GEOTEC Software Inc.
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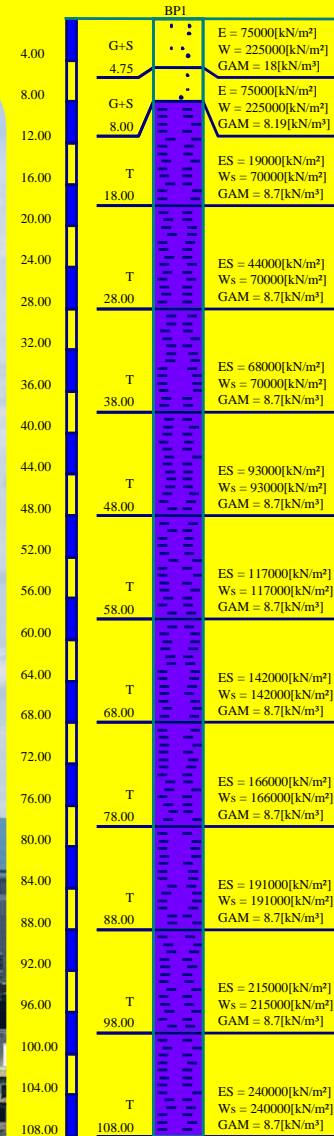# Analysis and Design of Piled Raft Foundation by the Program *ELPLA*

## ■ Description:

*ELPLA* (*EL*astic *PLA*te) is a program for analyzing piled raft foundations of arbitrary shape, variable thickness and foundation depth with the real subsoil model.
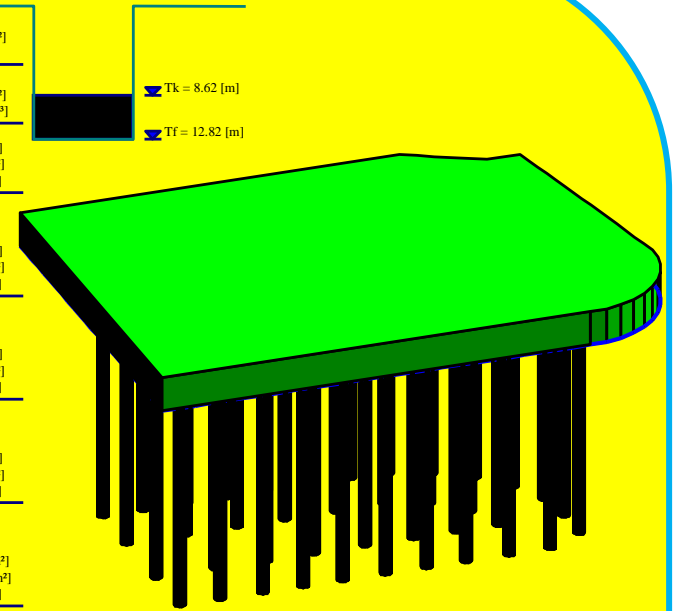
The program can analyze different types of subsoil models, especially the three dimensional continuum model that considers any number of irregular layers in vertical and horizontal directions.

Three known subsoil models for the analysis of piled raft foundations (standard models) are considered. The subsoil models are the Simple Assumption Model, the Winkler Model and the Continuum Model.
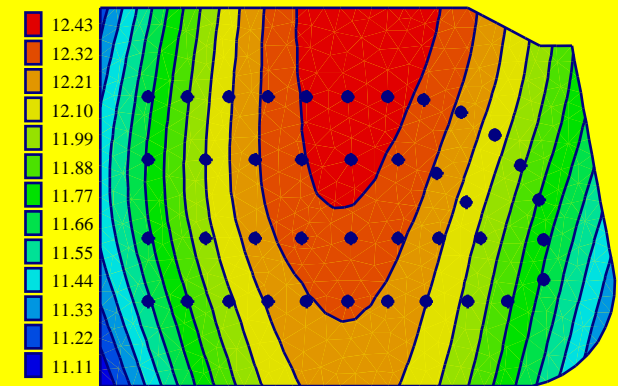
In the analysis, the slab can be treated as elastic or rigid slab. The mathematical solution of the slab is based on the finite element method.



**Boring log**

Boring log values (BP1):

| Depth | Layer | Properties |
|---|---|---|
| 4.00 | G+S 4.75 | E = 75000 [kN/m²], W = 225000 [kN/m²], GAM = 18 [kN/m³] |
| 8.00 | G+S 8.00 | E = 75000 [kN/m²], W = 225000 [kN/m²], GAM = 8.19 [kN/m³] |
| 18.00 | T | ES = 19000 [kN/m²], Ws = 70000 [kN/m²], GAM = 8.7 [kN/m³] |
| 28.00 | T | ES = 44000 [kN/m²], Ws = 70000 [kN/m²], GAM = 8.7 [kN/m³] |
| 38.00 | T | ES = 68000 [kN/m²], Ws = 70000 [kN/m²], GAM = 8.7 [kN/m³] |
| 48.00 | T | ES = 93000 [kN/m²], Ws = 93000 [kN/m²], GAM = 8.7 [kN/m³] |
| 58.00 | T | ES = 117000 [kN/m²], Ws = 117000 [kN/m²], GAM = 8.7 [kN/m³] |
| 68.00 | T | ES = 142000 [kN/m²], Ws = 142000 [kN/m²], GAM = 8.7 [kN/m³] |
| 78.00 | T | ES = 166000 [kN/m²], Ws = 166000 [kN/m²], GAM = 8.7 [kN/m³] |
| 88.00 | T | ES = 191000 [kN/m²], Ws = 191000 [kN/m²], GAM = 8.7 [kN/m³] |
| 98.00 | T | ES = 215000 [kN/m²], Ws = 215000 [kN/m²], GAM = 8.7 [kN/m³] |
| 108.00 | T | ES = 240000 [kN/m²], Ws = 240000 [kN/m²], GAM = 8.7 [kN/m³] |

Tk = 8.62 [m]
Tf = 12.82 [m]



**Piled raft of *Westend 1***



Settlement legend [cm]: 12.43, 12.32, 12.21, 12.10, 11.99, 11.88, 11.77, 11.66, 11.55, 11.44, 11.33, 11.22, 11.11

**Settlement [cm] according to nonlinear analysis using the German recommendations "EA-piles"**

**Practical example 1: Piled raft foundation of *Westend* 1 in Frankfurt**

## ■ Features:

- User interface and help system are available in 3 languages: English, German and Arabic
- Analysis of an elastic or a rigid combined piled raft foundation
- Analysis of a rigid pile group or free-standing raft on a rigid pile group
- Numerical model of soil-structure interaction is under 9 calculation methods
- Design of the raft according to ACI, EC 2, DIN 1045 and ECP
- Generation of the FE mesh of the raft with different element types
- Automatic generation of the FE mesh of the raft
- Powerful mesh generator (for the generation of square, rectangular, circular and annular rafts)
- Beam elements for modeling stiff walls on the raft
- Translational and rotational springs on the raft can be added at nodes
- Elastic or fixed rotations and deflections can be taken into account.
- Determining contact pressures, settlements, internal forces, subgrade reactions, reinforcement and pile loads
- Node coordinates and boundary nodes of the FE mesh can be imported from a table via MS Excel
- Arbitrary shape of slabs, holes are also possible
- Variable slab thickness and foundation depth in vertical and horizontal directions
- Consideration of the reduction coefficients α according to DIN 4019 Part 1
- Point loads, line loads, area loads and moments at any position independent of the finite element net
- Polygonal load with variable ordinates and line moment
- Loading and reloading modulus of compressibility are considered
- The soil is defined by a number of borings each boring has multi-layers with different soil material
- Variable thickness and discontinuous soil strata
- Consideration of the variation of the subsoil in the three directions according to three methods
- Drawing soil layers by different symbols and colors according to DIN 4023 for easy identification
- Consideration of groundwater and overburden pressure effects
- Color representation of the dimensions, slab plans and results on the screen or printer
- Presentation of the results as values in the plan, contour lines, circular diagrams
- Drawing results in isometric view
- Distribution of results in plan
- Drawing deformations as deformed mesh
- Principal moments as streaks
- Drawing sections of results from several calculation methods in one view
- Data and results of several projects can be displayed together
- Tabulation of data and final results on the screen or printer
- Results can be saved in an ASCII file
- The drawings can optionally be saved as a WMF file
- There are detailed explanations in the user manual with numerical examples
- Short help information can be requested at any interface location
- Import or export the data to MS Excel
- Export the results and diagrams to MS Excel
- Export the data and results to MS Word
- A group of data with results together in one presentation
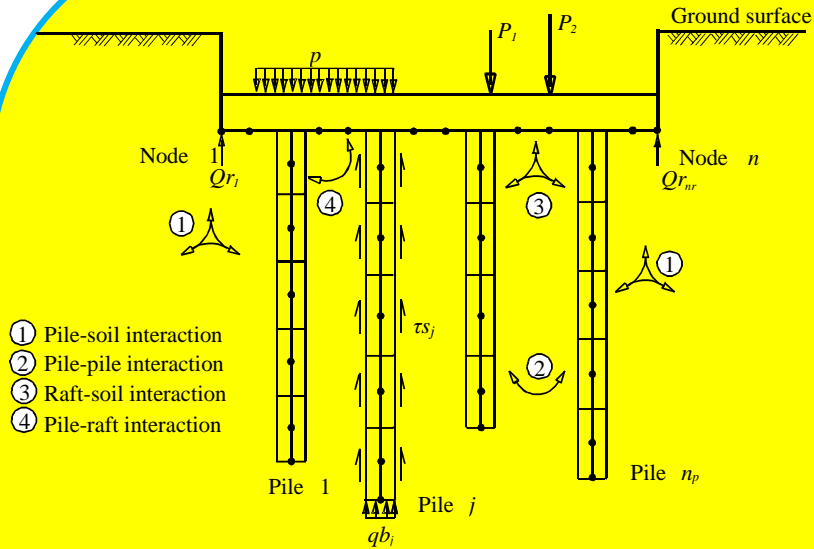- Copying drawings to the clipboard for use in word processors
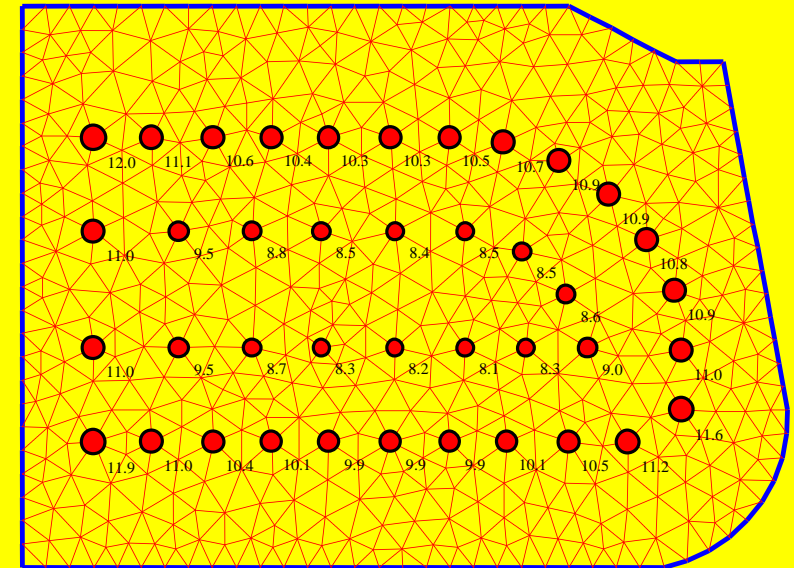


**Pile loads [MN] for the elastic piled raft with using a hyperbolic function for load-settlement curve of the pile**
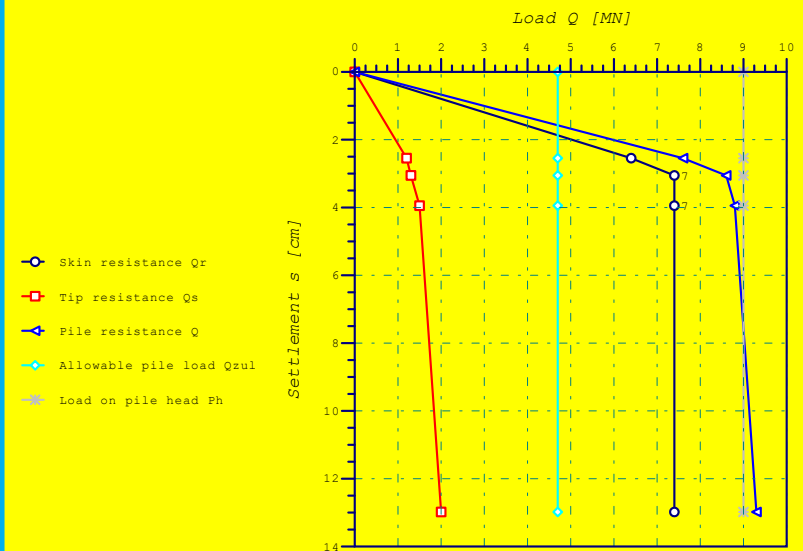


**Pile No. 1 - Pile label: P1**
**Load-settlement curve of pile according to**
**German Standard DIN 4014**

## Modeling a piled raft foundation



Ground surface

$P_1$ $P_2$

$p$

Node 1

$Qr_1$

Node $n$

$Qr_{nr}$

① Pile-soil interaction
② Pile-pile interaction
③ Raft-soil interaction
④ Pile-raft interaction

$\tau s_j$

Pile 1    Pile $j$    Pile $n_p$

$qb_j$

## Piled raft foundation

$P_2$ $P_1$

$p$

1  2  3  4  5  6  7  8  9  10  11  12  13  $n_r = 14$

$Q_1$    $Ph_1$    $Ph_4$    $Q_{32}$

Pile 1    Pile 4

## Statical system of the foundation according to the composite coefficient technique

$w_1$    $w_n$

$wo_1$    $wo_4$
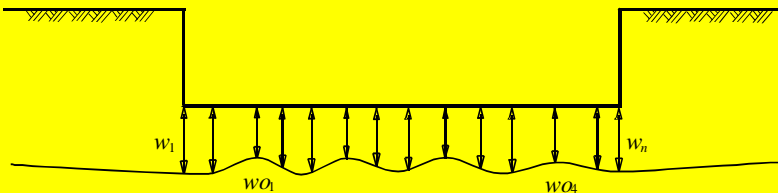
## Bodensetzung für elastische Pfahl-Plattengründung

C.L.

$S_1$    $S_n$

$\theta_y$    $S_o$    $S_i$

## Soil settlement for rigid piled raft foundation

## Multiple models for analyzing piled raft foundations

The behavior of the pile-soil system can be examined by considering linearly or nonlinearly analysis.

One distinguishes between the following nonlinear analyses of piled raft foundations by:

1- a hyperbolic function for load-settlement curve of the pile

2- Using German Standard "DIN 4014" for load-settlement curve of the pile

3- Using German recommendations "EA-Piles" for load-settlement curve of the pile

4- a given load-settlement curve of the pile

## Calculation methods

In the analysis of piled raft, each pile is treated as two units - pile shaft and pile base - with a uniform settlement along the pile shaft and in the pile base. This assumption allows modeling of non-linear behavior based on the empirical relationship of the load-settlement line according to DIN 4014 or EA-Piles.

As a combination of empirical and theoretical approaches, a new method has been developed for the nonlinear computation of piled raft. It meets the requirements of the KPP Directive.
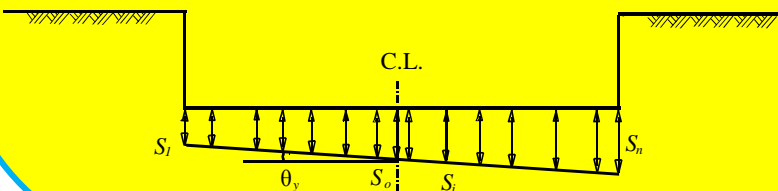


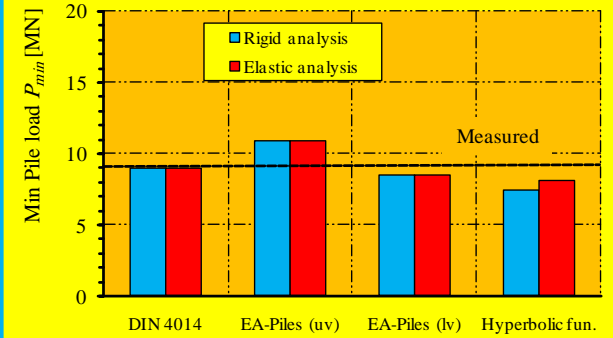**Comparison of Min pile load according to various analyses and field measurement for *Westend* 1 in Frankfurt**
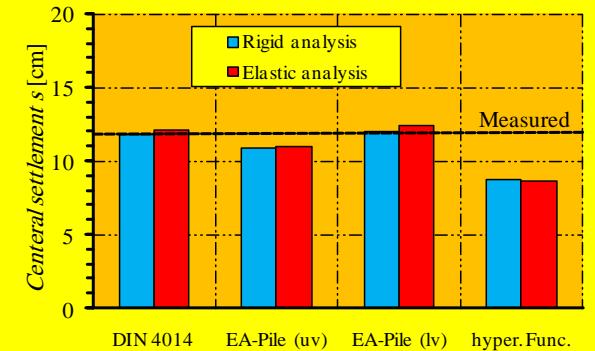


**Comparison of the piled raft settlement at the center of the plate according to various analyses and field measurement for *Westend 1* in Frankfurt**
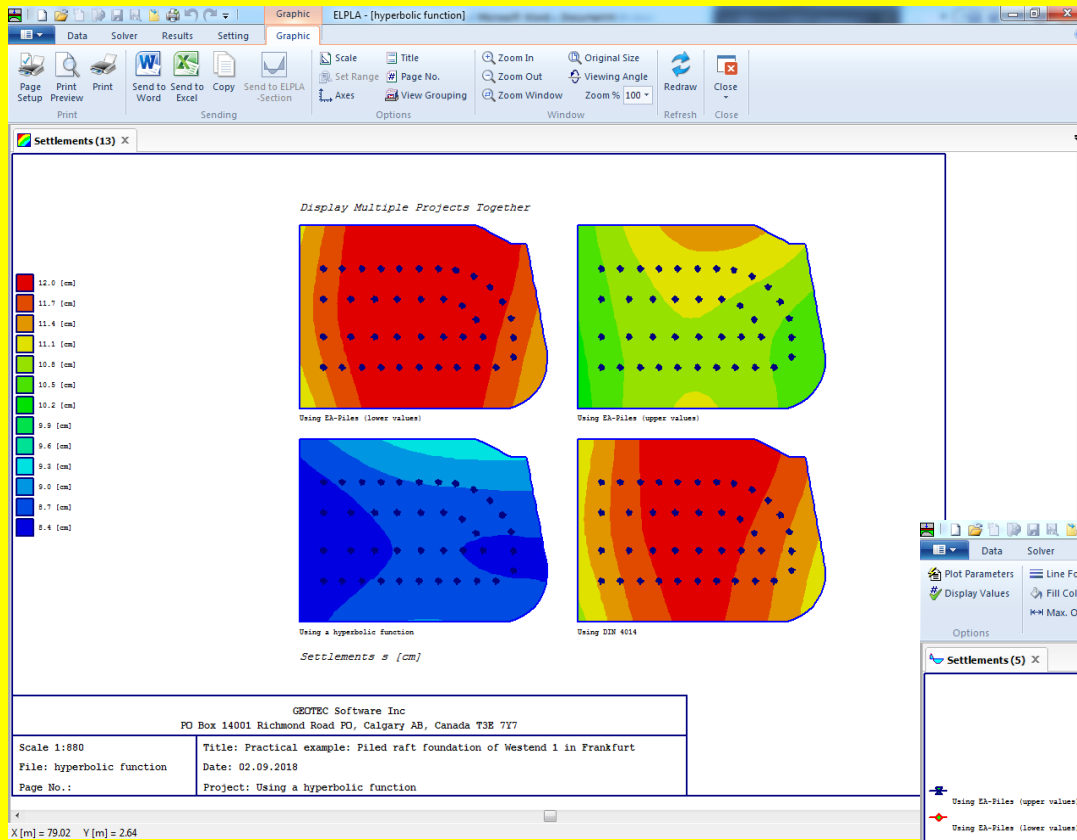
**Display multiple projects together in a single view:**

A feature in ELPLA allows the user to display data or results from multiple projects in a single view.

The following figure shows in a single view four different projects, which were carried out by various analyses.
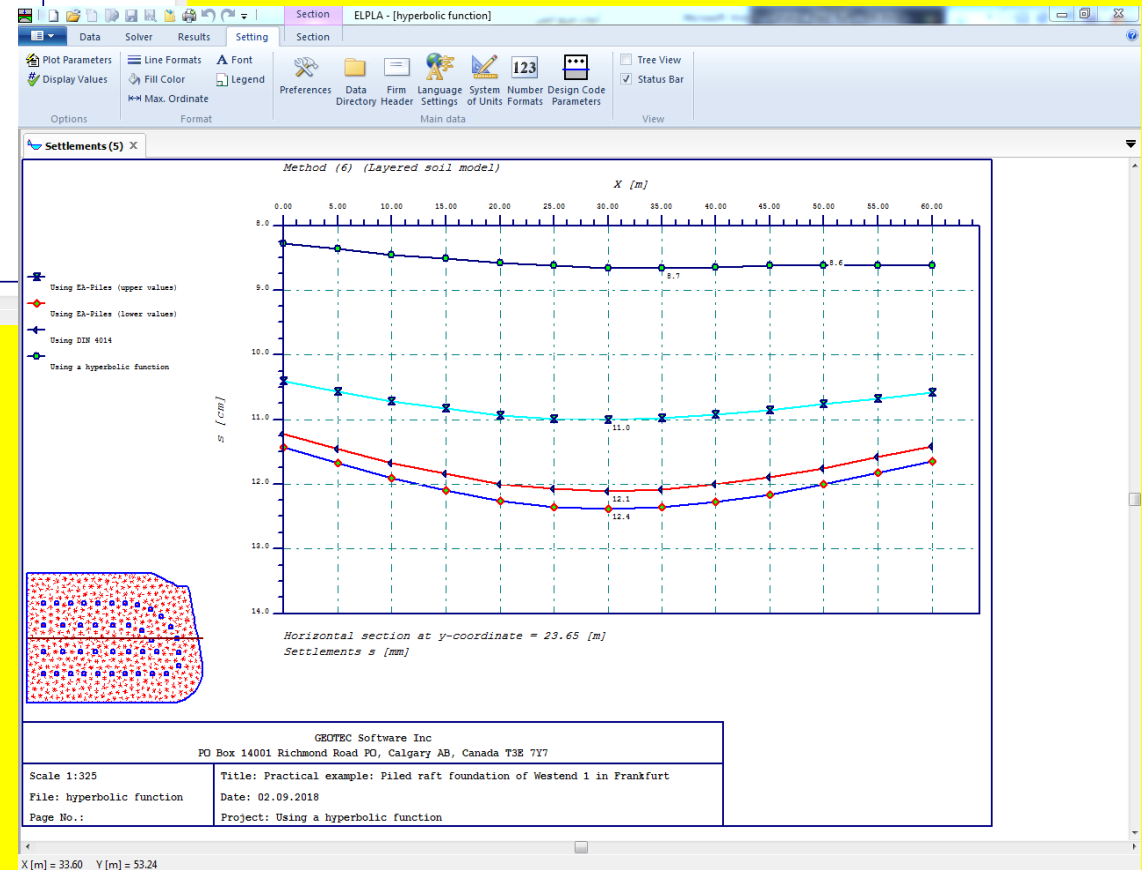
**Combination of multiple projects in one diagram:**

The option "Display Multiple Projects Together" allows the user to display charts from different load cases, soil models, calculation methods, soil properties, boundary conditions, and special cases in a particular section or area in a single diagram.
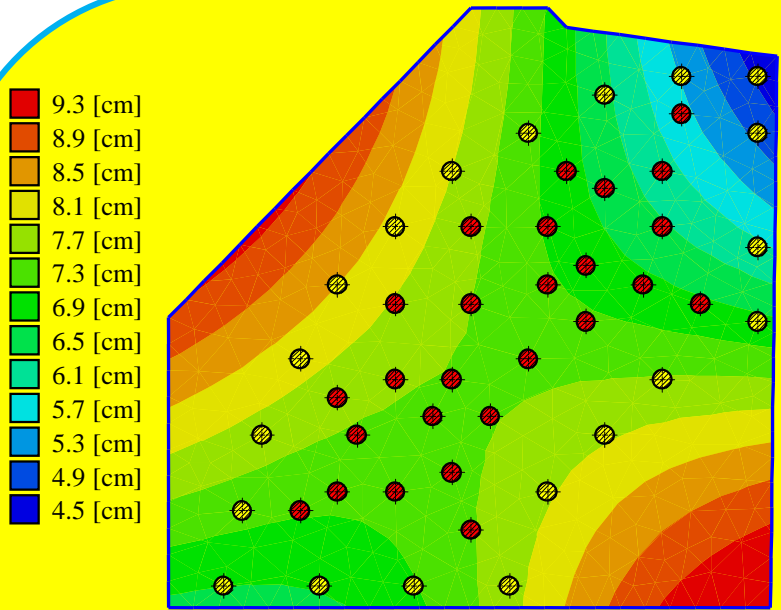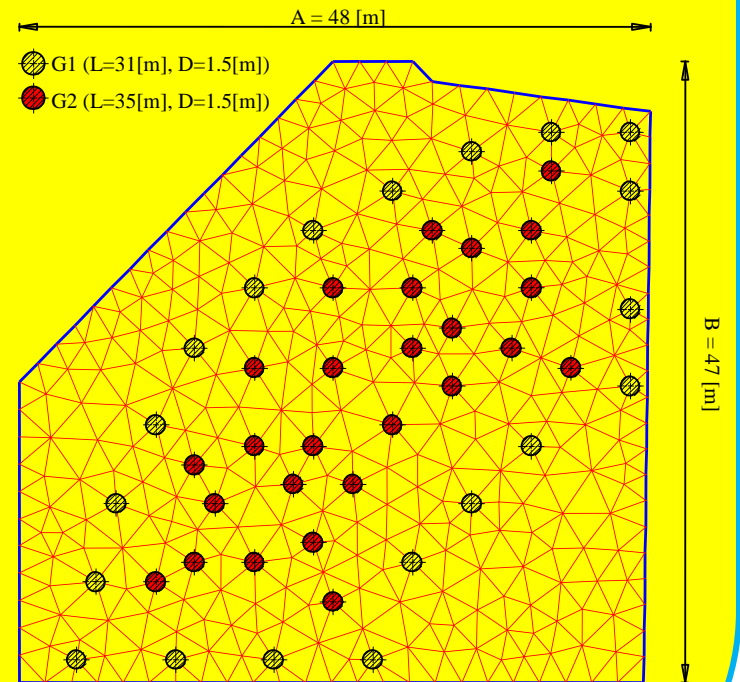
Settlement [cm] for elastic piled raft according to: nonlinear analysis using German Standard DIN 4014

9.3 [cm]
8.9 [cm]
8.5 [cm]
8.1 [cm]
7.7 [cm]
7.3 [cm]
6.9 [cm]
6.5 [cm]
6.1 [cm]
5.7 [cm]
5.3 [cm]
4.9 [cm]
4.5 [cm]
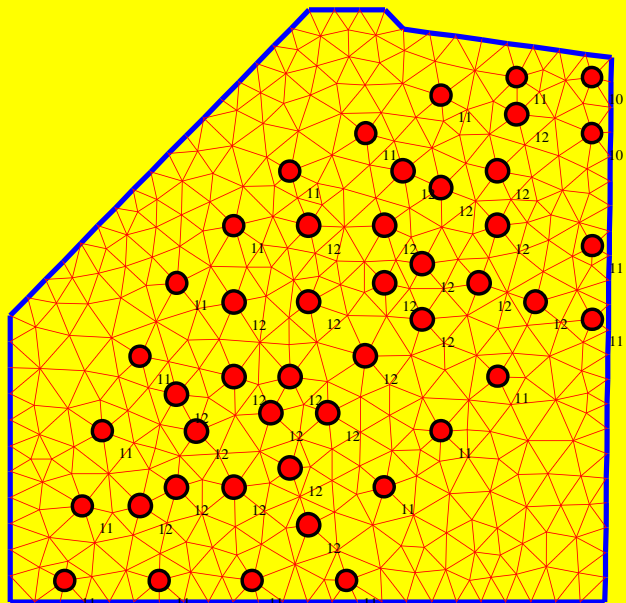
Pile loads [MN] for elastic piled raft according to: nonlinear analysis using German Standard DIN 4014

Piled raft of *Skyper*

$A = 48$ [m]

G1 (L=31[m], D=1.5[m])
G2 (L=35[m], D=1.5[m])

$B = 47$ [m]
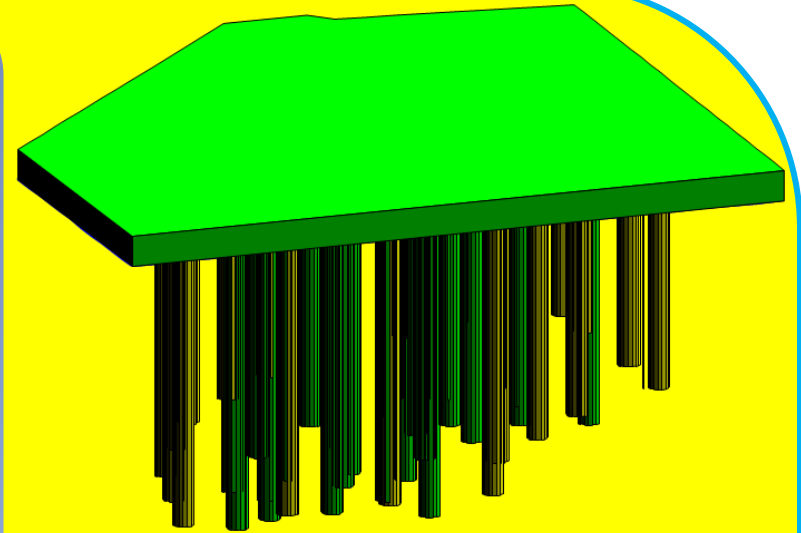
Net of piled raft of *Skyper* with piles

**Practical example 2: Piled raft foundation of *Skyper* in Frankfurt**

**Boring log**

GW ▽ 2.50

| Depth | Soil | Properties |
|---|---|---|
| 1.5 | S | $E = 34.5 [MN/m^2]$, $W = 103.5 [MN/m^2]$, $GAM = 0.018 [MN/m^3]$ |
| 2.5 | S | $E = 11.5 [MN/m^2]$, $W = 34.5 [MN/m^2]$, $GAM = 0.018 [MN/m^3]$ |
| 3.7 | S | $E = 11.5 [MN/m^2]$, $W = 34.5 [MN/m^2]$, $GAM = 0.008 [MN/m^3]$ |
| 9.8 | Ktst | $E = 500 [MN/m^2]$, $W = 1500 [MN/m^2]$, $GAM = 0.008 [MN/m^3]$ |
| 16.0 | Sst | $E = 50 [MN/m^2]$, $W = 150 [MN/m^2]$, $GAM = 0.008 [MN/m^3]$ |
| 23.5 | Sst | $E = 250 [MN/m^2]$, $W = 750 [MN/m^2]$, $GAM = 0.008 [MN/m^3]$ |
| 26.5 | Sst | $E = 140 [MN/m^2]$, $W = 420 [MN/m^2]$, $GAM = 0.008 [MN/m^3]$ |
| 31.0 | Sst | $E = 140 [MN/m^2]$, $W = 420 [MN/m^2]$, $GAM = 0.008 [MN/m^3]$ |
| 52.5 | Gst | $E = 310 [MN/m^2]$, $W = 930 [MN/m^2]$, $GAM = 0.008 [MN/m^3]$ |
| 71.0 | Gst | $E = 405 [MN/m^2]$, $W = 1215 [MN/m^2]$, $GAM = 0.008 [MN/m^3]$ |
| 93.5 | Gst | $E = 560 [MN/m^2]$, $W = 1680 [MN/m^2]$, $GAM = 0.008 [MN/m^3]$ |
| 140.5 | Ust+Tst | $E = 405 [MN/m^2]$, $W = 1215 [MN/m^2]$, $GAM = 0.008 [MN/m^3]$ |

▽ Tk = 6.35 [m]
▽ Tf = 10.05 [m]

**Legend:**
- S, Sand
- Ktst, Calc tufa
- Sst, Sandstone
- Gst, Conglomerate
- Ust, Siltstone
- Tst, Mudstone

Contour scale [mm]: 48, 46, 44, 42, 40, 38, 36, 34, 32, 30, 28, 26, 24
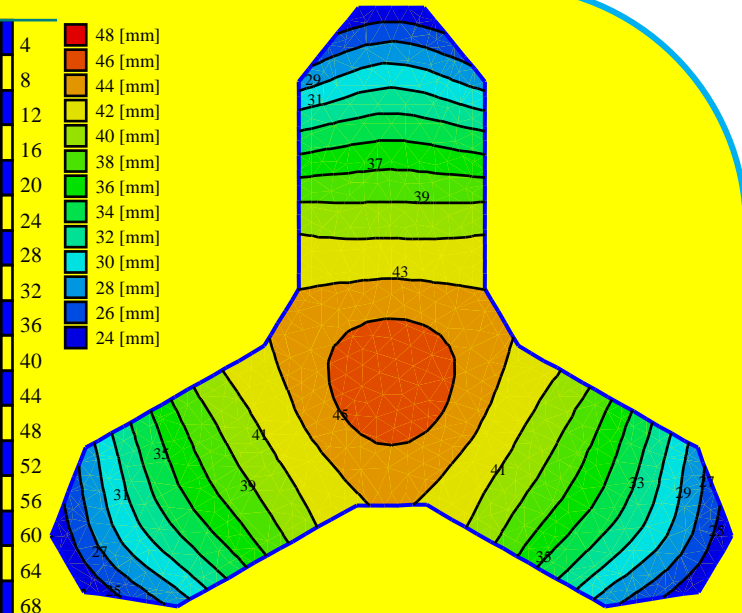
**Settlement [cm] for elastic piled raft with 80% of the load according to nonlinear analysis with using a given load-settlement curve of the pile**
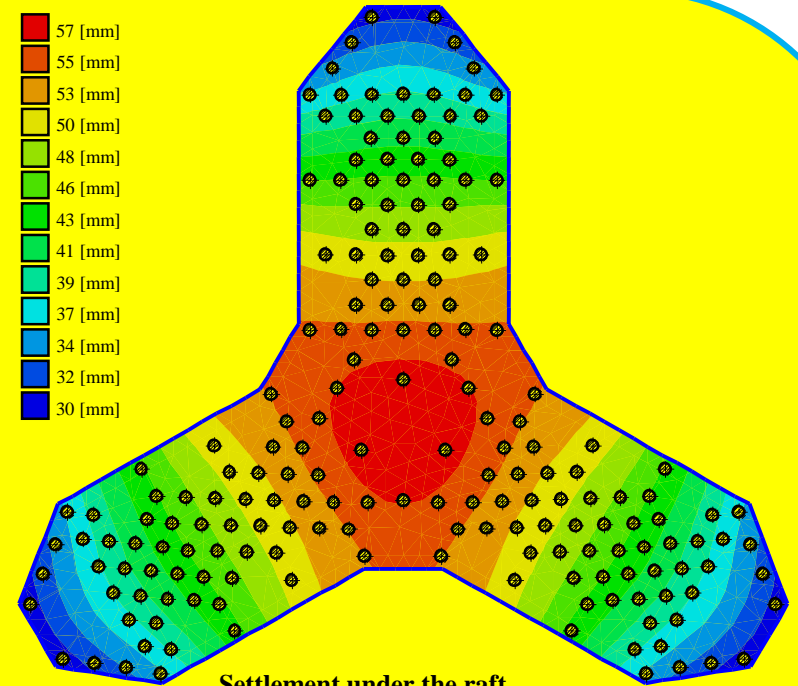
**Load-settlement relation of pile from pile load test**

Load [MN] — axis: 0, 10, 20, 30, 40, 50, 60, 70
Settlement $s$ [mm] — axis: 0, 2, 4, 6, 8, 10, 12, 14, 16
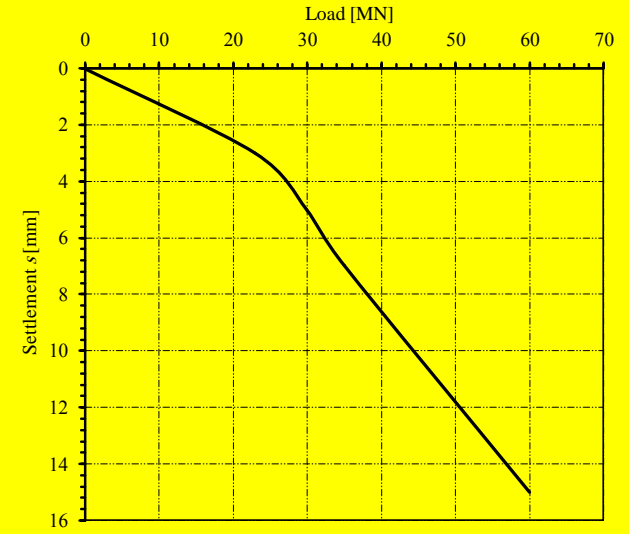
**Practical example 3: Piled raft foundation of *Burj Khalifa* in Dubai**
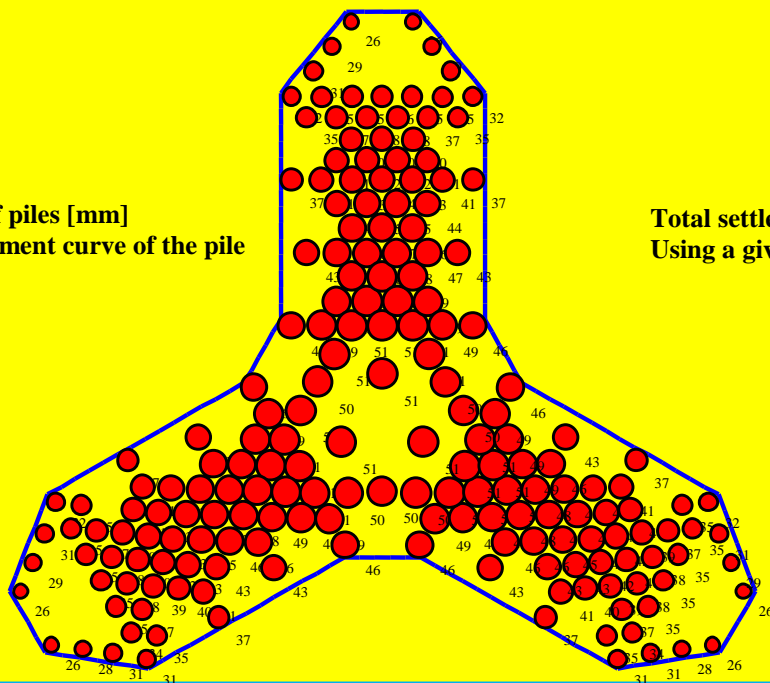
**Self-settlement of piles [mm]**
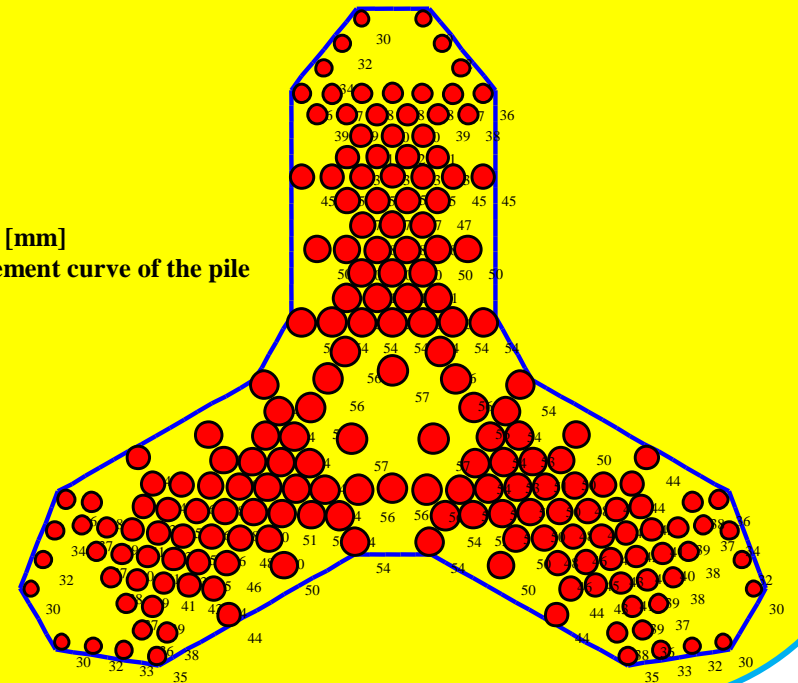**Using a given load-settlement curve of the pile**
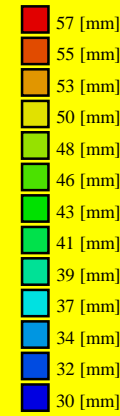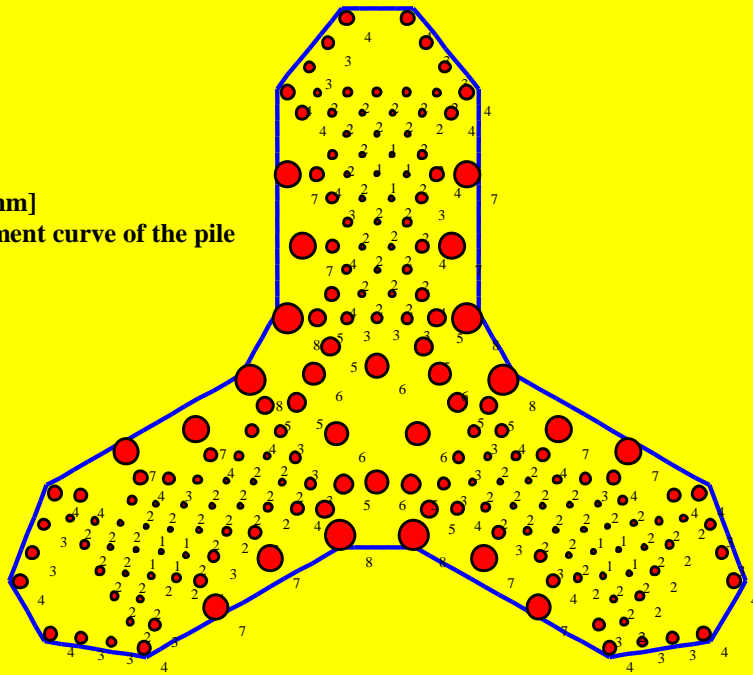
**Settlement under the raft**
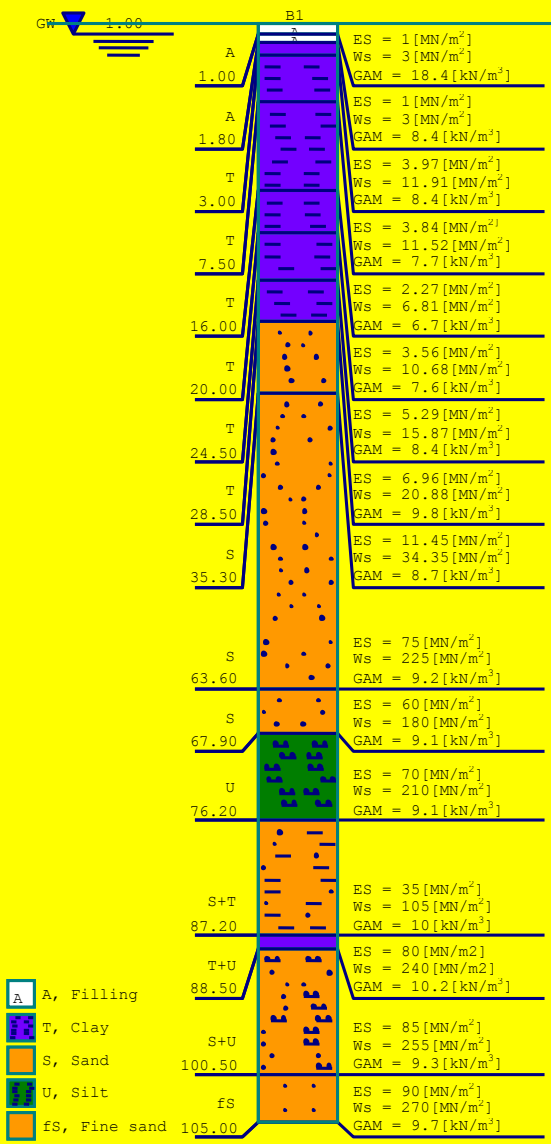**Using a given load-settlement curve of the pile**

**Interaction settlement of piles [mm]**
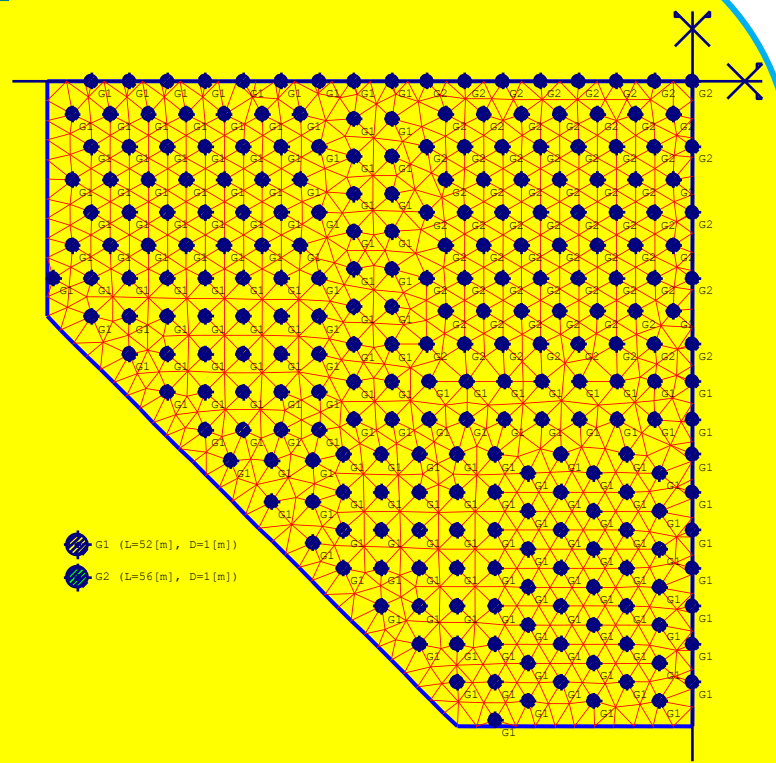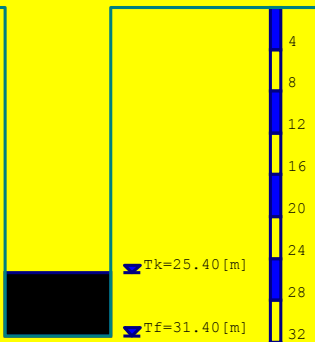**Using a given load-settlement curve of the pile**

**Total settlement of piles [mm]**
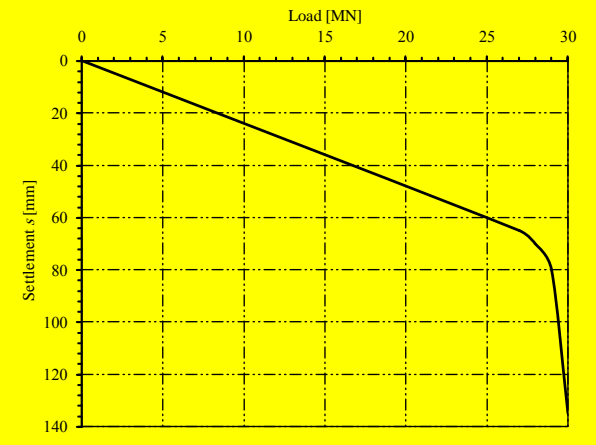**Using a given load-settlement curve of the pile**

GW ▽ 1.00

B1

**Boring log**

| Depth | Soil | Properties |
|---|---|---|
| A 1.00 | A | ES = 1 [MN/m²], Ws = 3 [MN/m²], GAM = 18.4 [kN/m³] |
| A 1.80 | A | ES = 1 [MN/m²], Ws = 3 [MN/m²], GAM = 8.4 [kN/m³] |
| T 3.00 | T | ES = 3.97 [MN/m²], Ws = 11.91 [MN/m²], GAM = 8.4 [kN/m³] |
| T 7.50 | T | ES = 3.84 [MN/m²], Ws = 11.52 [MN/m²], GAM = 7.7 [kN/m³] |
| T 16.00 | T | ES = 2.27 [MN/m²], Ws = 6.81 [MN/m²], GAM = 6.7 [kN/m³] |
| T 20.00 | T | ES = 3.56 [MN/m²], Ws = 10.68 [MN/m²], GAM = 7.6 [kN/m³] |
| T 24.50 | T | ES = 5.29 [MN/m²], Ws = 15.87 [MN/m²], GAM = 8.4 [kN/m³] |
| T 28.50 | T | ES = 6.96 [MN/m²], Ws = 20.88 [MN/m²], GAM = 9.8 [kN/m³] |
| S 35.30 | S | ES = 11.45 [MN/m²], Ws = 34.35 [MN/m²], GAM = 8.7 [kN/m³] |
| S 63.60 | S | ES = 75 [MN/m²], Ws = 225 [MN/m²], GAM = 9.2 [kN/m³] |
| S 67.90 | S | ES = 60 [MN/m²], Ws = 180 [MN/m²], GAM = 9.1 [kN/m³] |
| U 76.20 | U | ES = 70 [MN/m²], Ws = 210 [MN/m²], GAM = 9.1 [kN/m³] |
| S+T 87.20 | S+T | ES = 35 [MN/m²], Ws = 105 [MN/m²], GAM = 10 [kN/m³] |
| T+U 88.50 | T+U | ES = 80 [MN/m2], Ws = 240 [MN/m2], GAM = 10.2 [kN/m³] |
| S+U 100.50 | S+U | ES = 85 [MN/m²], Ws = 255 [MN/m²], GAM = 9.3 [kN/m³] |
| fS 105.00 | fS | ES = 90 [MN/m²], Ws = 270 [MN/m²], GAM = 9.7 [kN/m³] |

Tk=25.40 [m]
Tf=31.40 [m]

Legend:
- A, Filling
- T, Clay
- S, Sand
- U, Silt
- fS, Fine sand

G1 (L=52 [m], D=1 [m])
G2 (L=56 [m], D=1 [m])

**FE-Net of *Shenghai* piled raft with pile groups**

**Load-settlement relation of pile from pile load test**
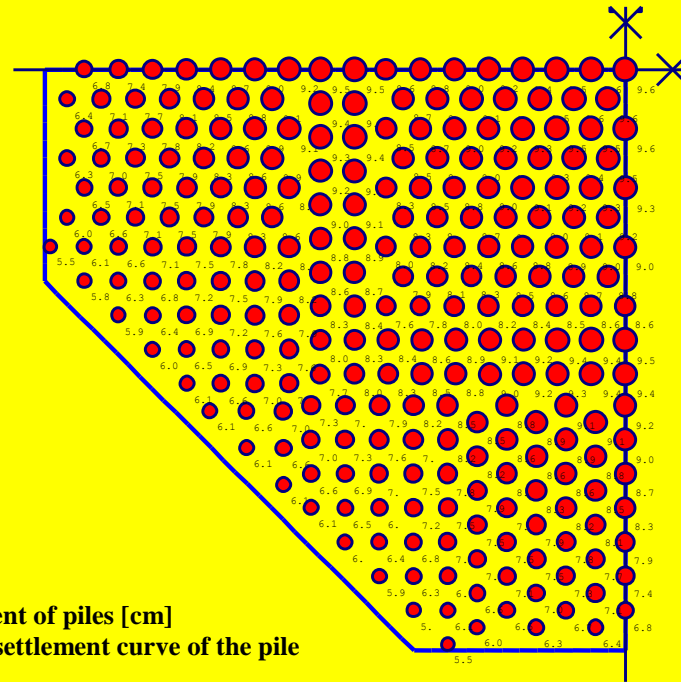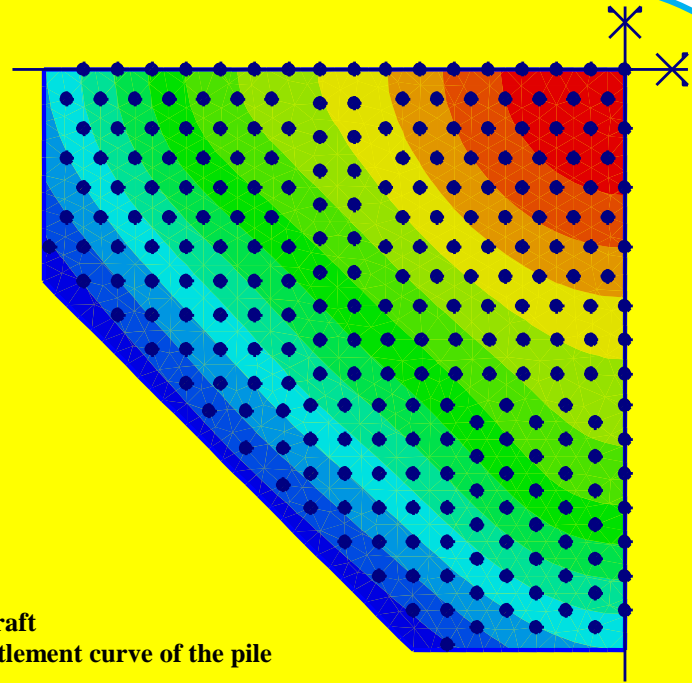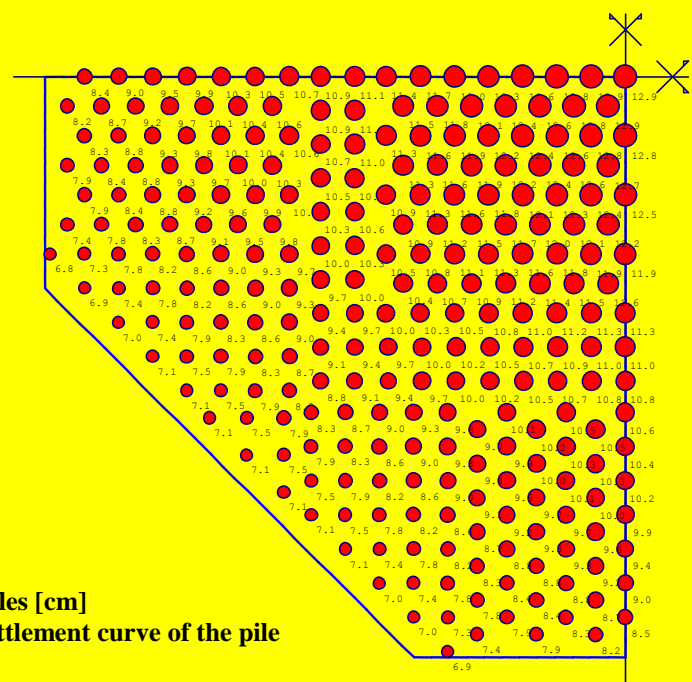
Load [MN]
Settlement s [mm]

**Practical example 4: Piled raft foundation of *Shenghai* in Shenghai**
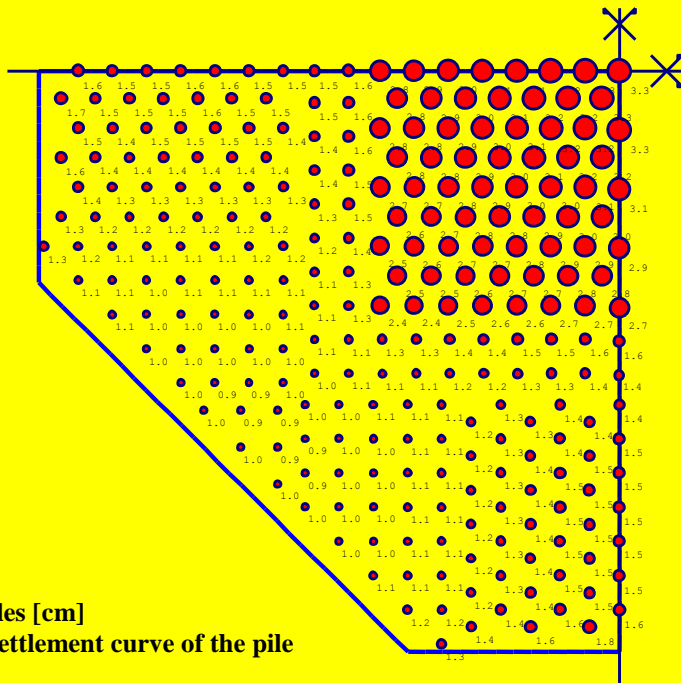
**Self-settlement of piles [cm]**
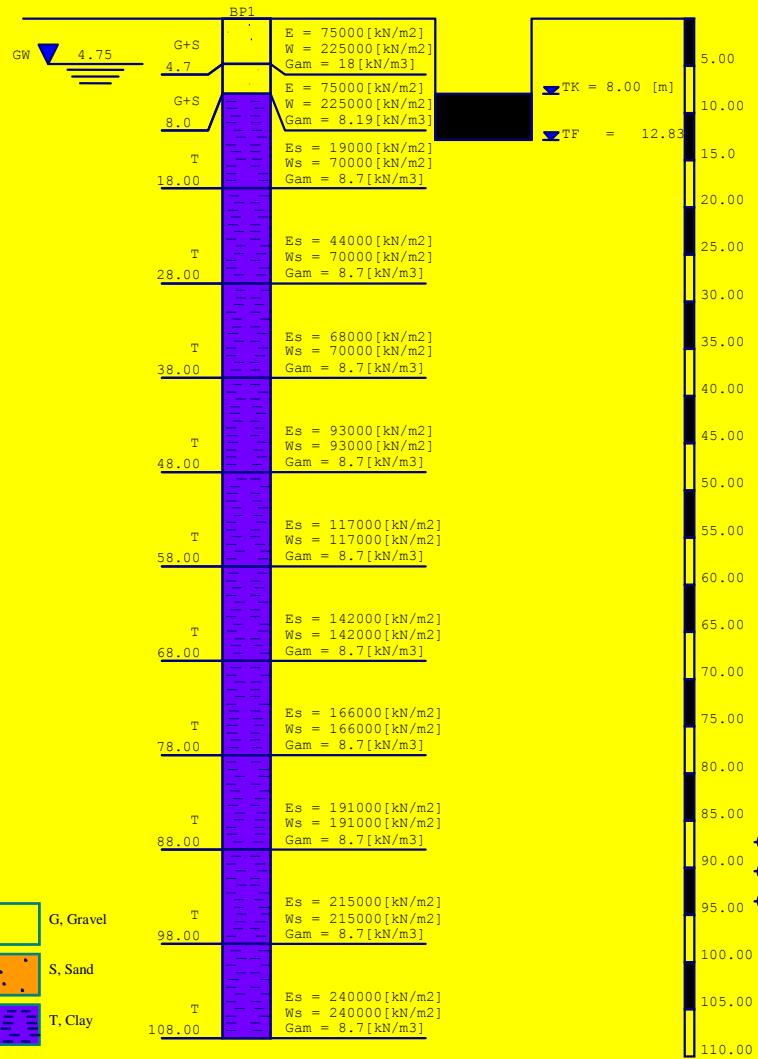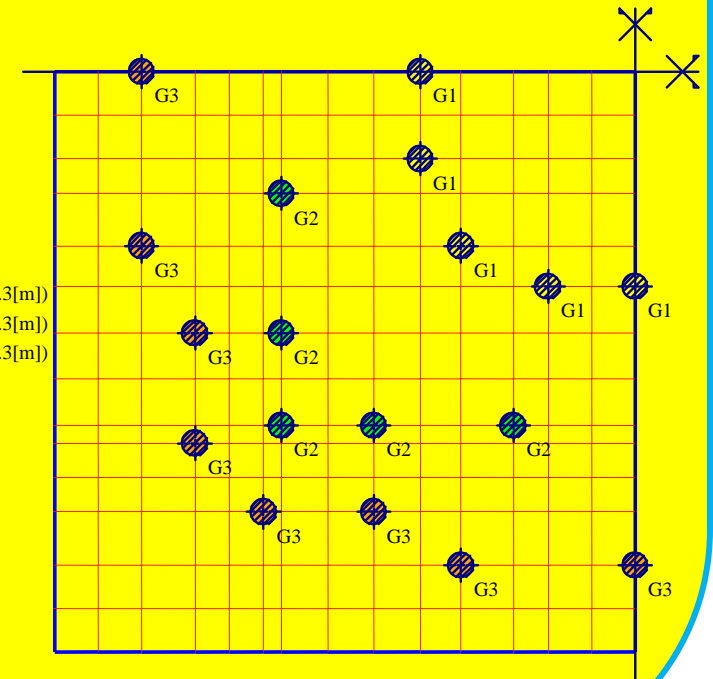**Using a given load-settlement curve of the pile**
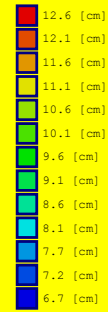
**Settlement under the raft**
**Using a given load-settlement curve of the pile**

12.6 [cm]
12.1 [cm]
11.6 [cm]
11.1 [cm]
10.6 [cm]
10.1 [cm]
9.6 [cm]
9.1 [cm]
8.6 [cm]
8.1 [cm]
7.7 [cm]
7.2 [cm]
6.7 [cm]

**Interaction settlement of piles [cm]**
**Using a given load-settlement curve of the pile**

**Total settlement of piles [cm]**
**Using a given load-settlement curve of the pile**

## Boring log

**Boring log data (BP1):**

| Depth | Layer | Parameters |
|---|---|---|
| GW 4.75 | | |
| 4.7 | G+S | E = 75000[kN/m2], W = 225000[kN/m2], Gam = 18[kN/m3] |
| 8.0 | G+S | E = 75000[kN/m2], W = 225000[kN/m2], Gam = 8.19[kN/m3] |
| 18.00 | T | Es = 19000[kN/m2], Ws = 70000[kN/m2], Gam = 8.7[kN/m3] |
| 28.00 | T | Es = 44000[kN/m2], Ws = 70000[kN/m2], Gam = 8.7[kN/m3] |
| 38.00 | T | Es = 68000[kN/m2], Ws = 70000[kN/m2], Gam = 8.7[kN/m3] |
| 48.00 | T | Es = 93000[kN/m2], Ws = 93000[kN/m2], Gam = 8.7[kN/m3] |
| 58.00 | T | Es = 117000[kN/m2], Ws = 117000[kN/m2], Gam = 8.7[kN/m3] |
| 68.00 | T | Es = 142000[kN/m2], Ws = 142000[kN/m2], Gam = 8.7[kN/m3] |
| 78.00 | T | Es = 166000[kN/m2], Ws = 166000[kN/m2], Gam = 8.7[kN/m3] |
| 88.00 | T | Es = 191000[kN/m2], Ws = 191000[kN/m2], Gam = 8.7[kN/m3] |
| 98.00 | T | Es = 215000[kN/m2], Ws = 215000[kN/m2], Gam = 8.7[kN/m3] |
| 108.00 | T | Es = 240000[kN/m2], Ws = 240000[kN/m2], Gam = 8.7[kN/m3] |

TK = 8.00 [m]
TF = 12.83

Depth scale: 5.00, 10.00, 15.0, 20.00, 25.00, 30.00, 35.00, 40.00, 45.00, 50.00, 55.00, 60.00, 65.00, 70.00, 75.00, 80.00, 85.00, 90.00, 95.00, 100.00, 105.00, 110.00

Legend:
- G, Gravel
- S, Sand
- T, Clay

## Load-settlement curve

**Load Q [MN]** (axis 0 to 6)
**Settlement s [cm]** (axis 0.0 to 14.0)

Legend:
- Skin resistance Qr
- Tip resistance Qs
- Pile resistance Q
- Allowable pile load Qzul
- Load on pile head Ph
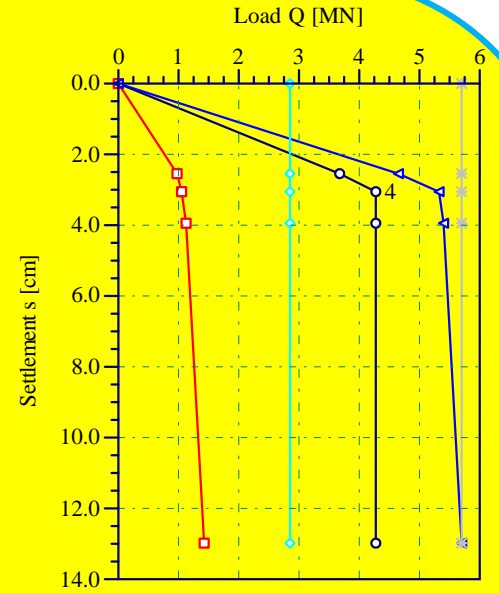
**Pile No. 1 - Pile label: P1**
**Load-settlement curve of pile according to German Standard DIN 4014**

## FE-Net of *Messeturm* piled raft with pile groups
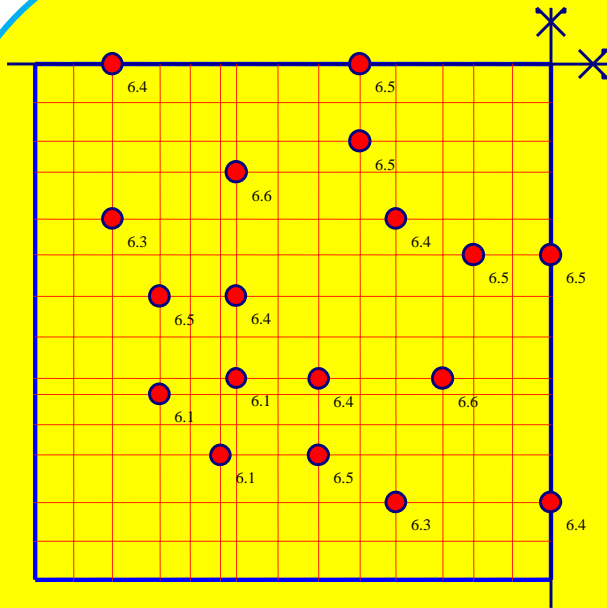
- G1 (L=34.9[m], D=1.3[m])
- G2 (L=30.9[m], D=1.3[m])
- G3 (L=26.9[m], D=1.3[m])

**Practical example 5: Piled raft foundation of *Messeturm* in Frankfurt**
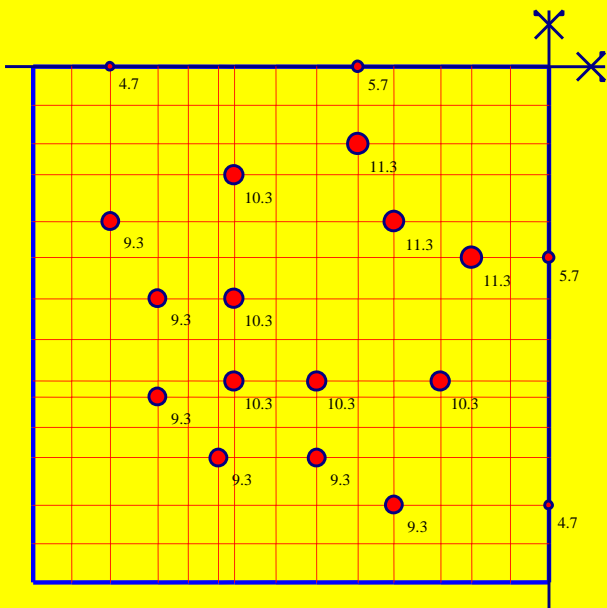
**Interaction settlement of piles [cm] according to nonlinear analysis using German Standard DIN 4014**
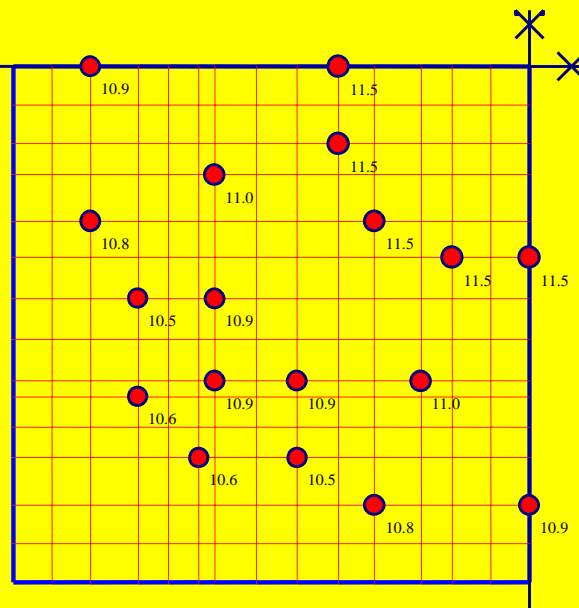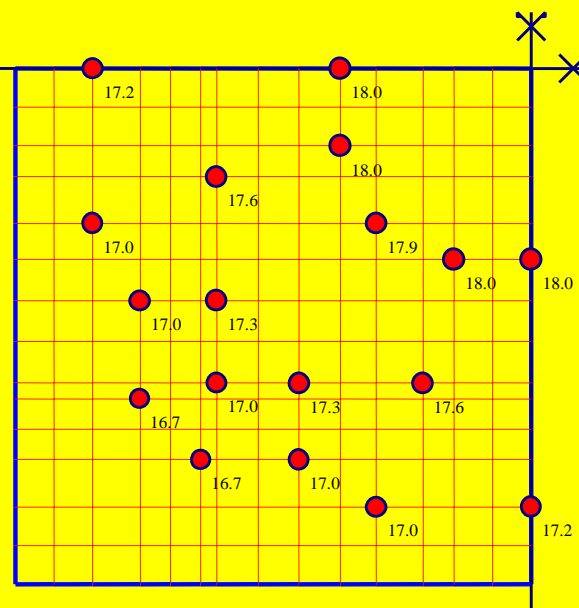
**Self-settlement of piles [cm] according to nonlinear analysis using German Standard DIN 4014**
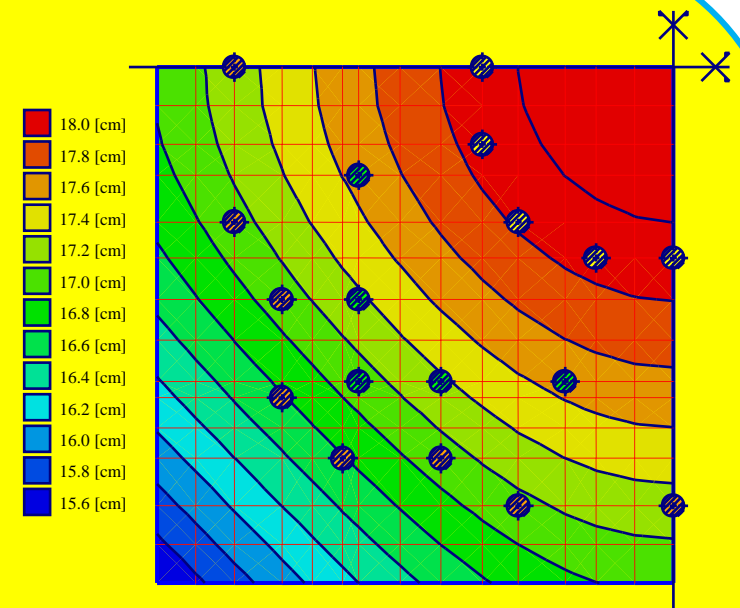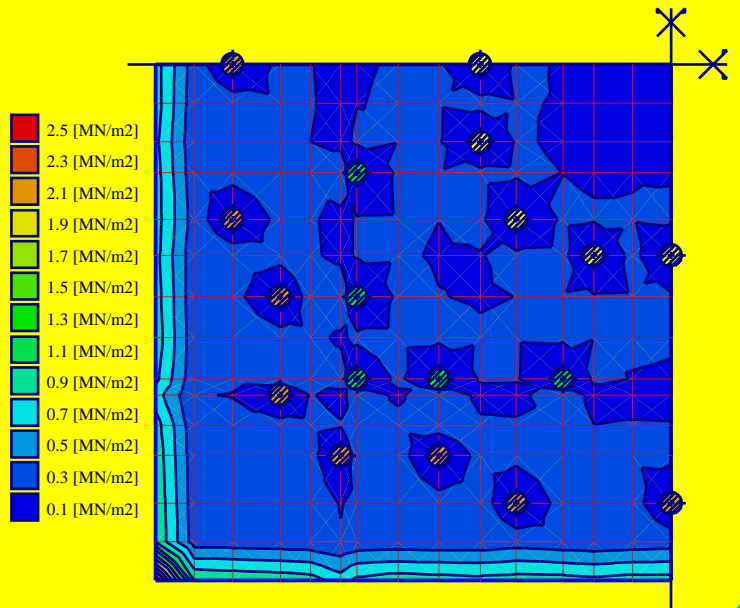
**Settlement under the raft according to nonlinear analysis using German Standard DIN 4014**

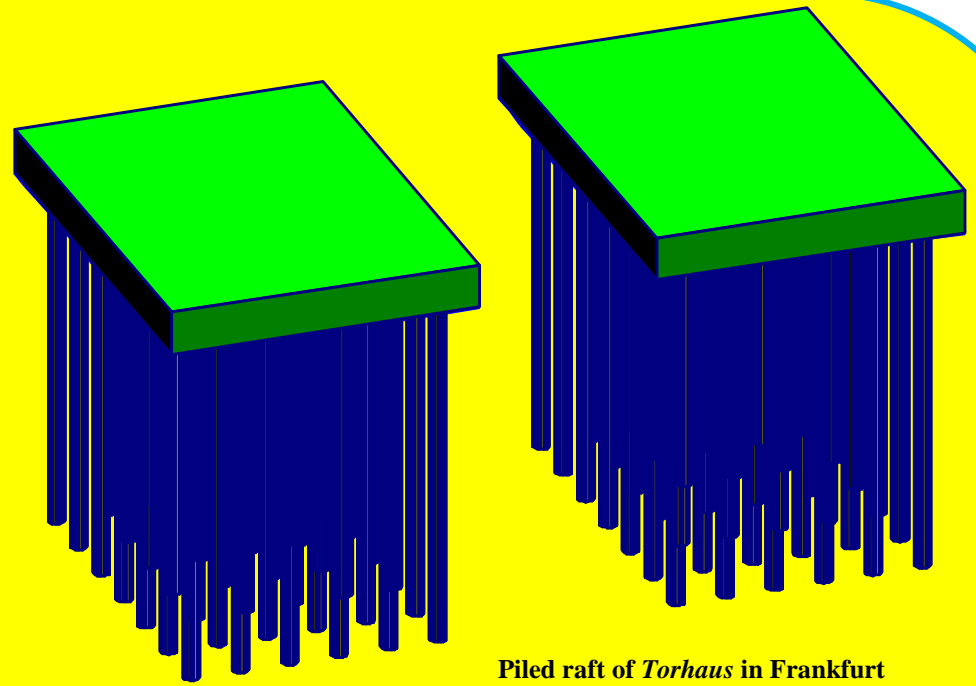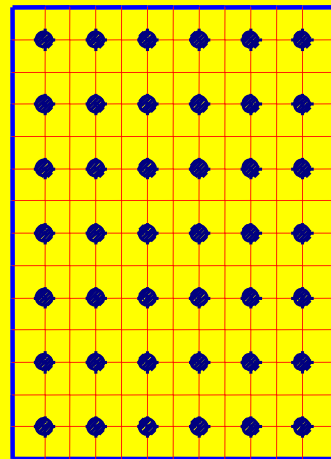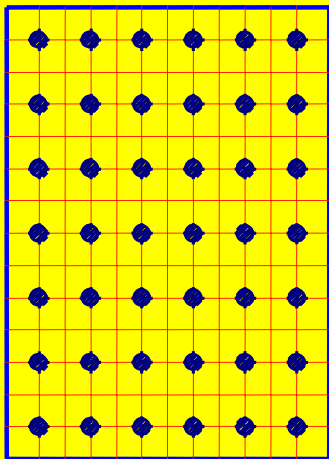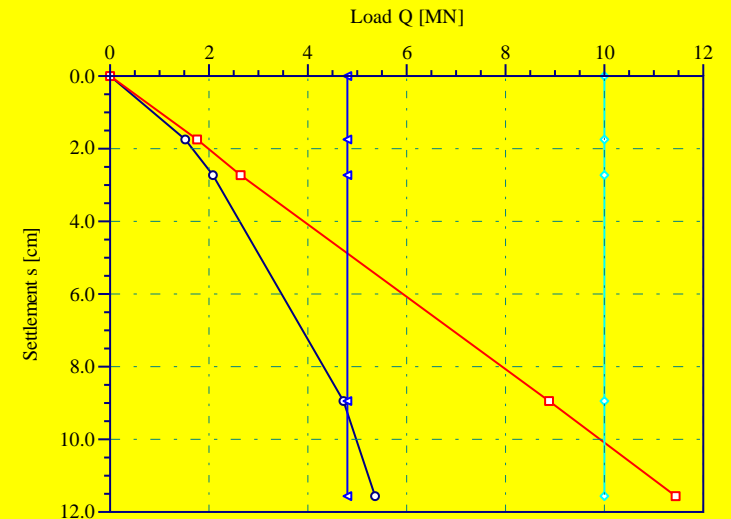**Pile reactions [MN] according to nonlinear analysis using German Standard DIN 4014**

**Total settlement of piles [cm] according to nonlinear analysis using German Standard DIN 4014**

**Contact pressure under the raft according to nonlinear analysis using German Standard DIN 4014**

**Piled raft of *Torhaus* in Frankfurt**

A = 45.00 [m]

B = 24.50 [m]

**FE-Net of *Torhaus* piled raft with piles**

- ○ Nonlinear load Qn
- □ Linear load Ql
- ◁ Load on pile head Ph
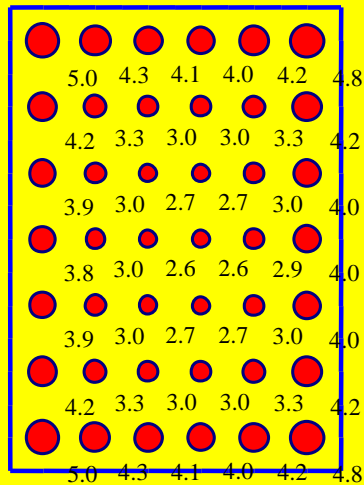- ◇ Limit pile load Qlim

Load Q [MN]

Settlement s [cm]

**Pile No. 1 - Pile label: P1**
**Load Settlement Curve of the Pile**
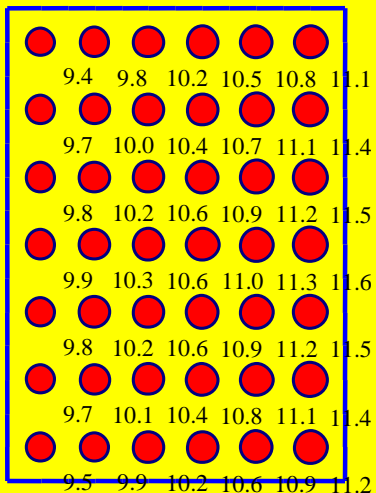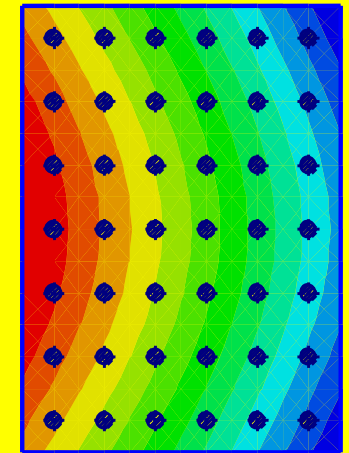**Nonlinear analysis using a hyperbolic function for load-settlement**
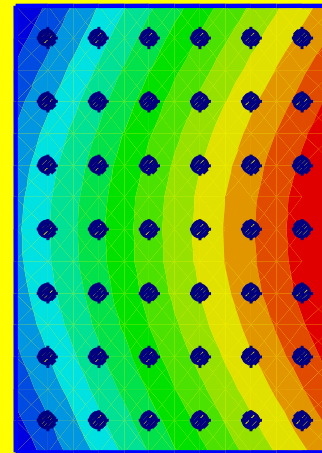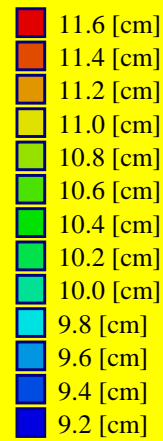
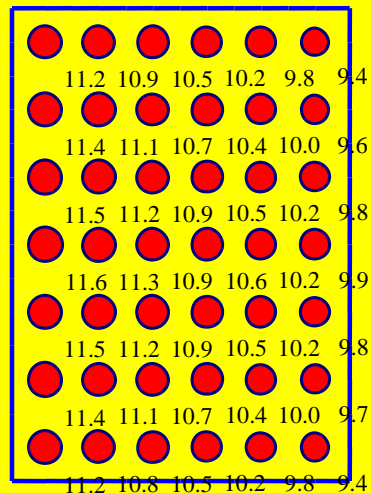**Practical example 6: Piled raft foundation of *Torhaus* in Frankfurt**
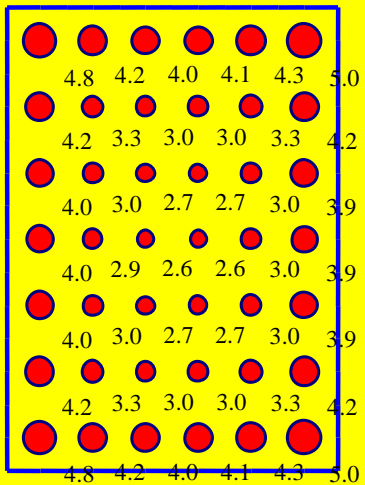
**Pile reactions [MN] using a hyperbolic function for load-settlement curve of the pile**

**Settlement under the raft using a hyperbolic function for load-settlement curve of the pile**

**Pile settlements [cm] using a hyperbolic function for load-settlement curve of the pile**

**Contact pressure under the raft using a hyperbolic function for load-settlement curve of the pile**