Symposium „Pile design and displacements“

TECHNISCHE UNIVERSITÄT DARMSTADT

The Hague, The Netherlands, 27th May 2016

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

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- Board Member of the German Tunnel Association (STUVA)
- Board Member of the German Geotechnical Society (DGGT)
- Publicly Certified Expert and Independent Checking Engineering (ICE)

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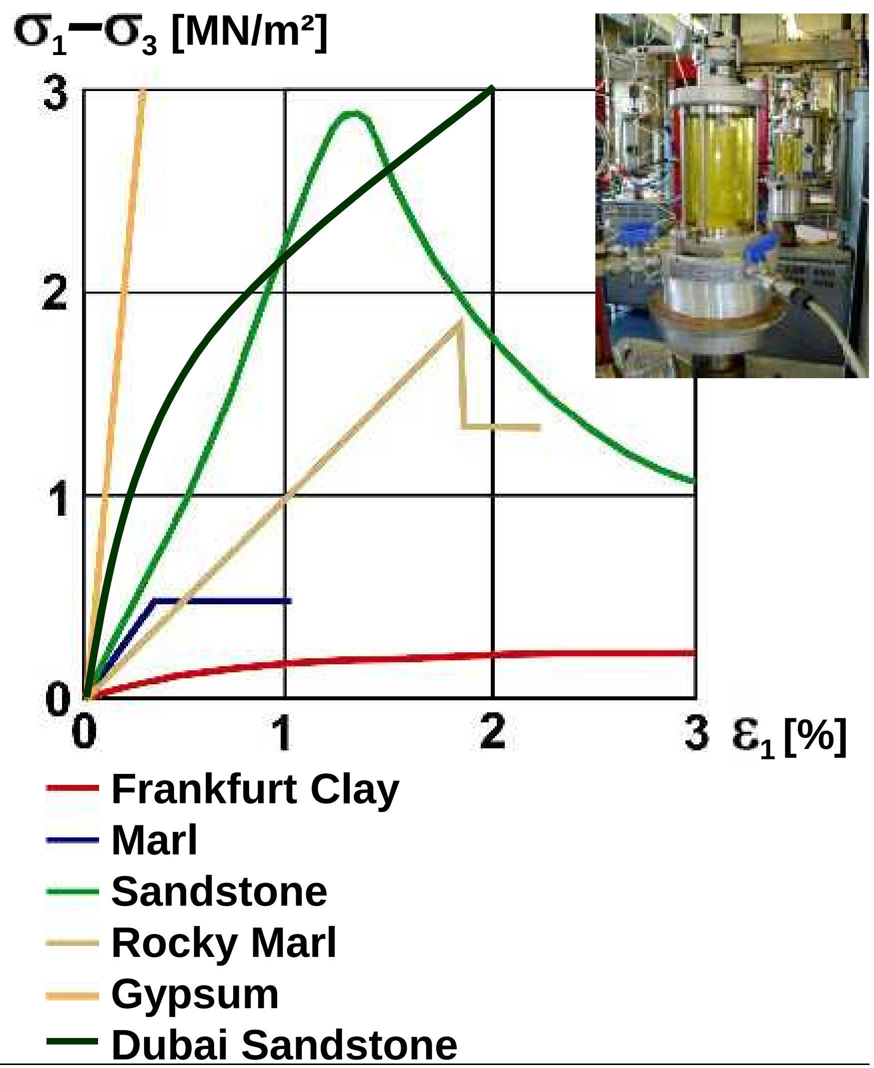
Soil-structure interaction

What's the problem?

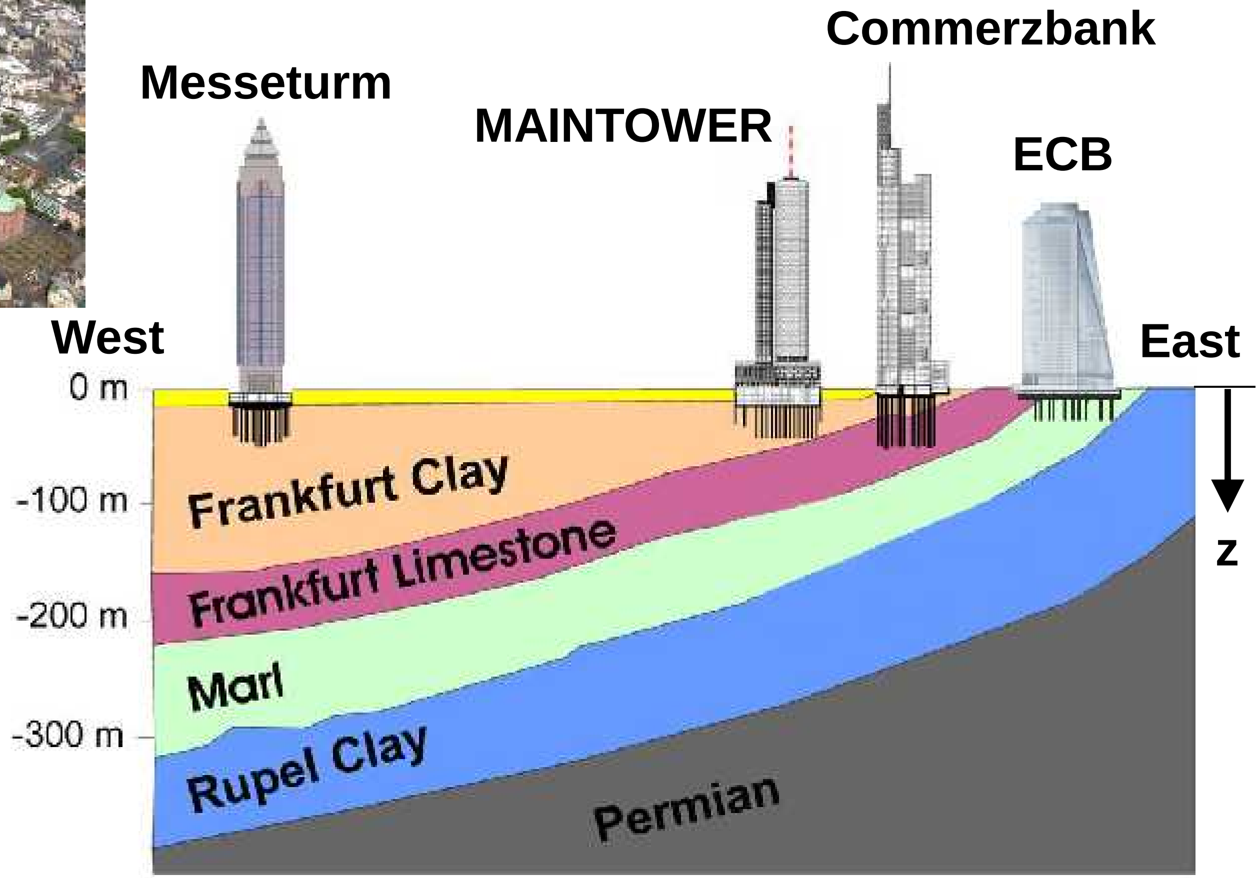
- Settlements
- Differential settlements
- Tilting

Deep foundation systems

- planning
- design
- construction
- utilisation



Subsoil in Frankfurt am Main, Germany



$E_s(z) = 15 - 50\ MN/m^2$

$E_s(z) > 250\ MN/m^2$

Marriott-Hotel · Frankfurt am Main, Germany

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

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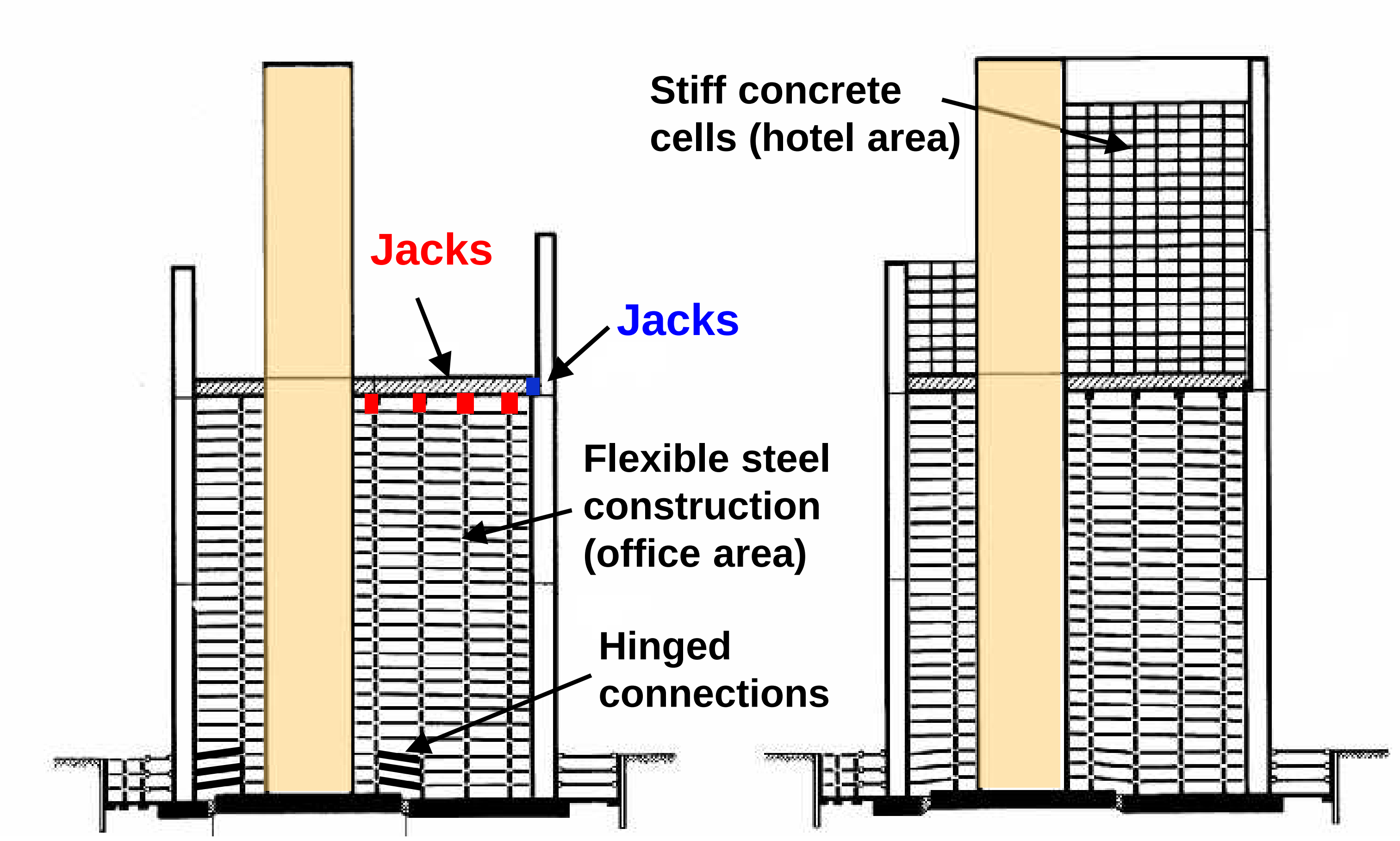
Marriott-Hotel · Frankfurt am Main, Germany

Compensation of the settlements differences



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Foundation:

raft foundation

Height:

155 m

Settlements:

min.	**10 cm**
max.	**22 cm**
Δ	**12 cm**

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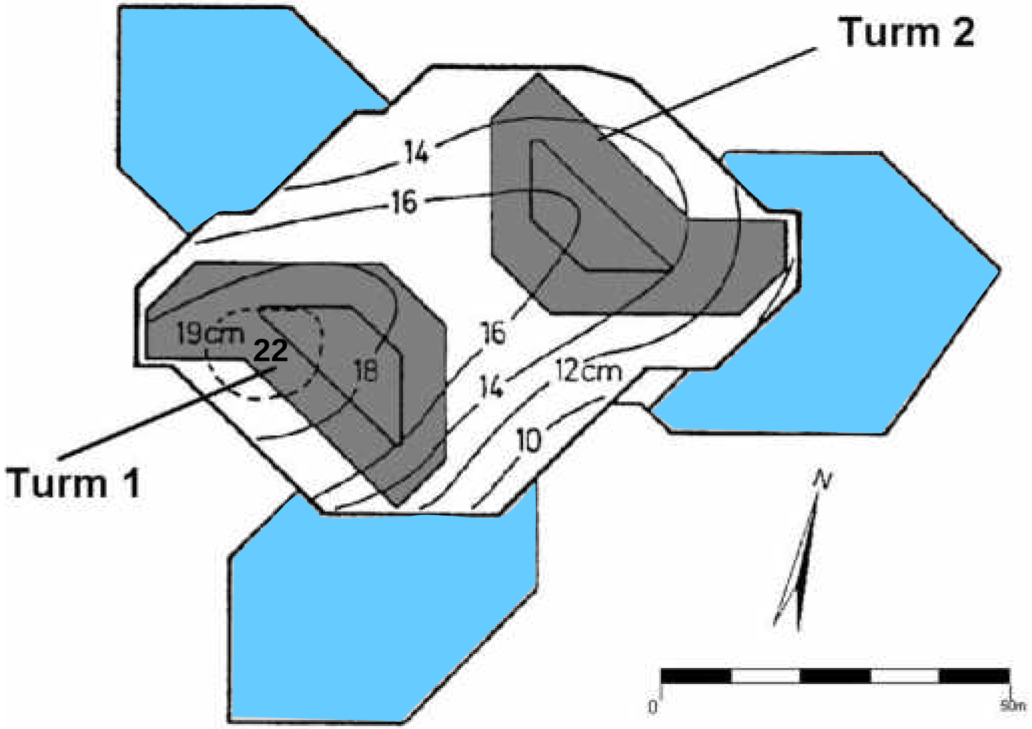
Settlement isolines



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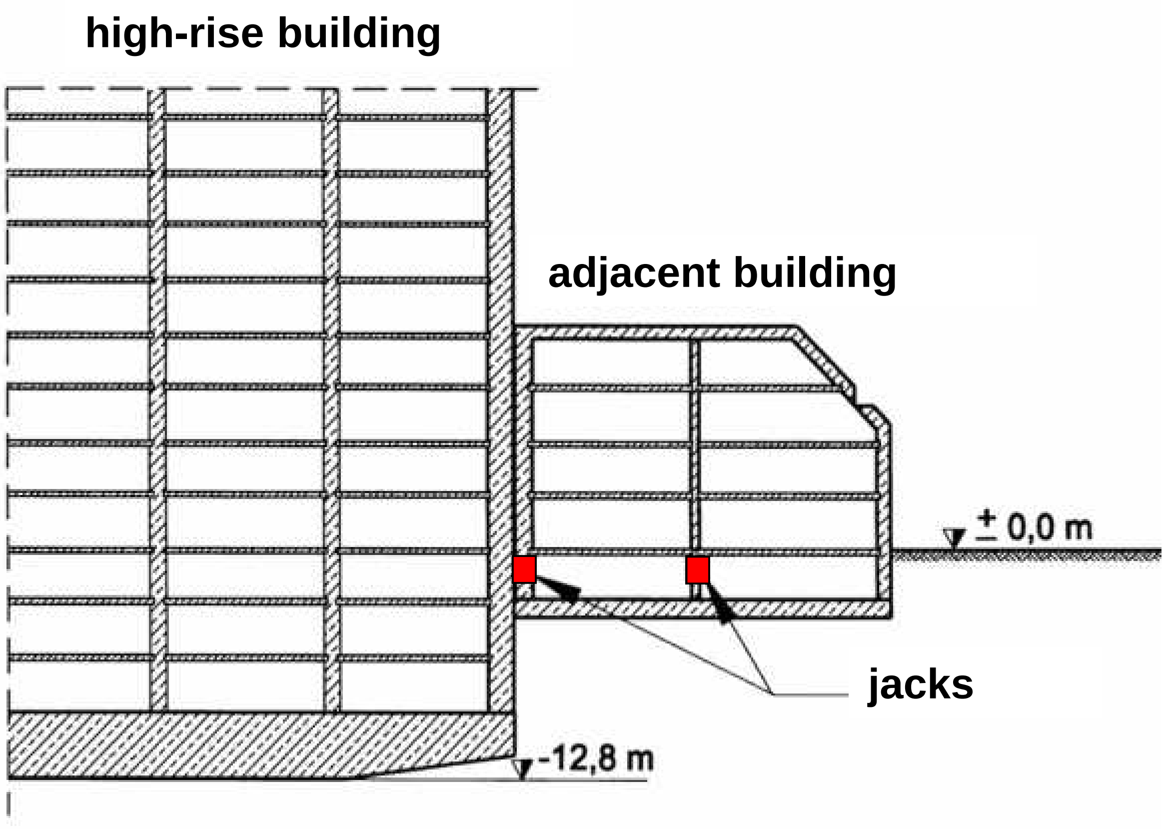
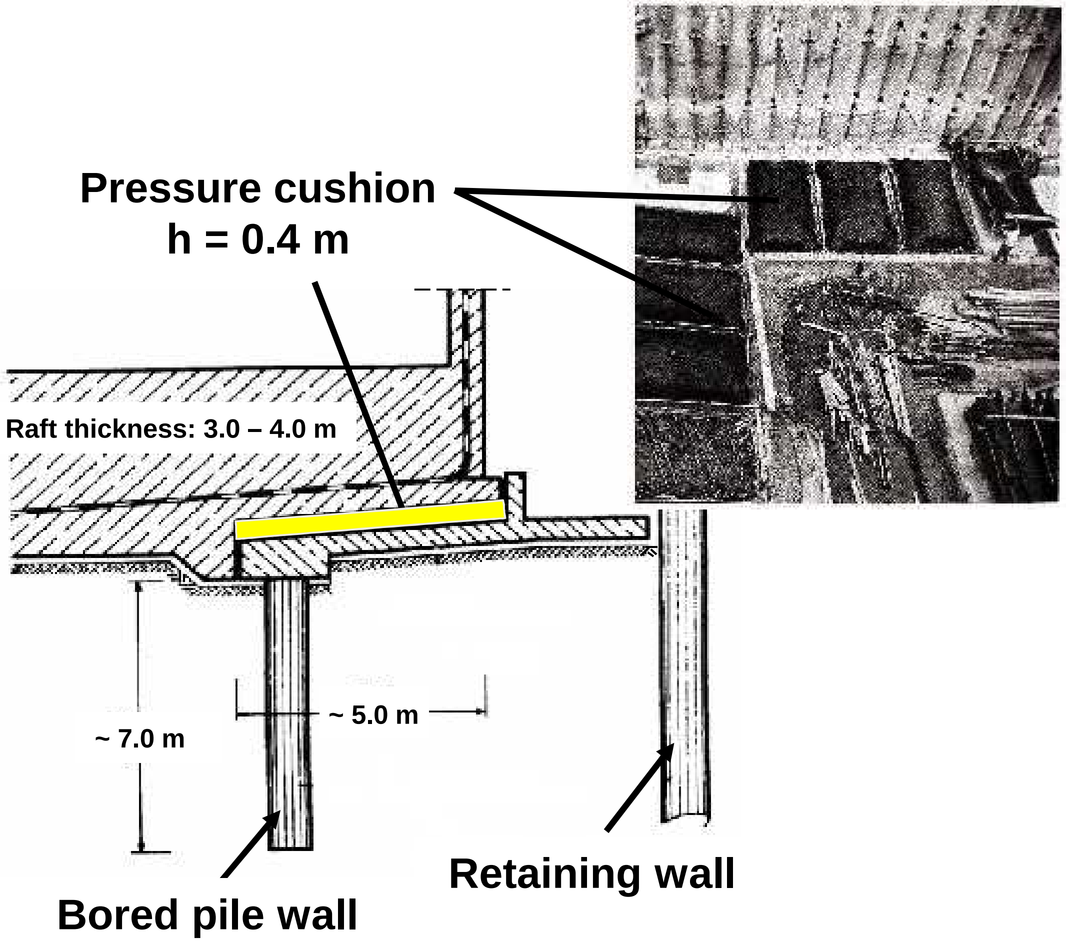
Compensation system in the joint between high-rise building and the adjacent building



Old Dresdner Bank Hochhaus · Frankfurt



Construction time: 1975 - 1978

max. settlements: 20 cm

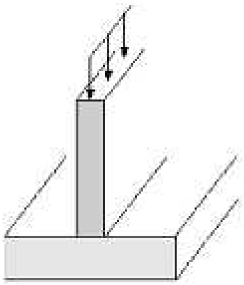
Soil-structure interaction

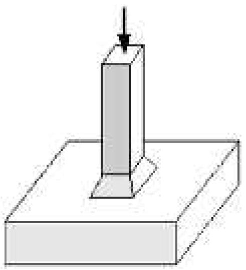
Foundations

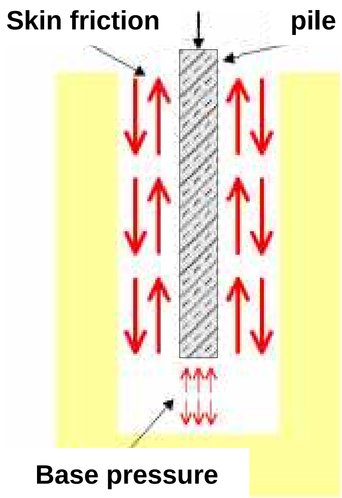
Shallow foundations

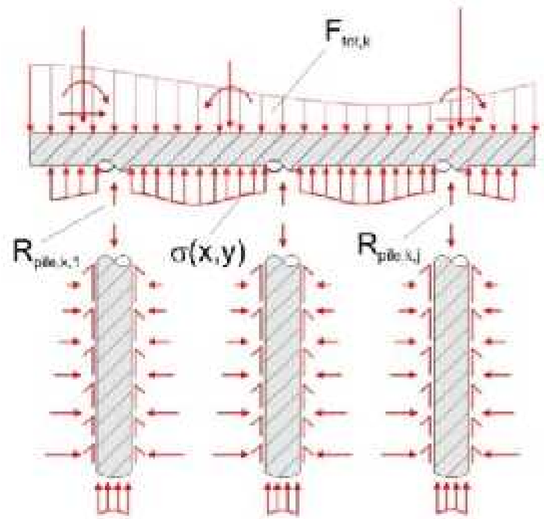
Pile foundations

Combined Pile-Raft Foundation (CPRF)









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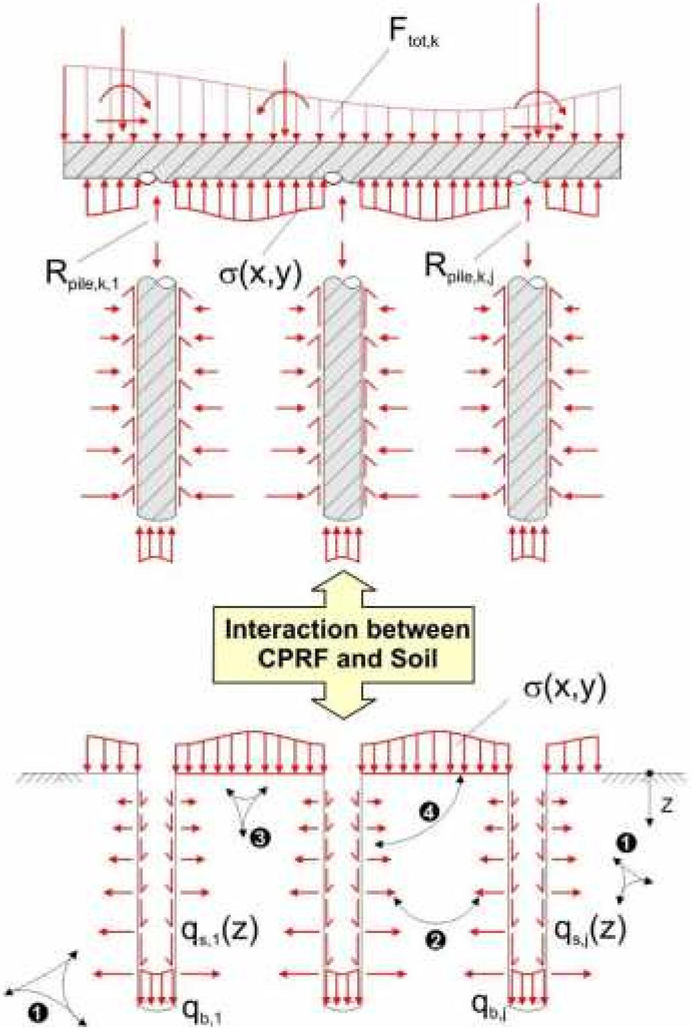
Combined Pile-Raft Foundation (CPRF)



Total resistance of the CPRF:

$$R_{tot,k}(s) = \sum_{j=1}^{m} R_{pile,k,j}(s) + R_{raft,k}(s)$$

Pile resistance:

$$R_{pile,k,j}(s) = R_{b,k,j}(s) + R_{s,k,j}(s)$$

Raft resistance:

$$R_{raft,k}(s) = \iint \sigma(s,x,y)\,dx\,dy$$

Interactions:

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

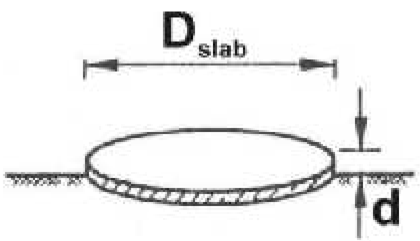
CPRF coefficient:

$$\alpha_{CPRF} = \frac{\sum_{j=1}^{m} R_{pile,k,j}(s)}{R_{tot,k}(s)}$$

Combined Pile-Raft Foundation (CPRF)

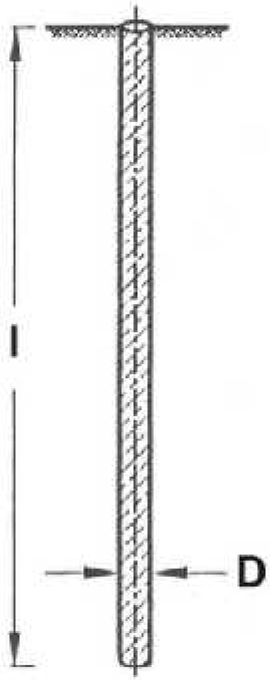
Three foundation types

Circular Raft

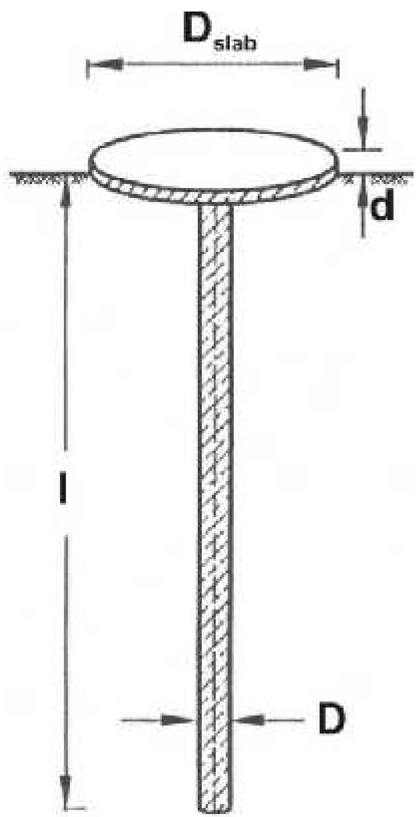


l	=	30.0 m
D	=	1.5 m
D_{slab}	=	12.0 m
d	=	1.0 m

Single Pile

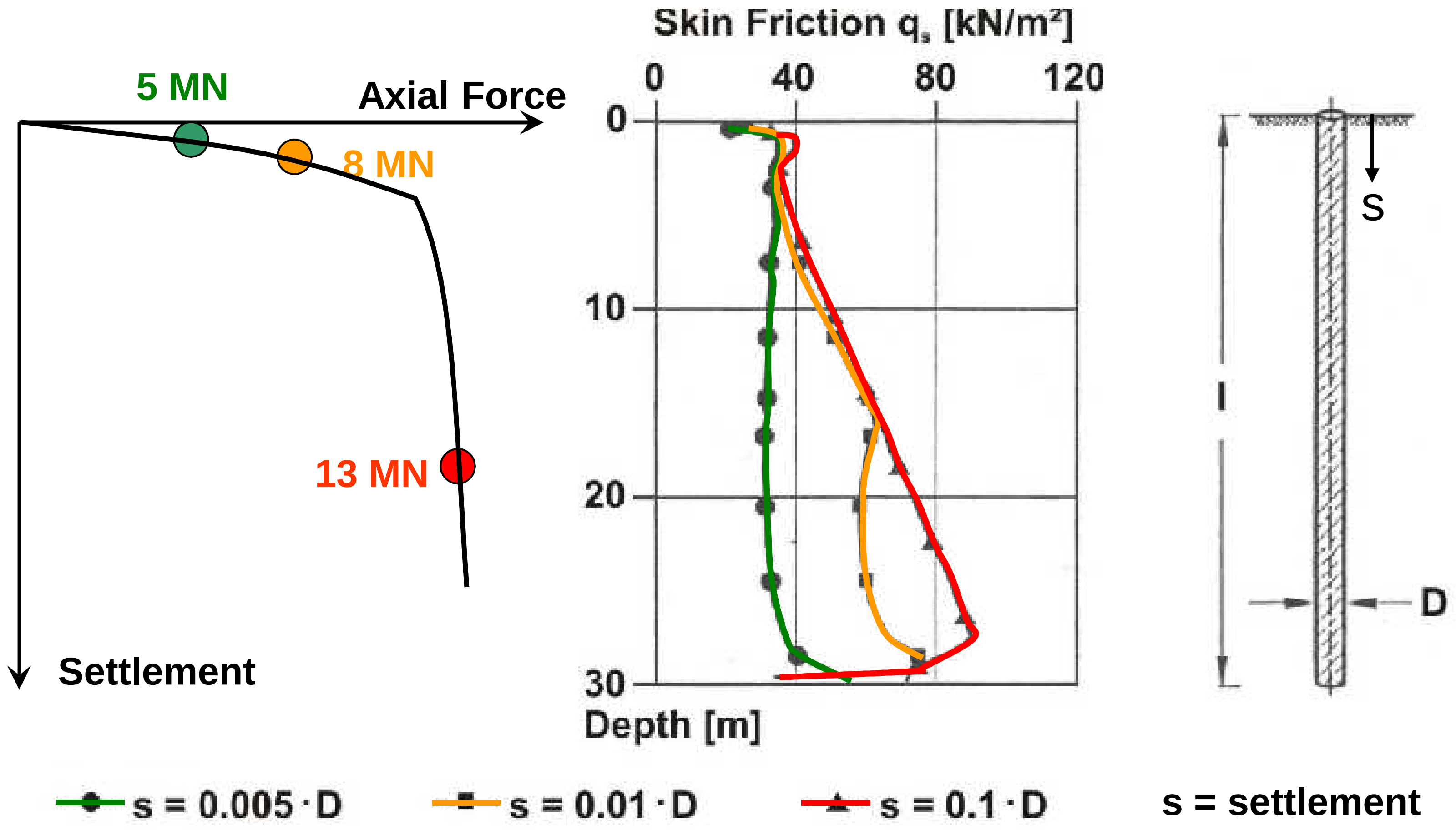


"1-Pile-Raft-Model"



Combined Pile-Raft Foundation (CPRF)

Single pile foundation



Combined Pile-Raft Foundation (CPRF)

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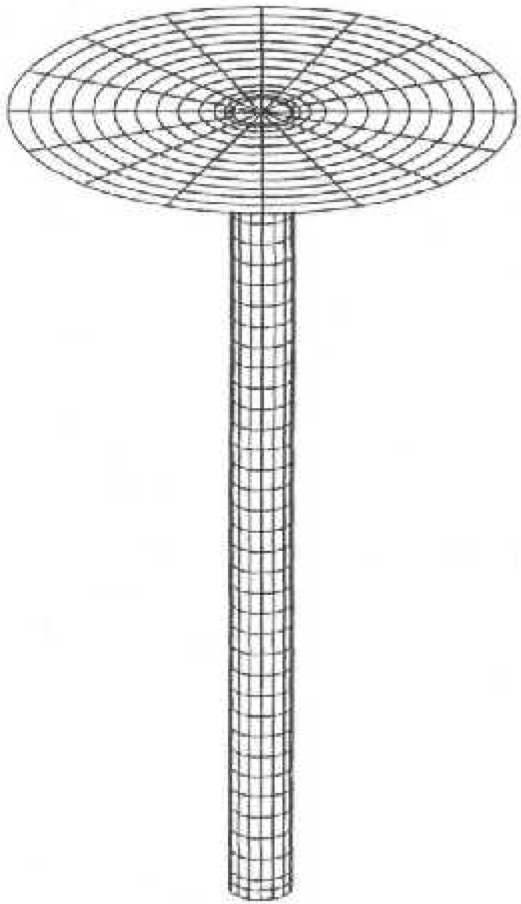
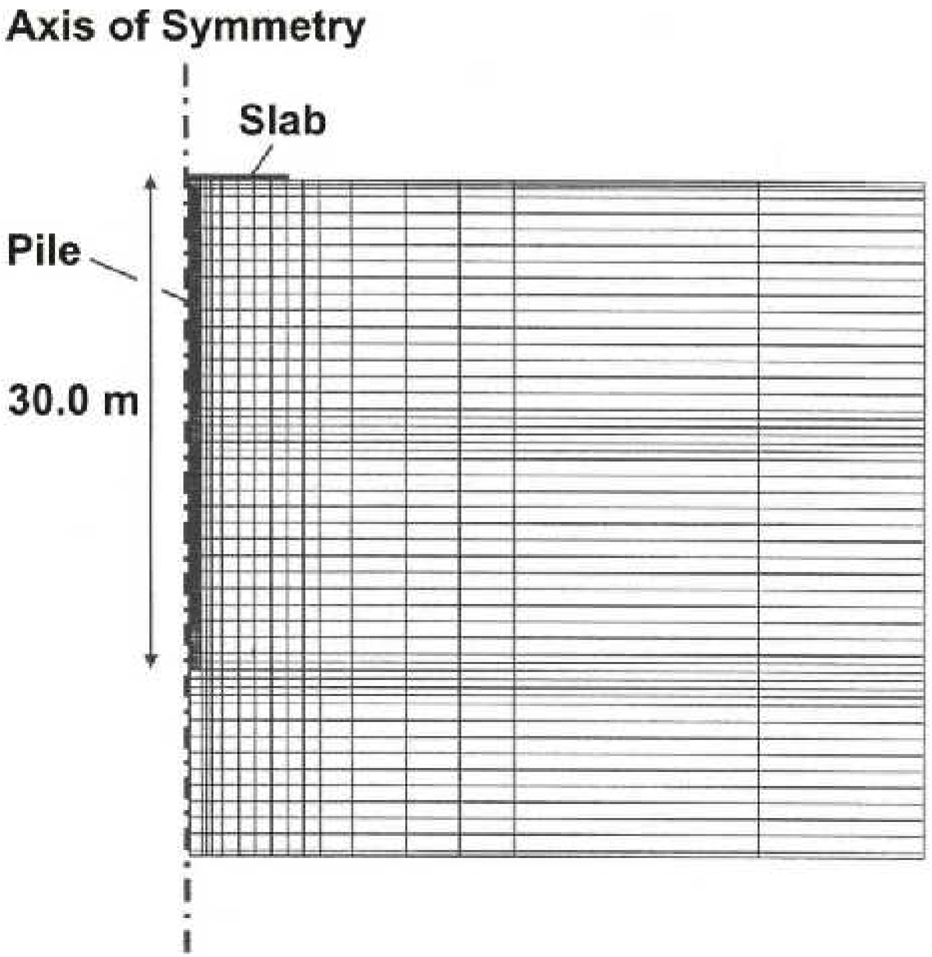
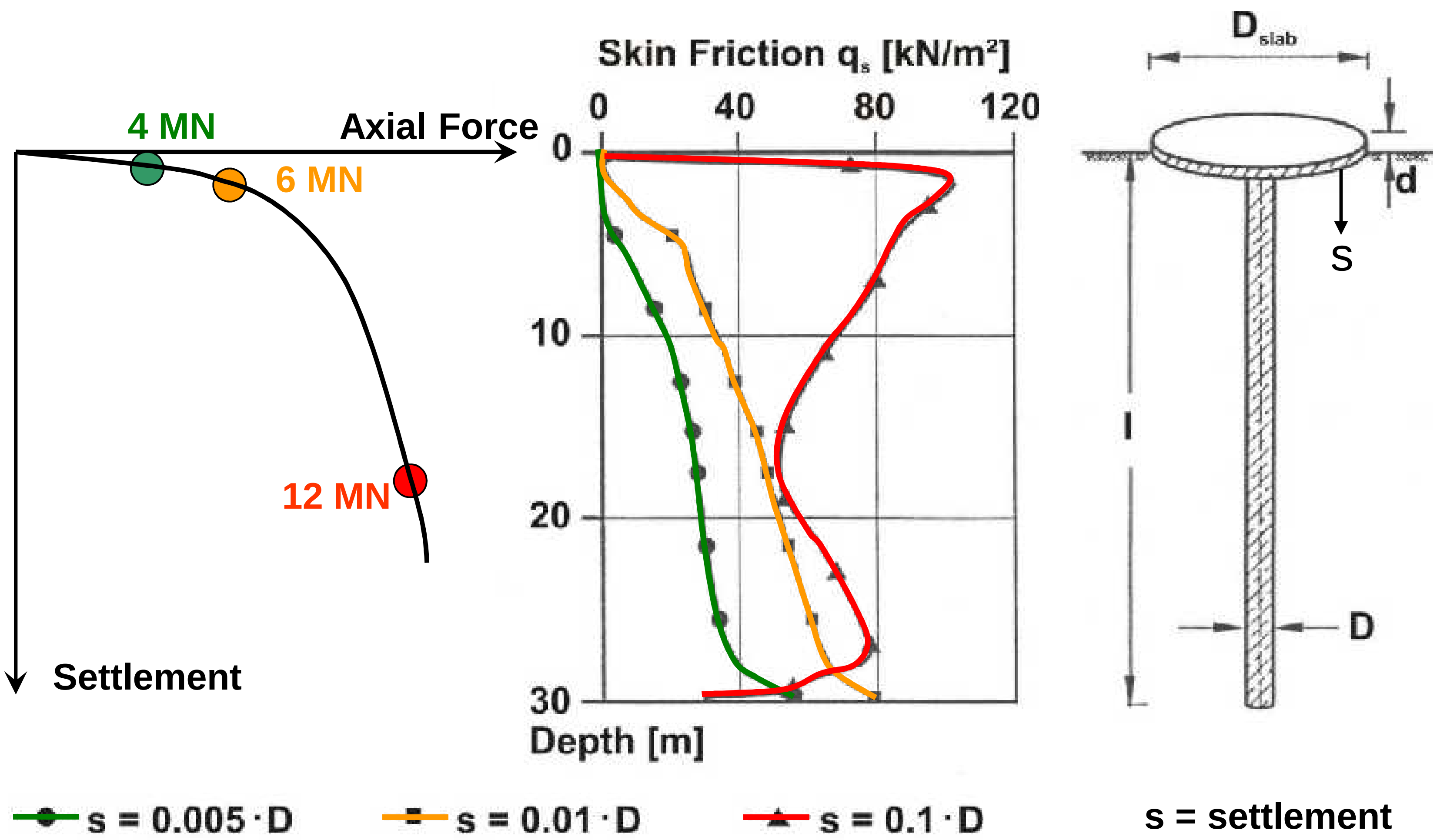




Combined Pile-Raft Foundation (CPRF)

"1-Pile-Raft-Model" → Pile-Raft Interaction



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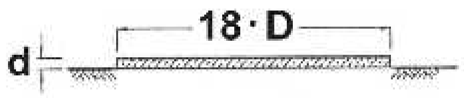
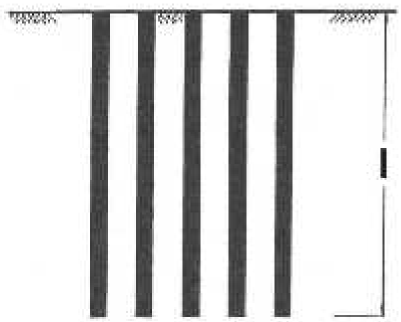
Basic studies on the pile-pile interaction

Numerical Studies

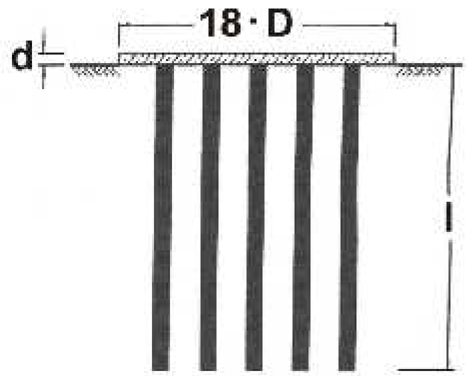
Spread Foundation



Pile Foundation



Combined Pile Raft Foundation



Thickness of raft: d = 1.0 m

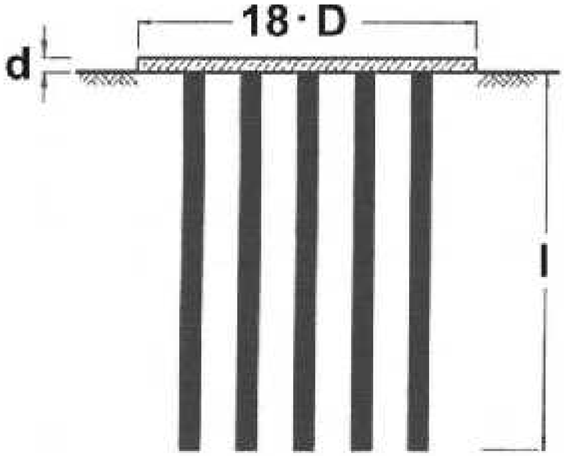
Diameter of pile: D = 1.5 m

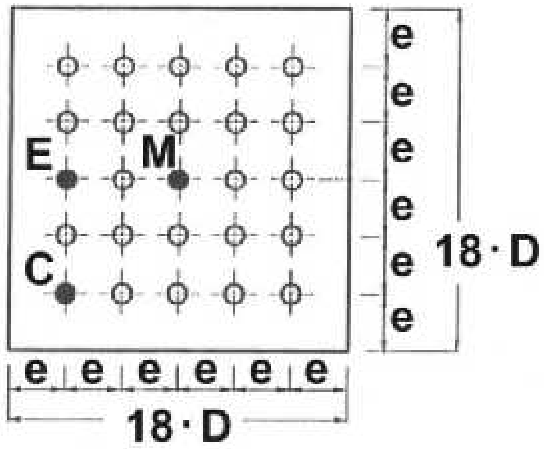
Variations of pile center distance: e/D = 3.0 / 6.0 / 8.5

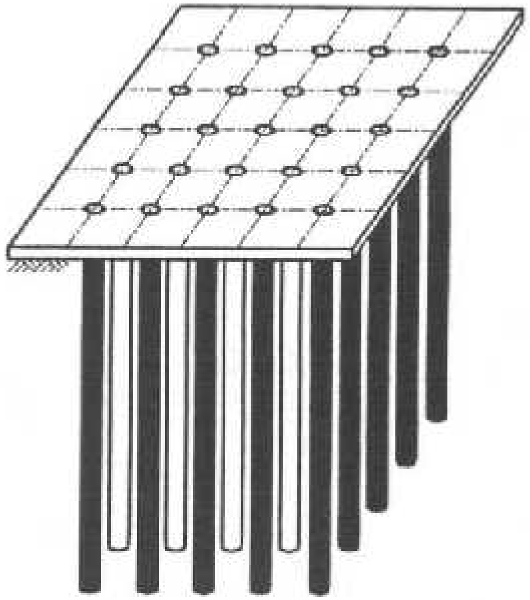
Variations of pile length: l/D = 10 / 20 / 30

Basic studies on the Pile-Pile Interaction

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







M: Center Pile

E: Edge Pile

C: Corner Pile

d = 1.0 m

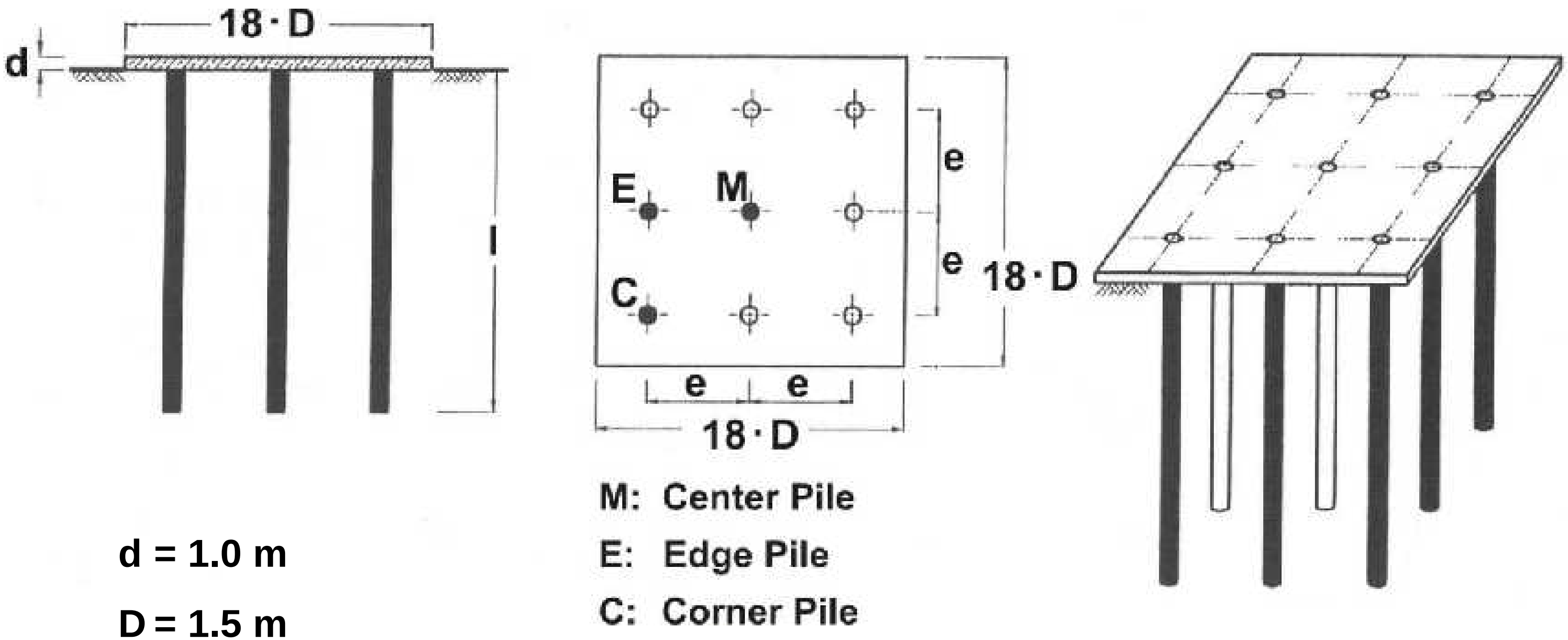
D = 1.5 m

e = 3 · D = 4.5 m

l = 20 · D = 30 m

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

$e = 6 \cdot D = 9$ m

$l = 20 \cdot D = 30$ m

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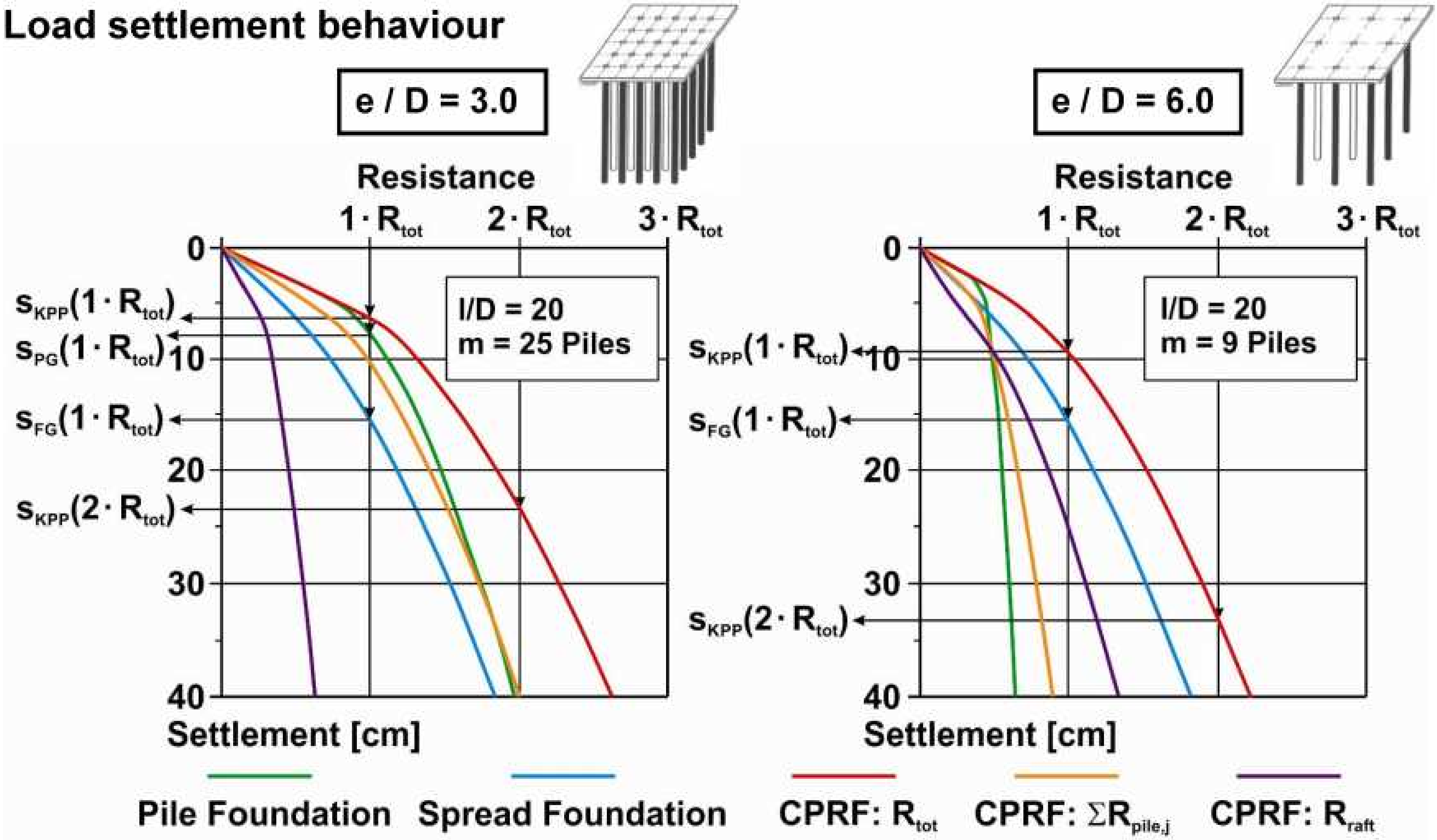
Basic studies on the Pile-Pile Interaction

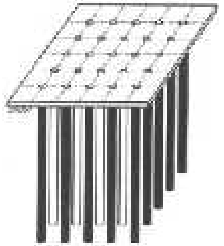


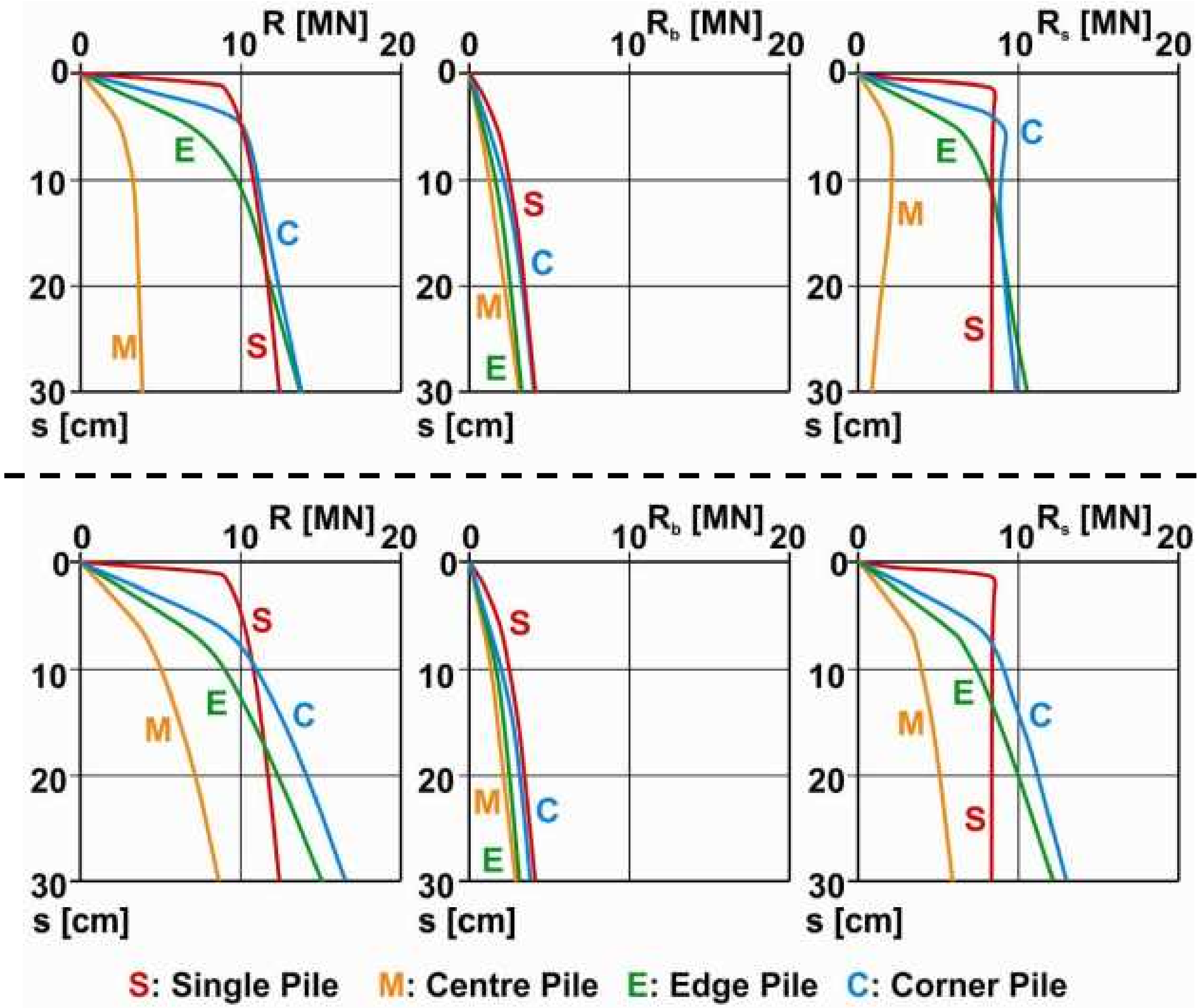
Basic studies on the Pile-Pile Interaction

Load settlement behaviour

Pile Foundation

e = 3 · D





CPRF

e = 3 · D

Basic studies on the Pile-Pile Interaction

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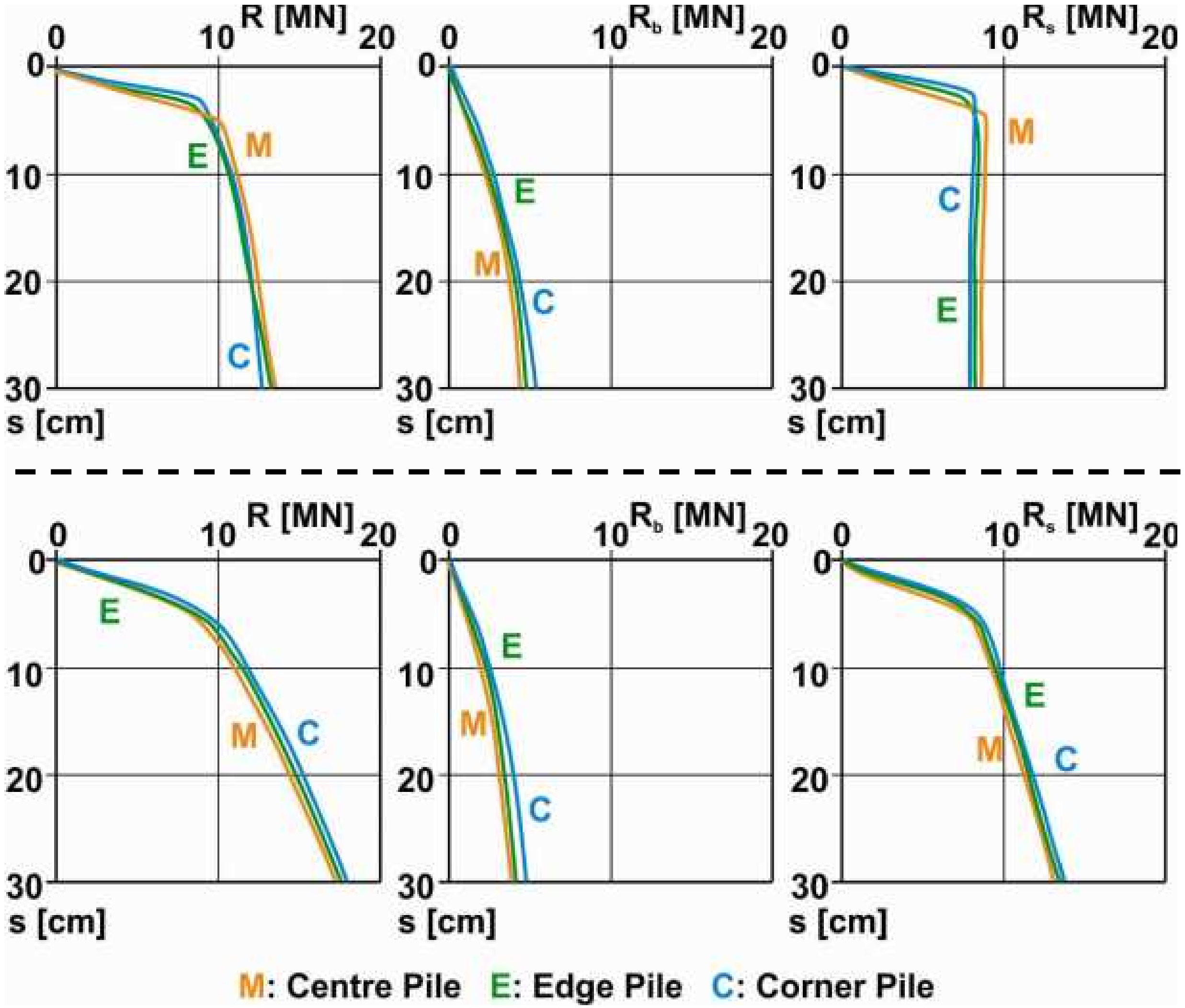
Load settlement behaviour

Pile Foundation

e = 6 · D

CPRF

e = 6 · D



Proof and safety concept for CPRF

Proof and Safety Concept

Ultimate Limit State

External Bearing Capacity

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

γ_G, γ_Q, γ_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

$$\eta = \gamma_G \cdot \gamma_R \approx 2.00$$

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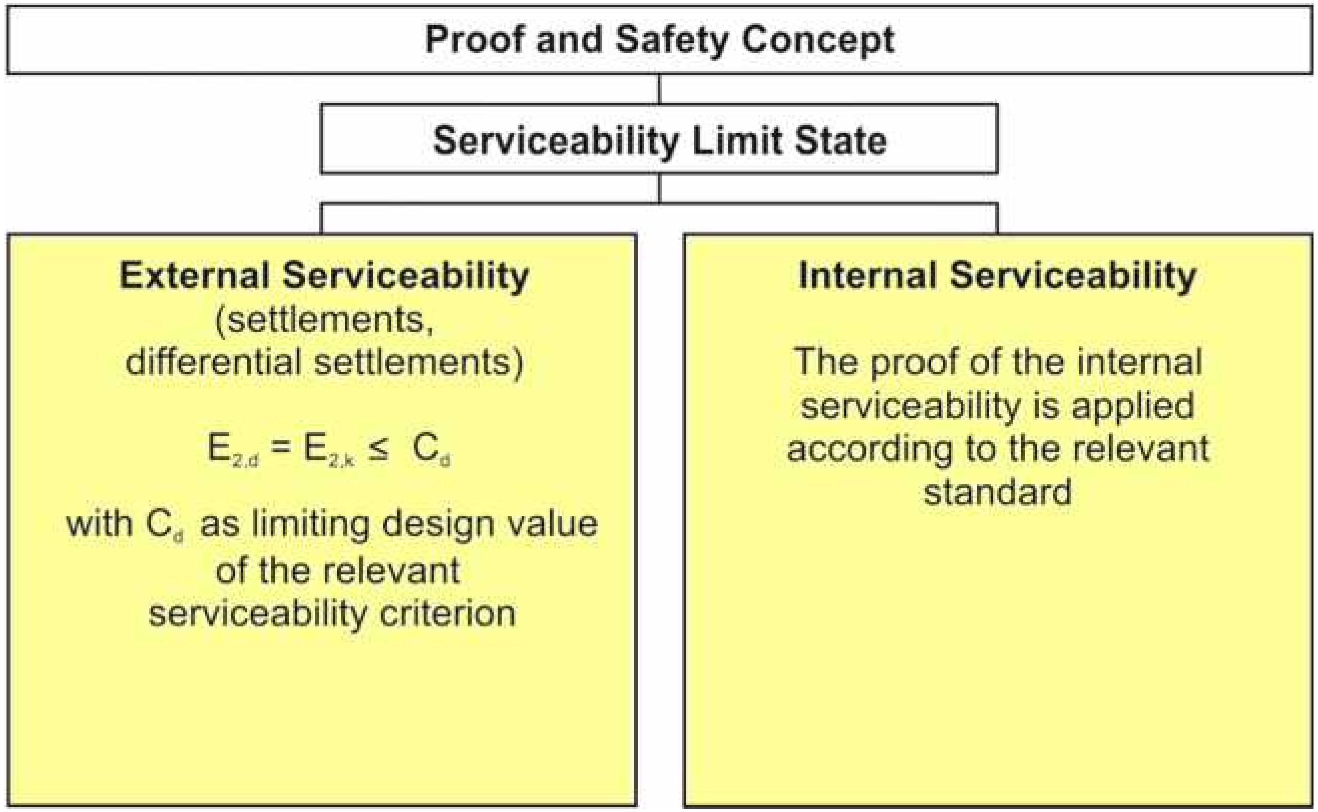
Proof and safety concept for CPRF



SLS is more relevant!

ISSMGE ·
Technical Committee TC 212 Deep Foundations

SIMSG ISSMGE

International Society for Soil Mechanics and Geotechnical Engineering
Société Internationale de mécanique des sols et de la géotechnique

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- 1 -

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

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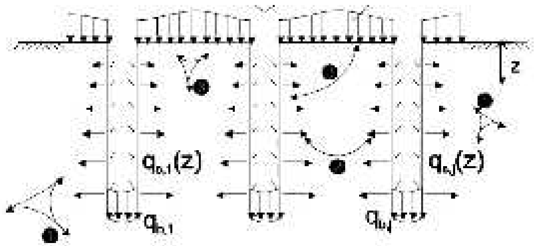
Weidong Wang, China
Limin Zhang, Hong Kong
A.A. Zhussupbekov, Kazakhstan



$$R_{tot,k}(s) = \sum_{j=1}^{m} R_{pile,k,j}(s) + R_{raft,k}(s)$$

International CPRF-Guideline

Details: www.issmge.org/tc212

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Modelling soil-structure interaction

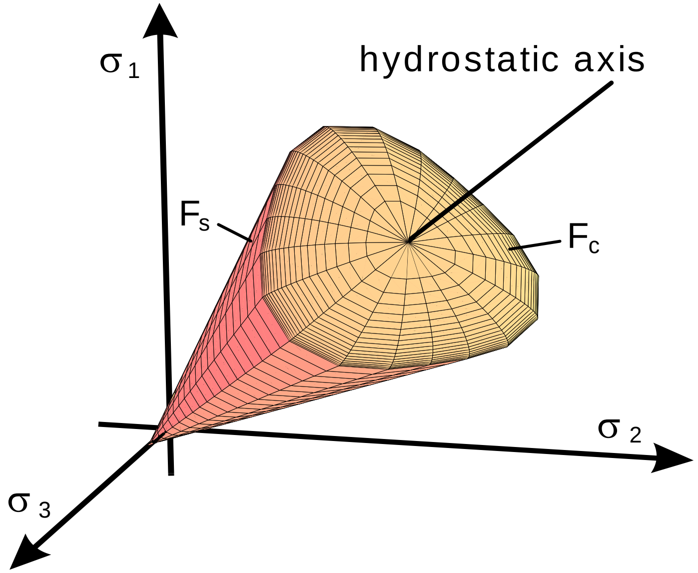
Numerical Analysis

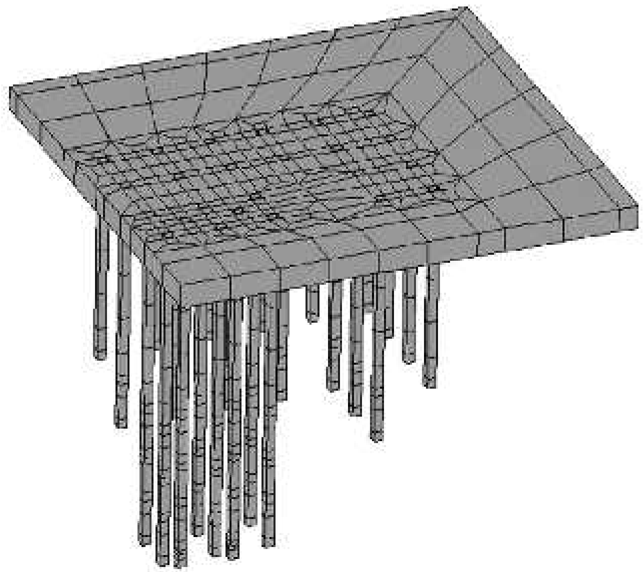
Constitutive law

(non-linear and stress dependent)

Geometry

(3-dimensional model)





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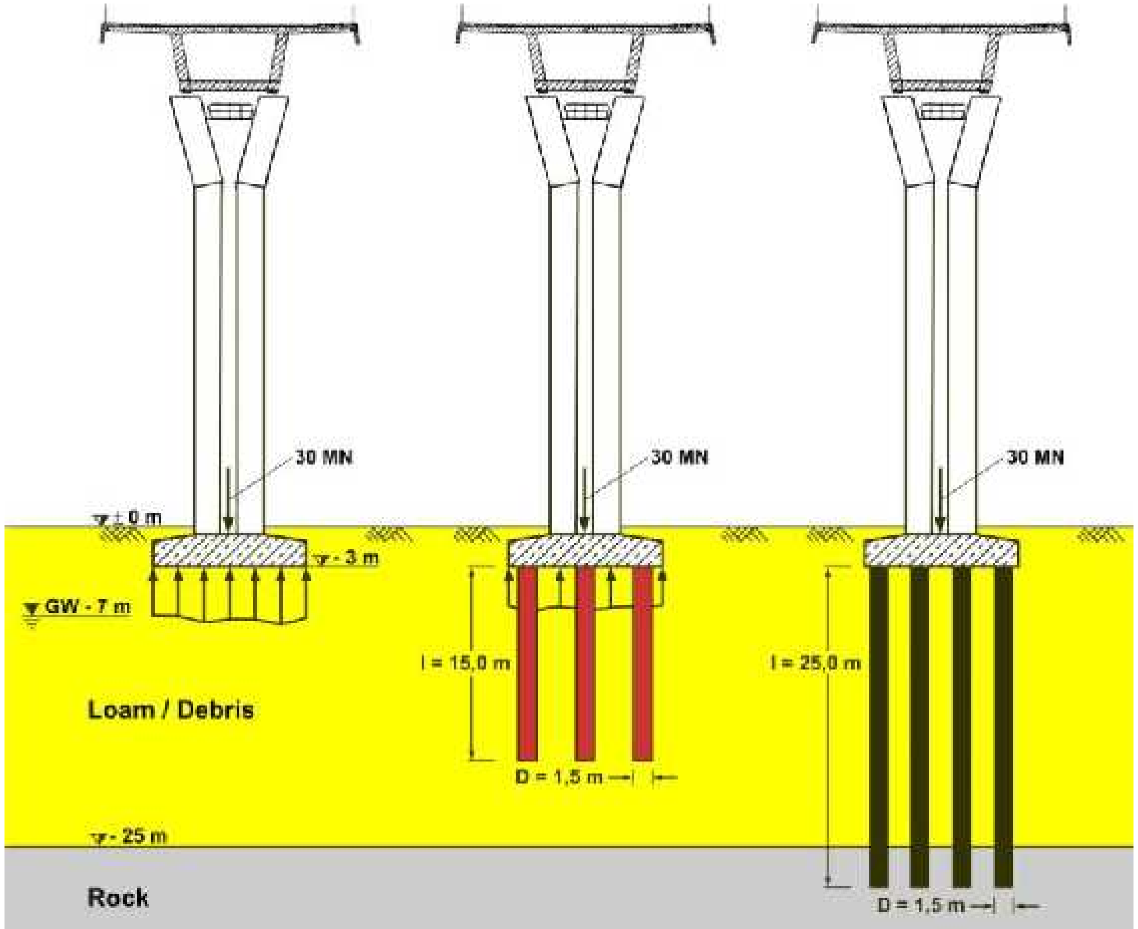
Bridge pier foundation types



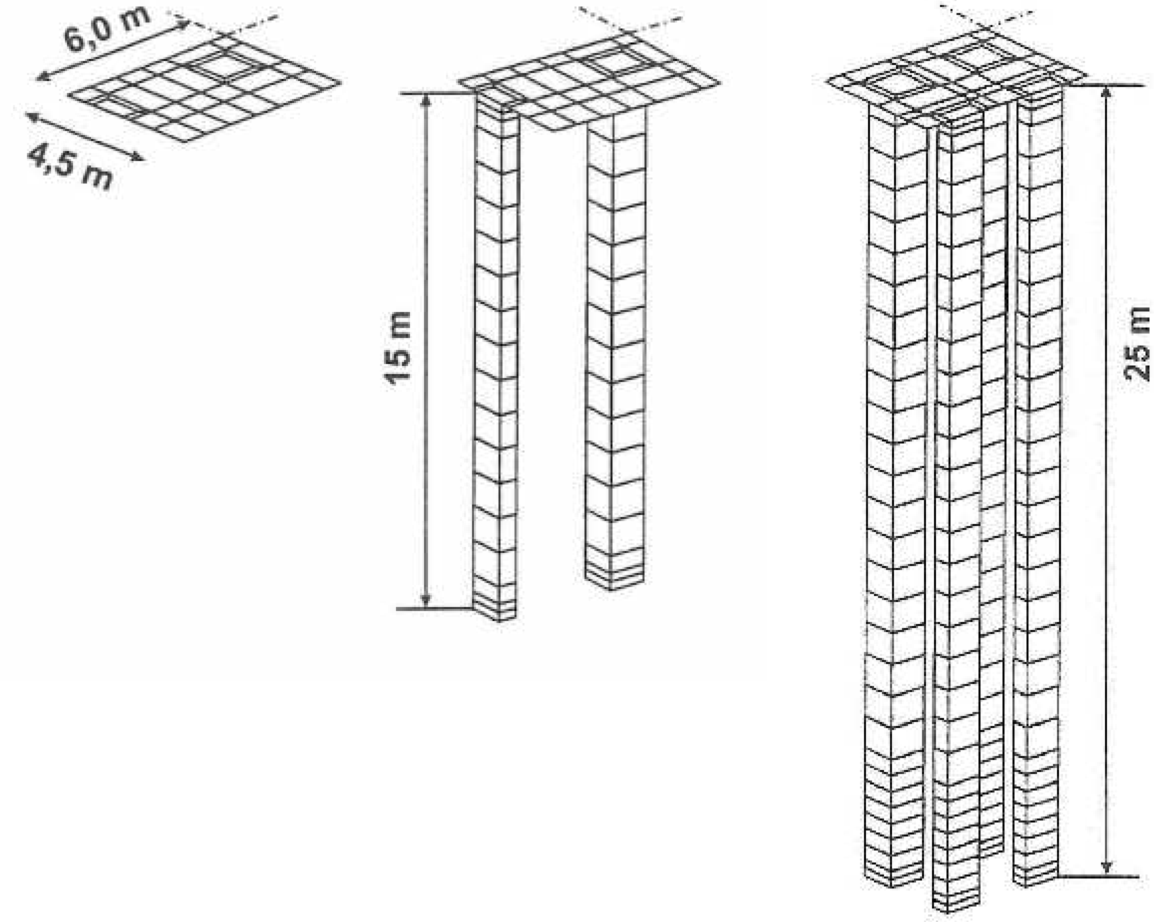
Option 1:
Spread Foundation

Option 2:
CPRF with 6 Piles

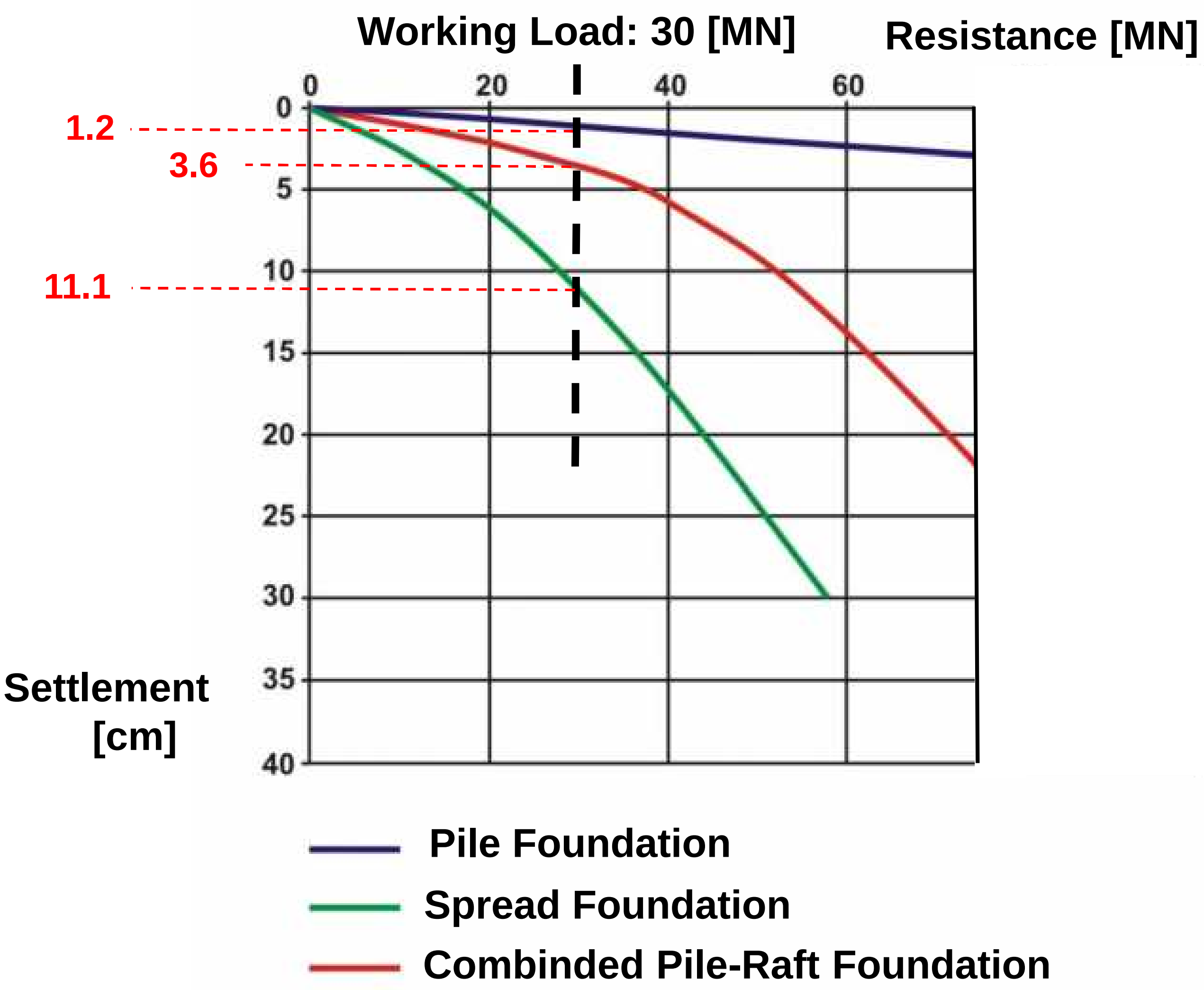
Option 3:
Pile Foundation with 12 Piles

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



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Comparison of costs

	Settlement	Costs of pile production (Assumption: 600 € per meter)
Spread Foundation	11.1 cm	-
CPRF (6 Piles)	3.6 cm	55,000 €
Pile Foundation (12 Piles)	1.2 cm	180,000 €

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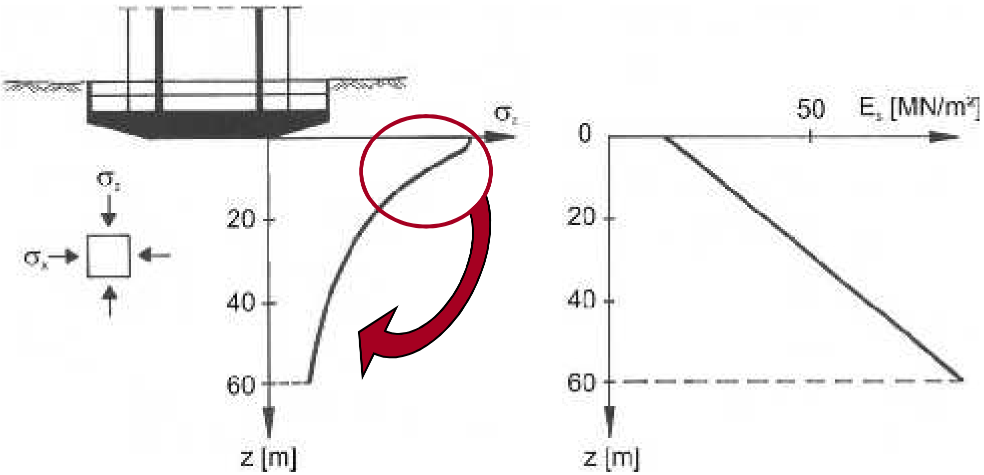
Messeturm · Frankfurt am Main, Germany

Settlements calculated for a shallow foundation: **s > 40 cm**

z = 0 - 20 m → 75 - 80 %



Settlements: $$s = \int_0^z \frac{\sigma(z)}{E(z)} dz$$

→ Combined Pile-Raft Foundation (CPRF)

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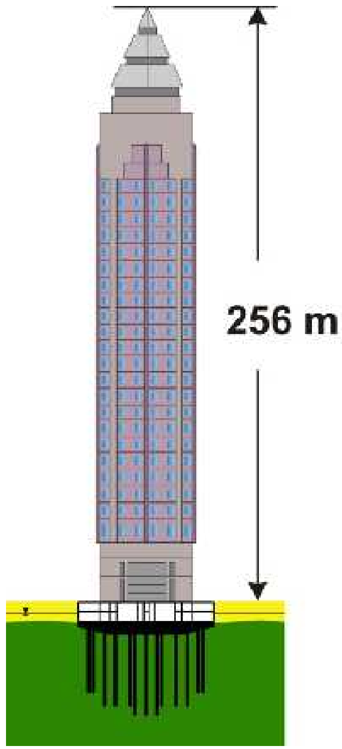

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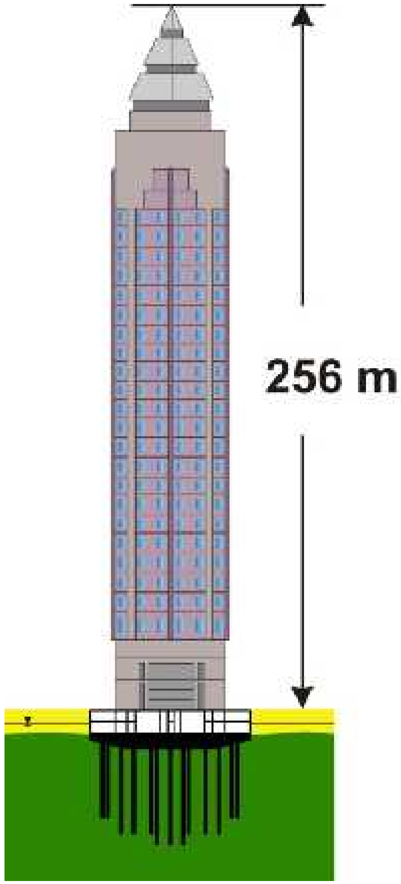
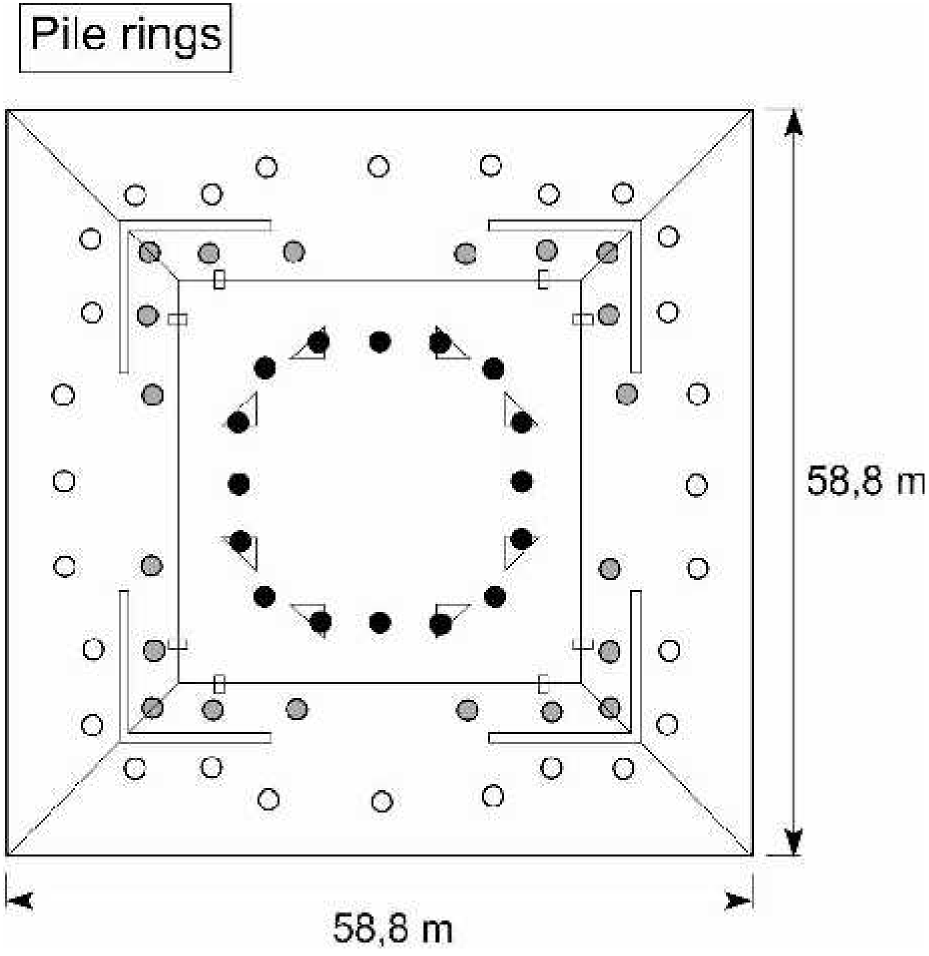
Messeturm · Frankfurt am Main, Germany

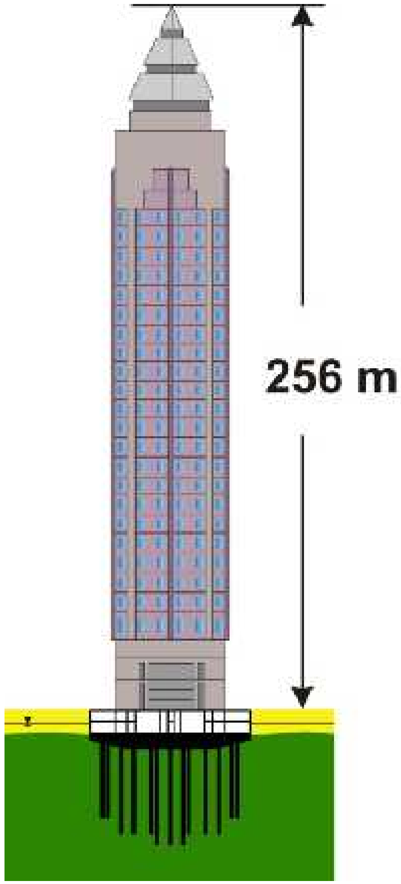
Construction time: 1988 - 1990





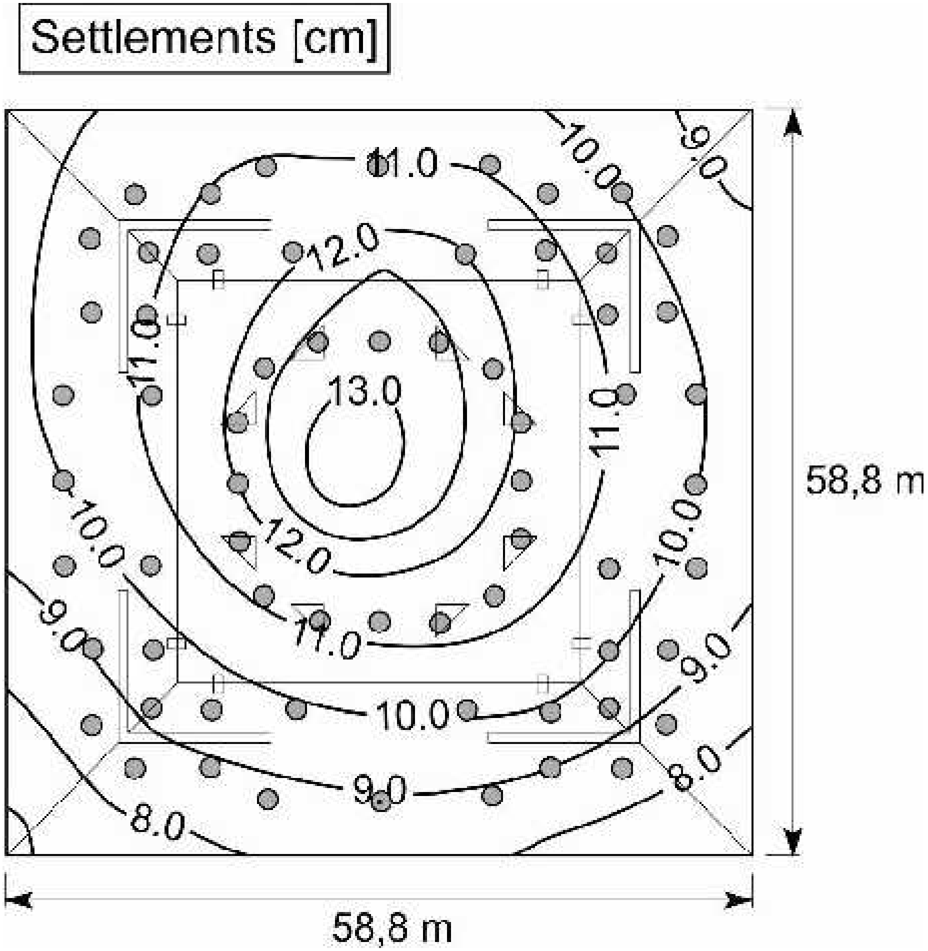
Messeturm · Frankfurt am Main, Germany

Construction time: 1988 - 1990

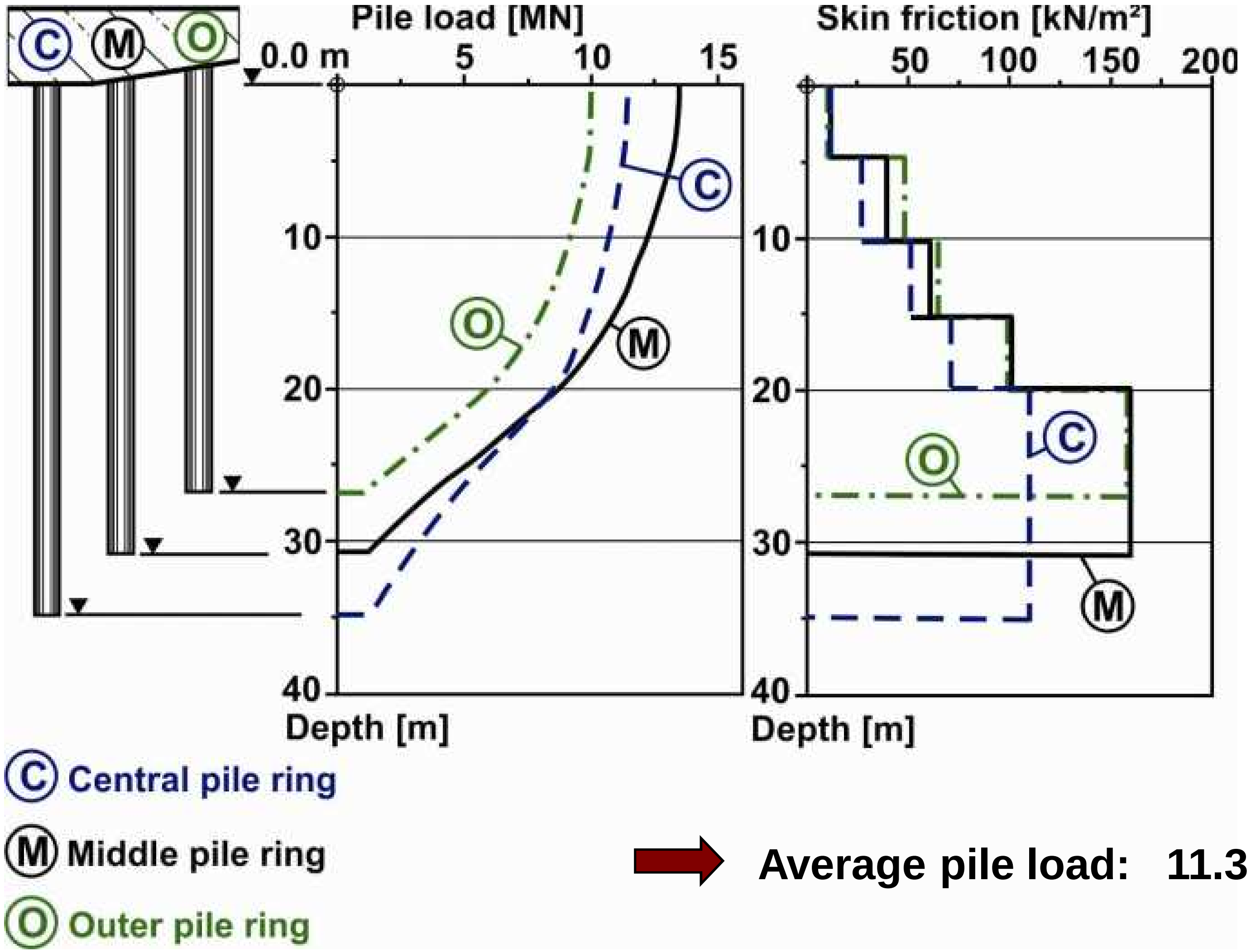


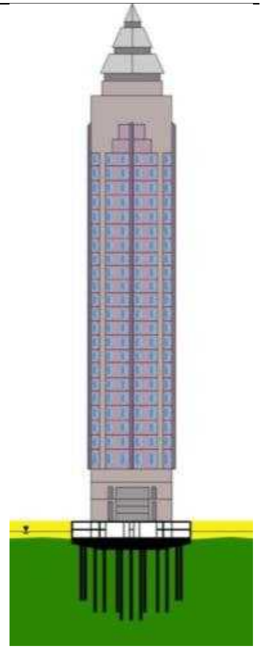
Quaternary sand and gravel

Frankfurt Clay



Messeturm · Frankfurt am Main, Germany





Average pile load: 11.3 MN

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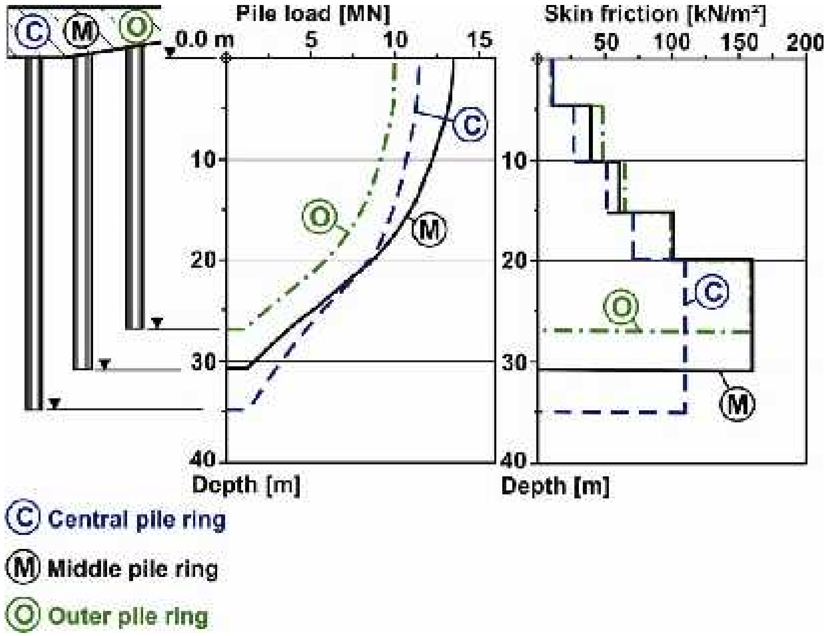
Effective building load: = 1.570 MN

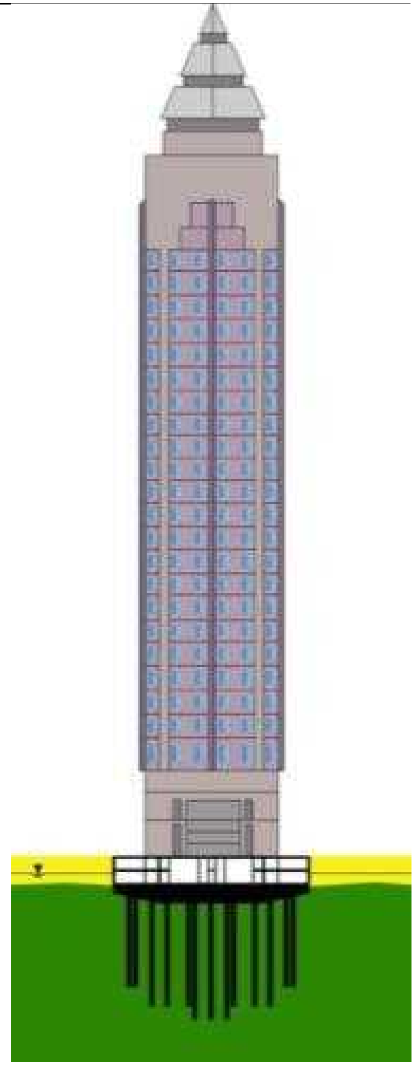
Ultimate pile load: 64 x 11.3 MN = 725 MN

Load transfer by raft: = 845 MN

Contact pressure: 250 kN/m²

$\alpha_{CPRF} = 0.46$





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Messeturm · Frankfurt am Main, Germany

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 ù **1.2 Mio. €**

Pile foundation: 316 piles (l = 30 m)

Costs of pile production:
316 piles of 30 m at 600 €/m ù **5.7 Mio. €**

Savings in costs of pile production **4.5 Mio. €**

CO_2 reduction: 2,500 t

European Central Bank · Frankfurt am Main, Germany

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Comparison of costs for the piles

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

Costs of pile production:
97 piles of 30 m at 600 €/m ù **1.7 Mio. €**

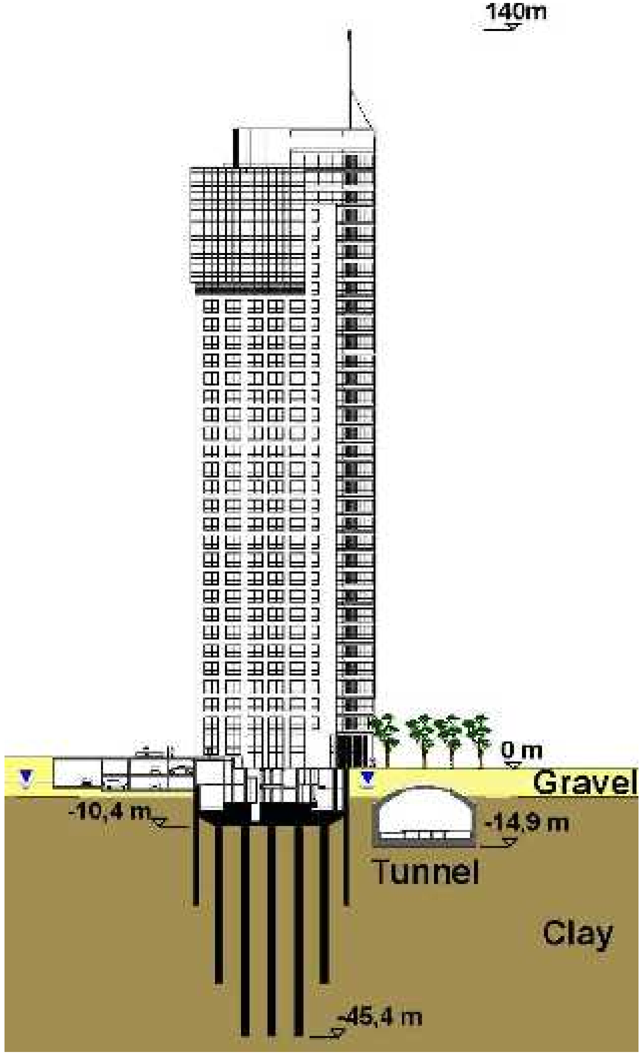
Pile foundation: 490 piles (l = 30 m)

Costs of pile production:
490 piles of 30 m at 600 €/m ù **8.8 Mio. €**

Savings in costs of pile production **7.1 Mio. €**

CO_2 reduction: 3,300 t

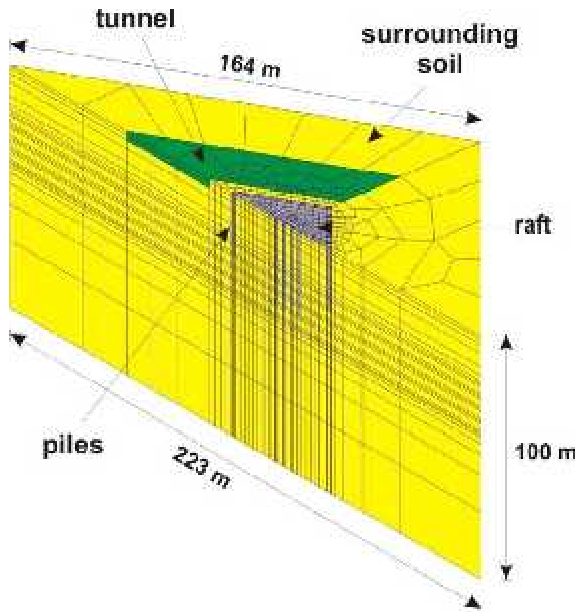
City Tower · Offenbach am Main, Germany



Construction Period: 2001 - 2003

Foundation: CPRF

Height: 120 m



City Tower · Offenbach am Main, Germany

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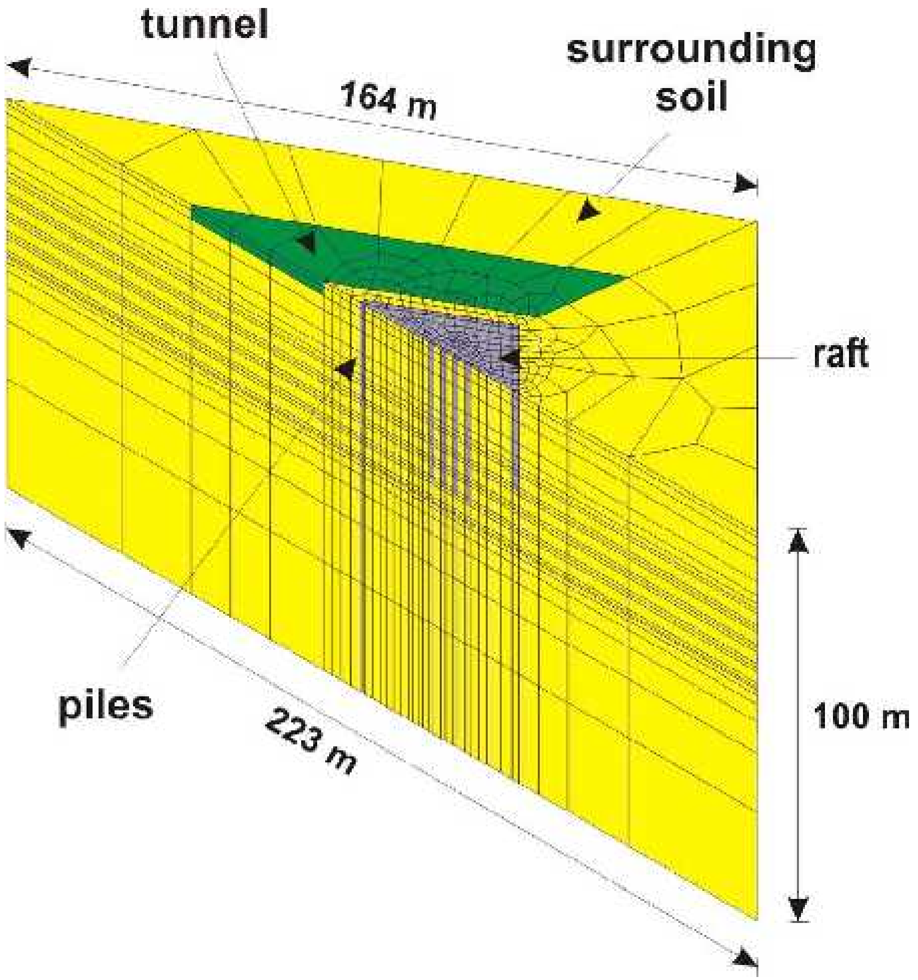

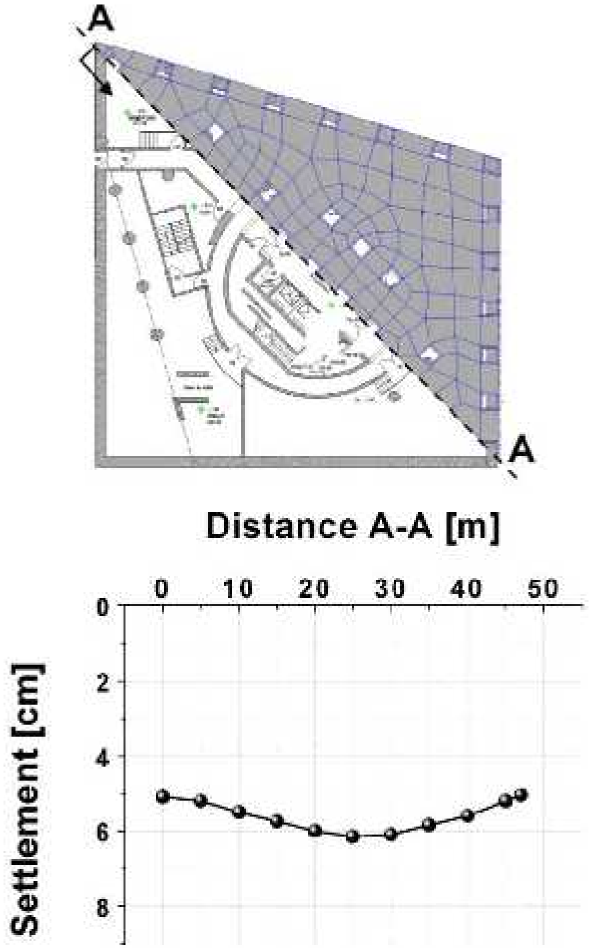

City Tower · Offenbach am Main, Germany

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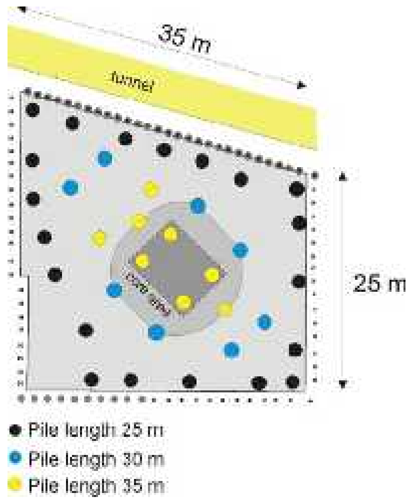
Comparison of costs for the piles

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

Costs of pile production:
36 piles of ù 30 m at 600 €/m ù **0.7 Mio. €**



Pile foundation: 113 piles (l = 30 m)

Costs of pile production:
113 piles of 30 m at 600 €/m ù **2.0 Mio. €**

Savings in costs of pile production: **1.3 Mio. €**

CO_2 reduction: 1,900 t

Opernturm · Frankfurt am Main, Germany

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Comparison of costs for the piles

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

Costs of pile production:
57 piles of 40 m at 600 €/m ù **1.4 Mio. €**

Pile foundation: 246 piles (l = 30 m)

Costs of pile production:
246 piles of 30 m at 600 €/m ù **4.4 Mio. €**

Savings in costs of pile production: **3.0 Mio. €**

CO_2 reduction: 2,250 t

Maintower · Frankfurt am Main, Germany

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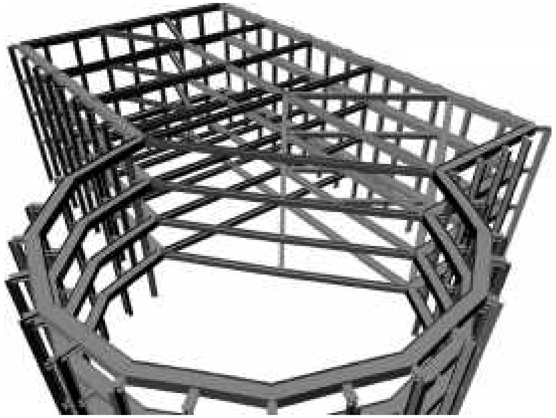
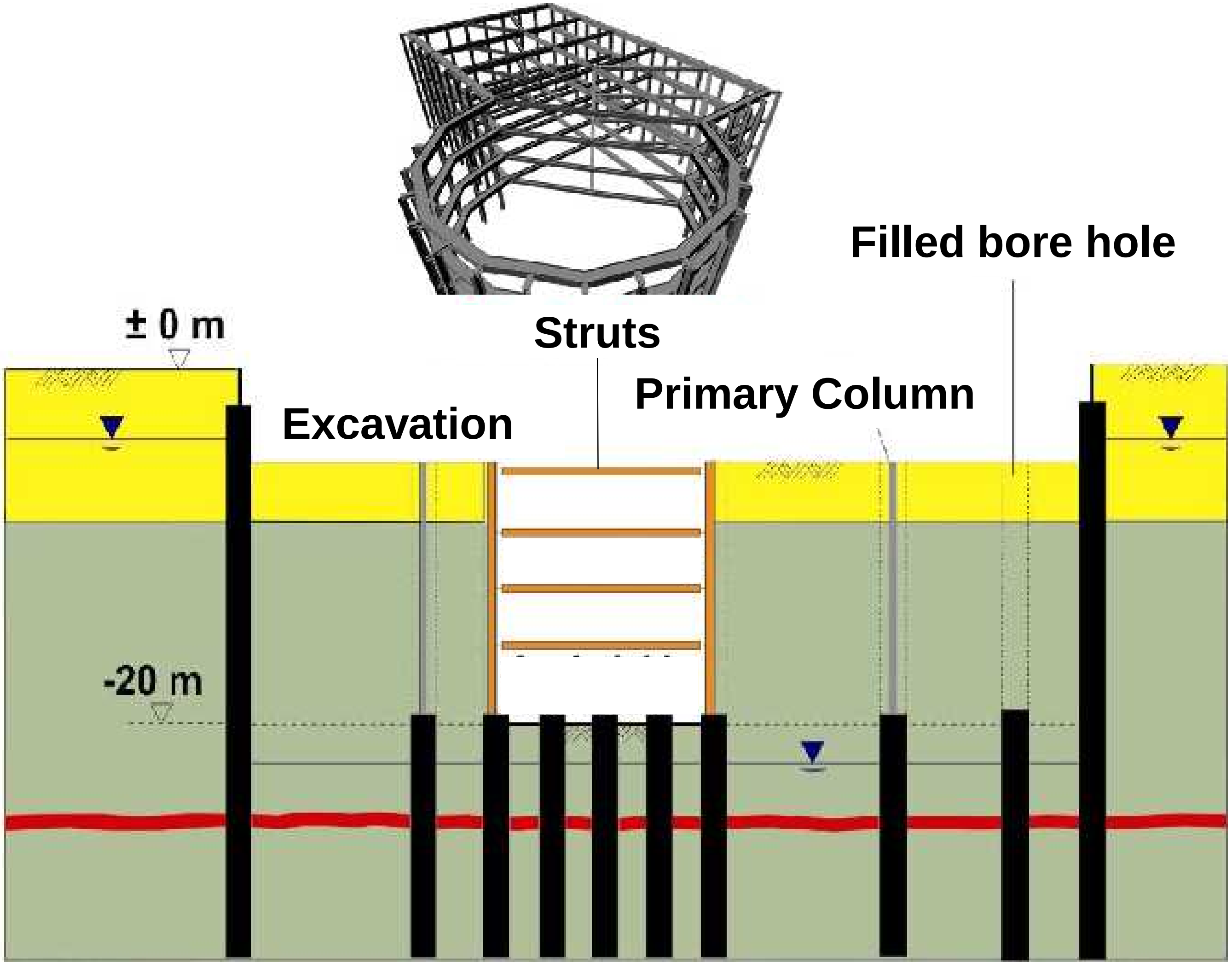
Optimisation by construction in 2 directions:

Tow-down method



Maintower · Frankfurt am Main, Germany



Maintower · Frankfurt am Main, Germany

Results of optimised design:

- minimised deformations
- minimised construction time

Maintower · Frankfurt am Main, Germany

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Comparison of costs for the piles

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

Costs of pile production:
112 piles of 30 m at 600 €/m ù **2.0 Mio. €**

Pile foundation: 277 piles (l = 30 m)

Costs of pile production:
277 piles of 30 m at 600 €/m ù **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

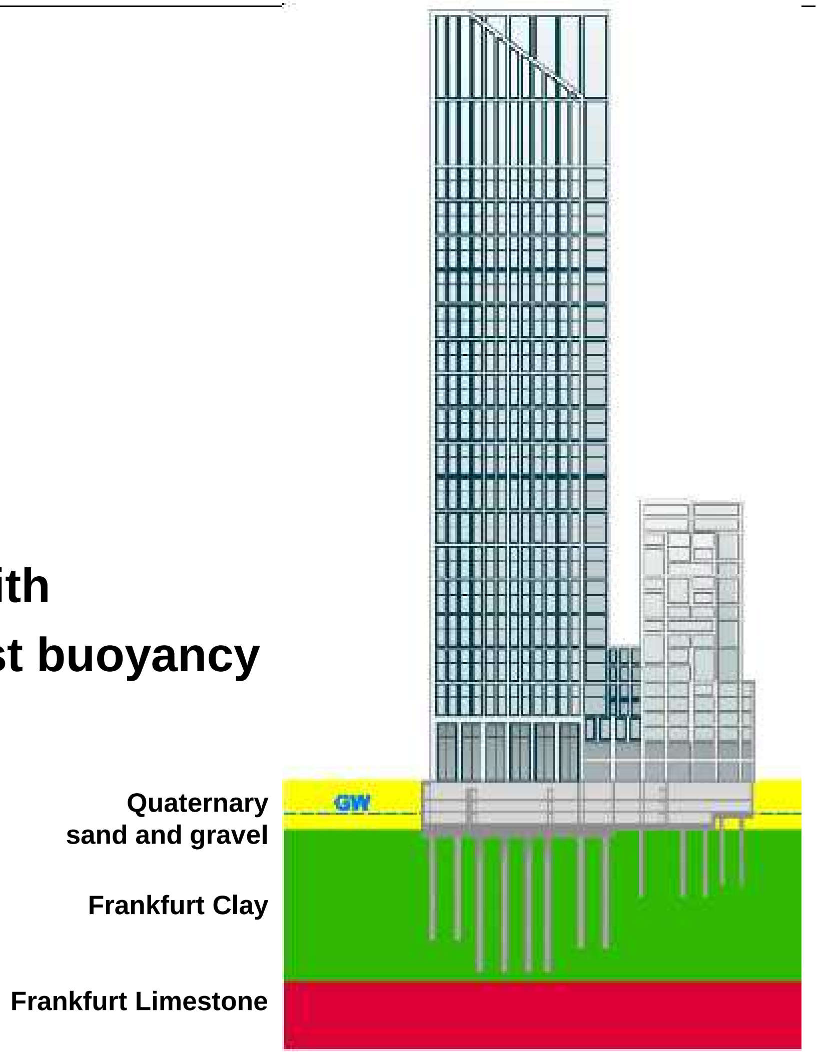
Height: 170 m

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



Taunusturm · Frankfurt am Main, Germany

Living tower:

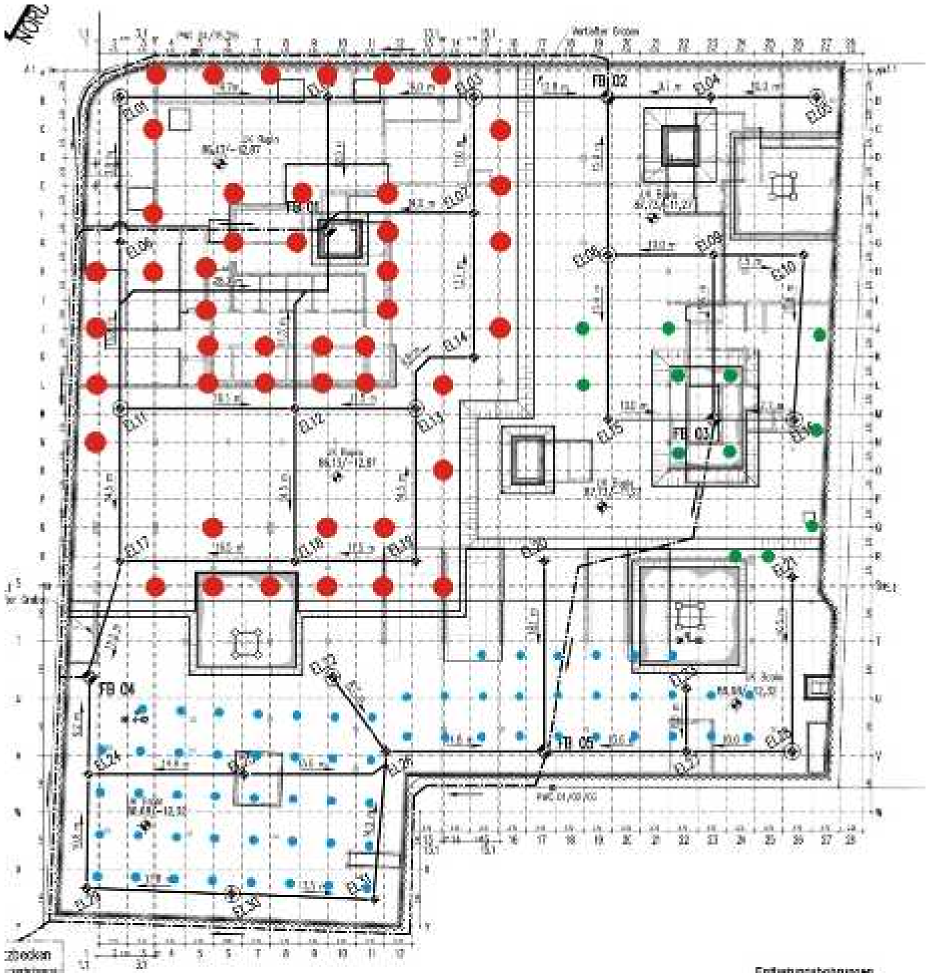
- **piles: 12**
- **foundation raft: 1.2 m**

High-rise buildings:

- **piles: 46**
- **foundation raft: 2.8 m**

Underground parking:

- **piles: 65**
- **foundation raft: 0.9 m**



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Taunusturm · Frankfurt am Main, Germany

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Taunusturm · Frankfurt am Main, Germany

Taunusturm · Frankfurt am Main, Germany

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Comparison of costs for the piles

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

Costs of pile production:
46 piles of 25 m at 600 €/m ù **0.7 Mio. €**

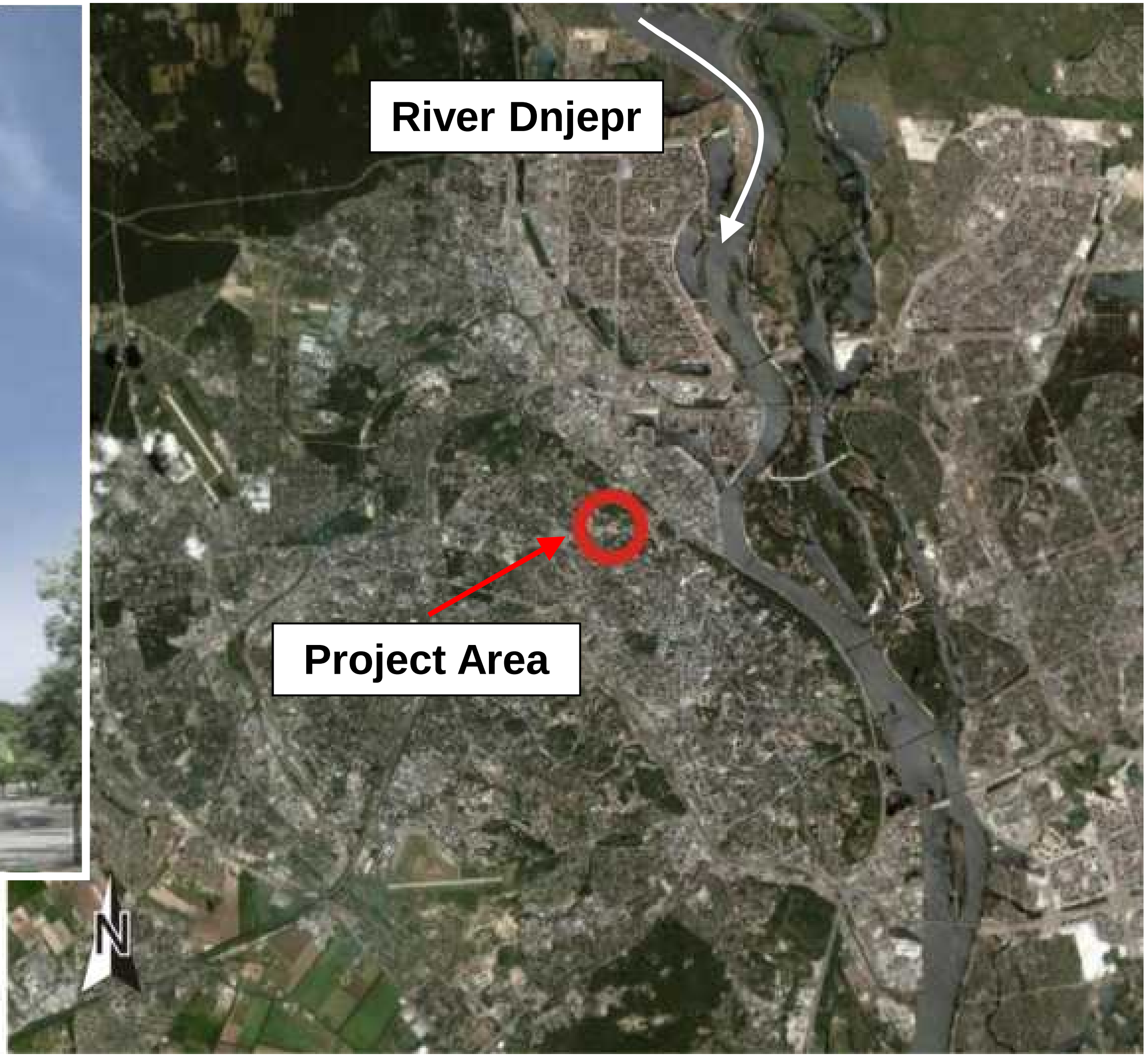
Pile foundation: 277 piles (l = 30 m)

Costs of pile production:
230 piles of 30 m at 600 €/m ù **4.1 Mio. €**

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

CO_2 reduction: 2,540 t

Mirax Plaza Tower A · Kiev, Ukraine



Mirax Plaza Tower A · Kiev, Ukraine

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Foundation systems

Barrette foundation:

120 Barrettes

l = 40 m

2.8 m x 0.8 m

Load tests

Invention of a numerical model

Foundation design

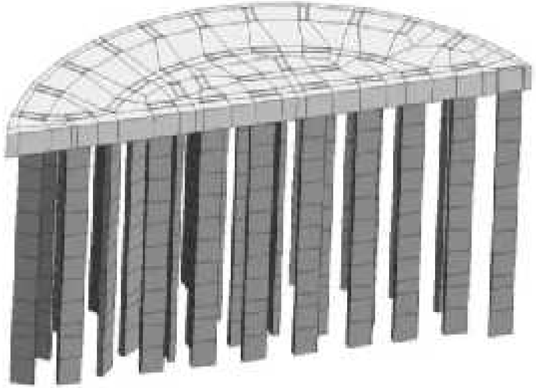
Realised foundation

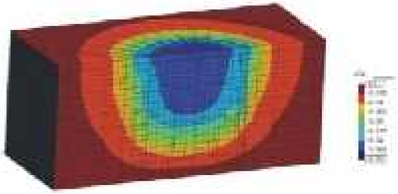
CPRF:

64 Barrettes

l = 33 m

2.8 x 0.8 m





First CPRF

in Ukraine (α_{CPRF} = 0.88)

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 ù **1.9 Mio. €**

Barrett foundation: 120 barretts (l = 40 m)

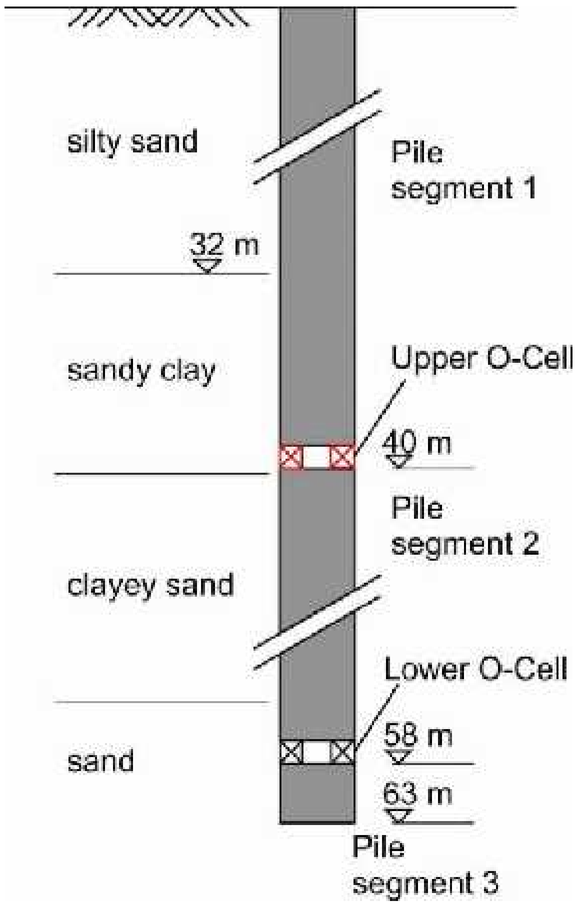
Costs of barrett production:
120 barretts of 40 m at 920 €/m ù **4.4 Mio. €**

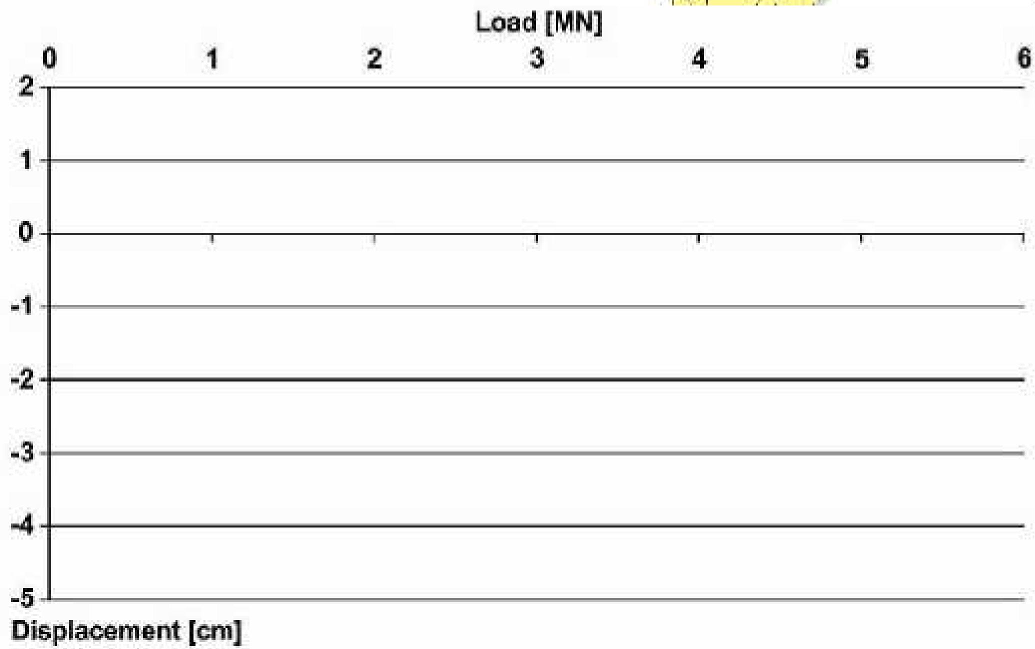
Savings in costs of barrett production: 2.5 Mio. €

CO_2 reduction: 1,550 t

Back analysis for calibration of numerical simulations ĕ Lagos, Nigeria

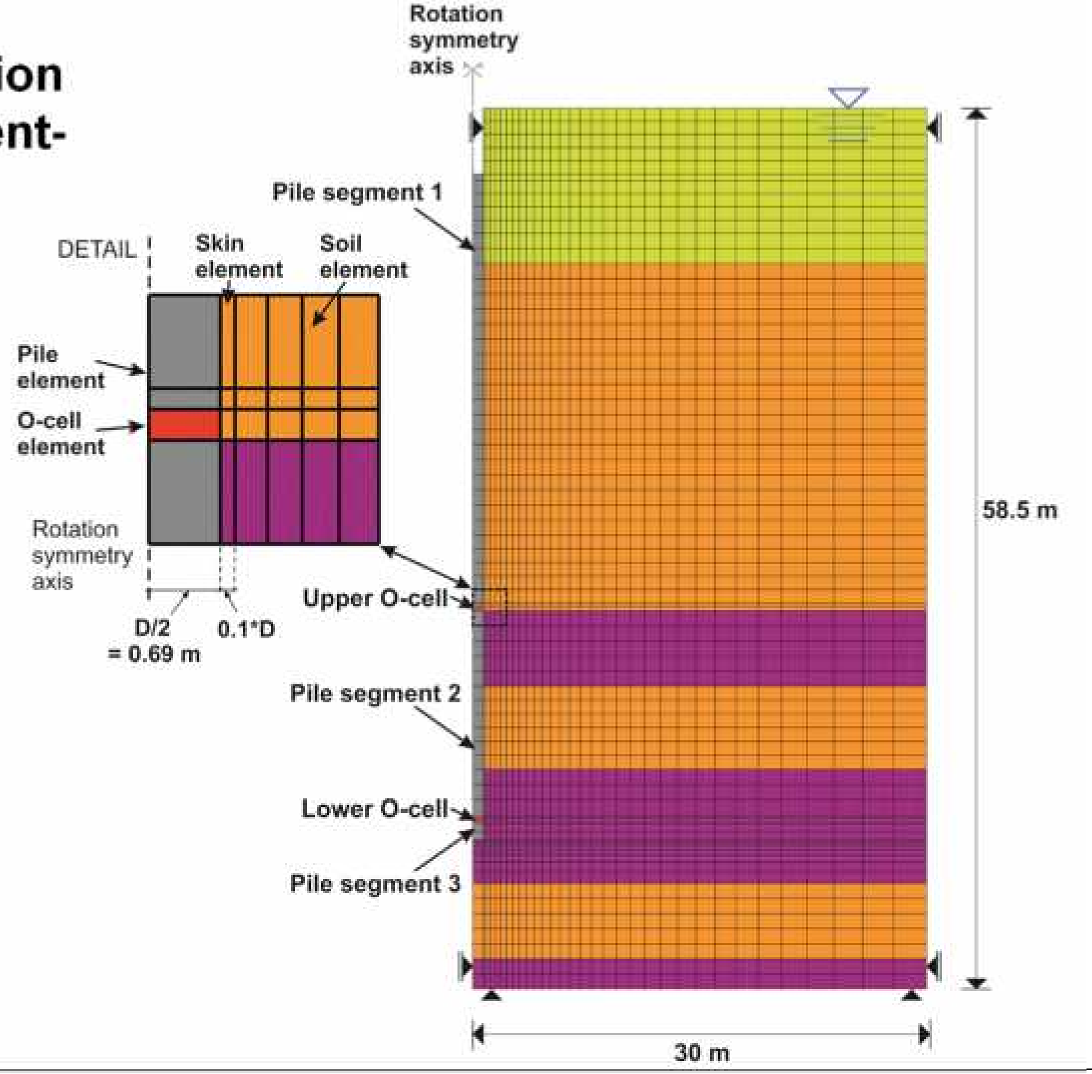
Pile load test with Osterberg-Cells (O-Cells)





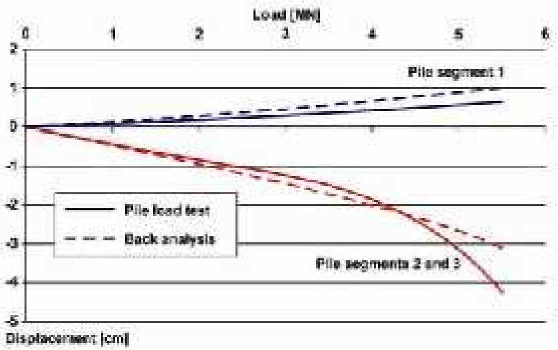
Back analysis for calibration of numerical simulations – Lagos, Nigeria

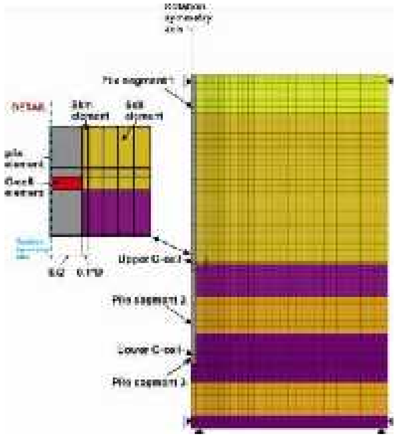
- **Numerical simulation using Finite-Element-Method (FEM)**

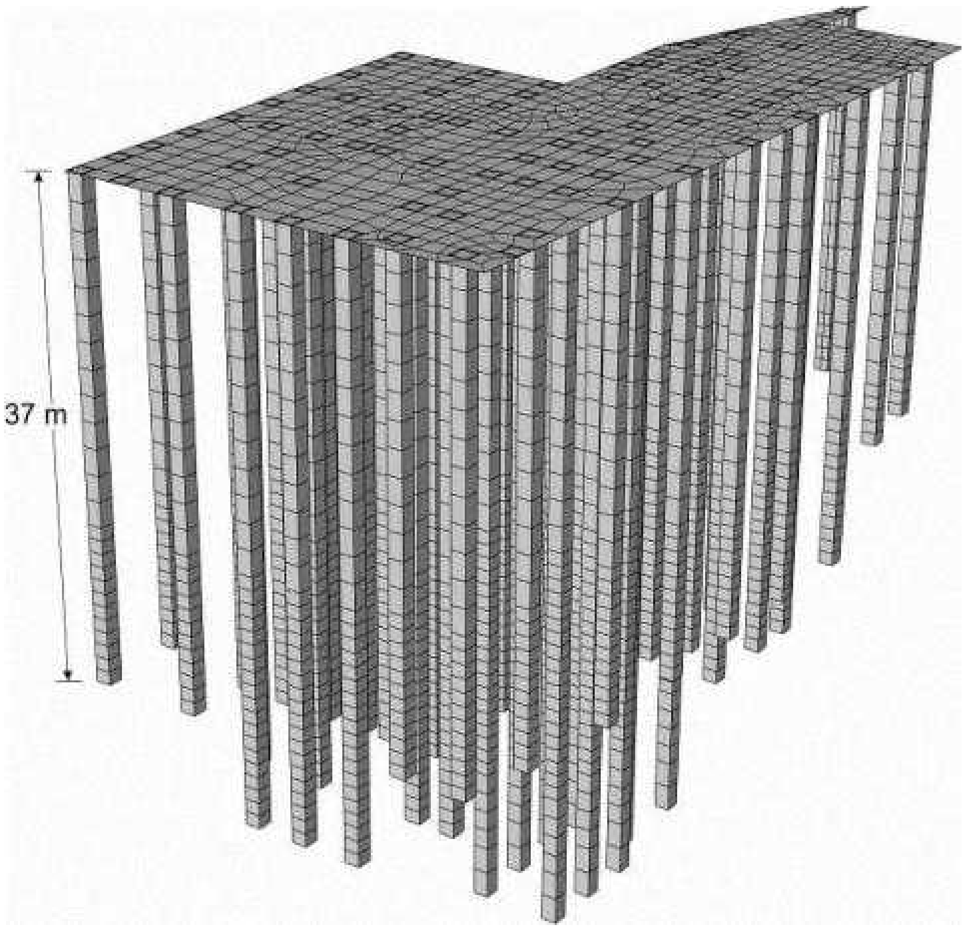


Back analysis for calibration of numerical simulations ĕ Lagos, Nigeria

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

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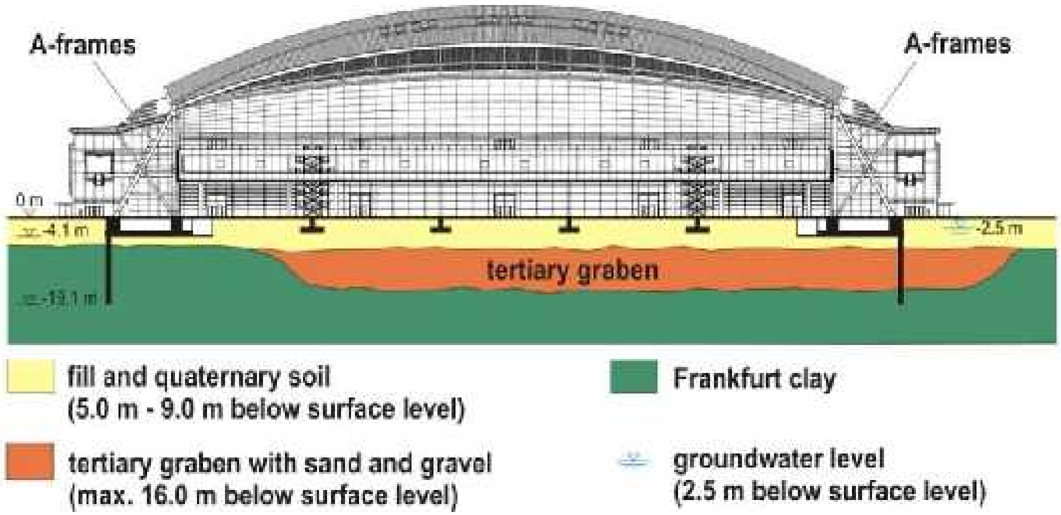
New Exhibition Hall 3 in Frankfurt am Main

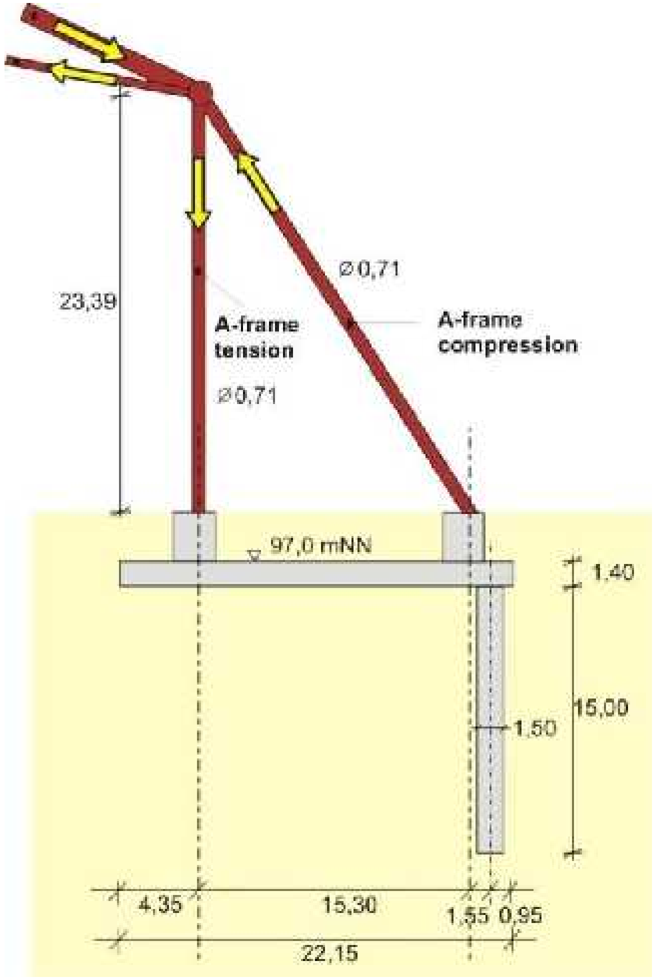
- roof with a free span of 165 m
- horizontal loads on foundation (CPRF) resulting from arch trust of the roof



Combined Pile-Raft Foundation (CPRF) and horizontal loading

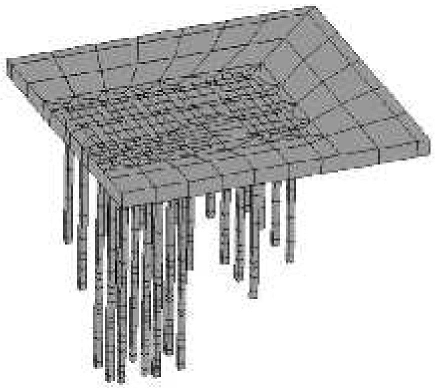
New Exhibition Hall 3 in Frankfurt am Main

- 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:** $\alpha_{CPRF} = 0.5 \; \dots \; 0.7$



CPRF coefficient:

$$\sim_{CPRF} = \frac{\sum_{j=1}^{m} R_{pile,k,j}(s)}{R_{tot,k}(s)}$$

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Thank you for your kind attention!

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