based on our recommendations and also monitor the settlements.

THANK YOU