Case History

Geotechnical Design for the Nakheel Tall Tower

By Chris Haberfield, Darren Paul, Max Ervin,
Golder Associates Pty Ltd, Melbourne, Australia

1. Introduction

The recently announced Nahkeel Tower in Dubai, UAE (Figure 1) will extend to in excess of 1 km in height and at about 2,000,000 tonnes dead load it will be one of the heaviest buildings on earth. The bearing pressures applied to the ground coupled with the soft rock ground conditions present at the site provided a significant challenge to the design of the footing system. The following presents a brief summary of the ground investigation undertaken and of the development of the footing system which is currently being installed.

Figure 1: Nakheel Tower, Dubai, UAE

2. Geology

An arid climate prevailed in the area during Holocene times facilitating the formation of coral reefs and shallow marine carbonate deposits. In addition, evaporite or Sabkha deposits, containing mainly gypsum are common and are associated with intertidal conditions on flat topography. The carbonate rich sedimentary sequence underlying the site comprises mainly carbonate cemented siltstone (calcisiltite). Gypsum layers of up to 2.5 m thick are interbedded with the carbonate materials at levels lower than 75 m below ground level. Recent aeolean deposits (sand dunes) form a capping over vast areas of the United Arab Emirates, including the Nakheel Tower site. Owing to different rainfall and groundwater regimes associated with past climates, the dune sands have become partially cemented forming calcarenite beds. At the Nakheel Tower site, the sand dune capping extends about 20 m below ground level.

Case History (continued)

Geotechnical Design for the Nakheel Tall Tower

3. Footing concept

Based on preliminary information, the proposed footing concept for the tower comprised a raft supported by large diameter piles or barrettes. The base of the raft would found below the sand dunes at about 20 m depth within the carbonate cemented siltstone with piles or barrettes extending perhaps to depths of 60 m to 70 m below this level. As piles/barrettes were to be installed from the surface, and given the expected ground conditions, it was considered that installing bored circular piles to these depths may prove to be problematic if not impractical, and hence the decision was made relatively early in the design process to adopt barrettes for the main deep foundation elements. The temporary basement retention system, constructed through the sand dune deposits, would comprise a circular diaphragm wall which was to be installed prior to the foundation barrettes. The barrettes were to be installed from the surface, with excavation to pile cut-off level to proceed once barrette installation was complete.

4. Ground investigation

On the basis of our previous experience at other sites in Dubai we were aware that when sampled and brought to the surface the carbonate cemented siltstone undergoes significant stress relief. This results in samples tested in the laboratory displaying significantly lower strength and modulus properties than measured by insitu testing. Significant emphasis was therefore placed on insitu testing, which comprised pressuremeter testing, cross hole sonic testing, water pressure testing and the testing of three full scale test barrettes. Laboratory testing was also undertaken to better understand the constitutive behaviour of the cemented carbonate materials. Laboratory testing comprised characterisation tests and specialist testing. Classification testing included unconfined compressive strength (UCS) testing with modulus measurement (end platten measurement) and tests for carbonate content, unit weight, specific gravity, moisture content and dry density. Specialist laboratory testing comprised cyclic and monotonic constant normal stiffness direct shear testing, resonant column testing, drained triaxial testing, cyclic triaxial testing and high pressure oedometer testing.

The ground investigation was undertaken by Fugro Middle East in accordance with specifications provided by Golder Associates Pty Ltd, Melbourne, Australia, office. Golder Associates' staff were on site during the ground investigation and independently logged the rock core. Preliminary analysis of the footing design concept was undertaken using PLAXIS 2D and assuming axisymmetric conditions. These analyses indicated that more than 50% of the calculated footing settlement would occur below the toe of the barrettes. For this reason, significant attention was paid to estimating stiffness parameters of the ground below the toe of the barrettes (from about 80 m depth to 200 m depth).

Nine geotechnical boreholes were drilled to between 150 m and 200 m depth using PQ triple tube drilling techniques. Immediately upon being recovered from the borehole, core was logged, photographed and samples were extracted. Moisture content testing was undertaken on site and samples scheduled for off site testing were wrapped in plastic film, placed in snug-fitting cardboard tubes and sealed in wax. As the rock materials were essentially unweathered, the application of a weathering classification system would be of little if any benefit. A relatively crude and simple hardness test was therefore developed to provide a continuous assessment of the core. The hardness test comprised inserting a knife into the core using a relatively constant pressure and measuring the penetration. The hardness values obtained through this process allowed assessment of the variation in ground conditions across the site and an estimate of potential tilt of the building under gravity loading. Pressuremeter testing was undertaken at 5 m intervals in three boreholes. Pressuremeter tests were taken to the working limits of the equipment and incorporated "hold" stages of up to an hour to measure the creep characteristics of the ground. Due to the significant depths at which testing was to be undertaken, pressure measurements were taken within the probe. The pressuremeter test results provided data on rock stiffness, strength and creep characteristics. Crosshole seismic testing to 200 m depth was undertaken in a further two boreholes. Two receiver boreholes placed 3 m and 6 m from the source boreholes were utilised in this testing. The cross hole seismic testing was analysed to provide continuous profiles of small strain shear modulus with depth.

5. Constitutive behavior and properties

The founding conditions comprise predominately carbonate or gypsum cemented materials with a relatively high void ratio (0.4 to 0.7). Laboratory and insitu testing indicated the material has a relatively high stiffness below a "bond yield strength" after which the compressibility of the material increases significantly and exhibits properties similar to an uncemented, normally consolidated material at the same void ratio. Prior to reaching the bond yield strength the behaviour of the rock is dominated by the intergranular cementation and displays approximately linear elastic behaviour with deformations occurring essentially instantaneously. As the bond yield strength is approached, deformations become time dependent and consolidation and creep displacements dominate. Satisfactory performance of the footing system for the tower therefore required that the stress increase in the ground due to the loads from the tower were kept below the bond yield stress. A primary aim of the ground investigation was therefore to obtain good estimates of the variation of rock modulus and bond yield strength with depth. Figure 2 compares the Youngs modulus values estimated from the pressuremeter, cross hole seismic and laboratory UCS tests. The pressuremeter test results display similar initial loading and unload reload moduli values which is consistent with the absence of jointing in the rock and the domination of the cementation. The Youngs modulus values obtained from the pressuremeter and cross hole seismic tests show reasonable agreement (see Figure 2) if the small strain modulus values obtained in the cross hole seismic tests are reduced by a factor of five.

Case History (continued)

Geotechnical Design for the Nakheel Tall Tower

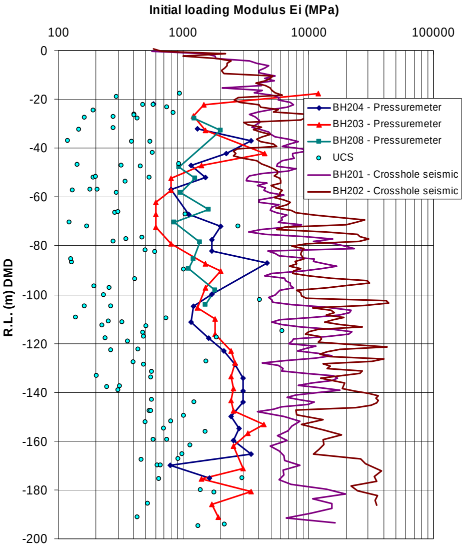

Figure 2: Young's modulus variation with elevation (surface level RL+2.5 m DMD)

An elastic, perfectly plastic (purely cohesive) constitutive model was found to provide an excellent fit to the pressuremeter expansion curves. This is consistent with the dominance of the intergranular cementation below the bond yield strength and should not be confused with "undrained" yield strength behaviour. We have interpreted the shear strength so obtained as an estimate of the bond yield strength. Figure 3 compares the shear strengths measured in the UCS tests (taken as UCS/2) and those estimated from the pressuremeter tests assuming a purely cohesive strength criterion. Figures 2 and 3 show that stiffness and strength properties measured in the laboratory were significantly less than obtained from insitu tests, and supported our hypothesis that the core samples were undergoing significant stress relief even with the care that was undertaken during the drilling, retrieval, storage, transportation and testing processes.The full scale barrette load tests (see below) confirmed that the properties obtained from the insitu testing were reasonable and that the laboratory test results significantly under-estimated the properties of the insitu rock.

6. Barrette load tests

As part of the ground investigation, three full scale test barrettes were installed and tested in accordance with a specification provided by Golder Associates. The test barrettes were installed by a Soletanche-Bachy/Intrafor Joint Venture and load testing of the barrettes was carried out by Loadtest International Inc. The load tests comprised two levels of Osterberg cells in each test barrette as shown in Figure 4. Each level of cells was capable of providing a working bi-directional load of 54 MN. However, during testing loads were increased to the capacity of the equipment resulting in bi-directional loads of up to 83 MN. On the basis of a preliminary concept for the footing design, barrettes were located under the main load bearing elements of the structure. This resulted in barrettes at relatively close centres and, as a consequence, most of the applied load would be transferred towards the toe of the barrettes. For this reason the Osterberg cells were positioned to measure performance of the lower 20 m or so of the barrettes. The test barrettes were instrumented with displacement telltales and strain gauges. In addition, instrumentation was also located in the rock below the toe of the barrette to directly measure the displacement of the rock at this location. The barrette load tests were used to investigate load deformation behaviour of the shaft and base of the barrette under static, cyclic and long term conditions. The measured load versus displacement performance of the two shorter test barrettes (TB02 and TB03) for loading at the lower and upper levels of Osterberg cells are shown in Figures 5 and 6 respectively. Also shown are the true Class A predictions of the performance. The Class A predictions were obtained on the basis of the adopted design properties for the ground and on the as-constructed barrette geometry. The predictions of performance were completed prior to testing of the barrettes.

For the Class A prediction, the rock-socket software ROCKET97 (Seidel, 2000) was used to calculate the shaft resistance performance of the test barrettes. The calculated shaft resistance performance was then used in an axisymmetric PLAXIS V8 model to obtain the calculated load versus displacement response shown in Figures 5 and 6. The comparison between the measured and predicted response is excellent, which provided further confidence that the design properties adopted on the basis of the insitu testing were appropriate. PLAXIS V8 was also used to calculate the design top-of-barrette load versus displacement performance shown in Figure 7. Figures 5, 6 and 7 clearly demonstrate the relatively stiff and strong response of barrettes in these ground conditions. Similar results were obtained from the other two test barrettes.

Case History (continued)

Geotechnical Design for the Nakheel Tall Tower

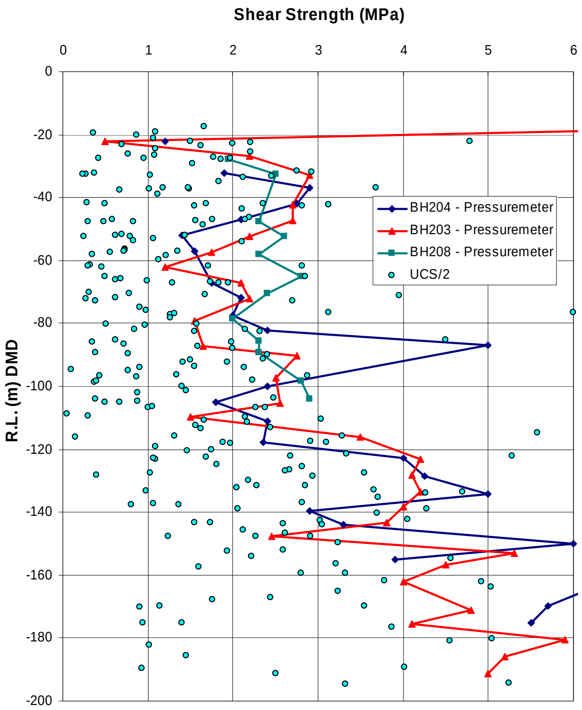

Figure 3: Shear strength variation with elevation surface level RL+2.5 m DMD)

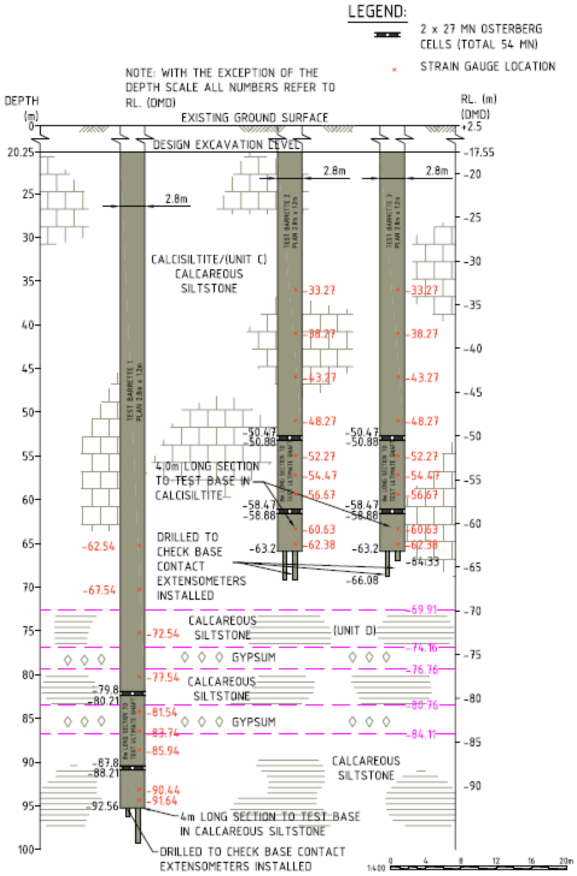

Figure 4: Test barrette configuration

7. Footing design and analysis

The results of the above investigations were used to assess design profiles of strength and Youngs modulus with depth to a depth of 200 m. Profiles of credible upper and lower bound properties were also assessed.Preliminary analyses of the footing system were undertaken using PLAXIS V8 (axisymmetric). Barrettes were modelled either as rings of equivalent structural plate elements or equivalent concrete/rock blocks. Interface elements were used to model the shaft resistance performance of the barrettes, with shaft resistance values adjusted to account for the difference in shaft area between the two-dimensional model and the actual three-dimensional conditions. Similar results were obtained using both plate elements and concrete/rock blocks. Significant consideration was given to the practicality of obtaining clean bases (free from debris) to the barrettes, and hence analyses were undertaken assuming both full and no base resistance. Another important consideration was to stagger the length of the barrettes such that the concentration of load towards the toe of the barrettes was spread over a greater volume of rock and the risk of exceeding the bond yield strength of the ground was reduced.

The PLAXIS V8 results were further analysed to provide estimates of individual top-of-barrette stiffness values and stiffness values for the rock supporting the raft. Due to the axisymmetric assumption, stiffness values varied with radius from the centre of the tower. On the basis of additional analyses, barrette stiffness values were adjusted according to their location within a group of barrettes (eg at the corner and centre of a group). The stiffness values were provided to the structural engineers for the project for use in their structural models of the tower. This allowed column loads to be refined and the barrette layout and raft thickness to be modified accordingly. The above process was repeated until there was convergence between the structural and geotechnical models for the footing system refined by the above process. Detailed three dimensional analyses of this footing system were then undertaken using the finite element software PLAXIS 3D. In general, the three dimensional analyses gave settlement profiles and barrette structural actions (loads, shear forces, bending moments) that were consistent with those obtained from the axisymmetric (PLAXIS V8) analyses. PLAXIS 3D analyses were undertaken for several serviceability and ultimate limit state load cases; design, credible upper and lower bound properties, and assuming full and no base resistance to the barrettes. The analyses indicated acceptable performance under all conditions analysed. Probablistic analyses were also carried out to assess the potential tilt of the tower due to variations in ground conditions across the site and to provide a probabilistic estimate of settlement. Measured field hardness values were used as the basis of the assessing the variability.

Case History (continued)

Geotechnical Design for the Nakheel Tall Tower

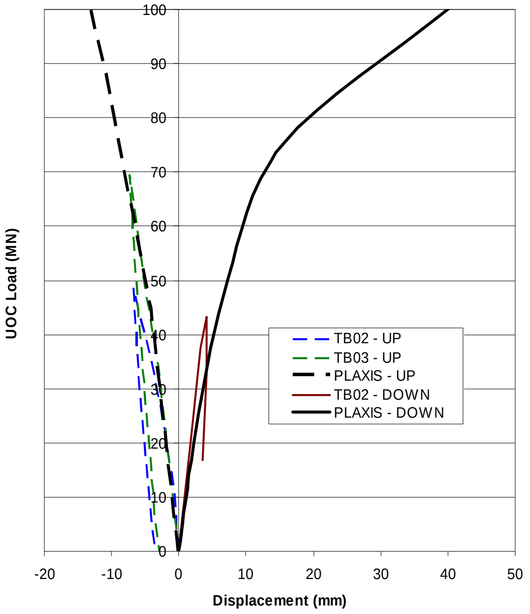

Figure 5: Measured vs predicted performance for loading at upper cells

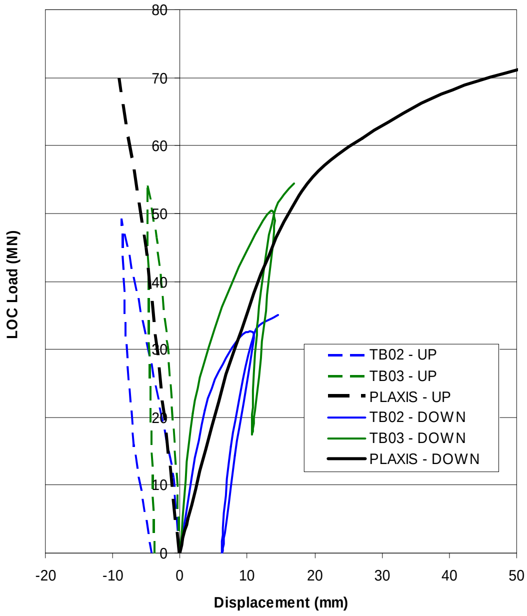

Figure 6: Measured vs predicted performance for loading at lower cells

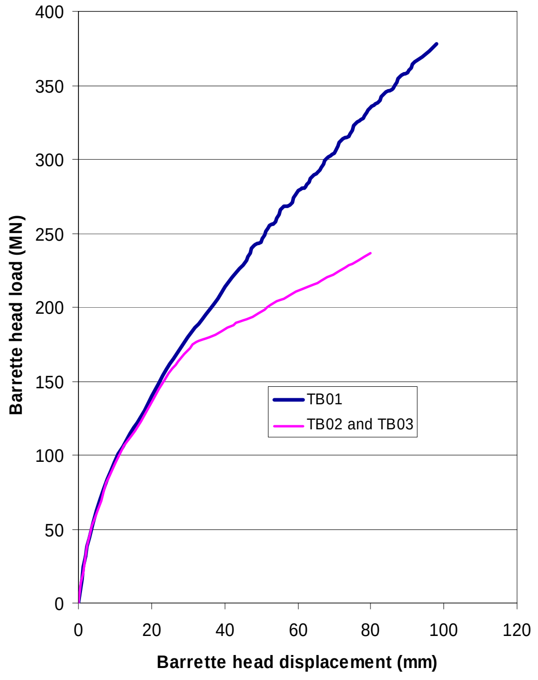

Figure 7: Calculated barrette head load

versus displacement performance

8. Closing comments

Construction of the foundation system is currently underway. Golder Associates has personnel on site to assist in maintaining the quality of construction of the barrettes. This is being facilitated through base drilling of select barrettes, cross hole sonic testing, maintenance and quality control of drilling fluids and checking of positioning and measurements. It is intended that instrumentation will be installed to monitor surface displacements and barrette loads during construction.

9. Acknowledgement

The authors gratefully acknowledges FoundationQA Pty Ltd for the use of ROCKET97

10. References

Seidel, J.P. (2000). *ROCKET97 Help Manual*. Department of Civil Engineering, Monash University