Case study 7

Analysis of Piled raft of *Burj Khalifa* in Dubai by the program *ELPLA*

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Content

7 Case study 7: *Burj Khalifa* piled raft

7.1 General

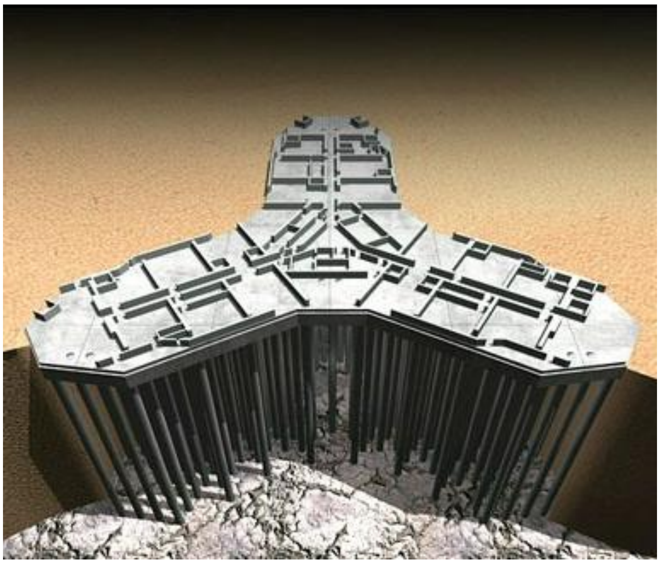
Burj Khalifa is a 163-storey skyscraper in Dubai, United Arab Emirates. The total height of the building is 829.8 [m], with a podium development at its base, including a 4 to 6-story garage. With a total height of 829.8 [m] and a roof height (excluding antenna) of 828 [m], *Burj Khalifa* has been the tallest structure and building in the world since its topping out in late 2008, Figure 7-1.

The *Burj Khalifa* is located on a 42 000 [m^2] site. The tower is founded on a 3.7 [m] thick raft supported on 192 bored piles, 1.5 [m] in diameter, extending 47.45 [m] below the base of the raft; podium structures are founded on a 0.65 [m] thick raft (increased to 1 [m] at column locations) supported on 750 bored piles, 0.9 [m] in diameter, extending 30–35 [m] below the base of the raft. The tower raft consists of three wings each is 50 [m] long and 25 [m] wide forming an area of 3305 [m^2]. Figure 7-2 shows an isometric view of *Burj Khalifa* Tower foundation system and a plan for pile locations.

Extensive studies using different calculation methods were carried out by *Poulos* and *Bunce* (2008), *Badelow & Poulos* (2016) and *Russo etc. al.* (2013).

Figure 7-1   Burj Khalifa [1]

[1] https:// tadalafilforsale.net/group/burj-khalifa-images/#photo_27



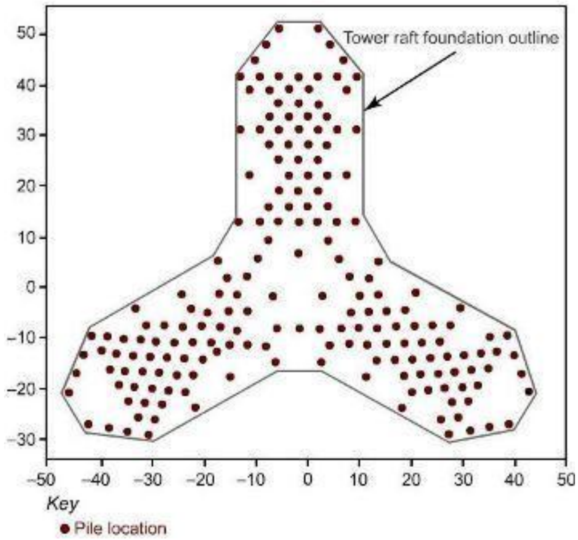


Figure 7-2 *Burj Khalifa* Tower Foundation system

7.2 Analysis of the piled raft

Using the available data and results of the *Burj Khalifa* piled raft, which have been discussed in detail in the previous references, 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 for Load-Settlement Curve.
2- Given Load-Settlement Curve.

The foundation system is analyzed as an elastic piled raft in which the raft is considered as an elastic plate supported on equal 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*.

7.3 FE-Net

The raft is divided into triangular elements with a maximum length of 2.0 [m] as shown in Figure 7-3. Piles are divided into five elements with 9.49 [m] length.

7.4 Loads

Only long-term conditions have been considered, and for most of the early analyses, an average load per pile of 23.21 [MN] has been used (this is a representative of the design dead and live loads) and has been applied as an uniformly distributed load on the tower raft of about 1250 [kPa].

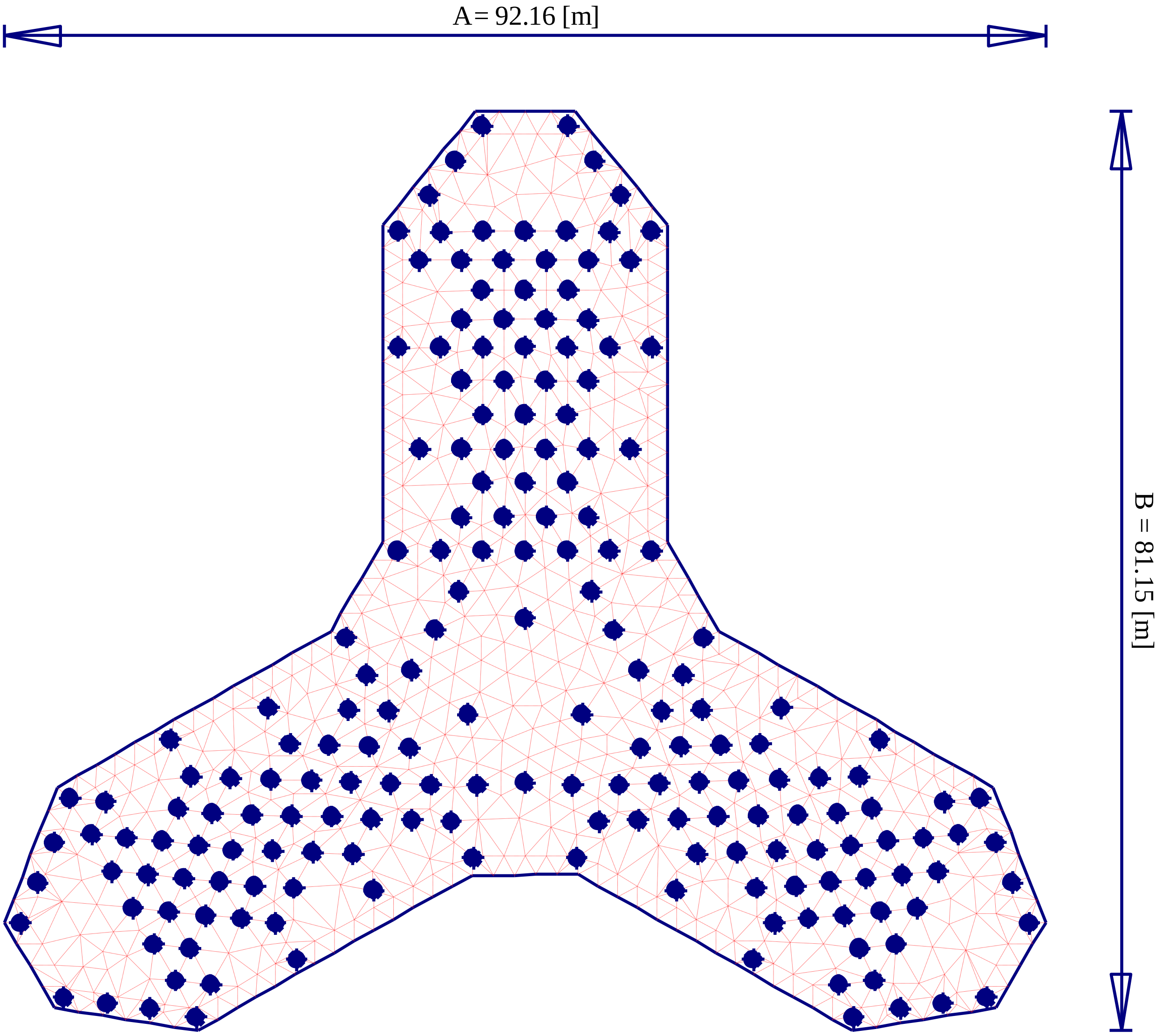


Figure 7-3 Mesh of *Burj Khalifa* piled raft with piles of element length = 2.0 [m]

7.5 Pile and raft material

The raft is 3.7 [m] thick and was poured utilizing C50 (cube strength) self-consolidating concrete. The Tower raft is supported by 192 bored cast-in-place piles. The C60 self-consolidating concrete piles are 1.5 [m] in diameter and 47.45 [m] long.
The following values were used as pile and raft material:

For the raft:

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

For piles:

Modulus of elasticity	E_p	=	36406	[MN/m^2]
Unit weight	γ_b	=	23.60	[kN/m^3]

7.6 Soil properties

The ground conditions comprise a horizontally stratified subsurface profile which is complex and highly variable, due to the nature of deposition and the prevalent hot arid climatic conditions. Medium dense to very loose granular silty sands (Marine Deposits) are underlain by successions of very weak to weak sandstone interbedded with very weakly cemented sand, gypsiferous fine grained sandstone/siltstone and weak to moderately weak conglomerate/calcisiltite.

Groundwater levels are generally high across the site and excavations were likely to encounter groundwater at approximately 2.5 [m] below ground level.

The drilling was carried out using cable percussion techniques with follow-on rotary drilling methods to depths between 30 [m] and 140 [m] below ground level.

The ground profile and derived geotechnical design parameters assessed from the investigation data are summarized in Table 7-1.

Table 7-1 Summary of Geotechnical Profile and Parameters

Strata	Sub-Strata	Subsurface Material	Level at top of stratum [m DMD]	Thickness H [m]	UCS q_s [MPa]	Undrained Modulus E_u [MPa]	Ult. Comp. Shaft Frict. f_s [kPa]
1	1a	Medium dense silty Sand	+2.50	1.50	-	34.5	-
	1b	Loose to very loose silty Sand	+1.00	2.20	-	11.5	-
2	2	Very weak to moderately weak Calcarenite	-1.20	6.10	2.0	500	350
3	3a	Medium dense to very dense Sand/ Silt with frequent sandstone bands	-7.30	6.20	-	50	250
	3b	Very weak to weak Calcareous Sandstone	-13.50	7.50	1.0	250	250
	3c	Very weak to weak Calcareous Sandstone	-21.00	3.00	1.0	140	250
4	4	Very weak to weak gypsiferous Sandstone/ calcareous Sandstone	-24.00	4.50	2.0	140	250
5	5a	Very weak to moderately weak Calcisiltite/ Conglomeritic Calcisiltite	-28.50	21.50	1.30	310	285
	5b	Very weak to moderately weak Calcisiltite/ Conglomeritic Calcisiltite	-50.00	18.50	1.70	405	325
6	6	Very weak to weak Calcareous/ Conglomerate strata	-68.50	22.50	2.50	560	400
7	7	Weak to moderately weak Claystone/ Siltstone	-91.00	>46.79	1.70	405	325

To carry out the analysis, the subsoil under the raft is considered as indicated in the boring log of Figure 7-4 that consists of 12 soil layers. The total depth under the ground surface is taken to be 140 [m].

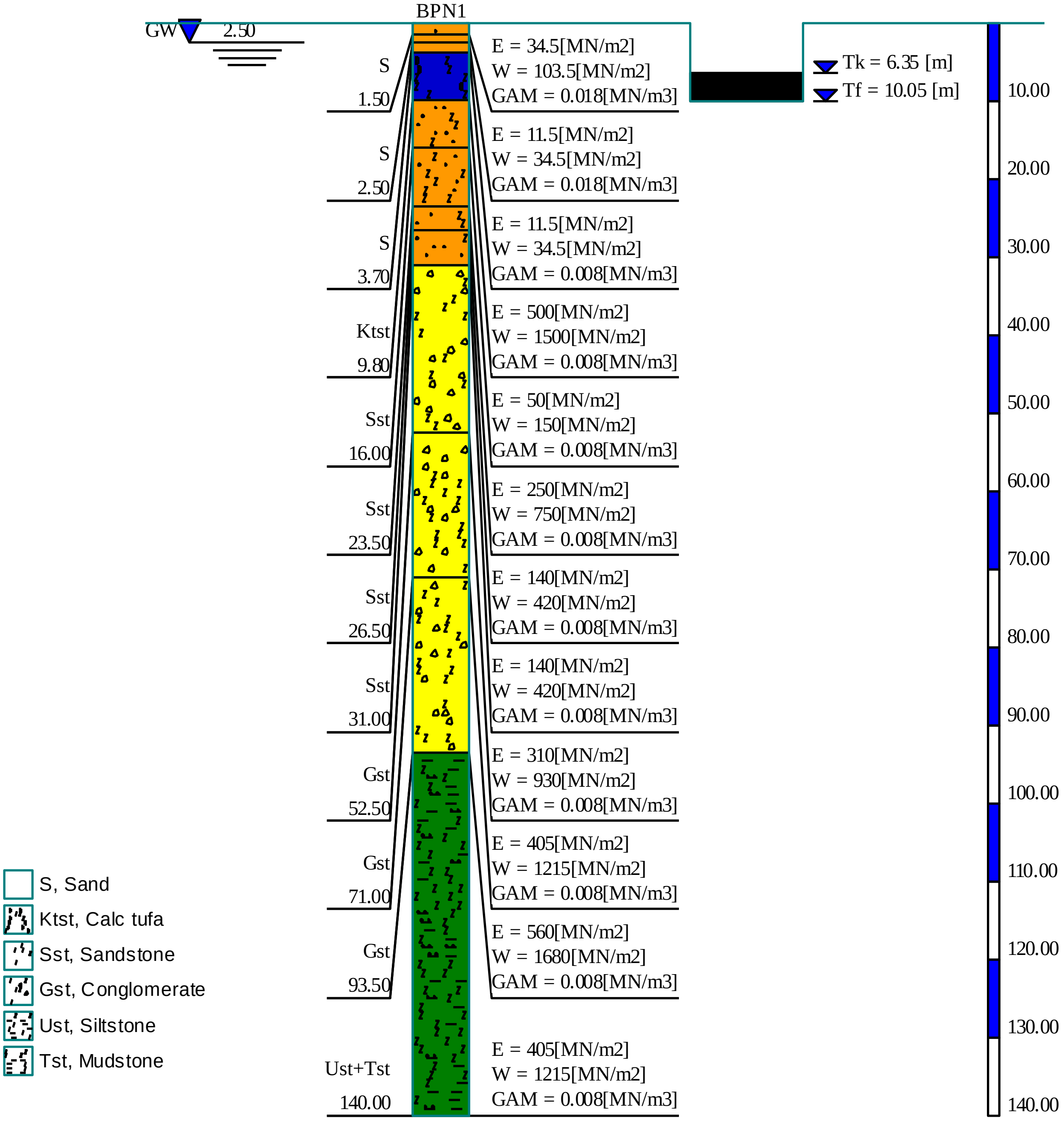


Figure 7-4 Boring log

Figure 7-5 to Figure 7-6 show load-settlement relations for the different analyses.

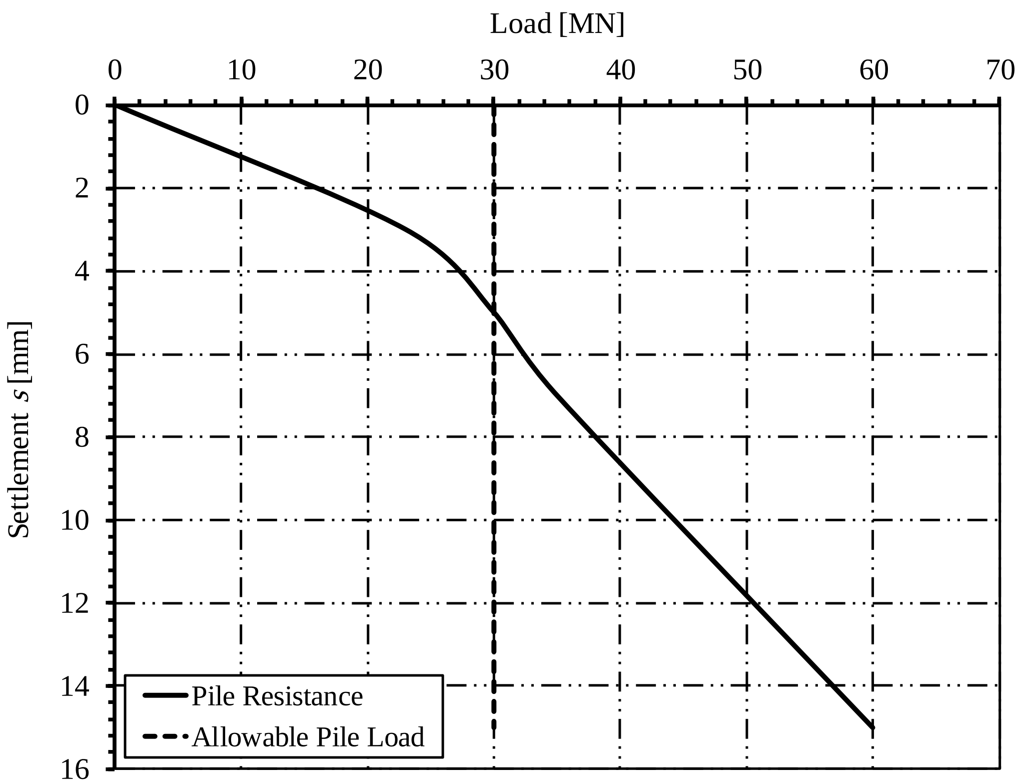


Figure 7-5 Load-settlement relation from pile load test

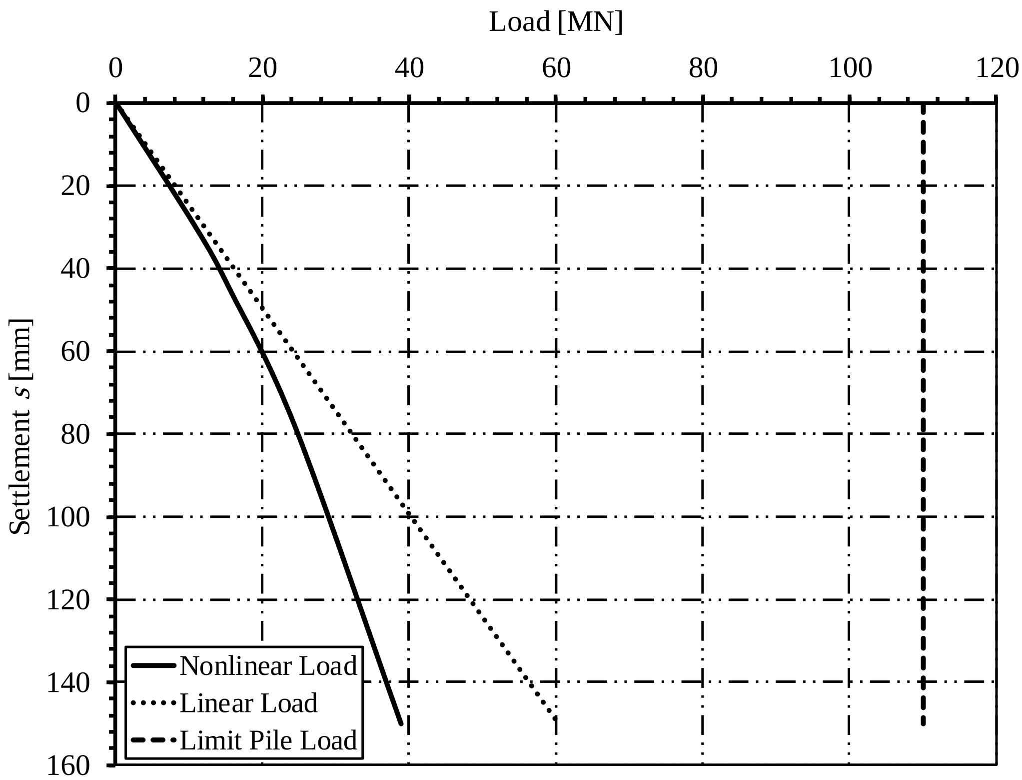


Figure 7-6 Load-settlement relation according to a hyperbolic function

7.7 Results

As examples for results of different analyses by *ELPLA*, Figure 7-8 and Figure 7-7 show the settlement for elastic piled raft of *Burj Khalifa* using methods: "Hyperbolic Function for Load-Settlement Curve" and "Given Load-Settlement Curve from pile-load test", respectively. Besides, Figure 7-9, Figure 7-10 and Figure 7-11 show self-settlement S_v, interaction settlement S_{rv} and total settlement S_r of piles using the method "Given Load-Settlement Curve from pile-load test".

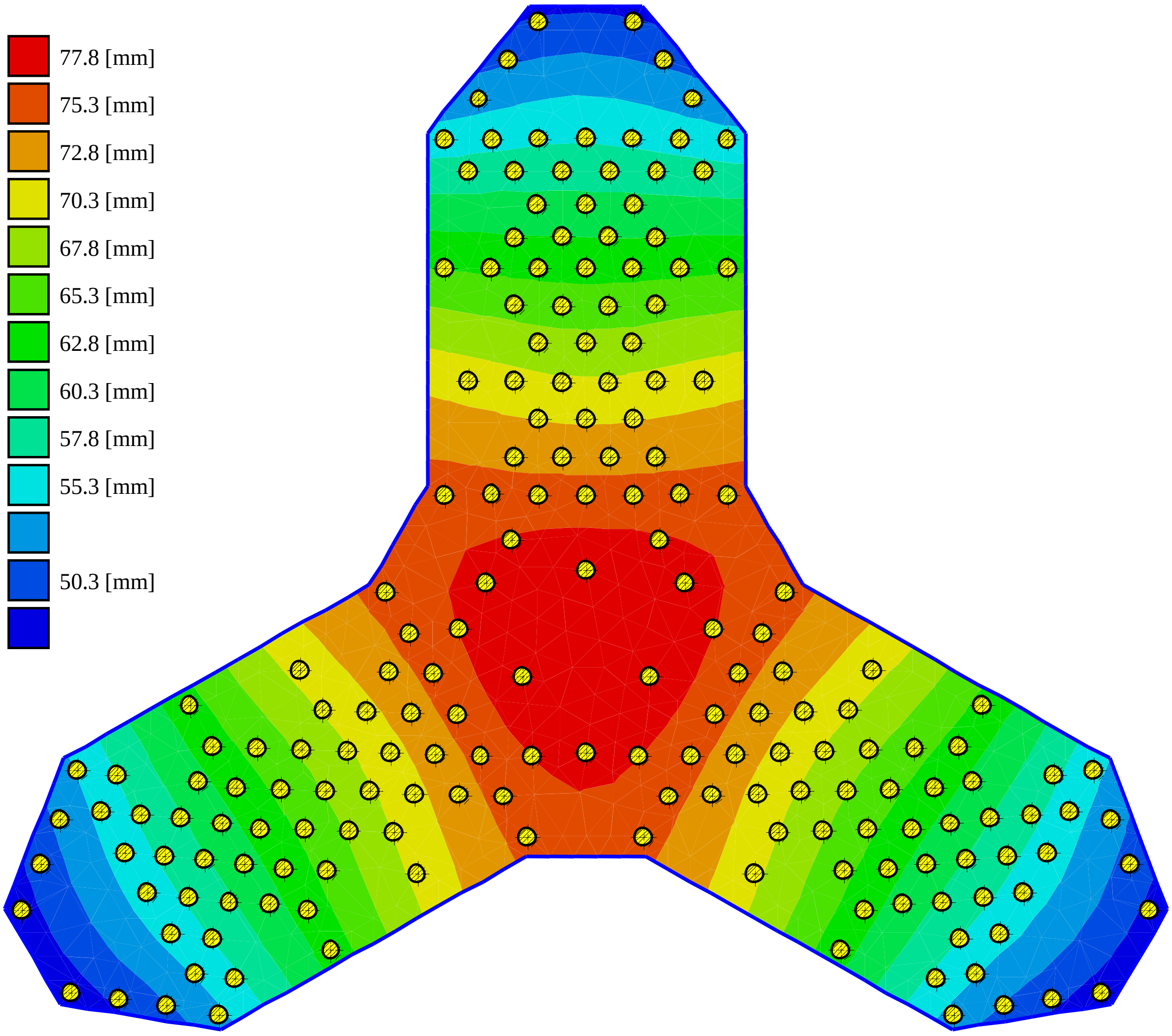


Figure 7-7 Settlement using the method "Hyperbolic Function for Load-Settlement Curve"

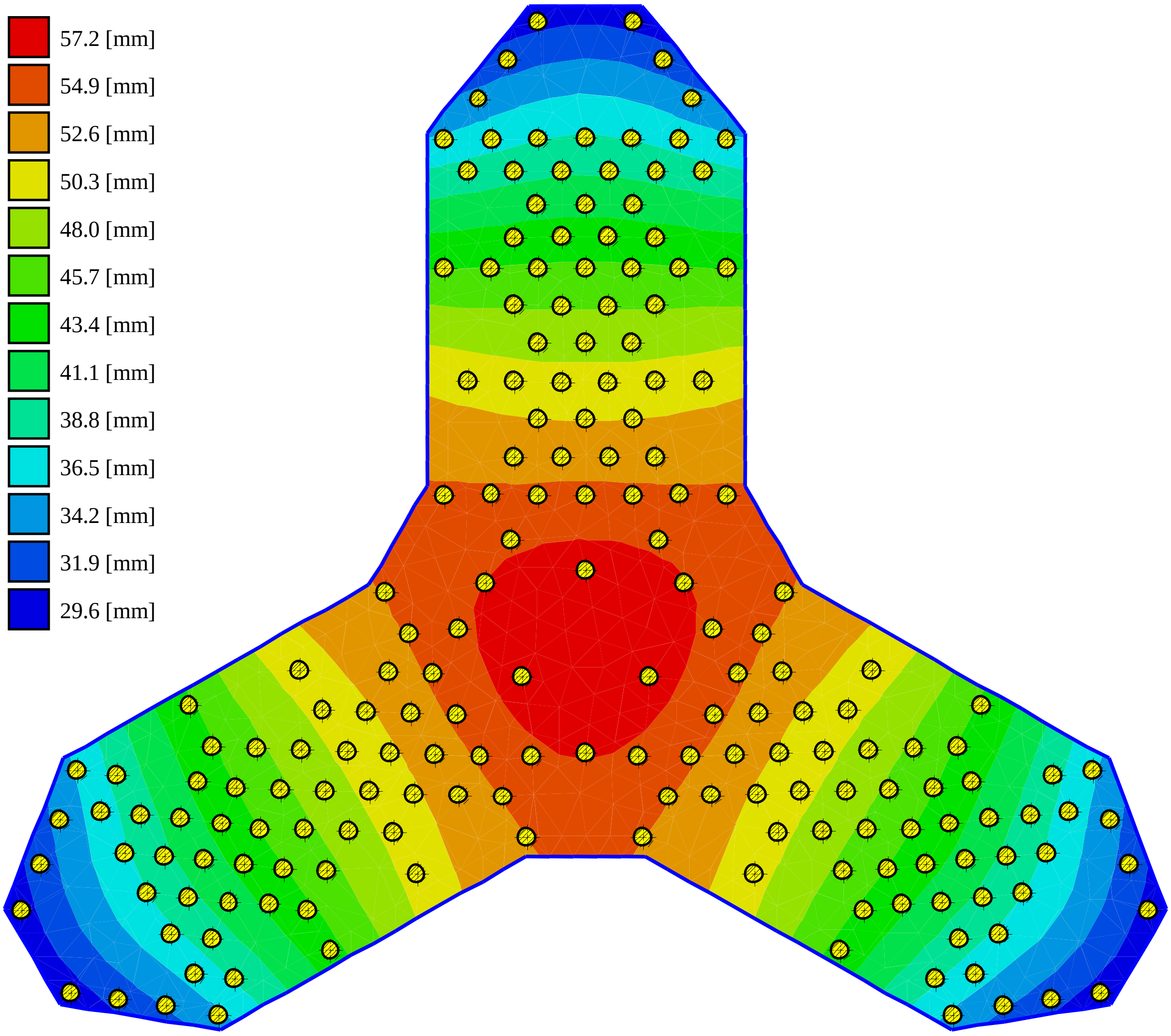


Figure 7-8 Settlement using the method "Given Load-Settlement Curve"

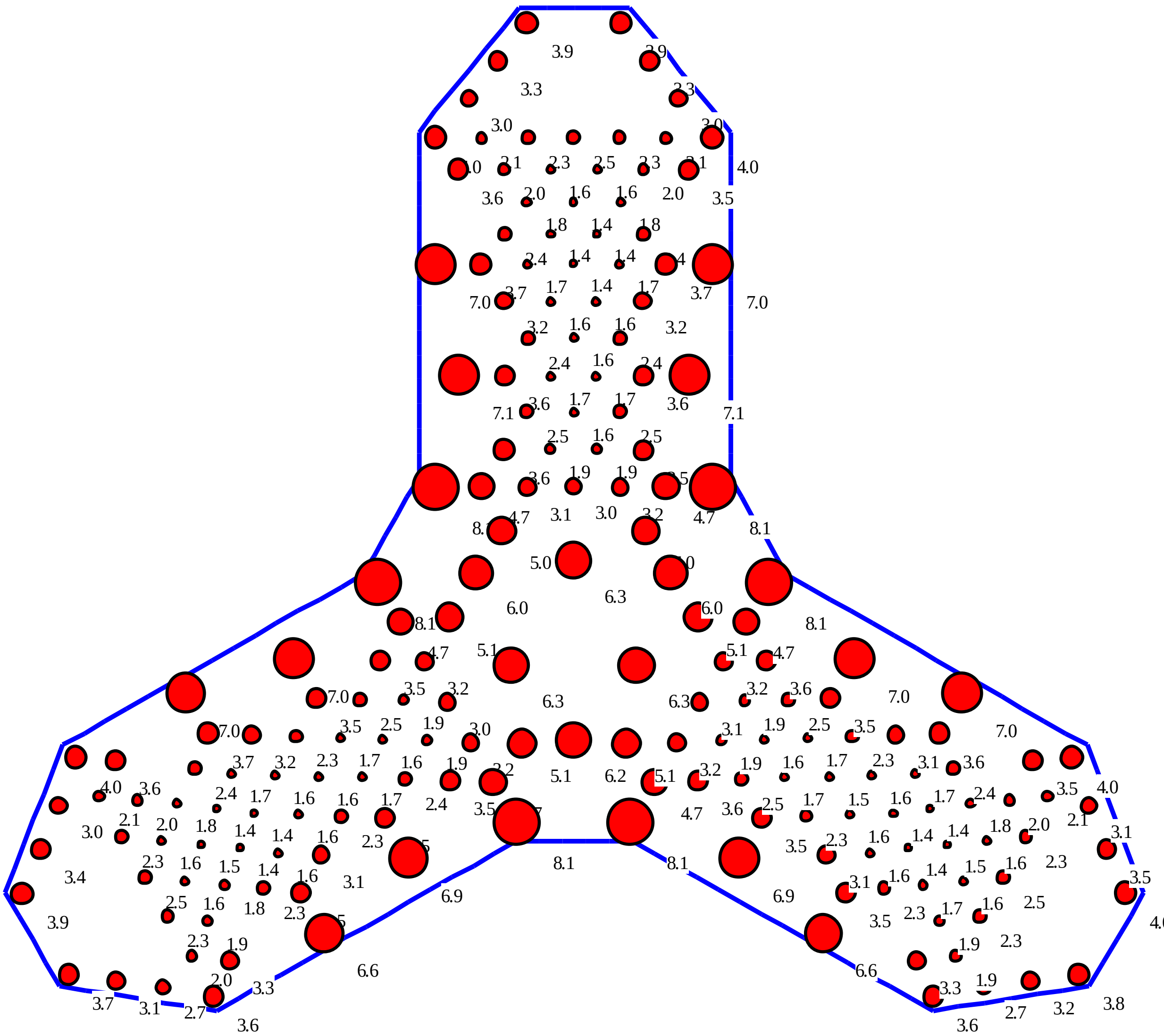


Figure 7-9 Self settlement of piles S_v [mm] using the method "Given Load-Settlement Curve"

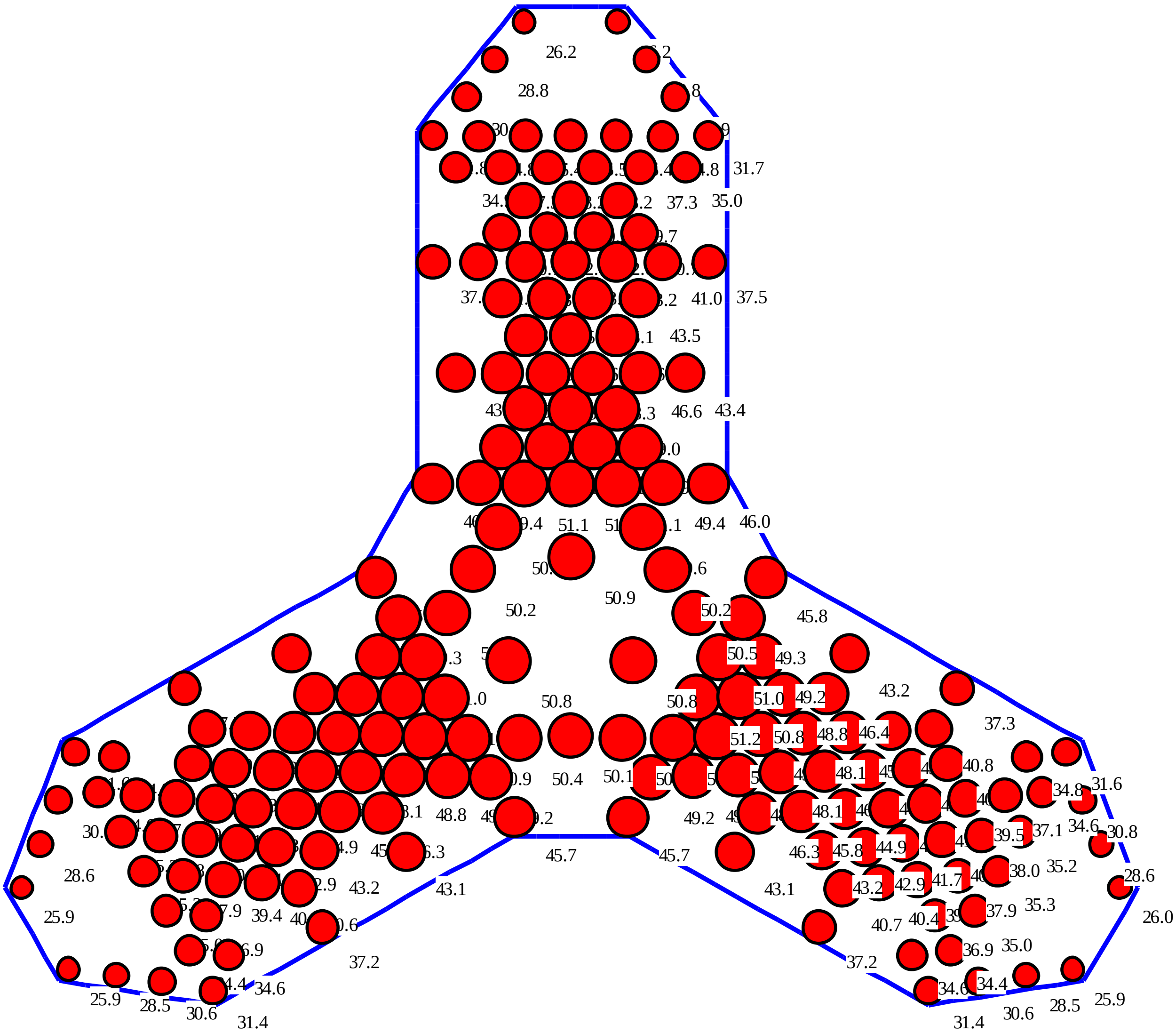


Figure 7-10 Interaction settlement of piles S_{rv} [mm] using the method "Given Load-Settlement Curve"

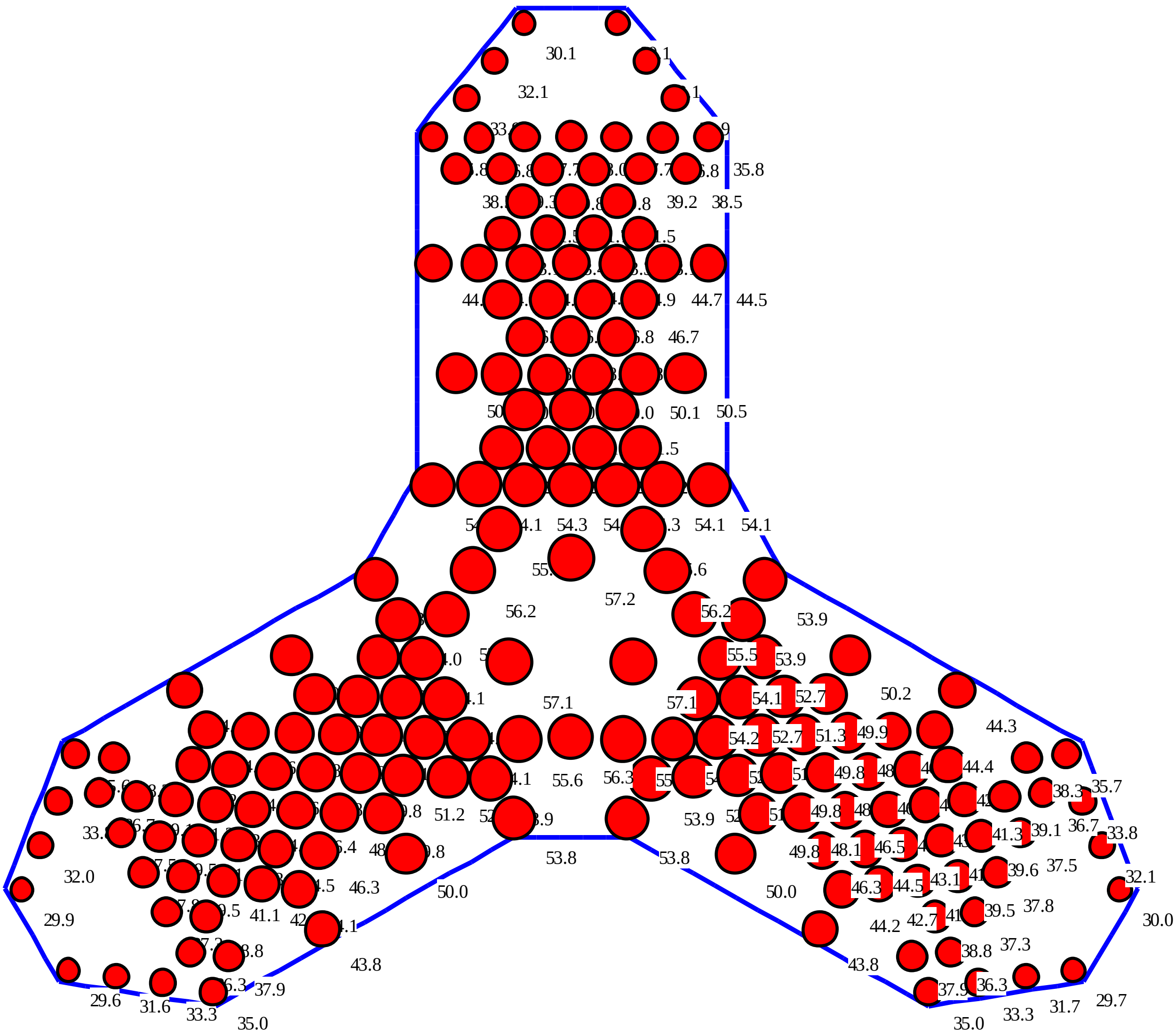


Figure 7-11 Total settlement of piles S_r [mm] using the method "Given Load-Settlement Curve"

7.8 Measurements and other results

7.8.1 Measured settlement

The construction of *Burj Khalifa* began on 6 January 2004, with the exterior of the structure completed on 1 October 2009. According to *Badelow & Poulos* (2016) the settlement of the tower raft was monitored from completion of concreting till 18 February 2008. The recorded maximum settlement at 18 February 2008 was 43 [mm] under nearly 80 % of the building load.

A comparison is presented between the measured settlement on 18 February 2008 under 80% of the total load and that computed by *ELPLA* using Method: "Given Load-Settlement Curve". Figure 7-12 shows a comparison between measured settlement (Feb. 2008) and computed settlement under 80 % of the total load at a cross section of the Wing c, while 0 shows a comparison between extreme values of measured settlement and that calculated for the same case.

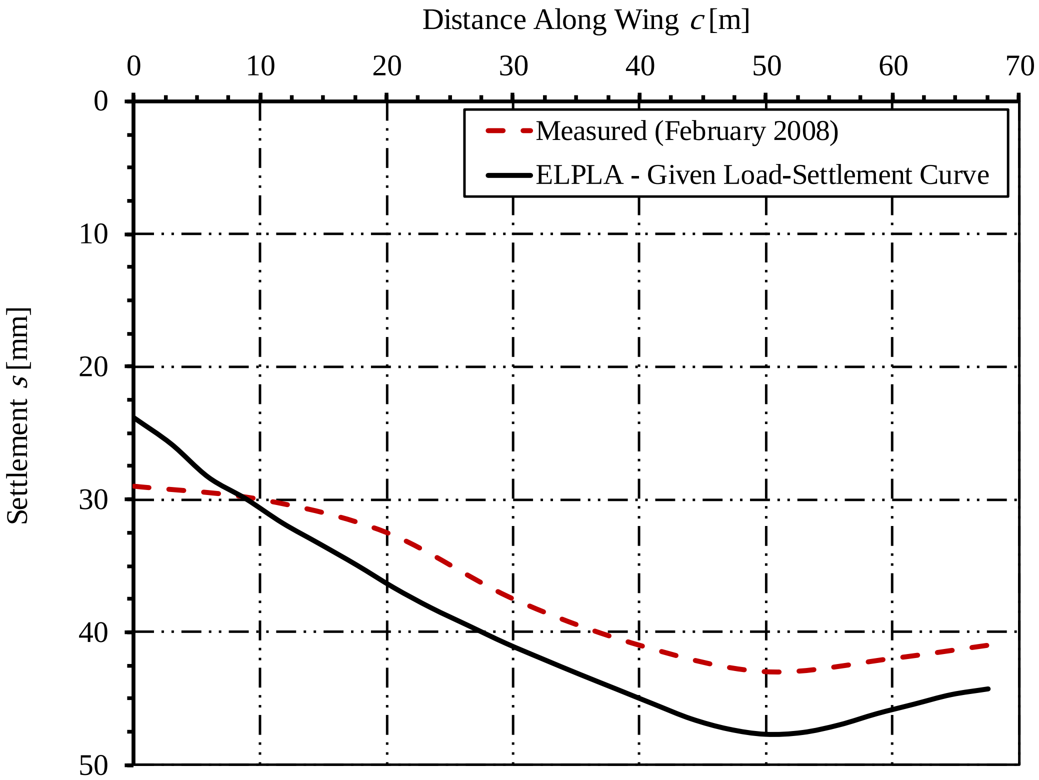


Figure 7-12 Measured settlement (Feb. 2008) and computed settlement under 80 % of total load

Table 7-2 Comparison between measured settlement at February 2008 and that calculated by *ELPLA* under 80 % of the total load

Method	$S_{max.}$ [mm]	$S_{min.}$ [mm]	$S_{Diff.}$ [mm]
Measured (18 February 2008)	43	29	14
ELPLA – Method: "Given Load-Settlement Curve"	48	24	24

Figure 7-13 shows contours of measured settlement [mm] at February 2008 and that calculated by *ELPLA* under 80 % of the total load using method "Given Load-Settlement Curve"

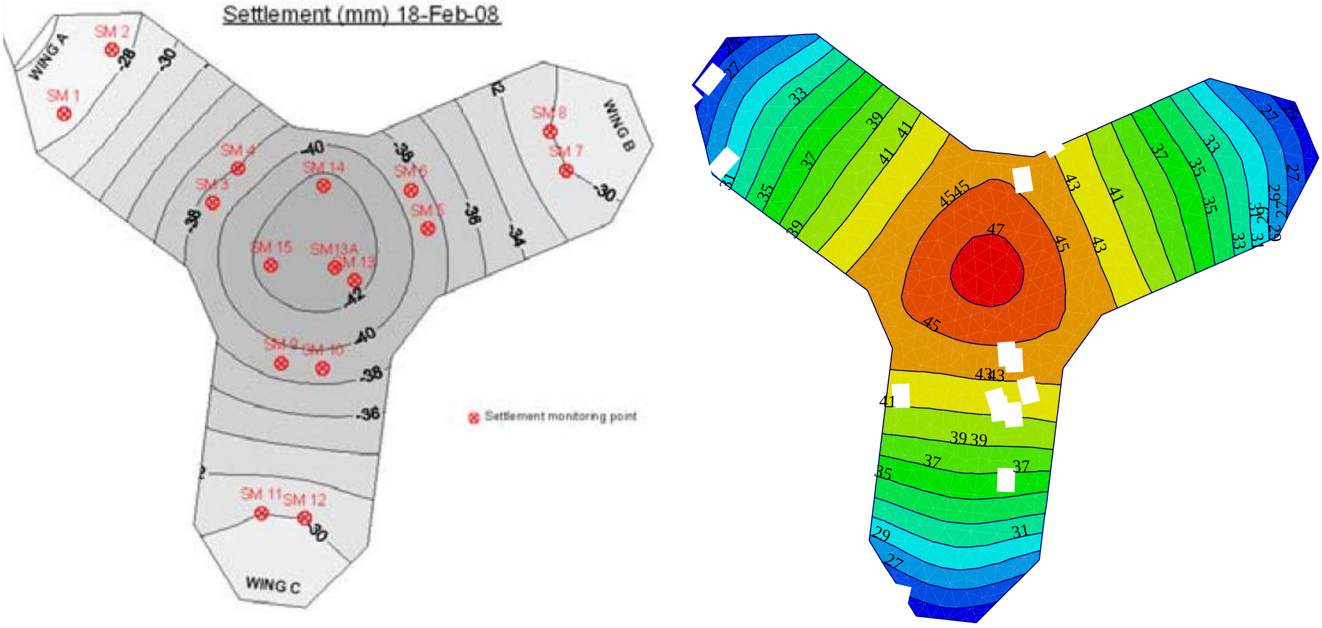


Figure 7-13 Contours of measured settlement [mm] at February 2008 and that calculated by *ELPLA* under 80 % of the total load using method "Given Load-Settlement Curve"

The above comparison of the piled raft under 80 % of the total load illustrates that the maximum and minimum results of *ELPLA* are in good agreement with the measured settlement with difference not exceed 1 [cm]. The measured differential settlement is considerably smaller than that computed because the building stiffness is not considered in *ELPLA* analysis in this case, which would reduce the differential settlement.

7.8.2 Calculated final settlement

Several analyses were used to assess the response of the foundation for the *Burj Khalifa* Tower and Podium. The main design model was developed using a Finite Element (*FE*) program *ABAQUS* run by a specialist company *KW Ltd*, based in the UK. Other models were developed to validate and correlate the results from the *ABAQUS* model using other software programs. The design values of settlement were presented by *Poulos* and *Bunce* (2008).

Russo etc. al. (2013) deals with the re-assessment of foundation settlements for the *Burj Khalifa* Tower in Dubai. Re-assessment was carried out using the computer program Non-linear Analysis of Piled Rafts *NAPRA* with neglecting the structure stiffness effect on raft settlement.

A comparison is presented between the computed settlement in other references and the computed settlement by *ELPLA* using different Nonlinear analysis methods. The comparison is presented as a cross section at Wing c and tables as in Figure 7-14 and Table 7-3, respectively.

The comparison shows that the results of two methods in *ELPLA* are in good agreement with the calculated results of *Russo etc. al.* (2013). The second method (Load-Settlement relation as a Hyperbolic Function for Load-Settlement Curve) results are closer to the design results presented by *Poulos* and *Bunce* (2008).

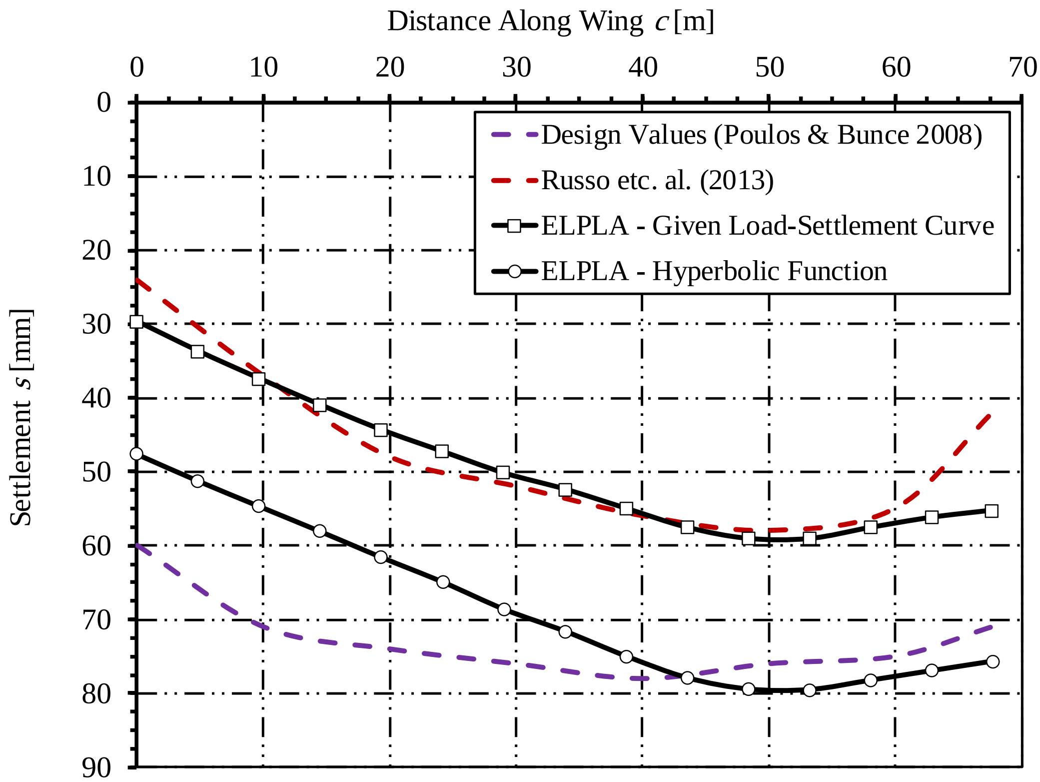


Figure 7-14 Final settlement for elastic piled raft using different analysis models

Table 7-3 Comparison between various calculated settlement profiles

Method	$S_{max.}$ [mm]	$S_{min.}$ [mm]	$S_{Diff.}$ [mm]
Design Values (*Poulos* and *Bunce* 2008)	78	60	18
Russo etc. al. (2013)	58	24	34
ELPLA – Given Load-Settlement Curve	58	29	29
ELPLA – Hyperbolic Function for Load-Settlement Curve	79	47	32

7.8.3 Calculated final pile loads

The maximum and minimum pile loads were obtained from the three-dimensional finite element analysis for all loading combinations by *Poulos* and *Bunce* (2008). The maximum loads were at the corners of the three “wings” and were of the order of 35 [MN], while the minimum loads were within the center of the group and were of the order of 12-13 [MN].

Figure 7-15 and Figure 7-16 show pile loads obtained by *ELPLA* using method: "Hyperbolic Function for Load-Settlement Curve" and method "Given Load-Settlement Curve from pile-load test", while Table 7-4 compares results of max and min pile loads obtained by *ELPLA* with those of *Poulos* and *Bunce* (2008).

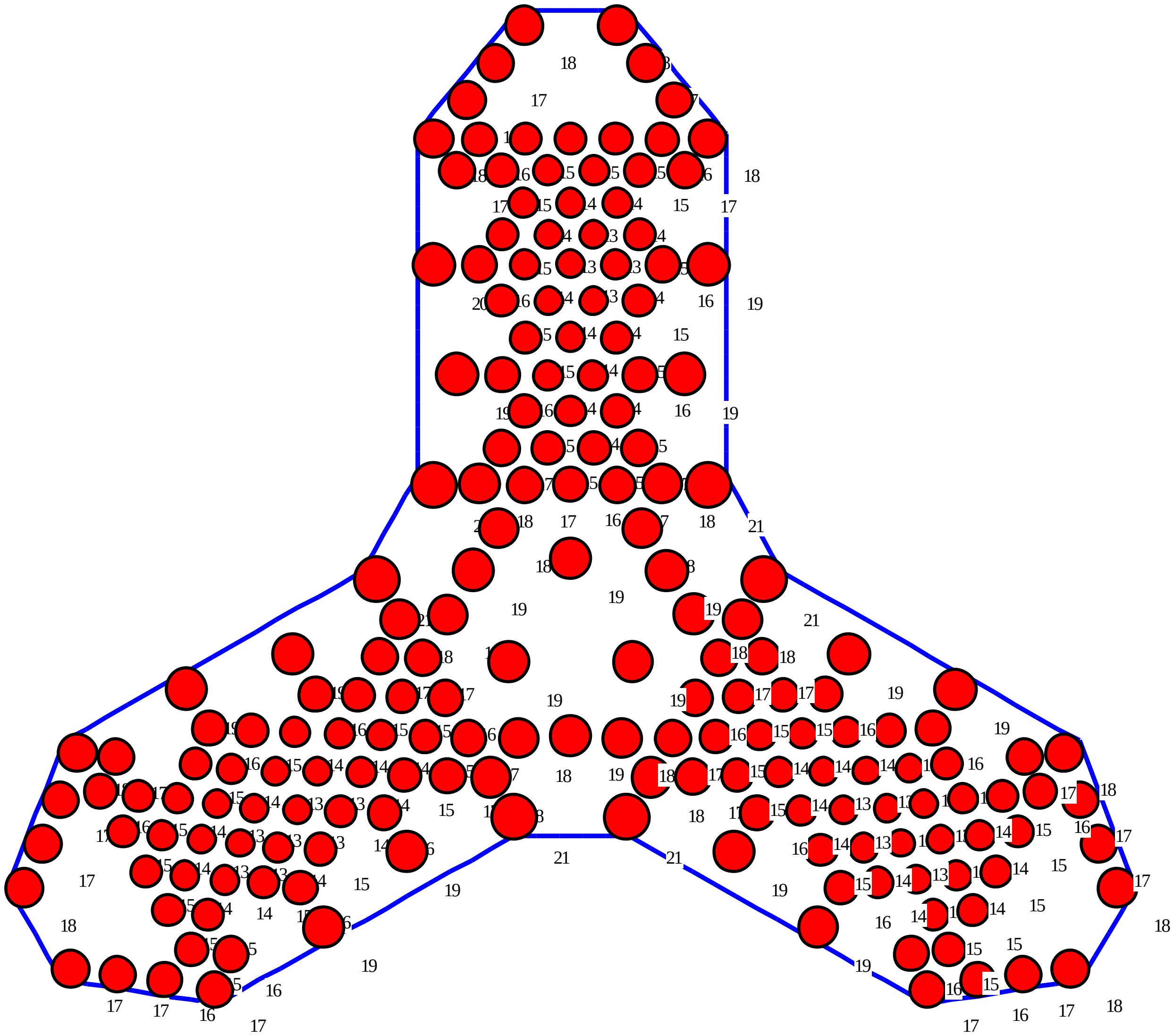


Figure 7-15 Pile load [MN] using the method "Hyperbolic Function for Load-Settlement Curve"

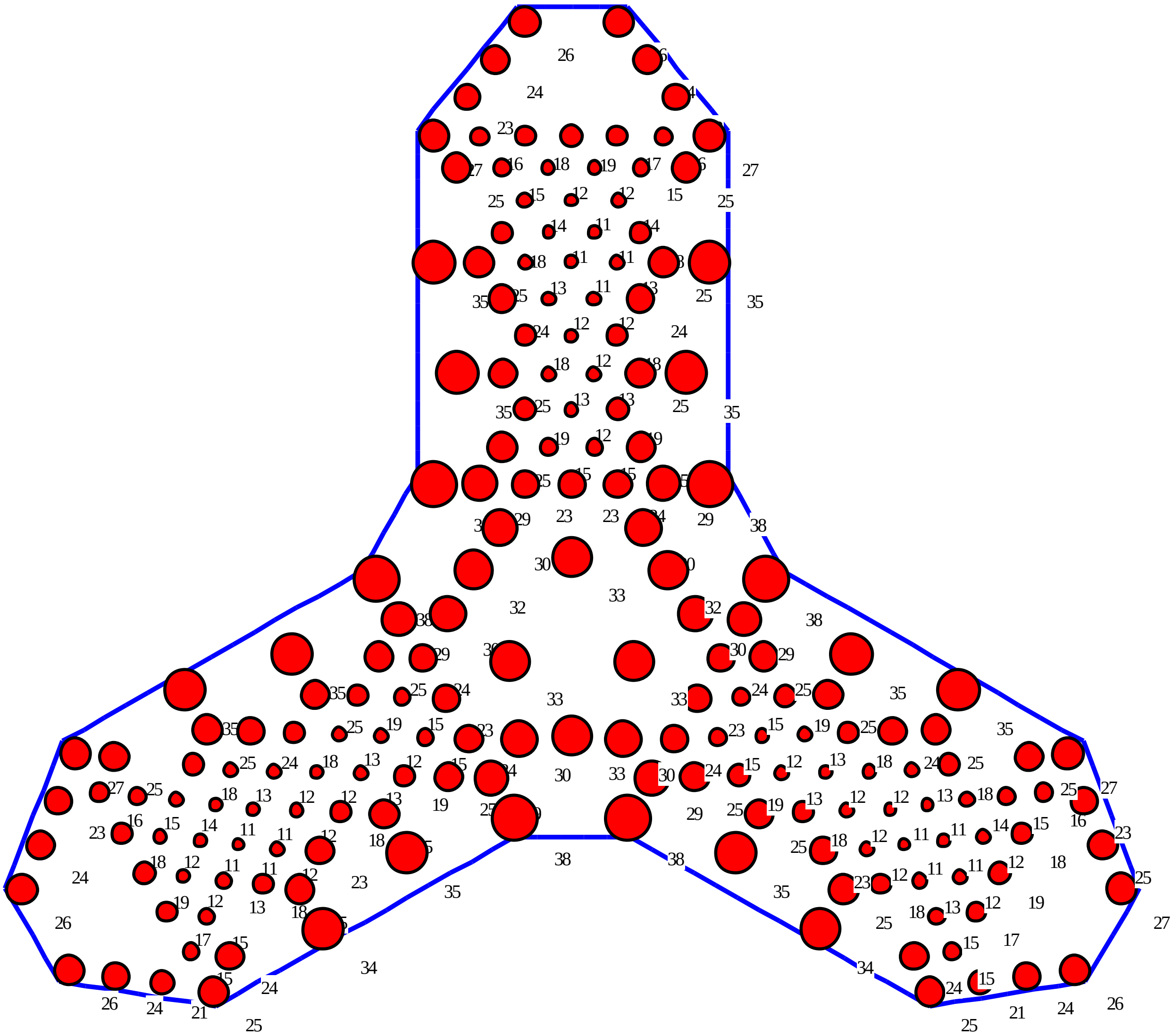


Figure 7-16 Pile load [MN] using the method "Given Load-Settlement Curve"

Table 7-4 Comparison between various calculated pile loads

Method	$P_{max.}$ [MN]	$P_{min.}$ [MN]
FEA (*Poulos* and *Bunce* 2008)	35	12-13
ELPLA – Given Load-Settlement Curve	38	11
ELPLA – Hyperbolic Function for Load-Settlement Curve	21	13

7.9 Conclusion

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

7.10 References

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[2] *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

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