Case study 4

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

M. El Gendy
A. El Gendy

PO Box 14001 Richmond Road PO, Calgary AB, Canada T3E 7Y7
Tele.:+1(587) 332-3323
geotec@geotecsoftware.com
www.geotecsoftware.com

2021

Content

Page

4 Case study 4: *Messeturm* piled raft

4.1 General

Messeturm was the tallest high-rise building in Europe until 1997, Figure 4-1. The building lies in Frankfurt city in Germany. It is 256 [m] high and standing on a piled raft foundation.

Figure 4-1 Messeturm[1]

[1] http://de.wikipedia.org/wiki/Messeturm_(Frankfurt)

Using instruments installed inside this foundation, 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 chance for many authors to verify their analysis methods for piled raft. Since *Messeturm* was built many authors have studied its behavior. Some of them are *Sommer* (1989), *Sommer/ Katzenbach* (1990), *Thaher* (1991), *Sommer et al.* (1991), *EL-Mossallamy* (1996), *Katzenbach et al.* (2000), *Reul/ Randolph* (2003) and *Chow/ Small* (2005).

Figure 4-2 shows a layout of *Messeturm* with the piled raft according to *Chow/ Small* (2005). The building has a basement with two underground floors and 60 stories with a total estimated load of 1880 [MN]. The foundation is a square piled raft of 58.8 [m] side founded on Frankfurt clay at a depth 14 [m] under the ground surface. Raft thickness varies from 6 [m] at the middle to 3 [m] at the edge. A total of 64 bored piles with equal diameters of 1.3 [m], are arranged under the raft in 3 rings. Pile lengths vary from 26.9 [m] for the 28 piles in the outer ring to 30.9 [m] for the 20 piles in the middle ring and to 34.9 [m] for the 16 piles in the inner ring. The subsoil at the location of the building consists of gravels and sands up to 8 [m] below the ground surface underlay by layers of Frankfurt clay extending to great depth of more than 100 [m] below the ground surface. The groundwater level lies at 4.75 [m] under the ground surface.

The construction of *Messeturm* started in 1988 and finished in 1991. According to *Katzenbach et al.* (2000), the recorded settlement at the center of the raft in March 1990 was 8.5 [cm], while the last recorded settlement in December 1998 was 14.4 [cm] according to *Reul/ Randolph* (2003). If *Messeturm* stands on a raft only, the expected settlement would be between 35 [cm] and 40 [cm] based on geotechnical studies according to *Sommer* (1989). Therefore, to reduce the settlement, a piled raft was considered where the expected final settlement in this case would be between 15 [cm] and 20 [cm] according to *Sommer/ Katzenbach* (1990). Using the available data and results of the *Messeturm* piled raft, which have been discussed in details in the previous references, the present piled raft analysis is evaluated and verified. Thus by dealing the piled raft as a rigid foundation where the rigid analysis of piled raft is considered as an easy method to check results of any other complicated models.

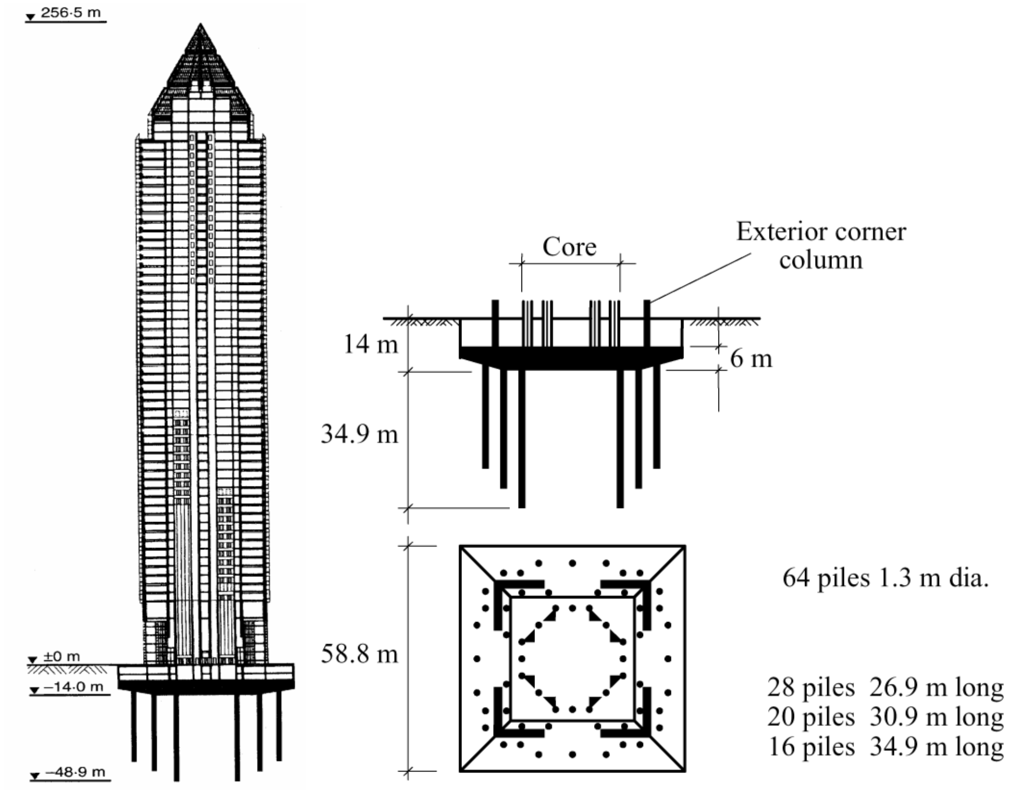

Figure 4-2 Layout of *Messeturm* with piled raft after *Chow/ Small* (2005)

4.2 Analysis of the piled raft

A series of comparisons are carried out to evaluate the nonlinear analysis of piled raft using DIN 4014 [5] for load-settlement relation. In which, results of other analytical solutions and measurements are compared with those obtained by the present analysis. In the comparisons the present analysis is termed NPRD.

Taking advantage of the symmetry in shape, soil and load geometry about both *x*- and *y*-axes, the analysis is carried out for a quarter of the piled raft. The raft is divided into elements with maximum length of 2.0 [m] as shown in Figure 4-3. Element sizes in *x*- and *y*-directions for a quarter of the raft are:

$$2 \times 2.2 + 2.69 + 2 \times 1.74 + 0.89 + 3 \times 2.35 + 2.06 + 2.65 + 1.76 + 2 \times 2.2 = 29.4 \text{ [m]}$$

Similarly, piles are divided into elements with 2.0 [m] in maximum length.

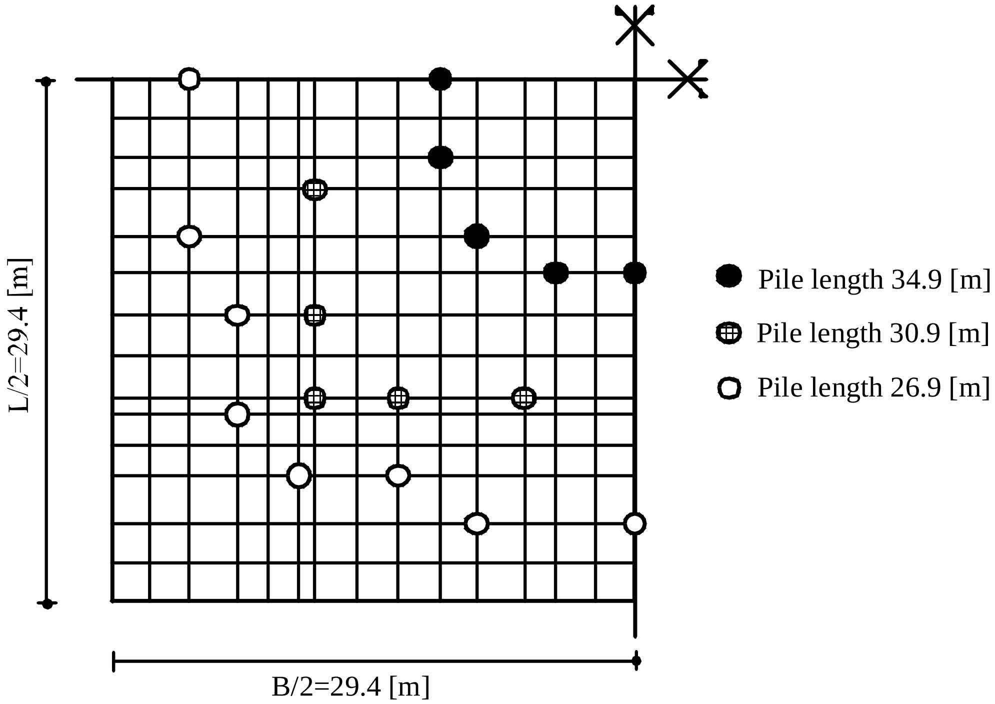

Figure 4-3 Mesh of *Messeturm* piled raft with piles (Max. element length = 2.0 [m])

a) Comparison with Randolph's analysis

To examine NPRD for the *Messeturm* piled raft, results are compared with those using *Randolph's* analysis, which was carried out by *EL-Mossallamy* (1996). The raft is considered to be rigidly supported on equal rigid piles with an average length equal to 30.15 [m]. A soil layer of H = 90 [m] with a constant elastic modulus is considered. Two cases of analyses are carried out with two different soil parameters as indicated in Table 3-1. For NPRD, the load-settlement relation is determined using an average undrained cohesion of c_u = 300 [kN/m^2] in both cases. The uplift pressure on the raft due to groundwater is considered to be P_w = 275 [kN/m^2]. Consequently, the total effective applied load on the raft including own weight of the raft and piles is assumed to be N = 1600 [MN].

Table 3-2 summarizes the results of the immediate and total settlements for *Randolph's* analysis (1994) and NPRD while Table 3-3 summarizes the results of the bearing factors of piled raft for both of the analyses. Although the principles of both of the analyses are different, the results indicate a good agreement in settlement and a difference in bearing factor of piled raft ranges from 3.4 [%] to 7.7 [%].

Table 3-1 Soil properties used in *Randolph's* analysis and NPRD

Case No.	Undrained conditions		Drained conditions	
	E_s [MN/m^2]	ν_s [-]	E'_s [MN/m^2]	ν'_s [-]
Case 1	70.4	0.5	62.4	0.33
Case 2	91.4	0.5	81.0	0.33

Table 3-2 Settlements *s* [cm] (*Randolph's* analysis vs. NPRD)

Case No.	Immediate		Total	
	Randolph's analysis	NPRD	*Randolph's* analysis	NPRD
Case 1	13.0	12.9	17.1	18.1
Case 2	10.0	10.1	13.7	14.0

Table 3-3 Bearing factors of piled raft α_{kpp} [%] (*Randolph's* analysis vs. NPRD)

Case No.	Immediate		Total	
	Randolph's analysis	NPRD	*Randolph's* analysis	NPRD
Case 1	35.2	31.8	44	39
Case 2	35.2	27.5	44	38

b) Comparison with Thaher's analysis

To analyze piled raft, *Thaher* (1991) had presented an analytical model using equivalent raft method, which was checked by the centrifuge model test results. He applied his model to the *Messeturm* piled raft to assess the rigid settlement.

4.3 Soil properties

The average clay properties used in *Thaher's* 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/m²]

E_{so} Initial modulus of compressibility, $E_{so} = 7$ [MN/m²]

z Depth measured from the clay surface, [m]

W_s Modulus of compressibility for reloading [MN/m²]

Undrained cohesion

The undrained cohesion c_u of Frankfurt clay increases with depth from c_u = 100 [kN/m²] to c_u = 400 [kN/m²] in 70 [m] depth under the clay surface according to *Sommer/ Katzenbach* (1990). To carry out NPRD, an average undrained cohesion of c_u = 300 [kN/m²] is considered.

Poisson's ratio

Poisson's ratio of Frankfurt clay is taken to be $\nu_s = 0.25$ [-].

To carry out the analysis, the subsoil under the raft is considered as indicated in the boring log of Figure 4-4 that consists of 10 soil layers. The total depth under the ground surface is taken to be 102.83 [m].

Figure 4-4 Boring log

Table 3-4 lists the results of settlement, bearing factor of piled raft and tip resistance obtained by NPRD compared with those obtained by *Thaher* (1991). The table shows that settlement and bearing factor of piled raft for the both analyses are nearly the same. Only a difference of 0.6 [MN/m^2] in the maximum tip resistance is found.

In Table 3-5, load on each pile in inner, middle and outer rings obtained by both NPRD and the centrifuge model test by *Thaher* (1991) are shown. Also, the table includes the measured total pile loads after the completion of the structural frame, presented by *Sommer et al.* (1991). The table indicates that results are in a good agreement.

Also, Table 3-5 shows that the piles transfer the load to the soil mainly by skin friction, as observed from the measurements (*Katzenbach et al.* (2000)). The measurements indicate that the load distribution within the pile group is quite homogeneous. This behavior is also noticed in NPRD not only for the pile load but also for the pile settlement.

As shown in Table 3-6, NPRD can introduce the individual settlement in the pile due to pile load itself or due to pile-pile and pile-raft interactions. Table 3-6 shows that the most of the settlement is due to self settlement of the pile compared with the settlement due to pile-pile and pile-raft interactions for loading or reloading. The self-settlement of the pile ranges between 52 and 55 [%] of the total settlement in the pile.

Table 3-4 Comparison between results obtained by *Thaher's* analysis and NPRD

Analysis	Settlement s_r [cm]	Bearing factor α_{kpp} [%]	Min. tip resistance [MN/m^2]	Max. tip resistance [MN/m^2]
Thaher's analysis	19.00	40.00	1	1.5
NPRD	18.77	40.44	1	2.1

Table 3-5 Pile load for NPRD, centrifuge model test and measured results

Pile ring	NPRD			Total pile load from centrifuge model test [MN]	Measured total pile load [MN]
	Tip force [MN]	Shaft force [MN]	Total pile load [MN]		
Inner ring	2.71	8.55	11.26	14	11
Middle ring	2.74	7.57	10.31	13	13
Outer ring	2.72	6.59	9.31	10	10

Table 3-6 Settlement in piles

Pile ring	Self settlement s_p [cm]	Settlement due to pile-pile and pile-raft interactions		Total settlement s_r [cm]	Self/ Total s_p/s_r [%]
		Loading s_e [cm]	Reloading s_w [cm]		
Inner ring	9.75	4.97	4.05	18.77	52
Middle ring	10.29	4.78	3.70	18.77	55
Outer ring	9.86	5.10	3.81	18.77	53

Comments

The maximum difference between the settlements in step *i* and next step *i* + 1 is considered as an accuracy number. In this case study, the accuracy number was chosen to be 0.0001 [cm].

For a single run of analysis, the results were obtained in relatively short time (17 [Sec] for analysis *a* and 1.2 [Min] for analysis *b* using Pentium 4 PC with 512 MB RAM). This is related to the following parameters:

- Flexibility coefficients due to pile-pile interaction are determined only for two forces: shaft and base forces

- As the settlement due to load on pile itself is determined from DIN 4014 [5], flexibility coefficients can be determined without numerical problems using closed form equations instead of equations that must be evaluated by numerical integration

- There is no need to determine a global stiffness matrix for the soil since the flexibility matrix is generated every step in the iteration cycle

- Instead of determining flexibility coefficients due to pile-pile interaction from settlement equations, the coefficients are determined from the load-settlement relation according to DIN 4014 [5]

This case study shows that NPRD is not only an acceptable method to analyze piled raft but also a practical one for analyzing large piled raft problems. Beside that NPRD gives a good agreement with previous theoretical and empirical nonlinear analyses of piled raft, it takes less computational time compared with other complicated models using three dimension finite element analyses. As further comparative example to proof that an analysis of *Messeturm* using three dimensional finite element analysis after *Randolph* (1994) and *Reul/ Randolph* (2003) gave a settlement of 17.4 [cm] at the center while that of NPRD gave 18.77 [cm].

4.4 References

[1] *Amann, P./ Breth, H./ Stroh, D.* (1975): Verformungsverhalten des Baugrundes beim Baugrubenaushub und anschließendem Hochhausbau am Beispiel des Frankfurter Ton Mitteilungen der Versuchsanstalt für Bodenmechanik und Grundbau der Technischen Hochschule Darmstadt, Heft 15

[2] *Basile, F.* (1999): Non-Linear analysis of pile groups
Proc. Instn Civ. Engrs Geotech. Engng, 137, 105-115

[3] *Basile, F.* (2003): Analysis and design of pile groups
Numerical Analysis and Modelling in Geomechanics,
Spon press (eds J. W. Bull), London, Chapter 10, pp 278-315

[4] *Chow, H./ Small J.* (2005): Behaviour of Piled Rafts with Piles of Different Lengths and Diameters under Vertical Loading
GSP 132 Advanced in Deep Foundations, ASCE

[5] DIN 4014: Bohrpfähle Herstellung, Bemessung und Tragverhalten
Ausgabe März 1990

[6] *Duncan, J./ Chang, C.* (1970): Non-linear analysis of stress and strain in soils
Journal of Soil Mechanics and Foundation Engineering Division
Proceedings of the American Society of Civil Engineers, 96, No. SM5, pp. 1121-1124

[7] ECP 197: Egyptian Code for Soil Mechanics-Design and Construction of Foundations
Part 4, Deep Foundations (in Arabic) (1995)

[8] *El Gendy, M./ Hanisch, J./ Kany, M.* (2006): Empirische nichtlineare Berechnung von Kombinierten Pfahl-Plattengründungen
Bautechnik 9/06

[9] *Kany, M./ El Gendy, M./ El Gendy, A.* (2006): Benutzerhandbuch für das Programm *ELPLA* (eingebunden in das Programmsystem GEOTEC), Zirndorf

[10] *Katzenbach, R./ Arslan, U./ Moormann, C.* (2000): Piled raft foundation projects in Germany
Chapter 13 in: Design application of raft foundations
Edited by Hemsley, Thomas Telford

[11] *Mandolini, A./ Viggiani, C.* (1997).: Settlement of piled foundations
Géotechnique, 47, No. 4, 791-816

[12] *Mindlin, R.* (1936): Force at a point in the interior of a semi-infinite-solid
Physics 7, S. 195-202

[13] *EL-Mossallamy, Y.* (1996): Ein Berechnungsmodell zum Tragverhalten der Kombinierten Pfahl-Plattengründung
Dissertation, Technische Hochschule Darmstadt, Darmstadt, D17

[14] *Poulos, H./ Davis, E.* (1980): Pile Foundation Analysis and Design
John Wiley & Sons, Inc.

[15] *Randolph, M.F.* (1994): Design methods for pile groups and pile rafts
XXX ICSMFE New Dehli, India, Rotterdam Balkema Vol. 4, S. 61-82

[16] *Reul, O./ Randolph, M.F.* (2003): Piled rafts in overconsolidated clay: comparison of in situ measurements and numerical analyses
Géotechnique 53, No. 3, 301-315

[17] *Russo, G.* (1998): Numerical analysis of piled raft
Int. J. Numer. Anal. Meth. Geomech., 22, 477-493

[18] *Sommer, H.* (1989): Entwicklung der Hochhausgründungen in Frankfurt/ Main
Festkolloquium 1989, 20 Jahre Grundbauinstitut, Darmstadt

[19] *Sommer, H./ Katzenbach, R.* (1990): Last-Verformungsverhalten des Messeturmes Frankfurt/ Main
Vorträge der Baugrundtagung 1990 in Karlsruhe, Seite 371-380

[20] *Sommer, H./ Tamaro, G./ DeBenedittis, C.* (1991): Messe Turm, foundation for the tallest building in Europe
4th International Conference on Piling and Deep Foundations, Italy, 139-145

[21] *Thaher, M.* (1991): Tragverhalten von Pfahl-Platten-Gründungen im bindigen Baugrund, Berechnungsmodelle und Zentrifugen-Modellversuche
Dissertation, Institut für Grundbau der Ruhr-Universität, Bochum, Heft 15

[22] *Viggiani, C.* (1998): Pile groups and pile raft behaviour
Proc. of the 3rd int. Geot. Sem. on Deep Foundations on Bored and Auger Piles
Ghent, Belgien 19.-21- Oct.
Balkema Rotterdam, S. 77-91

[23] *Witzel, M./ Kempfert, H. G.* (2005): A simple approach to predict the load settlement behavior of precast driven piles with due consideration of the driving process
GSP 132 Advanced in Deep Foundations, Proceeding of Sessions of the Geo-Frontiers Congress, Austin, Texas, ASCE

[24] Richtlinie für den Entwurf, die Bemessung und den Bau von Kombinierten Pfahl-Plattengründungen (KPP) - (KPP-Richtlinie)
Hrg.: Arbeitskreis "Pfähle" der Deutschen Gesellschaft für Geotechnik e.V., Juli 2001

Enthalten in: Kombinierte Pfahl-Plattengründungen
Hrg.: *Hanisch, J./ Katzenbach, R./ König, G.* (2002)
Ernst & Sohn