Design of Post-Tensioned Raft and Piled Raft Foundation in the Amazon Region

Fábio Albino de Souza
Civil Engineer - CEO EBPX – Escritório Brasileiro de Protensão
Master of Science – State University of Campinas
fabio@ebpx.com.br
About Brazil

Demographic Census 2010
Total Resident Population = 190,732,694
Territorial Area = 8,515,767 km²

Capital = Brasília – DF
Official Currency = Real (R$)
1 US$ ~ 2.22 R$

Minimum wage
2010 ~ US$ 292
2013 ~ US$ 335
2014 ~ US$ 323

Official Language = Portuguese

Population
51% Female
49% Male
84.4% - Urban
15.6% - Rural
About the state of Amazonas

Demographic Census 2010
Population = 3,807,923
Total Area = 1,559,159 Km²
Capital = Manaus

Populational Density = 2.44 inhabitants/Km²

Native Indigenous Population = 4.8%

Holds 98% of preserved forest cover and one of the planet’s greatest fresh water reservoirs.

Housing Deficit = 10.4%
About Manaus

Demographic Census 2010

52% of the State of Amazon’s population live in Manaus.

Populational Density = 158.06 inhabitants/Km²

Number of households with monthly per capita income greater than 5 minimum wages range from 8.01% to 23.44%.

6th richest city in Brazil and its only Free Trade Zone.

One of the greatest industrial areas in the country.
What we have been doing

Minha Casa
Minha Vida

In English:
My Home
My Life

Brazilian Government Dwelling Program: started in March 2009, subsiding low-cost houses and apartments for lower-class families to build one million homes at an estimated total cost of about R$ 34 Bi ~ US$ 17 Bi.
About PT – Market in Brazil

Average Monthly Market – Unbonded Tendons (Ton)

<table>
<thead>
<tr>
<th>Year</th>
<th>Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>682</td>
</tr>
<tr>
<td>2011</td>
<td>853</td>
</tr>
<tr>
<td>2012</td>
<td>997</td>
</tr>
<tr>
<td>2013</td>
<td>1,395</td>
</tr>
</tbody>
</table>

1 year = 16,740 ton
## About PT – Market in Brazil

### Representative cost of one ton of material USD

<table>
<thead>
<tr>
<th></th>
<th>Swiss</th>
<th>USA</th>
<th>Colombia</th>
<th>Brazil</th>
<th>Mexico</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tendon</strong></td>
<td>11,100</td>
<td>2200</td>
<td>1700</td>
<td>2250</td>
<td>1350</td>
</tr>
<tr>
<td><strong>Rebar</strong></td>
<td>1,550</td>
<td>1000</td>
<td>900</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Ratio</strong></td>
<td>7.2</td>
<td>2.2</td>
<td>1.9</td>
<td>1.5</td>
<td>1.35</td>
</tr>
</tbody>
</table>

We have a good potential to grow.
What we have been doing

Some successful experiences in Brazil - slab-on-ground or mat/raft foundations:

Bank of Brazil Building in São Paulo in the 1950s.

Hotel Le Méridien Copacabana opened in 1975 in the city of Rio de Janeiro. The building has forty floors.

Residential Building in Fortaleza in August 1999. The building has fourteen floors.
Case Study

Some of the project’s features:

Project = 9 blocks with 4 floors each
Each Apartment Building = 1,440 m²
Total Height of Each Block = 14 m
Type of Construction = Structural Masonry (Concrete)
Location: Manaus
State: Amazonas
Country: Brazil
Case Study

Some of the project’s features:

Photo of the construction site

Land Area = 17,000 m²
Case Study

Some of the project´s features:

Soil Investigation

Two points for each block

SPT (Standard Penetration Test)
CBR Test
Liquid Limit
Plastic Limit
Plasticity Index
Soil Classification

Before Earthwork

After Earthwork
Case Study

Some of the project’s features:

Soil Investigation

SPT – Standard Penetration Test

Water level

Soil - Standard Penetration Test - SPT
Case Study

Some of the project’s features:

Soil Investigation

CBR Test

Analysis depth = 0.80 – 2.10 m

CBR (2.54mm) = 11.02%

Expansion = 0.36%
Case Study

Some of the project’s features:

Soil Investigation

Analysis depth = 0.80 – 2.10 m

Soil Classification

% Gravel = 2%
% Sand = 67%
% Mo (Silt) = 5%
% Clay = 26%

ASTM Soil Classification System = SC
AASHTO Soil Classification = A-2-6
Case Study

Some of the project’s features:

Soil Investigation
Analysis depth = 0.80 – 2.10 m

Liquid Limit = 36.75%
Plastic Limit = 19.72%
Plasticity Index = 17.03%
Case Study

Some of the project’s features:

**Soil Investigation**

- Liquid Limit = 36.75%
- Plastic Limit = 19.72%
- Plasticity Index = 17.03%

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### Soil expansivity prediction by liquid limit

<table>
<thead>
<tr>
<th>Degree of expansion</th>
<th>Chen$^6$</th>
<th>IS 1498$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt;30</td>
<td>20–35</td>
</tr>
<tr>
<td>Medium</td>
<td>30–40</td>
<td>35–50</td>
</tr>
<tr>
<td>High</td>
<td>40–60</td>
<td>50–70</td>
</tr>
<tr>
<td>Very high</td>
<td>&gt;60</td>
<td>70–90</td>
</tr>
</tbody>
</table>

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### Soil expansivity predicted by plasticity index

<table>
<thead>
<tr>
<th>Degree of expansion</th>
<th>$I_p$: %</th>
<th>Chen$^6$</th>
<th>Holtz and Gibbs$^{10}$</th>
<th>IS 1498$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt;20</td>
<td>0–15</td>
<td>0–15</td>
<td>&lt;12</td>
</tr>
<tr>
<td>Medium</td>
<td>12–34</td>
<td>10–35</td>
<td>10–35</td>
<td>12–23</td>
</tr>
<tr>
<td>High</td>
<td>23–45</td>
<td>20–55</td>
<td>20–55</td>
<td>23–32</td>
</tr>
<tr>
<td>Very high</td>
<td>&gt;32</td>
<td>&gt;35</td>
<td>&gt;35</td>
<td>&gt;32</td>
</tr>
</tbody>
</table>

Case Study

Some of the project’s features:

Soil Investigation

Expansive soils: main occurrences in Brazil

New Discovered Area (Manaus)


Areas of sedimentary rocks with montmorillonites potentially subjected to expansion.
Case Study

Some of the project’s features:

Soil Investigation

Earthworks project established a level where this layer of expansive soil was removed. So the project was conceived in non-expansive soil after all.

Natural Topography of the Land (Contour Levels)

Level Design
Case Study

Some of the project’s features:
Design of Post-Tensioned Raft and Piled Raft Foundation

FEM – Finite Element Method

ADAPT
Structural Concrete Software

EDGE + MAT
Case Study

Some of the project’s features:

Design of Post-Tensioned Raft and Piled Raft Foundation

FEM – Finite Element Method
Shell Element
Cell Size = 0.50 meters
Maximum Distance = 0.50 meters
Case Study

Some of the project’s features:

Design of Post-Tensioned Raft and Piled Raft Foundation

FEM – Finite Element Method
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Cell Size = 0.50 meters
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Case Study

Some of the project’s features:

Design of Post-Tensioned Raft and Piled Raft Foundation

04 – Blocks with Piled Raft Foundation
05 – Blocks with Raft Foundation
Case Study

Some of the project’s features:
Design of Post-Tensioned Raft and Piled Raft Foundation

- Slab Thickness = 18 cm
- Slab Thickness = 22 cm
- Edge Beams = 20 cm x 40 cm
- 05 Blocks with Raft Foundation
Case Study

Some of the project’s features:
Design of Post-Tensioned Raft and Piled Raft Foundation

04 Blocks with Piled Raft Foundation

Slab Thickness = 22 cm

Slab Thickness = 18 cm

Edge Beams = 20 cm x 40 cm

And the length of the piles foundation ??? The piles foundation require much attention!!!
Case Study

Some of the project’s features:
Design of Post-Tensioned Raft and Piled Raft Foundation

- Design of Post-Tensioned Raft and Piled Raft Foundation
- Settlement by the soil
- Maximum Allowable Load of the Pile Foundation
- Aoki-Velloso Method – One of the main methods applied in Brazil.

Settlement by the soil
Settlement by the elastic shortening
Total Settlement

Type of the Pile Foundation: = Auger Piles

Maximum Allowable Load of the Pile Foundation
Aoki-Velloso Method – One of the main methods applied in Brazil.
Case Study

Some of the project’s features:

- Design of Post-Tensioned Raft and Piled Raft Foundation
- Safety Factor $= 73/39.5$
- Safety Factor $= 1.85$
- Recommends the safety factor greater than 1.5 for the group of piles.

Then OK!!
Case Study

Some of the project’s features:
Design of Post-Tensioned Raft and Piled Raft Foundation

Stages of implementation of the pile (Auger Pile)

1. Preparation of site
2. Drilling of holes
3. Placement of reinforcement
4. Curing of concrete
Case Study

Some of the project’s features:
Design of Post-Tensioned Raft and Piled Raft Foundation

The Brazilian Standard NBR6122 recommends 1% of the executed piles to be trialed.
Case Study

Some of the project’s features:

Results

Post-Tensioned Piled Raft Foundation

All loads are transmitted only to the piles.

<table>
<thead>
<tr>
<th>Load Combination</th>
<th>Minimum Displacement (mm)</th>
<th>Maximum Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service</td>
<td>0.17</td>
<td>3.24</td>
</tr>
<tr>
<td>Strength</td>
<td>0.43</td>
<td>4.55</td>
</tr>
<tr>
<td>Initial</td>
<td>0.00</td>
<td>0.89</td>
</tr>
</tbody>
</table>
Case Study

Some of the project’s features:

Results

Reinforced Piled Raft Foundation

All loads are transmitted only to the piles.

<table>
<thead>
<tr>
<th>Load Combination</th>
<th>Minimum Displacement (mm)</th>
<th>Maximum Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service (TL)</td>
<td>0.17</td>
<td>3.84</td>
</tr>
<tr>
<td>Strength (DLO)</td>
<td>0.24</td>
<td>5.37</td>
</tr>
<tr>
<td>Cracked Sustained Load</td>
<td>0.17</td>
<td>4.05</td>
</tr>
</tbody>
</table>
Case Study

Some of the project’s features:

Results

Reinforced Piled Raft Foundation

Reduced Rotational Stiffness About XX and YY
### Case Study

**Some of the project’s features:**

<table>
<thead>
<tr>
<th>Design Reference</th>
<th>SOG Area (m³)</th>
<th>SOG Volume (m³)</th>
<th>Weight Rebar (kg)</th>
<th>Weight Tendon (kg)</th>
<th>Rate Rebar (kg/m³)</th>
<th>Rate Tendon (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced Concrete</td>
<td>432.86</td>
<td>99.68</td>
<td>4,250</td>
<td>--------</td>
<td>42.64</td>
<td>--------</td>
</tr>
<tr>
<td>Post-Tensioned + Reinforced Concrete</td>
<td>432.86</td>
<td>99.68</td>
<td>1,790</td>
<td>1,207</td>
<td>17.95</td>
<td>12.11</td>
</tr>
</tbody>
</table>
Case Study

Some of the project’s features:

Design of Post-Tensioned Raft and Piled Raft Foundation

Piled Raft Foundation
Preliminary Design – Reinforced Concrete
Case Study

Some of the project’s features:

Results

Post-Tensioned Raft Foundation

Allowable Soil Bearing = 0.17 Mpa (1.7 kgf/cm²)
Modulus of soil reaction = 2.00 – 3.00 kgf/cm³

<table>
<thead>
<tr>
<th>Load Combination</th>
<th>Minimum Displacement (mm)</th>
<th>Maximum Displacement (mm)</th>
<th>Minimum Soil Pressure - MPa</th>
<th>Maximum Soil Pressure - MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service</td>
<td>0.04</td>
<td>3.18</td>
<td>0.007</td>
<td>0.09</td>
</tr>
<tr>
<td>Strength</td>
<td>0.30</td>
<td>4.43</td>
<td>0.01</td>
<td>0.13</td>
</tr>
<tr>
<td>Initial</td>
<td>0.02</td>
<td>0.60</td>
<td>0.001</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Case Study

Some of the project's features:

Results
Post-Tensioned Raft Foundation
Top and Bottom Stresses with Allowable Values

Calculated Stress
Allowable Stress
Case Study

Some of the project’s features:

Design of Post-Tensioned Raft and Piled Raft Foundation

Raft Foundation
Preliminary Design – Post-Tensioned
Case Study

Some of the project’s features:

Results

Reinforced Raft Foundation

![Diagram of reinforced raft foundation]

Allowable Soil Bearing = 0.17 Mpa (1.7 kgf/cm²)
Modulus of soil reaction = 2.00 – 3.00 kgf/cm³

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<td>3.93</td>
<td>0.01</td>
<td>0.12</td>
</tr>
<tr>
<td>Strength (DLO)</td>
<td>0.12</td>
<td>5.50</td>
<td>0.02</td>
<td>0.17</td>
</tr>
<tr>
<td>Cracked Sustained Load</td>
<td>0.09</td>
<td>4.54</td>
<td>0.01</td>
<td>0.14</td>
</tr>
</tbody>
</table>
Case Study

Some of the project´s features:

Results

Reinforced Raft Foundation

Reduced Rotational Stiffness About XX and YY
Case Study

Some of the project’s features:
Design of Post-Tensioned Raft and Piled Raft Foundation

Raft Foundation
Preliminary Design
Reinforced Concrete
Case Study

Some of the project’s features:

Summary

<table>
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<tr>
<th>Design Reference</th>
<th>SOG Area (m³)</th>
<th>SOG Volume (m³)</th>
<th>Weight Rebar (kg)</th>
<th>Weight Tendon (kg)</th>
<th>Rate Rebar (kg/m³)</th>
<th>Rate Tendon (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforced Concrete</td>
<td>432.86</td>
<td>99.68</td>
<td>4,404</td>
<td>------------------</td>
<td>44.19</td>
<td>------------------</td>
</tr>
<tr>
<td>Post-Tensioned + Reinforced Concrete</td>
<td>432.86</td>
<td>99.68</td>
<td>1,402</td>
<td>1,216</td>
<td>14.07</td>
<td>12.20</td>
</tr>
</tbody>
</table>
Case Study

Conclusion – Raft Foundation

The summary data are very interesting and deserve the following comments.

1-. In Brazil the ratio of tendon cost $\times$ rebar cost is 1.5 and it is a competitive value.

2-) Calculating it we have $1,216 \times 1.5 = 1,824 + 1,402 = 3,227$ kg – Steel. The economy of using post tensioned slab-on-ground is $(4,404 - 3,227) = 1,177$ kg – Steel/slab-on-ground.

3-) 26.7% would be saved.

4-) It is noticed that in this case almost 2 full foundations could be saved which would result in much higher profit. When we overlook at all the work involved in these two foundations that could be saved the benefits are much better.
Case Study

Conclusion – Piled Raft Foundation

The summary data are very interesting and deserve the following comments.

1. In Brazil the ratio of tendon cost x rebar cost is 1.5 and it is a competitive value.

2-) Calculating it we have 1,207*1.5 = 1,810 +1,790 = 3,600 kg – Steel. The economy of using post tensioned slab-on-ground is (4,250 – 3,600) = 650 kg – Steel/ slab-on-ground.

3-) 15.3% would be saved.

4-) It is noticed that in this case almost 1 full foundations could be saved.
Case Study

Conclusion

The summary data are very interesting and deserve the following comments.

Almost 3 full foundations could be saved.

USD 25,000 saved.
TIKUNA´S TOWER – MANAUS

Post-Tensioned Raft Foundation

Some of the project´s features:

- 36 Floor Stories
- 112 meters high
- 14,100 m²
- Coefficient Gamma Z (Brazilian Parameter)
  - Gamma Z (X) = 1.18
  - Gamma Z (Y) = 1.11
- P-Delta
  - Wind (X) = 13.49%
  - Wind (Y) = 7.95%
TIKUNA´S TOWER – MANAUS

Some of the project’s features:

- Column with maximum load = 28,450 kN
- Horizontal Displacement
- Displacement X = 3.70 cm
- Displacement Y = 2.60 cm
- Total Auger Piles = 121
- External Ring (outer) = 80 cm -> 18 meters
- Internal Ring (inner) = 90 cm – 100 cm -> 25 meters
- Slab Thickness = 2.50 meters
Questions and /or Comments
Thank you !!!