FOUNDATION INVESTIGATION IN WEAK SLAKING ROCK, DARWIN, AUSTRALIA

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ABSTRACT

Most of the Darwin CBD is underlain by a Mesozoic rock locally termed porcellanite. Much of this is a silcrete which can be up to 8 m thick and is typically high to very high strength. Many of Darwin's buildings are supported on shallow footings founded on porcellanite and there is little available geotechnical information of relevance to foundation design in the weathered Proterozoic phyllite underlying the porcellanite.

This paper describes a foundation investigation and design for a 34 storey building with sunken lift core in Darwin which, when complete will be the tallest in that city. Preliminary footing design by others was based on the precedent of shallow footings supported in the porcellanite. A preliminary geotechnical investigation (by others) comprising boreholes to a depth of about 15 m, indicated that a significant thickness of porcellanite underlies only part of the site and that footings would need to be supported on older deeply weathered phyllite or a thin layer of porcellanite overlying phyllite. Based on low soil stiffness properties estimated mainly on the basis of low SPT 'N' values large diameter deep bored piles were proposed as a means of reducing differential settlement.

To further investigate the proposed footing solution options, a supplementary geotechnical investigation was undertaken to obtain estimates of the engineering properties of the phyllite. Diamond core drilling with pressuremeter testing was undertaken. However core recovery was poor and the results of the pressuremeter testing were affected by the slaking of the phyllite. The stiffness of the phyllite was subsequently estimated using dynamic load testing of precast concrete piles placed into pre-drilled sockets at select depths. Analyses using the estimated stiffness properties of the phyllite suggested that differential settlements could be kept within acceptable limits using a shallow footing solution, which was subsequently adopted. The footing system has since been constructed and construction is near completion. Settlement monitoring indicates settlements less than design predictions.

1 INTRODUCTION

"Evolution on Gardiner" (Evolution) is a 34 storey residential development under construction in Darwin, Northern Territory and is currently the tallest building in that city.

The Northern Territory Geological Survey, 1:100,000 scale, Darwin map sheet indicates that central Darwin, including the site of Evolution is underlain by about 3 m to 10 m of the Mesozoic Age Bathurst Island Formation. This formation is noted on the map sheet to comprise horizontally bedded, silicified (silcrete), ferruginous or kaolinised siltstone or claystone (referred to as porcellanite), with a thin basal unit of quartz conglomerate. This formation unconformably overlies the Proterozoic age Burrell Creek Formation, comprising steeply dipping, metamorphosed siltstones and phyllites with numerous quartz veins. The contact between the units is irregular, undulating, faulted in places and typically marked by a band of rounded quartz pebbles.

The design of Evolution incorporates a 34 level central tower (12 m by 24 m plan dimensions) and a five level podium structure (38 m by 38 m plan dimensions). Tower column loads are in the range of about 12 MN to 27 MN and podium column loads in the range of about 3 MN to 5MN. Historically, the low rise buildings in Darwin have been founded upon the porcellanite. An allowable bearing pressure of about 800 kPa has been adopted for footings founded on this material. It was in general accordance with this precedent that conceptual footing designs for Evolution were developed. Figure 1 shows the conceptual footing design for Evolution comprising a raft footing beneath the central lift core and shallow pad footings supporting the tower and podium columns.

Geotechnical investigations undertaken at the site by others suggested that at the proposed founding level porcellanite was not encountered over the entire plan area of the site. Shallow footings on the eastern side of the site would be supported on weathered phyllite. Core recovery in boreholes drilled on the eastern side of the site was poor. Field descriptions of the strength of the phyllite describe it as predominantly extremely low. In some boreholes, the test results suggested an apparent weakening of the weathered phyllite with depth. It was inferred that the difference in thickness within the porcellanite was due to a fault running through the site at the approximate location shown by the thick broken line in Figure 1.

Based primarily on the limited geotechnical data available, finite element analyses were undertaken by others. The Young's modulus of the phyllite was estimated as 36 MPa to 60 MPa. The results of the analyses suggested that for the concept footing design, differential settlements of 40 mm to 90 mm could occur. Settlements of this magnitude were considered unacceptable. Large diameter bored piles were suggested as a means of reducing differential settlements. However, this posed significant practical difficulties to the development as suitable piling equipment was not available in Darwin.

It was also suggested by others that with a better measure of ground stiffness, such as might be gained from *in situ* testing, analyses could be repeated to gain a better estimate of differential settlement. The client opted to pursue this course of action and commissioned a supplementary geotechnical investigation comprising additional drilling and pressuremeter testing.

The primary objectives of the supplementary geotechnical investigation were to:

- better define the geotechnical properties beneath the site, in particular the strength and stiffness of materials
- assess the variation in the strength and stiffness of the weathered phyllite with depth and
- undertake further analyses based on new geotechnical information and, if appropriate, revise foundation recommendations.

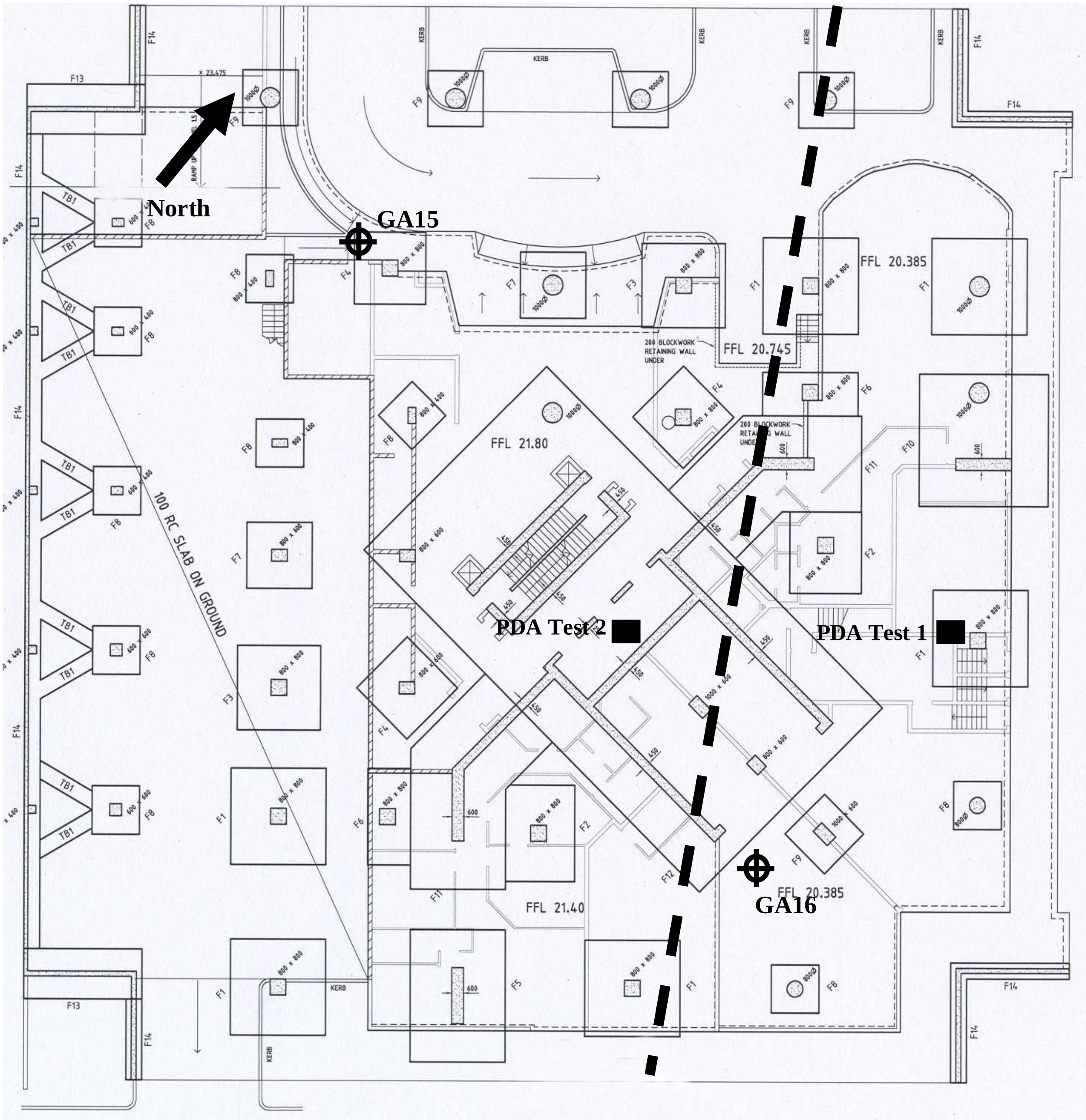

Figure 1: Conceptual footing design showing approximate location of inferred fault (dashed line).

2 SUPPLEMENTARY GEOTECHNICAL INVESTIGATION

Two additional boreholes were drilled on the site to depths of 50 m and 22 m. One borehole was drilled on each side of the site, at locations either side of the inferred fault and with inferred different thickness of Porcellanite, as shown in Figure 1. With greater depth drilled, core recovery within the weathered phyllite became less. Below 30 m depth, core recovery was less than 70 % and below 40 m less than 30%. The phyllite was found to have a strong vertically oriented fabric and there was no apparent decrease in weathering grade over the length that the borehole was drilled.

The materials recovered in the boreholes are summarized in Table 1 below.

Table 1: Summary of Subsurface Conditions – Golder Associates' Boreholes

Unit	BHGA15 (RL 21.9 m AHD)		BHGA16 (RL 20.4 m AHD)	
	Inferred Depth Range (m)	***RL (m AHD)***	**Inferred Depth Range (m)**	***RL (m AHD)***
Unit 1 Clayey GRAVEL	0.0 – 2.0	*21.9 – 19.9*	0.0 – 1.3	*20.4 – 19.2*
Unit 2a Porcellanite	2.0 – 8.4	*19.9 – 13.5*	1.3 – 4.8	*19.2 – 15.7*
Unit 2b Siltstone/Sandstone	8.4 – 10.4	*13.5 – 11.5*	-	-
Unit 3 Phyllite/Clay	10.4 – 50.0*	*11.5 to -28.1**	4.8 – 22.0*	*15.7 to -1.5**

* End of Borehole

A brief summary of the units encountered is presented below:

Unit 1 clayey Gravel –This unit was generally very loose to medium dense, fine to medium grained, subangular, red-brown or yellow-brown with some ferricrete. It is inferred to be a product of the lateritic weathering of the underlying porcellanite.

Unit 2a – Porcellanite (silicified siltstone or silcrete) - This unit was encountered within both boreholes immediately beneath the Gravel, extending to depths of between 4.8 m and 8.4 m below ground level. This unit was slightly to highly weathered, of medium to high rock strength, pale grey, white, red or brown with no discernable bedding.

Porcellanite was observed within the excavations on site and was noted to contain zones of highly fractured material. Discontinuities within the porcellanite were typically irregular, with smooth to rough surfaces. This unit is inferred to represent silicified Bathurst Island Formation.

Unit 2b – Siltstone/Sandstone/Conglomerate - Highly weathered, medium rock strength, fine to medium grained white and red brown siltstone and sandstone was encountered below Unit 3a in one of the boreholes. This unit is inferred to represent a basal unit of the Bathurst Island Formation that has derived from mechanical weathering of the underlying phyllite of the Burrell Creek Formation (Pietsch 1983). Given that it was not encountered in both boreholes, this unit may be confined to channels or localised pockets.

Unit 3 – Weathered Phyllite - Unit 3b is unconformably underlain by Phyllite of the Burrell Creek Formation. This low grade metamorphic rock appears to have undergone significant and deep weathering and was typically recovered as pale brown or yellow brown, extremely weathered, very low to extremely low rock strength material. The two boreholes encountered this unit at 10.4 m and 4.8 m respectively below ground level and both boreholes terminated within this unit.

A strong fabric oriented at between 70° and 90° (from horizontal) was observed within this material.

3 *IN SITU* AND LABORATORY TESTING

Pressuremeter testing was undertaken but was largely unsuccessful within the phyllite. Figure 2 presents the results of pressuremeter tests undertaken within porcellanite, and phyllite. Also shown on the same chart are the results of a test in which the pressuremeter probe was expanded outside of the borehole (free air expansion). The results obtained in the porcellanite appear reasonable. However, results in the phyllite suggest that the probe was probably not reaching the sides of the borehole.

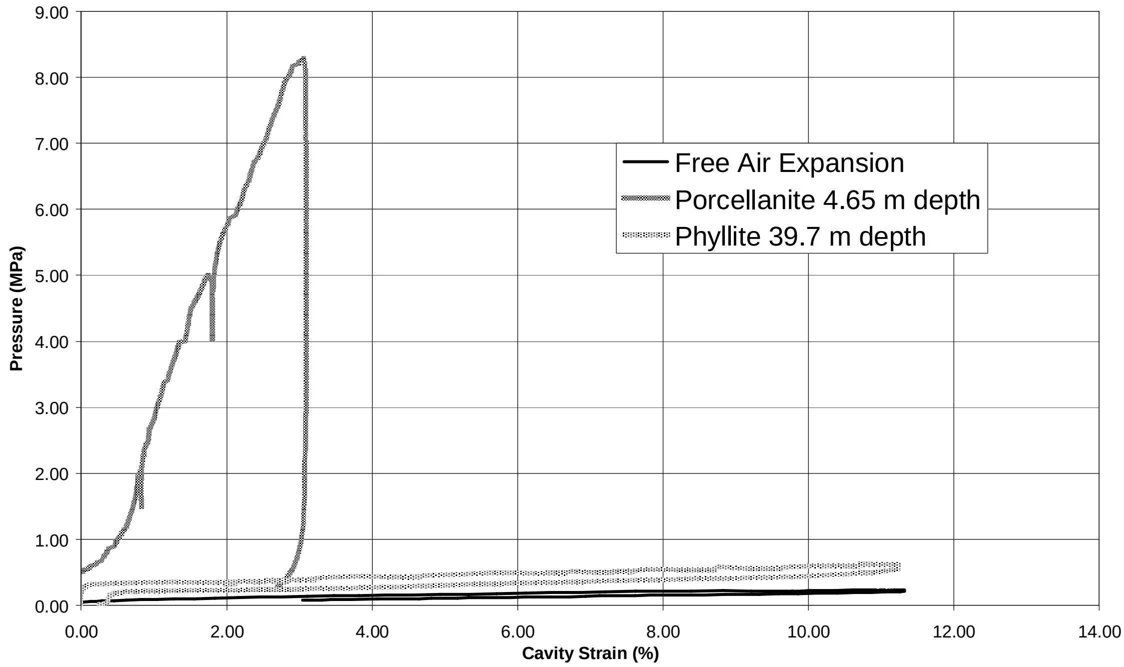

Figure 2: Results of pressuremeter testing showing typical test in porcellanite, phyllite and free air expansion

Suitable samples for UCS testing were not obtained. Moisture content testing was undertaken and the results are presented in Figure 3. Measured moisture contents are relatively high, being typically of the order of 10 % to 30 %. There appears to be a slight trend towards increasing moisture content with depth which may be a function of stress relief within the material.

The results of the supplementary geotechnical investigation suggest that the weathered phyllite is highly susceptible to slaking. It was inferred that in drilling the boreholes, using wireline diamond coring with mudflush the weathered phyllite was slaking, causing the borehole to be oversized and core to be undersized. Therefore pressuremeter testing was not successful and core recovery poor. Alternative means of drilling were not available at the time of the geotechnical investigation.

The slaking characteristics of the phyllite were further investigated by observing the behaviour of the material when placed into a container of water. Almost immediately upon contact with still water, the material was observed to break apart, leaving sediment and some larger pieces of rock on the base of the container.

The two additional boreholes and pressuremeter testing did not achieve the objective of providing suitable strength and stiffness data to allow reassessment of the footing system. However, they did provide sufficient information to allow a conceptual geotechnical model for the site to be developed.

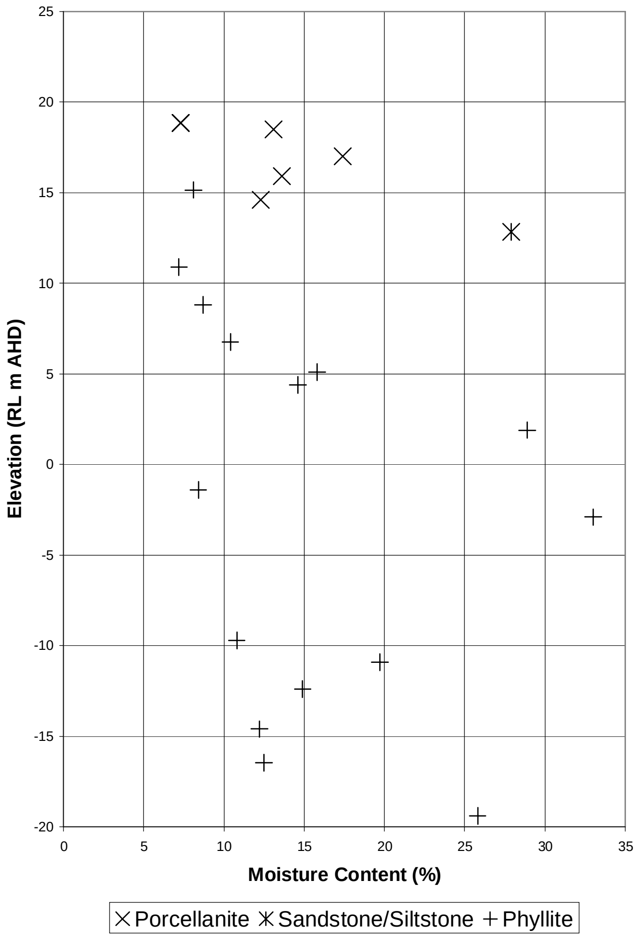

Figure 3: Moisture content versus elevation.

4 CONCEPTUAL MODEL

Figure 4 presents a three dimensional sketch of the inferred subsurface conditions on the basis of the results of the supplementary geotechnical investigation described above. The conceptual footing system is also indicated on the sketch. The inferred conceptual model is described below.

Phyllite forms the bedrock of the site and is deeply weathered to depths in excess of 50 m. The phyllite has a strong vertically oriented fabric and so is likely to have anistropic strength and stiffness characteristics. In addition, vertical hydraulic conductivity is likely to be much greater than horizontal hydraulic conductivity.

The Proterozoic phyllite is much older than the overlying Mesozoic porcellanite. The phyllite was extensively chemically and mechanically weathered prior to the deposition of the sandstones and siltstones that were to form the matrix of the porcellanite. The upper surface of the phyllite is irregular and there are a number of channels eroded into the top of the phyllite. These channels are now infilled by sandstone, siltstone and conglomerate.

A past arid climate and associated leaching of minerals from within the phyllite has resulted in the formation of a silcrete cap (porcellanite) over the phyllite. After formation of the porcellanite faulting has occurred, giving rise to the variable thickness of the porcellanite on the site. Recent lateritic weathering has resulted in the formation of clayey gravel at the surface of the phyllite.

The groundwater level is about 2 m below the surface. The porcellanite appears to be relatively impermeable compared with the underlying phyllite.

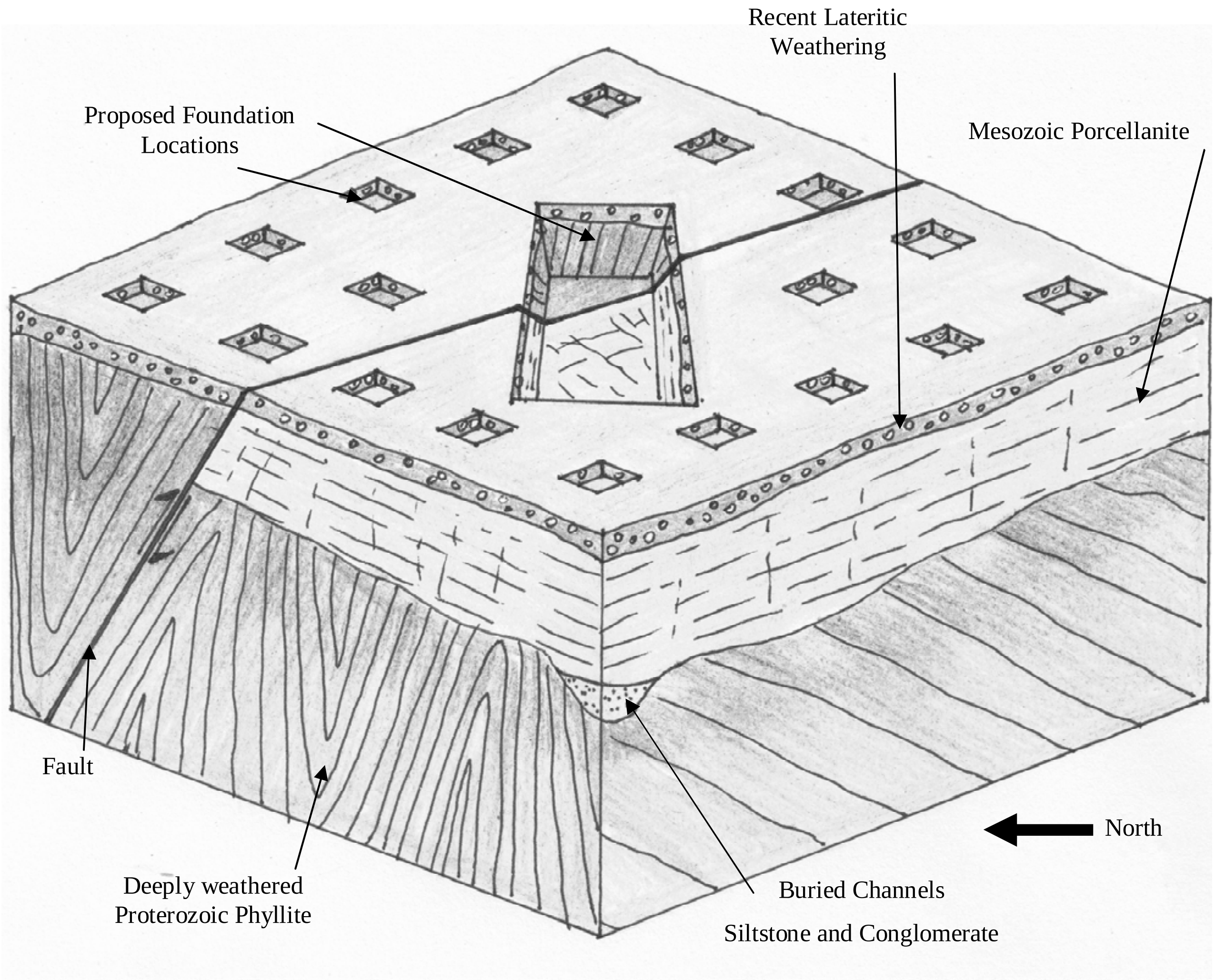

Figure 4: Inferred 3 dimensional conceptual model.

5 CONSEQUENCES OF CONCEPTUAL MODEL

Based on the inferred model developed and described above, implications for the Evolution foundations were identified. It was apparent that heavy slaking of phyllite at the borehole walls had occurred during drilling. This suggested that the earlier field descriptions of strength (undertaken by others and upon which initial settlement analyses were undertaken) were probably unreliable. Similarly, pressuremeter testing results were also unreliable.

The slaking properties of the phyllite could make the construction of bored piles difficult. Slaking of materials from the sides of the bored socket and groundwater inflows could reduce the friction potentially mobilized on the sides of the pile socket.

Given the apparently high void ratio and assuming that minerals (such as silica) have been leached from the phyllite, it was assumed that its *in situ* strength is derived from the interlocking nature of the minerals. A “stack of pins model” was assumed whereby, if the interlocking mineral structure is undisturbed, stress placed on the phyllite is transferred through these interlocking minerals. If the structure is disturbed, collapse behaviour is observed and slaking occurs. This implies that the *in situ* mass strength and stiffness of the phyllite may be many times greater than that of the disturbed borehole walls and core samples.

Based on this model, it was proposed that a foundation system, such as shallow footings, that do not significantly disturb the mineral structure of the phyllite may be suitable. It remained to test the *in situ* Young's Modulus of the phyllite in order to obtain properties that would be suitable for settlement analyses.

6 PILE DRIVING TESTING

Pile driving tests were recommended as a means of measuring the *in situ* stiffness at various depths within the weathered phyllite. A total of 5 pile driving tests was undertaken on two 450 mm square precast driven piles. These tests were undertaken at two locations on the site one within the proposed lift core and the second beneath one of the columns as shown in Figure 1.

A 900 mm diameter hole was drilled through the upper porcellanite layer to allow testing to be undertaken in the underlying weathered phyllite. The precast pile was then placed in the predrilled hole and the annulus between the pile and the predrilled hole loosely backfilled with sand. The pile was then driven, whilst it was monitored using Pile Driving Analysis (PDA) equipment and the resulting stress waves were recorded.

The preboring was undertaken using a solid auger. It was noted during the preboring that there was high drilling resistance to the auger. Slaking of the sides of the borehole was evident and groundwater inflows from the phyllite were high.

Tests at various elevations were undertaken by withdrawing the precast pile and further advancing the prebored hole to a new elevation. In this manner tests were undertaken at elevations of 12.5 m, 8.2 m and 7.65 m (AHD).

The permanent set of the piles during driving was relatively low, with a maximum permanent toe displacement of 12.7 mm measured. Interpretation of the results using CAPWAP signal matching software was undertaken by others and an Estimate of the Young's Modulus of the material at the test depth was made. The results are summarised in Table 2.

Table 2: Summary of Young's modulus estimated from pile driving tests.

Test Pile No.	Elevation of Pile Toe (m AHD)	Estimated Young's Modulus (MPa)
1	12.5	575
	8.2	365
	7.65	1,600
2	0.6	186
	0.6	345

The results for Pile 1 indicate that the highly weathered phyllite at about RL 12.5 m has a Young's modulus of about 500 MPa to 600 MPa. This reduces to about 350 MPa at RL 8.2 m in material described as extremely weathered to highly weathered phyllite. However, this value may have been increased due to compaction of the phyllite below the pile toe due to the driving process. The high value of 1600 MPa obtained for Pile 1 at RL 7.65 m may also reflect some compaction of the phyllite below the toe of the pile.

The results for Pile 2 indicated Young's modulus values of between about 190 MPa and 350 MPa for material described from borehole core as extremely weathered phyllite. The higher value of about 350 MPa may reflect some compaction of the phyllite below the toe of the pile.

Following an assessment of the test results, Young's modulus values of 150 MPa and 300 MPa were assumed to bracket the likely *in situ* mass modulus of the extremely weathered phyllite at about RL 0 m. These values were adopted for finite element analysis of the building. These adopted values were about five times greater than the 36 MPa to 60 MPa assumed in the initial analyses.

7 SETTLEMENT ANALYSIS

The concept foundation system, comprising shallow pad footings to support columns and a raft slab to support the lift core of the building was re-analysed using the ground stiffness properties estimated on the basis of the PDA testing. It was assumed that the building footings applied a bearing pressure of 800 kPa.

The finite element analysis was undertaken using PLAXIS 2D finite element software. The two dimensional model adopted for the analysis and the stiffness properties assumed is shown graphically in Figure 5. It should be noted that the 2D analysis is an approximation to the 3D geometry of this problem. However, given the uncertainty associated with the parameters, it is considered that the 2D analysis would provide a prudent and practical estimate of settlement. A range of Young's moduli (upper and lower bound) was adopted for the phyllite which would provide a range of likely settlement for the parameters chosen.

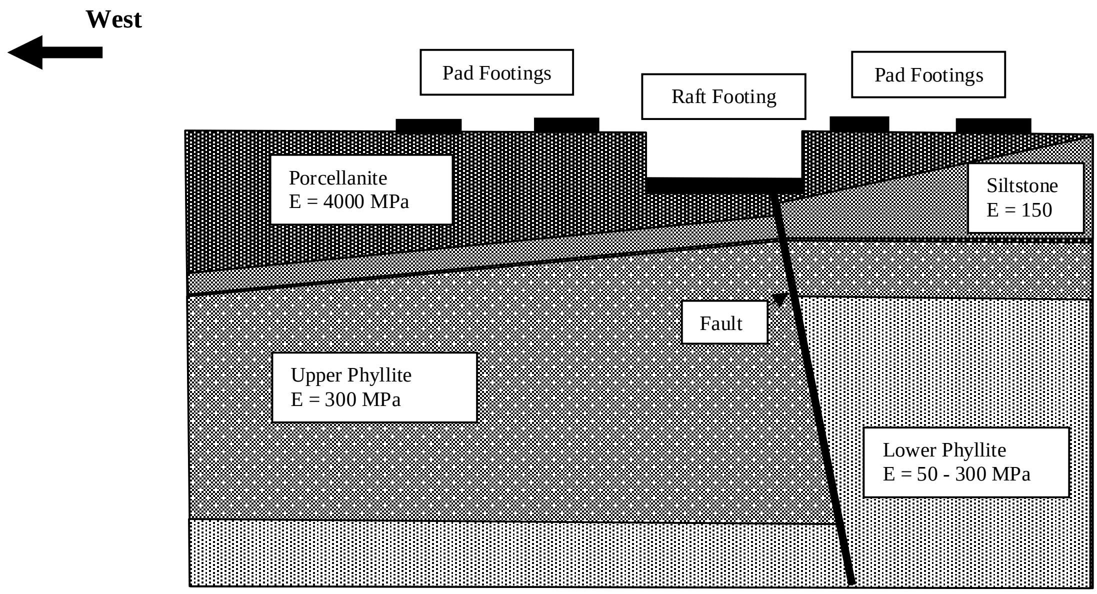

Figure 5: Properties adopted for PLAXIS analysis.

The settlement profile estimated from the PLAXIS analysis for the lower and upper bound Young's modulus values assumed is shown in Figure 6. For comparison, a settlement profile for elastic modulus of 50 MPa in the phyllite (similar to the initial estimates of 36 MPa to 60 MPa) is also shown.

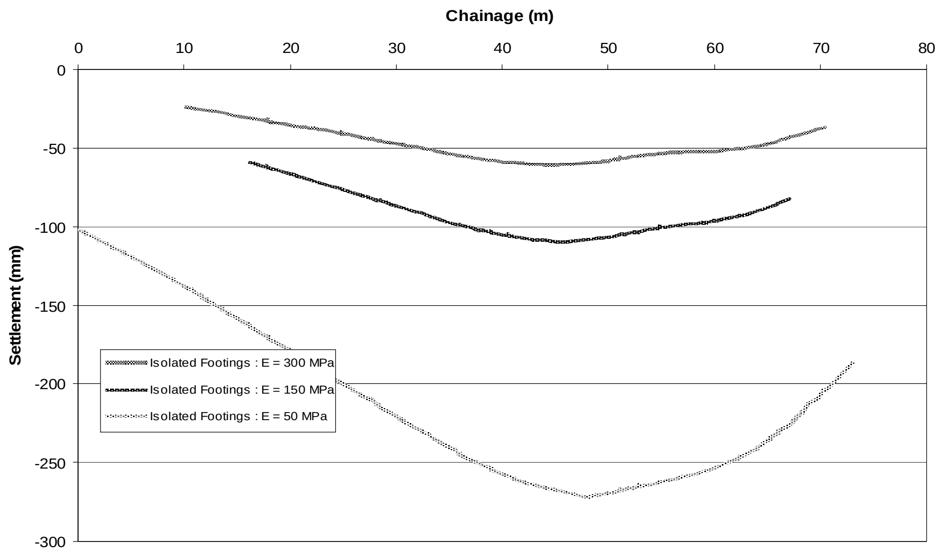

Figure 6: Results of settlement analyses.

Figure 6 shows estimated settlement of 60 mm to 110 mm at the centre of the tower and about 30 mm to 60 mm at the edge of the building footprint. The higher settlement values are for the lower bound mass modulus of 150 MPa.

Maximum estimated gradient of the deformed surface profile ranges from about 1/400 to 1/700 for Young's modulus values in the phyllite of 150 MPa and 300 MPa respectively.

These displacement estimates were considered acceptable by the structural engineer and client and the concept footing design was subsequently adopted. Measurements of footing displacement were undertaken during construction when the building height reached levels 7, 13, 19, 25, and 34. No discernable footing displacement (measured to the nearest 1 mm) has been recorded.

8 CONCLUSIONS

This paper presents an example of a case where traditional ground investigation techniques were unable to provide suitable engineering properties to facilitate foundation design. This occurred due to the slaking characteristics of the weathered phyllite of the Burrell Creek Formation. The development of a conceptual model consistent with the observed material behaviour aided in allowing an alternative means of geotechnical investigation to be employed. In this case, dynamic load testing of precast piles placed in predrilled holes at various depths was used to estimate the mass modulus of the weathered phyllite of the Burrell Creek Formation.

9 ACKNOWLEDGEMENTS

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10 REFERENCE

Pietsch, B.A., 1:100,000 Geological Map Series, Explanatory Notes, Darwin 5073, Northern Territory Geological Survey, 1983.