

# DESIGN OF A PILED RAFT FOUNDATION FOR TWIN GOLD COAST TOWERS

G. A. Chapman<sup>1</sup>, D. Emery<sup>2</sup> & C.M. Haberfield,<sup>3</sup>

<sup>1</sup> Associate, Golder Associates Pty Ltd, Melbourne, <sup>2</sup> General Manager Engineering, Grocon Pty Ltd Sydney, <sup>3</sup> Principal, Golder Associates Pty Ltd, Melbourne,

## 1. INTRODUCTION

Golder Associates Pty Ltd (Golder Associates) Melbourne office was commissioned by Grocon Pty Ltd (Grocon) to assess the feasibility of engineering a piled raft foundation for the twin 50 storey and 40 storey towers of the Oracle.

The twin towers are to be joined by a multilevel basement and a podium structure. A three level basement excavation is to be up to 10 m deep and is to be supported by a driven and anchored sheet pile wall.

The 3 level podium structure and the towers were initially proposed to be supported either on bored or continuous flight auger (CFA) piles some of which were required to resist permanent uplift loads. The site investigation revealed the presence of a stiff clay layer up to 10 m thick which was present above the weathered siltstone which underlies the site at depth. Up to 15 m thickness of dense to very dense sand extends from basement excavation level to the top of the stiff clay.

Initial geotechnical calculations, carried out by others, indicated that a raft founded on the dense sands would settle between 280 mm and 550 mm under the centre of the 50 storey tower. It was therefore recommended that the towers be supported on bored piles founded into the lower siltstone.

A later analysis of the performance of a piled raft carried out by Golder Associates, indicated that acceptable piled raft settlement performance and bearing capacity could be obtained without the need to extend piles to the rock. A more rigorous analysis carried out for final design, including additional geotechnical investigations and laboratory testing of the clay material, confirmed that a piled raft would provide acceptable settlement performance providing the piles were extended to below the clay layer.

The piled raft analysis provided the structural engineers with estimated pile and ground stiffness values that were incorporated into the structural design models used to predict design actions for the raft and the piles.

The design performance of the piles was confirmed by high strain dynamic pile testing and initial on site monitoring of the CFA piles to confirm that the piles were being constructed to the design depth and with full penetration of the clay layer.

## 2. SITE GROUND CONDITIONS

The initial foundation investigation by others comprised the drilling of four deep and 2 shallow boreholes at the site. The deep boreholes (two under each tower footprint) indicated a foundation stratigraphy as shown in Table 1.

**Table 1 Site Stratigraphy**

Strata	Depth RL (m)		Thickness (m)
	From	To	
Loose Sand FILL	5.3 to 4.6	4.0 to 2.0	0.0 to 4.0
Loose -Medium Dense SAND	5.0 to 2.0	1.0 to -1.0	3.0 to 5.0
Very Dense SAND	1.0 to -1.0	-20.0	18.0 to 19.5
Very Stiff CLAY	-20.0	-22.0 to -26.0	3.0 to 6.0
Hard CLAY	-22.0 to -26.0	-26.0 to -28.0	3.0 to 6.0
Very Dense sandy/clayey GRAVEL	-25.5 to -32.0	-26.0 to -33.0	2.5 – 7.0
SILTSTONE	-30.5 to -33.5	Below RL -44.0	More than 10.5m

The proposed basement excavation was to be taken to RL -4.5 m. This is some 10.5 m below existing ground level which varies between RL 4.8 m and 5.7 m across the site, and up to 5.8 m below the predicted maximum site ground water level.

The site ground water table was measured to vary between about RL - 0.7 m and RL +1.0 m. The site is close to the Nerang River, and a potential increase in ground water level of up to 1.35 m was predicted for extreme tidal or river variations including the possible effects of climate change.

### 3. INITIALLY PROPOSED FOUNDATION SYSTEM

The initial site investigation report recommended supporting the towers and the podium structures either on large diameter bored piles or on 600 mm diameter CFA piles socketed into, or drilled to refusal on top of the underlying siltstone respectively.

Preliminary estimates of a raft only foundation using assumed stiffness values for the clay layer indicated that settlements of between 280 and 550 mm at the centre of the 50 storey tower and 100 to 150 mm at the edge may occur. These settlements were considered to be too large for a raft to be a viable foundation option, and design was progressed on a bored pile solution.

The basement excavation was proposed to be supported either by driven steel sheet piles, a contiguous or secant CFA pile wall or a diaphragm wall, all supported by temporary ground anchors.

### 4. ALTERNATIVE PILED RAFT FOUNDATION

When enquired into indicative costs and availability of piling rigs with sufficient capacity to construct sockets into the siltstone showed potential problems, Golder Associates was engaged to carry out a feasibility study into the use of a piled raft foundation for the towers. The aim of the piled raft alternative foundation was to reduce the number and required length of piles required to provide a suitable foundation for the two towers. After this study produced positive results, Golder Associates was requested to complete additional works. These included the preparation of a final design including carrying out additional geotechnical borehole investigations and laboratory testing, and finally on site QA inspection and verification of pile construction and the preparation of the subgrade upon which the piled raft was poured.

The initial raft foundation solution was rejected because the estimated raft settlements were too high. This was thought to be in part due to the use of a conservative modulus for the clay layer. Most of the computed settlements could be shown to be caused by the imposition of building loads on the clay layer that was present between the upper dense sands and the siltstone. If the clay layer was not present, it would have been possible to found the proposed buildings on a raft foundation as settlements of the dense sands underlying the raft would be small.

By introducing 600 mm diameter CFA piles extending through, or towards the bottom of the clay layer, it was possible to effectively stiffen the settlement response of the clay layer and thus reduce the expected settlements of the piled raft to acceptable values.

Preliminary calculations indicated that long term settlements of less than about 25 mm in the centre of the piled raft, and less than 10 mm at the edge of the piled raft under the action of the tower long term dead and live loads could be achieved by adopting a piled raft solution.

Based on this information, Grocon commissioned Golder Associates to proceed with a detailed design for a piled raft, and to work closely with the project structural engineers to develop the final design of a piled raft foundation.

### 5. METHOD OF ANALYSIS

A series of 2D and 3D analyses were conducted using the commercially available geotechnical finite element package PLAXIS V8 (Plaxis 2002). The analyses included quasi 3D axisymmetric analyses centred on the middle of the lift core of each tower, and 2D analyses of sections taken across the long and short directions of the proposed tower rafts.

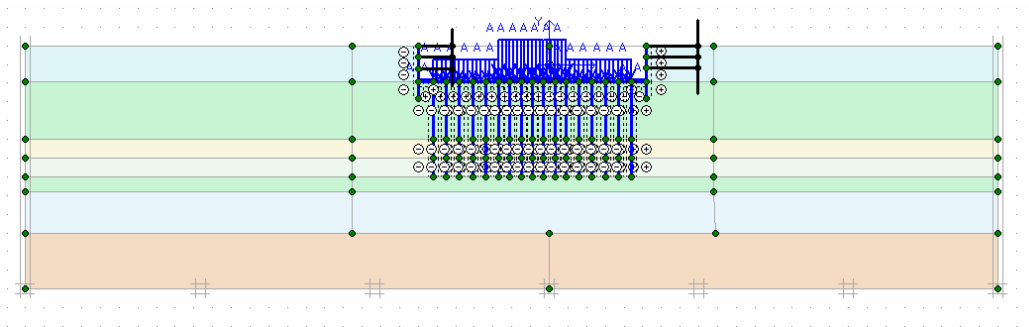
The settlement estimates obtained from the PLAXIS analyses were confirmed with 3D elastic settlement calculations carried out using the 3D layered elastic settlement calculation package FLEA (1999).

Long term drained effective stress parameters were used in the strain hardening PLAXIS soil models to model the behaviour of the foundation soils. The 600 mm piles were modelled as elasto-plastic plate elements, with pile stiffness smeared over the out-of-plane dimension of the pile plate elements in accordance with the adopted pile spacings. The main parameters adopted for the PLAXIS models are presented in Table 2 where the modulus values represent the secant soil modulus at 50 % failure strain under deviatoric loading.

**Table 2 Plaxis Model Parameters**

Elevation Range (RL m)	Strata	Modulus (MPa)	Pile ultimate Shaft Resistance (kPa)
5.3 to 1.0	Loose to Medium dense FILL/SAND	40	
1.0 to -1.0	Dense SAND	45	
-1.0 to -20.0	Very dense SAND	175	200
-20.0 to -25.0	Very stiff silty CLAY	30	70
-25.0 to -30.0	Hard silty CLAY	70	150
-30.0 to -32.0	Very dense sandy clay GRAVEL	175	
-32.0 to -34.0	Very low to low Strength SILTSTONE	175	
-34.0 to -45.0	Low strength SILTSTONE	1000	
Below -45.0	Medium to high strength SILTSTONE	5000	

The PLAXIS models took account of basement excavation and the effects of soil unloading prior to reloading by the piled raft. Possible long term increases in ground water level were also included in the analyses. A typical PLAXIS finite element model used for the analysis is presented in Figure 1.



**Figure 1 : Typical finite element model used for analysis of towers**

The outputs of the PLAXIS analyses were interrogated to obtain estimates of raft deflection and pile loads, as well as raft bending moment and shear force distributions. PLAXIS results were compared with 3D settlement results obtained from axisymmetric PLAXIS models and FLEA analyses.

The estimated pile loads and raft deflections at pile locations were used to obtain values of pile spring stiffness (in units of MN/mm) at working loads as well as raft ground spring stiffness (in units of kPa/mm). These values, together with estimates of raft shear and bending moment distribution and pile loads, were passed to the structural engineers for inclusion in their structural modelling of the building and its foundations.

Typical results showing the variation in pile and raft stiffness with radius from the centre of the piled raft are presented in Figures 2 and 3. The data points in Figures 2 and 3 represent the result from the PLAXIS analyses. The solid lines represent the design lines for structural analysis.

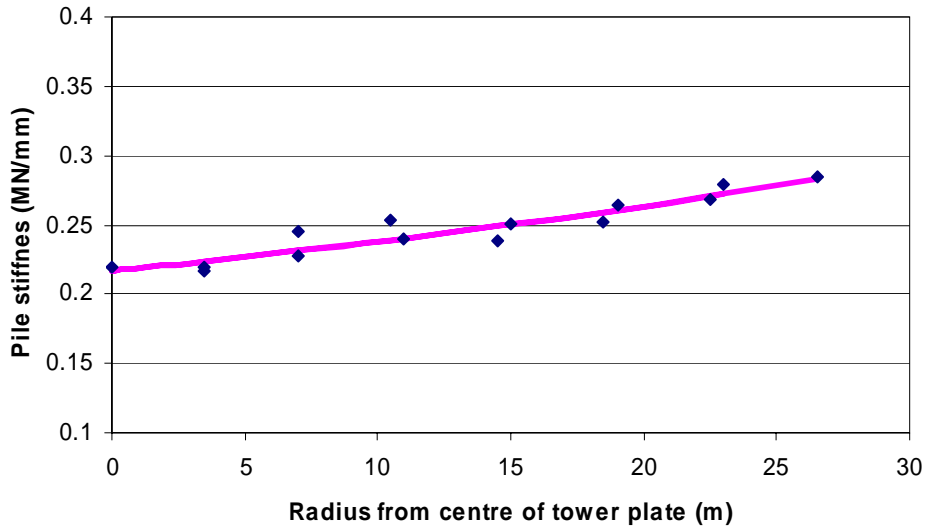


Figure 2 : Typical pile stiffness values calculated from PLAXIS analysis

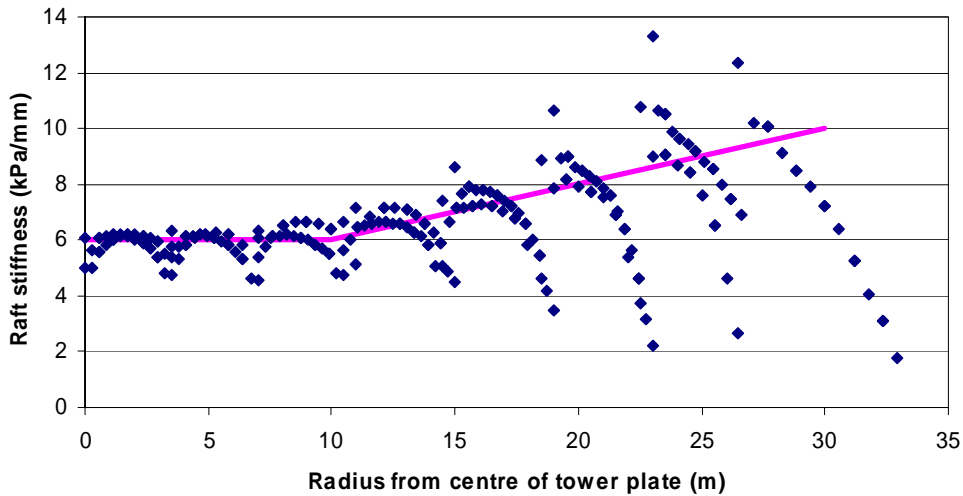


Figure 3 : Typical raft ground stiffness values calculated from PLAXIS analysis

The spacing of piles beneath the raft was adjusted to even out the estimated raft settlement profile as much as practical. The raft was loaded with a series of uniformly distributed loads obtained from spreading the earlier fully piled design large diameter bored pile loads across the tower piled raft footprints. Several different loaded areas were used in the analyses, and raft thicknesses of 1.0 m and 2.5 m were analysed to examine the effect of raft thickness on pile loads and raft deflection.

Sensitivity analyses of the effect of the CFA piles not fully penetrating the clay layer were also carried out. This indicated that as long as the CFA piles penetrated more than 2/3 of the clay layer, settlements would be acceptable.

Sensitivity analyses were also conducted by varying the assumed properties of the clay layer and its thickness, and the overall stiffness of the entire foundation profile from underside of raft to well into the siltstone. The sensitivity analyses indicated that the predicted settlements were not particularly sensitive to changes in the clay layer stiffness alone with differences in maximum settlement of less than 5 mm for variations in modulus of the clay from lowest credible to highest credible values. Results of the calculated raft settlement profiles obtained from the sensitivity analyses in which the stiffness of the whole subsurface profile were changed are presented in Figure 4.

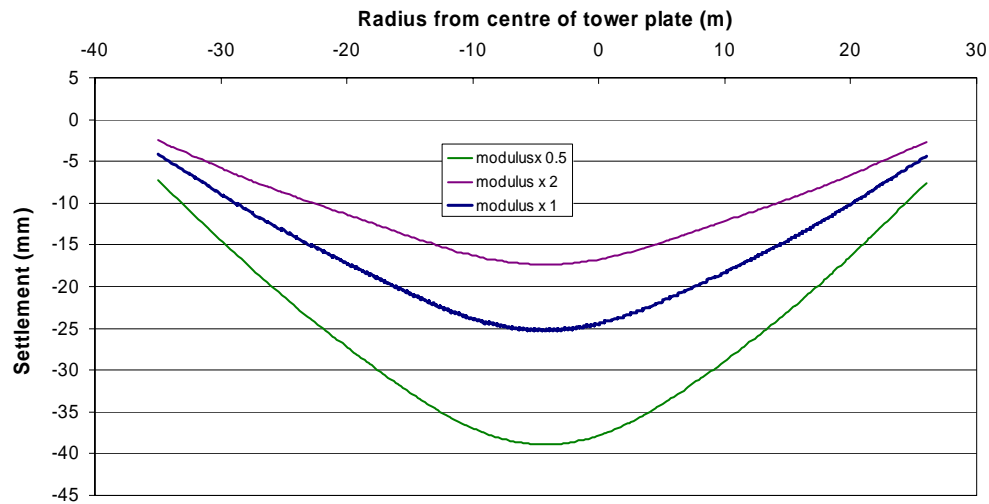


Figure 4 – Profiles of calculated raft settlement for range of stiffness for subsurface materials

## 6. ADDITIONAL FOUNDATION INVESTIGATIONS AND LABORATORY TESTS

As part of the final design process, additional investigation drilling, sampling and testing was carried out. It was initially proposed to carry out pressuremeter testing in the deep clay layer to provide a more accurate assessment of the insitu stiffness of the clay layer. This proposal had to be abandoned on site after the drilling contractor who had insufficient casing to drill to the clay without using drilling fluid for borehole wall support expressed concern that the pressuremeter may be lost down the borehole due to collapse of the overlying sands. A planned thin walled sampling of the clay layer was able to be carried out and tube samples were selected for one dimensional oedometer testing to provide additional data on the clay stratum stiffness.

The oedometer test results showed that the clay layer was of relatively high stiffness, and that the measured stiffness of the samples was being affected by compliance errors in the test machines and by creep in the porous stones.

The results of the oedometer tests were used as input for the final PLAXIS analyses after making allowance for machine compliance and creep of the porous stones.

## 7. FOUNDATION INSTALLATION QUALITY ASSURANCE

As part of the final design solution, it was necessary to confirm that the CFA piles penetrated the clay layer, and that the foundation subgrade on which the tower rafts supported by the CFA piles were to be cast was satisfactory.

The penetration of the clay layer by the CFA piles, which was a building owner requirement for the adoption of the piled raft foundation solution, was confirmed by a geotechnical engineer logging the installation of the first 8 piles installed in each tower raft footprint. Confirmation that the CFA piles had fully penetrated the clay layer was provided by observing the presence of sand on the tip of the CFA auger with clay above it as the auger was extracted. The first piles were spread over each tower raft footprint to provide a reasonable coverage of the entire raft area. It was also possible to observe the depth at which the top of the clay layer was encountered in the records provided by Frankipile, the piling contractor for the project, from their onboard CFA pile rig instrumentation records which were provided for review.

The piled raft design solution relied upon the raft being cast on the dense sand that was present at the proposed underside of raft level across the site. Prior to casting each segment of the tower rafts, a geotechnical engineer attended site and carried out a series of hand held dynamic cone penetrometer tests in each area to verify that the subgrade comprised compacted dense sand. In one area of the lift pit excavation in one tower that had been over excavated and backfilled, the testing revealed medium density sand. This area was rejected and the loose material was excavated and re-compacted in layers. Additional testing confirmed the backfill, and the material below it was all dense sand and the raft segment in the lift pit was then poured.

## 8. BENEFITS PROVIDED BY THE ADOPTION OF A PILED RAFT

The adoption of a piled raft foundation provided a number of significant benefits to the project. These included the following:

- A reduction in the number, diameter and length of piling required for the foundations
- The ability to source more CFA piling equipment with the capacity to install the piles
- An overall reduction in piling costs
- A reduction in construction time for the foundations because CFA piles can be constructed much faster than large diameter, bored piles rock socketed into the underlying siltstone. Typically ten to twelve 26 m long CFA piles were able to be constructed in one day with one piling rig, compared to a likely production rate of one large diameter rock socketed bored pile per day per rig
- A reduction in set up time and equipment required on site for CFA piling as compared to that required for bored piles under drilling fluid
- A reduction in the amount of bored pile spoil to be removed from site.



Figure 5 – Photograph of site during pouring of tower raft slab

## 9. CONCLUSIONS

A redesign of the proposed bored pile foundations for the twin high rise towers of the Oracle project currently under construction by Grocon on the Gold Coast has allowed the adoption of a pile raft in lieu of a fully piled foundation solution.

The piles for the piled raft could be constructed using Frankpile's available CFA piling equipment in a shorter time frame than the originally proposed bored piles.

The piled raft was designed to deliver satisfactory settlements under working loads. Additional geotechnical investigation and laboratory testing confirmed that the settlement arising from the deep clay layer, initially considered to be the source of large settlements for a raft only foundation, could be controlled by the introduction of a reduced number of CFA piles penetrating the clay stratum.

## 10. REFERENCES

- FLEA, (1999). "Finite Layer Elastic Analysis Version 5.0" Users Manual, Centre for Geotechnical Research, University of Sydney.
- Plaxis, B.V. (2002). "PLAXIS 2D –Version 8" Edited by R.B.J. Brinkgreve, Delft University of Technology & PLAXIS BV. A. A. Balkema, The Netherlands