Case study 5

Piled raft of *Westend 1* in Frankfurt

Content

5 Case study 5: *Westend 1* piled raft

5.1 General

Westend 1 is 208 [m] high skyscraper and standing on a piled raft. The tower lies in Frankfurt city, Germany. It was completed in 1993. The tower was the third tallest skyscraper in Frankfurt and also in Germany until 1993, Figure 5-1.

Using instruments installed inside the foundation of *Westend 1*, an extensive measuring program was established to monitor the behavior of the building. Because these instruments record raft settlements, raft contact pressures and loads on pile heads and along pile shafts, the building was a good opportunity to verify analysis methods for piled raft foundation and compare them with the recorded data Extensive studies were carried out by *Poulos et al.* (1997) *Poulos* (2001), *Reul* and *Randolph* (2003) and *Chaudhary* (2010) on analyzing the piled raft by methods of *Poulos and Davis* (1980), *Poulos* (1991), *Poulos* (1994), *Ta and Small* (1996), *Sinha* (1996), *Franke et al.* (1994), Randolph (1983) and *Clancy and Randolph* (1993).

The building has a basement with three underground floors and 51 stories with an average estimated applied pressure of 412 [kN/m^2]. The foundation area is about 2900 [m^2] founded on Frankfurt clay at a depth of 14·5 [m] under the ground surface. Raft thickness varies from 4·65 [m] at the middle to 3 [m] at the edge. A total of 40 bored piles, 30 [m] length by 1.3 [m] diameter. Piles are arranged in 2 rings under the heavy columns of the superstructure. The subsoil consists of gravels and sands up to 8 [m] below the ground surface underlay by layers of Frankfurt clay extended to more than 100 [m] below the ground surface. The groundwater level lies at 4.75 [m] under the ground surface.

Figure 5-1 *Westend 1* [1]

[1] https://en.wikipedia.org/wiki/Westendstrasse_1

Figure 5-2 shows a layout of *Westend 1* with the piled raft according to *Reul and Randolph* (2003).

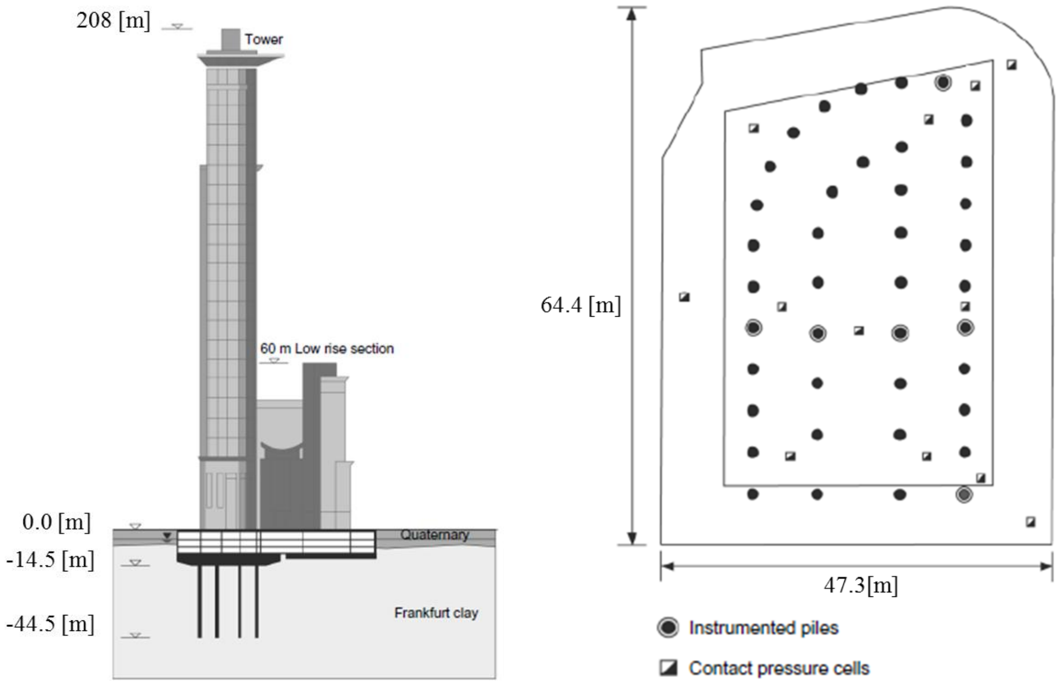

Figure 5-2 Layout of *Westend 1* with piled raft after *Reul* and *Randolph* (2003)

5.2 Analysis of the piled raft

Using the available data and results of the *Westend 1* 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 equally rigid piles.

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

5.3 FE-Net

The raft is divided into triangular elements with a maximum length of 2.0 [m] as shown in Figure 5-3. Similarly, piles are divided into elements with 2.0 [m] length.

5.4 Loads

The uplift pressure on the raft due to groundwater is P_w = 81 [kN/m^2]. Consequently, the total effective applied load on the raft including own weight of the raft and piles is N = 950 [MN]. The load is defined by a uniform load of 412 [kN/m^2] on the entire raft.

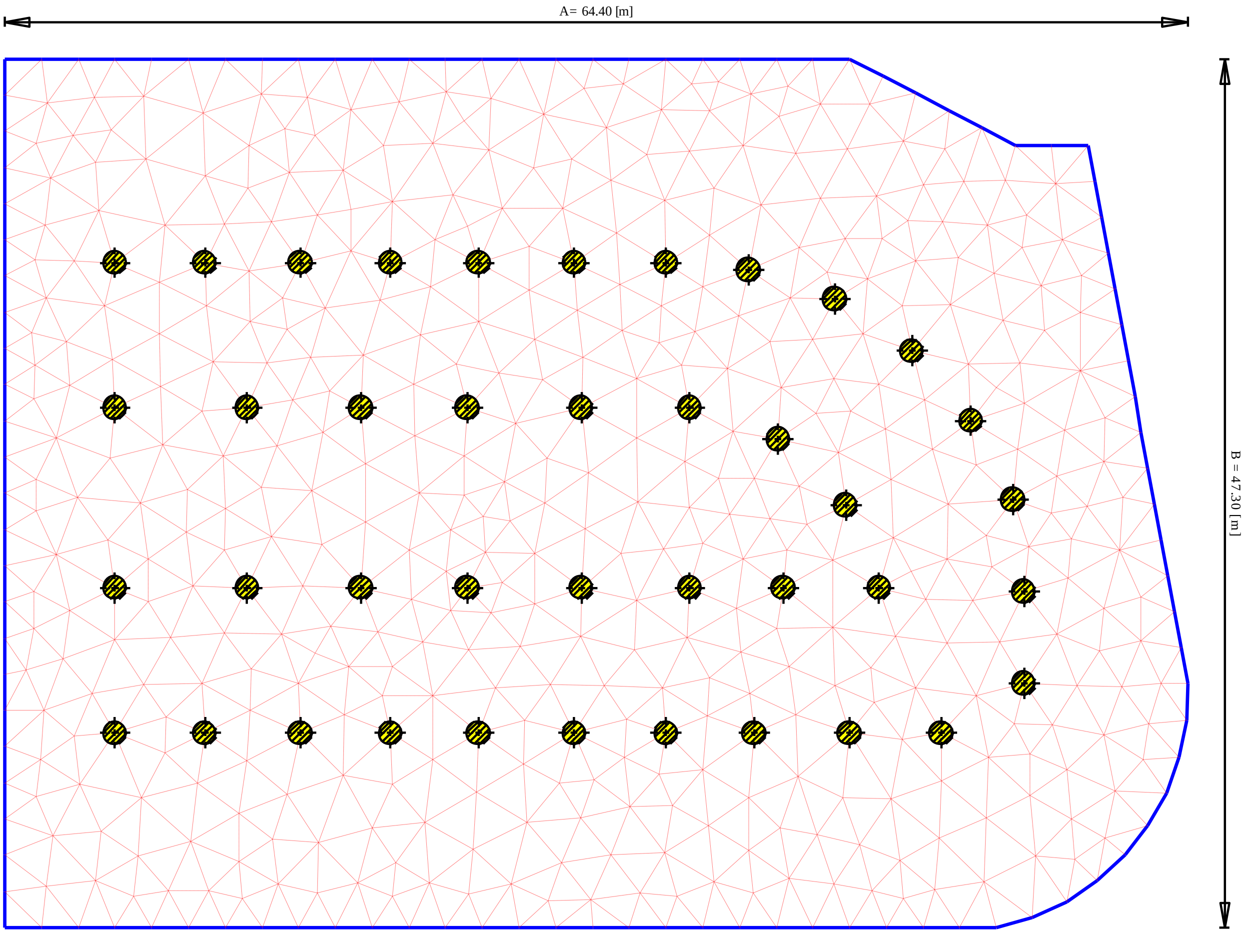

Figure 5-3 Mesh of *Westend 1* piled raft with piles of element length = 2.0 [m]

5.5 Pile and raft material

The average raft thickness is 4.2 [m]. All piles are 30 [m] length and 1.3 [m] diameter. The following values are used for pile and raft material:

For the raft:

Modulus of elasticity	E_p	=	34 000	[MN/m^2]
Poisson's ratio	ν_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]

5.6 Soil properties

The average clay properties used in the 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:

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

while that for reloading is:

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

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] at 70 [m] depth under the clay surface according to *Sommer/ Katzenbach* (1990). To carry out the analyses using German standards and recommendations, an average undrained cohesion of c_u = 200 [kN/m^2] is considered.

Limit pile load Ql

Russo (1998) suggested a shaft friction of 180 [kN/m^2] for undrained shear strength of 200 [kN/m^2]. To carry out the analysis using a hyperbolic function, a shaft friction of τ = 180 [kN/m^2] is assumed, which results in pile shaft capacity of Q_l = 22 [MN] as shown in equation 2.3

$$Q_l = \tau * \pi * D * l = 180 * \pi * 1.3 * 30 = 22054\,[\mathrm{kN}] = 22\,[\mathrm{MN}] \qquad (2.3)$$

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 [-].

The boring log for the subsoil under the raft consists of 12 soil layers as shown Figure 5-4. The total depth under the ground surface is 108 [m].

Figure 5-5 to Figure 5-8 show the load settlement relations for the different analyses.

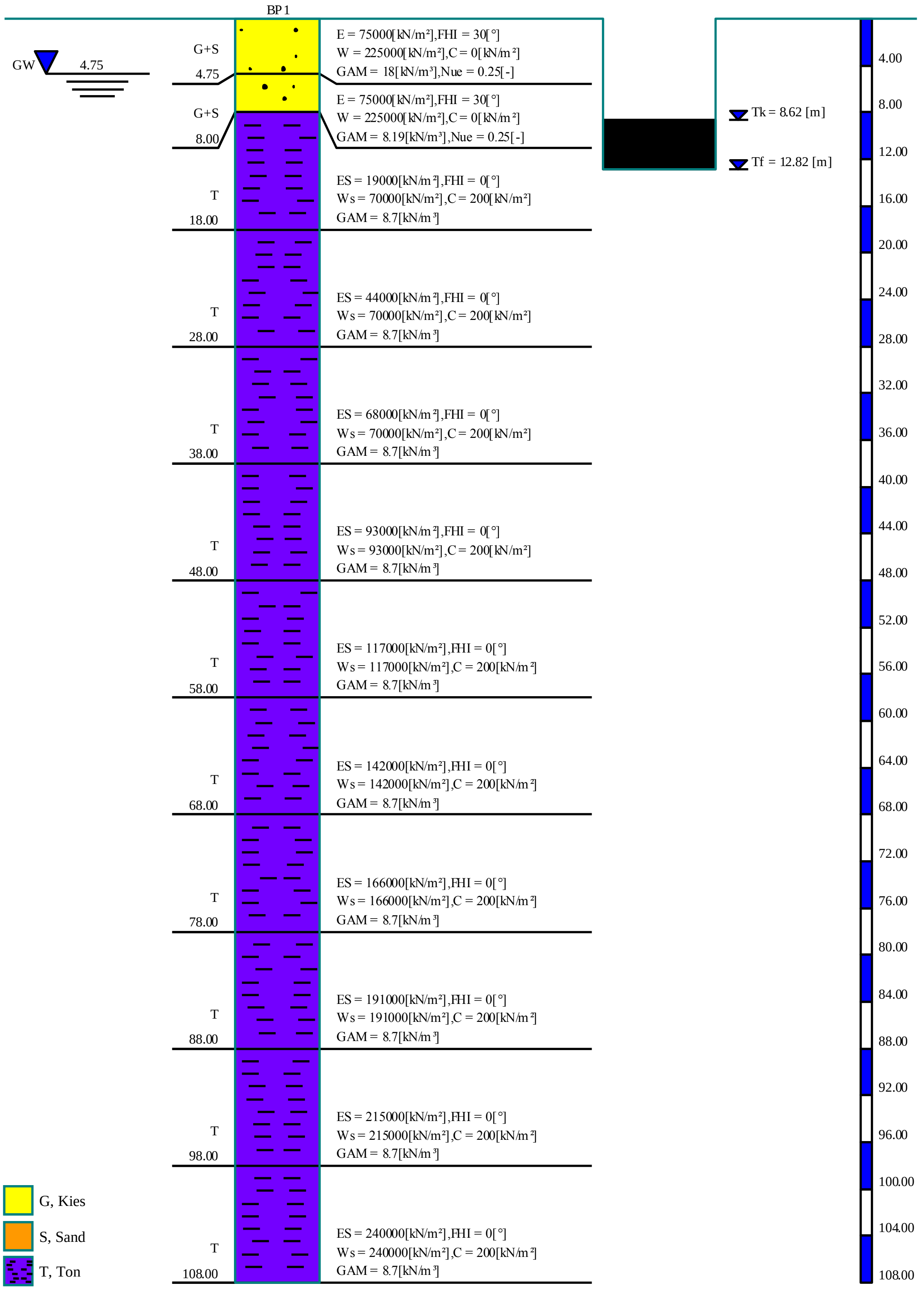

Figure 5-4 Boring log

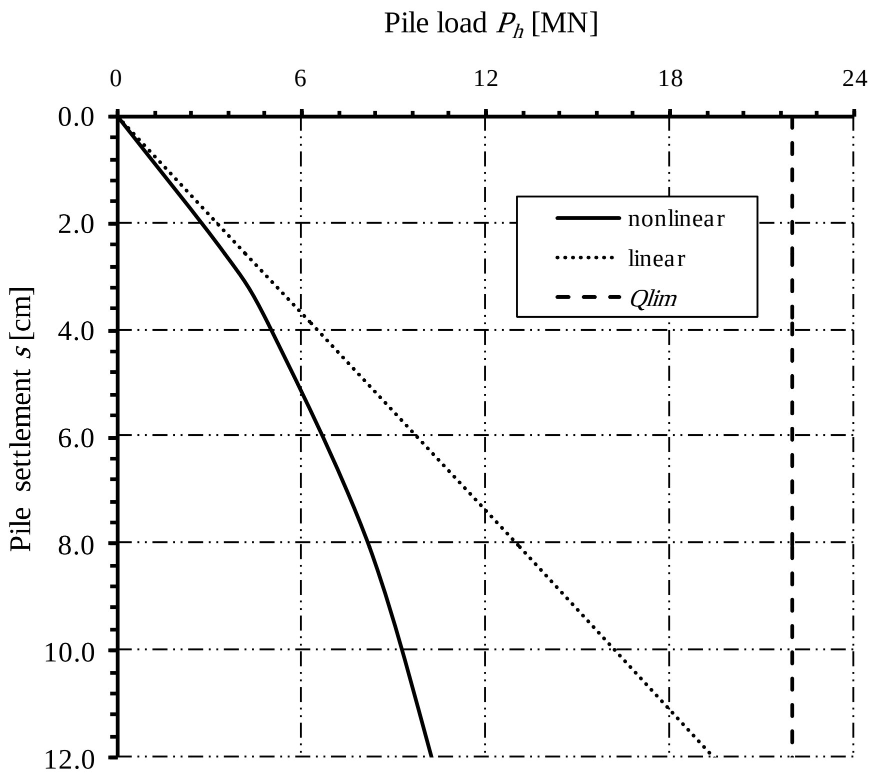

Figure 5-5 Load-settlement (hyperbolic function)

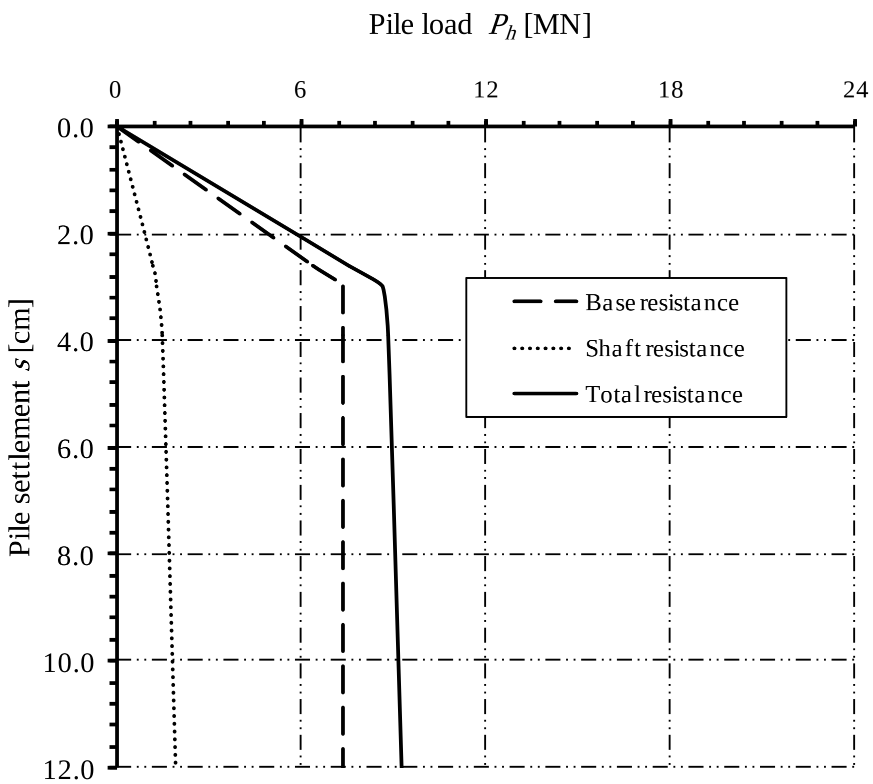

Figure 5-6 Load-settlement (DIN 4014)

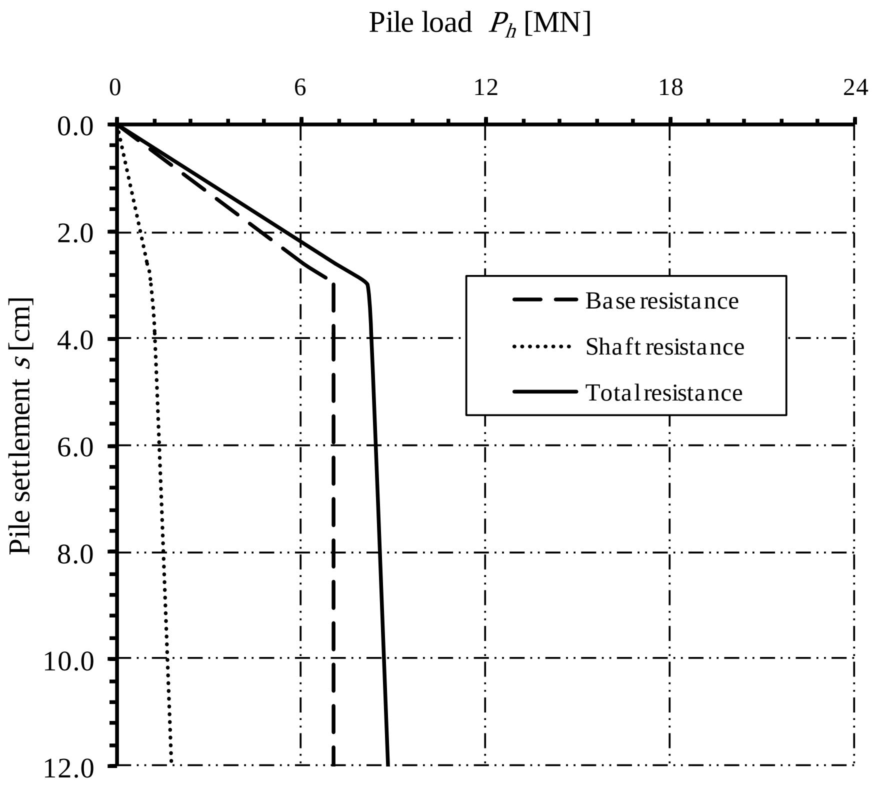

Figure 5-7 Load-settlement (EA-Piles, lower values)

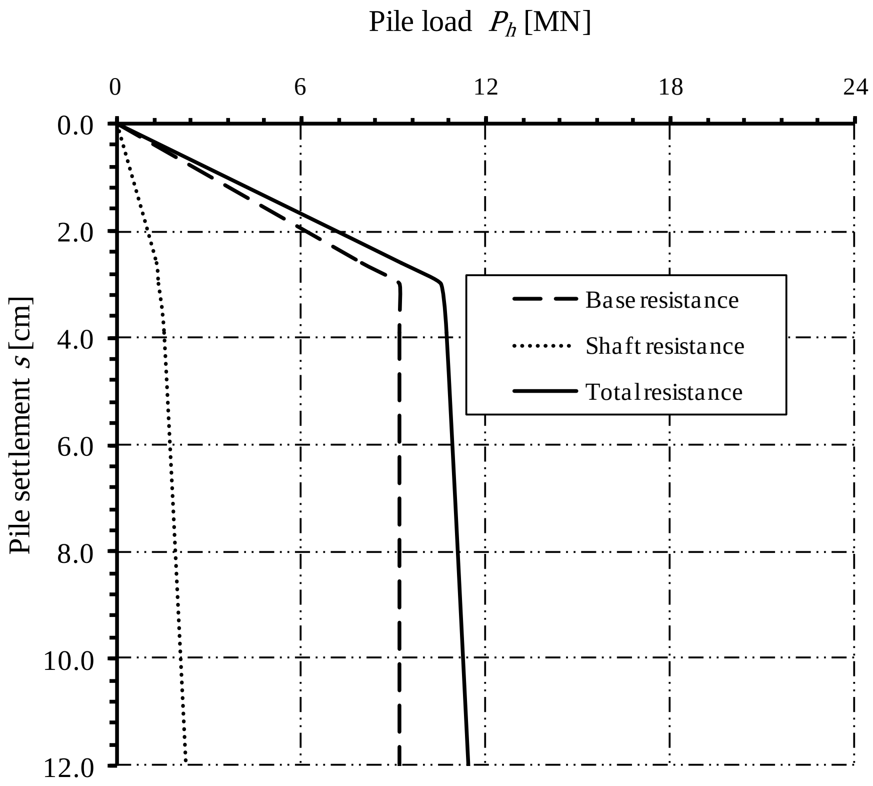

Figure 5-8 Load-settlement (EA-Piles, upper values)

5.7 Results

For a sample of the results for the different analyses by *ELPLA*, Figure 5-9 and Figure 5-10 show the settlement for both rigid and elastic piled rafts using German recommendations EA-Piles for upper and lower values, while Figure 5-11 and Figure 5-12 show the pile load for both rigid and elastic piled rafts using the hyperbolic function.

5.8 Measurements and other results

The construction of *Westend 1* started in 1990 and finished in 1993. According to *Lutz et al.* (1996), the recorded settlement at the center of the raft 2·5 years after completion of the shell of the building is 12 [cm]. The bearing factor from the measured pile loads is α_{kpp}= 0.49. The measured minimum and maximum pile loads of 9·2 [MN] and 14·9 [MN] respectively are according to *Franke and Lutz* (1994).

Figure 5-13 compares the settlement, bearing factor of piled raft and min and max pile load values calculated by *ELPLA* with those of measurements. For more comparison, Figure 5-14 shows the rest of the results for the different methods presented by *Reul* and *Randolph* (2003). 999

5.9 Evaluation

This case study shows that ELPLA is a practical tool for analyzing large piled raft problems in significantly lowered computational time.

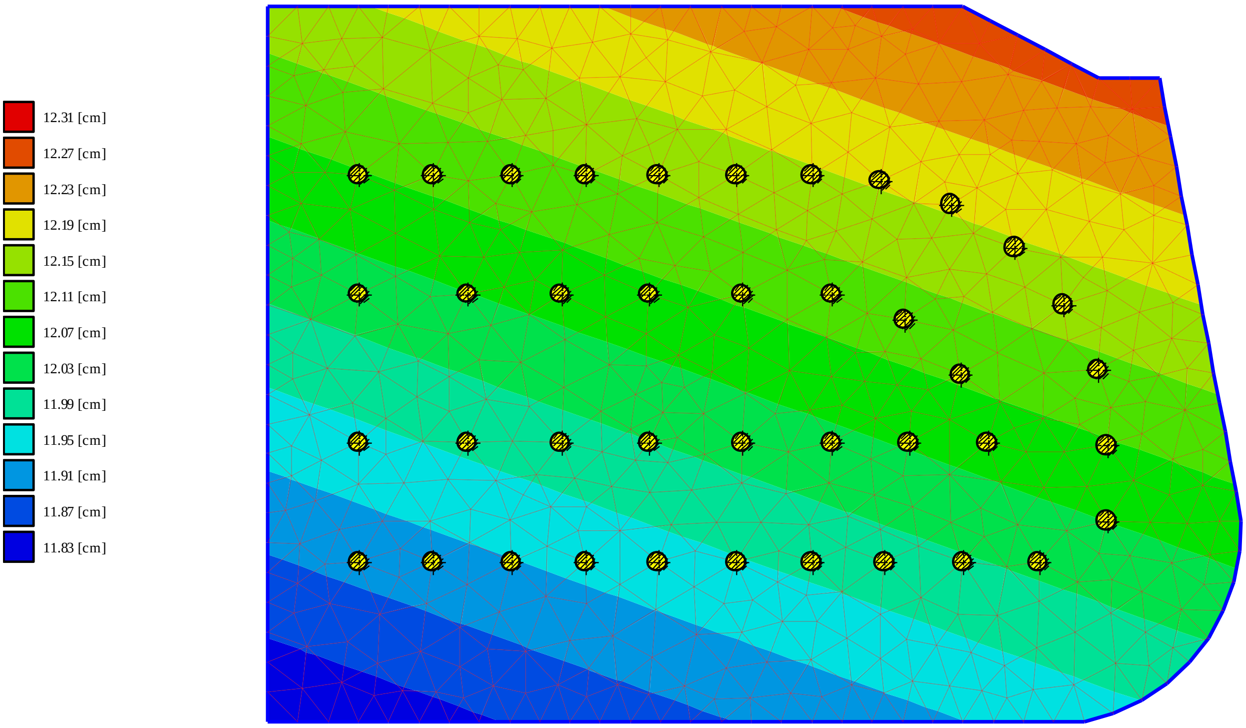

Figure 5-9 Settlement for rigid piled raft using German recommendations EA-Piles for lower values

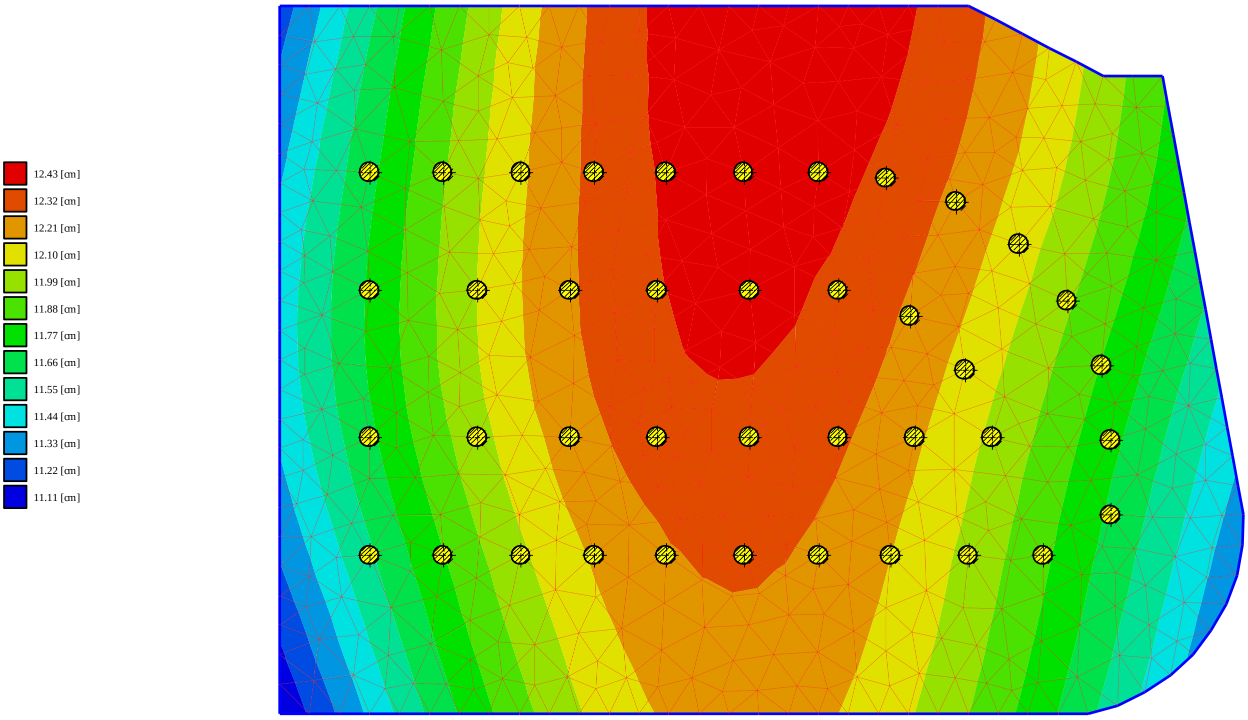

Figure 5-10 Settlement for elastic piled raft using German recommendations EA-Piles for lower values

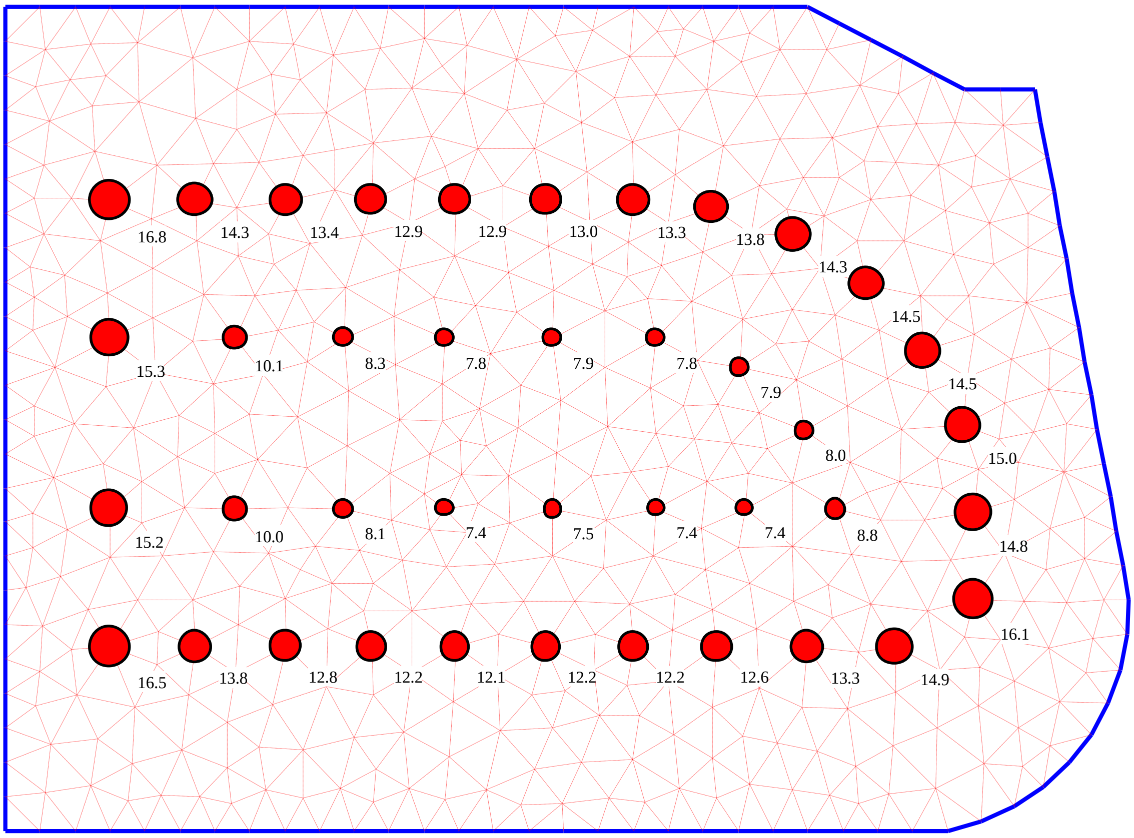

Figure 5-11 Pile load [MN] for rigid piled raft using hyperbolic function

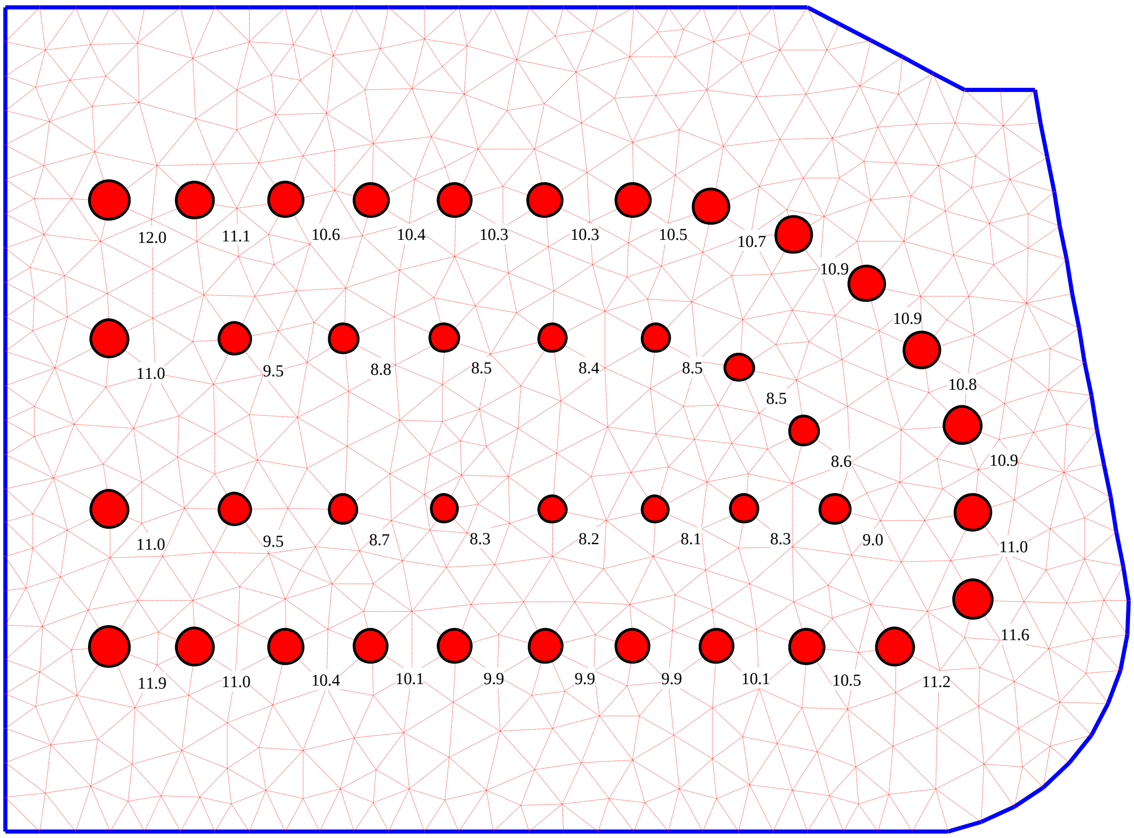

Figure 5-12 Pile load [MN] for elastic piled raft using hyperbolic function

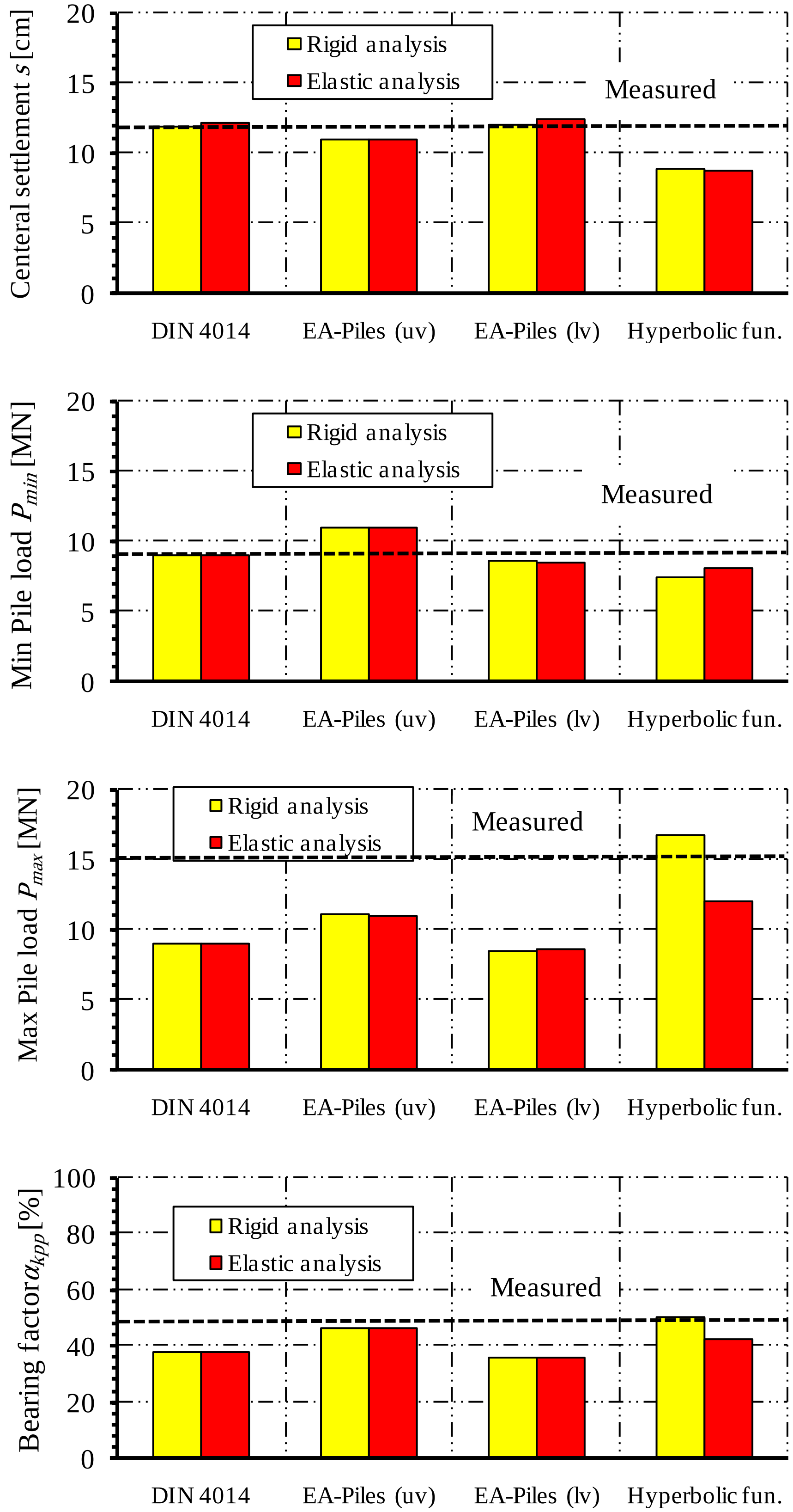

Figure 5-13 Results obtained from measurements and *ELPLA*

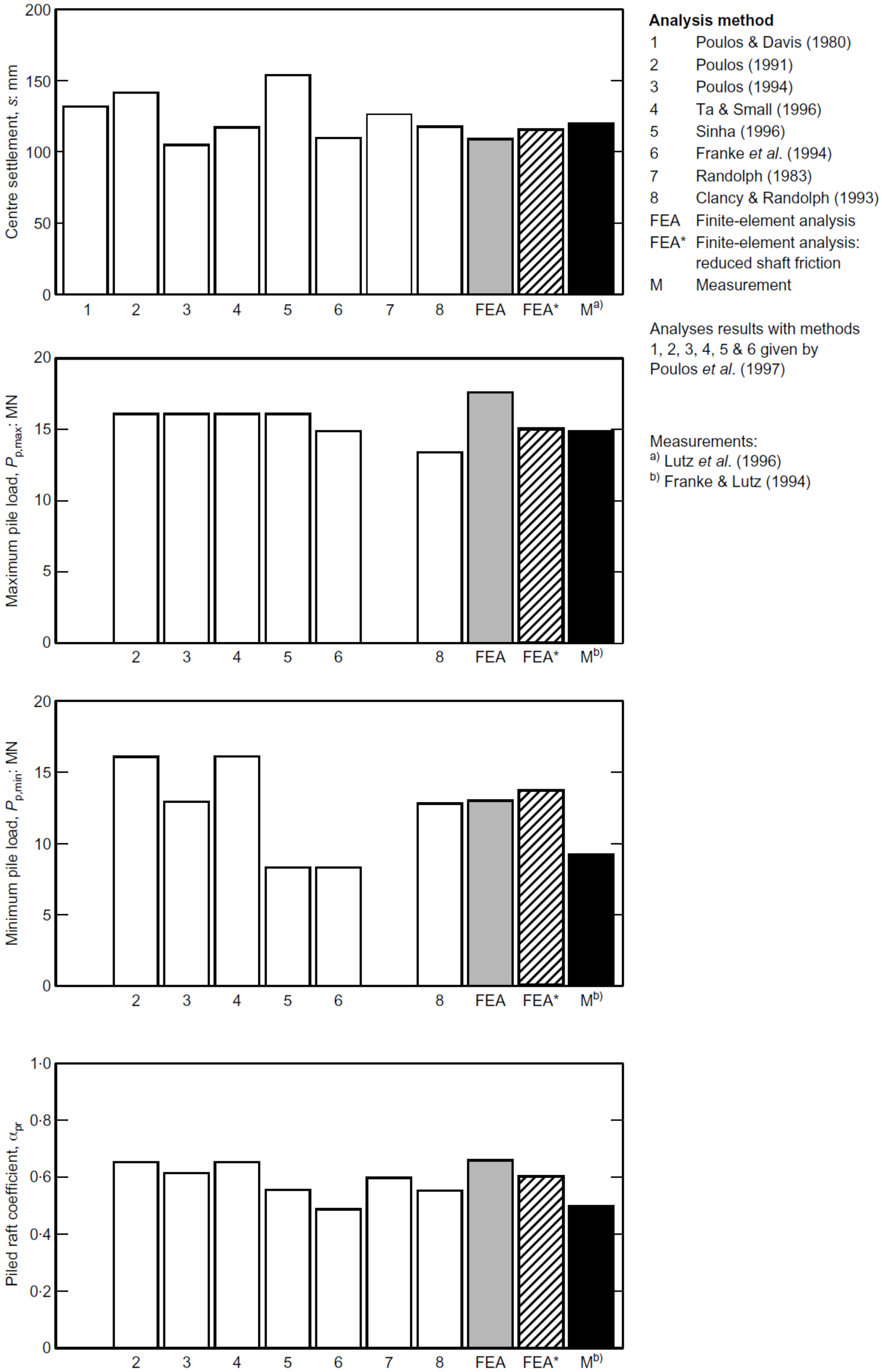

Figure 5-14 Comparison of different methods and measurements (*Reul* and *Randolph* (2003))

5.10 References

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