Case study 6

Piled raft of *Skyper* in Frankfurt

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6 Case study: *Skyper* piled raft foundation

6.1 General

Skyper is 154 [m] high-rise building supported on a piled raft foundation. The tower was one of the tallest three skyscrapers in Frankfurt, Germany when it was completed in 2004, Figure 6-1.

The tower has a basement with three underground floors and 38 stories with an average estimated applied load of 426 [kN/m^2]. The raft of the *Skyper* tower has a uniform thickness of 3.5 [m] supported by 46 bored piles with a diameter 1.5 [m]. Piles are arranged under the core structure in 2 rings; external ring has 20 piles, 31 [m] long while the internal ring has 26 piles, 35 [m] in length. The raft has an irregular plan shape with an area of 1900 [m^2]. The raft founded on a typical Frankfurt clay at a depth 13.4 [m] below ground surface. The subsoil at the location of the building consists of gravels and sands up to 7.4 [m] below ground surface underlay by layers of Frankfurt clay extending to a depth of 56.4 [m] below ground surface followed by incompressible Frankfurt Limestone layer. The groundwater level is 5 [m] below ground surface.

Extensive studies using different calculation methods were carried out by *Saglam* (2003), *El-Mossallamy et al.* (2009), *Sales et al.* (2010), *Richter and Lutz* (2010), *Vrettos, C.* (2012), *Bohn* (2015) to evaluate the ***Skyper*** piled raft foundation design

Figure 6-1 *Skyper* [1]

[1] https://en.phorio.com/file/703520609/

Figure 6-2 shows a layout of the *Skyper* piled raft foundation.

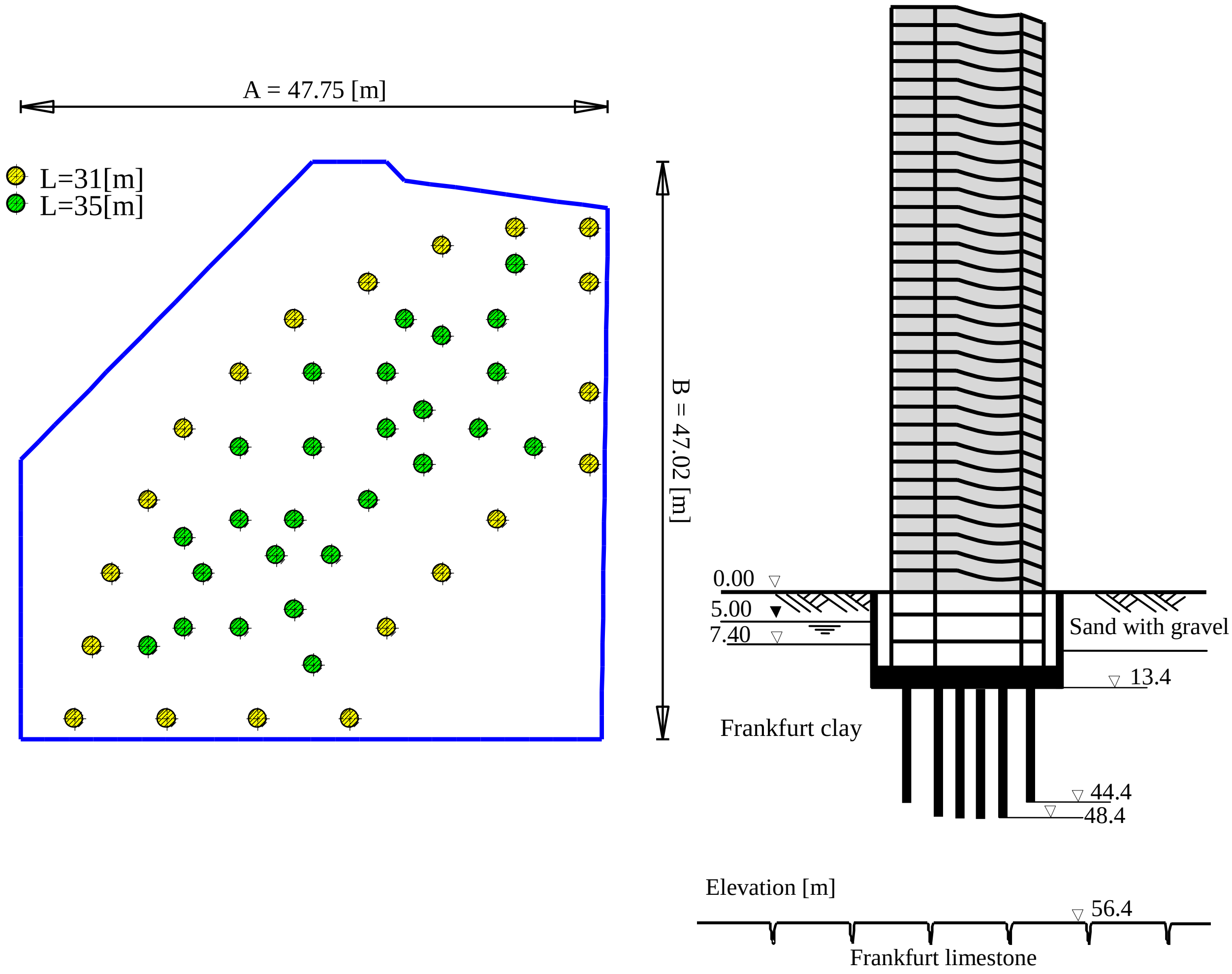

Figure 6-2 Layout of the *Skyper* piled raft foundation

6.2 Analysis of the piled raft

Using the available data and results of the *Skyper* piled raft, the nonlinear analyses of piled raft in *ELPLA* are evaluated and verified using the following load-settlement relations of piles, *El Gendy et al.* (2006) and *El Gendy* (2007):

1- Hyperbolic function.
2- German standard DIN 4014.
3- German recommendations EA-Piles (lower values).
4- German recommendations EA-Piles (upper values).

The foundation system is analyzed as rigid or elastic piled rafts. In which, the raft is considered as either rigid or elastic plate supported on rigid piles.

A series of comparisons are carried out to evaluate the nonlinear analyses of piled raft for load-settlement relations of piles. In which, results of other analytical solutions and measurements are compared with those obtained by *ELPLA*.

6.3 FE-Net

The raft is divided into triangular elements with maximum length of 2.0 [m] as shown in Figure 6-3. Similarly, piles are divided into elements with 2.0 [m] length.

6.4 Loads

The uplift pressure on the raft due to groundwater is P_w = 160 [kN/m^2]. Consequently, the total effective applied load on the raft including own weight of the raft and piles is N = 810 [MN].

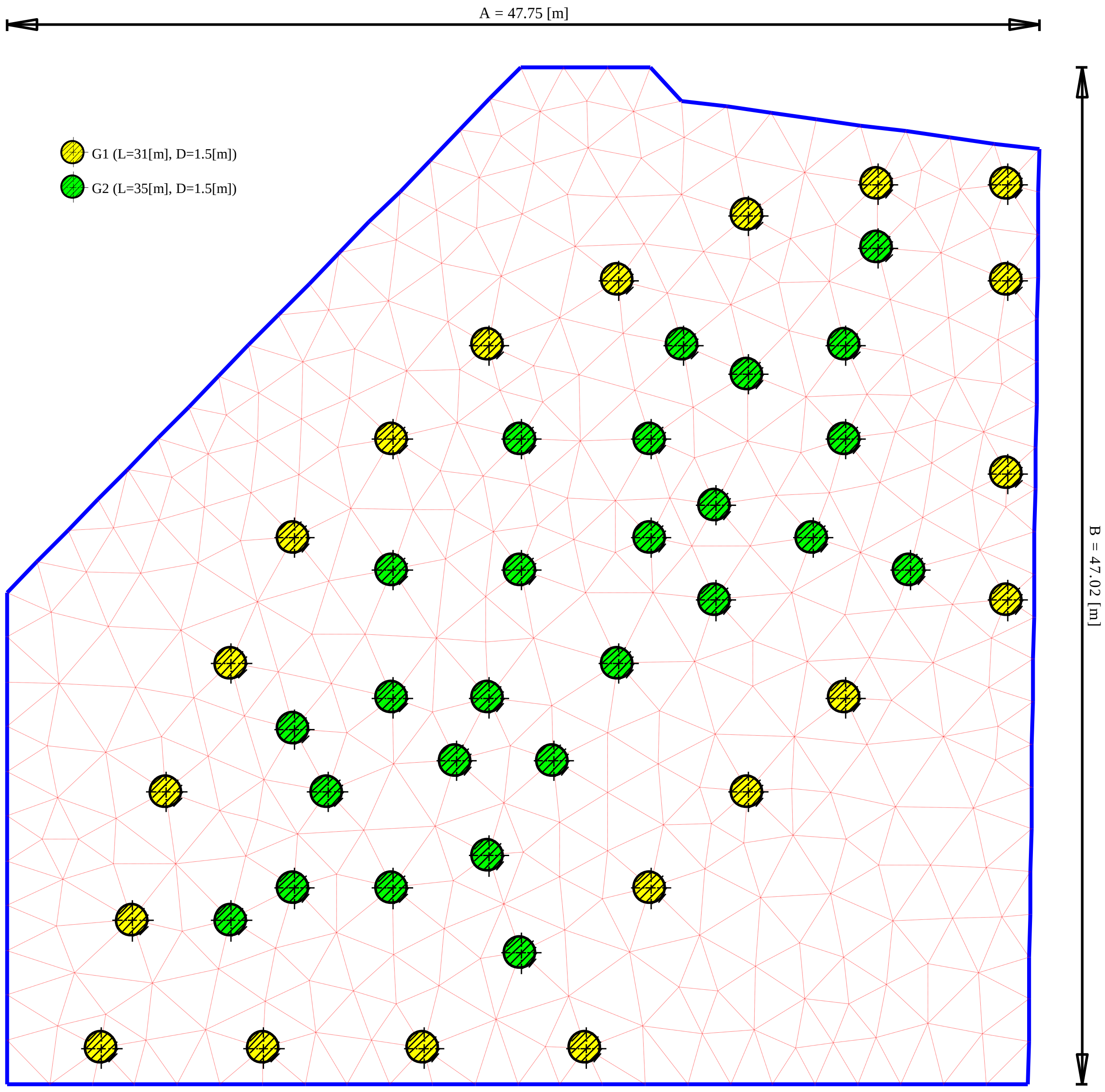

Figure 6-3 Mesh of *Skyper* piled raft with piles

6.5 Pile and raft material

The raft thickness is 3.5 [m]. The piles are 1.5 [m] in diameter and 31 [m] and 35 [m] in length. The following values were used for pile and raft material:

For the raft:

Modulus of elasticity	E_p	=	34 000	[MN/m^2]
Poisson's ratio	v_p	=	0.25	[-]
Unit weight	γ_b	=	0.0	[kN/m^3]

For piles:

Modulus of elasticity	E_p	=	22 000	[MN/m^2]
Unit weight	γ_b	=	0.0	[kN/m^3]

6.6 Soil properties

The clay properties used in analysis can be described as follows:

Modulus of compressibility

Based on the back analysis presented by *Amann et al.* (1975), the distribution of modulus of compressibility for loading of Frankfurt clay with depth is defined by the following empirical formula:

$$E_s = E_{so}\left(1 + 0.35\, z\right) \tag{3.1}$$

while that for reloading is:

$$W_s = 70\left[\mathrm{MN/m^2}\right] \tag{3.2}$$

where:

E_s Modulus of compressibility for loading [MN/m^2]

E_{so} Initial modulus of compressibility, E_{so} = 7 [MN/m^2]

z Depth measured from the clay surface, [m]

W_s Modulus of compressibility for reloading [MN/m^2]

Undrained cohesion c_u

The undrained cohesion c_u of Frankfurt clay increases with depth from c_u = 100 [kN/m^2] to c_u = 400 [kN/m^2] in 70 [m] depth under the clay surface according to *Sommer/ Katzenbach* (1990). To carry out the analyses using German standard and recommendations, an average undrained cohesion of c_u = 200 [kN/m^2] is considered.

Limit pile load Ql

Russo (1998) suggested a limiting shaft friction not less than 180 [kN/m^2] meeting undrained shear strength of 200 [kN/m^2]. To carry out the analysis using a hyperbolic function, a limit shaft friction of τ = 180 [kN/m^2] is assumed. The limit pile load for pile group 1 is calculated from:

$$Q_{l1} = \tau * \pi * D * l = 180 * \pi * 1.5 * 31 = 26295\,[\mathrm{kN}] = 26\,[\mathrm{MN}] \tag{2.3}$$

while that for pile group 2 from:

$$Q_{l2} = \tau * \pi * D * l = 180 * \pi * 1.5 * 35 = 29688\,[\mathrm{kN}] = 30\,[\mathrm{MN}] \tag{2.4}$$

where:
Q_l Limit pile load, [MN]
τ Limit shaft friction, τ = 180 [kN/m^2]
D Pile diameter, [m]
l Pile length, [m]

Poisson's ratio
Poisson's ratio of gravels and sands is taken to be ν_s = 0.25 [-].

To carry out the analysis, the subsoil under the raft is considered as indicated in the boring log of Figure 6-4 that consists of 7 soil layers. The total depth under the ground surface is taken to be 56.4 [m].

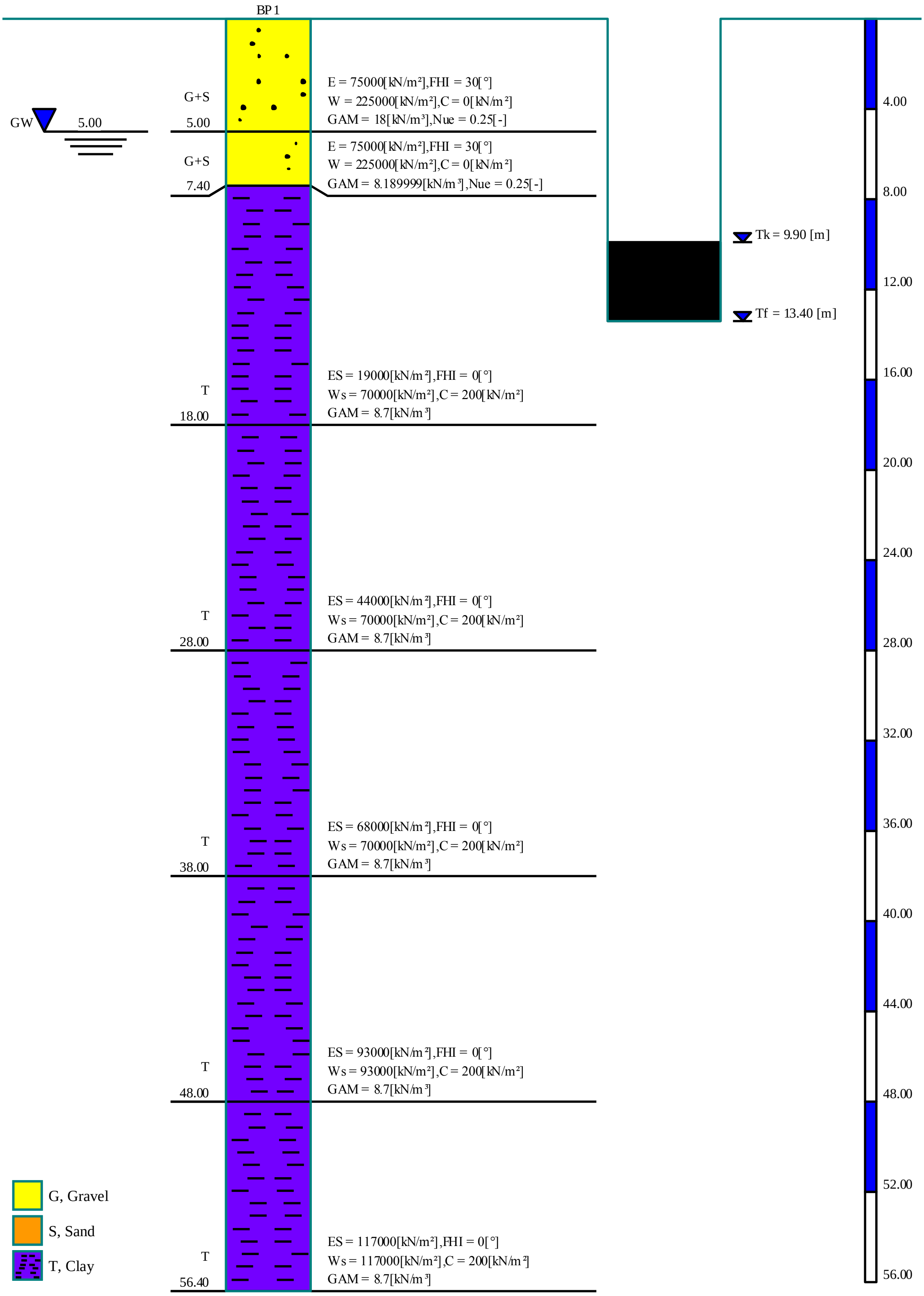

Figure 6-4 Boring log

6.7 Results

As examples for results of different analyses by *ELPLA*, Figure 6-5 and Figure 6-6 show the settlement, while Figure 6-7 and Figure 6-8 show the pile load for both rigid and elastic piled rafts using German recommendations EA-Piles for upper values.

6.8 Measurements and other results

The construction of *Skyper* started in 2003 and finished in the first half of 2004. According to *Richter and Lutz* (2010), all calculations resulted in a predicted settlement of 5 up to 7.5 [cm] for the tower, while according to *El-Mossallamy et al.* (2009) the bearing factor of piled raft α_{kpp} was computed in a range of 60% to 85%. The observed settlement was 5.5 [cm] directly after the completion of the shell only. After *Lutz et al.* (2006) with $\alpha_{kpp} \approx 0.6$, the average max. pile forces ranges between 12 to 14 [MN], while min. pile forces ranges between 10 to 11[MN].

Figure 6-9 compares results of settlement, bearing factor of piled raft and min and max pile loads obtained by *ELPLA* with the predicted results from the other methods. For more comparison, Table 6-1 shows the other results for another different methods presented by *Richter* and *Lutz* (2010). Based on settlement measurements 4 years after construction, the maximum settlement under the foundation is about 5 to 5.5 [cm]. Using the three-dimensional finite element method, a settlement of 6.3 [cm] was calculated according to *Richter and Lutz* (2010).

6.9 Evaluation

It can be concluded from Figure 6-9 that results obtained from different analyses available in *ELPLA* can present rapid and acceptable estimation for settlement, bearing factor of the piled raft and pile loads. This case study shows also that analyses available in *ELPLA* are practical for analyzing large piled raft problems. Because of they are taking less computational time compared with other complicated models using three dimension finite element analyses.

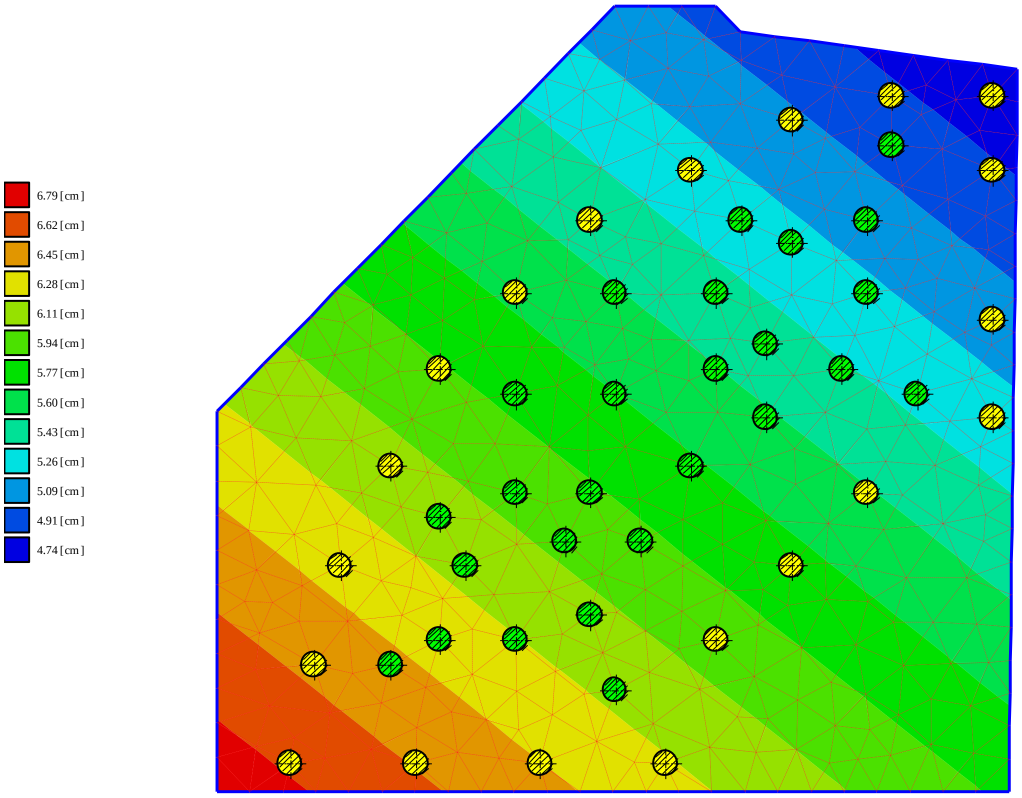

Figure 6-5 Settlement for rigid piled raft using German recommendations EA-Piles for upper values

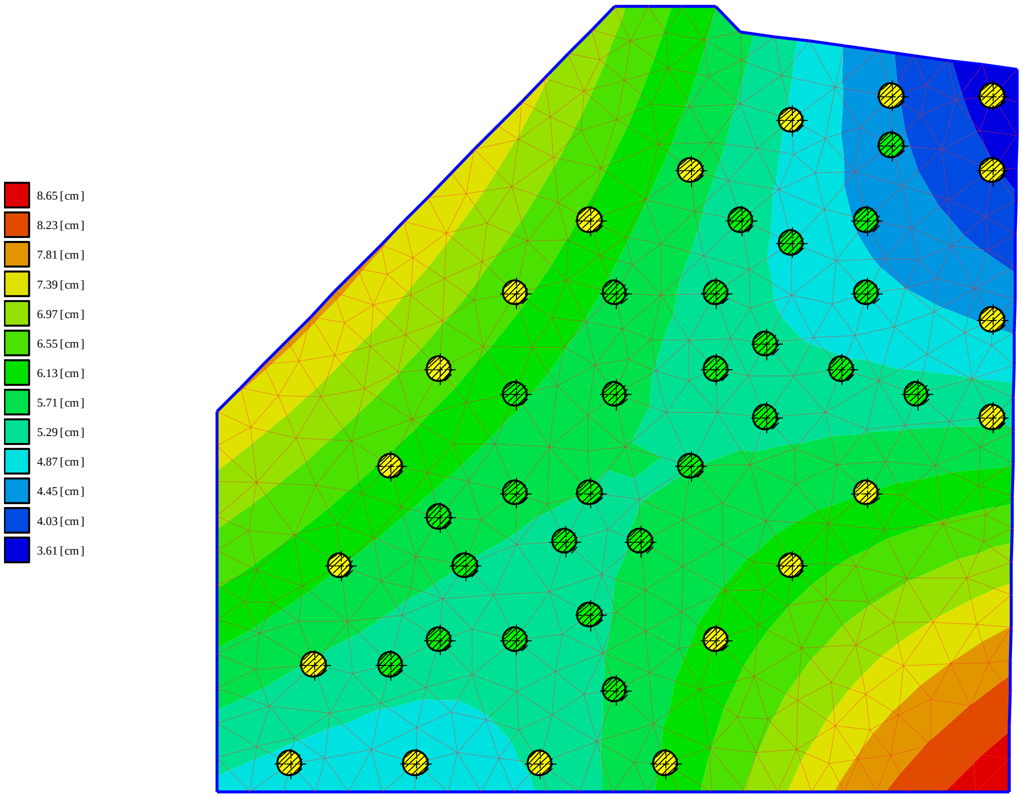

Figure 6-6 Settlement for elastic piled raft using German recommendations EA-Piles for upper values

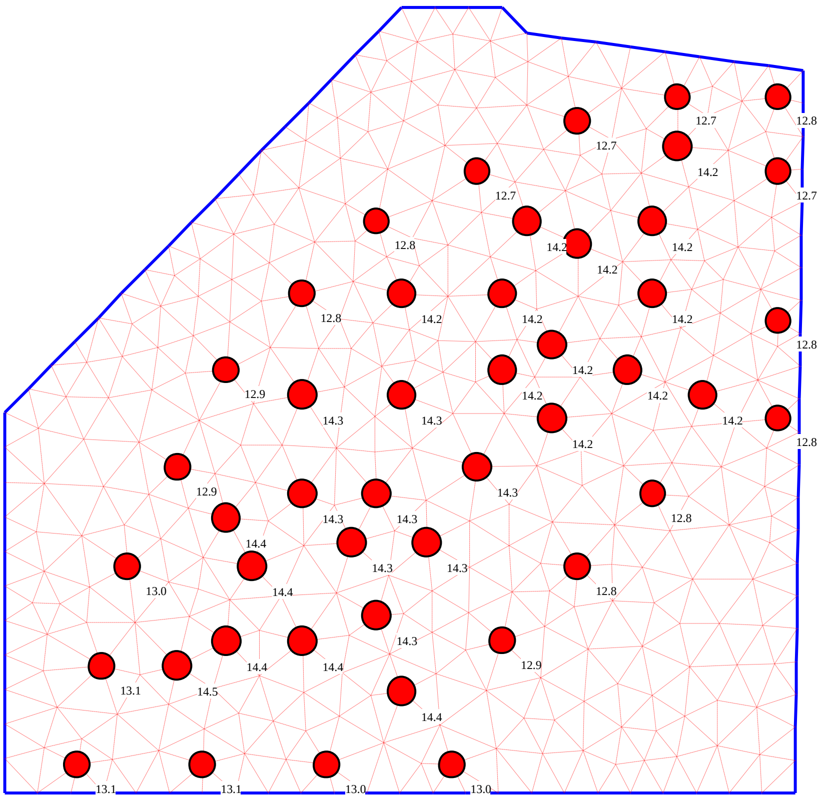

Figure 6-7 Pile load [MN] for rigid piled raft using German recommendations EA-Piles for upper values

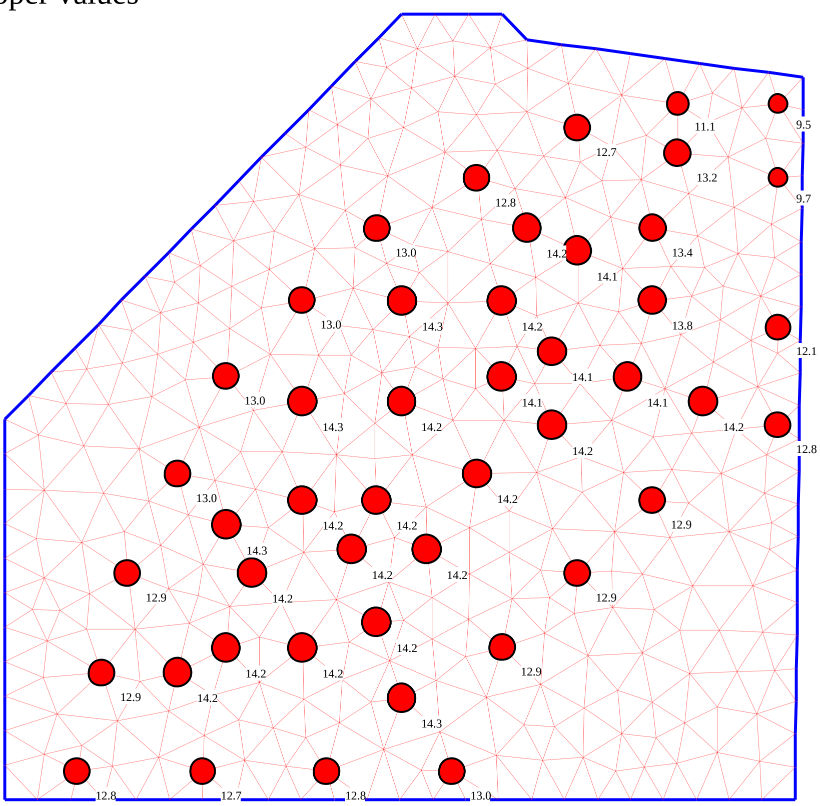

Figure 6-8 Pile load [MN] for elastic piled raft German recommendations EA-Piles for upper values

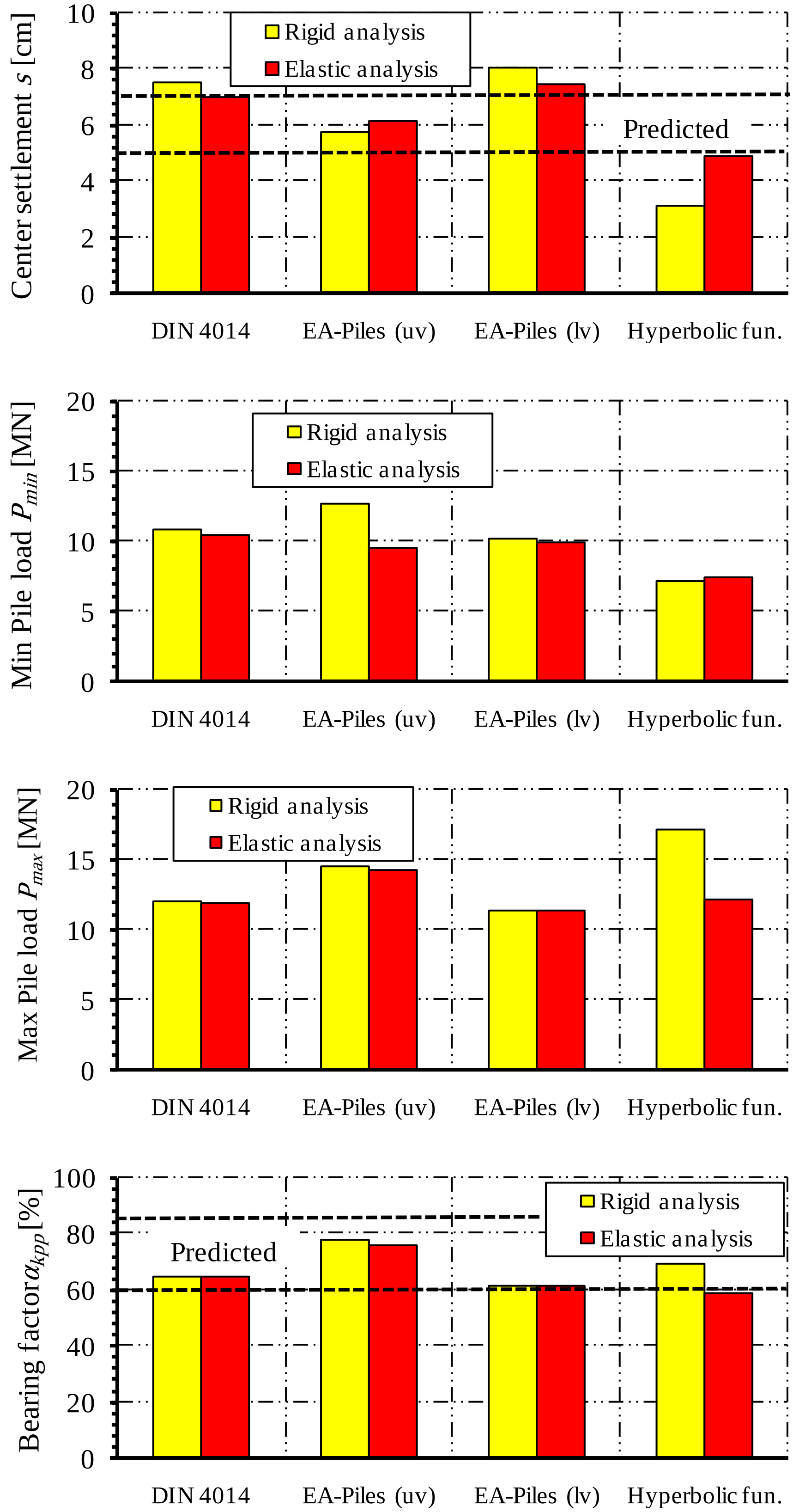

Figure 6-9 Results obtained from measurements and *ELPLA*

Table 6-1 Overview of calculation results of other models after *Richter* and *Lutz* (2010)

Method			BEM	FEM	Elast. half space	Measured
Average settlement	S_{kpp}	[cm]	4.8	6.3	5.0-7.3 (9.5)	
Max. settlement	S_{max}	[cm]	6.0	7.5	-	5.5*
Bearing factor	α_{kpp}	[%]	71	82	59-79	
Modulus of subgrade	k_s	[MN/m^3]	about 2.0		1.6-2.8	
Average pile load	Q_p	[MN]	12.5	14.3	10.3-13.9	
Min. pile load	$Q_{p,min}$	[MN]	9.9	11.6	8.5-10.1	
Max. pile load	$Q_{p,max}$	[MN]	16.1	17.6	13.8-20.5	
Average pile stiffness	k_p	[MN/m]	261	301	125-280	

* Directly after the completion of the shell only

6.10 References

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