Geotechnical Analysis of Deep Foundation for Nakheel Tower using 3D Finite Element Modelling

N.S. Nilaweera
Golder Associates (NZ) Limited, Christchurch, New Zealand

C.M. Haberfield
Golder Associates Pty Ltd, Richmond, Victoria, Australia

ABSTRACT : This paper discusses the geotechnical modelling and analytical procedure adopted for the design of the foundation system for over one kilometer-high Nakheel Tower in Dubai. The geological and geotechnical conditions at the site were modelled based on the results of a comprehensive geotechnical investigation and testing program. The generalized geotechnical model comprised variably cemented sand to about 20 m depth followed by calcareous mudstone which is interbedded with stronger gypsum layers below a depth of around 75 m. The strength and stiffness properties of the subsurface materials were estimated mainly from the in-situ testing. A deep foundation system using closely spaced barrettes (deep foundations similar to drilled cast-in-place piles that are constructed in a rectangular shape), capped with a reinforced concrete raft system for the tower footprint of about 100 m diameter area was modeled using commercially available PLAXIS 3D Foundation, a three-dimensional finite element program for geotechnical applications. Several groups of large barrettes with a maximum penetration depth up to about 60 m below the raft slab were used to analyze the geotechnical effects of over two-million-tones dead load, live load and wind load combinations from the proposed structure to the foundation.

1 INTRODUCTION

The Nakheel Tall Tower design incorporated up to 1,200 m high tower with an approximately circular footprint of about 105 m in diameter. With a planned height over 1 km and a weight in excess of 2,000,000 tones, the tower was designed to become not only the world tallest but also one of the heaviest.

An excavation to a level of about 20 m below the existing ground level was to be made to accommodate the proposed raft slab footing supported on barrettes and basement space. A podium structure is to be constructed around the tower to a diameter of about 290 m and to a depth of about 6 m below the finished ground level.

The Nakheel Tall Tower project was shelved with the construction of foundation two third completed due to the Dubai property market crash in 2009.

2 SUPERSTRUCTURE AND LOADING CONDITIONS

The main body of the tower comprised 4 basic vertical structural components that transfer the superstructure loads eventually to the foundation system. They are the drum wall acting as the main spine of the tower, the hammer walls spring outwards to enlarge the structure at the perimeter of the building, the fin walls spring inward primarily to support the gravity loads of the core area, and the mega columns at the perimeter of the tower (Fig. 1).

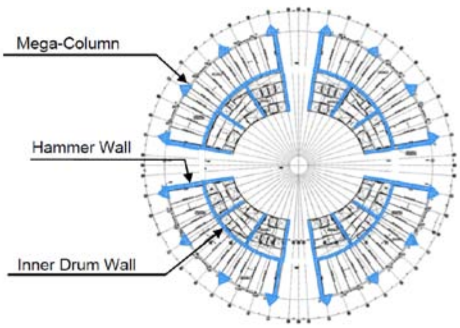

Fig. 1 Main structural elements

The foundation has to be analysed for three working load combinations and two ultimate load combinations as defined below.

Working load combinations:

i) Dead Load (DL) +Live Load (LL)
ii) DL + 0.8 Wind Load (WL)
iii) DL + 0.75 LL + 0.6 WL

Ultimate load combinations:

iv) 1.2 DL + 0.5 LL + WL
v) 1.2 DL + 0.5 LL + Earthquake Load (E)

The moment and lateral loads were translated to vertical loads and base shear, respectively for the analysis.

3 GEOTECHNICAL CONDITIONS

The geotechnical condition at the site was assessed based on the detailed site investigation which included nine cored boreholes drilled up to 200 m depth. The different geological units encountered beneath the site and their inferred constitutive behaviour are presented below.

Unit A, Silty SAND – Fine to medium grained, typically loose to medium dense sand encountered from the ground surface to between 5.7 m and 7.0 m depth.

Unit B, Variably Cemented Sands – Predominantly fine to medium grained sand and silty sand. The sand is variably cemented. Where cemented, the sand typically occurs as a low to medium strength sandstone. Measured Is(50) values within the sandstone are typically less than 0.9 MPa but values of up to 1.93 MPa were measured. This unit immediately underlies Unit A and has its base between 19.5 m and 21.3 m depth.

Unit C, Calcisiltite – Calcareous deposits, mostly comprising calcisiltite were encountered immediately below the cemented sands of Unit B and extended to a level of between 43.0 m and 47.0 m depth. This material is typically massive. It is interbedded with minor calcareous siltstone and calcarenite.

Unit D, Calcareous Siltstone/Calcisiltite with Gypsum – A conformable sedimentary sequence comprising predominantly calcisiltite and calcareous siltstone underlies Unit C. This material is characterised by interbedded gypsum layers of up to 3.5 m thick. These gypsum layers are of significantly higher strength than the sedimentary layers within which they are interbedded. As such, Unit D has been divided into subunits over the depth that it was investigated. The subunits are defined on the basis of the observed gypsum layers, designated G1 to G14. A non-dilatant, purely cohesive Mohr-Coulomb model has been assumed for this material.

The geotechnical parameters used in the analysis are summarised in Table 1.

Table 1. Summary of Parameters Used for Analysis – Lower Bound/Best Estimate/Upper Bound

Geological Unit		Depth (m)		E (MPa)	s_u ; ϕ',c' (kPa ; deg, kPa)	σ_t (kPa)
Main Unit	Sub Unit	From	To			
A		0	7.0	100/100/2000	ϕ' = 35°/35°/40°	0
B		7.0	19.8	100/100/2000	ϕ' = 35°/35°/40° c' = 0/0/100 kPa	0/0/30
C	C1	19.8	45.0	800/1500/3000	s_u =1300/2500/5000	s_u/3
D	D1	45.0	76.7	500/1000/2000	s_u =833/1670/3300	s_u/3
	G2	76.7	79.7	2000/5000/10000	3300/8300/16700	s_u/3
	D3	79.7	83.3	500/1000/2000	830/1670/3300	s_u/3
	G3	83.3	86.3	2000/5000/10000	3300/8300/16700	s_u/3
	D4 – D8 G4 - G7	86.3	125.0	800/1500/3000	1300/2500/5000	s_u/3
	D9 – D12 G8 – G11	125.0	180.0	2000/2500/4000	3300/4170/6700	s_u/3
	D13, G12, G13	180.0	190.0	800/1500/3000	1333/2500/5000	s_u/3
	D14, G14	190.0	220.0	2000/2500/4000	3300/4170/6700	s_u/3
		>220		2000/5000/10000	3300/8300/16700	s_u/3

4 PLAXIS 3D FOUNDATION MODELLING

PLAXIS 3D Foundation is a commercially available three dimentional finite element program developed for geotechnical modelling and analysis including deep foundation syatems such as piled rafts. The program allows for an automatic generation of vertically aligned quadratic 15-node wedge elements that are generally defined by two triangular horizontal faces and three vertical faces. The stratigraphy is defined by means of boreholes. The structural elements, loads, or construction stages are defined on horizontal work planes.

For modelling of geotechnical condition, the data from 5 boreloles drilled at the fooprint of the tower was used so as to define the rather inclined soil stratigraphy (Fig. 2).

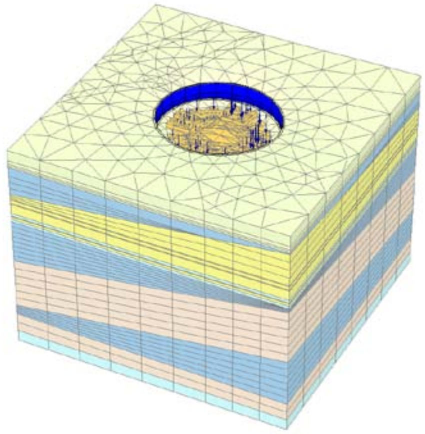

Fig. 2 PLAXIS 3D model with inclined stratigraphy

About 20 m deep excavation was required to accommodate the raft slab and the basement space. In order to support this excavation, a cantilivered retaining wall was modelled along a curcumference of 60 m radius. This wall was not analysed in detail as it was out of the scope, but maintained the wall stability throug its circular shape and hoof stress development.

The schematic design for the Nakheel Tall Tower comprised about 4 m to 8 m thick raft slab, founded at about 20.0 depth and supported by barrettes. The schematic design for the footing system compiled by the structural engineer contained 184 barrettes of 2.8 m by 1.2 m (plan dimension) and 224 barrettes of 2.8 m by 1.5 m.

The raft slab and barrette arrangement with load locations are provided in Fig. 3.

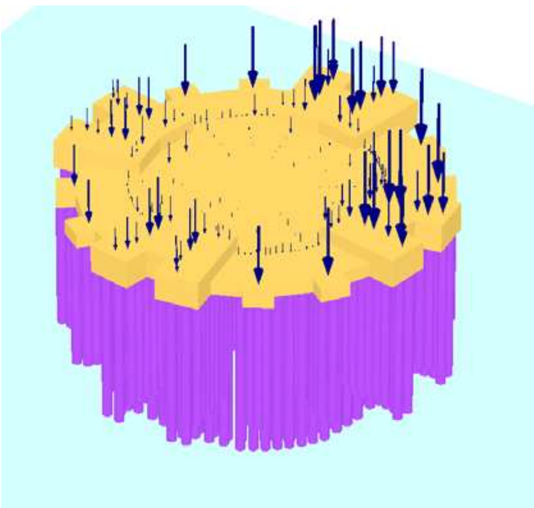

Fig. 3 Raft and barrettes arrangement

The barrette layout, including the total number of barrettes has been revised and optimized during the iterative process of the analysis. The revised barrette layout is shown in Fig. 4. The optimized barrette depths are as follows

- Barrettes supporting the Drum wall extend about 58 m below the base of the raft slab through the upper-most thick gypsum layer and found a minimum of 0.5 m into the Unit D material below.
- Barrettes supporting the Mega columns found at about 38 m below the base of the raft slab.
- Barrettes supporting the Hammer walls found at either 38 m or 43 m below the base of the raft slab. The barrettes located directly under the Hammer wall (centre row of barrettes) and the outer most barrettes supporting the Hammer wall found at 43 m. The adjacent row of barrettes either side of the central row of barrettes found at 38 m.
- All other barrettes not specifically identified above found at 38 m.

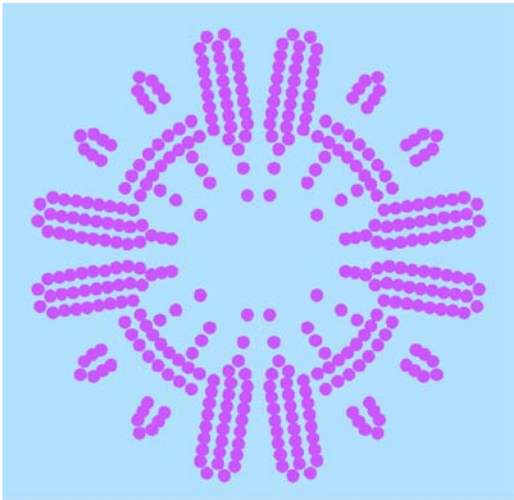

Fig. 4 Revised barrettes layout

5 ANALYSIS

Analyses were undertaken for each working load combination assuming two alternative base conditions; barrettes with full base resistance and with no base resistance. It is considered that the analyses assuming full base resistance provide a reasonable estimate of short term performance while the analyses with no base resistance provide a conservative estimate of long term performance. For each analysis, the vertical settlement and loads at the head of the barrettes, the axial stiffness of each barrette and the geotechnical factor of safety for each barrette were evaluated.

The maximum and minimum settlements under working load conditions are summarised in Table 2.

For the load case of DL + LL, the calculated settlements assuming full base resistance are about 10 mm to 15 mm less than those obtained from the analyses assuming no base resistance. As indicated in Table 2, it is considered that the analyses assuming full base resistance provide a reasonable estimate of settlement performance of the tower footing system in the short-term (for the parameters assumed).

Table 2. Computed Settlements of Major Columns and Walls

Load Case	Full Base Resistance			No Base Resistance		
	Hammer Walls	Drum Wall	Mega Columns	Hammer Walls	Drum Wall	Mega Columns
DL + LL	66 – 72 mm	70 mm	62 mm	82 – 87 mm	82 mm	74 mm
DL + 0.8 WL						
Windward (minimum)	34 – 45 mm	46 mm	35 mm	42 – 57 mm	54 mm	45 mm
Leeward (minimum)	74 – 80 mm	74 mm	70 mm	90 – 99 mm	93 mm	87 mm
DL + 0.75LL+ 0.6 WL						
Windward (minimum)	50 – 60 mm	56 mm	46 mm	62 – 70 mm	66 mm	58 mm
Leeward (minimum)	78 – 82 mm	76 mm	72 mm	96 – 100 mm	90 mm	86 mm

The maximum axial load in the 1.2 m x 2.8 m and 1.5 m x 2.8 m barrettes under the working load cases analysed are 64 MN and 79 MN respectively. These are less than the barrette structural working load capacities of 64.5 MN and 80.6 MN.

Barrette stiffness under ultimate loading varies between 0.12 MN/mm and 0.83 MN/mm. Raft stiffness is about 12 MN/mm where the raft is 4 m thick or greater.

6 CONCLUSIONS

The proposed footing system for Nakheel Tall Tower in Dubai was analysed using three dimensional finite element modelling software, PLAXIS 3D Foundation. The analyses undertaken for three working load (gravity and wind) and two ultimate (gravity, wind and earthquake) load case combinations provided reasonable estimates of short and long term settlement and tilt; axial loads, displacements and spring stiffness within individual barrettes; and structural actions (bending moments and shear forces) in barrettes.

Based on the analysis, the design short term settlement of the tower is 70 mm to 80 mm with the potential for post construction settlement of about 15 mm over the lifetime of the structure. Long term tilt of the tower is less than 1/2000.The calculated maximum loads within the barrettes are satisfactory with respect to geotechnical and structural capacity requirements.

The performance of the tower footing system is dependent on the resistance developed at the base of the barrettes. The installation of the barrettes should adopt procedures that minimise the potential for debris to accumulate at the base of the barrette excavation prior to the placement of concrete.

ACKNOWLEDGMENTS

The authors acknowledge Golder Associates for the support provided during preparation of this manuscript.

REFERENCES

Nakheel Tall Tower Geotechnical Design Development Report, Report no. 077619011/047 (2008), Golder Associates Pty Ltd, Melbourne, Australia.

Nakheel Tall Tower Schematic Design Report, Report no. 077612011/046 (2008), Golder Associates Pty Ltd, Melbourne, Australia.

Nakheel Tall Tower Report on Test Barrettes, Report no. 077619011/043 (2008) Golder Associates Pty Ltd, Melbourne, Australia.

Plaxis 3D Foundation Manual (2007), Plaxis bv, Netherlands.