Case study 8

Analysis of Piled Raft of *Shanghai* Tower in Shanghai by the Program *ELPLA*

M. El Gendy
A. El Gendy
O. El Gendy

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

22-11-2018

Content

Page

8 Case study 8: *Shanghai* Tower piled raft 3

8.1 General 3

8.2 Analysis of the piled raft 5

8.3 FE-Net 5

8.4 Loads 6

8.5 Pile and raft material 7

8.6 Load settlement curve 8

8.7 Soil properties 8

8.8 Results 11

8.9 Measurements and other results 16

8.9.1 Measured settlement 16

8.9.2 Calculated final settlement 16

8.10 Conclusion 16

8.11 References 17

8 Case study 8: *Shanghai* Tower piled raft

8.1 General

The *Shanghai* Tower is a mega tall skyscraper in Lujiazui, Pudong, Shanghai, Figure 8-1. It is considered the second-tallest building in the world after *Burj Khalifa*. The height of the tower is 632 meters. It consists of a 124-storey tower, a 7-storey podium and a 5-storey basement.

The tower has a 5-storey basement, and its foundation depth is 31.4 [m]. The thickness of the raft under the tower is 6 [m] and the area of the raft is 8945 [m^2]. The raft of *Shanghai* tower is supported by 955 bored piles with a diameter 1.0 [m]. The spacing between the piles is 3 [m] and the piles are distributed in different foundation arrangements where the entire raft area is divided into four sub areas *A*, *B*, *C* and *D* as shown in Figure 8-2. The length of the pile in area *A* is 56 [m], while the length of the pile in other zones is 52 [m].

Extensive studies with different calculation methods were carried out by *Sun etc. al.* (2011), *Xiao etc. Al.* (2011), *Tang* and *Zhao* (2014), (2014), *Su etc. al.* (2013), (2014) and *Zhao, X.* and *Liu, S.* (2017).

Figure 8-1 *Shanghai* Tower [1]

[1] https://upload.wikimedia.org/wikipedia/commons/3/32/Shanghai_Tower_2015.jpg

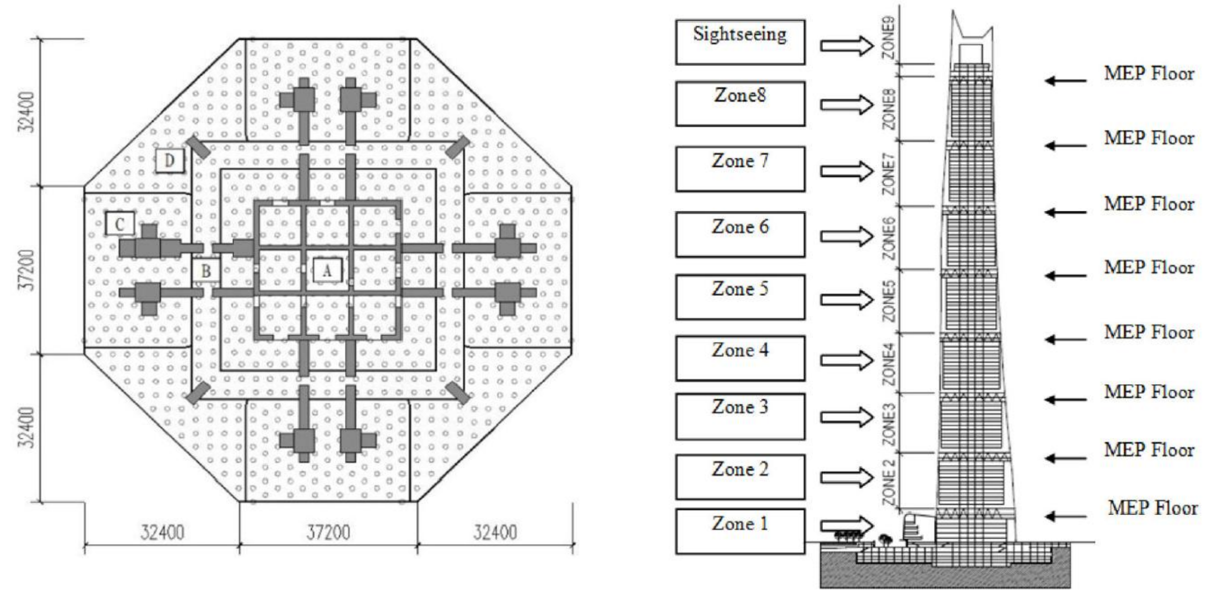

Figure 8-2 *Shanghai* Tower Foundation system and vertical zoning of the Tower (*Zhao, X.* and *Liu, S.* (2017))

8.2 Analysis of the piled raft

Using the available data and results of the *Shanghai* piled raft, which have been discussed in detail in the references, the nonlinear analysis of piled raft in *ELPLA* according to *El Gendy et al.* (2006) and *El Gendy* (2007) is evaluated and verified using the load-settlement relation of piles from the pile load test given by *Xiao etc. Al.* (2011).

For simplicity, the piled raft is considered double symmetric and only a quarter of the foundation system is analyzed. The foundation system is analyzed as an elastic raft supported on unequal rigid piles.

8.3 FE-Net

The raft is divided into triangular elements with a maximum length of 1.5 [m] as shown in Figure 8-3. Piles are divided into five elements with 14 [m] length.

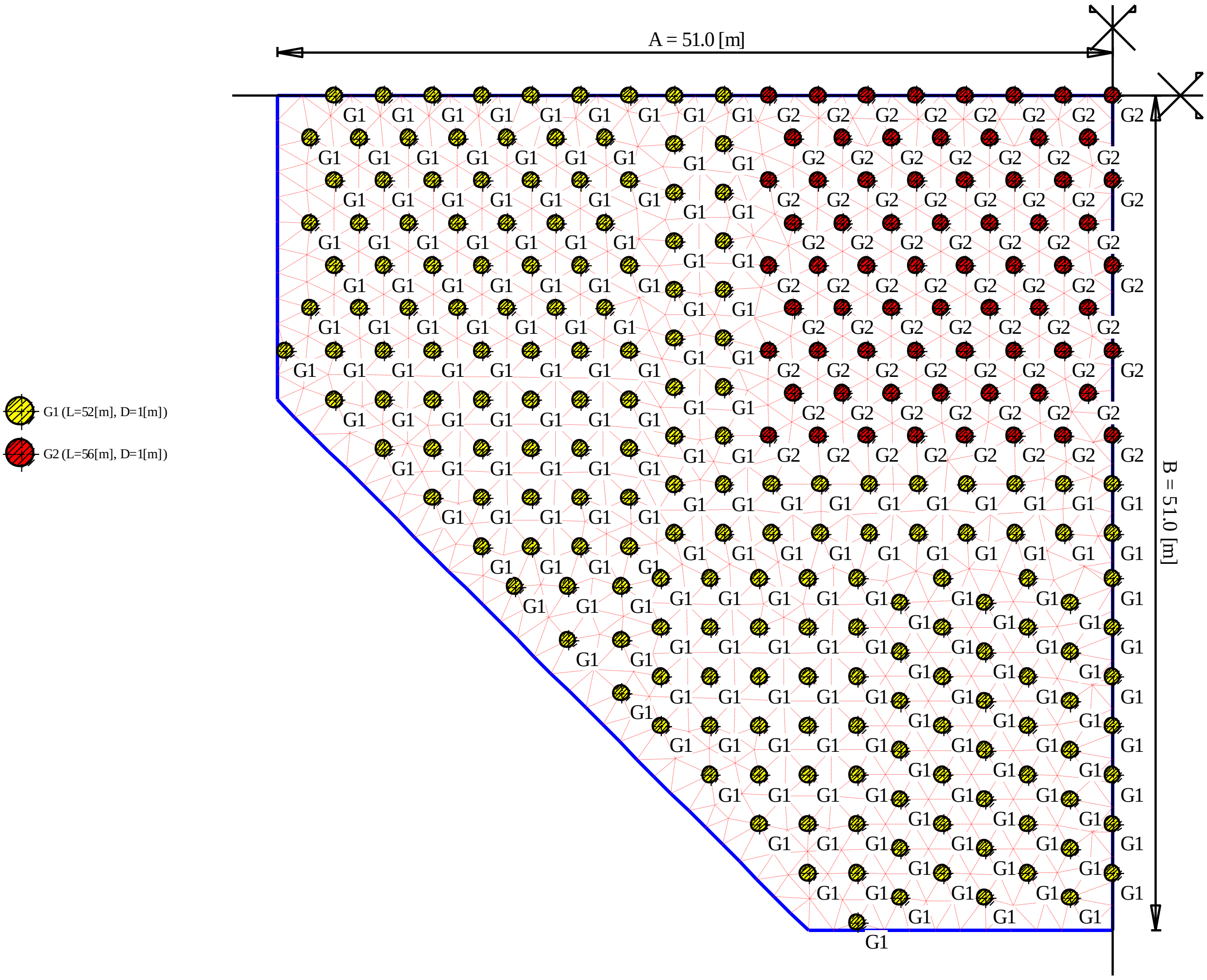

Figure 8-3 FE-mesh of *Shanghai* tower piled raft with piles

8.4 Loads

According to *Tang* and *Zhao* (2014), the tower foundation carries a total dead and live loads of 6710 [MN] and 963 [MN], respectively. The total vertical load used in calculating the settlement is 7672 [MN]. The column and wall sections and loads are listed in Table 8-1The system of loading acting on the piled raft is shown in Figure 8-4.

Table 8-1 Section and load of columns and walls

	Section	Average load [MN]	Distributed load [MPa]
Horizontal super columns	5.3×3.7[m]	4×450.16	22.96
Vertical super columns	3.7×5.3[m]	4×461.75	23.55
Diagonal columns	5.5×2.4[m]	4×231.22	17.52
Core walls	t_{flange} = 1.2[m], t_{web} = 0.9[m]	3099.87	16.50

Total load		7672.387	

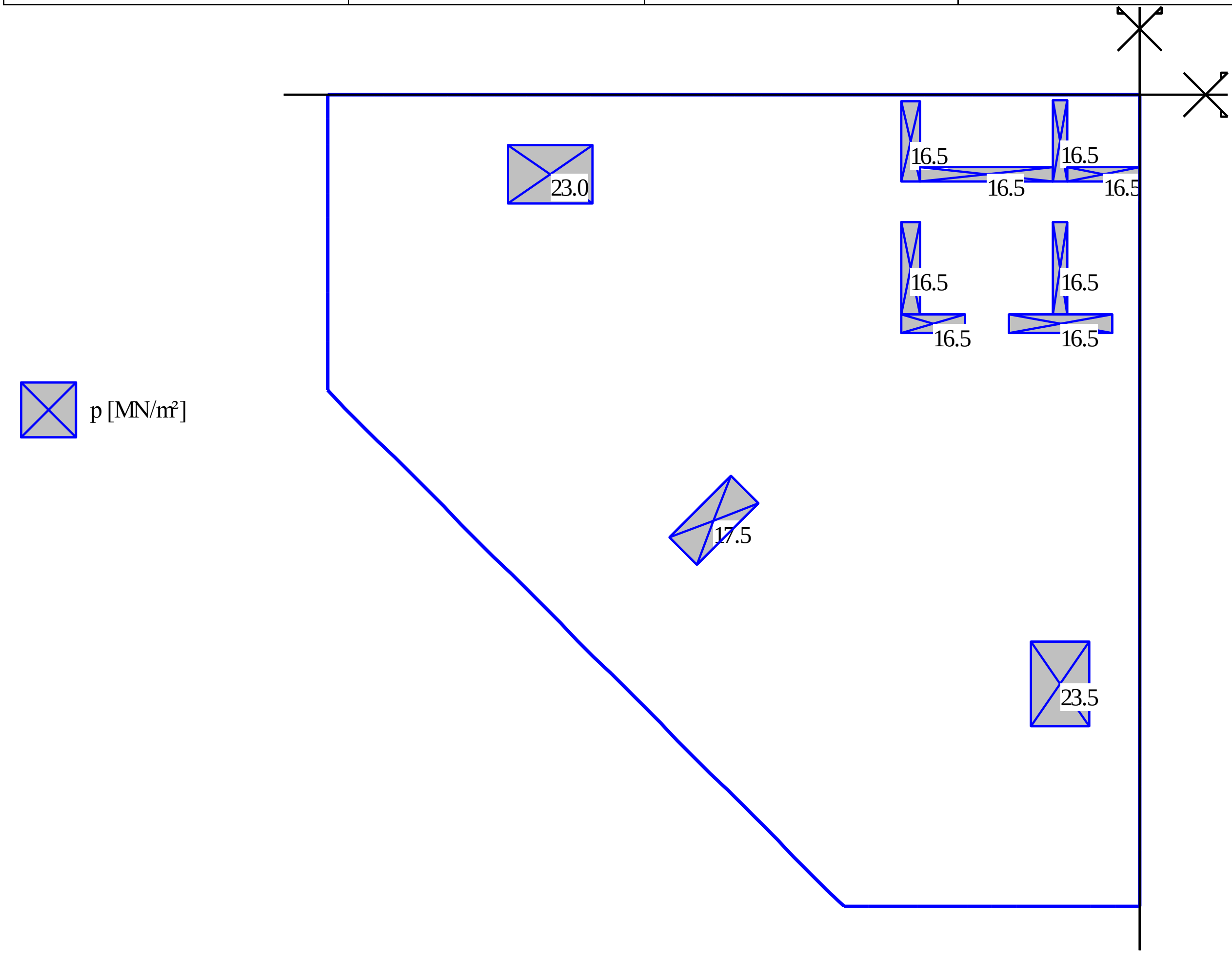

Figure 8-4 System of loading acting on the piled raft

8.5 Pile and raft material

The concrete grade of the raft and piles is C50. The following values were used as pile and raft material:

Modulus of elasticity	E_p	=	33234	[MN/m^2]
Poisson's ratio	v_p	=	0.167	[-]
Unit weight	γ_b	=	23.60	[kN/m^3]

8.6 Load settlement curve

Figure 8-5 shows the load-settlement relation resulted from the pile load test given by *Xiao etc. Al.* (2011).

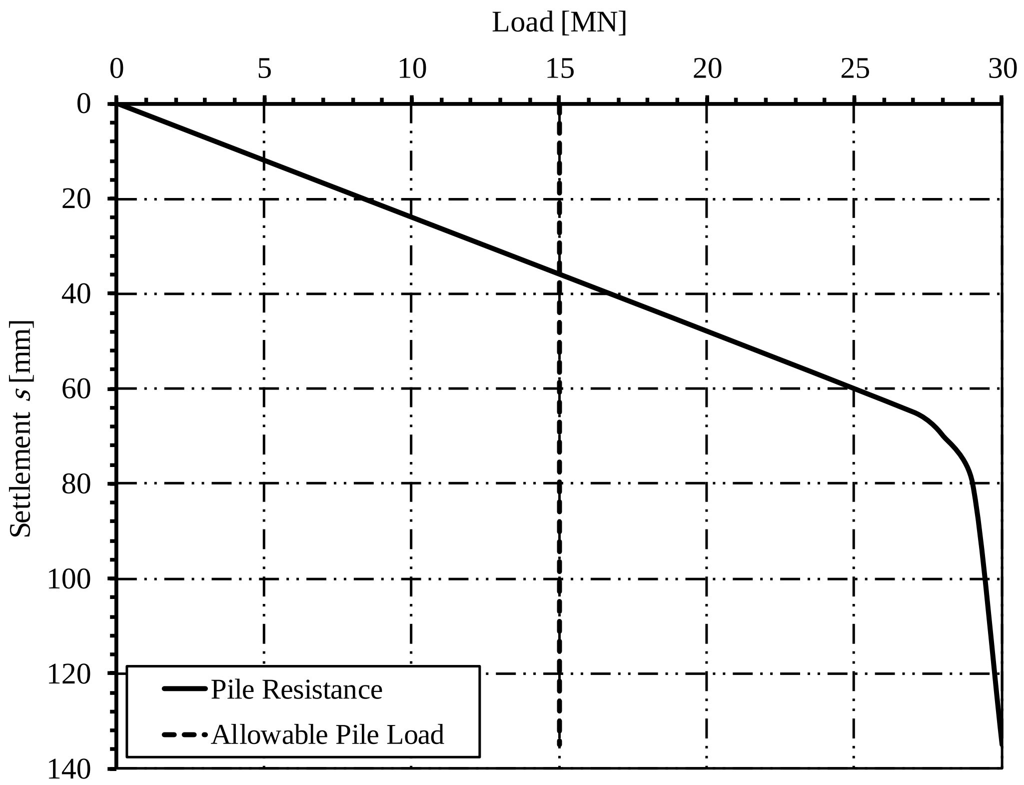

Figure 8-5 Load-settlement relation from pile load test

8.7 Soil properties

The site for the *Shanghai* Tower is in the new *Pudong* development district of Shanghai. The groundwater level is about 0.5~1.5 [m] below ground level. The foundation depth of the tower is 31.4 [m] below ground level.

Geotechnical investigation indicates that the ground conditions comprise horizontally stratified subsurface profile which is complex and highly variable. The subsoil below the ground level is composed of clay, silty clay and sand, underlain by a completely decomposed granite. According to the soil type and physical properties, the subsoil is divided into nine layers and fourteen sub-layers. The top layer is the bearing layer for shallow foundation while the fifth, seventh and ninth layers are the end-bearing layers for piles.

The soil profile and geotechnical parameters are summarized in Table 8-2. The subsoil layer under the raft up to 105 [m] deep are indicated in the boring log shown in Figure 8-6.

Table 8-2 Summary of geotechnical profile and parameters

Strata	Sub-strata	Subsurface Material	Level at top of stratum z [m]	Modulus of compressibility E_s [MPa]	Bulk Density γ_{Bulk} [kN/m^3]
1		Fill	4.5	0	
2		Plastic to soft-plastic silty clay	2.7	3.97	18.4
3		Flow plastic muddy silty clay interspersed with sandy silt	1.5	3.84	17.7
4		Flow plastic muddy clay	-3.0	2.27	16.7
5	1-a	Soft plastic clay	-11.5	3.56	17.6
	1-b	Soft plastic to plastic silty clay	-15.5	5.29	18.4
6		Hard plastic clay	-20.0	6.96	19.8
7	1	Medium dense to dense silty sand with sandy silt	-24.0	11.45	18.7
	2	Dense silty sand	-30.8	75	19.2
	3	Dense silty sand with sandy silt and clay	-59.1	60	19.1
8		absent			
9	1	Dense sandy silt	-63.4	70	19.1
	2-1	Dense silty sand with coarse and gravelly sand and clay	-71.7	80	20.2
	2t	Hard plastic to plastic silty clay with clayed silt	-82.7	35	20.0
	2-2	Dense silty sand with fine sand and sandy silt	-84.0	85	19.3
	3	Dense fine sand	-96.0	90	19.7
	3t	Hard plastic to plastic silty clay with clayed silt	-100.5	35	19.1

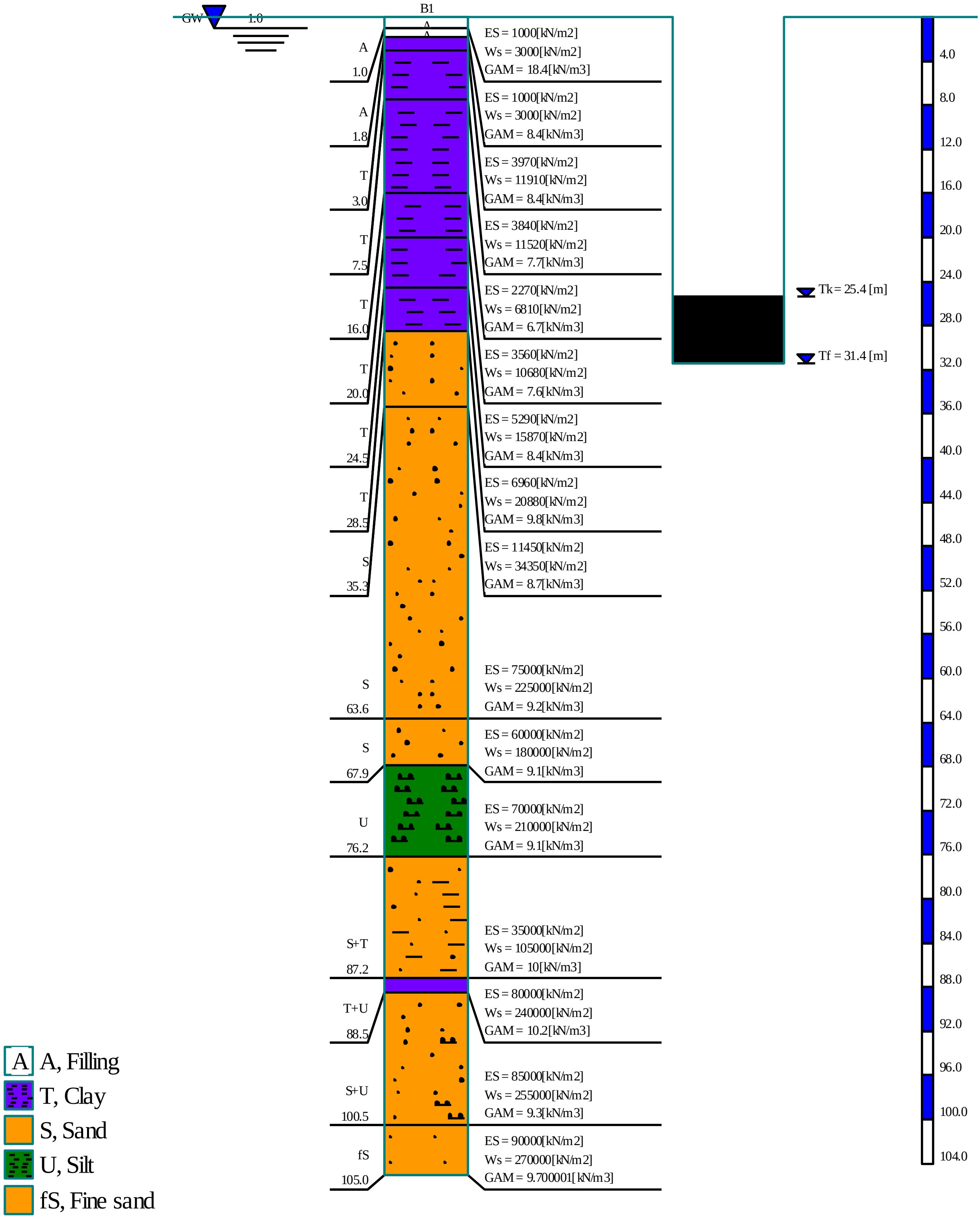

Figure 8-6 Boring log used in *ELPLA* analysis

8.8 Results

Figure 8-7 to Figure 8-11 show the settlement and pile reactions for the piled raft analyzed using the "Given load-settlement curve from pile load test" method.

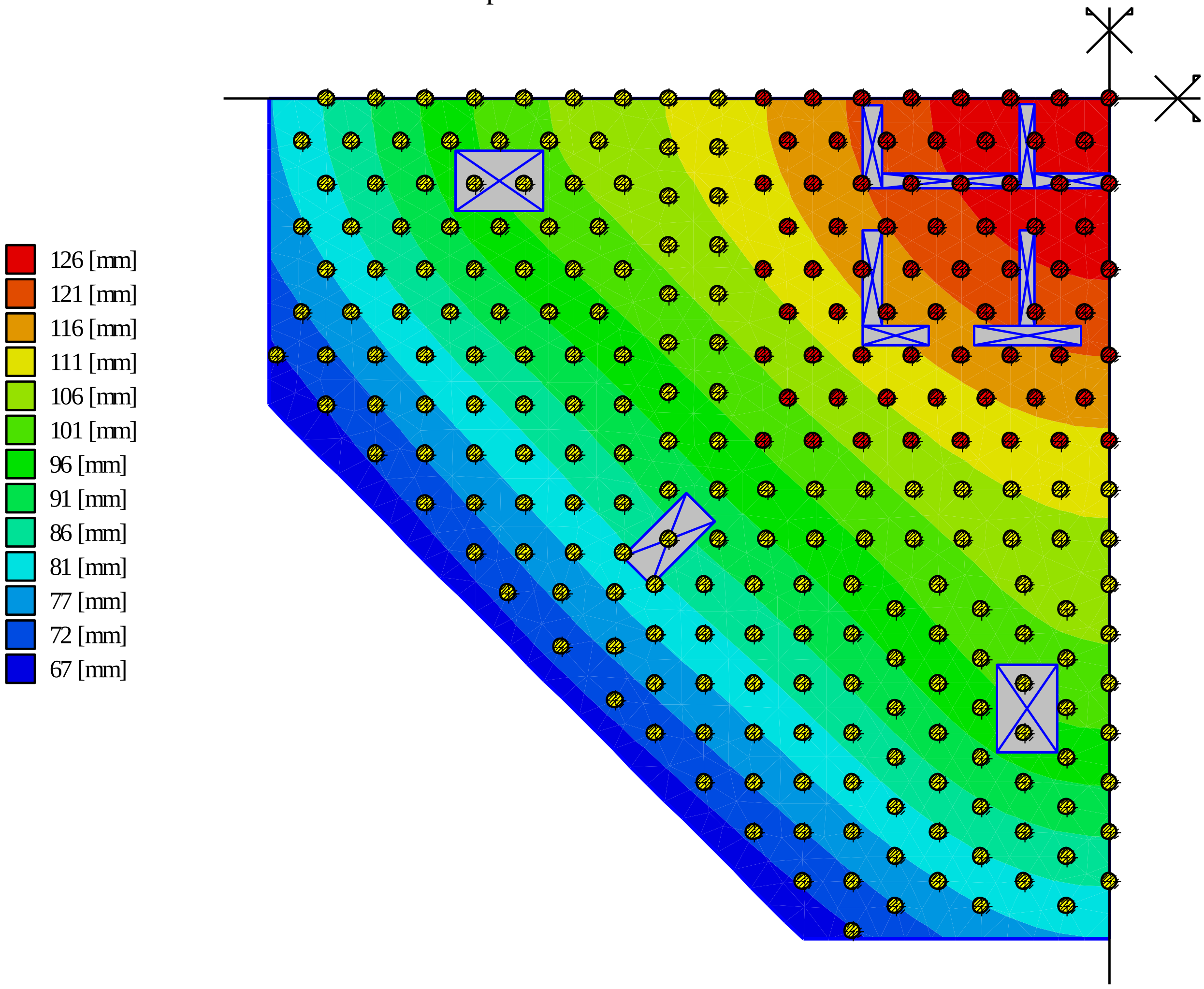

Figure 8-7 Settlement under the piled raft

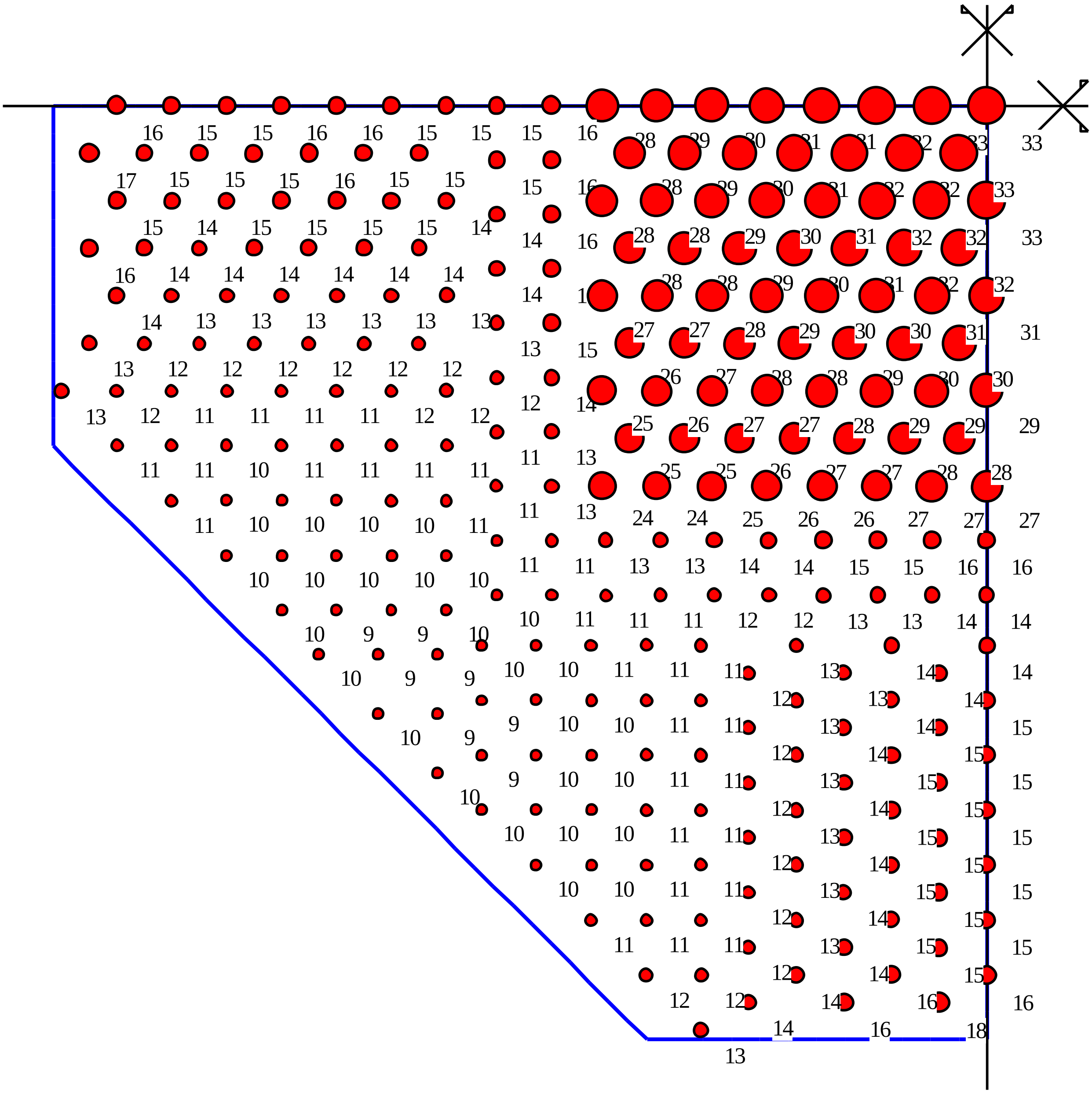

Figure 8-8 Self settlement of piles S_v [mm]

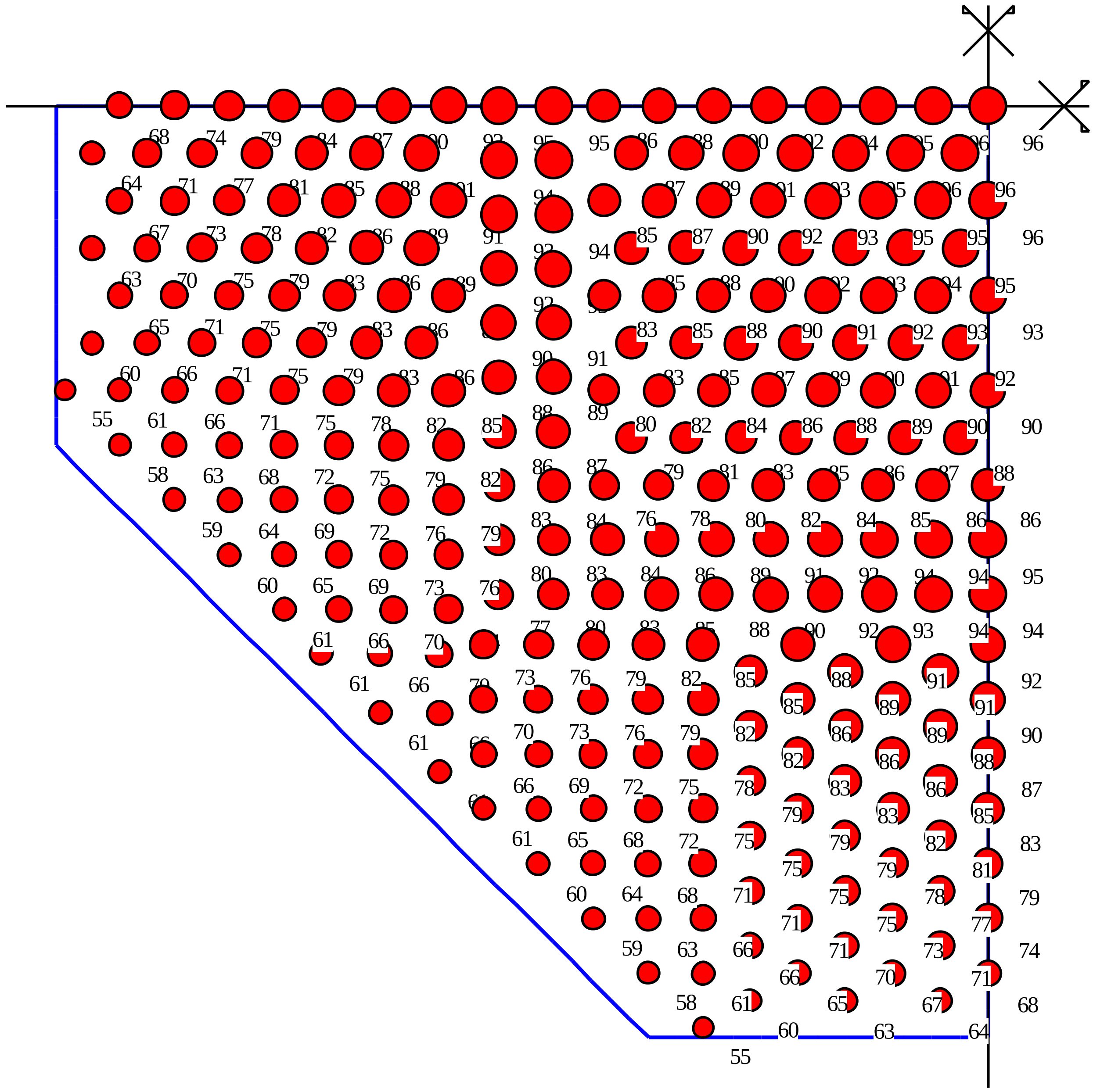

Figure 8-9 Interaction settlement of piles S_{rv} [mm]

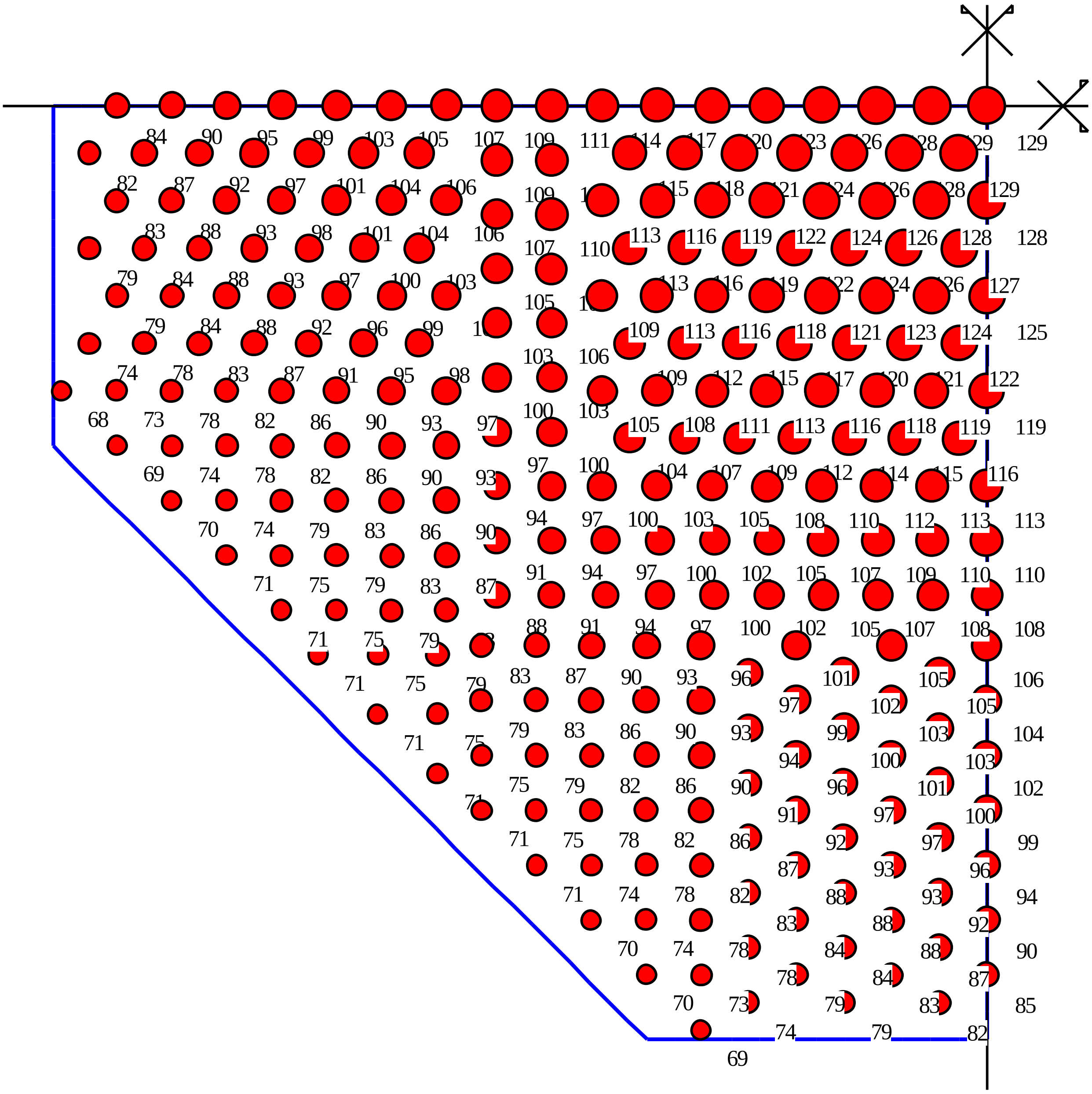

Figure 8-10 Total settlement of piles S_r [mm]

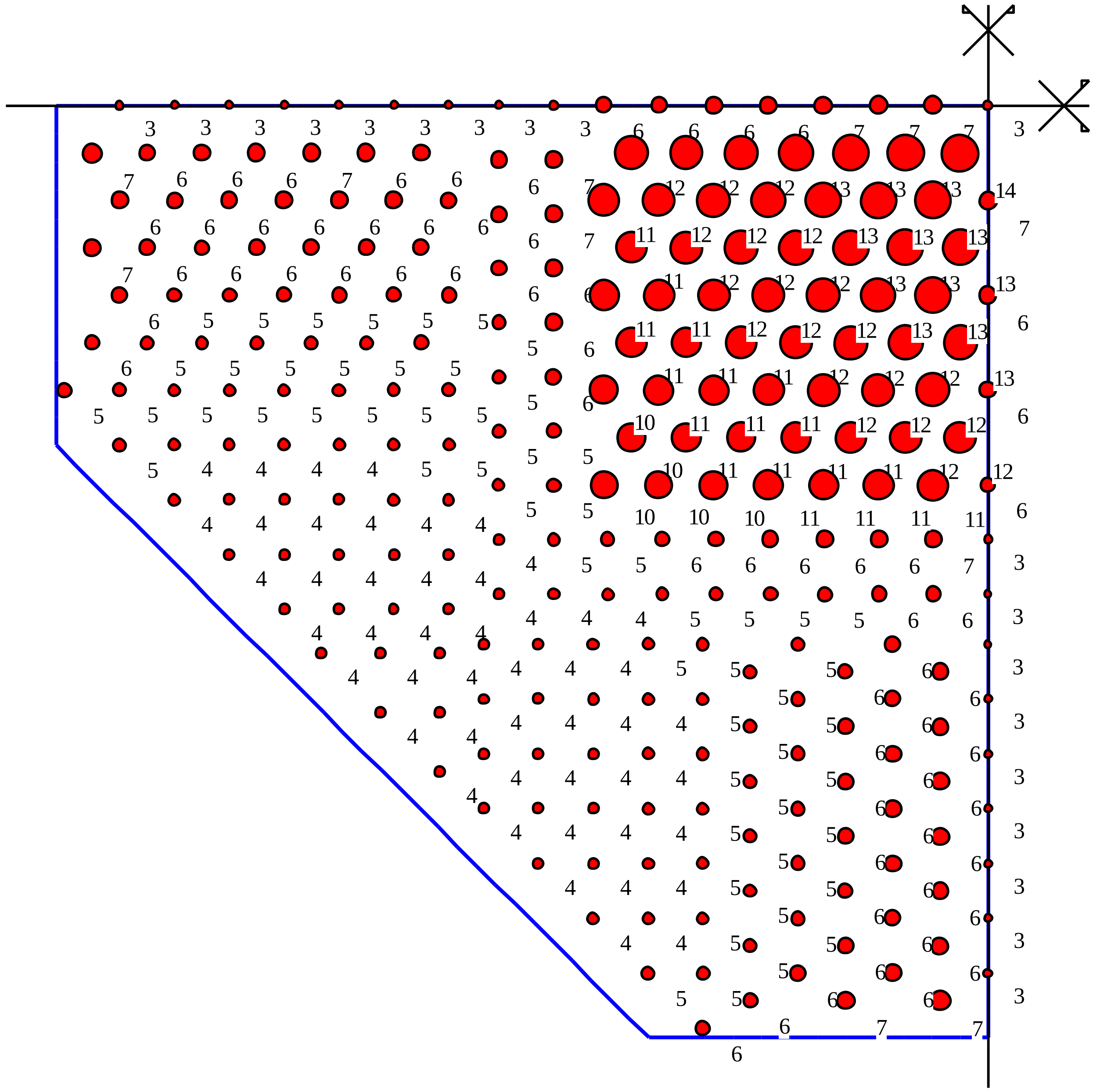

Figure 8-11   Pile reactions [MN]

8.9 Measurements and other results

8.9.1 Measured settlement

The construction of *Shanghai* started 29 November 2008 and finished on 6 September 2014. According to *Su etc. al.* (2014), the settlement of the core and mega columns reached 60 and 45 [mm], respectively; on 30 April 2013 under nearly 75% of the building load. As expected, these values are less than the computed values because it doesn't consider the long term settlement due to the consolidation of the clay layers. The soil below the tower will continue to consolidate until reaching the final settlement therefore calculation methods need to take consolidation effect into account.

8.9.2 Calculated final settlement

Several analyses were used to assess the response of the foundation for the *Shanghai* Tower. According to *Sun etc. al.* (2011), the computed values of maximum settlement ranges between 101 and 143 [mm].

A comparison between the computed settlement obtained by *ELPLA* and that obtained by other methods is presented in Table 8-3.

Table 8-3 Comparison between *ELPLA* results and those of other methods

Method	$S_{max.}$ [mm]	$S_{min.}$ [mm]	$S_{Diff.}$ [mm]
ELPLA	129	64	65
Xiao etc. al. (2011) - Computed	143	44	99
Xiao etc. al. (2011) - Predicted	112	68	44
Tang and Zhao (2014) - Hybrid Method	107	90	17
Tang and Zhao (2014) - Empirical Formula	121	-	-
Tang and Zhao (2014) - Predicted Method	>120	-	-
Sun etc. al. (2011) - Computed	101	37	64

8.10 Conclusion

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

8.11 References

[1] *El Gendy, M.* (2007): Formulation of a composed coefficient technique for analyzing large piled raft. Scientific Bulletin, Faculty of Engineering, Ain Shams University, Cairo, Egypt. Vol. 42, No. 1, March 2007, pp. 29-56

[2] *El Gendy, M./ El Gendy, A.* (2018): Analysis of raft and piled raft by Program *ELPLA* GEOTEC Software Inc., Calgary AB, Canada.

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

[4] *Su, J./ Xia, Y./ Xu, Y./ Zhao, X./ Zhang, Q*. (2014): Settlement Monitoring of a Supertall Building Using the Kalman Filtering Technique and Forward Construction Stage Analysis. Advances in Structural Engineering Vol. 17 No. 6 2014.

[5] *Su, J.Z./ Xia, Y./ Chen, L./ Zhao, X./ Zhang, Q.L./ Xu, Y.L./ Ding, J.M./ Xiong, H.B./ Ma, R.J./ Lv, X.L./ Chen, A.R.* (2013): Long-term structural performance monitoring system for the Shanghai Tower. Journal of Civil Structural Health Monitoring, Vol. 3, No. 1, pp. 49–61.

[6] *Sun, H.H./ Zhao, X./ Li, X.P./ Ding, J.M./ Zhou, Y.* (2011): Performance analysis of basement fin wall of the Shanghai tower based on the interaction between pile-raft foundation and superstructure. Procedia Engineering, Vol. 14, pp. 1367–1375.

[7] *Tang, Y. J/ Zhao, X. H.* (2014): 121-story Shanghai Center Tower foundation re-analysis using a compensated pile foundation theory. Structural Design of Tall and Special Buildings 23: 854–879.

[8] *Tang, Y. J/ Zhao, X. H.* (2014): Deformation of compensated piled raft foundations with deep embedment in super-tall buildings of Shanghai. Struct. Design Tall Spec. Build. (2014).

[9] *Xiao, J. H/ Chao, S./ Zhao, X.H.* (2011): Foundation design for Shanghai Center Tower. Advanced Materials Research 248–249: 2802–2810.

[10] *Zhao, X./ Liu, S.* (2017): Foundation Differential Settlement Included Time-dependent Elevation Control for Super Tall Structures. International Journal of High-Rise Buildings March 2017, Vol 6, No 1, 83-89.