Piling Foundations
General Aspects of the Worldwide State of Art

Prof. Renato P. Cunha
Civil Engineer, Associate Professor, M.Sc., Ph.D.
rpcunha@unb.br

University of Brasília
Brasília, Brazil
LAYOUT

- General Aspects / Displacement x Non Displacement Piles
- Execution Aspects and Failure Mechanisms
- Design Considerations / Piled Groups x Piled Rafts
- Future Trends
GENERAL ASPECTS OF PILE FOUNDATIONS

DISPLACEMENT X NON DISPLACEMENT PILES
Whatever the case for which piles are under consideration, the fundamental step for the design is a proper selection of the pile type as derived taking into account the following aspects(*):

- EFFECTIVENESS

- PRATICALNESS

- CHEAPNESS

(*) These objectives apply to piling as to any other item
Whatever the case for which piles are under consideration, the fundamental step for the design is a proper selection of the pile type as derived taking into account the following aspects(*):

- **EFFECTIVENESS**

- **PRATICALNESS**

- **CHEAPNESS**

To be effective, piles must carry the loads which the supported structure imparts to them, together with any additional forces which may result from deformations of the soil mass in which they are embedded (consolidation, earthquake, movements induced by nearby structures, ……).
Whatever the case for which piles are under consideration, the fundamental step for the design is a proper selection of the pile type as derived taking into account the following aspects(*):

- **EFFECTIVENESS**

- **PRATICALNESS**

- **CHEAPNESS**

To be practical, piles must be of a such type as will permit access for piling equipment to the locations where they are required. The design must recognize the limits of what is possible in current practice in terms of the equipment available and the method of construction must recognize and seek to minimize the difficulties related to ground conditions which could impede proper construction.
Whatever the case for which piles are under consideration, the fundamental step for the design is a proper selection of the pile type as derived taking into account the following aspects(*):

- **EFFECTIVENESS**
- **PRATICALNESS**
- **CHEAPNESS**

To be **cheap**, the design must be such as to maximize the bearing capacity of each pile while at the same time providing an adequate margin of safety against failure or excessive deformation of either individual piles or pile group.
World Pile Market nowadays offers a great number of pile types, forcing engineers to be continuously updated about new available technologies.

"SOME" PILE TYPE (source www.geoforum.com)

PILE CLASSIFICATION

TYPES OF BEARING PILE

DISPLACEMENT

- AUGER SCREEN PILES
  - TOTALLY OR PARTIALLY PREFORMED
    - DRIVEN CAST IN PLACE
      - Hollow
        - Steel
        - Concrete
        - Steel
        - Timber
        - Concrete
        - Soil
      - Pre-cast reinforced
      - Pre-cast prestressed
      - Jointed by splicing
      - Jointed using a proprietary system
    - The tube is filled with concrete and left in position
    - The tube is driven into the ground to form a solid
    - The tube is
  - VCC

NON DISPLACEMENT

- BORED CAST IN PLACE
  - Grouped CFA
  - Grouped CFA
  - Concrete is introduced into the tube through the auger
  - The tube is filled with concrete
  - The tube is

By back-screwing to leave a helical (screw) shaped pile
- Straight ation to leave a
- Straight ation to leave a

- Large diameter
  - Straight shafted cast-in-place
  - Preformed units are grouted in place (partially pre-formed pile)

- Small diameter
  - Straight shafted cast-in-place
  - Preformed units are grouted in place (partially pre-formed pile)

- The basic system comprises driving a re-usable tube and forming a pile with or without an enlarged base.

- Concrete is introduced into the tube through the auger
- Concrete is introduced into the tube through the auger

- In these piles, concrete is cast against the soil (unless deliberately isolated by a membrane).
When used for foundation problems, piles not necessarily represent 'the solution of all the problems'.

More rationally, if properly used piles could help in improving those aspects of the unpiled foundation behavior that are not fulfilling design requirements:

- failure load
- average settlement
- differential settlement
- internal stresses into the structural element connecting pile heads (typically, a reinforced concrete raft)
- ...........

**PROVIDED THEY ARE DESIGNED TAKING EXPLICITELY ACCOUNT THE REASON(S) FOR WHICH THEY ARE TAKEN UNDER CONSIDERATION**
Soil is laterally displaced during the insertion of pile, reducing porosity (if the case), hence increasing relative density and shear resistance.
Soil is laterally displaced during the insertion of pile, reducing porosity (if the case), hence increasing relative density and shear resistance.

Soil is removed and substituted by the pile, increasing porosity (if the case), hence decreasing relative density and shear resistance.
NON DISPLACEMENT PILES

CONTINUOUS FLIGHT AUGER, CFA

Developed in The Netherlands, ’60s
Large use in Europe, not appreciated in USA (forbidden by FHWA)

Trevisani, 1992

Mandolini, 2004
NON DISPLACEMENT PILES

CONTINUOUS FLIGHT AUGER, CFA
<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TYPE</th>
<th>PERCENTAGE</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP</td>
<td>SCREW</td>
<td>7</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>PREFABRICATED</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DRIVEN CAST IN PLACE</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>NDP</td>
<td>BORED</td>
<td>26</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>CFA</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>

Lehane B. (2005): “It is only a matter of time before they will dominate the market of medium scale bored piles”
EXECUTION EFFECTS

FAILURE MECHANISMS
Installation effect on shaft resistance

Ata & O’Neill (1997): Bored piles in sand, \( d = 0.914 \text{ m}; \ L = 10 \text{ m} \)

- Bentonite cake < 1 mm
- Polymer no cake
- Bentonite cake \( \approx 10 \text{ mm} \)

\[ \beta = \frac{\tau_{\text{slim}}}{\sigma'_v} \]

Longer time for bentonite mud into the hole resulted in 90% reduction of the shaft resistance !!!!
REMARKS

Two identical piles (length, L; diameter, d) made by the same pile material (i.e., reinforced concrete) and installed in the same “native” soil are expected to exhibit different behaviour. Such difference will depend on the way in which the properties of the “native” soil have been changed by the specific procedures adopted for their installation.

VERY COMPLEX PROBLEM, NOT EASY TO MANAGE IN DAILY PRACTICE

......

SOMETIMES EVEN MORE COMPLICATE FOR UNKNOWN ‘SITE ASPECTS’
Ultimate axial pile capacity predictions are an essentially empirical and rather uncertain exercise

Poulos et al. (S.O.A. XV ICSMGE, Istanbul 2001)

“It is difficult to recommend any single approach as being the most appropriate for estimating ultimate axial pile capacity”

Pile response is strongly affected by the properties of the soil close to the pile itself.

The soil surrounding the piles is strongly modified (improved, worsened) by the specific installation procedure adopted.

It follows that piles always interact with a modified soil (i.e. different from that existing before their installation).
Several design methods are proposed for estimating ultimate pile capacity taking into account for the installation procedure. They can be grouped as follows:

(a) SEMI-EMPIRICAL METHODS
   (direct correlations with in situ test results like SPT, CPT, PMT, . . .
(b) RATIONAL METHODS
   (simplified soil or rock mechanics theories based on soil properties)
(c) ADVANCED METHODS
   (analytical, numerical)

With reference to classical methods (a) and (b), a huge number of suggestions are given in literature to estimate the average ultimate shaft friction \(q_{s,u}\) and the ultimate end-bearing resistance \(q_{b,u}\)
Poulos et al. (2001)

Some "distilled" Suggestions for EMPIRICAL methods

Table 5.1: Total stress approaches for estimating $f_s$ for piles in clay, $f_s = \alpha \sigma_u$

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A = 0.5</td>
<td>$z_d \geq 70$ kPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interpolate linearly between</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Effectiveness stress approaches for estimating ultimate shaft friction $f_s = \beta \tan \delta$, $\tan \delta = \tan \delta$.

<table>
<thead>
<tr>
<th>Pile type</th>
<th>Soil type</th>
<th>Details</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driven</td>
<td>Sand</td>
<td>$\beta' = \beta'<em>{cr} - \Delta \beta'</em>{cr}$</td>
<td>Jardine &amp; Chew (1996)</td>
</tr>
<tr>
<td>Driven</td>
<td>Clay</td>
<td>$E_n = \frac{1}{2}(0.02 + 0.04) \sigma_u_{eq}$</td>
<td>Jardine &amp; Chew (1996)</td>
</tr>
</tbody>
</table>

$\beta$-method

$\alpha$-method
EXAMPLE IN NAPLES (ITALY)

CENTRO DIREZIONALE DI NAPOLI

BAY OF NAPLES
145 Static Load Tests on different piles over ~ 10 years

20 on trial instrumented piles along the shaft
125 on production piles (in some case, also instrumented along the shaft)

Pile types:
- ND - bored (with temporary casing, with bentonite mud)
- ND - bored CFA
- D - screwed (Pressodrill)
- D - driven (Franki)

Pile geometry:
- diameter \( d = 0.35-2.00 \) m
- length \( L = 9.5-42.0 \) m
- slenderness \( L/d = 16-61 \)

Representative database of different cast in situ piles in a relatively homogeneous soil conditions

(Mandolini et al., S.O.A. XVI ICSMGE Osaka 2005)
CALCULATION SCHEME:

$L = \text{pile length}; \; d = \text{pile diameter}$

$q_{s,u} = \text{average ultimate shaft friction}$
$q_{b,u} = \text{ultimate end-bearing resistance}$

$S_{\text{ult}} = q_{s,u} \cdot \pi \cdot d \cdot L \quad P_{\text{ult}} = q_{b,u} \cdot \pi \cdot d^2/4 \quad Q_{\text{ult}} = S_{\text{ult}} + P_{\text{ult}}$

$\gamma_p = \text{pile unit weight}$

$W = \gamma_p \cdot L \cdot \pi \cdot d^2/4$

$\frac{Q_{\text{ult}}}{W} = \frac{1}{L \cdot \gamma_p} \cdot \left( q_{b,u} + 4 \cdot \frac{L}{d} \cdot q_{s,u} \right)$
The effects determined by installation procedure are generally “measured” in terms of change of:

**RESISTANCE**

<table>
<thead>
<tr>
<th>Pile type</th>
<th>((Q_{ult}/W)_{av})</th>
<th>(\text{COV}(Q_{ult}/W))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND - Bored</td>
<td>12,1 (1)</td>
<td>0,26</td>
</tr>
<tr>
<td>ND - Bored CFA</td>
<td>37,5 (≈ 3)</td>
<td>0,25</td>
</tr>
<tr>
<td>D - Screwed, Driven</td>
<td>73,1 (≈ 6)</td>
<td>0,08</td>
</tr>
</tbody>
</table>

Ultimate load \(Q_{ult}\) was taken at \(w = 10%d\)

Ultimate axial loads can vary on the average up to 6 times.
SUMMARIZING: pile response to load is mainly governed by the modified soil properties (strongly depending on the specific installation method).

A good theory coupled with well-conducted and well-interpreted soil investigation is unable to allow a reliable prediction of the pile behaviour if installation aspects are not properly taken into account.
Mechanisms of pile group failure

Collapse of the pile group may occur either by failure of the individual piles or as failure of the overall block of soil containing piles (Terzaghi & Peck, 1948).

Kezdi (1957): \[ Q_{PG,ult} = \eta \cdot \sum_{i=1}^{n} Q_{lim,i} \]

\( \eta \) = efficiency at failure = \( f \) (pile layout, pile type, soil type)

Depending on the values assumed by the ratio \( q_b/q_s \), block failure becomes more likely than single pile failure where the increase in base area \( A_b \) is offset by a much larger decrease in surface area \( A_s \).
GRANULAR SOILS

\[ q_b/q_s = 50 \text{ to } 200 \]

Block failure less likely than single pile failure, except for those groups consisting of closely spaced long piles \((B/L \ll 1)\)

COHESIVE SOILS

\[ q_b/q_s = 10 \text{ to } 20 \]

Check is always necessary, except for very large spaced piles \((B/L \gg 1)\)
GRANULAR SOILS ($\eta>1$)

COHESIVE SOILS ($\eta<1$)
Cooke, 1986: rem. London clay - 1-g lab model

- $n = 3^2, 5^2, 7^2, 9^2$
- $L/d = 24, 48$
- $s/d \leq 4$
- $w = 10\%B$

\( \frac{Q}{c_u d^2} \times 10^{-3} \)

- exp., pile groups

![Diagram showing experiment results for pile groups 7x7 and 5x5 with spacing/diameter ratio (s/d) and critical spacing/diameter ratio (s_{crit}/d).](image-url)
Cooke, 1986: rem. London clay - 1-g lab model

\[ Q_P < \eta \times Q_S \]

Block failure
\[ \eta < 1 \]

\( n = 3^2, 5^2, 7^2, 9^2 \)
\( L/d = 24, 48 \)
\( s/d \leq 4 \)
\( w = 10\% B \)

\( \eta = \text{efficiency at failure} \)

\( s_{\text{crit}}/d \)

spacing / diameter, \( s/d \) [-]
Cooke, 1986: rem. London clay - 1-g lab model

\( n = 3^2, 5^2, 7^2, 9^2 \)
\( L/d = 24, 48 \)
\( s/d \leq 4 \)
\( w = 10\%B \)

\[ Q_p < \eta \times Q_s \]
**Block failure**
\( \eta < 1 \)

\[ Q_p = \eta \times Q_s \]
**Individual failure**
\( \eta = 1 \)

\( n = 3, 5, 7, 9 \)
\( L/d = 24, 48 \)
\( s/d \leq 4 \)
\( w = 10\%B \)

\[ \eta = \text{efficiency at failure} \]

\( (Q / c_d^2) \times 10^{-3} \)

**exp., pile groups**
For a given pile group layout and soil type, a critical value of the spacing ratio $s_{crit}/d$ exists below which a block failure occurs.

Experiments suggest to adopt piles at large spacing to exclude unwanted effect like block failure.
DESIGN CONSIDERATIONS

PILED GROUP X PILED RAFT
Distinct Philosophies to Consider the Pile Design

CBD generally is unrealistic in practice

modified from Mandolini et al., 2005
[1] The raft alone is able to satisfy the conditions:

a) design resistance $R_d \geq$ design action $E_d$ (based on EC7 and NTC rules)

b) $w \leq w_{adm}$

No piles are needed

modified from Mandolini et al., 2005
[2,3] the raft alone is not able to satisfy the both the conditions:

a) design resistance $R_d \leq$ design action $E_d$ (based on EC7 and NTC rules)

b) $w \geq w_{adm}$

Piles are needed to increase both resistance and stiffness (CSBD approach)

modified from Mandolini et al., 2005
[4,5] the raft alone is able to satisfy only the ULS condition ($R_d \geq E_d$) but large displacements (average, differential) are expected ($w \geq w_{adm}$).

Piles are needed to increase only overall foundation stiffness (SBD or DSBD approach)

modified from Mandolini et al., 2005
PILE GROUP X PILED RAFT

A pile foundation is a system acting as a composite construction consisting of three elements: raft, piles and subsoil
A pile foundation is a system acting as a composite construction consisting of three elements: *raft*, *piles* and *subsoil*. 

\[ Q_{TOT} = Q_s + \sum_{i=1}^{n} Q_{p,i} = Q_s + Q_p \]
A pile foundation is a system acting as a composite construction consisting of three elements: raft, piles and subsoil.

\[
Q_{TOT} = Q_S + \sum_{i=1}^{n} Q_{p,i} = Q_S + Q_p
\]

Load taken by the piles

\[
\alpha_{pr} = \frac{\sum_{i=1}^{n} Q_{\text{pile},i}}{Q_{TOT}} = \frac{Q_{PG}}{Q_{TOT}}
\]

Load taken by the raft

\[
\alpha_{rp} = 1 - \alpha_{pr}
\]
Current practice is based on the assumption that the raft is clear from the ground, hence neglecting the contribution of the raft-soil contact.

At normal spacing \((s=3-4d)\), the cap transfers to the soil at least \(20\%Q_{\text{TOT}}\).

It follows that piles are assumed to be overloaded in the design stage.
The lateral load resistance provided by pile caps can be very significant, and that in some cases the cap resistance is as large as the resistance provided by the piles themselves.

**LATERAL RESISTANCE**
ANOTHER EXAMPLE IN NAPLES

Two full scale tall buildings (Mandolini & Viggiani, 1992)

Business Centre in Naples (ITALY)  
Holiday Inn + Office Building

2 towers $H = 86.5$ m

2 independent rafts: 40mx32.7m

\[ q = \frac{Q}{(B \times L)} = 0.16 \text{ MPa} \]

\[ q_{lim,UR} = 0.5 \times F_\gamma \times N_\gamma \times \gamma \times B \sim 1.7 \text{ Mpa} \]

FS > 10, but ........
637 CFA PILES: \( L = 20 \text{ m}; d = 0,60 \text{ m} \)

\[ Q_{\text{lim},S} = 2,2 \text{ MN} \]

\[ F_{S_P} = 2,5 \text{ (Italian Code)} \]

\[ Q_S = 0,9 \text{ MN} \]
DSDB (de Sanctis et al., 2002)

318 piles CFA $d = 0.6$ m; $L = 20$ m

Using 318 piles "well located":

$w \sim + 10\%$

$\Delta w \sim - 25\%$
DSDB (de Sanctis et al., 2002)

318 piles CFA \( d = 0.6 \text{ m}; \ L = 20 \text{ m} \)

\[ n \cdot L \approx 12700 \text{ m} \]

\[ n \cdot L \approx 6300 \text{ m} \]

Better behaviour with less piles (50% SAVINGS !!!)
**CBD - capacity based design**

The traditional **Capacity-Based Design** approach (i.e. total applied load transmitted to the soil entirely through the piles, no contribution of the raft) is generally too much over-conservative, automatically leading to many piles uniformly distributed over the raft area.

**Consequences of CBD:**
- unnecessarily small settlements
- large factors of safety

88 full scale case histories – piled foundations

- \( w < 10 \text{ mm} \): 32 cases (36%)
- \( w < 30 \text{ mm} \): 67 cases (76%)
- \( w < 50 \text{ mm} \): 80 cases (91%)
So.... What happens when the CAP is in contact with the superficial soil?

\[
\frac{Q}{c_d^2} \times 10^{-3}
\]

exp., pile groups
exp., piled rafts

\[
\frac{s_{\text{crit}}}{d}
\]

spacing / diameter, \(s/d\) [-]
At the same spacing for which block failure occurs, the cap-soil contact does not change the bearing capacity of the foundation system (SHIELD EFFECT).
At the same spacing for which individual pile failure occurs, the cap-soil contact increases the bearing capacity of the foundation system.
\[ \zeta_{PR} = \frac{Q_{PR}}{Q_P} \]

\[ \zeta_{PR} \sim 1 \quad \zeta_{PR} > 1 \]

- ○ exp., pile groups
- ● exp., piled rafts

\[ \frac{Q}{c_d d^2} \times 10^{-3} \]

\[ s_{crit}/d \]

7x7
5x5

spacing / diameter, s/d [-]
Full scale experiments
(Sales, 2000, Cunha & Sales, 2003)

Rs, PGs & PRs on clayey soils

<table>
<thead>
<tr>
<th>Test</th>
<th>Foundation</th>
<th>$Q_{ult}$ [kN]</th>
<th>$w_{max}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Square raft $B_R = 1 \text{ m}$</td>
<td>150</td>
<td>28.6</td>
</tr>
<tr>
<td>II</td>
<td>Single pile $L=5\text{m}; ; d=0.15\text{m}$</td>
<td>75</td>
<td>20.0</td>
</tr>
<tr>
<td>IV</td>
<td>$2^2$ Pile group $(s=5d)$</td>
<td>300</td>
<td>45.4</td>
</tr>
<tr>
<td>VI</td>
<td>$2^2$ Piled raft $(s=5d)$</td>
<td>400</td>
<td>27.7</td>
</tr>
<tr>
<td>VII</td>
<td>Square raft $B_R = 1 \text{ m}$</td>
<td>90</td>
<td>32.5</td>
</tr>
<tr>
<td>VIII</td>
<td>Single pile $L=5\text{m}; ; d=0.15\text{m}$</td>
<td>32</td>
<td>18.6</td>
</tr>
<tr>
<td>IX</td>
<td>Capped pile</td>
<td>120</td>
<td>28.6</td>
</tr>
</tbody>
</table>

$\zeta_{PR} = Q_{PR} / Q_P = 1.33$
Experimental findings for piled rafts resting on clay soils

<table>
<thead>
<tr>
<th>Test</th>
<th>Reference</th>
<th>L/d</th>
<th>s/d</th>
<th>n</th>
<th>B&lt;sub&gt;R&lt;/sub&gt;/d</th>
<th>ζ&lt;sub&gt;PR&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooke (1986)</td>
<td>48</td>
<td>3</td>
<td>49</td>
<td>22</td>
<td>1.29</td>
<td></td>
</tr>
<tr>
<td>Cooke (1986)</td>
<td>48</td>
<td>3</td>
<td>25</td>
<td>16</td>
<td>1.44</td>
<td></td>
</tr>
<tr>
<td>Cooke (1986)</td>
<td>48</td>
<td>3</td>
<td>9</td>
<td>10</td>
<td>1.31</td>
<td></td>
</tr>
<tr>
<td>Cooke (1986)</td>
<td>24</td>
<td>3</td>
<td>49</td>
<td>22</td>
<td>1.74</td>
<td></td>
</tr>
<tr>
<td>Cooke (1986)</td>
<td>24</td>
<td>3</td>
<td>25</td>
<td>16</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>Cooke (1986)</td>
<td>24</td>
<td>3</td>
<td>9</td>
<td>10</td>
<td>1.94</td>
<td></td>
</tr>
<tr>
<td>Cooke (1986)</td>
<td>48</td>
<td>4</td>
<td>49</td>
<td>28</td>
<td>1.62</td>
<td></td>
</tr>
<tr>
<td>Cooke (1986)</td>
<td>48</td>
<td>4</td>
<td>25</td>
<td>20</td>
<td>1.89</td>
<td></td>
</tr>
<tr>
<td>Cooke (1986)</td>
<td>48</td>
<td>4</td>
<td>9</td>
<td>12</td>
<td>1.71</td>
<td></td>
</tr>
<tr>
<td>Cooke (1986)</td>
<td>24</td>
<td>4</td>
<td>25</td>
<td>20</td>
<td>2.10</td>
<td></td>
</tr>
<tr>
<td>Cooke (1986)</td>
<td>24</td>
<td>4</td>
<td>9</td>
<td>12</td>
<td>2.50</td>
<td></td>
</tr>
<tr>
<td>Conte et al. (2003)</td>
<td>28.6</td>
<td>4</td>
<td>9</td>
<td>14.3</td>
<td>2.26</td>
<td></td>
</tr>
<tr>
<td>Conte et al. (2003)</td>
<td>30.2</td>
<td>4</td>
<td>49</td>
<td>28.6</td>
<td>2.43</td>
<td></td>
</tr>
<tr>
<td>Conte et al. (2003)</td>
<td>28.6</td>
<td>4</td>
<td>9</td>
<td>28.6</td>
<td>9.57</td>
<td></td>
</tr>
<tr>
<td>Conte et al. (2003)</td>
<td>14.3</td>
<td>4</td>
<td>49</td>
<td>28.6</td>
<td>3.74</td>
<td></td>
</tr>
<tr>
<td>Conte et al. (2003)</td>
<td>28.6</td>
<td>4</td>
<td>49</td>
<td>28.6</td>
<td>2.45</td>
<td></td>
</tr>
<tr>
<td>Brand et al. (1972)</td>
<td>40</td>
<td>5</td>
<td>4</td>
<td>7</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>Brand et al. (1972)</td>
<td>40</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>Brand et al. (1972)</td>
<td>40</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>1.13</td>
<td></td>
</tr>
<tr>
<td>Brand et al. (1972)</td>
<td>40</td>
<td>2.5</td>
<td>4</td>
<td>4.5</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>Liu et al. (1994)</td>
<td>45</td>
<td>4</td>
<td>16</td>
<td>15</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>Sales (2000)</td>
<td>33.3</td>
<td>5</td>
<td>4</td>
<td>6.7</td>
<td>1.33</td>
<td></td>
</tr>
<tr>
<td>Borel (2001)</td>
<td>27.1</td>
<td>-</td>
<td>1</td>
<td>4.4</td>
<td>1.90</td>
<td></td>
</tr>
</tbody>
</table>

2.5 < s/d < 5  
ζ<sub>PR</sub> > 1
3-D NUMERICAL ANALYSES by ABAQUS 6.2

**DIG – Università di Napoli Federico II**

**DIC – Seconda Università di Napoli**

**de Sanctis L., Mandolini A. (2003)**
On the ultimate vertical load of piled rafts on soft clay soils.
*Proc. BAP IV, Ghent, Belgium*

**de Sanctis L., Mandolini A. (2006)**
Bearing capacity of piled supported rafts on soft clay soils.
*ASCE, GT n°6*

\[ A_G/A_R = 0.1 \text{ to } 0.7 \]
3-D NUMERICAL ANALYSES by ABAQUS 6.2

\[ Q_{PR} = \alpha_R \times Q_R + \alpha_P \times Q_P \]

\( S > S_{crit} \)

\( \eta \sim 1 \)

\( \alpha_P \sim 1 \)

\( 0 < \alpha_R < 1 \)

CBD piled raft

many piles at small s/d (say 3-4)

\( A_G/A_R \sim 1 \)

\( FF \sim [1/4, 1/3], \alpha_R \sim 0 \)

Filling Factor for piled raft

\[ FF = (A_G/A_R) / (s/d) \]
3-D NUMERICAL ANALYSES by ABAQUS 6.2

\[ Q_{PR} = \alpha_R \times Q_R + \alpha_P \times Q_P \]

\[ S > S_{crit} \]

\[ \eta \sim 1 \]

\[ \alpha_P \sim 1 \]

\[ 0 < \alpha_R < 1 \]

Filling Factor for piled raft

\[ FF = \left( \frac{A_G}{A_R} \right) / (s/d) \]
3-D NUMERICAL ANALYSES by ABAQUS 6.2

\[ Q_{PR} = \alpha_R \times Q_R + \alpha_P \times Q_P \]

\[ s > s_{crit} \]

\[ \eta \sim 1 \]

\[ \alpha_P \sim 1 \]

\[ 0 < \alpha_R < 1 \]

**DSBD piled raft**

few piles at small s/d (say 6-8)

\[ A_G/A_R < 1 \]

\[ 0 < FF < 1, \ 0 < \alpha_R < 1 \]

Filling Factor for piled raft

\[ FF = (A_G/A_R) / (s/d) \]
BEARING CAPACITY OF PILED RAFTS

‘SHIELD’ EFFECT

\[ \alpha_P = 1 - 3 \frac{A_g/A}{s/d} \]

\[ Q_{PR,lim} = Q_P + \alpha_R \cdot Q_R \]

\[ \alpha_R = 1 - 3 \frac{A_g/A}{s/d} \]

Block failure

DE SANCTIS & MANDOLINI, 2006
GENERAL SUGGESTION FOR INNOVATIVE DESIGN

Piles uniformly distributed over the raft area

\((A_G/A_R \sim 1)\) at spacing larger than usual

or piles concentrated in a small portion of the raft

\((A_G/A_R < 1)\) at usual spacing make the structural element connecting the pile heads able to transmit a portion of the external load directly to the foundation soil \((\alpha_R > 0)\).
To control the **average settlement**, an optimum performance is achieved by the use of piles with $L > B$ spread below the whole raft area ($A_g/A > 80\%$). This is possible for small and medium rafts, but not for large ones. In the latter case, the average settlement is but slightly reduced by the addition of piles.

To control the **differential settlement** $\Delta w$, an optimum performance is achieved by suitably locating a relatively small number of piles, rather than using a larger number of piles uniformly spread or increasing the raft thickness.

**CONCLUDING REMARKS**
• The most suited location depends on the distribution of the external loads. In the case of uniform load, the piles are best concentrated in the central zone (20% < $A_g/A < 45\%$). Again, the longer the piles the most effective they are in reducing $\Delta w$.

• Thickness of the raft affects bending moments and $\Delta w$, but has little effect on load sharing between raft and piles and on average settlement.
Another Example in Naples

- **Steel tanks for the storage of sodium hydroxide - Napoli**

  - **D** = 10-12 m
  - **H** = 15 m
  - **V** = 1200-1700 m³
  - \( \gamma_{\text{sodium}} = 15 \text{ kN/m}^3 \)

  - **Static load**
    - \( w_R = 90-100 \text{ mm} \)
  
  - **Cyclic load**
    - \( w_R = 150-180 \text{ mm} \)
For a particular tank:

Raft $B = 15$ m under a total load $Q = 47$ MN resting on a fine grained soil ($c_u = 100$ kPa; $G = 10$ MPa; $\nu = 0.20$)

$$FS_R = 3; \ w_{t=0} = 67 \text{ mm}; \ w_f = 107 \text{ mm} (> w_{adm} = 50 \text{ mm})$$

CBD ($\alpha_{pr} = 1$) $5^2$ piles, $L = 25$ m, $d = 1$ m
- $FS_P = 2$
- $w_{t=0} = 26 \text{ mm}; \ w_f = 29 \text{ mm} (< w_{adm} = 50 \text{ mm})$

SBD
- $4^2$ piles, $L = 25$ m, $d = 1$ m ($\sim 40\%$ less !!)
- $FS_{PR} = 4.3$ (????? 🤔)
- $w_{t=0} = 32 \text{ mm}; \ w_f = 36 \text{ mm} (< w_{adm} = 50 \text{ mm})$
- $\alpha_{pr,0} = 0.86; \ \alpha_{pr,f} = 0.91$
Results for all the tanks

**Conventional CB design – 128 CFA piles d = 0,6 m, L = 11,3 m**

\[ \alpha_{pr} = 1 \]
\[ FS_p = 2,5 \]
\[ w = 11-13 \text{ mm} \]

**Innovative SB design – 52 CFA piles d = 0,6 m, L = 11,3 m**

\[ \alpha_{pr} = 0,6 \]
\[ FS_p = 1,5 \]
\[ w_{max} = 35 \text{ mm} \]
\[ Dw_{max} = 20 \text{ mm} \]

60% SAVINGS
- Piles uniformly spread below the raft \((A_g/A \sim 1)\) at small spacing (typically, \(s/d = 3\div4\))

- Piles loaded well below shaft resistance \(\rightarrow\) often too small settlement

The use of SBD approach can lead to substantial savings keeping a satisfactory behaviour of the foundation system
FUTURE TRENDS
\[ T = \text{variable} \]

- 5÷10 m from ground surface

- Piles, parking, metro stations, tunnels, ...

- ~ 50 m from ground surface

ENERGY FOUNDATION SYSTEMS → ENERGY PILES
Once installed, piles represent potential heat exchangers (ENERGY PILES).

At least one time, heat flow occurs to reach thermal equilibrium among pile and surrounding soil ($T_{soil} = 12\div16 \, ^\circ C$)
The thermodynamic problem is ruled by a number of aspects:

**GENERAL, among which**

- Climate conditions
- Soil temperature
- Energy needs of the structure

**SPECIFIC, among which**

- Thermal soil properties (i.e., heat conductivity and capacity)
- Pile properties (i.e., thermal resistance of pile material)
- Groundwater regime (hydrostatic or not)
If equipped with inlet and return pipes with a liquid heat career at a temperature $T$:

$T > T_{soil} \rightarrow$ pile gives heat to soil

$T < T_{soil} \rightarrow$ soil gives heat to pile

The flow of the liquid heat career can be adjusted by a reversible heat pumps (heating and cooling operational conditions)
REFERENCES

This course module was entirely based on class notes from Professor Alessandro Mandolini, in a series of lectures at the Federal University of Pernambuco, Recife, Brazil, in October 2011 and at the University of Brasília, Brasília, in November 2007.

It is presented with an authorization kindly provided by Prof. Mandolini himself, which is gratefully acknowledged here.