Symposium „Pile design and displacements“

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Combined Pile-Raft Foundations (CPRF) in theory and engineering practice • Current developments

Prof. Dr.-Ing. Rolf Katzenbach
• Director of the Institute and the Laboratory of Geotechnics  TU Darmstadt
• Past Chairman of the Technical Committee 212 “Deep Foundations“ (TC 212) of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE)
• Board Member of the German Tunnel Association (STUVA)
• Board Member of the German Geotechnical Society (DGGT)
• Publicly Certified Expert and Independent Checking Engineering (ICE)

Dipl.-Ing. Steffen Leppla
• Research Associate at the Institute and Laboratory of Geotechnics  TU Darmstadt
• Certified Independent Expert for Geotechnics of metro and tram systems
Soil-structure interaction

What’s the problem?

• Settlements
• Differential settlements
• Tilting

Deep foundation systems

➢ planning
➢ design
➢ construction
➢ utilisation

\[ \sigma_1 - \sigma_3 \text{ [MN/m}^2\text{]} \]

- Frankfurt Clay
- Marl
- Sandstone
- Rocky Marl
- Gypsum
- Dubai Sandstone
Subsoil in Frankfurt am Main, Germany

\[ E_s(z) = 15 - 50 \text{ MN/m}^2 \]
\[ E_s(z) > 250 \text{ MN/m}^2 \]
Marriott-Hotel  Frankfurt am Main, Germany

Construction time:  1973 - 1976
Height:  162 m
Foundation:  raft foundation
max. settlements:  34 cm (!!)
Compensation of the settlements differences

- Stiff concrete cells (hotel area)
- Flexible steel construction (office area)
- Hinged connections

Marriott-Hotel  Frankfurt am Main, Germany
Deutsche Bank  Frankfurt am Main, Germany

Foundation:
raft foundation

Height:
155 m

Settlements:
min. 10 cm
max. 22 cm
12 cm
Deutsche Bank · Frankfurt am Main, Germany

Settlement isolines
Compensation system in the joint between high-rise building and the adjacent building
Old Dresdner Bank Hochhaus  Frankfurt

Construction time: 1975 - 1978
max. settlements: 20 cm
Soil-structure interaction

Foundations

- Shallow foundations
- Pile foundations

Combined Pile-Raft Foundation (CPRF)

Skin friction

Base pressure
Combined Pile-Raft Foundation (CPRF)

Total resistance of the CPRF:
\[
R_{\text{tot},k}(s) = \sum_{j=1}^{m} R_{\text{pile},k,j}(s) + R_{\text{raft},k}(s)
\]

Pile resistance:
\[
R_{\text{pile},k,j}(s) = R_{b,k,j}(s) + R_{s,k,j}(s)
\]

Raft resistance:
\[
R_{\text{raft},k}(s) = \iint \sigma(s, x, y) dx \, dy
\]

Interactions:
1. Pile-Soil-Interaction
2. Pile-Pile-Interaction
3. Raft-Soil-Interaction
4. Pile-Raft-Interaction

CPRF coefficient:
\[
\alpha_{\text{CPRF}} = \frac{\sum_{j=1}^{m} R_{\text{pile},k,j}(s)}{R_{\text{tot},k}(s)}
\]
Combined Pile-Raft Foundation (CPRF)

Three foundation types

Circular Raft

Single Pile

“1-Pile-Raft-Model”

- $l = 30.0 \text{ m}$
- $D = 1.5 \text{ m}$
- $D_{\text{slab}} = 12.0 \text{ m}$
- $d = 1.0 \text{ m}$
Combined Pile-Raft Foundation (CPRF)

Single pile foundation

Axial Force

Settlement

Skin Friction $q_s$ [kN/m$^2$]

Depth [m]

$s = 0.005 \cdot D$

$s = 0.01 \cdot D$

$s = 0.1 \cdot D$

$s = \text{settlement}$
Combined Pile-Raft Foundation (CPRF)
Combined Pile-Raft Foundation (CPRF)

“1-Pile-Raft-Model” → Pile-Raft Interaction

Axial Force

Settlement

Skin Friction $q_s$ [kN/m$^2$]

Depth [m]

$s = 0.005 \cdot D$

$s = 0.01 \cdot D$

$s = 0.1 \cdot D$

$s = \text{settlement}$
Basic studies on the pile-pile interaction

Numerical Studies

Spread Foundation

Pile Foundation

Combined Pile Raft Foundation

Thickness of raft: \( d = 1.0 \text{ m} \)

Diameter of pile: \( D = 1.5 \text{ m} \)

Variations of pile center distance: \( e/D = 3.0 / 6.0 / 8.5 \)

Variations of pile length: \( l/D = 10 / 20 / 30 \)
Basic studies on the Pile-Pile Interaction

Configuration of the model with 25 piles (e/D = 3)

\[ d = 1.0 \text{ m} \]
\[ D = 1.5 \text{ m} \]
\[ e = 3 \quad D = 4.5 \text{ m} \]
\[ l = 20 \quad D = 30 \text{ m} \]

M: Center Pile
E: Edge Pile
C: Corner Pile
Basic studies on the Pile-Pile Interaction

Configuration of the model with 9 piles (e/D = 6)

- **d** = 1.0 m
- D = 1.5 m
- e = 6  D = 9 m
- l = 20  D = 30 m

M: Center Pile
E: Edge Pile
C: Corner Pile
Basic studies on the Pile-Pile Interaction

Load settlement behaviour

\[ e / D = 3.0 \]

\[ e / D = 6.0 \]

\[ I/D = 20 \]
\[ m = 25 \text{ Piles} \]

\[ I/D = 20 \]
\[ m = 9 \text{ Piles} \]
Basic studies on the Pile-Pile Interaction

Load settlement behaviour

Pile Foundation
\( e = 3 \ D \)

CPRF
\( e = 3 \ D \)

S: Single Pile  M: Centre Pile  E: Edge Pile  C: Corner Pile
Basic studies on the Pile-Pile Interaction

Load settlement behaviour

Pile Foundation  
\( e = 6 \cdot D \)

CPRF  
\( e = 6 \cdot D \)

\( M: \) Centre Pile  \( E: \) Edge Pile  \( C: \) Corner Pile
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Proof and safety concept for CPRF

Proof and Safety Concept

Ultimate Limit State

External Bearing Capacity

\[ E_d = E_{G,k} \cdot \gamma_G + E_{Q,k} \cdot \gamma_Q \leq \frac{R_{1,tot,l}}{\gamma_R} = R_{1,tot,d} \]

\( \gamma_G, \gamma_Q, \gamma_R \) dependent on the national standards

*Nota bene:*
There is no proof for the single pile necessary!

Internal Bearing Capacity

The proof of the internal bearing capacity is applied according to the relevant standard

\[ \eta = \gamma_G \gamma_R \approx 2.00 \]
Proof and safety concept for CPRF

Proof and Safety Concept

Serviceability Limit State

External Serviceability
(settlements, differential settlements)

\[ E_{z,d} = E_{z,k} \leq C_d \]

with \( C_d \) as limiting design value of the relevant serviceability criterion

Internal Serviceability

The proof of the internal serviceability is applied according to the relevant standard

SLS is more relevant!
ISSMGE
Technical Committee TC 212 Deep Foundations

ISSMGE Combined Pile-Raft Foundation Guideline

Prof. Jean-Louis Briaud, USA
Prof. Dr.-Ing. Rolf Katzenbach, Germany
Prof. Sang Seom Jeong, Korea
Prof. Deepankar Choudhury, India
Gary Axelsson, Sweden
Willem Bierman, Netherlands
Maurice Bottiau, Belgium
Dan Brown, USA

\[ R_{\text{tot}}(s) = \sum_{j=1}^{m} R_{\text{pile}, j}(s) + R_{\text{raft}}(s) \]

Details:
www.issmge.org/tc212
Modelling soil-structure interaction

Numerical Analysis

Constitutive law
(non-linear and stress dependent)

Geometry
(3-dimensional model)

\[ \sigma_1 \quad \sigma_2 \quad \sigma_3 \]

hydrostatic axis

\[ F_s \quad F_c \]
Bridge pier foundation types

Option 1: Spread Foundation

Option 2: CPRF with 6 Piles

Option 3: Pile Foundation with 12 Piles
Numerical model of foundation elements

Option 1: Spread Foundation
Option 2: CPRF with 6 Piles
Option 3: Pile Foundation with 12 Piles
Comparison of settlements

<table>
<thead>
<tr>
<th>Foundation Type</th>
<th>Settlemnt (cm)</th>
<th>Resistance (MN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile Foundation</td>
<td>1.2</td>
<td>30</td>
</tr>
<tr>
<td>Spread Foundation</td>
<td>3.6</td>
<td>30</td>
</tr>
<tr>
<td>Combined Pile-Raft Foundation</td>
<td>11.1</td>
<td>30</td>
</tr>
</tbody>
</table>
## Comparison of costs

<table>
<thead>
<tr>
<th>Settlement</th>
<th>Costs of pile production (Assumption: 600 € per meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spread Foundation</td>
<td>11.1 cm</td>
</tr>
<tr>
<td>CPRF (6 Piles)</td>
<td>3.6 cm</td>
</tr>
<tr>
<td>Pile Foundation (12 Piles)</td>
<td>1.2 cm</td>
</tr>
</tbody>
</table>
Messeturm  Frankfurt am Main, Germany

Settlements calculated for a shallow foundation:  
\[ s > 40 \text{ cm} \]
\[ z = 0 - 20 \text{ m} \rightarrow 75 - 80 \% \]

\[ s = \int_{0}^{z} \frac{\sigma(z)}{E(z)} \, dz \]

\[ \rightarrow \text{Combined Pile-Raft Foundation (CPRF)} \]
MesseTurm  Frankfurt am Main, Germany

Construction time: 1988 - 1990

Prof. Dr.-Ing. Rolf Katzenbach • Director of the Institute and the Laboratory of Geotechnics
Messeturm  Frankfurt am Main, Germany

Construction time: 1988 - 1990

Quaternary sand and gravel
Frankfurt Clay

Settlements [cm]
Messeeturm  Frankfurt am Main, Germany

Average pile load: 11.3 MN
Effective building load: \[= 1.570 \text{ MN}\]
Ultimate pile load: \[64 \times 11.3 \text{ MN} = 725 \text{ MN}\]
Load transfer by raft: \[= 845 \text{ MN}\]

Contact pressure: \[250 \text{ kN/m}^2\]

\[\alpha_{\text{CPRF}} = 0.46\]
Comparison of costs for the piles

Accomplished: CPRF of 64 piles (l_{average} = 30 m)

Costs of pile production:
64 piles of 30 m at 600 €/m \approx 1.2 \text{ Mio. €}

Pile foundation: 316 piles (l = 30 m)

Costs of pile production:
316 piles of 30 m at 600 €/m \approx 5.7 \text{ Mio. €}

Savings in costs of pile production
4.5 \text{ Mio. €}

CO_2 reduction: 2,500 t
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European Central Bank • Frankfurt am Main, Germany
European Central Bank  Frankfurt am Main, Germany
European Central Bank  Frankfurt am Main, Germany
Comparison of costs for the piles

Accomplished: CPRF of 97 piles ($l_{\text{average}} = 30 \text{ m}$)

Costs of pile production:
97 piles of 30 m at 600 €/m $\approx 1.7 \text{ Mio. } €$

Pile foundation: 490 piles ($l = 30 \text{ m}$)

Costs of pile production:
490 piles of 30 m at 600 €/m $\approx 8.8 \text{ Mio. } €$

Savings in costs of pile production $7.1 \text{ Mio. } €$

$\text{CO}_2\text{ reduction: } 3,300 \text{ t}$
City Tower  Offenbach am Main, Germany

Construction Period: 2001 - 2003
Foundation: CPRF
Height: 120 m
City Tower • Offenbach am Main, Germany

Comparison of costs for the piles

Accomplished: CPRF of 36 piles ($l_{\text{average}} = 35$ m)

Costs of pile production:
36 piles of $\approx 30$ m at 600 €/m $\approx 0.7$ Mio. €

Pile foundation: 113 piles ($l = 30$ m)

Costs of pile production:
113 piles of 30 m at 600 €/m $\approx 2.0$ Mio. €

Savings in costs of pile production: 1.3 Mio. €

$\text{CO}_2$ reduction: 1,900 t
Opernturm  Frankfurt am Main, Germany

Comparison of costs for the piles

Accomplished: CPRF of 57 piles ($l_{\text{average}} = 40 \text{ m}$)

 Costs of pile production:
57 piles of 40 m at 600 €/m  $\approx 1.4 \text{ Mio. €}$

Pile foundation: 246 piles ($l = 30 \text{ m}$)

 Costs of pile production:
246 piles of 30 m at 600 €/m  $\approx 4.4 \text{ Mio. €}$

Savings in costs of pile production: 3.0 Mio. €

$\text{CO}_2$ reduction: 2,250 t
Maintower  Frankfurt am Main, Germany

Optimisation by construction in 2 directions: Tow-down method
Maintower Frankfurt am Main, Germany
Prof. Dr.-Ing. Rolf Katzenbach • Director of the Institute and the Laboratory of Geotechnics

Maintower  Frankfurt am Main, Germany

Results of optimised design:

• minimised deformations
• minimised construction time
Maintower Frankfurt am Main, Germany

Comparison of costs for the piles

Accomplished: CPRF of 112 piles ($l_{\text{average}} = 30$ m)

Costs of pile production:
112 piles of 30 m at 600 €/m $\approx 2.0$ Mio. €

Pile foundation: 277 piles ($l = 30$ m)

Costs of pile production:
277 piles of 30 m at 600 €/m $\approx 5.0$ Mio. €

Savings in costs of pile production: 3.0 Mio. €

CO$_2$ reduction: 2,200 t
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Taunusturm  Frankfurt am Main, Germany

Height:  170 m

Construction time:  2011 - 2014

High-rise building and living tower:  CPRF

Underground parking:  Foundation raft with micro piles against buoyancy

Total building load ≈ 2,000 MN
Living tower:
- piles: 12
- foundation raft: 1.2 m

High-rise buildings:
- piles: 46
- foundation raft: 2.8 m

Underground parking:
- piles: 65
- foundation raft: 0.9 m
Taunusturm  Frankfurt am Main, Germany
Taunusturm  Frankfurt am Main, Germany
Taunusturm  Frankfurt am Main, Germany

Comparison of costs for the piles

Accomplished: CPRF of 46 piles ($l_{\text{average}} = 25$ m)

Costs of pile production:
46 piles of 25 m at 600 €/m  $\approx 0.7$ Mio. €

Pile foundation: 277 piles ($l = 30$ m)

Costs of pile production:
230 piles of 30 m at 600 €/m  $\approx 4.1$ Mio. €

Savings in costs of pile production:  $3.4$ Mio. €

$\text{CO}_2$ reduction: 2,540 t
Mirax Plaza Tower A  Kiev, Ukraine

Tower A  200 m  2.200 MN

Tower B

River Dnjepr

Project Area
Mirax Plaza Tower A  Kiev, Ukraine

Foundation systems

Barrette foundation:
- 120 Barrettes
- $l = 40 \text{ m}$
- $2.8 \text{ m} \times 0.8 \text{ m}$

Load tests

Invention of a numerical model

Foundation design

Realised foundation

First CPRF in Ukraine ($\alpha_{\text{CPRF}} = 0.88$)

CPRF:
- 64 Barrettes
- $l = 33 \text{ m}$
- $2.8 \times 0.8 \text{ m}$
Mirax Plaza Tower A  Kiev, Ukraine

Comparison of costs of the barretts

Accomplished: CPRF of 62 barretts (l = 33 m)

Costs of barrett production:
62 barretts of 33 m at 920 €/m  ≈ 1.9 Mio. €

Barrett foundation: 120 barretts (l = 40 m)

Costs of barrett production:
120 barretts of 40 m at 920 €/m  ≈ 4.4 Mio. €

Savings in costs of barrett production: 2.5 Mio. €

CO₂ reduction: 1,550 t
Back analysis for calibration of numerical simulations • Lagos, Nigeria

Pile load test with Osterberg-Cells (O-Cells)

- Silty sand
- Sandy clay
- Clayey sand
- Sand

Load [MN]

Displacement [cm]
Back analysis for calibration of numerical simulations • Lagos, Nigeria

Numerical simulation using Finite-Element-Method (FEM)
Back analysis for calibration of numerical simulations · Lagos, Nigeria

optimised design of the foundation systems

Combined Pile-Raft Foundation (CPRF)
Back analysis for calibration of numerical simulations · Lagos, Nigeria
Combined Pile-Raft Foundation (CPRF) and horizontal loading

New Exhibition Hall 3 in Frankfurt am Main, Germany
Combined Pile-Raft Foundation (CPRF) and horizontal loading

New Exhibition Hall 3 in Frankfurt am Main

- roof with a free span of 165 m
- horizontal loads on foundation (CPRF) resulting from arch trust of the roof
Combined Pile-Raft Foundation (CPRF) and horizontal loading

New Exhibition Hall 3 in Frankfurt am Main

- A-frame
- force transfer
Recommendations for the design of CPRF

- Piles have to be set directly under the load of the superstructure. The centre of the pile group should be under the centre of the loads.
- Few long piles are better than many short piles.
- The length of the piles has to be adapted to the loads. At the edge and the corners of the raft shorter piles and in the inner part of the raft longer piles are recommended.
- The calibration of the numerical model is necessary. Therefore the back analysis of pile load tests can be used.
- Optimum of the CPRF-coefficient: \( \alpha_{CPRF} = 0.5 \ldots 0.7 \)
Thank you for your kind attention!

www.geotechnik.tu-darmstadt.de