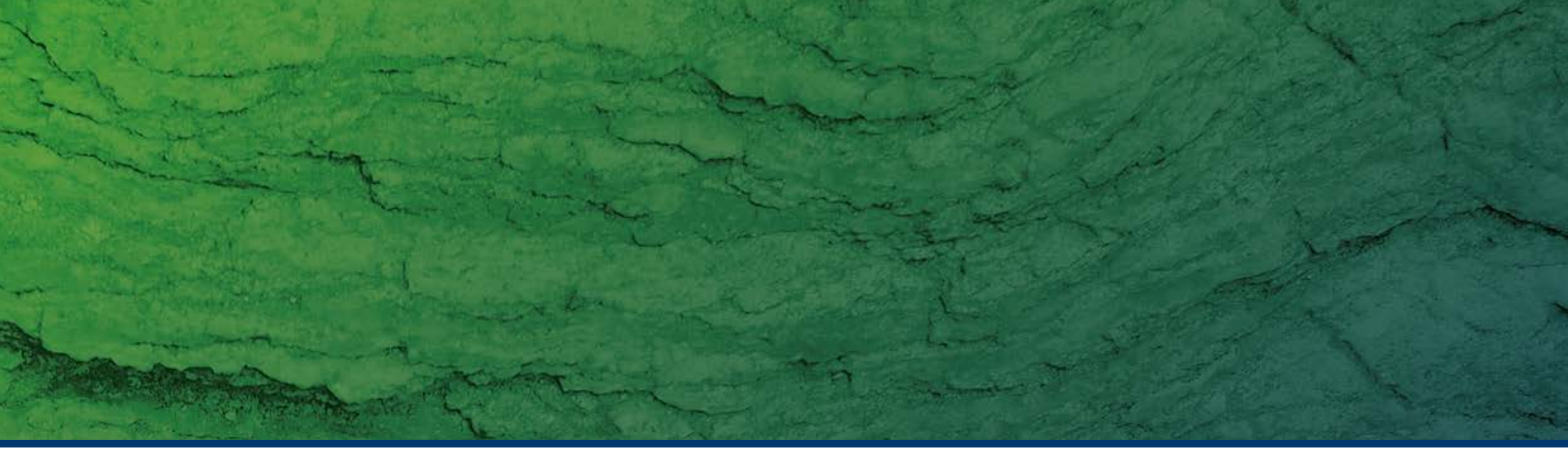
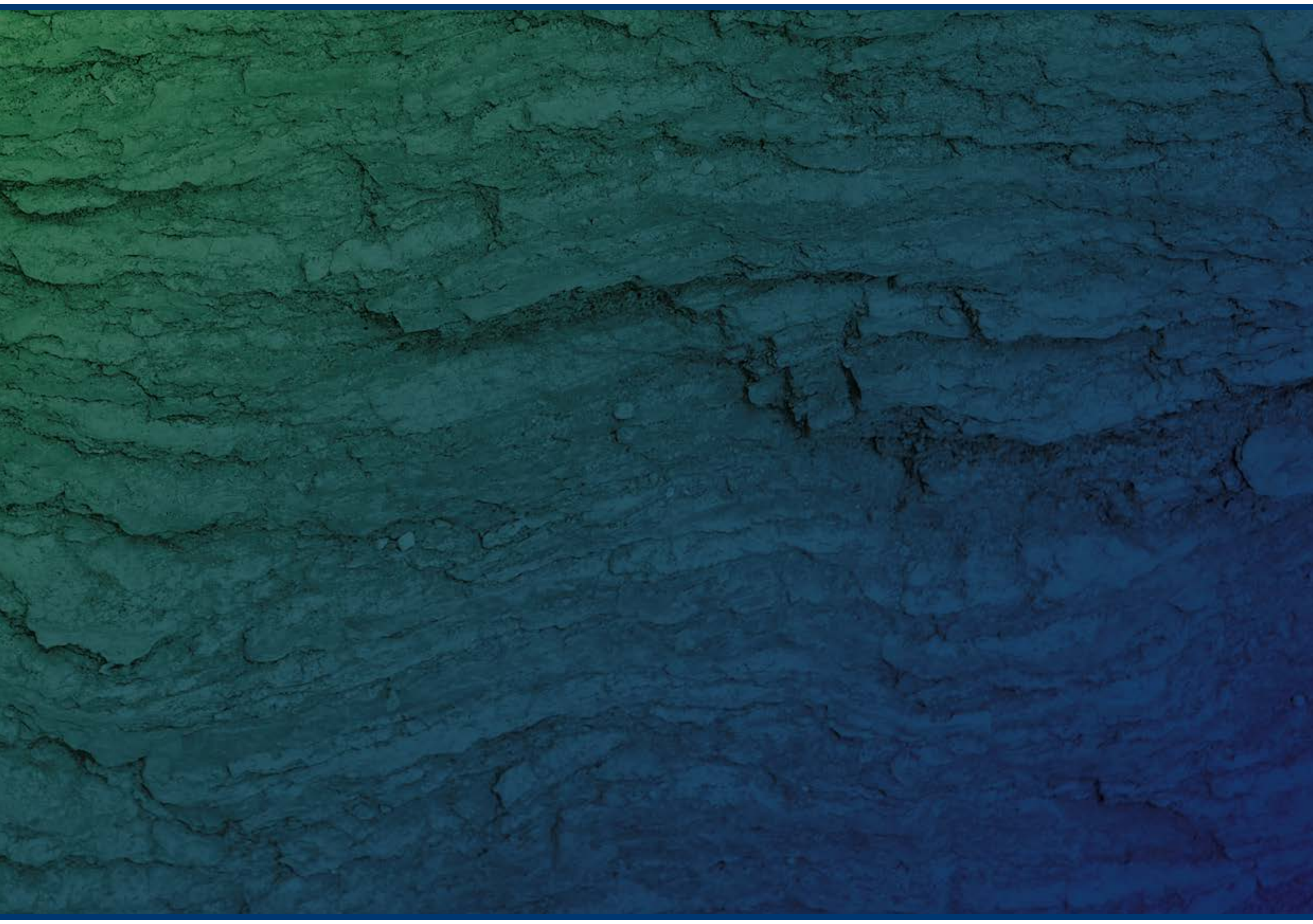


PROCEEDINGS

2019 AUSTRALIAN GEOMECHANICS SOCIETY VICTORIAN SYMPOSIUM

Geotechnical characterisation – managing design and construction risk

Wednesday, 30 October 2019, 8:00am – 7:00pm
Rydges Hotel, 186 Exhibition Street, Melbourne



AUSTRALIAN GEOMECHANICS SOCIETY
VICTORIA CHAPTER

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PREFACE

The Victorian chapter of the Australian Geomechanics Society invited academics and practitioners in the field of geotechnical and ground engineering to attend the 2019 Australian Geomechanics Society Victorian Symposium held on 30 October 2019.

In recent years Victoria has seen significant growth in the construction industry. Investment in both public infrastructure and commercial real estate is growing, and as our cities and infrastructure grow, so too does the need to develop parcels of land with challenging ground conditions. Economical and safe geotechnical design requires efficient and well thought through ground investigation and characterisation to identify and manage ground risks and opportunities.

The 2019 Australian Geomechanics Society Victorian Symposium presents an overview of current state of-the-art practices, innovation, new research results and case studies relating to geotechnical characterisation with an emphasis on its implications for addressing and managing design and construction risk. The 2019 Symposium brought together professional engineers, researchers, specialist contractors, regulators, educators and students to share and discuss their experiences on the topic of ground characterisation.

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Characterisation of ground conditions to reduce risk for building footing design in Melbourne, Victoria

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ABSTRACT

Footing systems for many of Melbourne's tall buildings are rarely governed by their ultimate capacity, rather, the allowable displacement of the footing system is likely to be the primary consideration. An appropriate geotechnical investigation must therefore assess the stiffness characteristics of the *in situ* ground, and in particular the founding materials that support these footing systems. In order to further characterise ground conditions and better manage ground risk, *in situ* pressuremeter testing can be used in conjunction with more traditional investigation methods and verification activities during construction to provide prudent yet not overly conservative geotechnical advice and design for these developments. This paper discusses two case studies comprising historical geotechnical investigations for buildings in Melbourne, where the use of pressuremeter testing in conjunction with traditional investigation methods have provided greater confidence on the deformation behaviour of founding conditions. This paper sets out how the results from the investigations were used to inform footing solutions to be designed and subsequently constructed, as well as discussing the value of verification activities to confirm design assumptions, further reducing the ground risk during construction and realising efficiencies in the footing design.

Keywords: geotechnical investigation, pressuremeter testing, footing design

1 INTRODUCTION

One of the largest elements of financial and technical risk for infrastructure and building projects typically lies in a lack of understanding of subsurface conditions, with unforeseen or variable ground conditions having the potential to significantly increase the cost of these large projects (Littlejohn et al., 1994). The increased risk to projects with decreasing geotechnical investigation cost has also been well documented, with typical geotechnical investigation costs for projects falling within the range of between about 0.1% to 4% of the total project cost (Whyte, 1995 and Look, 2006). For building developments, the percentage of cost allocated for the geotechnical investigation is often at the lower end of this range, even though the consequences of poor design of a large building development can result in significant rectification and legal costs.

The complex geology across the Melbourne area presents additional geotechnical challenges that need to be considered to provide increased confidence in footing system performance. The design of footing systems in these subsurface conditions are rarely governed by their ultimate capacity; rather serviceability considerations and the allowable displacement of these footing systems is likely to be the primary consideration for design (for example as described in Haberfield and Lochaden, 2019). Inadequate serviceability design can result in large movements of the footing systems that at best, may result in only minor aesthetic issues, and at worst, compromise the structural integrity of the building or result in damage that may make the structure uninhabitable.

2 OVERVIEW OF FOOTING INVESTIGATIONS FOR TALL BUILDINGS IN MELBOURNE

Due to the relatively large loads, investigations for tall buildings in Melbourne are typically focused on obtaining strength and deformation characteristics of the weathered bedrock underlying the soil strata, which form the founding conditions for the footing systems for these structures. Investigations for these buildings typically comprise the drilling of several boreholes across the site and obtaining rock samples for laboratory testing and analysis. The laboratory testing undertaken as part of these investigations may also be relatively limited due to cost constraints and typically focusses on assessing the strength and weathering profiles of the founding layers. Often, the laboratory testing is limited to a combination of uniaxial compressive strength (UCS) tests, point load index tests and saturated moisture content (MC) tests on recovered rock samples at regularly spaced intervals, with weathering and strength grades assessed based on local historical correlations (for example Chiu, 1981 and Gu, 2008).

In order to obtain information on the deformation characteristics of the founding layers, measurement of the strain deformation of UCS samples during testing can also be undertaken, which allows an estimate of the sample modulus to be made. However, there are several limitations with this approach, especially in weak sedimentary rock that can affect the calculated values from laboratory tests, including sample preparation issues, rock fabric structure influence and equipment accuracy. Underestimates of the rock strength from UCS and point load index laboratory tests are also often recorded due to premature failure on bedding discontinuity features within the rock sample. As such, it is well recognised that there are a number of challenges with correlating the strength and stiffness properties determined from a laboratory test on a small intact rock sample to the greater *in situ* weathered rock mass (Macklin et al., 2014).

2.1 Overview of *in situ* pressuremeter testing for ground characterisation

Based on the above described limitations and to further characterise ground conditions and hence manage risk, the use of pressuremeter (PM) testing can be undertaken to provide greater confidence in the deformation behaviour of founding materials that support the buildings footing systems.

PM testing is used to measure the displacement response of subsurface materials to an applied pressure. The results from the PM testing can be used to directly calculate an estimate of the shear modulus (G) of the material tested, with G equal to twice the measured gradient if plotted as pressure (ρ – measured in units of MPa) versus cavity strain (ε_c – measured in units of mm and converted to a percentage). From the data obtained, the Young's Modulus (E) of the *in situ* material may be calculated through elastic theory, and inferences made with respect to the failure strength of the material and its unload-reload behaviour (Clarke 1995). A detailed discussion on the theory and background of PM testing is outside the scope of this paper and previous work on this topic, such as Clarke (1995) can be referred to for further detail. More locally, work by Haberfield (1997) contains useful information on PM testing specifically relating to weak rock.

As discussed in Haberfield (1997), determination of design parameters from PM tests, such as *in situ* stress and undrained shear strength is often unreliable. However, PM testing can provide useful information to allow interpretation of rock mass modulus values, although careful consideration of the interpretation of initial modulus of less weathered rock (i.e. slightly weathered and fresh rock) should occur, due to the poor correlation between initial modulus and joint spacing (Benson and Haberfield, 2003). Nevertheless, despite these limitations PM testing provides a cost-effective method to directly assess modulus *in situ* when compared to other investigation methods.

An example pressure/cavity strain curve from a PM test in highly weathered siltstone in Melbourne is presented in Figure 1.

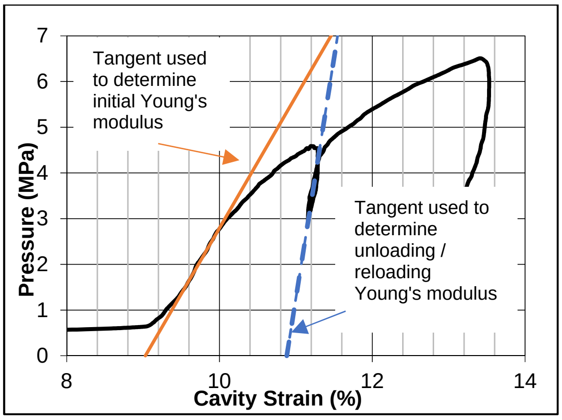

Figure 1. Typical PM test result in siltstone

For footing design in jointed or fissured rock, the pressure/cavity strain response behaviour over the initial elastic range of the tested zone is often adopted for a conservative but prudent assessment of modulus, although, the effects of borehole sidewall disturbance and stress relaxation need to be considered. For weaker materials, such as soils or highly fractured rock where significant disturbance of the borehole sidewall has likely occurred from drilling, or for retention analysis, where unload-reload behaviour is of more relevance, an assessment of the unloading-reloading pressure/cavity strain response behaviour may be more beneficial. The shape of the pressure/displacement response along with the maximum applied pressure during testing also provides additional information as to the strength and quality of the rock mass being tested.

An assessment of the Young's Modulus can then be undertaken using simple elastic theory, provided a Poisson's ratio (v) value is assumed for the material (i.e. from existing weathering correlations as described previously), based on the following relationship: $E = d\rho/d\varepsilon_c\,(1+v) = 2G\,(1+v)$ (1)

2.2 Case study examples

The following two case studies describe historical geotechnical investigations where the use of PM testing has provided greater confidence on the deformation behaviour of founding conditions and allowed for appropriate footing solutions to be designed and subsequently constructed.

The first case study details a historical investigation for spread footings founded on weathered siltstone where PM testing was used to develop a greater understanding and characterisation of rock mass deformation. When utilised in combination with verification activities, the PM testing allowed for increased confidence in adopting spread footing solutions with significantly higher design allowable bearing pressures than has been previously adopted in this formation.

The second case study details a historical geotechnical investigation where the use of PM testing resulted in a greater understanding of load deformation behaviour of the pile sockets, and when combined with more advanced numerical methods of analysis (compared with traditional empirical pile design methods) allowed for efficiencies to be realised during design and construction of the piles. Onsite design and verification was also undertaken which reduced the ground risk to the contractor by developing sockets that were tailored specific to the ground conditions encountered during drilling of each individual pile, rather than based on a single design stratigraphy applied across the site.

3 SHALLOW FOOTING DESIGN (CASE 1)

An example of the benefits of PM testing to inform shallow footing design can be outlined by a previous project in weathered siltstone of the Anderson Creek Formation, which forms the founding stratum in Box Hill (15 km east of Melbourne CBD) and poses several challenges with respect to characterisation of strength and deformation parameters due to the deeply weathered and weak nature of this rock when compared with the generally more competent Melbourne Formation. Unlike the Melbourne Formation, there is currently little information on weathering/strength correlations for this unit.

For this project, a supplementary investigation was undertaken for a proposed tower with the initial geotechnical investigation recommending relatively low design bearing pressures resulting in a piled footing solution being required for the more heavily loaded columns (design working loads for this tower typically ranged between about 4 MN and 50 MN).

Obtaining an understanding of the deformation and strength characteristics of the weak bedrock was critical in developing an efficient footing system for this tower, and the supplementary investigation comprised the drilling of an additional three boreholes, along with ten PM tests to measure the deformation characteristics of the weathered siltstone. Laboratory testing comprising 10 UCS and 90 MC tests were also undertaken on recovered (resaturated) weathered siltstone core.

The results of the investigation indicated that the site was predominantly underlain by weathered siltstone, observed to be initially in an extremely weathered state before grading to moderately weathered siltstone with depth. Although not encountered during the supplementary investigation, dyke material had been observed during the initial investigation over the upper profile of the site. Based on the results of the investigation and visual observations, predominantly highly and highly to moderately weathered siltstone was expected to be encountered at the proposed basement bulk excavation level. A selected core box photograph showing the typical highly to moderately weathered siltstone encountered at and below founding level is presented as Figure 2.

Figure 2. Example of typical highly to moderately weathered siltstone encountered at founding depth

The results of saturated MC laboratory test results showed significant scatter, although a general trend of decreasing MC with increasing depth was observed. However, the saturated MC results were higher than that historically observed for Melbourne Formation siltstone (ranging typically between about 18% for the extremely weathered siltstone down to about 8% for the moderately weathered siltstone), which was considered to be likely due to a higher clay (rather than silt) content within the Anderson Creek Formation rock mass when compared to the Melbourne Formation. Hence, traditional published correlations between saturated MC and strength could not be applied to this site, and if adopted would indicate higher weathering grades than that visually observed during the investigation. A summary plot of the saturated MC lab test results against elevation based on the adopted weathering grades (from visual observations) from this investigation is presented as Figure 3. Also shown on Figure 3 is a trendline based on the Gu et al. (2008) empirical correlation for saturated MC / weathering grade for the equivalent weathering grade visually observed during the investigation. To produce this trendline weathering grade thicknesses based on an average of the observed weathering grades from the supplementary three boreholes was adopted.

The results of UCS testing, undertaken on inferred highly to moderately and moderately weathered siltstone (based on visual observations) were typically in the range of between about 1.1 MPa and 2.2 MPa which indicated very low strength rock. However, virtually all of the tests failed on pre-existing planes of weakness and hence the results were considered to be an underestimate of the strength of the rock (visual logging indicated that whilst weak, the highly to moderately and less weathered rock observed at and below founding level was typically of about low strength).

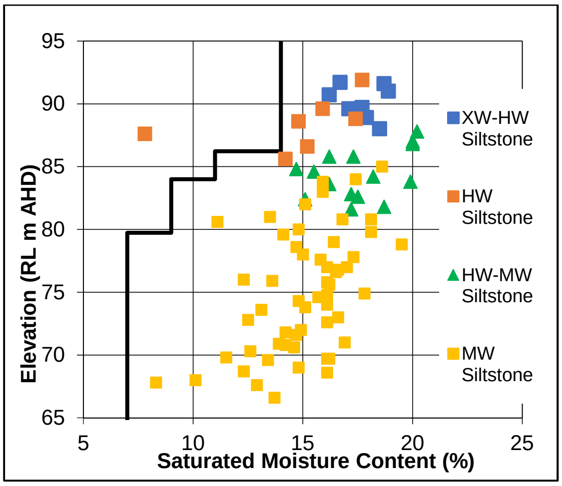

Figure 3. Saturated moisture content results against elevation (with trendline from Gu et al., 2008)

PM testing was able to provide a high level of confidence on the deformation behaviour of the weathered rock at bulk excavation level in order to inform footing design. The results of the PM testing typically indicated initial Young's Modulus values (E_i) at and below founding level of between about 700 MPa and 1000 MPa, with some higher values up to about 1950 MPa and one lower value of about 370 MPa. Unload-reload modulus values (E_{ur}) ranged from between about 1060 MPa to 3180 MPa.

A summary plot of recorded cavity strain against pressure variation from the PM testing for this site is presented as Figure 4 and a summary of the E_i and E_{ur} calculated from PM test results against elevation is presented as Figure 5. Also shown on Figure 5 for comparison is an estimated modulus range based on the Gu et al. (2008) recommended correlation for siltstone weathering grades of between highly and moderately weathered (E = 210 MPa to 608 MPa) and UCS values of between about 1.0 MPa and 2.5 MPa (E ~ 100 MPa and 270 MPa).

Based on the results of the PM testing it was considered that spread footings would provide a satisfactory footing option for the proposed tower with design bearing pressures greater than two and a half times that recommended in the initial geotechnical investigation adopted. Settlement of an individual spread footing was calculated as being between about 5 mm to 10 mm for

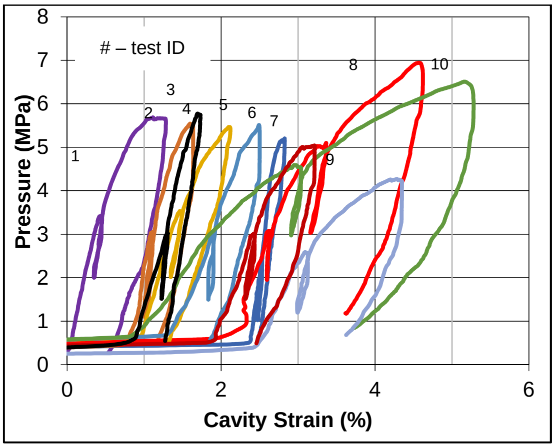

Figure 4. Summary plot of the ten PM test results

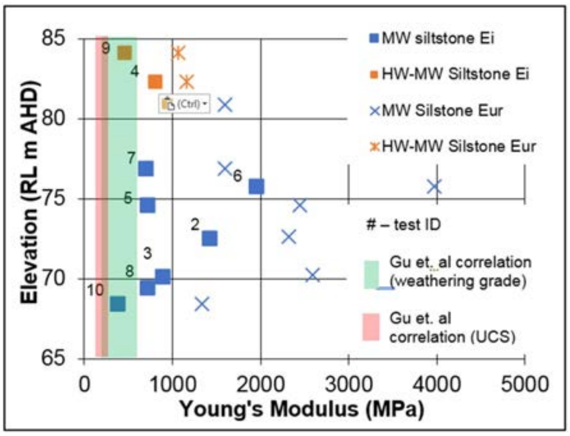

Figure 5. Summary of E_i and E_{ur} PM test results

To provide increased confidence in adopting the high design allowable bearing pressures, the bases of the spread footing were inspected during construction to confirm that founding conditions were in accordance with the design intent and adequate base cleaning had occurred prior to blinding. Founding conditions for most of the spread footings inspected comprised weathered siltstone of sufficient strength to support the design bearing pressures. However, at several spread footing locations weathered dyke material, typically comprising extremely to highly weathered material of extremely low strength was observed.

Where present, these materials were considered to be unsatisfactory for the proposed design allowable bearing pressures and either over-excavation (where the dyke was of limited extent) or redesign of these footings by increasing the base footprint (and hence adopting a reduced design bearing pressure) was undertaken following liaison with the structural engineer to confirm design working loads. Figure 6 presents an example of a footing base where founding conditions were observed to be consistent with design assumptions and Figure 7 presents an example of a footing base where dyke material of a weaker strength than that assumed during design was encountered. In this case, the footing design bearing pressure was reduced with the base of the footprint of the footing subsequently increased.

4 PILED FOOTING DESIGN (CASE 2)

An example of the benefits of PM testing in combination with onsite verification to inform piled footing design is also demonstrated by a geotechnical site investigation undertaken for two towers in East Melbourne. Design column loads for the towers were up to 10 MN. The geotechnical investigation comprised the drilling of a number of boreholes to depths of up to about 40 m, along with eight PM tests to measure the deformation characteristics of the weathered siltstone at depth. Laboratory testing comprising UCS, saturated MC and point load index tests were also undertaken on recovered core.

Figure 6. Spread footing with exposed HW-MW siltstone consistent with design assumptions

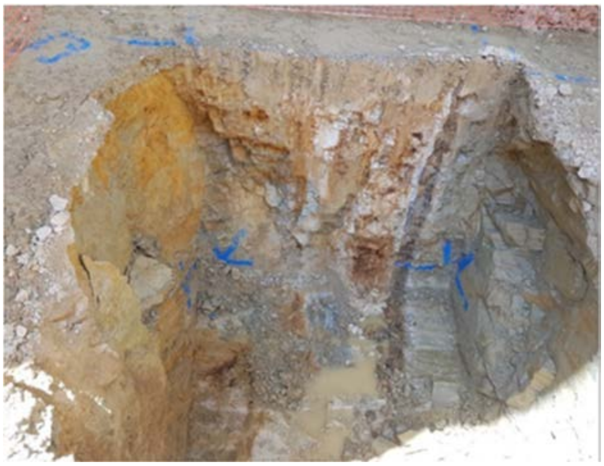

Figure 7. Spread footing (base not yet cleaned) with exposed weaker dyke material in base and sidewall

The results of the investigation indicated deep fill and residual clays with weathered Older Volcanics basalt encountered over one corner of the site. Beneath the overlying clays and weathered basalt Melbourne Formation siltstones were encountered from depths of between about 11 m and 14 m. The weathered siltstone was typically observed as extremely weathered before grading to slightly weathered at depth. Highly to moderately and less weathered siltstone was typically encountered within a few metres of the weathered siltstone surface. The results of the PM testing in the moderately and slightly weathered siltstone typically indicated very stiff rock mass conditions with initial Young's Modulus values of between 1600 MPa and greater than 10 000 MPa recorded.

Due to the depth to weathered rock across the site, rock socketed bored piles were proposed to support the proposed towers. The pile design was subsequently tendered under a design and construct package to piling contractors. Following engagement of the successful tenderer based on their bored pile design submission (pile lengths calculated using empirical design methods), detailed bored pile design and socket verification services (observations of drilling, sidewall roughening and base cleaning) using the Golder Associates Rocket Socket field Procedure (GARSP) approach was undertaken. The approach and benefits of GARSP for the design and construction of rock socketed bored piles have been previously presented in Haberfield and Collingwood (2006), and in summary, comprises a manually completed and computed design method allowing real time, serviceability based bored pile design to be completed in the field, allowing for both potential efficiencies in pile design, and a reduction in risk due to the onsite verification component.

Indicative rock socket lengths were assessed based on design tables derived from analysis completed using the software program ROCKET, developed in the late 1990s by Monash University, which allows for a fully non-linear load-displacement assessment of bored pile performance using a rock-joint simulation model, with analysis methods confirmed through large-scale laboratory and field testing of piles. Investigation results (including PM and laboratory testing) were used as input parameters into the ROCKET model as part of this analysis. Roughness parameters were selected based on correlations with Melbourne Formation published by Seidel and Haberfield (1995). As ROCKET is a settlement based analysis and the socket lengths are assessed using allowable settlements rather than allowable loads a design maximum settlement was assigned to each pile, and after providing a factor of safety on this settlement to account for uncertainty/variability of material parameters, the socket lengths were established based upon the required working load applied to the pile. Design tables and plots (assessment of shear stress against movement) for various pile types were determined from the analysis completed.

An example of a calculated pile shear (shaft) stress versus displacement plot for a 750 mm diameter pile in moderately to slightly weathered (MW-SW) siltstone from ROCKET using the site specific PM and UCS test results (with design parameters adopted comprising UCS value of 7.5 MPa, Young's modulus of 2000 MPa and an effective cohesion (c') of 1.5 MPa) for various roughness values is presented as Figure 8. In this figure the roughness values describe the socket roughness profile adopted in terms of chord length (λ)/mean roughness height (S_h). The performance envelope (labelled composite) defines the shear stress/vertical movement curve adopted in design based on the various roughness curve values.

A subsequently calculated design plot of displacement versus unit shaft load developed for the proposed 750 mm diameter piles based on the relevant calculated pile shaft stress from Figure 8 is presented as Figure 9, for various weathering grades between highly and moderately to slightly weathered.

During field activities rock socket lengths were logged during drilling with the socket lengths subsequently altered to match actual encountered conditions using the previously discussed pile design tables for the relevant pile diameter size and weathering grade. Overall cost savings were observed on this site using this design approach, despite the relatively low design loads. Of more significance, the use of this method also identified areas of differing weathering during piling supervision than that assumed in design and as a result a number of longer drilled socket lengths ended up being constructed than the original tender design socket lengths. Similarly, a number of drilled socket lengths also ended up being constructed shorter than the original design socket lengths.

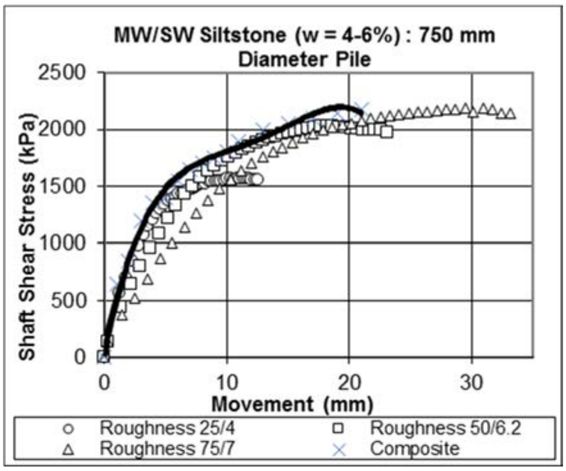

Figure 8. Example calculated pile shaft load versus displacement

In total, 78 rock socketed bored piles were installed on the site with total pile lengths constructed varying between 7.3 m and 27.2 m (including socket length and overlying total pile length), compared to the contractors originally calculated pile lengths of between 8.5 m and 26 m. In total, a total reduced pile length of 222 m was constructed resulting in a reduction of concrete use of about 95 m^3 compared to the original contractors' pile design. A comparison of tender and as constructed pile lengths is presented as Figure 10 (note this figure includes both socket length and overlying pile length). As can be seen, whilst overall a reduction in pile length was observed, several constructed pile lengths were greater than the original design due to more weathered material being encountered during drilling.

5 CONCLUSION

An appropriate geotechnical investigation for tall buildings must not only assess the strength of the founding materials that support these footing systems but also the stiffness characteristics of the *in situ* ground. In order to further characterise ground conditions and manage

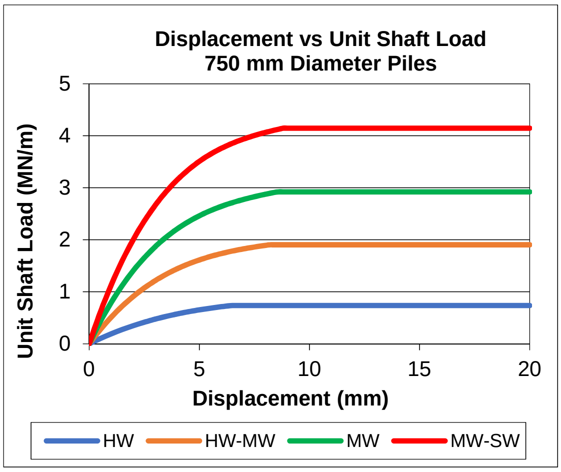

Figure 9. Example design plot developed from ROCKET output for onsite rock socket design

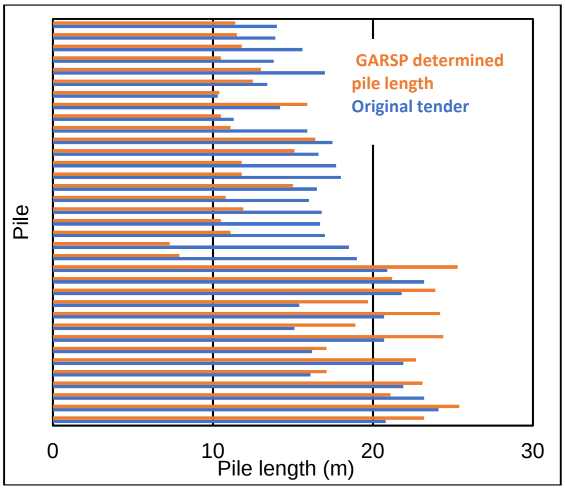

Figure 10. Summary of total pile lengths (contractor original tender design versus GARSP determined)

ground risk, PM testing can be used with more traditional investigation methods and verification during construction to provide prudent yet not overly conservative geotechnical advice and design for these developments. PM testing allows for a cost-effective method to directly assess modulus *in situ* rather than relying solely on laboratory test results and more traditional empirical correlations. Two case studies have been presented in this paper outlining how the use of PM testing has provided greater confidence on the deformation behaviour of founding conditions than if more traditional investigation methodologies and empirical correlations were adopted, allowing more efficient footing solutions to be constructed.

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REFERENCES

Benson, N. D. and Haberfield, C. M. (2003). Assessment of mass modulus of a weathered argillaceous rock. Proceedings international Society for Rock Mechanics 2003, Southern African Institute of Mining and Metallurgy: Johannesburg.

Chui. H. K. (1981). Geotechnical properties and numerical analyses for socketed pile design in weak rock. PhD Dissertation, Department of Civil Engineering, Monash University, Australia

Clarke, B. G. (1995). Pressuremeters in geotechnical design. Chapman & Hall, London, UK

Gu. D. X. Tamblyn, W., Lamb, I. and Ramsey, N. (2008) Effect of weathering on strength and modulus of basalt and siltstone, Proceedings 42nd US Rock Mechanics Symposium and 2nd US-Canada Rock Mechanics Symposium.

Haberfield, C. M. (1997). Pressuremeter testing in weak rock and cemented sand. Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, Vol 125, July, pp. 168-178

Haberfield, C. M. and Collingwood, B. (2006). Rock-socketed pile design and construction: a better way? Proceedings of the Institution of Civil Engineers Geotechnical Engineering 159, Issue G3, pp 207-217.

Haberfield, C.M. and Lochaden., A.L.E. (2019). Analysis and design of axially loaded piles in rock. Journal of Rock Mechanics and Geotechnical Engineering, Vol 11. pp 535-548.

Johnston, I. W. (1991). Geomechanics and the emergence of soft rock technology. Australian Geomechanics, December.

Littlejohn, G. S., Cole, K. W. and Mellors, T. W. (1994). Without site investigation ground is a hazard. Proceedings of the Institution of Civil Engineers – Civil Engineering, Vol. 102, May, pp. 72-78

Look, B. (2006). Handbook of geotechnical investigation and design tables. Taylor & Francis Group, London

Macklin, S., Schult, M., Terzic, Z. and Chu, D. (2014). Strain-dependent stiffness of the weathered Melbourne Formation. 15th Australasian Tunnelling Conference, Sydney.

Seidel, J.P and Haberfield., C.M. (1995). The axial capacity of pile sockets in rocks and hard soil. Ground Engineering, Vol 28. pp 33-38

Whyte, I. L. (1995). The financial benefit from site investigation strategy. Ground Engineering. October, pp. 33-36

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Geotechnical characterisation – managing design and construction risk

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