CG 22
DEEP (PILE) FOUNDATIONS

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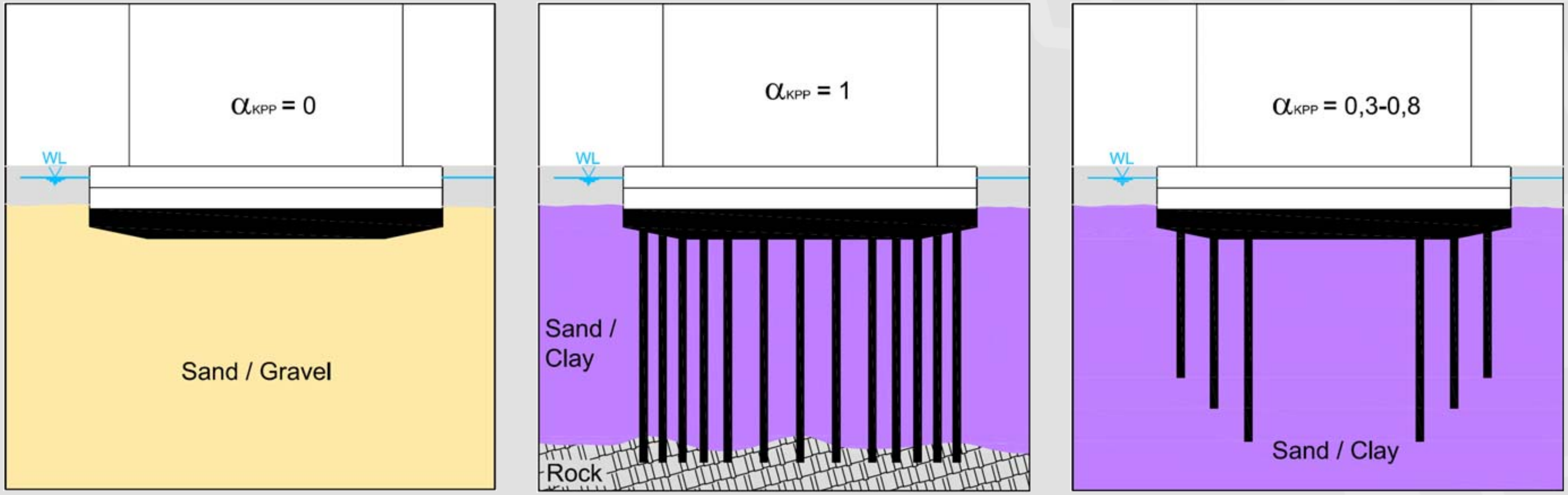
Acknowledgement for providing some of the material: H.-P. Nottrodt, P.-A. von Wolffersdorff

CONTENTS

- **Introduction**
- **Analysis of a single pile**
  - Influence of discretization
  - Influence of interface elements
  - Influence of dilatancy
- **Examples of practical applications**
- **Comments on 3D Foundation**

INTRODUCTION

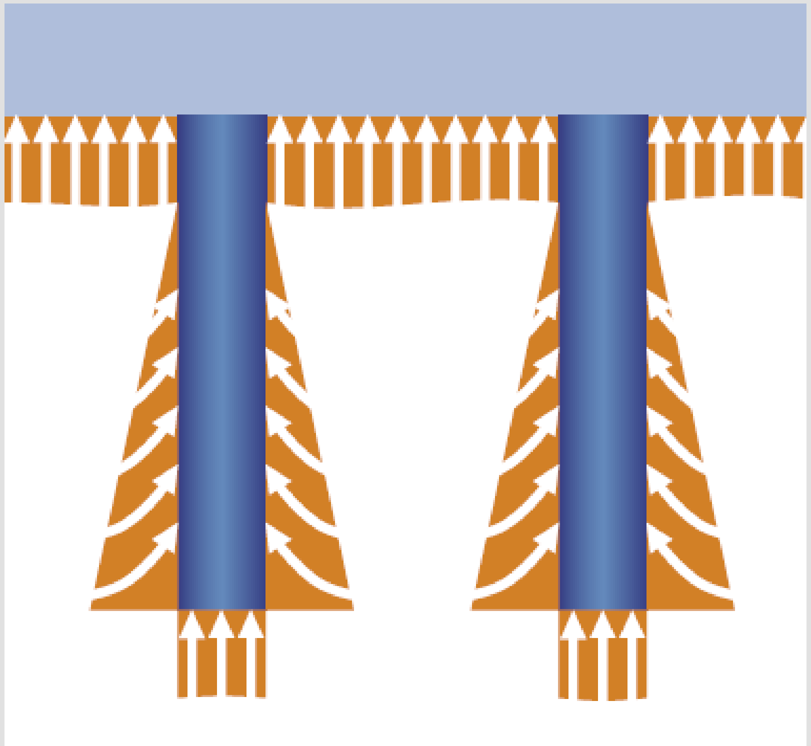
Typical types of foundations

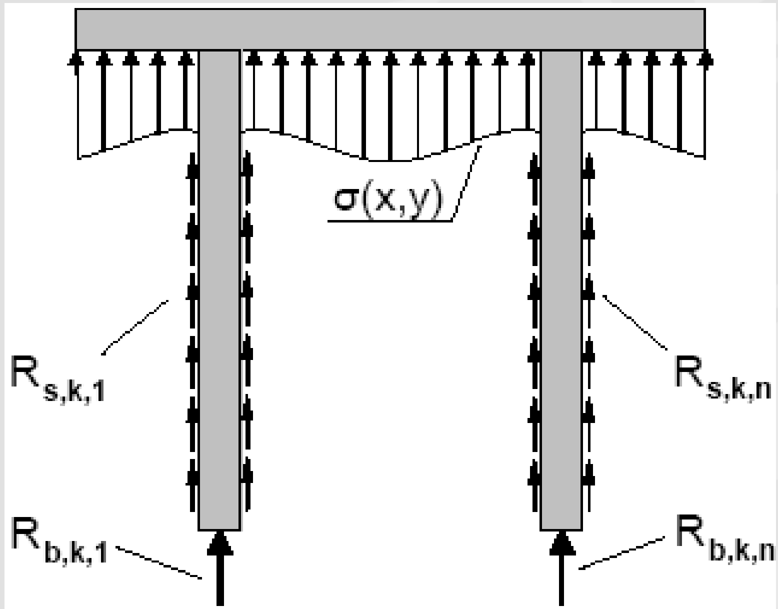


Foundation slab | Conventional pile foundation | Piled raft foundation

INTRODUCTION

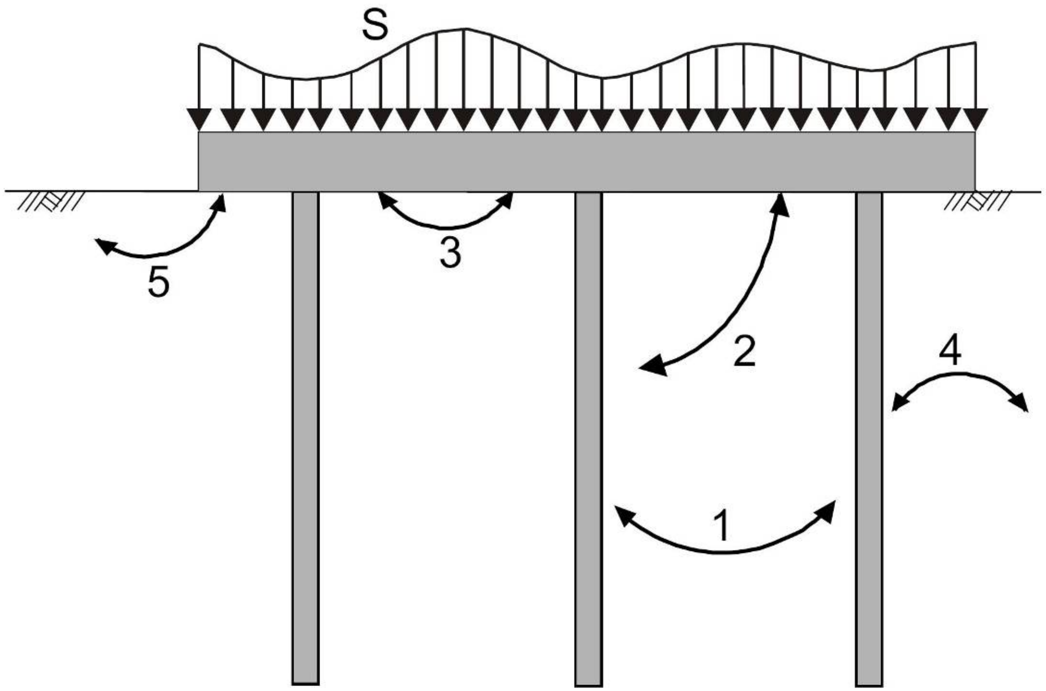
Piled raft foundation





INTRODUCTION

Piled raft foundation



1 Interaction pile - pile

2 Interaction pile - slab

3 Interaction slab - slab

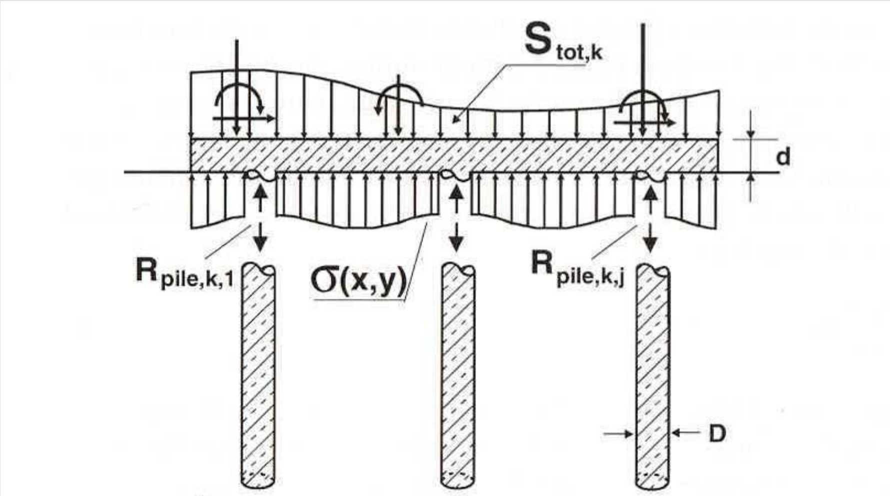
4 Interaction pile - soil

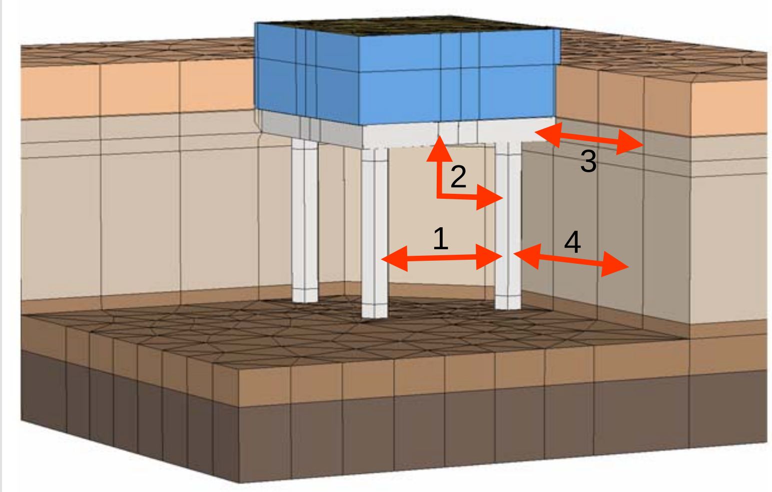
5 Interaction slab - soil

S … load from superstructure

INTRODUCTION

Piled raft foundation





1 pile - pile

2 pile - slab

3 soil - slab

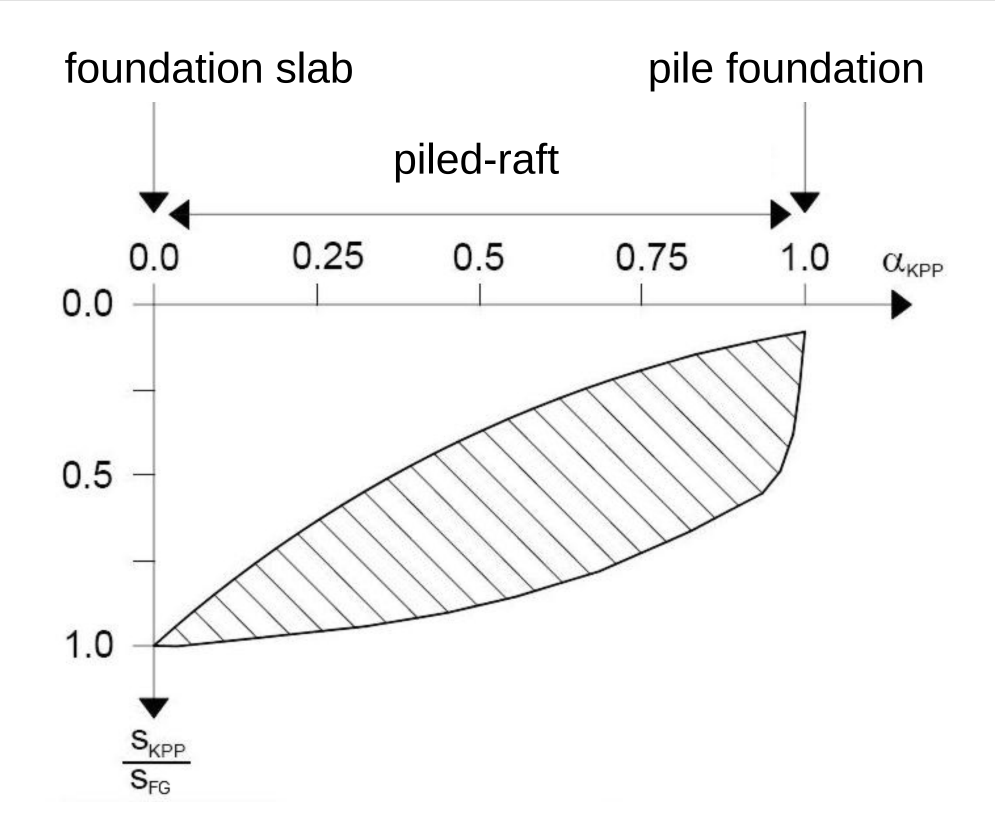
4 soil - pile

Pile-raft coefficient $\alpha_{KPP} = \frac{\sum R_{Pile,k}}{R_{kl}}$

R_{kl} from $\sigma_{(x,y)}$

INTRODUCTION

Range of settlement reduction to be expected from piled-raft foundation

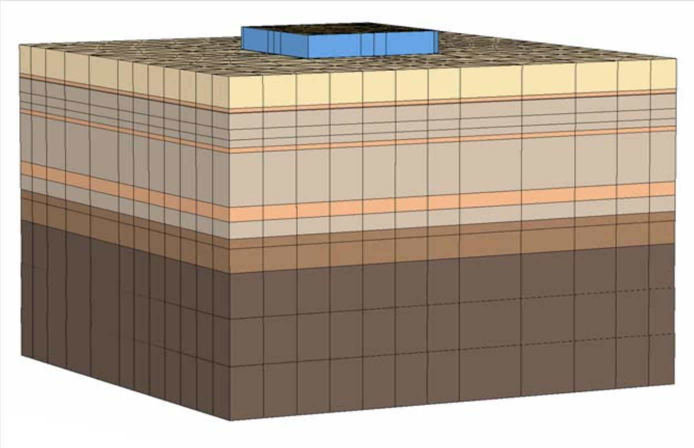


$$\alpha_{KPP} = \frac{\sum R_{Pile,k}}{R_{kl}}$$

from: Hanisch, J., Katzenbach, R. und König, G. (eds.), 2002

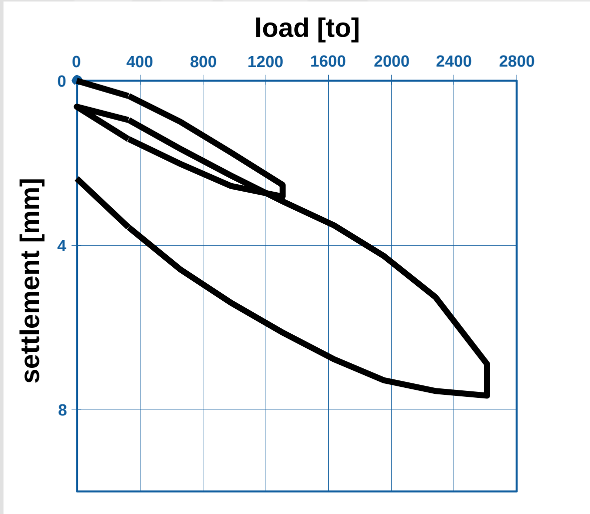
INTRODUCTION

Analysis of piled raft / pile foundations



Realistic modelling by means of numerical methods, e.g. finite element method

Pile load tests for assessment of settlement behaviour and bearing capacity of single piles or pile groups

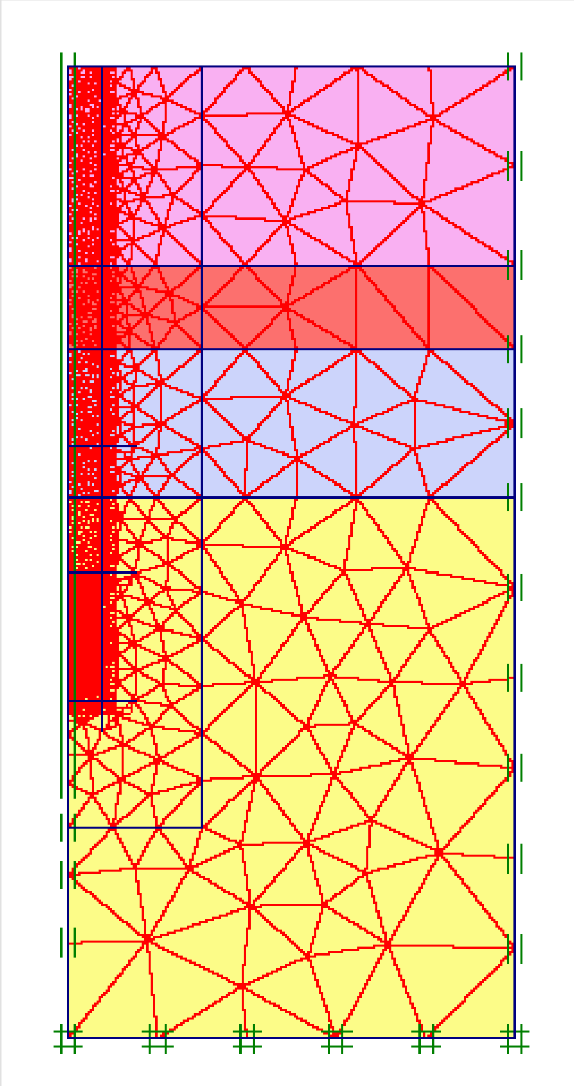


Validation of numerical model by analysing pile load test

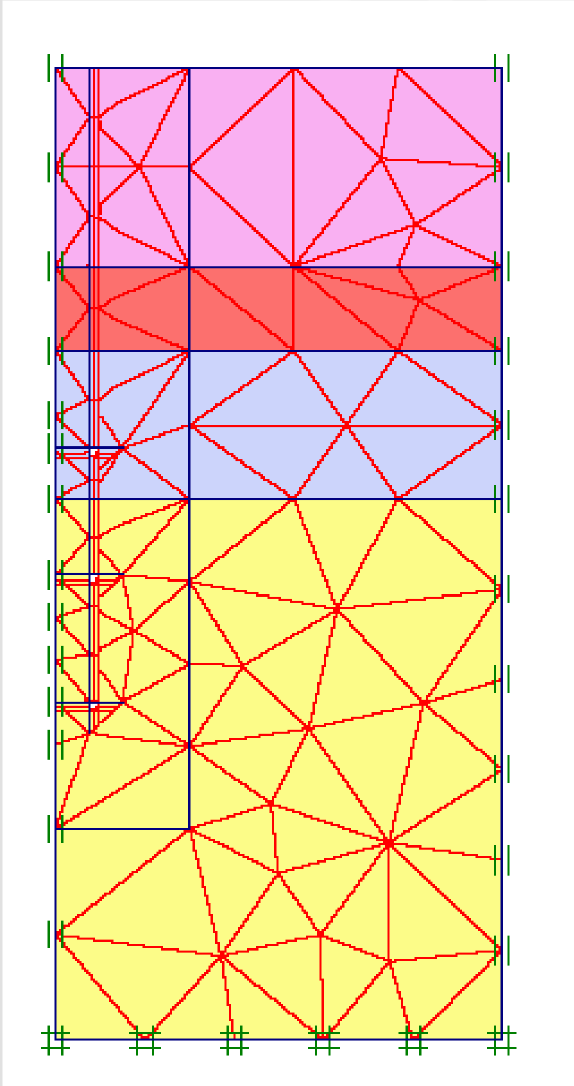
ANALYSIS OF A SINGLE PILE

l_{esf} .. local element size factor

fine mesh, l_{esf} = 0.1



coarse mesh, l_{esf} = 1.0

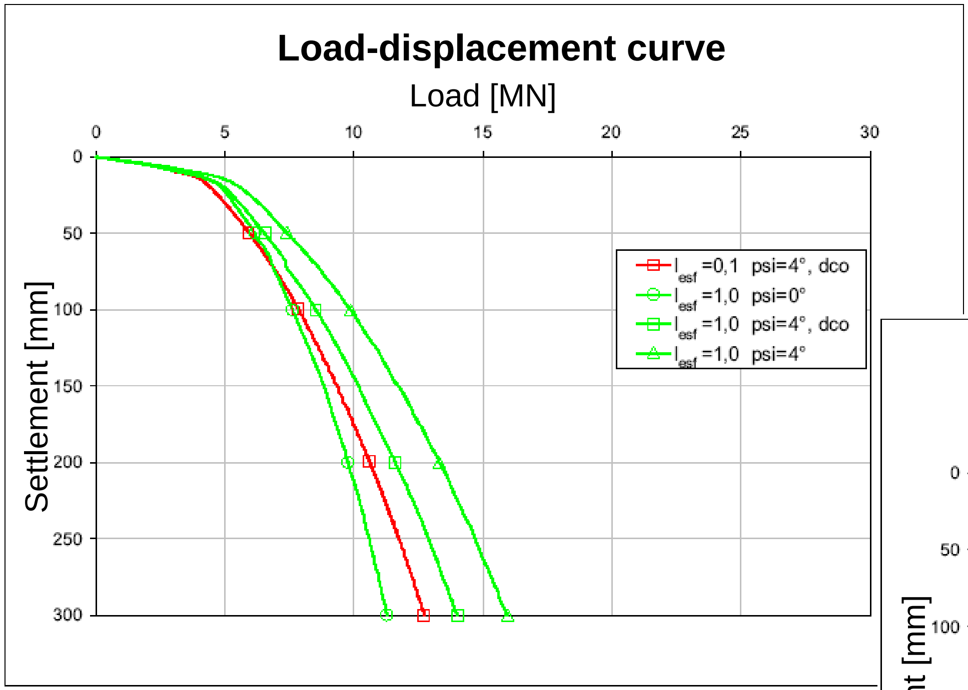


from M. Köbsch, 2007

Hardening Soil Model
R_{inter} = 1.0

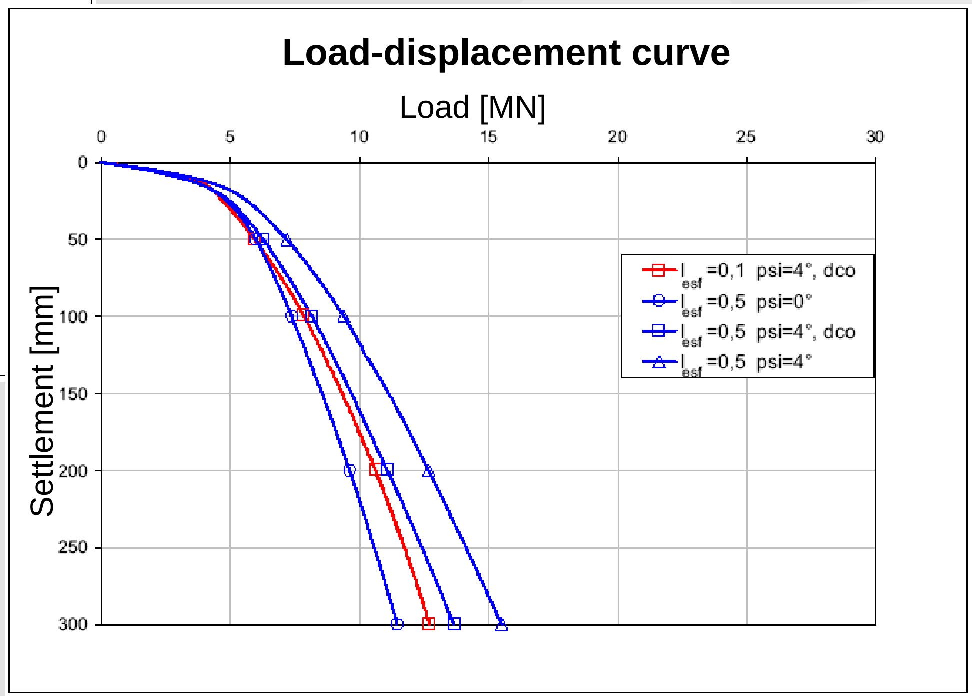
ANALYSIS OF A SINGLE PILE

Influence of discretization and dilatancy



dco … dilatancy cut off

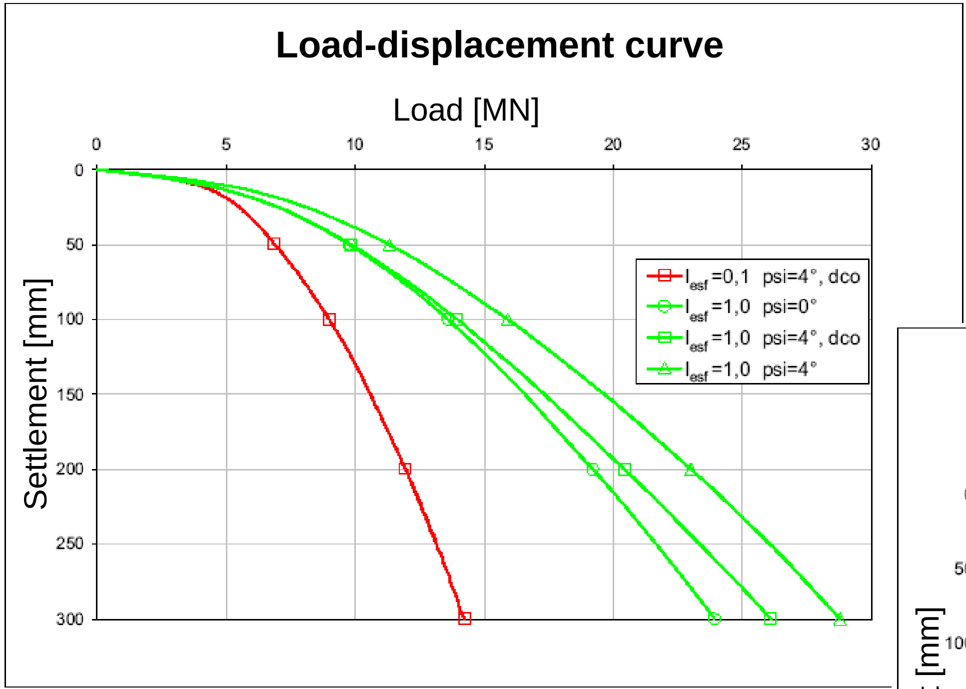
With interface elements



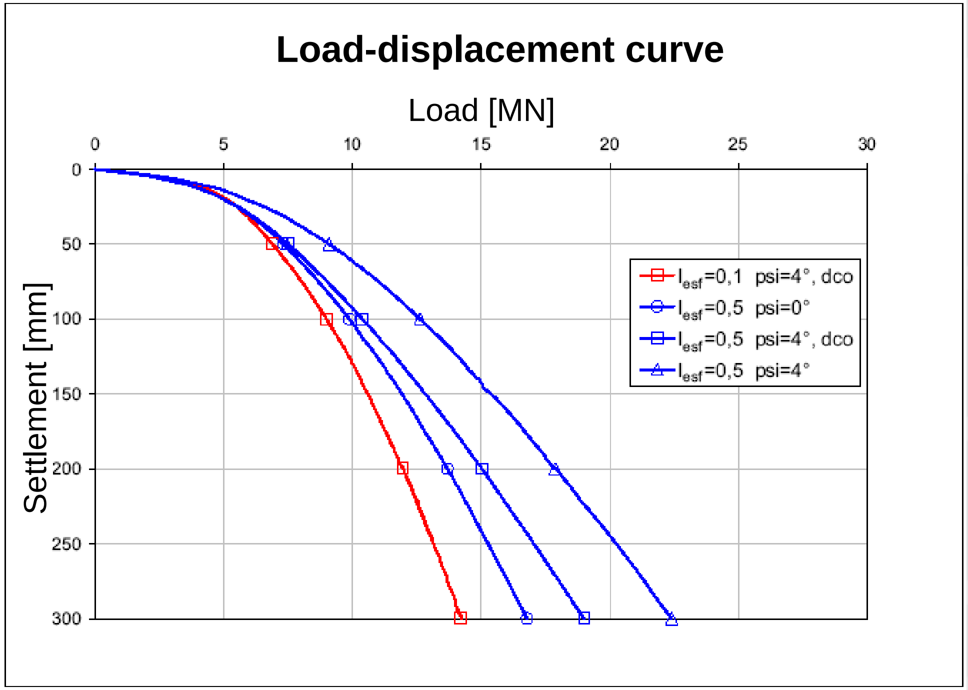
from M. Köbsch, 2007

ANALYSIS OF A SINGLE PILE

Influence of discretization and dilatancy



Without interface elements



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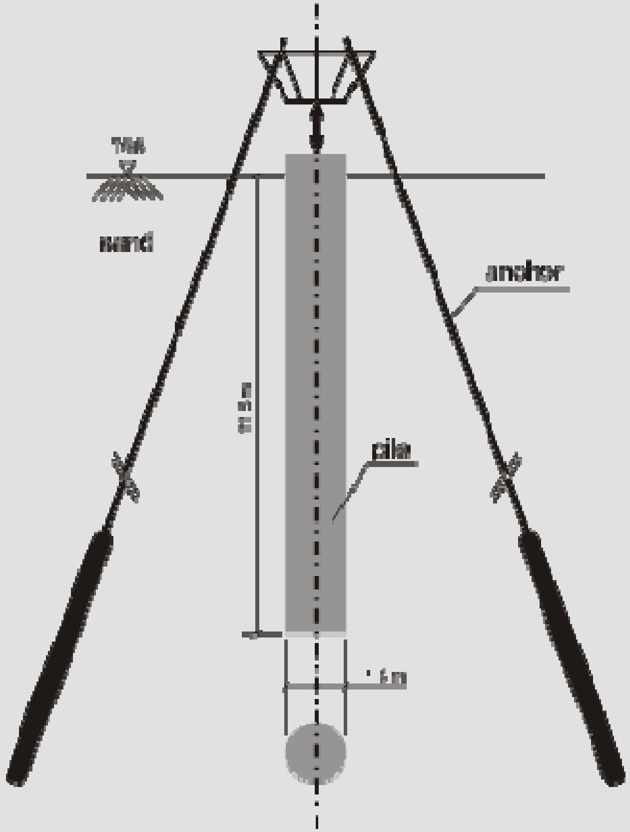
ANALYSIS OF A SINGLE PILE

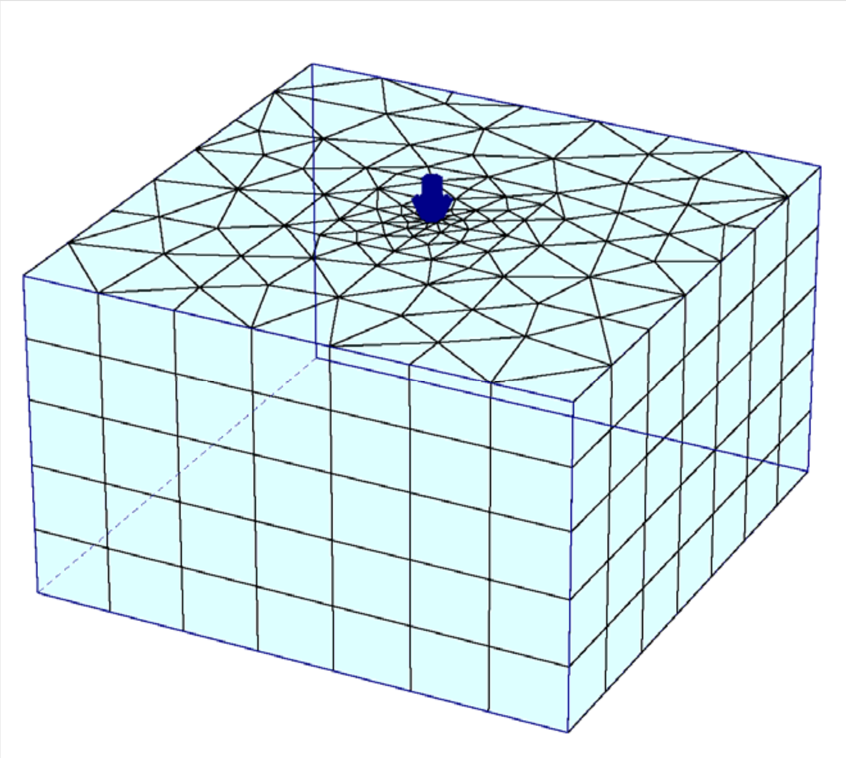


Properties \ Material		Sand	Pile
γ	[kN/m³]	21.0	25.0
c'	[kPa]	1.0	
φ'	[°]	35	
ψ'	[°]	5	
K_0^{nc}	[-]	0.426	
ν_{ur} / ν	[-]	0.2	0.2
E_{50}^{ref} / E	[kPa]	4.5E4	3.0E7
E_{oed}^{ref}	[kPa]	4.5E4	
E_{ur}^{ref}	[kPa]	1.35E5	
m	[-]	0.5	
p^{ref}	[kPa]	100	
R_{inter}	[-]	0.7	

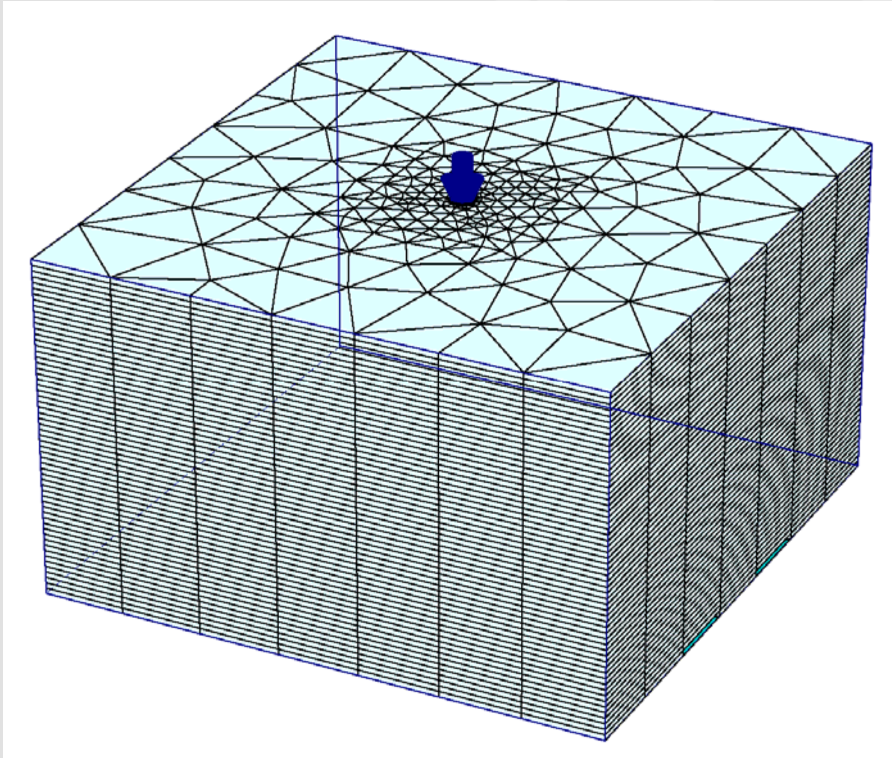
PLAXIS benchmark example

ANALYSIS OF A SINGLE PILE

Influence of discretization



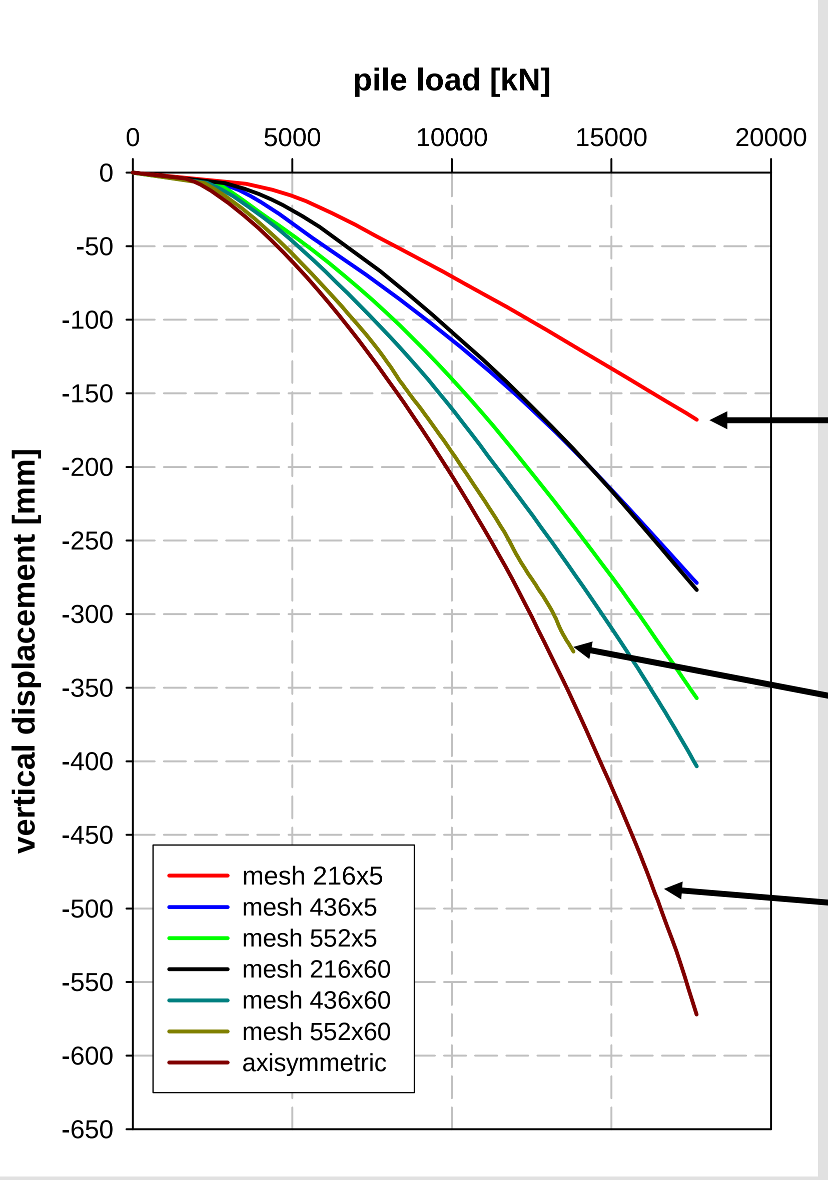
Mesh 216 x 5 elements



Mesh 552 x 60 elements

ANALYSIS OF A SINGLE PILE

Influence of discretization



216 x 5 elements

552 x 60 elements

Axisymmetric

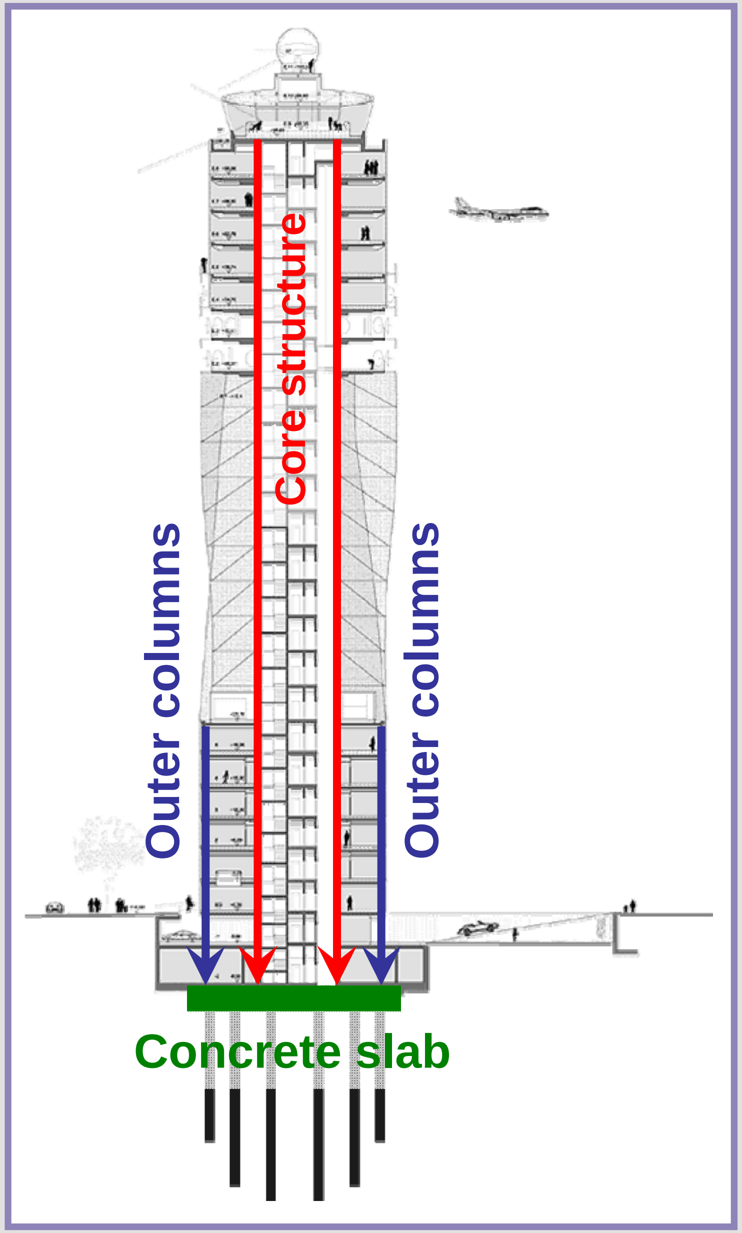
(850 15-noded elements)

Note: higher order element (equivalent to 15-noded in 2D) is not available in 3D

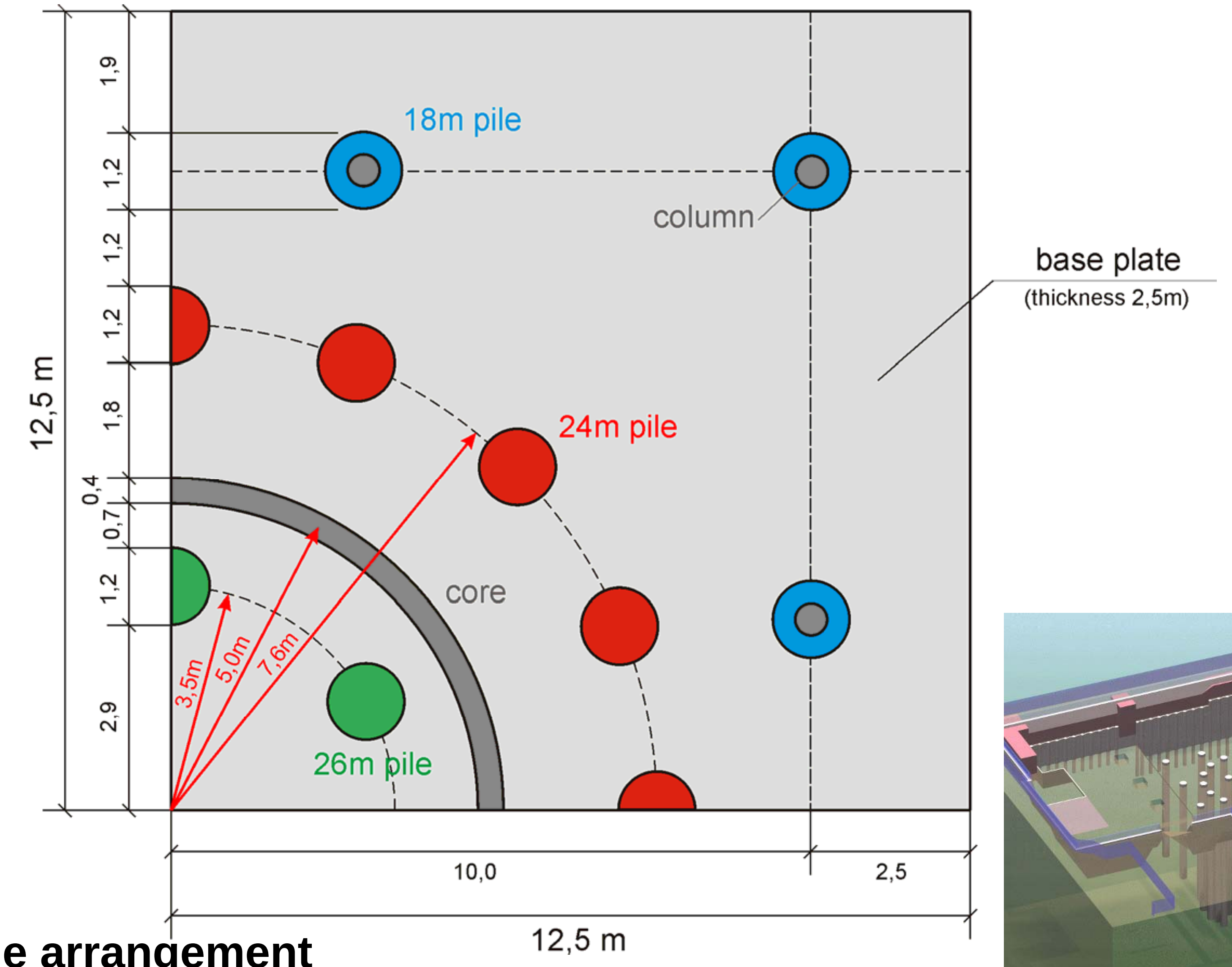
PRACTICAL EXAMPLE - AIRPORT TOWER VIENNA

- **Introduction**
  - Design layout
  - Soil layers, material properties
- **Modelling**
  - 3D Tunnel / 3D Foundation
  - Finite element mesh, calculation steps
- **Results**
  - Vertical displacements 3D
  - Vertical displacements of piles
  - Multiplied working loads
  - Comparison with measurements

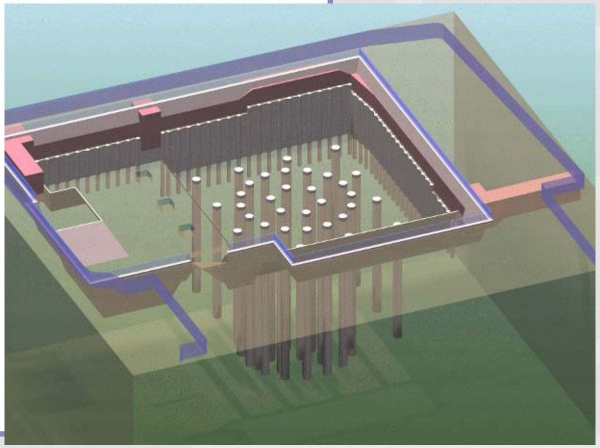
INTRODUCTION



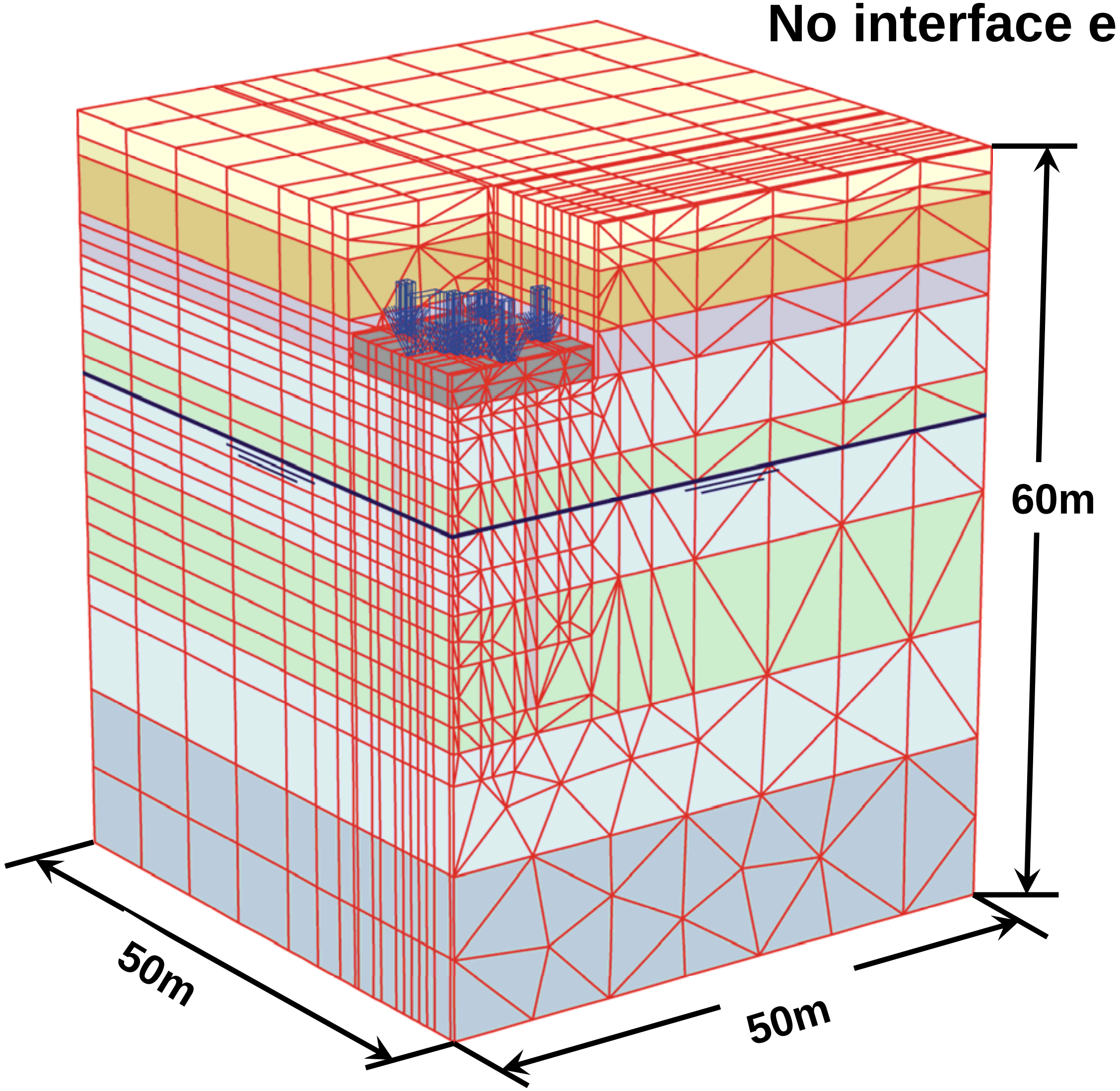
INTRODUCTION



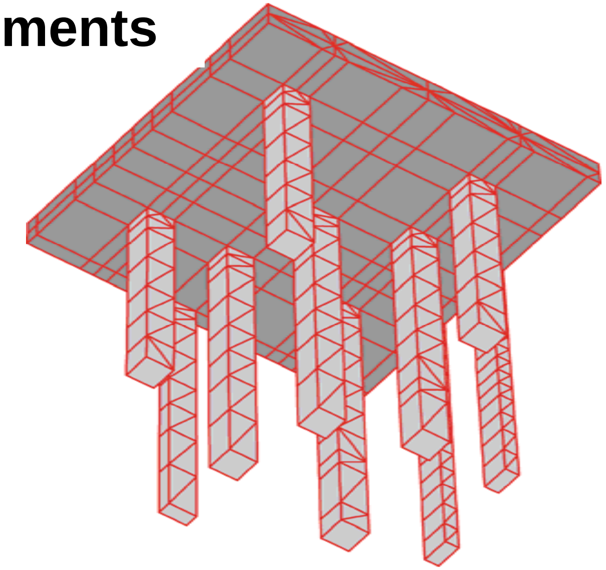
Pile arrangement



3D MODEL - 3D TUNNEL



No interface elements



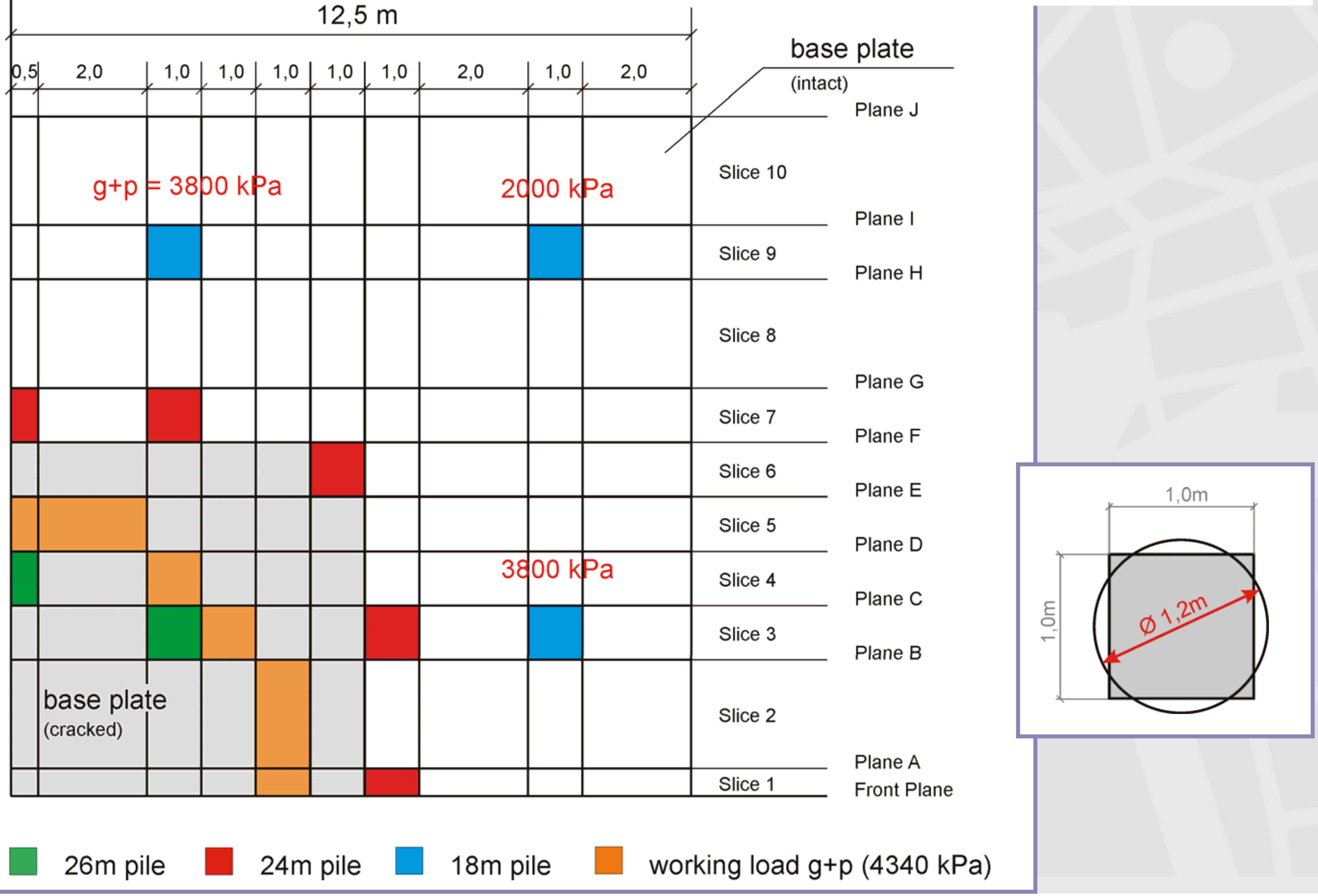
~450 **2D-elements**

19 **planes**

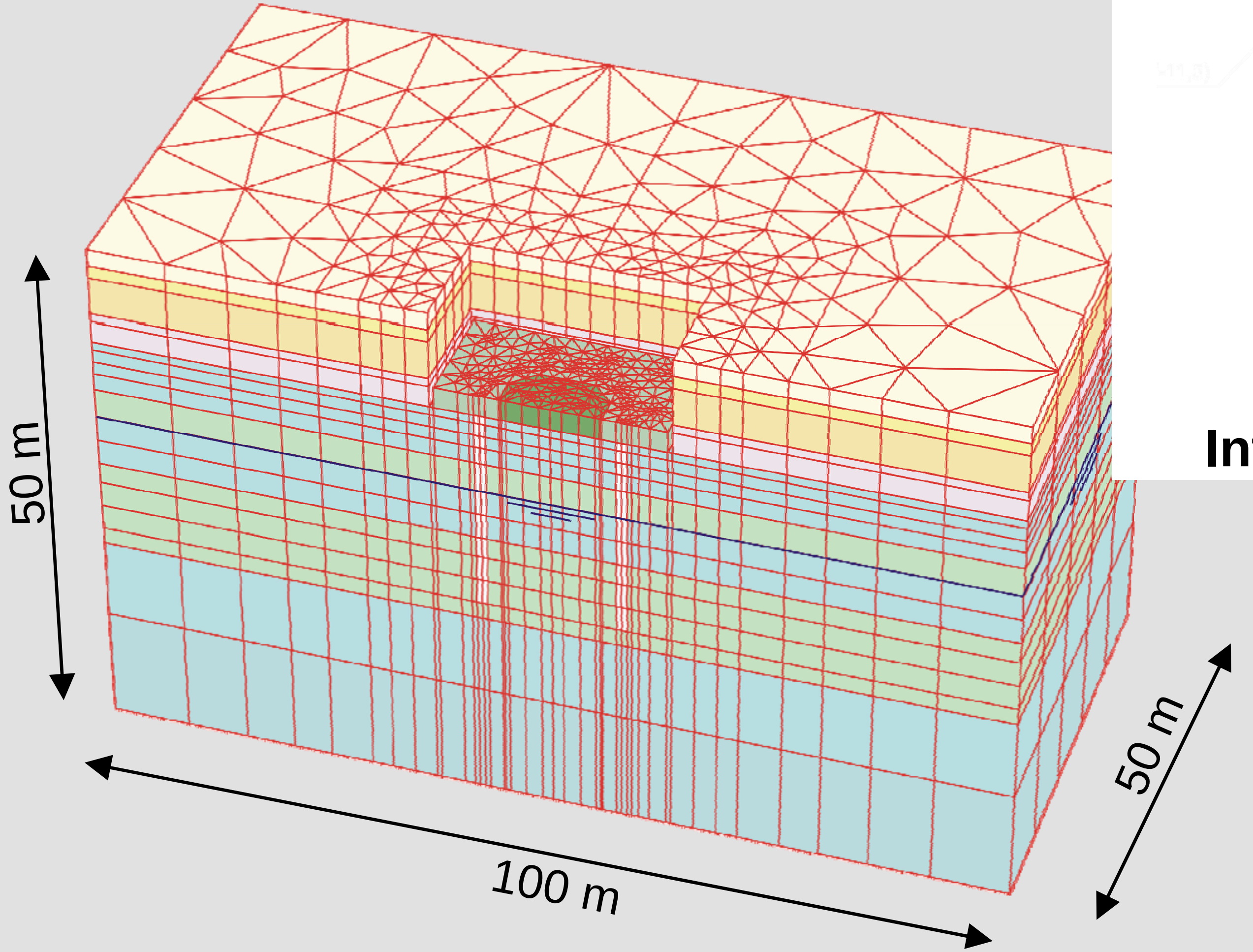
~8 500 **3D-elements**

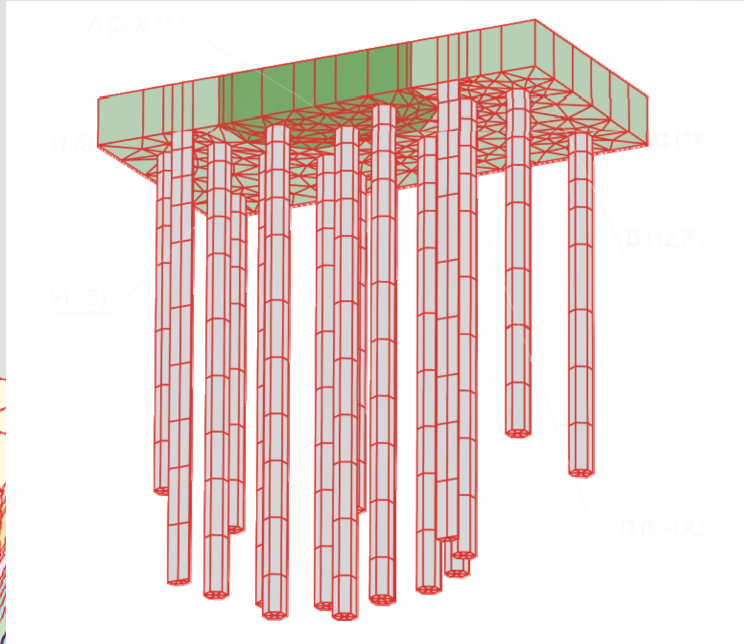
3D MODEL - 3D TUNNEL

Simplification of geometry for 3D tunnel

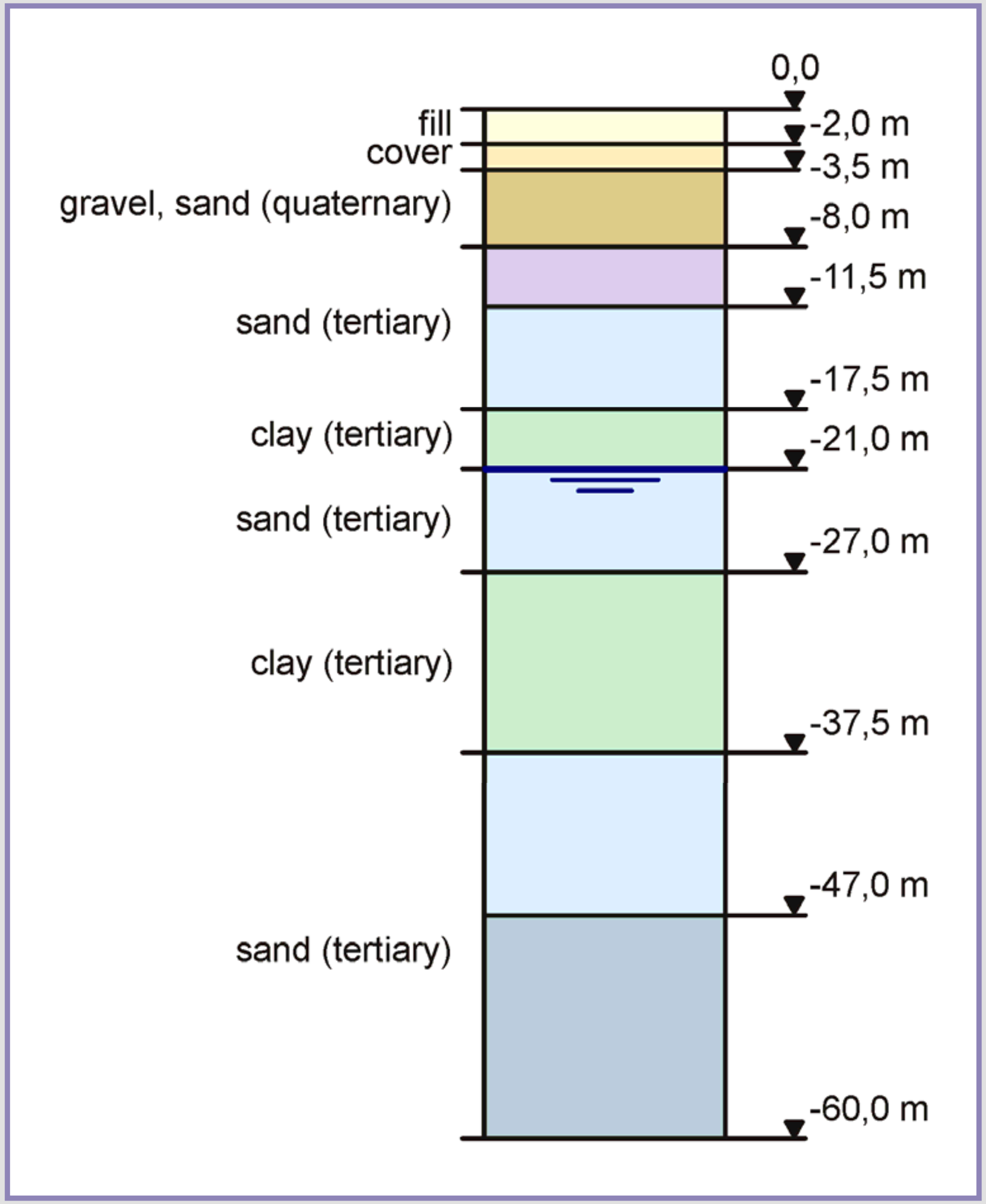


3D MODEL - 3D FOUNDATION





SOIL PROFILE



Soil investigation:

7 bore holes

4 penetration tests

↓

standard laboratory tests

↓

material properties

> Additional parameters required

for HS model from experience

MATERIAL PARAMETERS - HS MODEL

Material	Material-model	γ	γ_{sat}	c	φ	ψ	E / E_{50}^{ref}	E_{oed}^{ref}	E_{ur}^{ref}	ν / ν_{ur}	p^{ref}	m
		[kN/m³]	[kN/m³]	[kN/m²]	[°]	[°]	[kN/m²]	[kN/m²]	[kN/m²]	[-]	[kN/m²]	[-]
fill	**HS**	**21,0**	**21,0**	**(150,0)**	**30,0**	**0,0**	**15000**	**15000**	**37500**	**0,20**	**50**	**0,6**
cover	**HS**	**20,0**	**20,0**	**(150,0)**	**25,0**	**0,0**	**7500**	**7500**	**22500**	**0,20**	**50**	**0,8**
gravel, sand	**HS**	**22,0**	**22,0**	**(150,0)**	**32,5**	**2,5**	**75000**	**75000**	**150000**	**0,20**	**100**	**0,5**
sand	**HS**	**21,0**	**21,0**	**(150,0)**	**32,5**	**2,0**	**50000**	**50000**	**175000**	**0,20**	**200**	**0,5**
clay	**HS**	**21,0**	**21,0**	**40,0**	**20,0**	**2,0**	**20000**	**20000**	**80000**	**0,20**	**250**	**0,9**
sand	**HS**	**21,0**	**21,0**	**1,0**	**32,5**	**2,0**	**50000**	**50000**	**175000**	**0,20**	**200**	**0,5**
sand	**HS**	**21,0**	**21,0**	**1,0**	**32,5**	**2,0**	**150000**	**150000**	**525000**	**0,20**	**200**	**0,5**
slab (cracked)	**Elastic**	**25,0**	**25,0**	**-**	**-**	**-**	**2,0e+7**	**-**	**-**	**0,20**	**-**	**-**
slab (intact)	**Elastic**	**25,0**	**25,0**	**-**	**-**	**-**	**3,0e+7**	**-**	**-**	**0,20**	**-**	**-**
pile	**Elastic**	**25,0**	**25,0**	**-**	**-**	**-**	**3,0e+7**	**-**	**-**	**0,20**	**-**	**-**

CALCULATION STEPS

Objective of analysis:

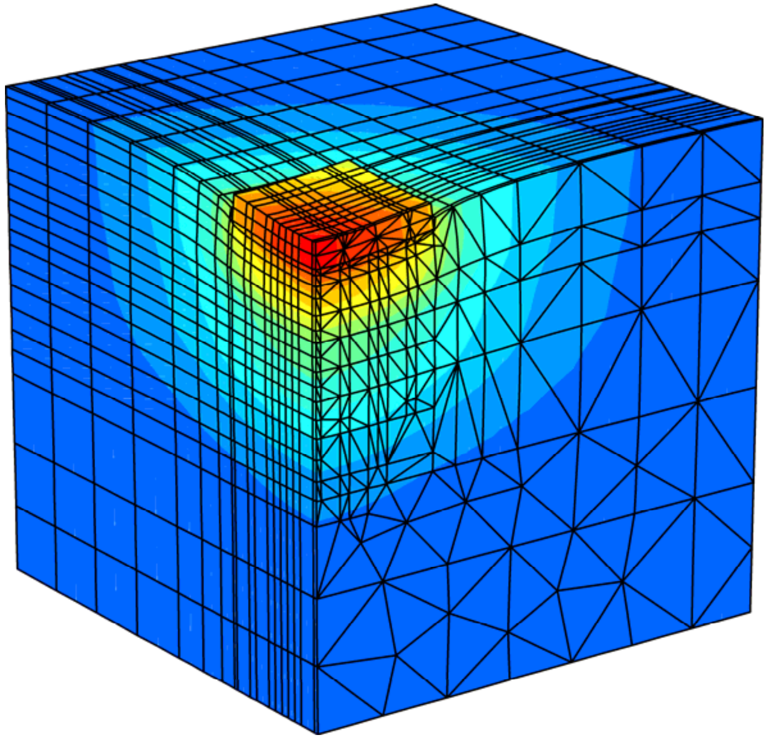
- Prove that piled raft foundation is acceptable
- Assess displacements at working load conditions
- Evaluate performance for increased loads
- Optimize number of piles

Note: original design was conventional pile foundation

- **Initial stress state ($\sigma_v = \gamma * h$, $\sigma_h = K_o * \gamma * z$, $K_o = 1 - \sin\varphi'$)**
- **Excavation of the soil to -11.5m (base of slab)**

  The excavation support using a bored pile wall is not included into the present calculation, since this construction stage is not relevant for the prediction of the final settlements. Stability for this calculation step is achieved by increasing the cohesion of the upper soil layers.
- **Activation of piles**
- **Activation of the slab**
- **Dead loads and working loads (core, columns) are applied**
- **Calculation of the settlements for multiplied loads (1.5, 2.0 und 2.5)**

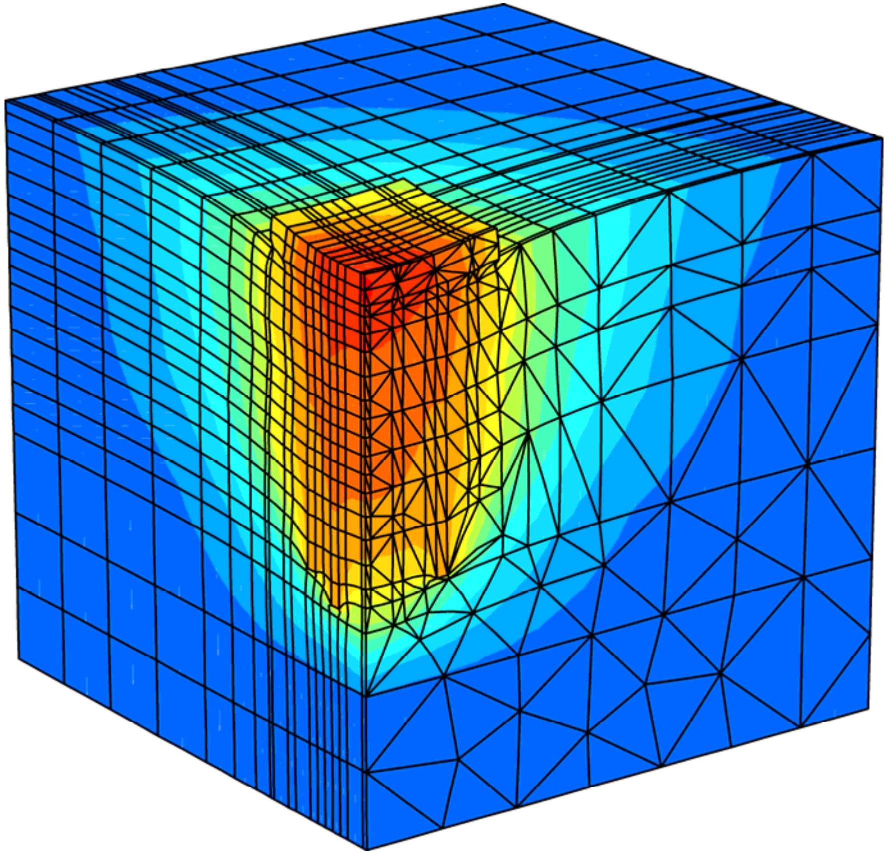
RESULTS



Without piles

max U_y = 53 mm

(working load conditions)

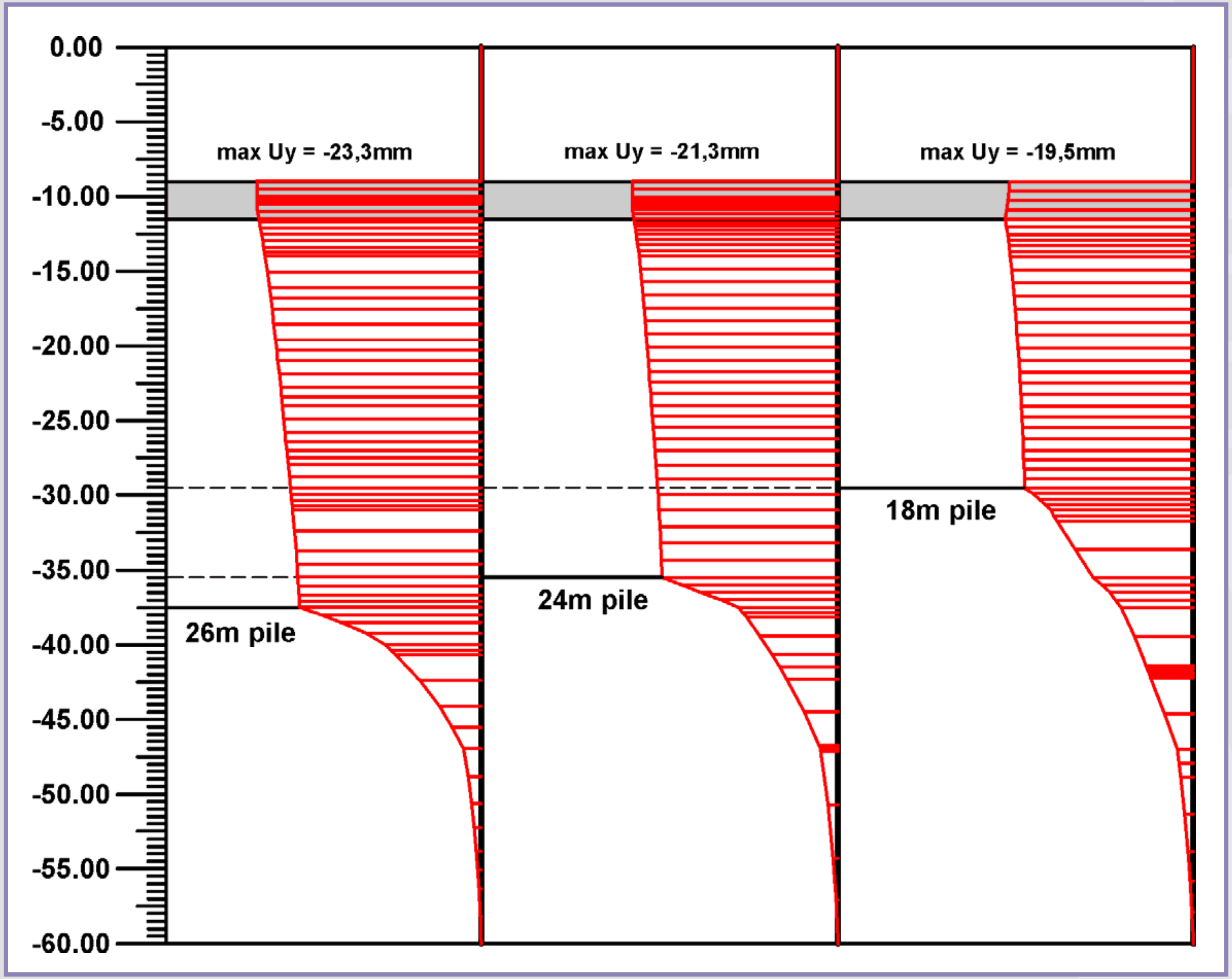


Piled raft

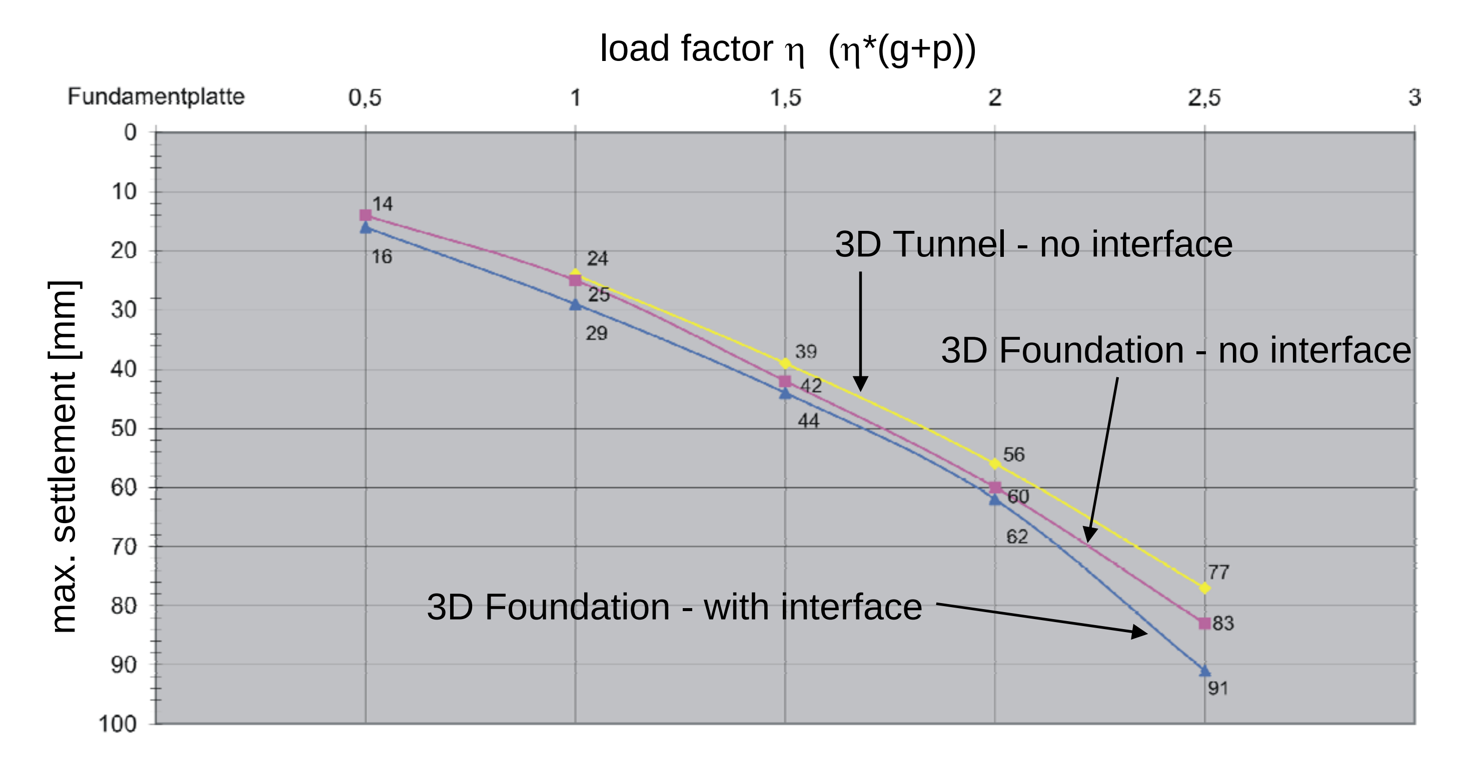
max U_y = 24 mm

(working load conditions)

RESULTS

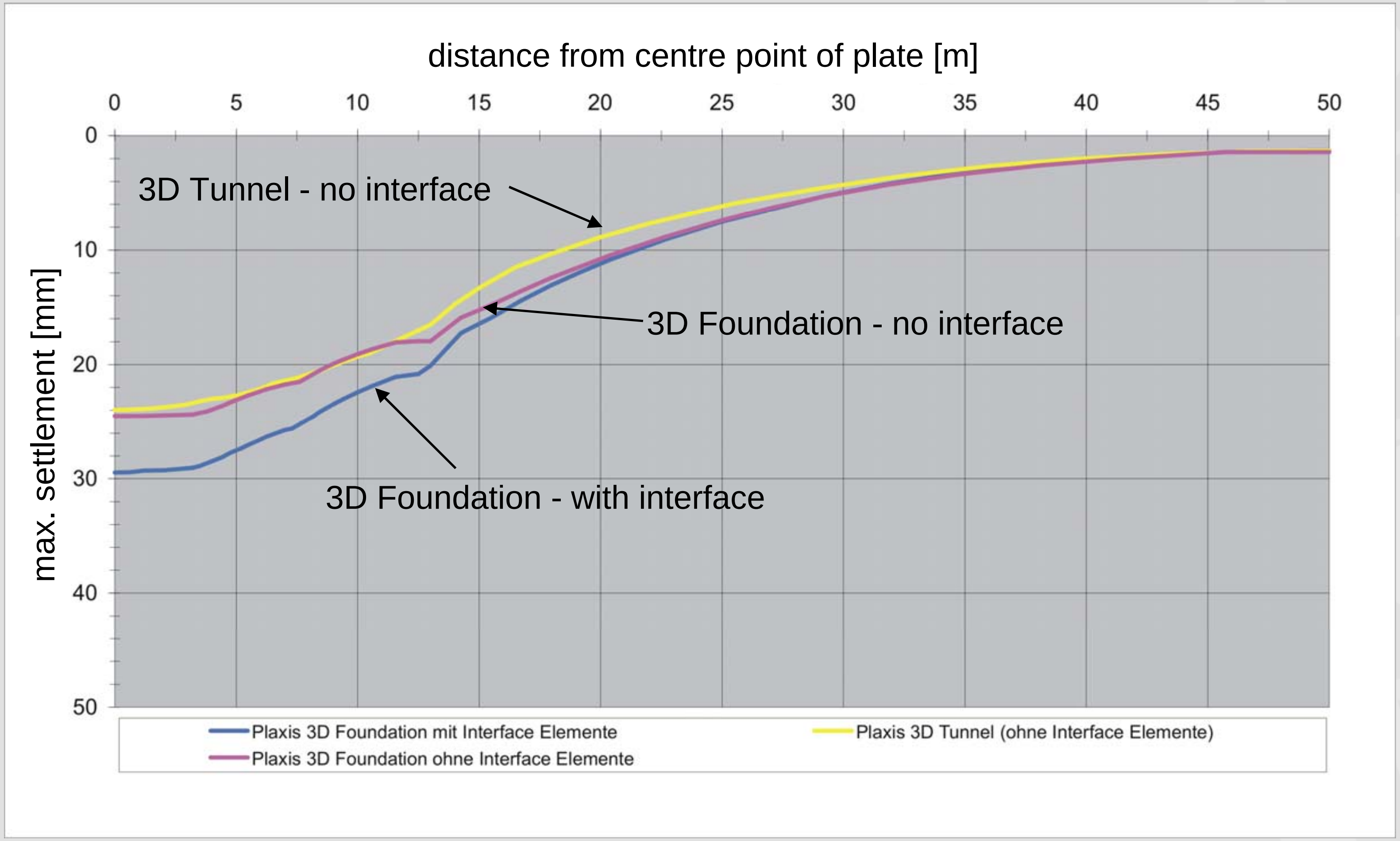

0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
-35.00
-40.00
-45.00
-50.00
-55.00
-60.00
max Uy = -23,3mm
max Uy = -21,3mm
max Uy = -19,5mm
26m pile
24m pile
18m pile

RESULTS - MAXIMUM SETTLEMENTS



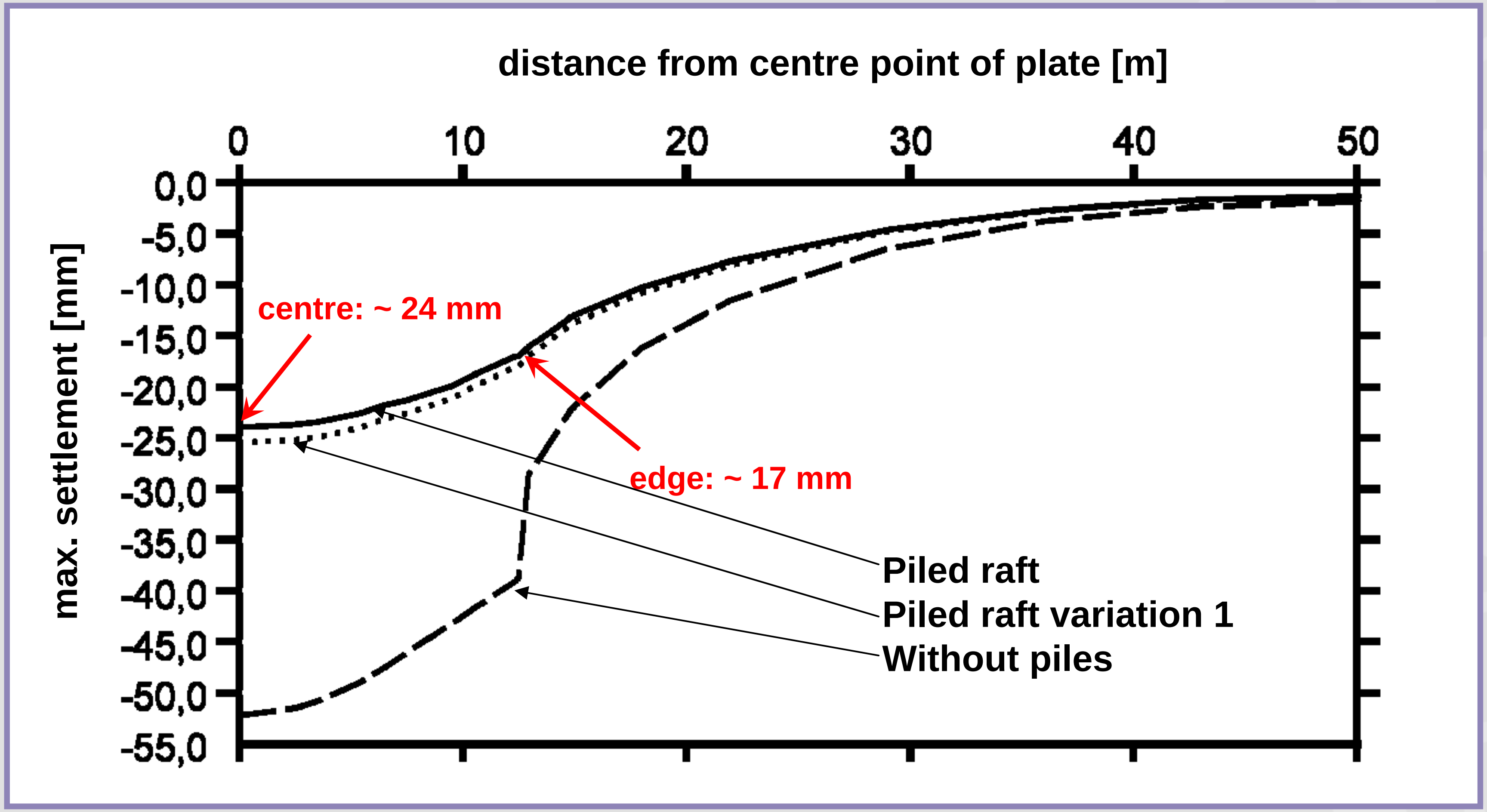
Vertical disp. [mm]	Load case			
	1,0 * (g+p)	1,5 * (g+p)	2,0 * (g+p)	2,5 * (g+p)
Piled raft foundation	24	39	56	77
Without piles	53	93	143	196

RESULTS - SETTLEMENT OF SLAB



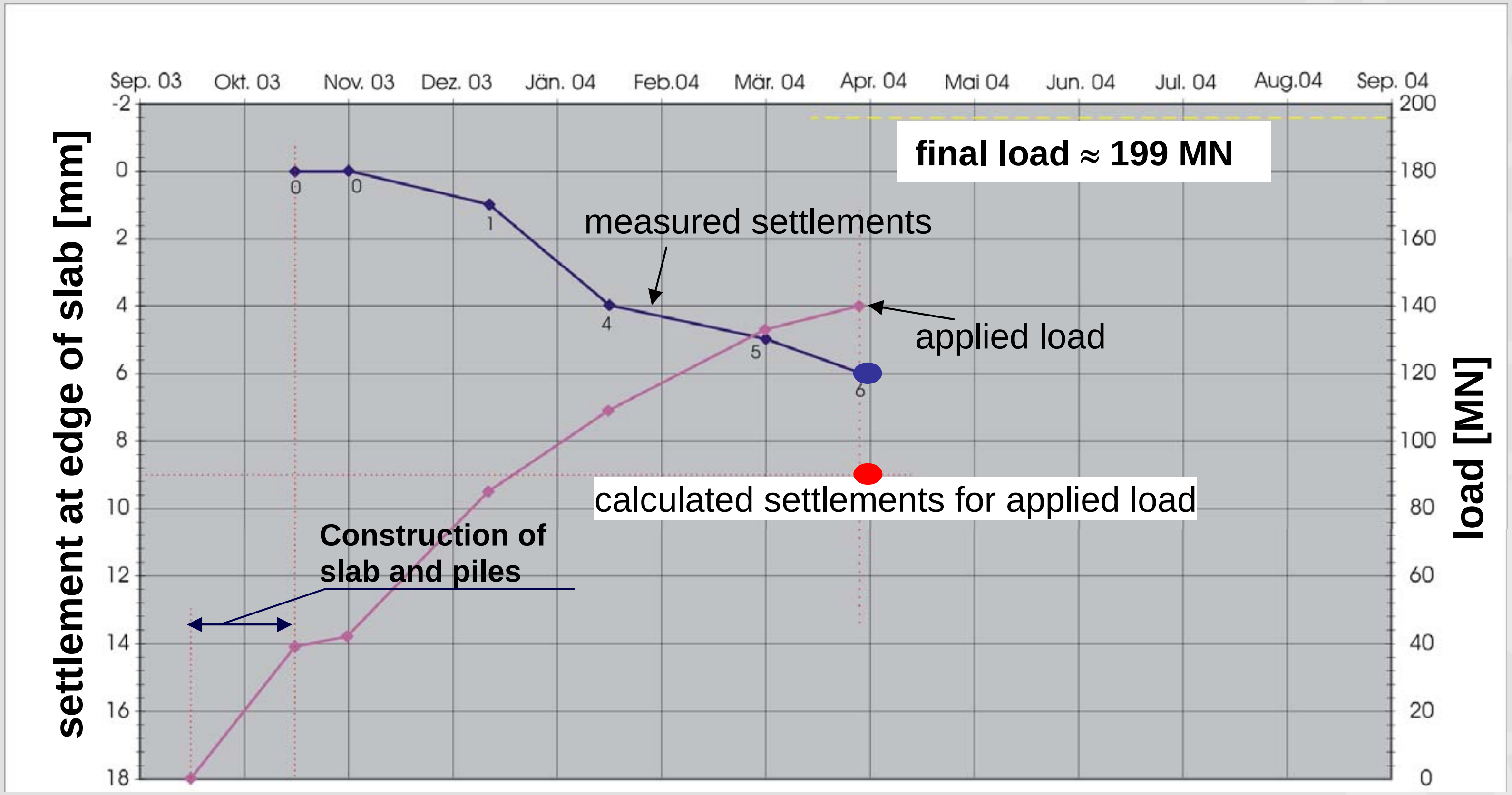
Influence of interface elements $\Delta s_{max} \approx$ 4 mm ($\approx$ 15%)

RESULTS



distance from centre point of plate [m]
0
10
20
30
40
50
0,0
-5,0
-10,0
-15,0
-20,0
-25,0
-30,0
-35,0
-40,0
-45,0
-50,0
-55,0
max. settlement [mm]
centre: ~ 24 mm
edge: ~ 17 mm
Piled raft
Piled raft variation 1
Without piles

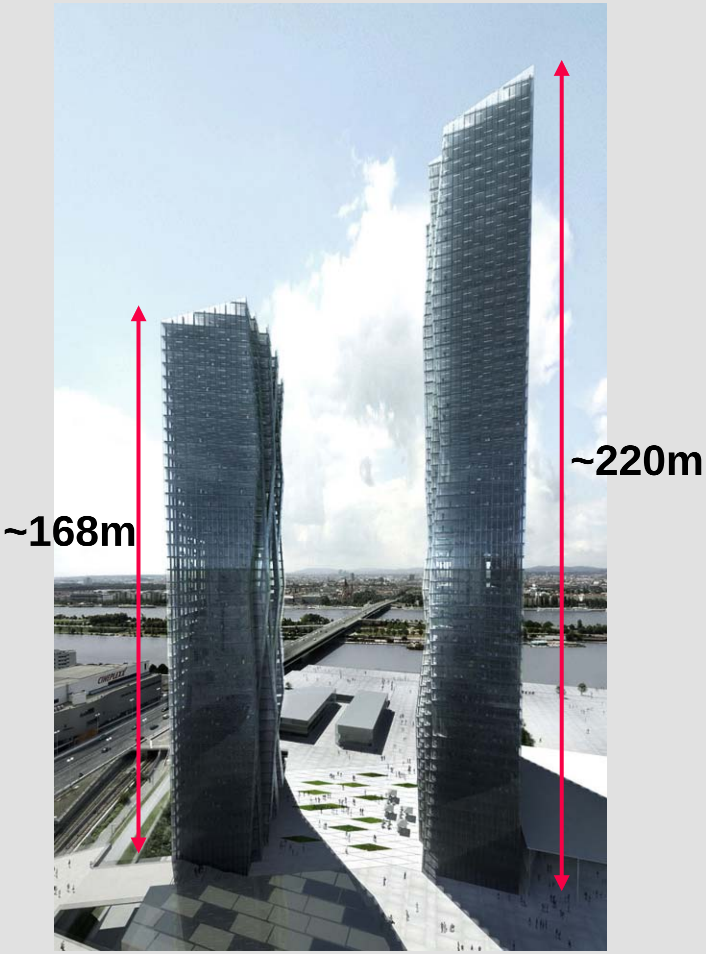
RESULTS - COMPARISON WITH MEASUREMENTS

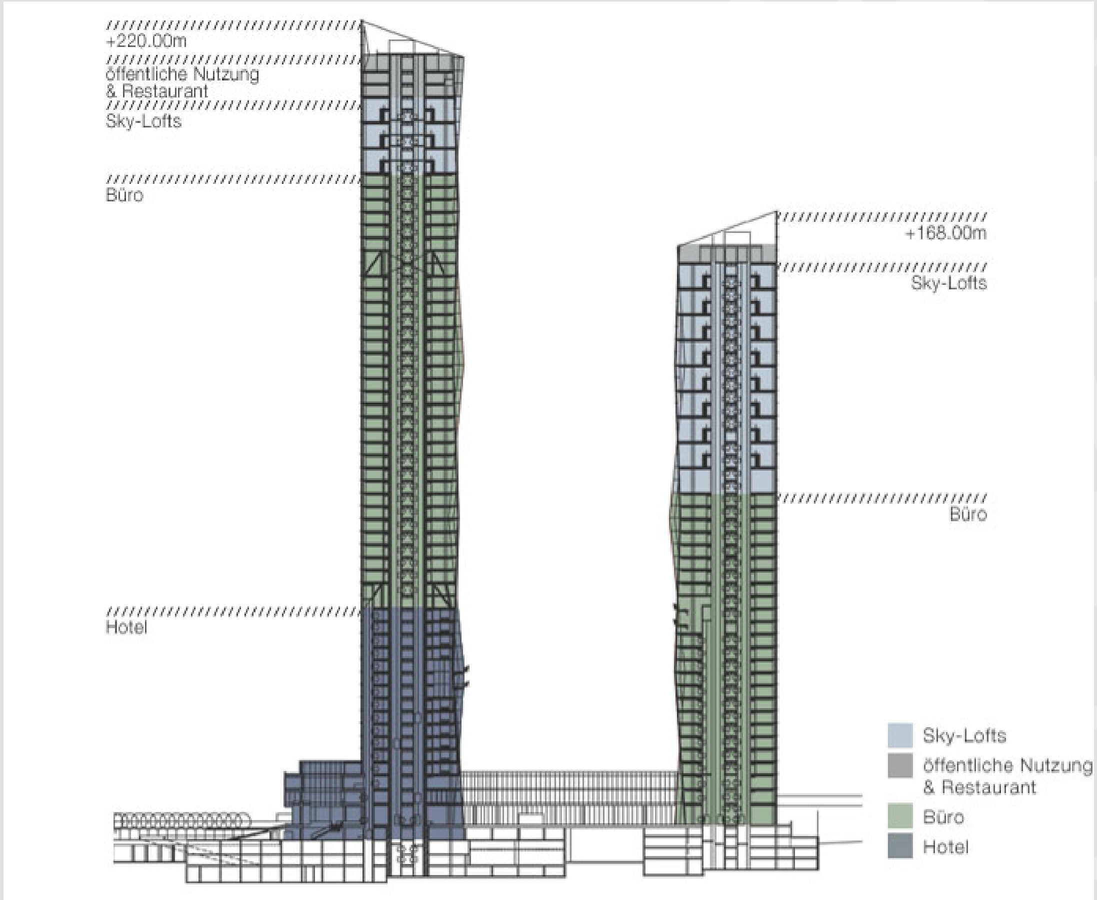


Measured average settlement at edge of slab **s ≈ 6 mm**

Calculated average settlement at edge of slab **s ≈ 9 mm**

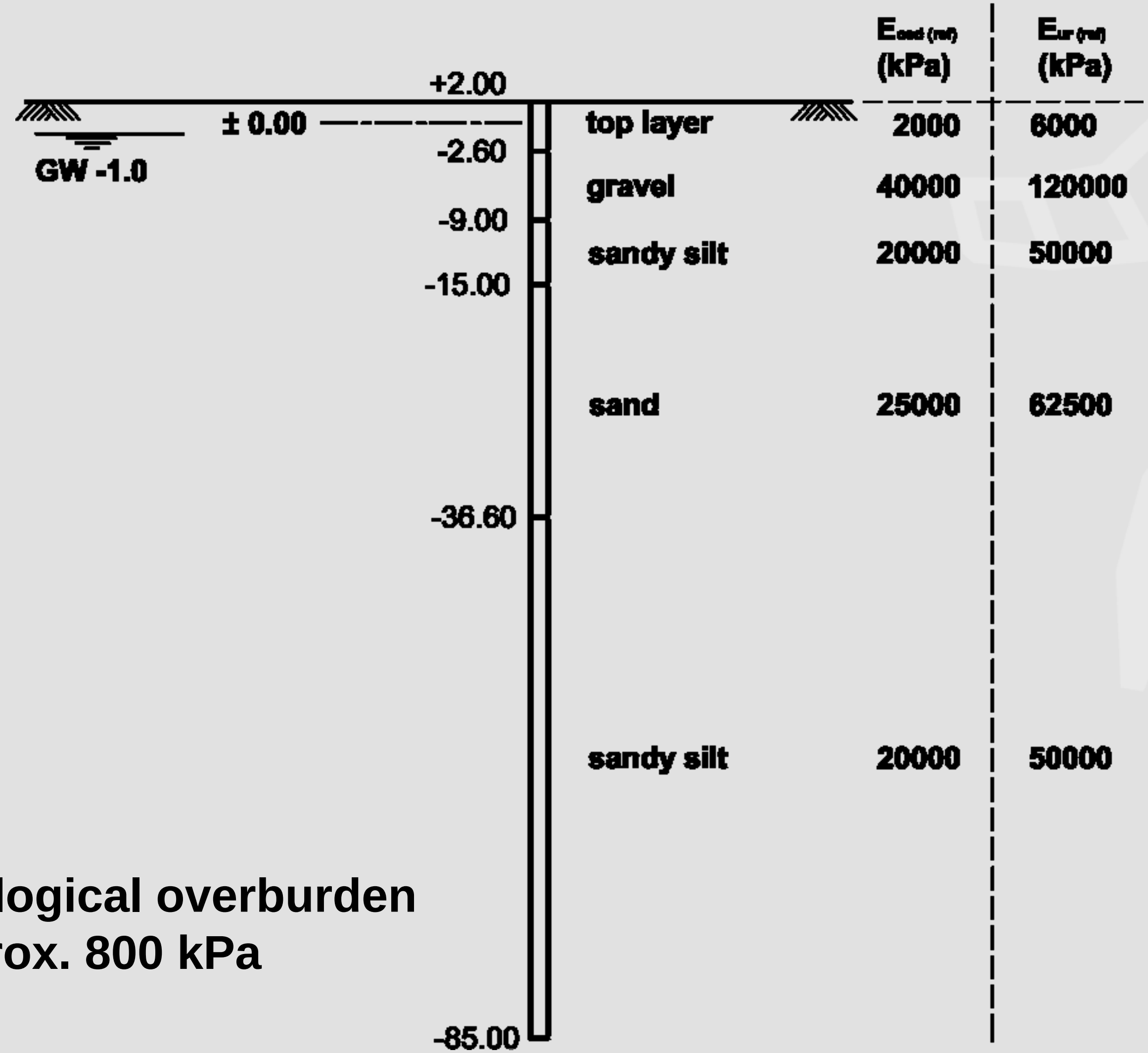
PRACTICAL EXAMPLE - TWIN TOWERS





Concept for foundation: deep foundation with diaphragm wall panels

SOIL PROFILE



Geological overburden approx. 800 kPa

CONSTITUTIVE MODEL AND SOIL PARAMETERS

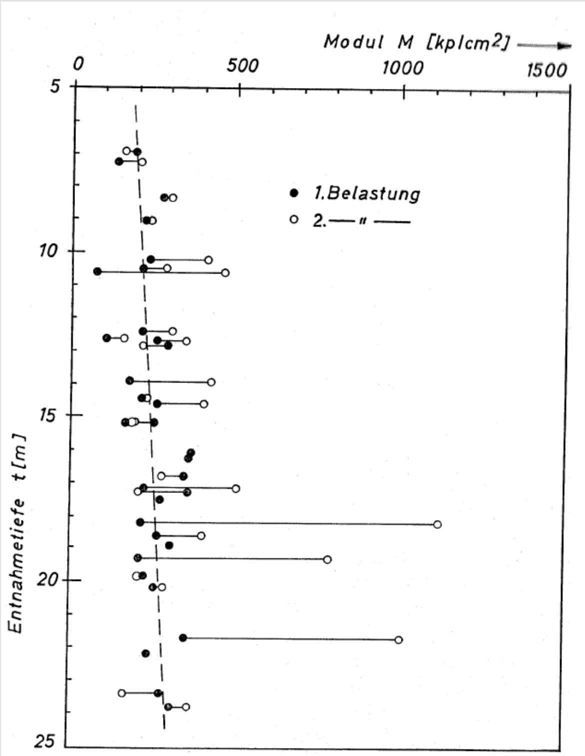
layer	type	γ_{unsat} *[kN/m³]*	γ_{sat} *[kN/m³]*	E_{50}^{ref} *[kN/m²]*	E_{oed}^{ref} *[kN/m²]*	E_{ur}^{ref} *[kN/m²]*	G_0 *[kN/m²]*	$\gamma_{0,7}$ *[-]*
top layer	HS[1] drained	17.5	20.5	2 000	2 000	6 000	-	-
gravel	HSS[2] drained	21.0	22.0	40 000	40 000	120 000	150 000	0.0001
sandy silt	HSS[2] drained	20.0	20.0	20 000	20 000	50 000	62 500	0.0002
sand	HSS[2] drained	20.0	21.0	25 000	25 000	62 500	78 125	0.0002

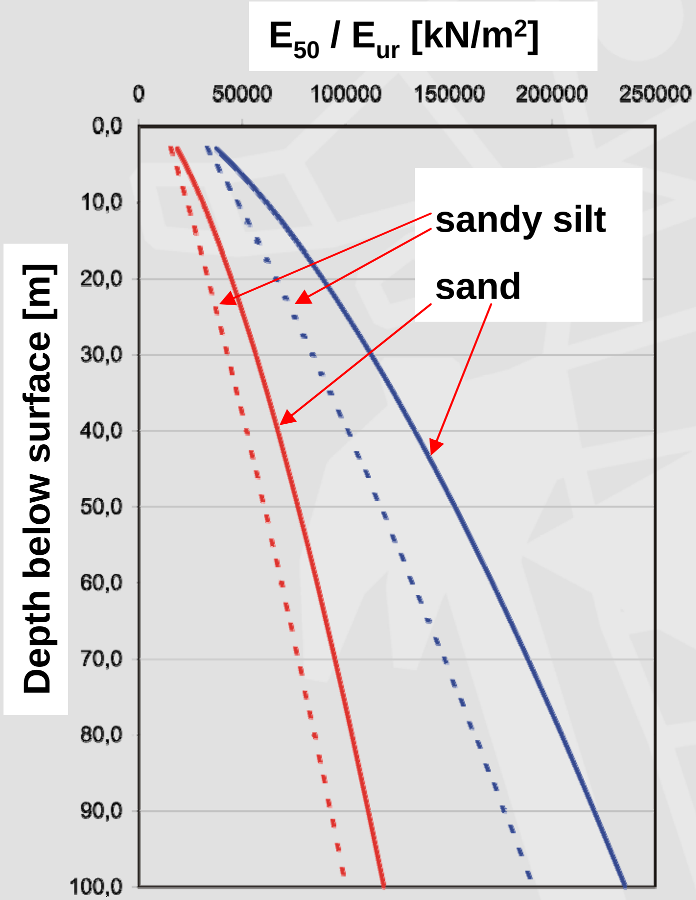
layer	type	c_{ref} *[kN/m²]*	φ *[°]*	ψ *[°]*	ν_{ur} *[-]*	p^{ref} *[kN/m²]*	**power (m)** *[-]*	K_0^{nc} *[-]*	R_f *[-]*
top layer	HS[1] drained	0.1	27.5	0.0	0.20	100	0.60	0.538	0.9
gravel	HSS[2] drained	0.1	35.0	5.0	0.20	100	0.00	0.426	0.9
sandy silt	HSS[2] drained	20.0	25.0	0.0	0.20	100	0.80	0.577	0.9
sand	HSS[2] drained	2.0	32.5	2.5	0.20	100	0.65	0.463	0.9

[1] Hardening Soil Model

[2] Hardening Soil Small Strain Model

CONSTITUTIVE MODEL AND SOIL PARAMETERS

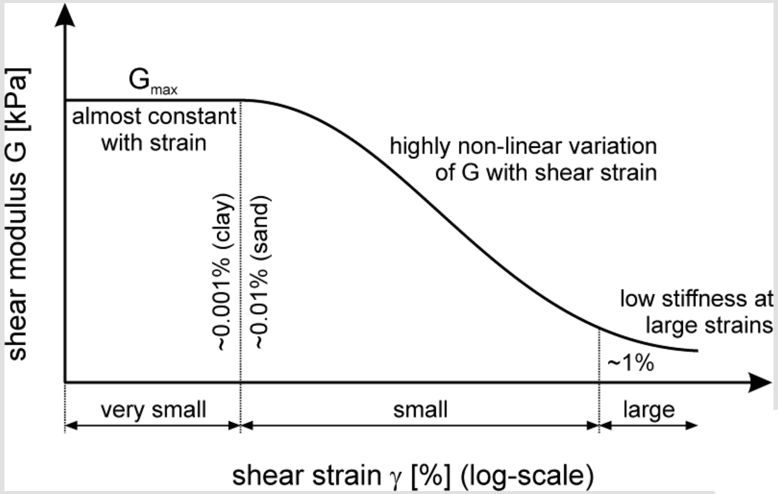


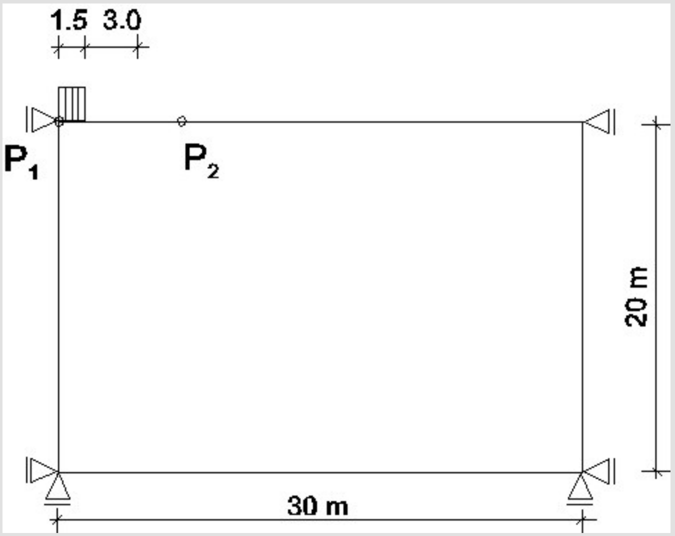


Data from literature:
Manfred Fross: *Untersuchungen über die Zusammendrückbarkeit vorbelasteter toniger Böden des Wiener Beckens*, Mitteilungen des Institutes für Grundbau und Bodenmechanik der Technischen Hochschule Wien, Heft 12, 1973.

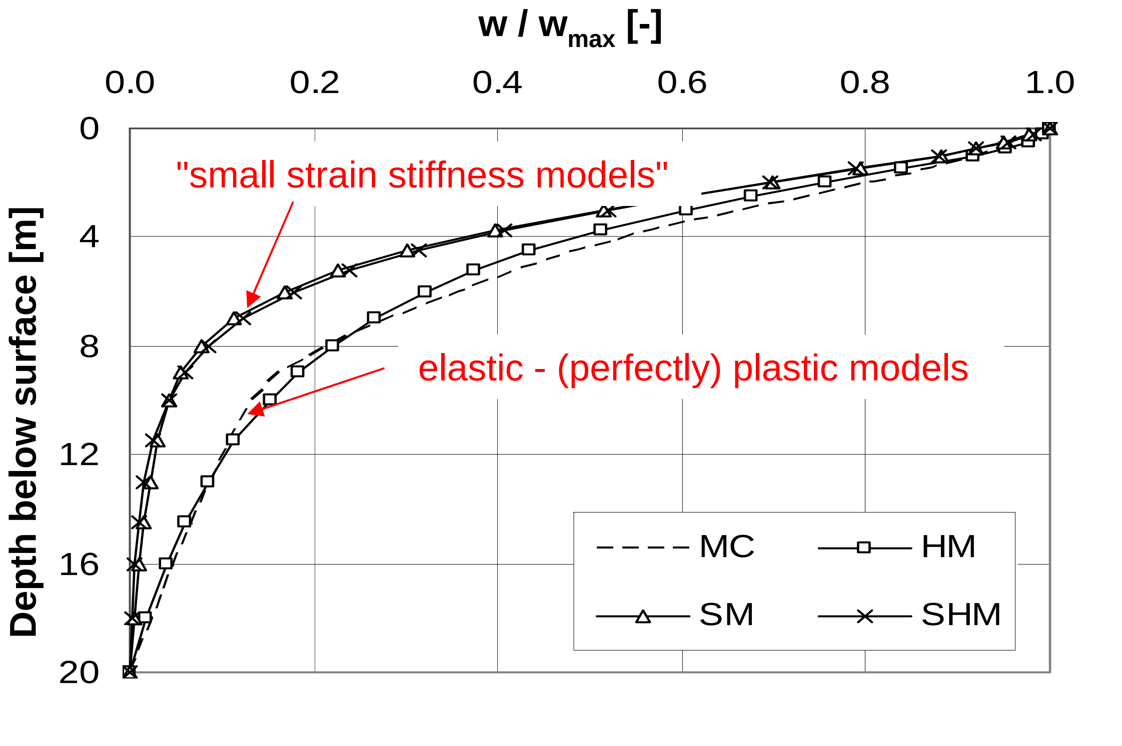
stiffness in HS model at initial state

CONSTITUTIVE MODEL AND SOIL PARAMETERS





Effect of small strain stiffness:
Distribution to settlements from deeper layers is reduced



CONSTITUTIVE MODEL AND SOIL PARAMETERS

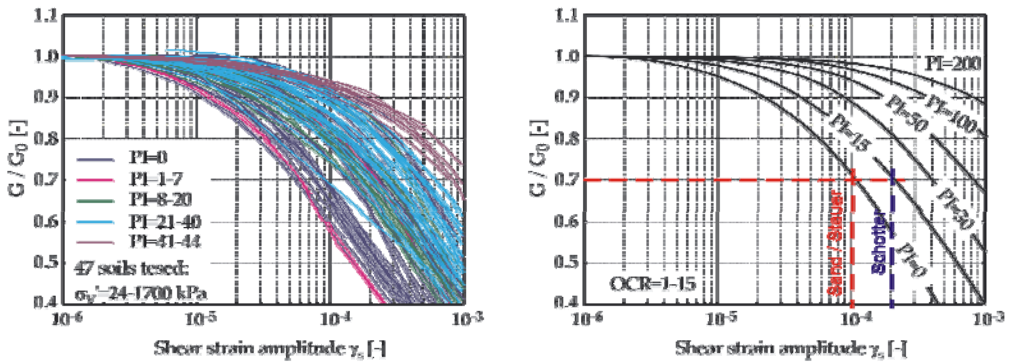


Figure 3.9: Influence of plasticity index (PI) on stiffness reduction: Left database for soils with different PI; Right: PI-chart by Vucetic & Dobry (after Hsu & Vucetic [64], and Vucetic & Dobry [188] respectively).

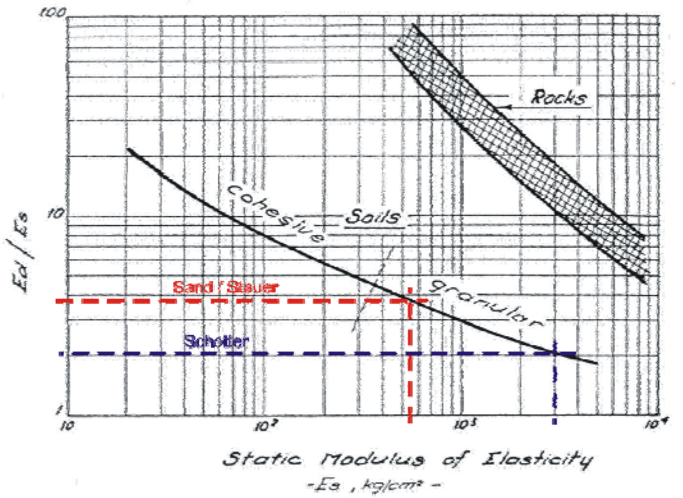
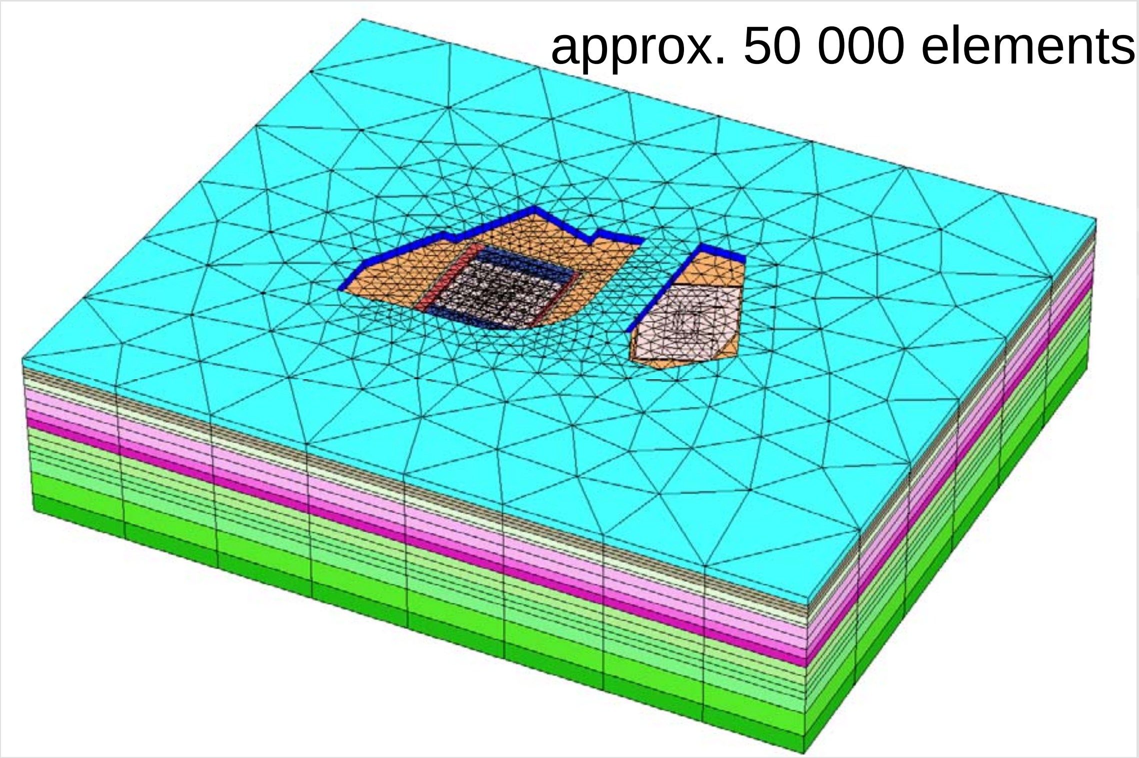


Figure 3.17: Correlation between very small-strain stiffness and stiffness at larger strains from conventional laboratory tests after Alpan (10 kg/cm² ≈ 1 MPa).

see also:
Thomas Benz, *Small-Strain Stiffness of Soils and its Numerical Consequences*, Mitteilung 55 des Instituts für Geotechnik, Universität Stuttgart, 2007.

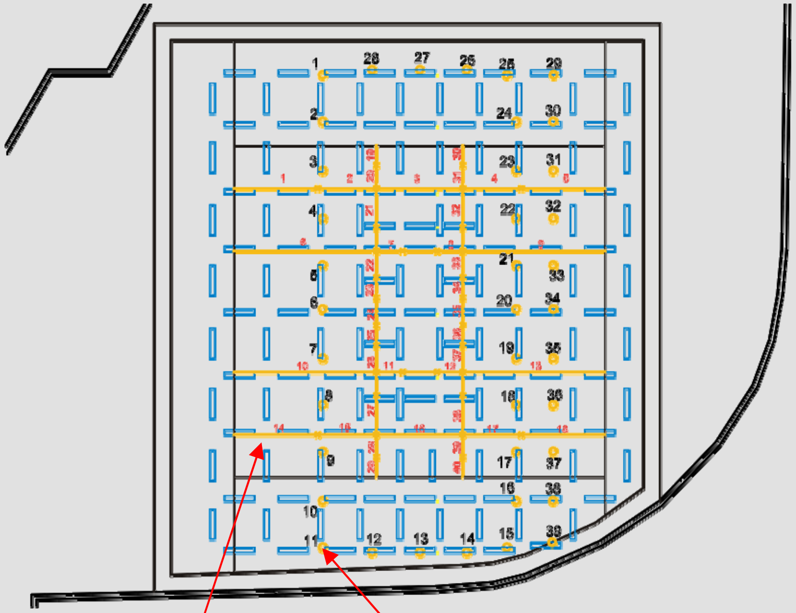
3D FE-MODEL



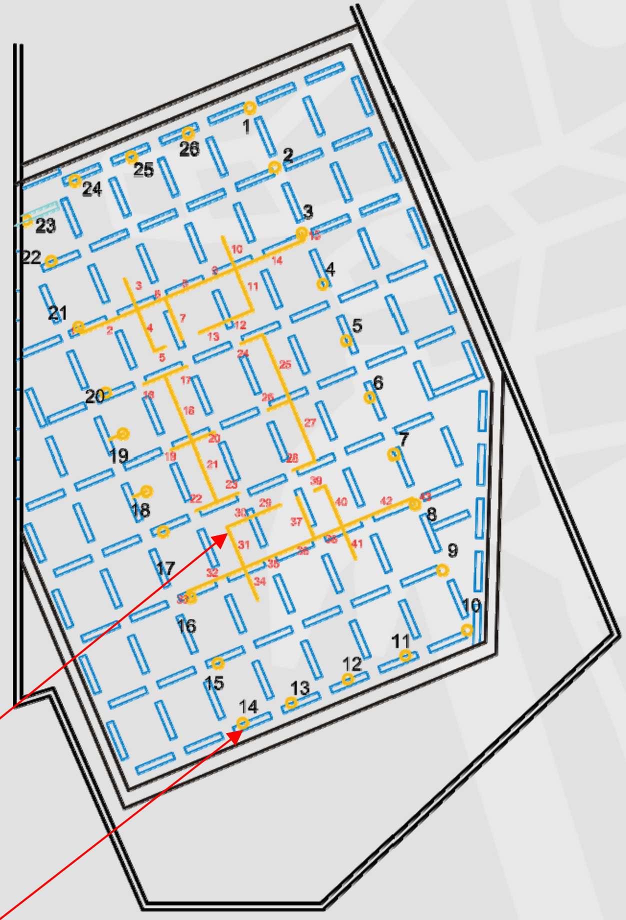
OBJECTIVE OF ANALYSIS:

- Assess displacements at working load conditions
- Assess influence of towers on adjacent structures
- Optimize length of piles to achieve symmetric settlement troughs (eccentric loading)

LOADS

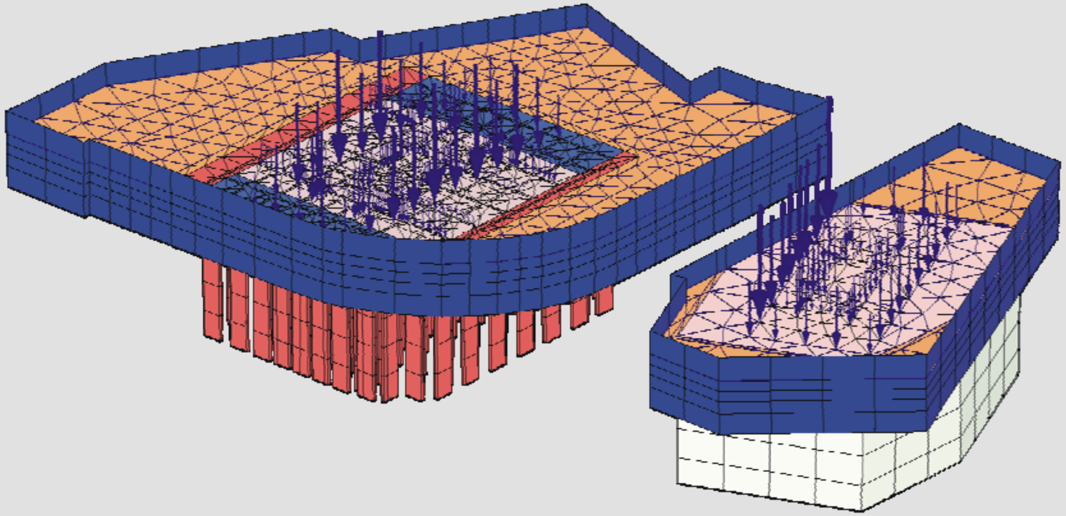


Line and point loads
Tower 1: approx. 1 600 MN

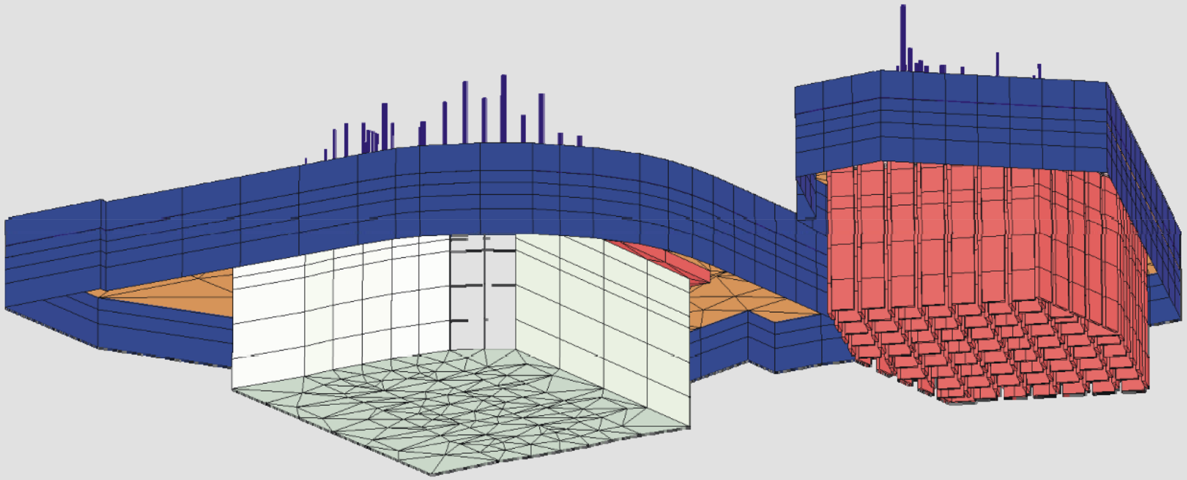


Line and point loads
Tower 2: approx. 1 200 MN

3D FE-MODEL



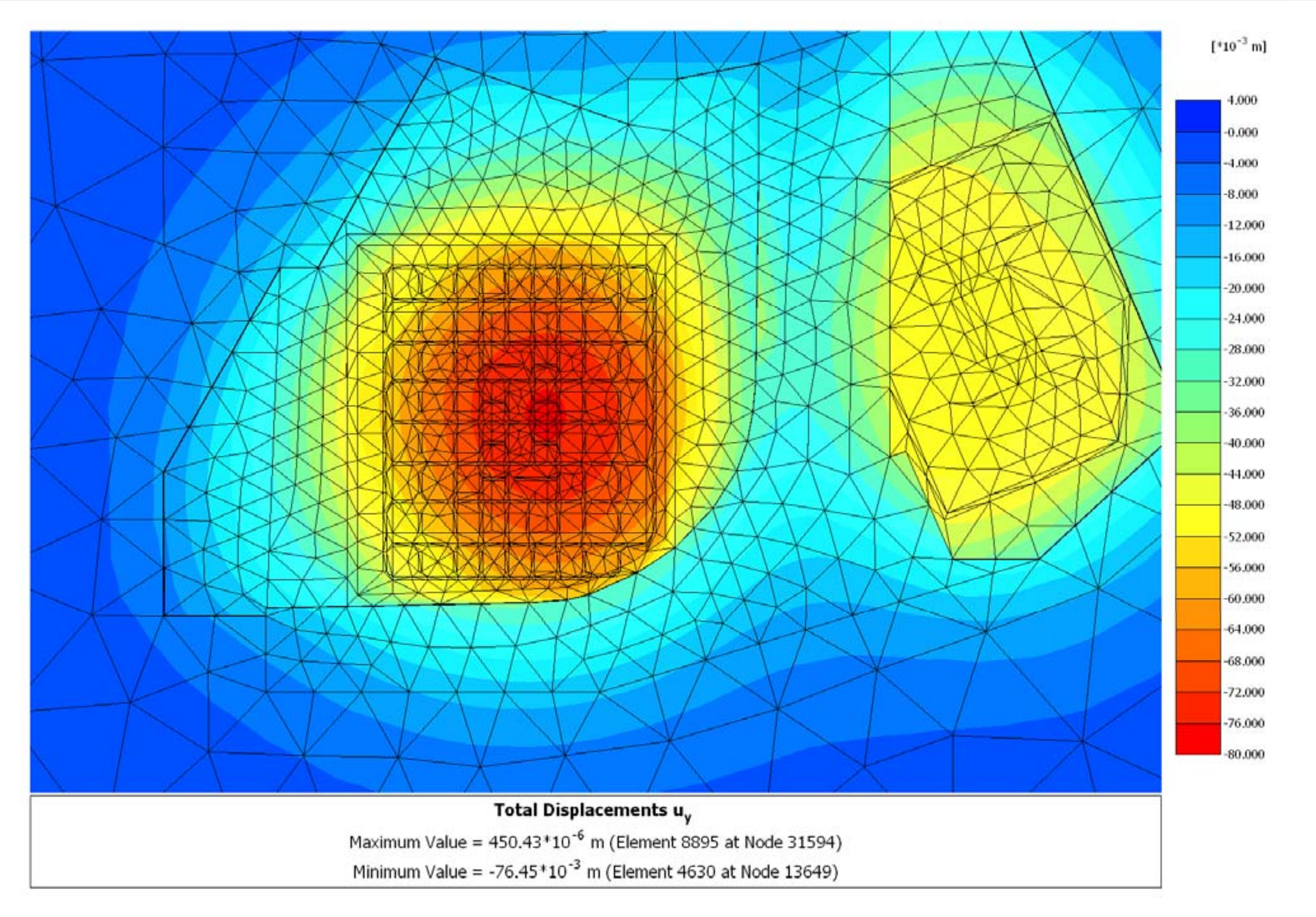
Model for Tower 1



Model for Tower 2

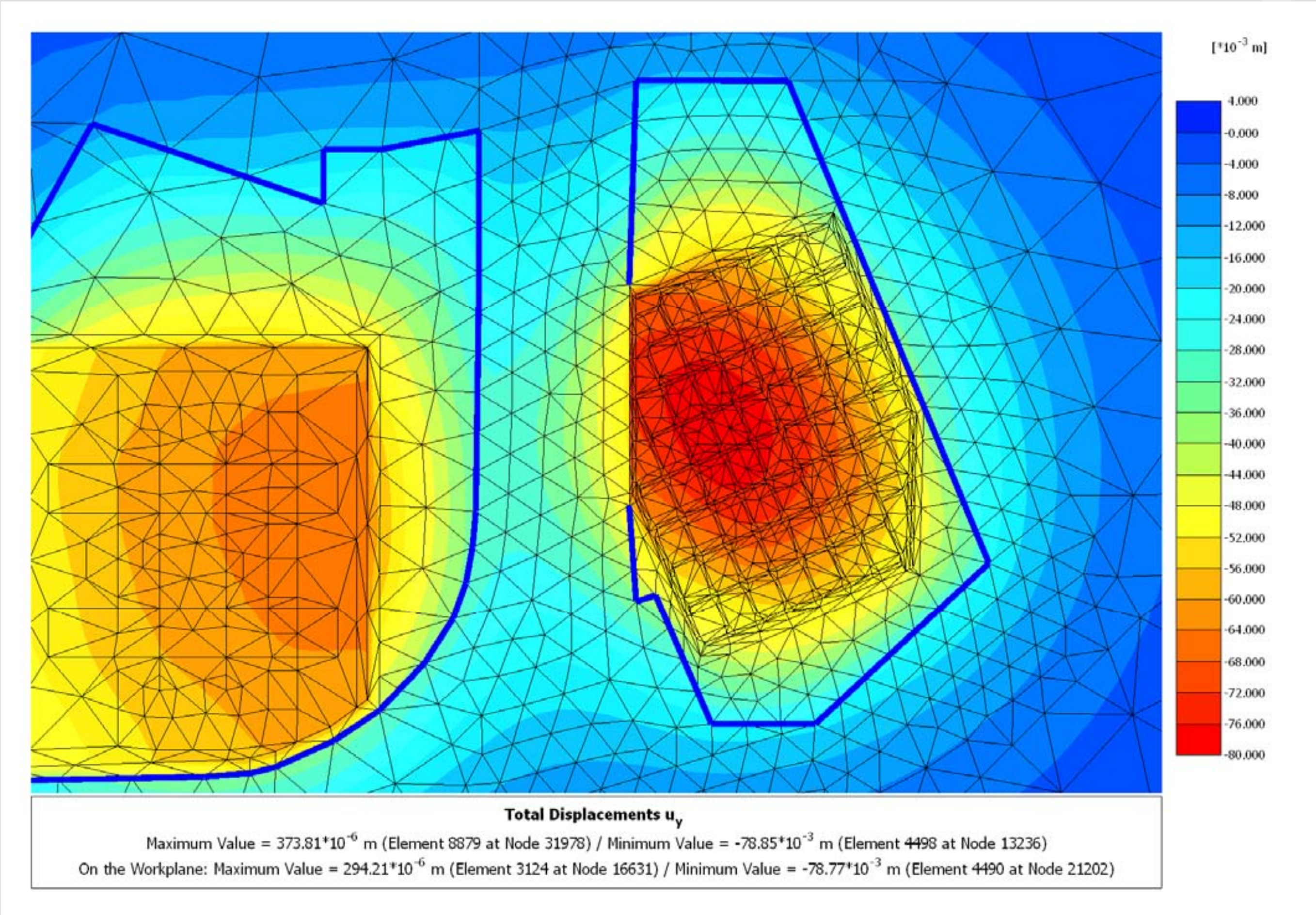
Concept for modelling (in order to reduce model size):
foundation panels of one tower are explicitely modelled, whereas a block model is assumed for the other tower

RESULTS - TOWER 1



All panels same length: max settlement ≈ 80 mm, but not symmetric

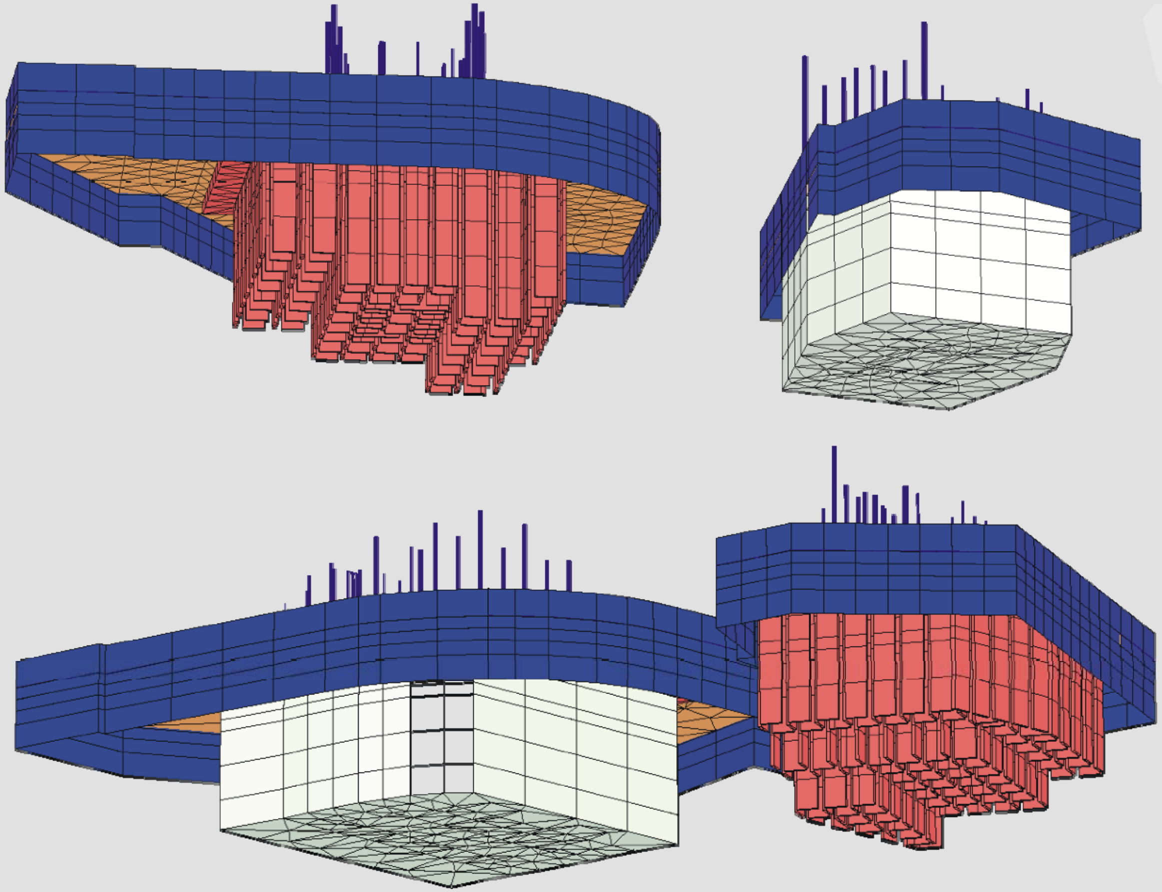
RESULTS - TOWER 2



All panels same length: max settlement ≈ 80 mm, not symmetric

3D FE-MODEL

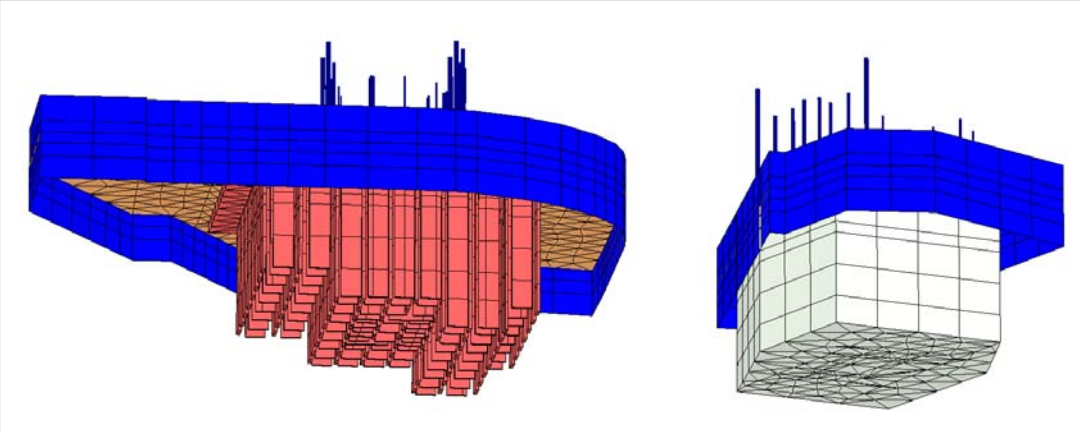
Variation of panel length

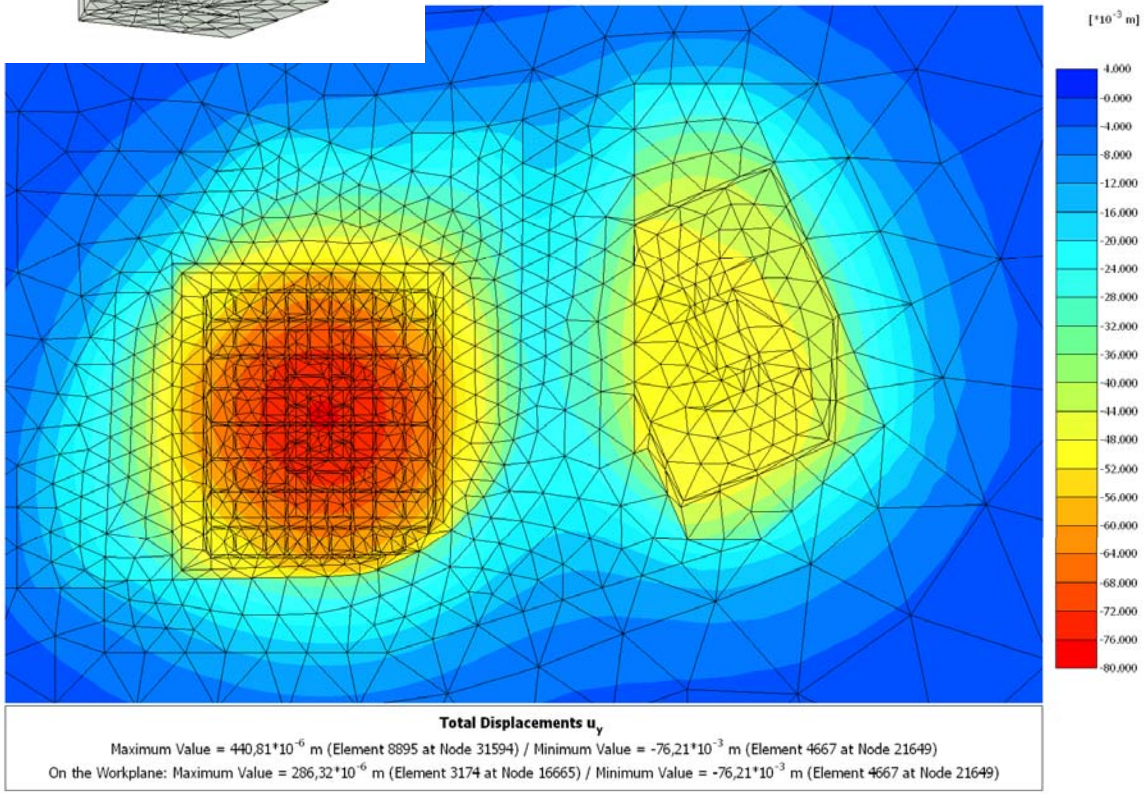


Improved model for Tower 1

Improved model for Tower 2

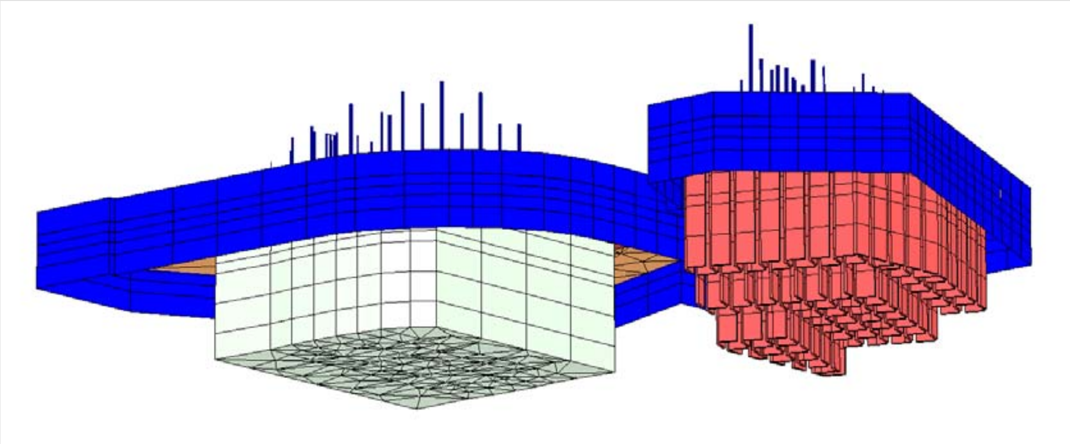
RESULTS - TOWER 1

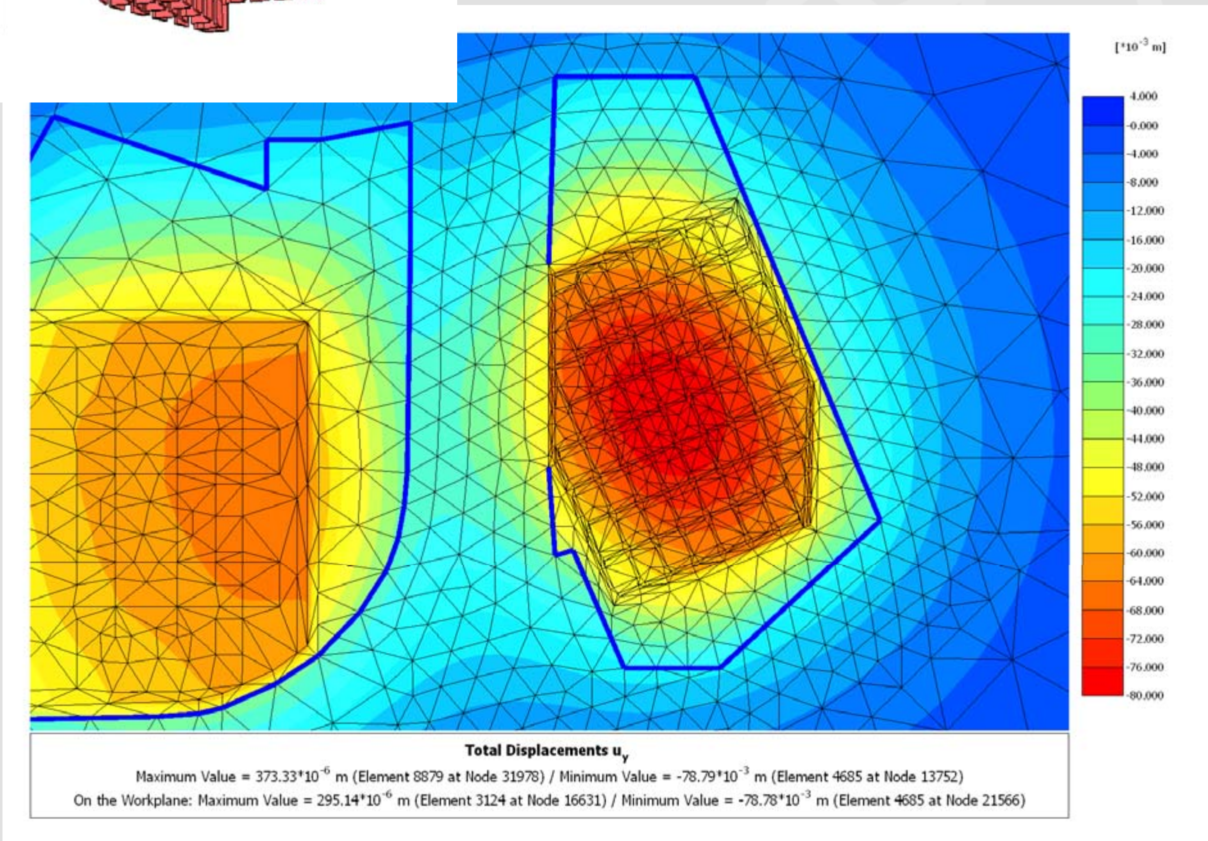




Panels with different lengths:
max settlement ≈ 80 mm
but symmetric

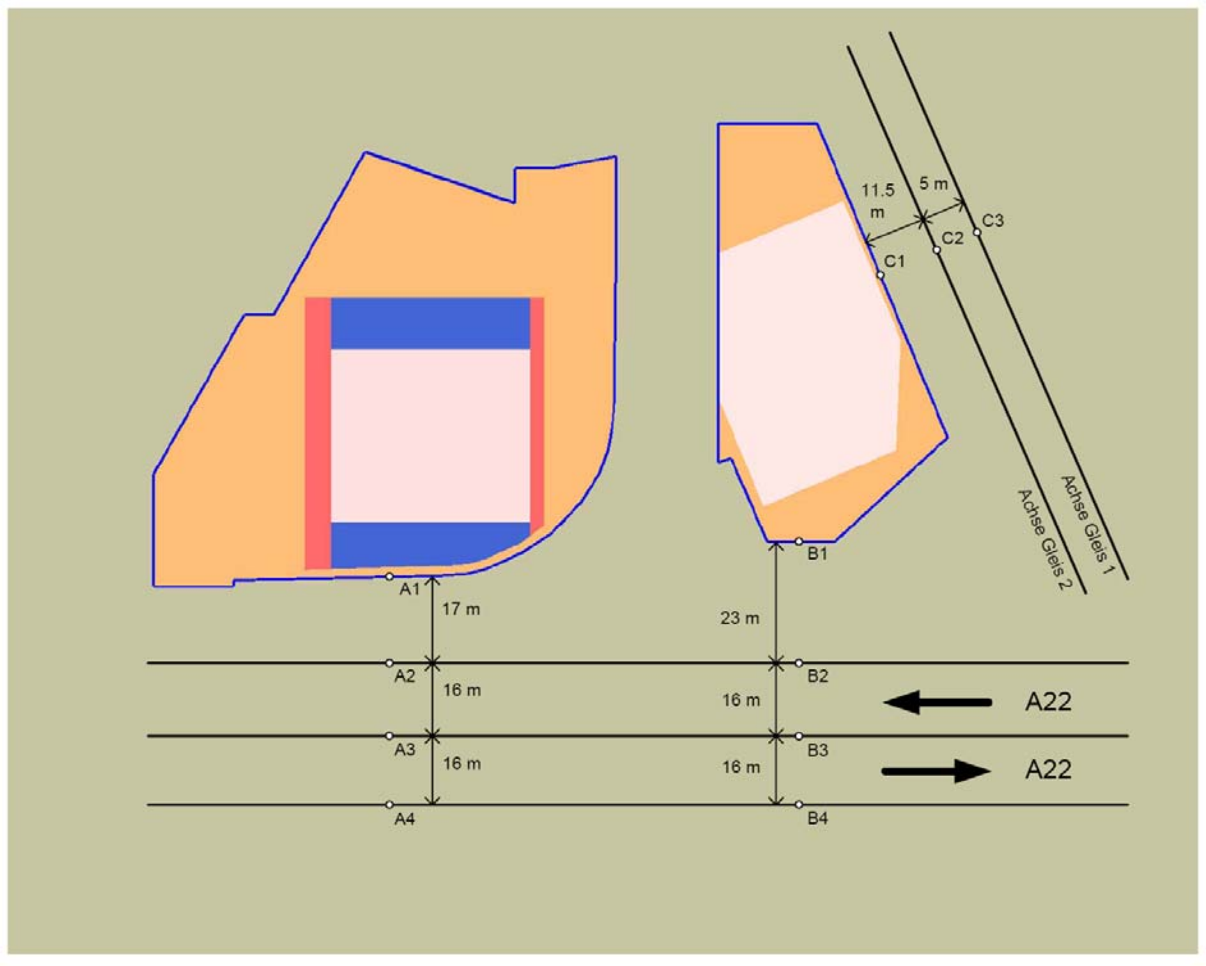
RESULTS - TOWER 2





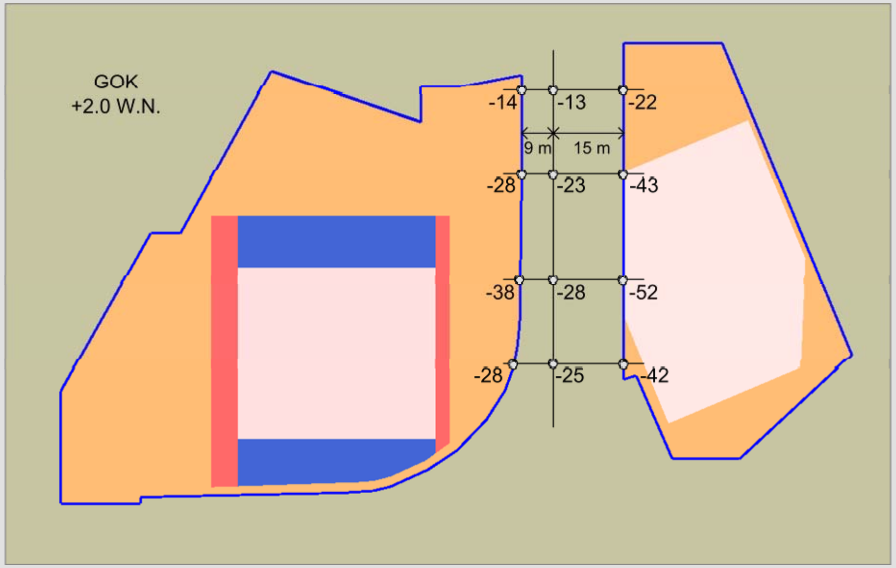
Panels with different lengths:
max settlement ≈ 85 mm,
but symmetric

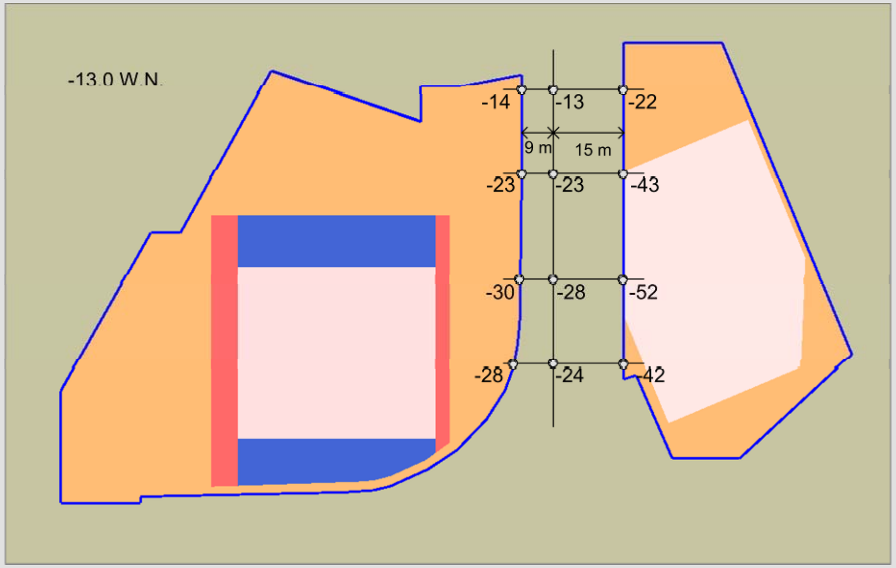
INFLUENCE ON ADJACENT STRUCTURES



	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3
Settlement [mm]	33	14	5	2	19	5	2	0	36	18	13
Distance [m]		17	16	16		23	16	16		11.5	5
Slope [1/x] x~		900	1750	5300		1600	5300	8000		600	1000

INFLUENCE ON ADJACENT STRUCTURES





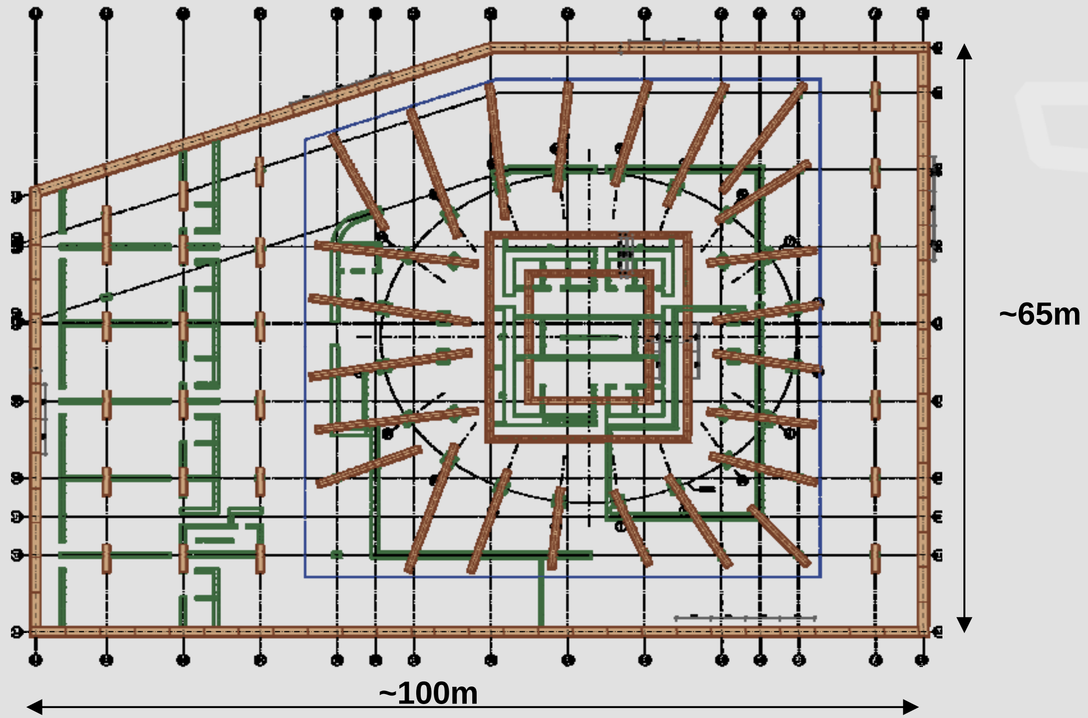
SUMMARY - TWIN TOWERS

- Modelling concept (combination of block model and discrete modelling of foundation panels) efficient to reduce model size
- Interaction of towers is taken into account
- Interface elements cannot be used for modelling wall friction of diaphragm wall panels (continuum elements) > slight underestimation of settlements
- Analysis shows that influence on adjacent structures is acceptable
- HS-small model has been used

PRACTICAL EXAMPLE - TOWER + SHOPPING MALL

PRACTICAL EXAMPLE - TOWER + SHOPPING MALL

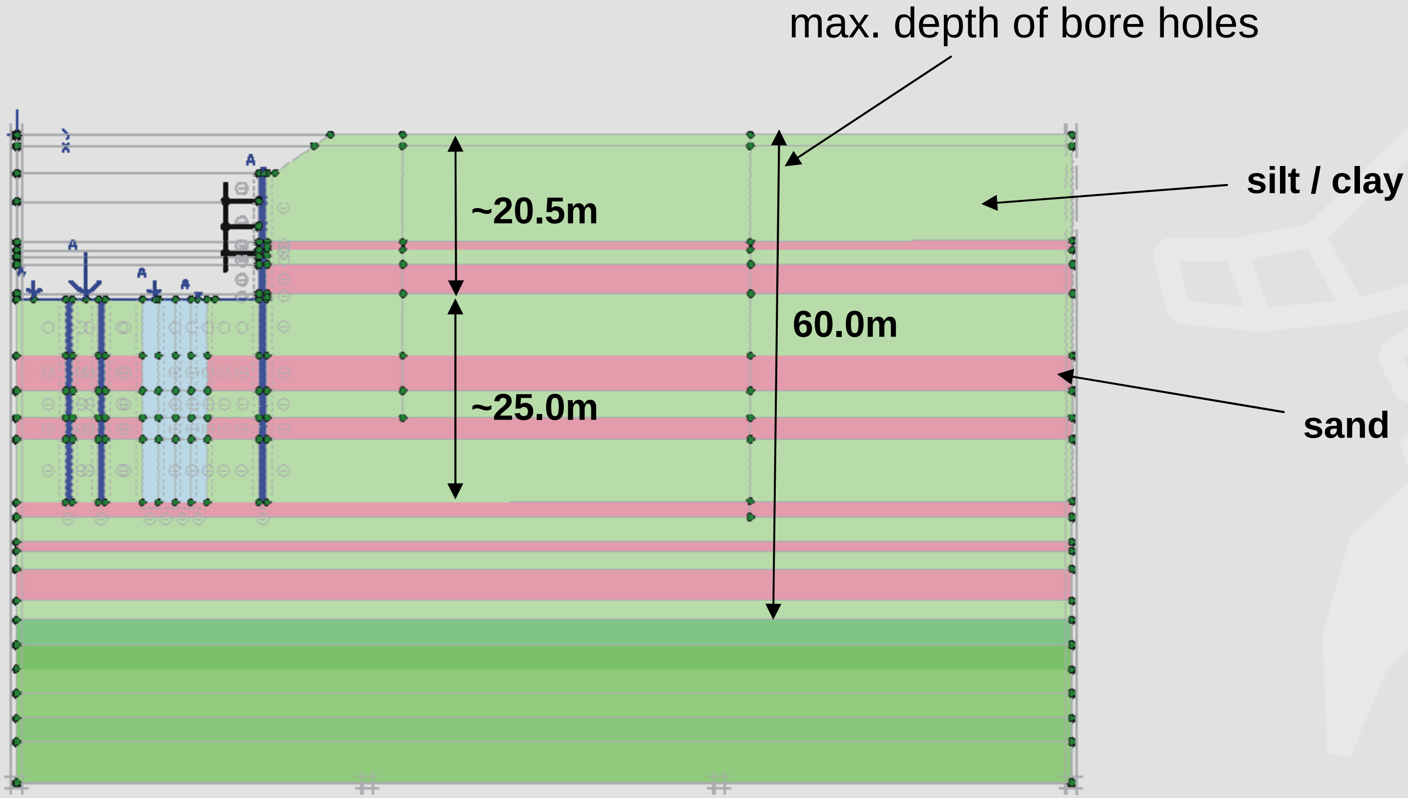
Concept for foundation



OBJECTIVE OF ANALYSIS:

- Calculate displacements at working load conditions
- Calculate differential settlement of foundation slab
- Optimize arrangement of diaphragm wall panels

SOIL PROFILE



Constitutive models:

- Soils > Hardening Soil Model
- Diaphragm walls > Mohr-Coulomb
- Floors > linear elastic

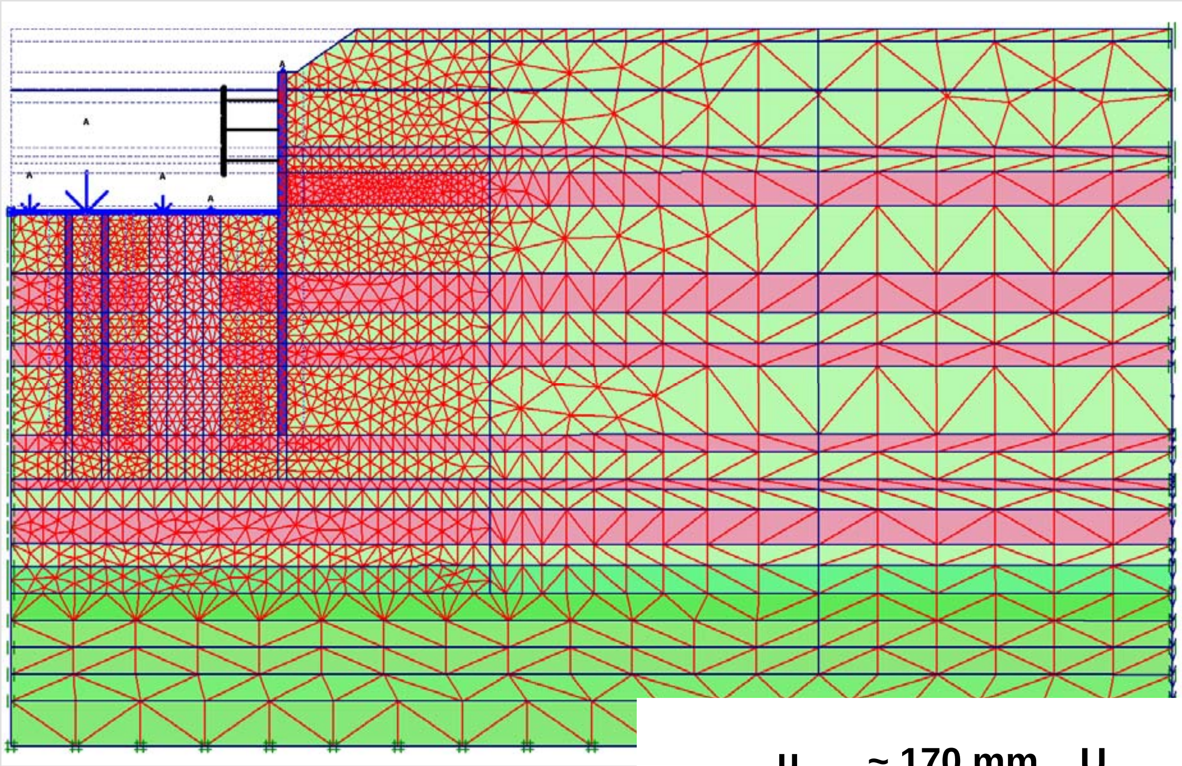
SOIL PARAMETERS

soil	Type	γ_{unsat}	γ_{sat}	E_{50}^{ref}	E_{oed}^{ref}	E_{ur}^{ref}	c_{ref}
		[kN/m³]	*[kN/m³]*	*[kN/m²]*	*[kN/m²]*	*[kN/m²]*	*[kN/m²]*
silt / clay	HS[1] drained	20.5	21.0	12 000	10 000	30 000	25.0
sand	HS[1] drained	21.0	21.5	30 000	30 000	90 000	0.1

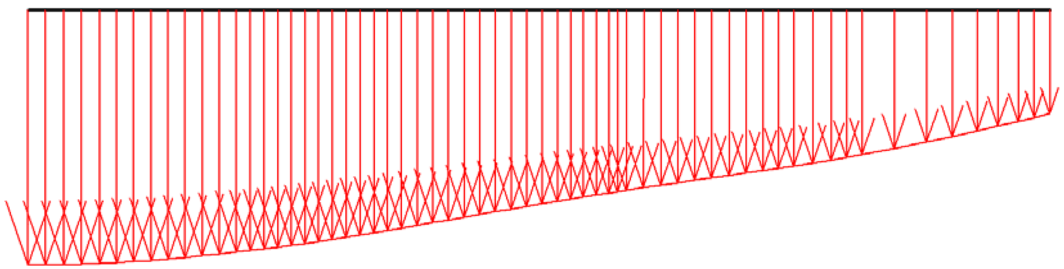
soil	φ	ψ	ν_{ur}	p^{ref}	power (m)	K_0^{nc}	R_f
	[°]	*[°]*	*[-]*	*[kN/m²]*	*[-]*	*[-]*	*[-]*
silt / clay	22.5	0.0	0.20	100	0.70	0.617	0.9
sand	32.5	2.5	0.20	100	0.65	0.463	0.9

[1] Hardening Soil Model

2D MODEL

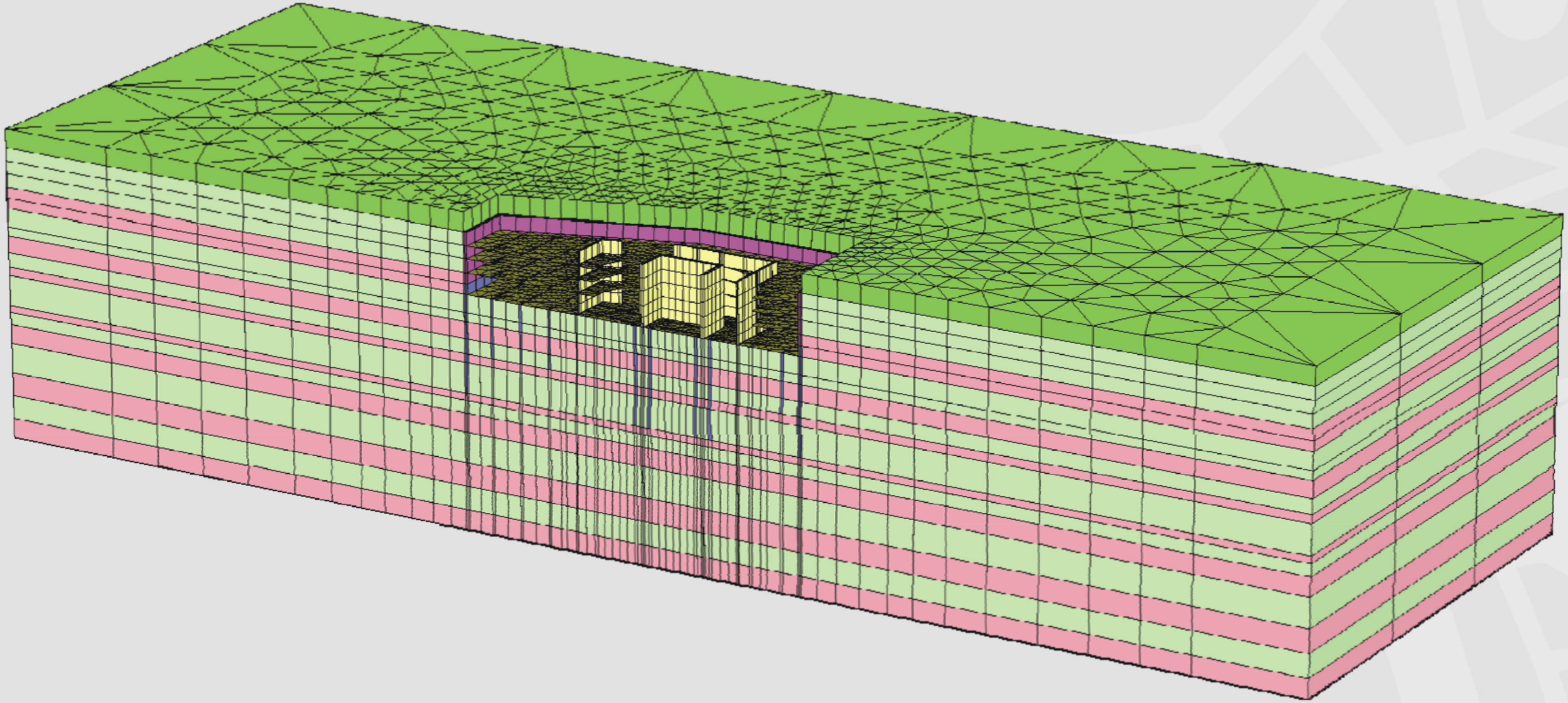


$u_{y,max}$~ 170 mm, $U_{v,diff.max}$ ~ 100 mm



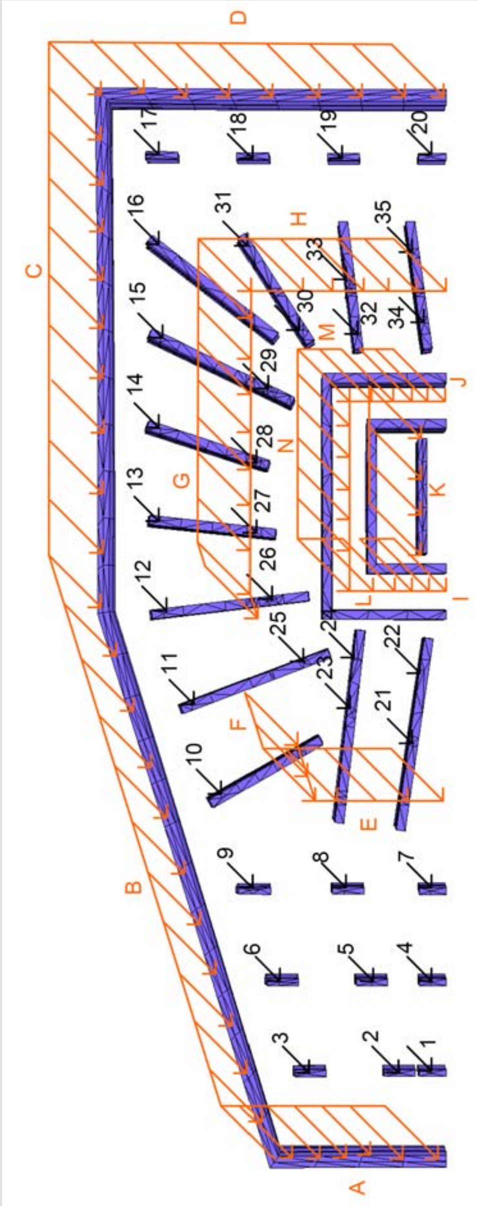
these deformations are not acceptable

3D MODEL



~51 000 elements

SCHEMATIC LAYOUT OF LOADS



point loads

number	load [kN]
1	1 700
2	2 150
3	1 650
4	2 700
5	2 600
6	1 450
7	2 850
8	5 550
9	1 800
10	2 400
11	2 800
12	2 350
13	2 150
14	2 050
15	2 050
16	2 350
17	1 500
18	2 150
19	2 300
20	2 250
21	11 150
22	12 000
23	12 500
24	13 000
25	14 900
26	5 750
27	0
28	0
29	3 700
30	6 400
31	4 550
32	7 650
33	6 850
34	5 650
35	12 150

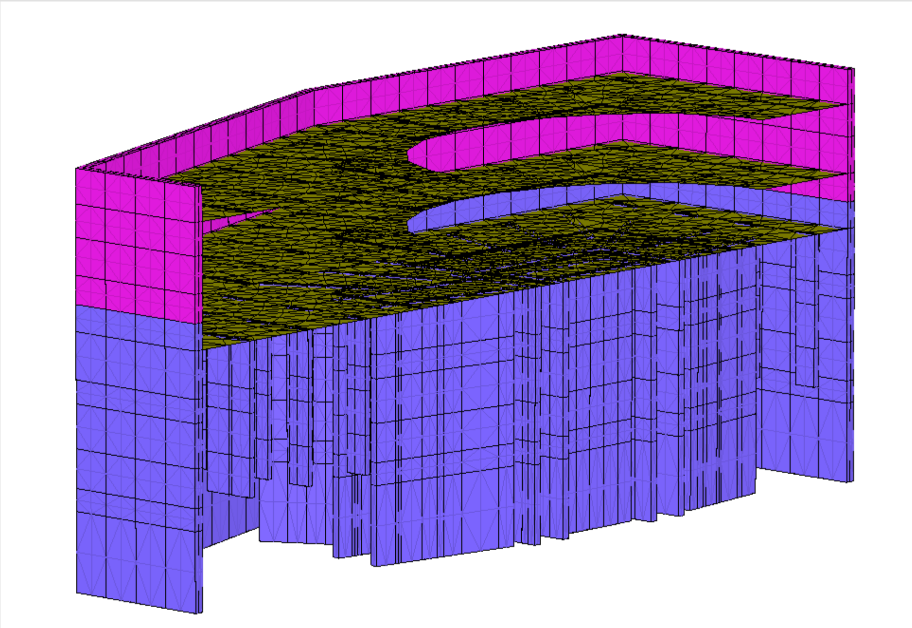
line loads

letter	load [kN/m]
A	860
B	830
C	830
D	710
E	120
F	4 770
G	3 270
H	1 130
I	6 130
J	6 040
K	1 280
L	7 770
M	7 930
N	6 670

CONSTRUCTION PHASES

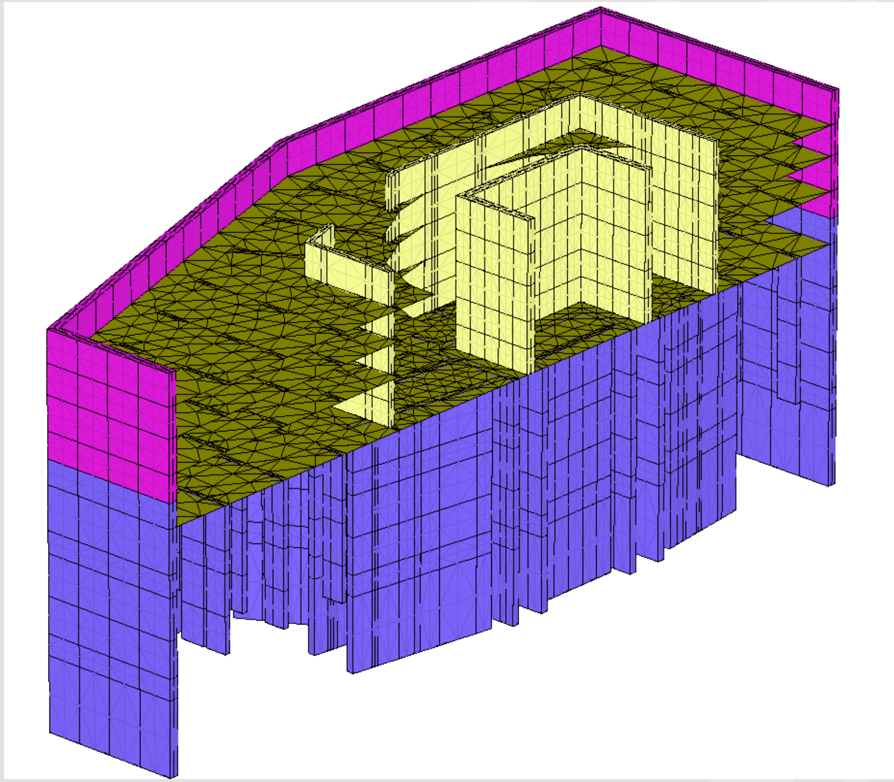
- Initial stresses
- Excavation to level -4.8 m
- Activation of diaphragm wall and panels (material model change > "wished-in-place")
- Groundwater lowering to -8.2 m
- Excavation to -8.2 m
- Activation of first level slab
- Groundwater lowering to -15.0 m
- Excavation to -15.0 m
- Activation of third level slab
- Groundwater lowering to -20.4 m (bottom of slab)
- Excavation to -20.4 m (bottom of slab)
- Activation of slab (reset displacements to zero)
- Activation of second level slab
- Activation of core walls
- End of groundwater lowering
- Loads from superstructure

CONSTRUCTION PHASES



Activation of slab (reset displacements to zero)

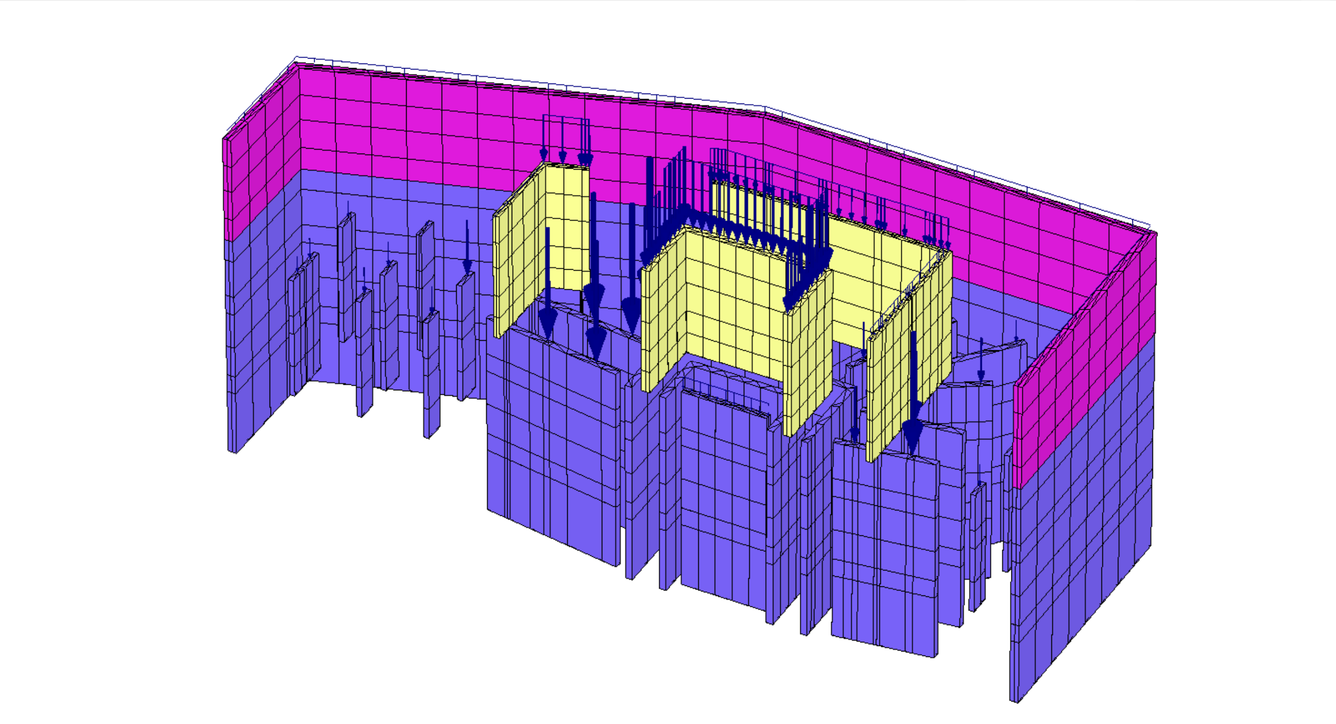
Slabs are modelled without weight but with stiffness (support for excavation phases)



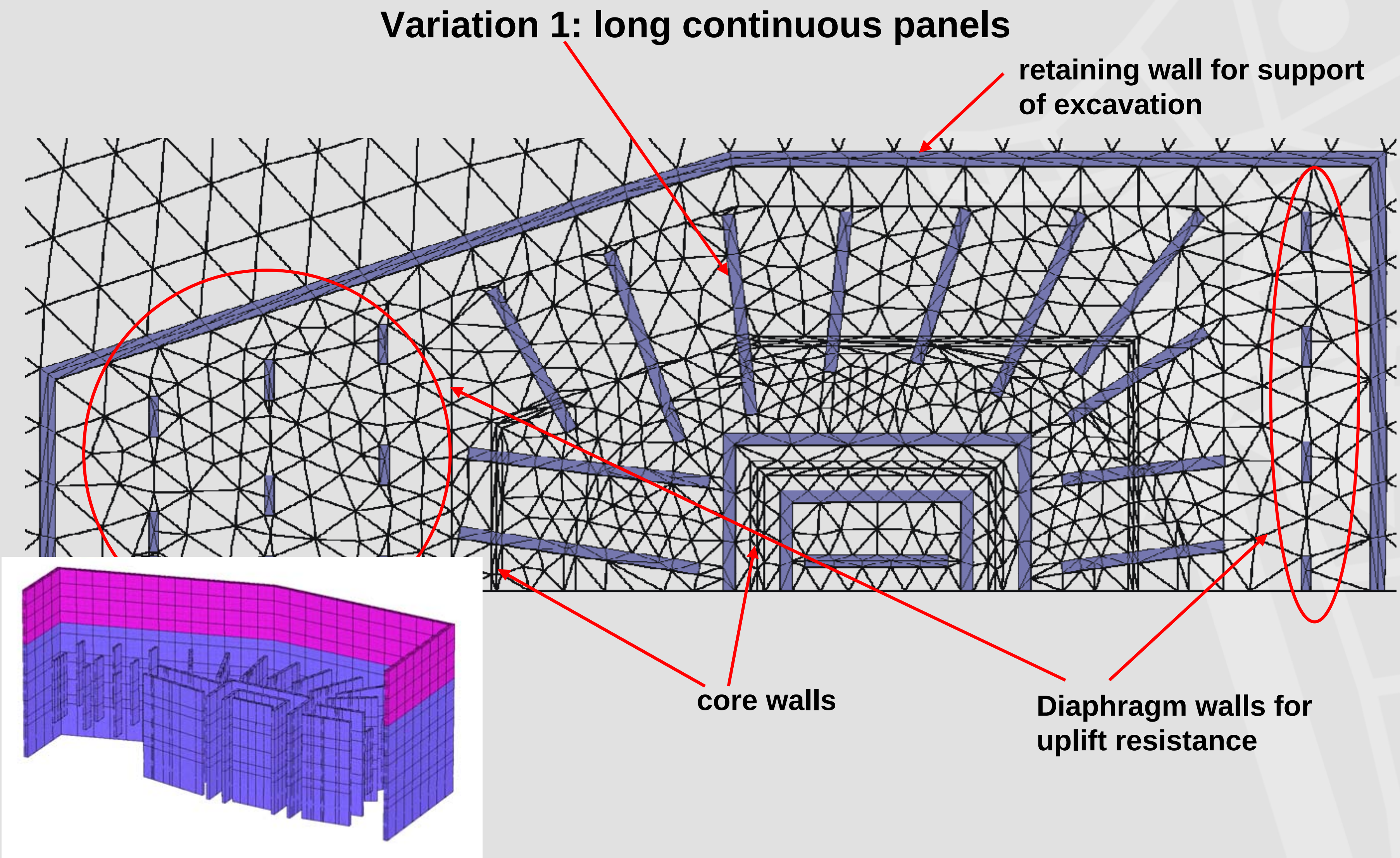
Activation of core walls

CONSTRUCTION PHASES

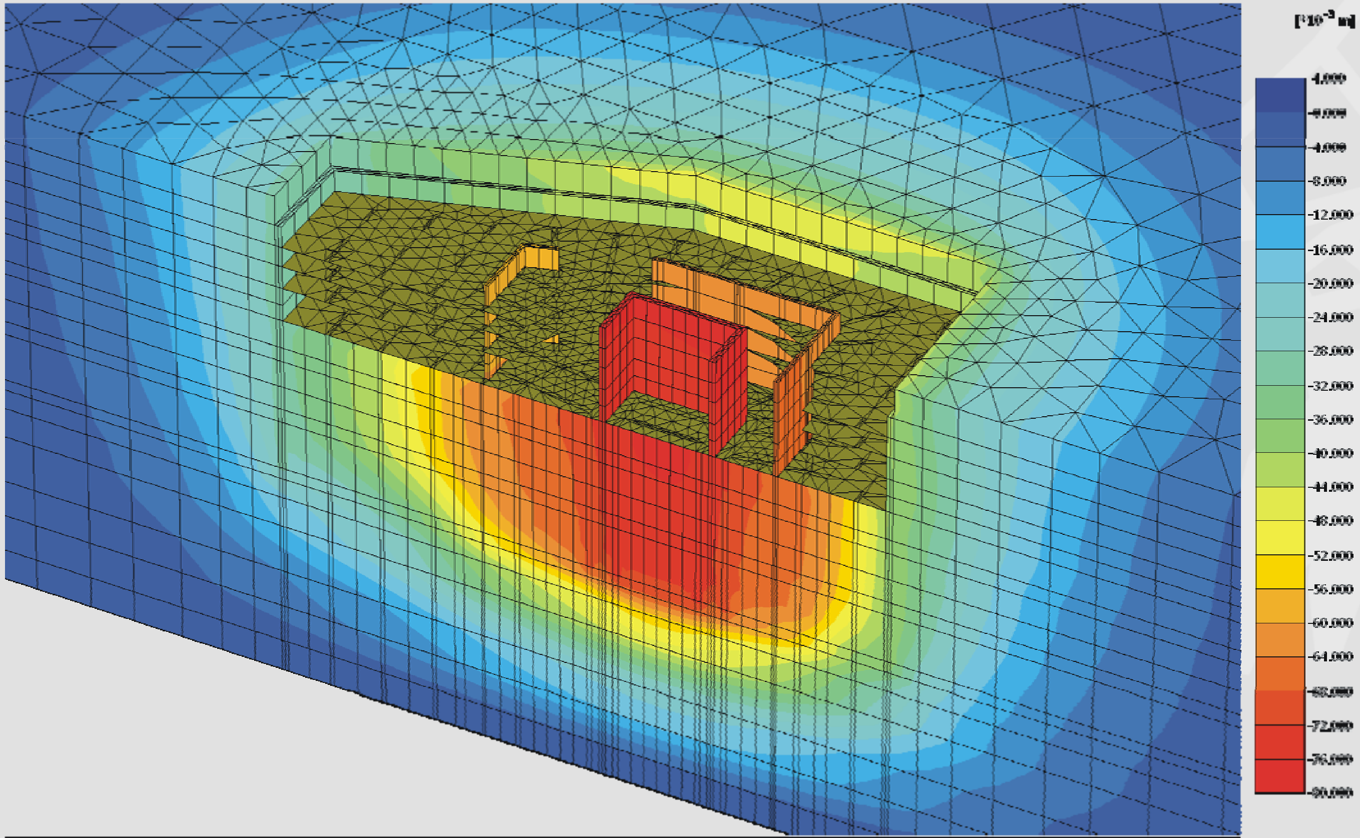
Activation of loads from superstructure



GEOMETRY OF PANELS



RESULTS - VARIATION 1



Total Displacements u_y

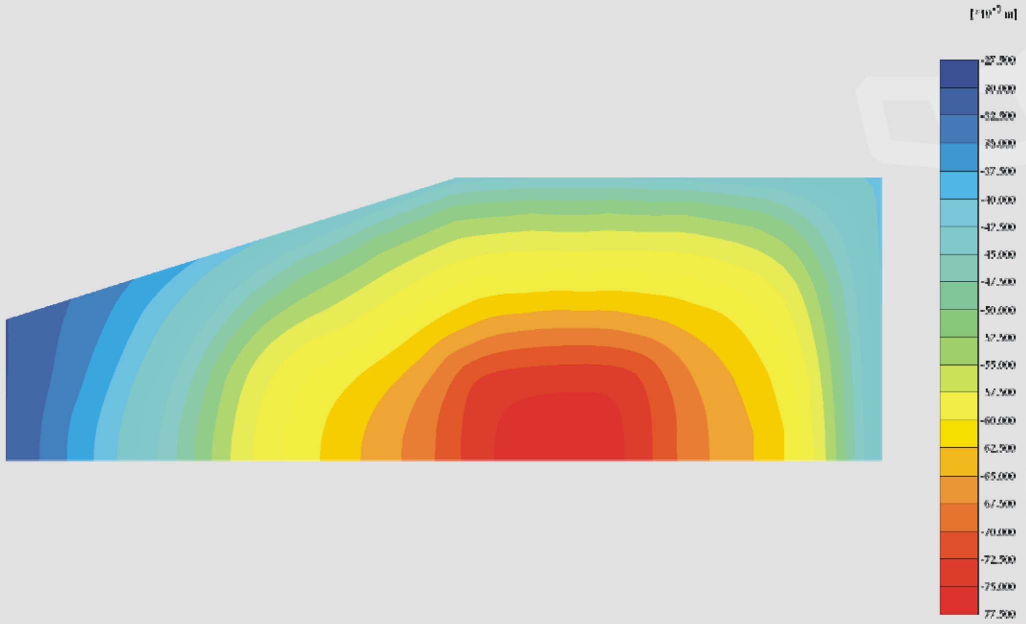
Maximum Value = $284{,}33 \cdot 10^{-6}$ m (Element 13326 at Node 41174)

Minimum Value = $-78{,}15 \cdot 10^{-3}$ m (Element 4743 at Node 11891)

Variation 1

$u_{y,max}$~ 80 - 90 mm

RESULTS - VARIATION 1



Total Displacements u_y

Maximum Value = $-29{,}89 \cdot 10^{-3}$ m (Element 120 at Node 41796)

Minimum Value = $-76{,}55 \cdot 10^{-3}$ m (Element 764 at Node 46206)

Variation 1

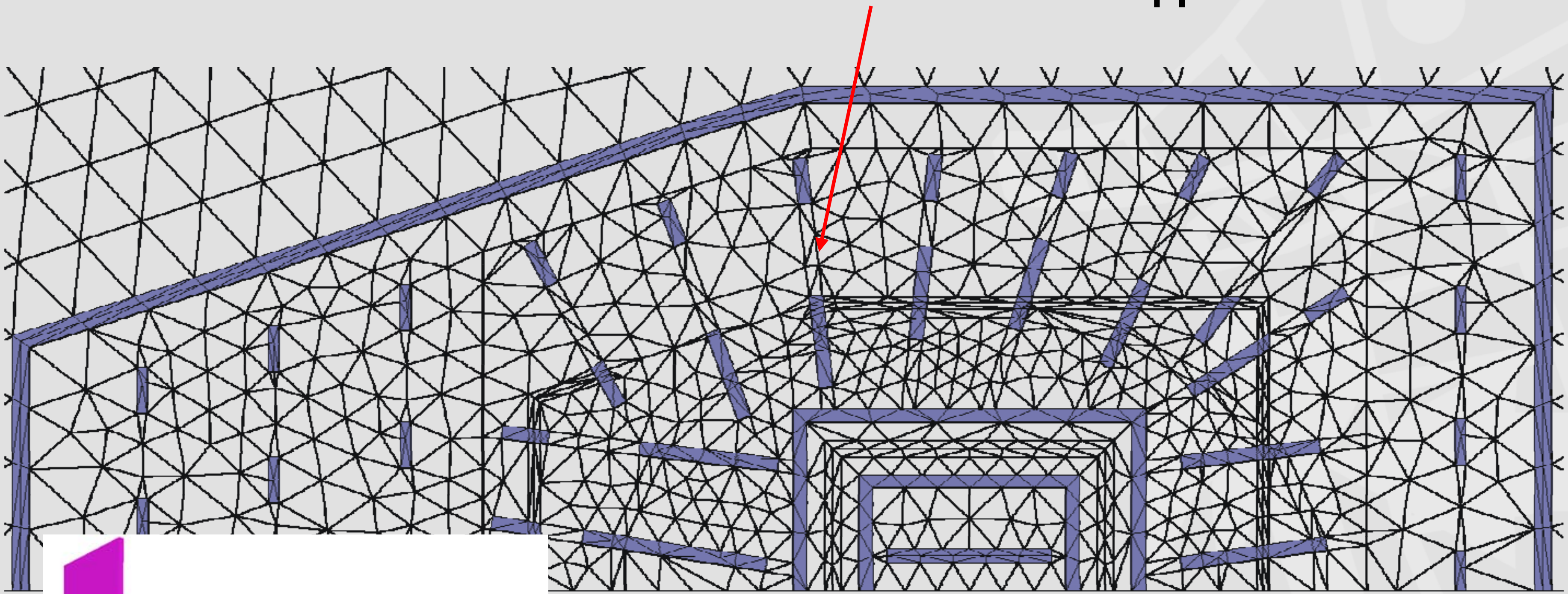
$u_{y,max}$~ 80 - 90 mm

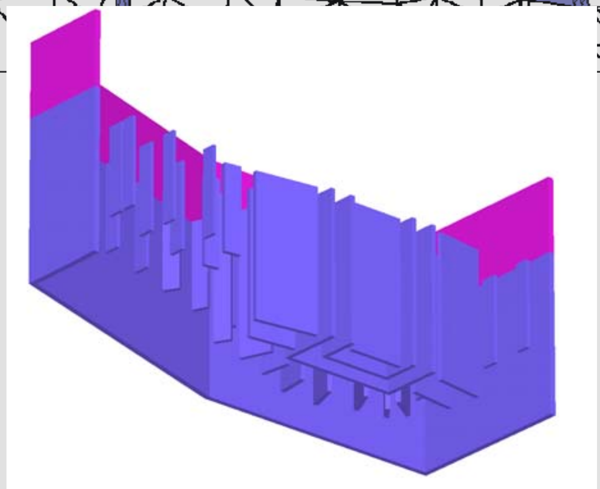
$U_{v,diff.max}$ ~ 50mm

GEOMETRY OF PANELS

Variation 2: discontinuous panels

max. settlements approx. 95 - 105 mm

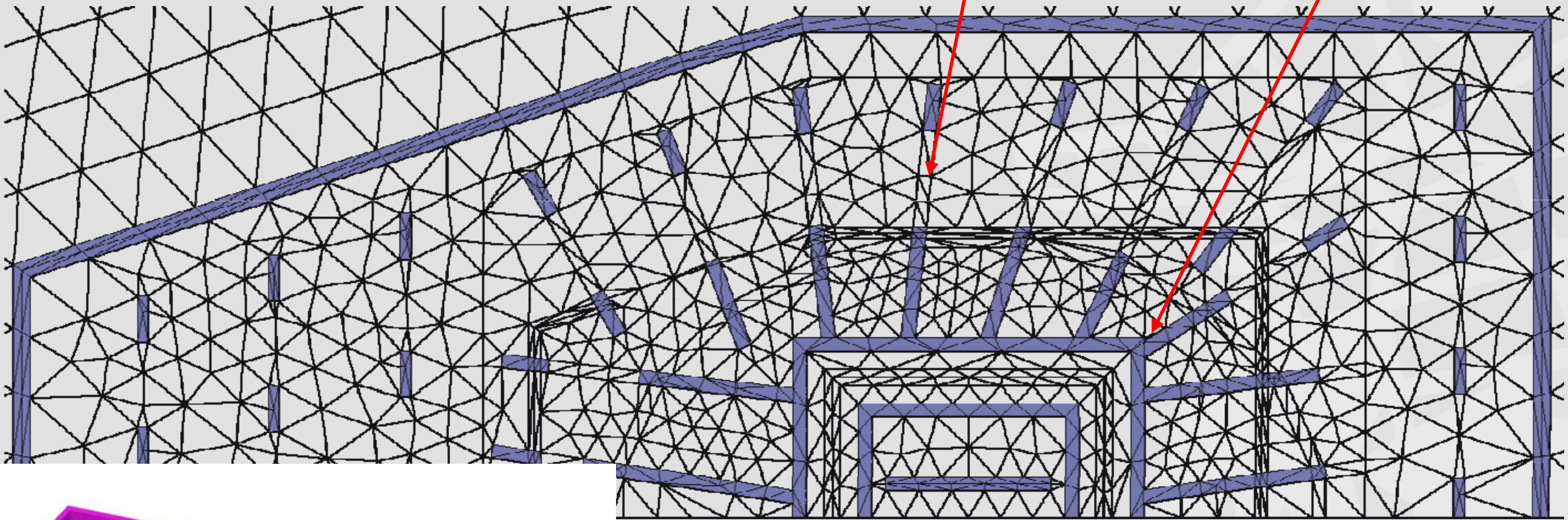


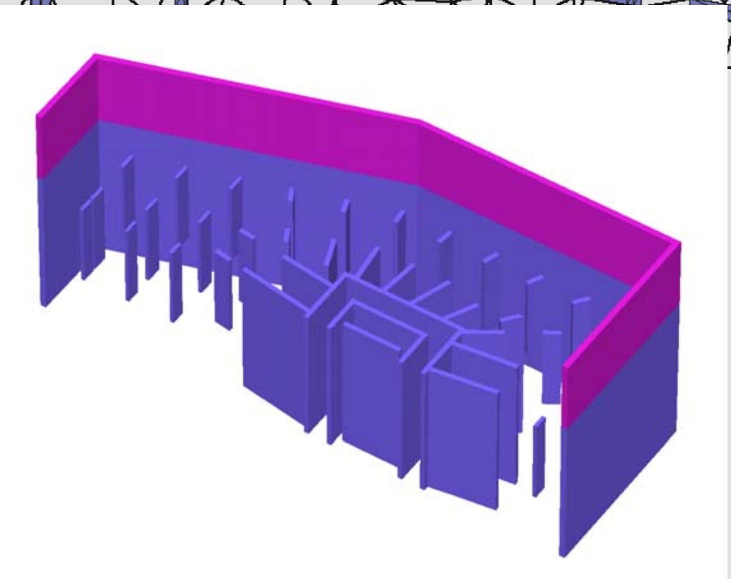


GEOMETRY OF PANELS

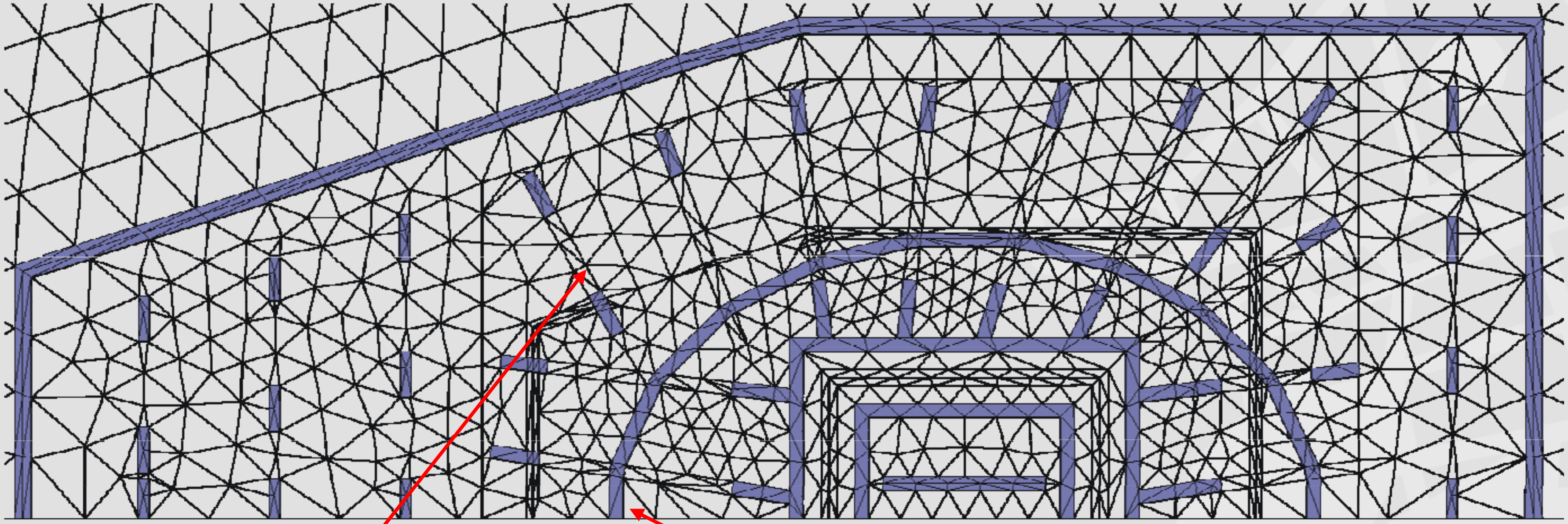
Variation 3: discontinuous panels connected to core

max. settlements approx. 90 - 100 mm



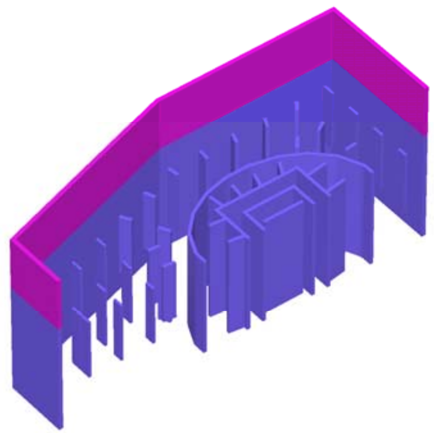


GEOMETRY OF PANELS

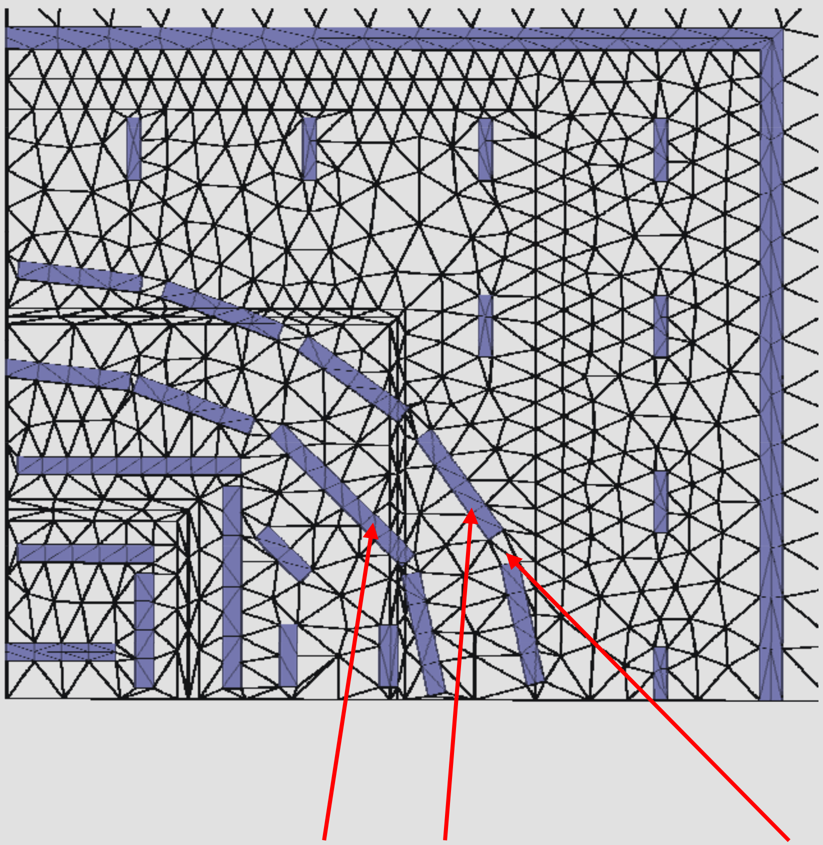


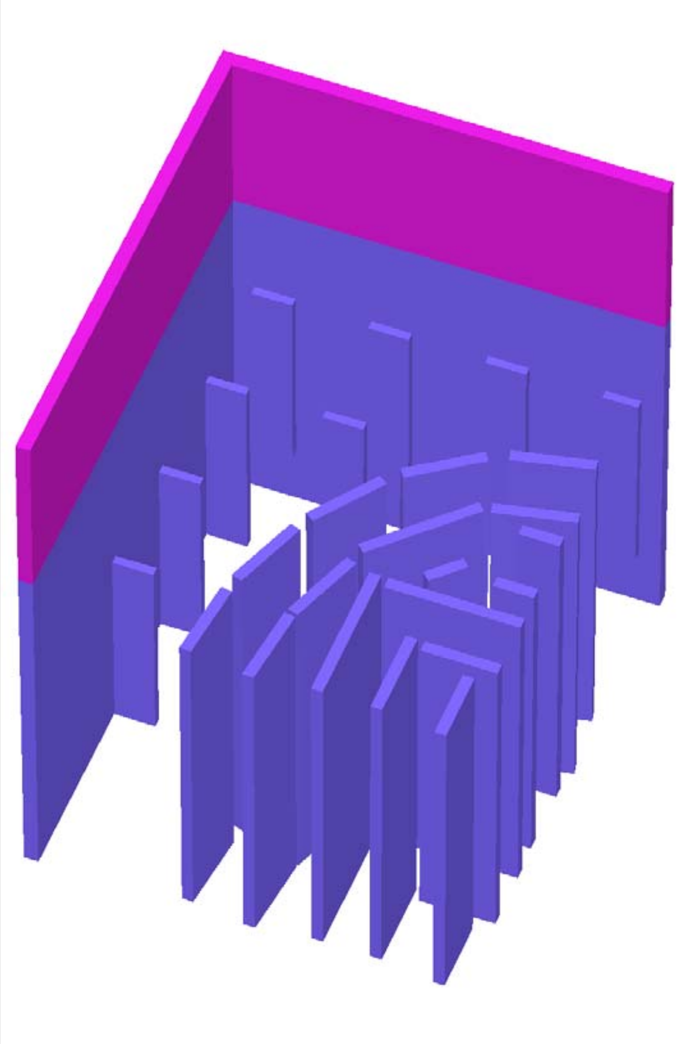
Variation 4: discontinuous panels + ring of panels

max. settlements approx. 95 - 105 mm



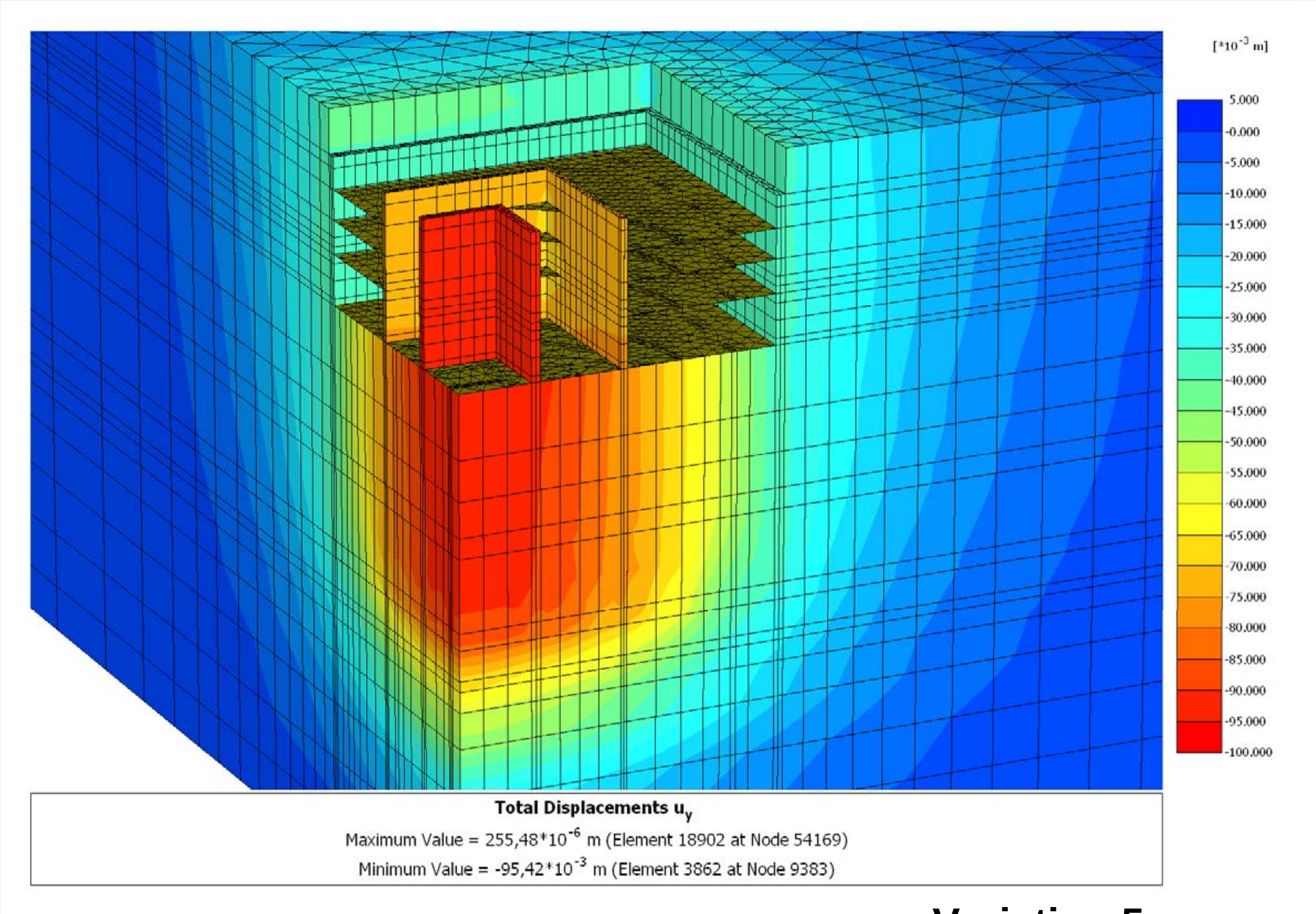
GEOMETRY OF PANELS





Variation 5: two rings of panels, not connected

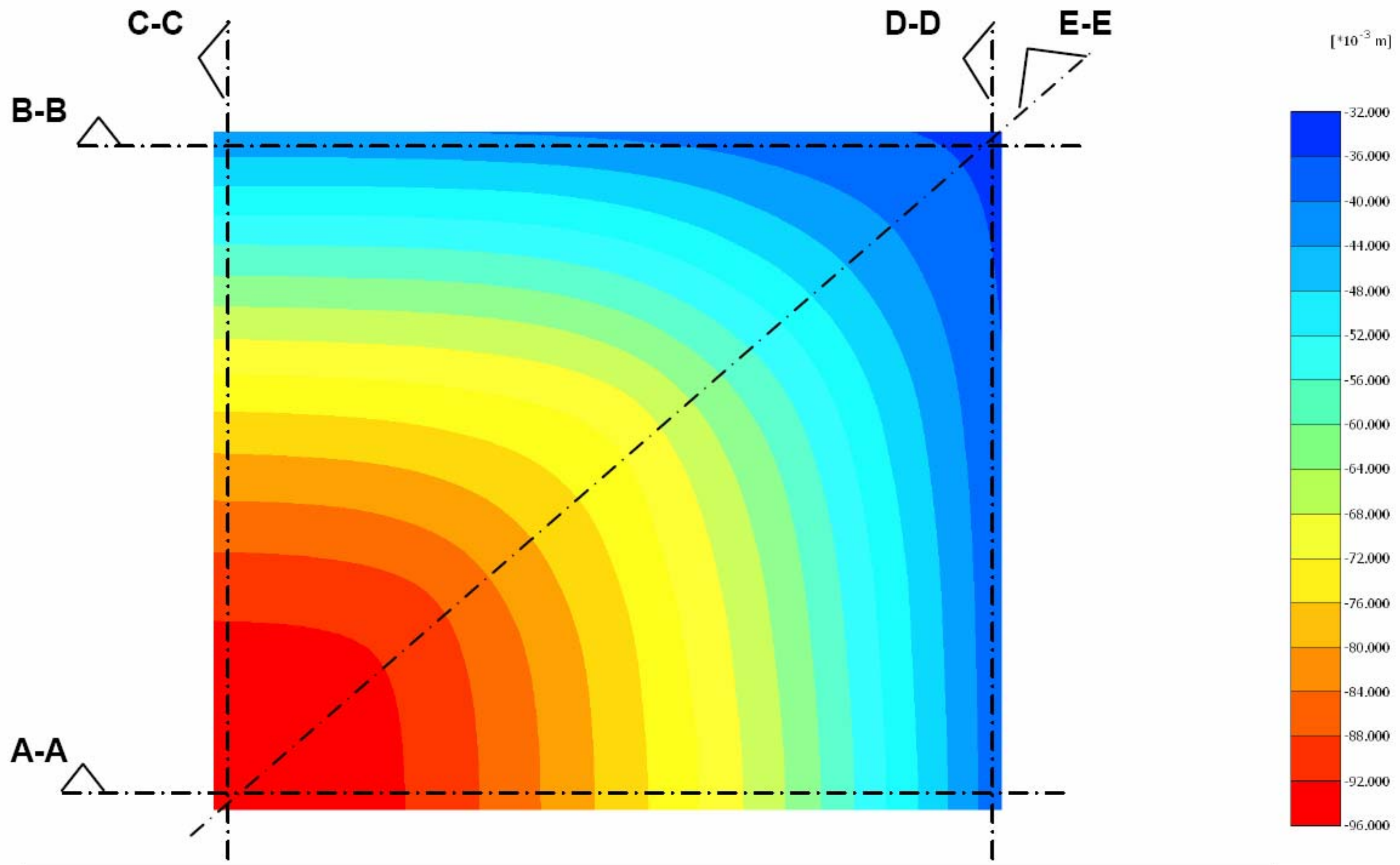
RESULTS - VARIATION 5



Variation 5

$u_{y,max}$~ 100 - 110 mm

RESULTS - VARIATION 5



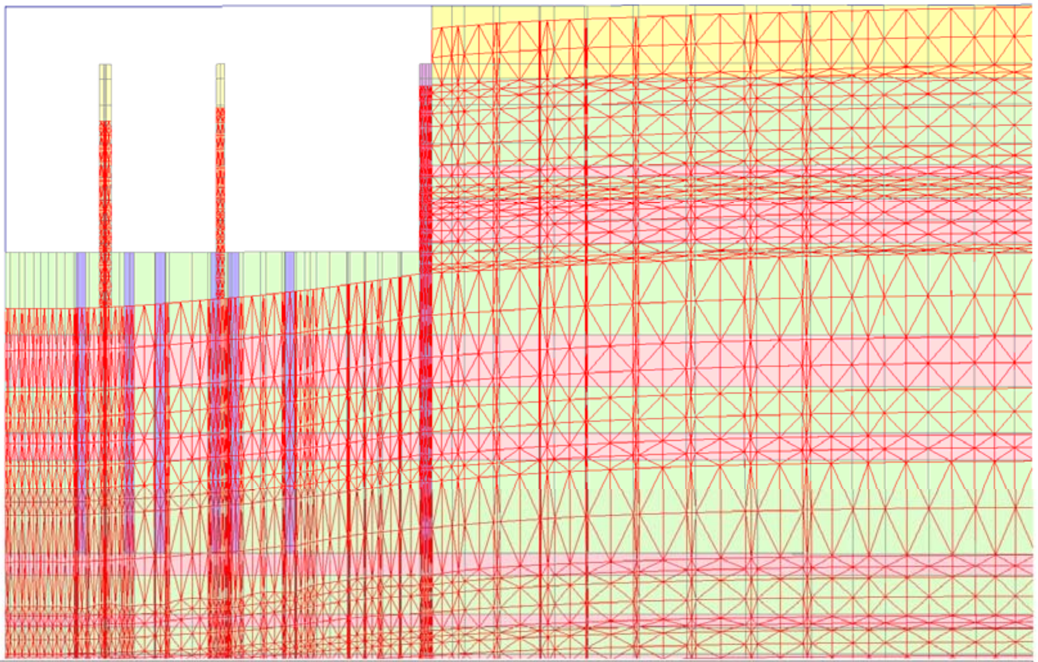
Total Displacements u_y

Maximum Value = $-35{,}07 \cdot 10^{-3}$ m (Element 2702 at Node 60130)

Minimum Value = $-94{,}83 \cdot 10^{-3}$ m (Element 3174 at Node 63160)

RESULTS - VARIATION 5

Section A - A



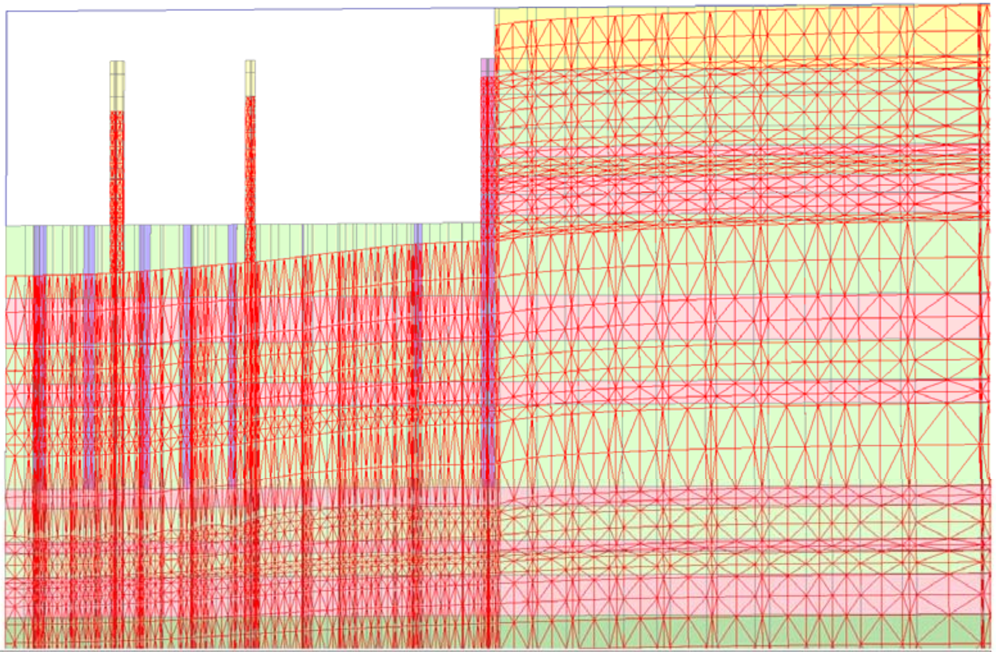
Total Displacements u_y (scaled up 50,00 times)

Maximum Value = $109{,}37 \cdot 10^{-6}$ m

Minimum Value = $-94{,}53 \cdot 10^{-3}$ m

RESULTS - VARIATION 5

Section E - E



Total Displacements u_y (scaled up 50,00 times)

Maximum Value = $165{,}99 \cdot 10^{-6}$ m

Minimum Value = $-95{,}38 \cdot 10^{-3}$ m

SUMMARY - EXAMPLE TOWER + SHOPPING MALL

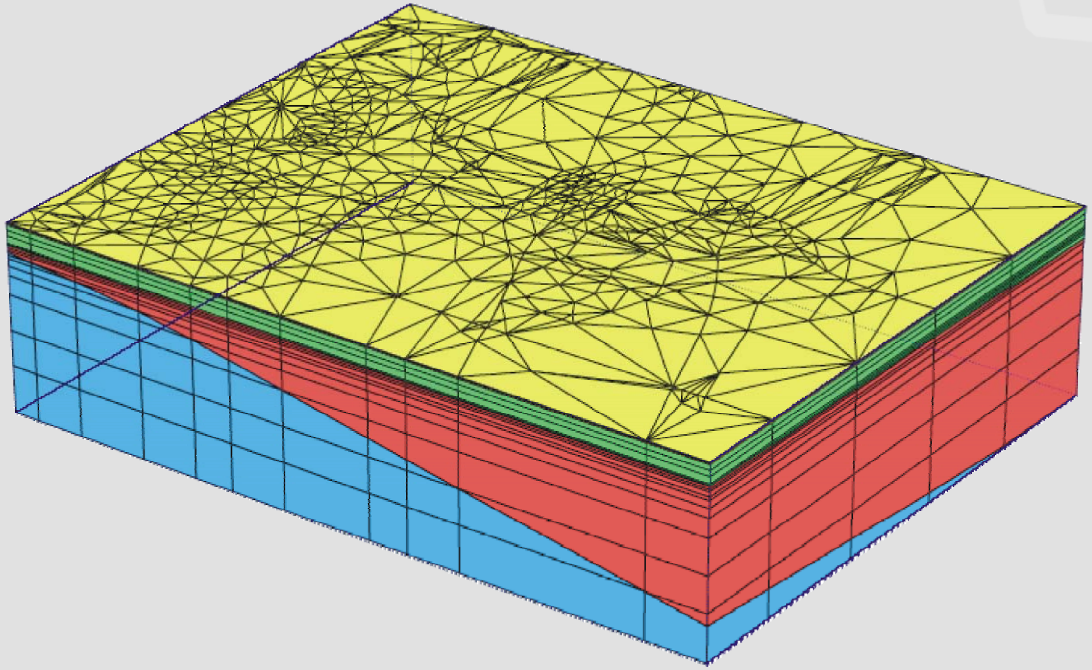
Variation	1	2	3	4	5
Max. settlement [mm]	80-90	95-100	90-100	95-105	100-105

Summary of calculated settlements

- **Due to geometric and loading conditions 2D-analysis not useful at all > significant overestimation of (differential) settlements**
- **Effect of different arrangement of foundation panels can be assessed with 3D model**
- **Interface elements cannot be used for modelling wall friction of diaphragm wall panels (continuum elements) > slight underestimation of settlements**
- **Model size of about 50 000 elements close to limit which can be handled > not sufficiently accurate to look at stresses, e.g. in the panels**

COMMENTS ON 3D FOUNDATION FOR MODELLING DEEP FOUNDATIONS

- **Number of elements increase significantly if non-horizontal layers are present and a relatively large number of workplanes is needed for geometric or output reasons (> new output features should improve this)**



- **Limitations in placing interface elements**
- **Problems with consolidation analysis for large models**
- **Type of connection between e.g. diaphragm wall and foundation slab somewhat restricted (depending on element type used)**