Case study 3

Analysis of Piled Raft of *Torhaus* in Frankfurt by the Program *ELPLA*

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Content

3 Case study 3: *Torhaus* piled raft

3.1 General

Torhaus is the first building in Germany with a foundation designed as a piled raft, Figure 3-1. The building lies in Frankfurt city in Germany. It is 130 [m] high and rests on two separate piled rafts, where a street passes under the building. Measured instruments were installed inside the foundation to record piled raft settlement and stress. Many authors studied the foundation of the *Torhaus* and applied their analysis methods on piled raft. Some of them are *Sommer et al.* (1985), *Sommer* (1989) and *Reul/ Randolph* (2003).

Figure 3-1 *Torhaus* (http://www.fussballportal.de/images/wm/fra_torhaus.jpg)

Figure 3-3 shows a layout of *Torhaus* with piled rafts. The building has no underground floors. The foundation is two separate equal piled rafts with rectangular shape areas, each of 17.5 [m] × 24.5 [m] sides. The distance between the two rafts is 10 [m]. The rafts are founded at a depth 3.0 [m] under the ground surface. The estimated total load on each raft is 200 [MN]. Raft thickness is 2.5 [m]. A total of 42 bored piles with a length of $l = 20$ [m] and diameter of $D = 0.9$ [m] are located under each raft. The pile spacing varies from 3.5 D to 3.0 D. The subsoil at the location of the building consists of gravel and sand up to 5.5 [m] below the ground surface, followed by layers of Frankfurt clay extending to great depth. The groundwater level lies below rafts.

The building was constructed between 1983 and 1986, the recorded maximum settlement at the raft middle in 1988 was about 12 [cm] according to *Sommer* (1989). If *Torhaus* stands on a raft only, the expected settlement would be about 26 [cm], based on geotechnical studies according to *Sommer et al.* (1985). Therefore, to reduce the settlement, piled rafts were considered. Using available data and results of *Torhaus* piled rafts, which have been discussed in details in the previous references, the present piled raft analysis is evaluated and verified for analyzing a piled raft.

3.2 Soil properties

Young's modulus

According to *Reul/ Randolph* (2003), *Young's* modulus of the sand with gravel layer under the rafts is E = 75000 [kN/m^2]. *Young's* modulus for reloading is taken to be $W = 3\ E$. Based on the back analysis after *Amann et al.* (1975), the distribution of modulus of compressibility for loading of Frankfurt clay with depth is defined by the following empirical formula:

$$E_s = E_{so}\left(1+0.35\,z\right) \tag{2.1}$$

while that for reloading is:

$$W_s = 70\left[\mathrm{MN/\,m^2}\right] \tag{2.2}$$

where:

E_s Modulus of compressibility for loading [MN/m^2]
W_s Modulus of compressibility for reloading [MN/m^2]
E_{so} Initial modulus of compressibility, E_{so}= 7 [MN/m^2]
z Depth measured from the clay surface, [m]

Undrained cohesion and limit pile load

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). *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 present analysis a limit shaft friction of τ = 180 [kN/m^2] is assumed, which gives a limit pile load of Ql = 10 [MN] where it is calculated from:

$$Ql = \tau * \pi * D * l = 180 * \pi * 0.9 * 20 = 10179[\mathrm{kN}] = 10[\mathrm{MN}] \tag{2.3}$$

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 the soil 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 3-2 that consists of 13 soil layers. The total depth under the ground surface is taken to be 113 [m].

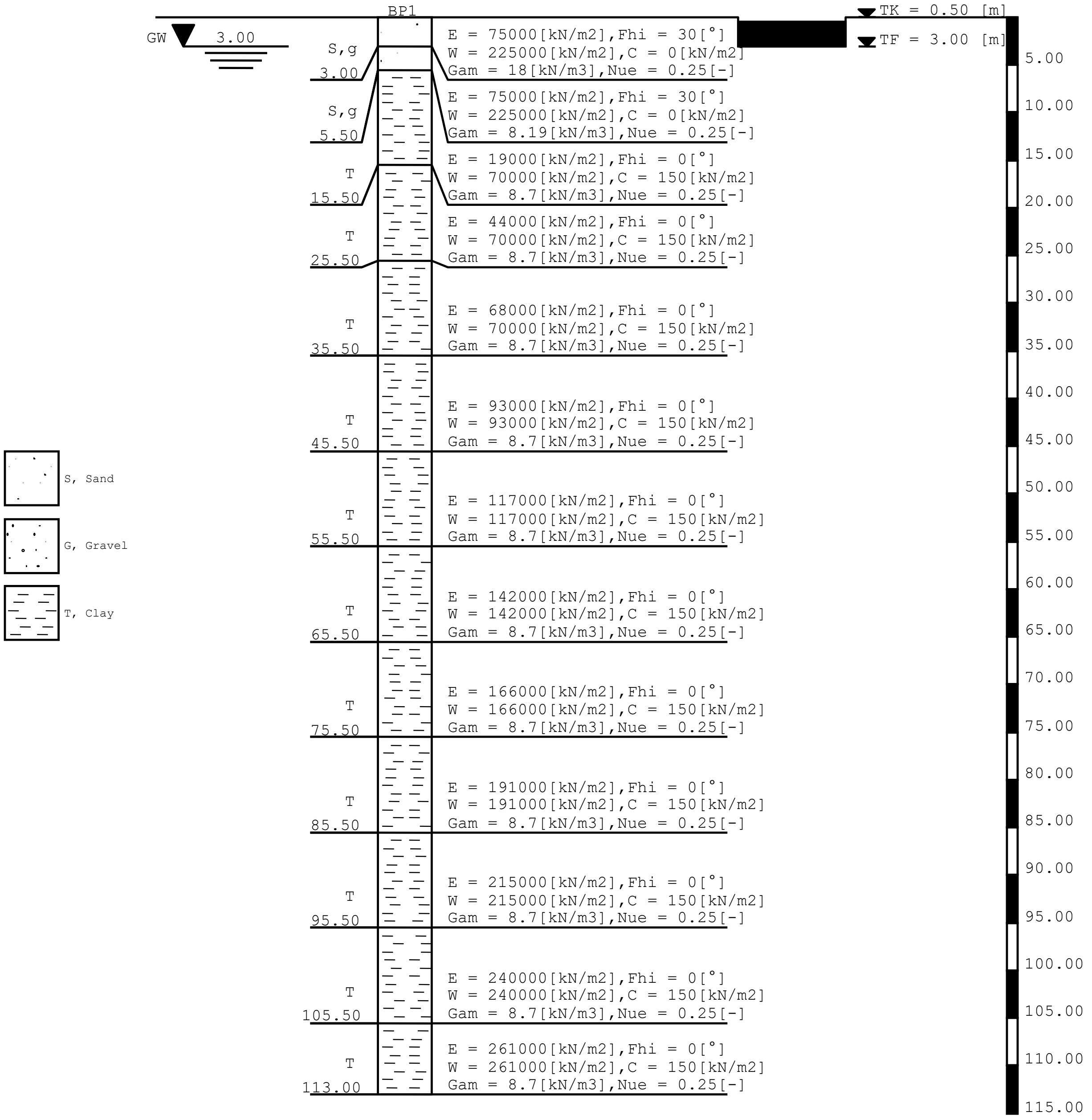

Figure 3-2 Boring log

3.3 Raft and pile material

Raft has the following material parameters:
Young's modulus E_b = 3.4×10^7 [kN/m^2]
Poisson's ratio ν_b = 0.2 [-]
Unit weight γ_b = 25 [kN/m^3]

while piles have the following material parameters:
Young's modulus E_b = 2.35×10^7 [kN/m^2]
Unit weight γ_b = 25 [kN/m^3]

3.4 Analysis of the piled raft

Comparisons are carried out to evaluate the nonlinear analysis of piled elastic raft using composed coefficient technique. Here results of three-dimensional finite element analysis and field measurements are compared with those obtained by the present analysis. In the comparisons the present analysis is termed NPRH.

The raft is divided into rectangular elements as shown in Figure 3-4. Element sizes in x-direction for a single raft are $1.75 + 10 \times 1.4 + 1.75 = 17.5$ [m], while those in y-direction are $14 \times 1.75 = 24.5$ [m]. Piles are divided into line elements with 2.0 [m] in length. The raft is considered to be elastic plate supported on rigid piles. The effective depth of the soil layers under the raft is taken to be $H = 110$ [m] as assumed by three-dimensional finite element analysis.

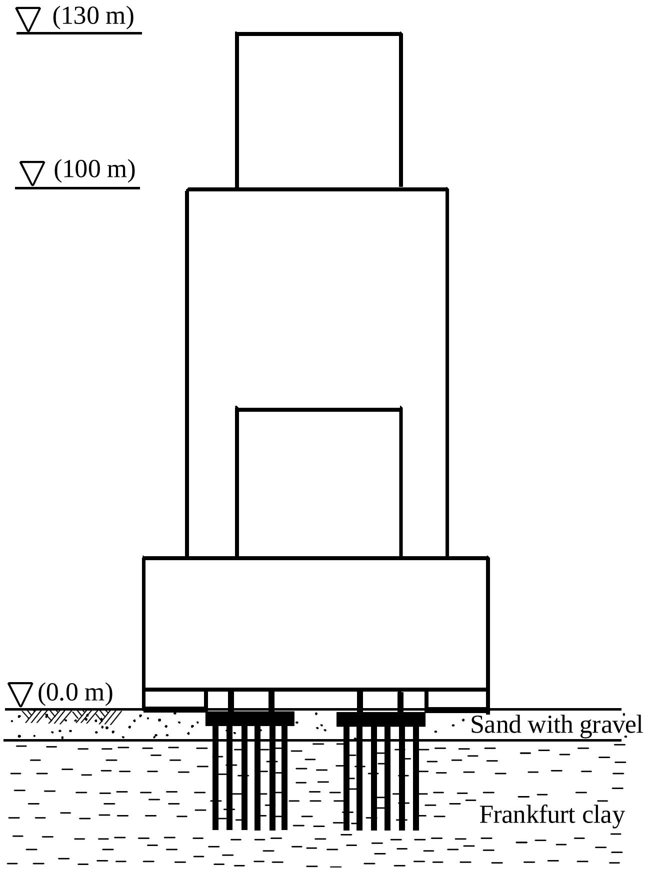

Figure 3-3 Layout of *Torhaus* with piled rafts

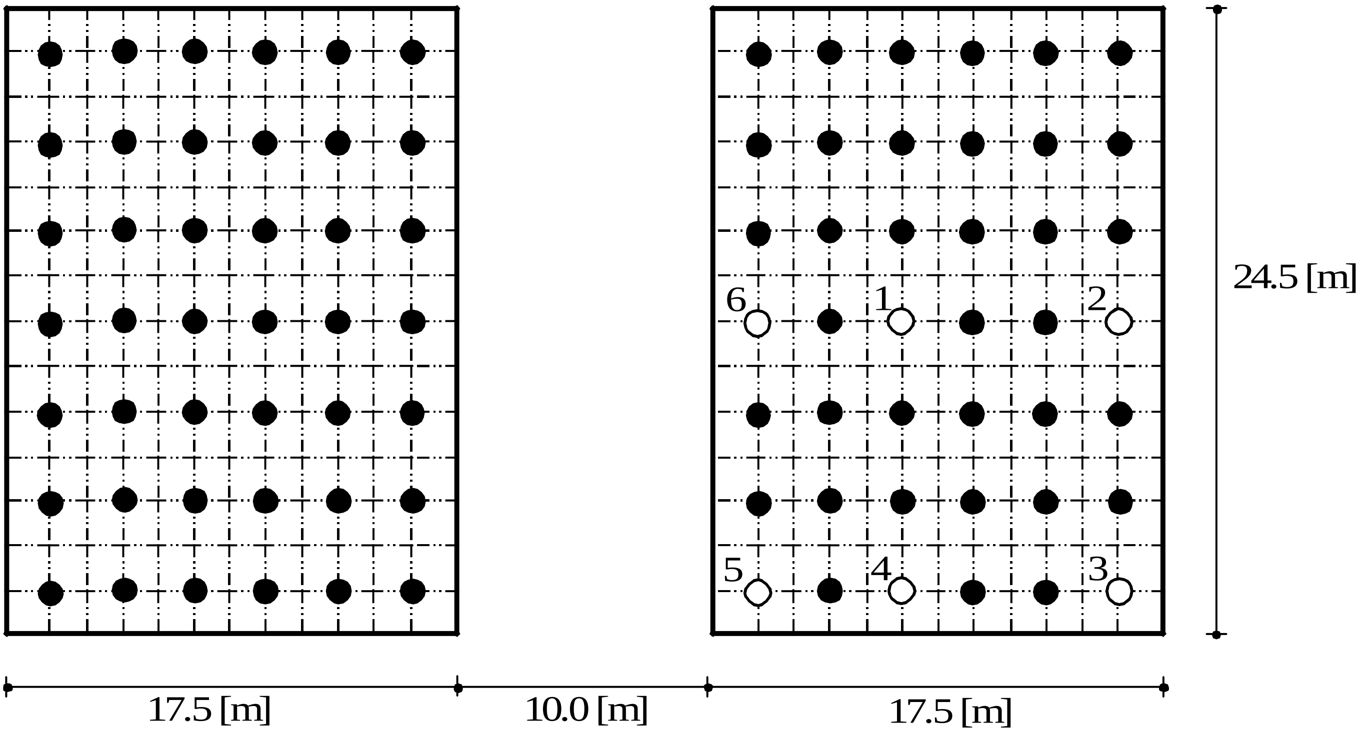

Figure 3-4 Mesh of *Torhaus* piled rafts with piles

3.5 Comparison with three-dimensional finite element analysis and field measurements

Reul/ Randolfph (2003) analyzed *Torhaus* piled rafts using three dimensional finite element model and compared their results with those obtained by field measurements according to *Sommer* (1989). For reducing the computational effort and time, they took the advantage of the symmetry in shape, soil and load geometry about both x- and y-axes to carry out the analysis for a quarter of a piled raft. In NPRH the two piled rafts are analyzed together to take the interaction among all elements of piled rafts. A linear analysis is carried out first to obtain the initial modulus of subgrade reaction. In this primary analysis the effect of reloading is taken into account. For the nonlinear analysis, the accuracy number is chosen to be 0.0002 [m]. Seven cycles in few minutes are required to obtain the nonlinear analysis of the piled rafts together. This is related to using composed coefficient technique that reduced the size of soil stiffness matrix from [1314 × 1314] to [390 × 390]. Accordingly, the total number of equations was reduced to 1170, where $n_{pr} = 1314$, $n_r = 390$ and number of unknown per node is 3 ($3\ n_r = 1170$).

Table 3-1 lists results of central settlement and bearing factor of piled raft obtained by NPRH and those obtained by *Reul/ Randolph* (2003) using three-dimensional finite element analysis. Also, the table includes the measured results presented by *Sommer* (1989). Figure 3-5 and Figure 3-6 compare loads on piles 1 to 6 (Figure 3-4) obtained by NPRH with those obtained by *Reul/ Randolph* (2003) using three-dimensional finite element analysis and with measured pile loads presented by *Sommer* (1989).

Table 3-1 Comparison between results obtained by 3D FE-Analysis and field measurements with those obtained by NPRH

Type of analysis	Measurement	3D FE-Analysis	NPRH
Central settlement s_{center} [cm]	12.4	9.6	11.2
Bearing factor α_{kpp} [%]	67	76	64

Table 3-1 shows that settlement and bearing factor of piled raft for NPRH is are in good agreement with field measurements. Results of pile loads in Figure 3-5 and Figure 3-6 are in good agreement with both those of three-dimensional finite element analysis and field measurements. Three-dimensional finite element analysis gave a relatively big difference in the bearing factor compared with that of field measurement and NPRH.

This case study shows that NPRH is not only an acceptable method to analyze piled raft but also a practical one for analyzing large piled raft problems. Besides the analysis gives good agreement with measured results, it takes less computational time and less effort for generating input data compared with other complicated models using three dimensional finite element analysis.

3.6 Comparing among different analysis types

To show the difference between results when analyzing piled raft of *Torhous* linearly and nonlinearly as piled elastic raft or piled rigid raft, piled raft of *Torhous* is analyzed four times as follows:

- Linear piled rigid raft
- Nonlinear piled rigid raft
- Linear piled elastic raft
- Nonlinear piled elastic raft

For the four analysis types, Table 3-2 shows central settlement and bearing factor of piled raft, while Figure 3-7 and Figure 3-8 show loads on piles 1 to 6. In general, it can be noticed from Table 3-2 and these figures that:

Settlement

- Settlement from nonlinear analysis for piled rigid raft or piled elastic raft is greater than that obtained from linear analysis
- The nonlinear settlement exceeds linear settlement by 48 [%] for piled rigid raft and by 29 [%] for piled elastic raft
- For a single analysis, either linear or nonlinear, the difference in settlement obtained from analyzing piled rigid raft or piled elastic raft is small. This means any of the analysis can be used for estimating the settlement

Bearing factor of piled raft

- Bearing factor of piled raft from nonlinear analysis is less than that obtained from linear analysis
- Bearing factor of piled raft from nonlinear analysis decreases by 13 [%] for analyzing piled rigid raft and by 15 [%] for piled elastic raft

Force on pile head

- Using nonlinear analysis redistributes pile loads by increasing values of inner piles (piles 1 and 6) and decreasing values of edge piles (piles 2, 3, 4 and 5)
- Total pile loads of piled rigid raft are greater than those of piled elastic raft
- Pile loads for edge piles of piled rigid raft are greater than those of piled elastic raft and vice verse for inner piles

Table 3-2 Comparison between results of different analysis types

Type of analysis	Piled rigid raft		Piled elastic raft	
	Linear	Nonlinear	Linear	Nonlinear
Central settlement s_{center} [cm]	7.0	13.4	8.0	11.2
Bearing factor α_{kpp} [%]	88	77	75	64

Applying different analysis types on piled raft of *Torhous* shows that the nonlinear analysis of piled elastic raft is the acceptable analysis type, where its results are in agreement with measured values.

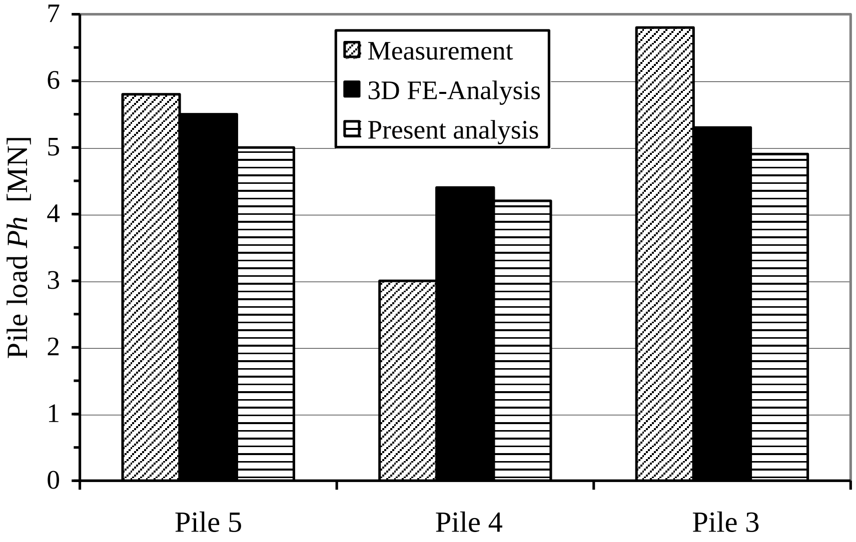

Figure 3-5 Comparison between pile loads obtained by 3D FE-Analysis and field measurements with those obtained by NPRH (Piles 3, 4 and 5)

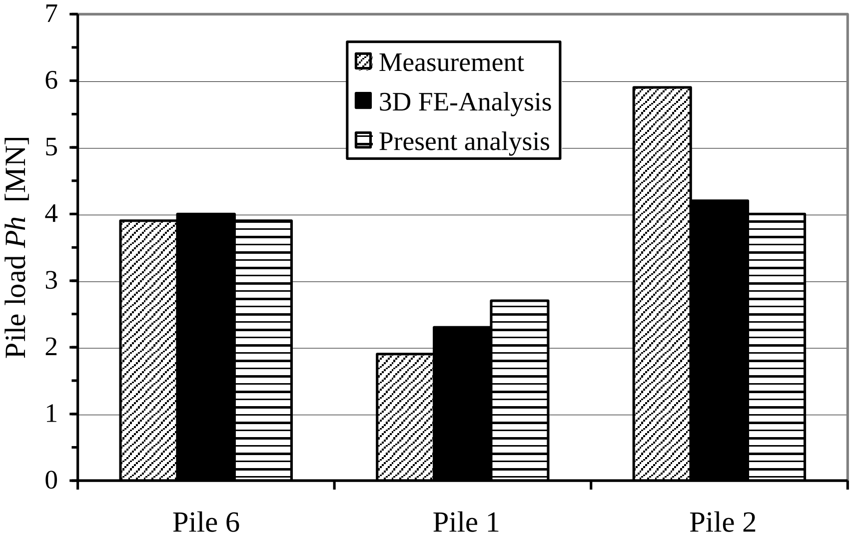

Figure 3-6 Comparison between pile loads obtained by 3D FE-Analysis and field measurements with those obtained by NPRH (Piles 1, 2 and 6)

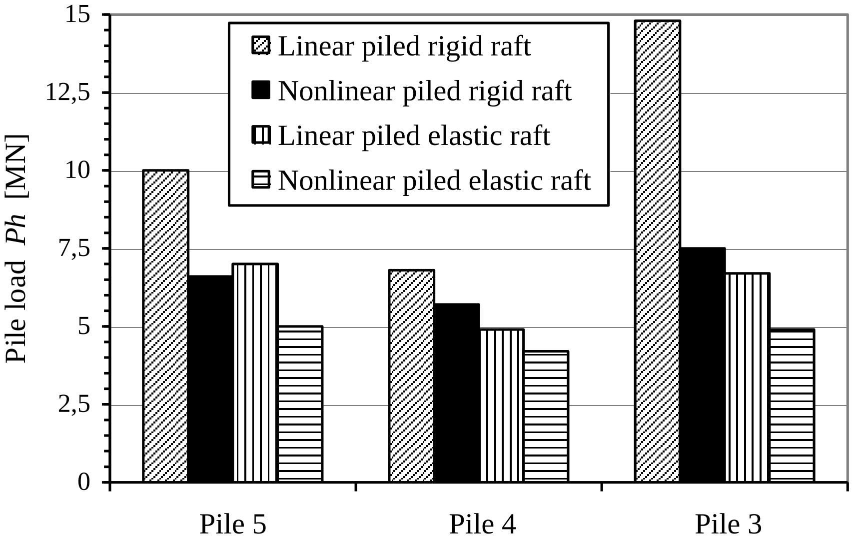

Figure 3-7 Comparison between pile loads of different analysis types (Piles 3, 4 and 5)

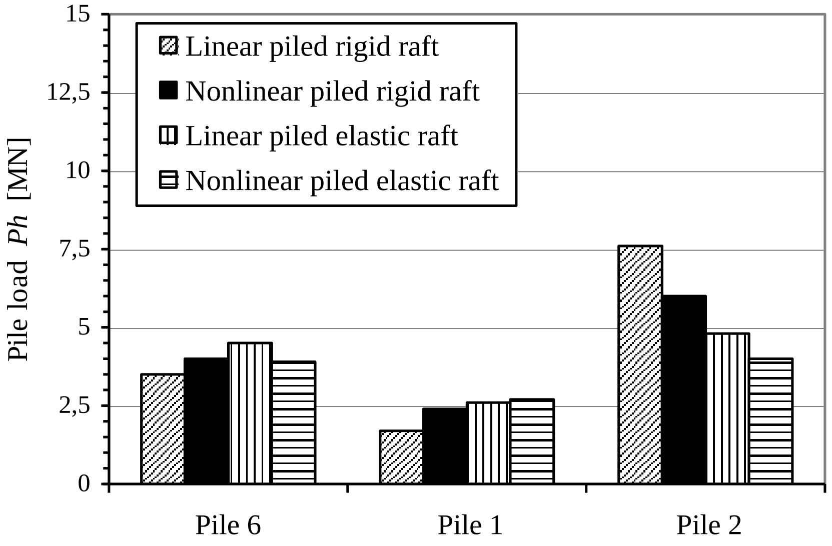

Figure 3-8 Comparison between pile loads of different analysis types (Piles 1, 2 and 6)

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