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The Impact of Spatial Variability on Deep Foundation Design for Tall Buildings

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Abstract: This paper discusses the vertical and horizontal spatial variation of geotechnical design parameters in weak carbonate rock formations, such as those typically found in the Middle East region. Improper consideration of such spatial variation, especially for design of deep foundations of heavy structures, can have a significant impact on the design foundation depth. Spatial variation of foundation design parameters from some of the world's tallest towers is discussed in this paper, and using data from one of the super tall residential towers, which is more than 300m tall, the potential risk of such large variation in design parameters is demonstrated. Use of geophysical data to reduce such risk, and the benefits of using design parameters derived from such geophysics data to validate other in -situ and lab test data, are also discussed with an example from the results of three load tests from a supertall tower project.

Keywords: foundations; spatial variation; geophysics; tall towers; carbonate rocks; risk.

1 Introduction

Spatial variation of geotechnical design parameters due to inherent ground variability, as well as the risk due to ground uncertainty, can have significant impact on the overall safety in design. Design of deep foundations in weak rock is often carried out using analytical methods or empirical correlations, which require characteristic values of ground properties to be estimated to represent ground behaviour along the significant depth of foundations across the footprint of the structure. Large diameter piles or barrettes are typically used to transfer loads from heavy structures like supertall towers, and their founding depth, in weak weathered rock formations, depends mainly on the strength and stiffness characteristics of the weak rock in which they are founded.

Several recent studies from reliability-based analysis in geotechnical engineering, demonstrate the use of random field theory and geostatistical models, to assess spatial variations of geotechnical parameters and ground uncertainties. However, the industry design practice often differs, and site characterisation and selection of representative design parameters often rely on geostatistical kriging using a limited available data set, or more often, by simply selecting conservative parameters based on experience and judgement. While the conservatism in selecting the parameters is aimed at achieving a higher factor of safety in design, lack of sufficient number of data sets and lack of a detailed analysis to assess the reliability of such selected parameters, often pose a risk in design. While an overly conservative approach, to account for uncertainty or lack of sufficient design data, can result in less sustainable solutions due to material over-consumption, improper consideration of the heterogeneity of the ground and spatial variation of soil and rock characteristics across the site, can pose a major risk in the design of such foundations.

This paper presents a high-level review of the spatial variation of ground design parameters, at a few selected tall tower site locations in the Middle East region, and demonstrates, with an example, the potential risk of improper consideration of such large variations in data. The use of data from geophysical investigations, mainly via the use of shear wave velocity, in determining the geotechnical design parameters, can potentially reduce variability of data and ground uncertainty. An example is presented, by validation using load test results from La Maison Tower in Dubai.

2 Geotechnical Parameters for Design of Deep Foundations in Weak Rock

2.1 Estimation of skin friction in weak rock

Deep foundations in weak, carbonate rock formations in the Middle East region, are typically designed as rock sockets, where most of the resistance is derived from the rock - pile interaction. End bearing resistances are mostly ignored in the calculations, as a regulated design practice in the region. CIRIA 181 (1999) and FHWA (2010) provides general design guidance for design of deep foundations in Intermediate Geo Materials (IGM), which is the classification that the weak carbonate rock formations in UAE typically fall into. The uncertainties in the methods of estimating ultimate loads on piles are also reflected in the relevant codes of practice for piling (ICE 2016). Design of deep foundations must ensure a sufficient factor of safety against shear failure, while ensuring that the settlements are within the allowable limits (Poulos, 2017). Piles and barrettes, which are typically the chosen foundation types for tall towers in weak rock formations, are designed using traditional methods or empirical relations, calculating ultimate capacity using a coefficient (α) along with the square root of the unconfined compressive strength (UCS) of rock. The unit skin frictional resistance (f_s) in most of these correlations is related to the UCS (in MPa) by the following equation:

$$f_s = \alpha\beta\sqrt{UCS}\ \text{MPa} \qquad (1)$$

where, α = Reduction factor depending on UCS
β = Correlation factor for rock mass discontinuity.

The reduction factor is also associated with adhesion at the pile-rock interface, which depends on the roughness of the rock socket. The reduction factor also varies with respect to the rock mass strength and effect of geological variations, differences in the back-analysis method adopted, and the variations in the construction method. The following Table 1 provides a summary of the various equations used in practice, based on a review of published literature.

Table 1. Estimation of skin friction - various equations in published literature

Author	Year	Equation for estimating Skin Friction (f_s) MPa	Condition for which the correlation is developed
Manoj et al.	2019	$0.52(UCS)^{0.5}$	Weak Carbonate rocks
Zhang and Einstein	1998	$0.40(UCS)^{0.5}$	Smooth interface. Based on load test results from various locations taken from literature
Rowe and Armitage	1987	$0.45(UCS)^{0.5}$	Regular surface interpreted from load tests
Carter and Kulhawy	1987	0.15(UCS)	-
Rowe and Armitage	1987	$0.60(UCS)^{0.5}$	Rough surface interpreted from load tests
Horvath et al.	1983	$(0.20\text{ to }0.30)(UCS)^{0.5}$	Interpreted from load tests in Shale/Mudstone. Factor of 0.2 to 0.3 for smooth to rough socket
Williams and Pells	1981	$\alpha\beta*(UCS)$	Sandstone, Shale and Mudstone
Williams et al.	1980	$\alpha\beta*(UCS)$	Melbourne Mudstone
Horvath and Kenney	1979	$(0.20\text{ to }0.25)(UCS)^{0.5}$	Shale and Mudstone Factor of 0.2 to 0.25 for smooth to rough socket
Horvath	1978	$0.33(UCS)^{0.5}$	Based on load test data
Rosenberg and Journeaux	1976	$0.375(UCS)^{0.515}$	Interpreted from load tests for weathered and soft rocks

It can be seen that most of the equations use a single parameter, that is, the UCS of rock, which then governs the design depth. UCS is defined as the uniaxial load acting per unit area of a cylindrical rock specimen of standard dimension, at which the failure of the specimen occurs in a compression test. The rock strength properties and rock classification, as per BS 5930 (2015), are done using UCS as the standard. Its value is broadly related to the porosity, and consequently to the dry density of the rock material.

Most of the equations in Table 1 do not provide any specific guidelines regarding selection of such representative, or characteristic, design value. The design depth, for the same structural requirements and design profile, varies significantly when using these different equations (Latapie et al. 2018; Manoj, et al. 2020). The common practice is then to characterize and subdivide the ground layer-wise, based on available site investigation data, to arrive at a representative ground profile, and then develop a representative design profile as an average profile along the significant depth. The UCS design profile thus derived as an average profile across site is used to estimate socket friction along that depth, which then determines the required founding depth.

It is important to use an appropriate and reliable profile of UCS, which well represents the entire load influence area, considering the spatial horizontal and vertical ground variations. The spatial variation of these parameters is discussed in Section 3, using some examples with design data from some of the supertall towers in Dubai.

2.2 Foundation Settlements

The settlement of deep foundations depends on many variable factors including intensity of load applied, ground-pile interaction, geometry of the pile, nature of soil/rock strata and its response in terms of stiffness and strength, the effect of pile installation in the state of soil stress and pile load distribution, and the exact load transfer point from the pile to the soil/rock. Many empirical, analytical, semi–empirical and numerical methods for estimating single and group pile settlement are available, and in use, today. Most of the prediction methods are based either on elastic theory, or empirical correlations relying on experience. Settlement predictions for large pile or barrette groups, which are usually the foundation system used for tall tower foundations, are made using numerical techniques such as the finite element analysis, which has proven to be a valuable method for making realistic settlement predictions. The accuracy of results from these numerical models, however, depends not only on the efficiency in modelling or the constitutive model used, but also on the reliability of the subsoil and rock properties and loading conditions.

The equations typically used to estimate pile and barrette settlements in weak rock use the deformation modulus or the average modulus of elasticity (E_s) in the estimation of settlement component from soil rock interface. The accurate estimation of the deformation modulus, which play a major role in the total settlement prediction, and use of appropriate value for the strain levels, is therefore very important. It is important to use stiffness parameters at the appropriate strain levels to predict group settlements realistically, which can often govern the design, and small strain modulus obtained from seismic testing has been found to correlate well with actual load settlement behaviour observed from load testing.

3 Ground Spatial Variation and its Impact on Foundation Design of Tall Towers

The UCS and Modulus of Elasticity (E) values from sites of five tall towers located in the same region and geological setting, in Dubai, are plotted in Figures 1a and 1b, to demonstrate the spatial variation of these design data across the ground and within the significant depth zones.

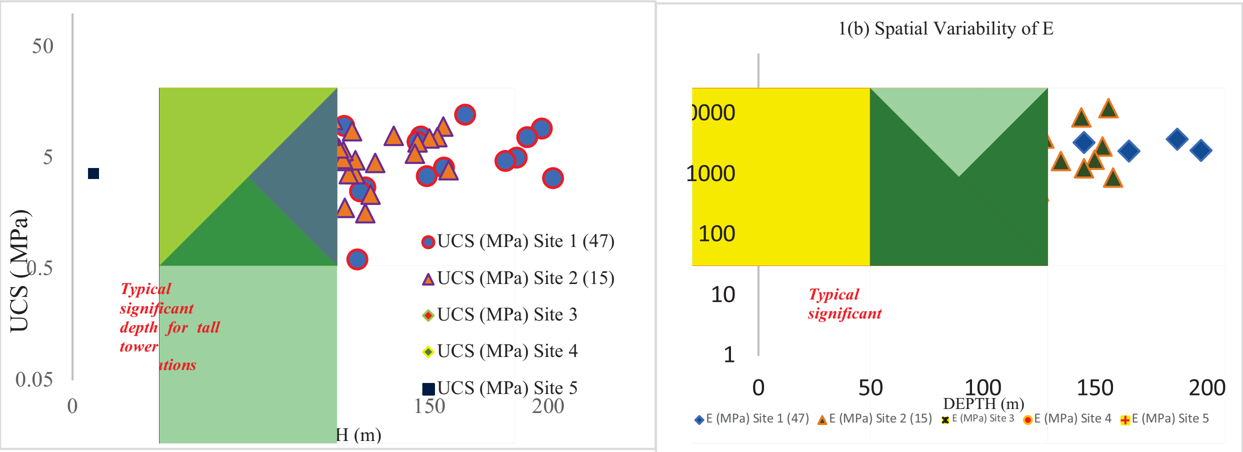

Figure 1. (a) and 1(b) Spatial variability of design parameters across five tall tower locations in Dubai a) UCS b) Modulus of Elasticity E

In order to demonstrate how a small variation in UCS will affect the foundation depth predictions, the design of deep foundations at the La Maison tower (Manoj et al. 2020) is presented as an example in Figure 2, which illustrates the impact of the spatial variation of the design parameters, across the site, on the foundation design depth. To plot the sensitivity of the foundation design depth to variation in average UCS profile, the ground profile is first divided into sublayers based on the rock type and geological profile, and average UCS values for each layer are assigned based on all available test data. This is the original profile denoted as 1 in the x axis. The foundation depth required for the design load of 40MN, for a 1.5m diameter pile, was then calculated for this original design profile. The design profile is then varied by 10% and design depth is estimated for every 10% increase in the UCS average profile across depth. The design depth is estimated using Hovarth and Kenny (1979) method. It can be seen that a 20% increase in the UCS results in a reduction of 5m depth of a single 1.5m diameter pile, which is significant amount of concrete, for a large size project.

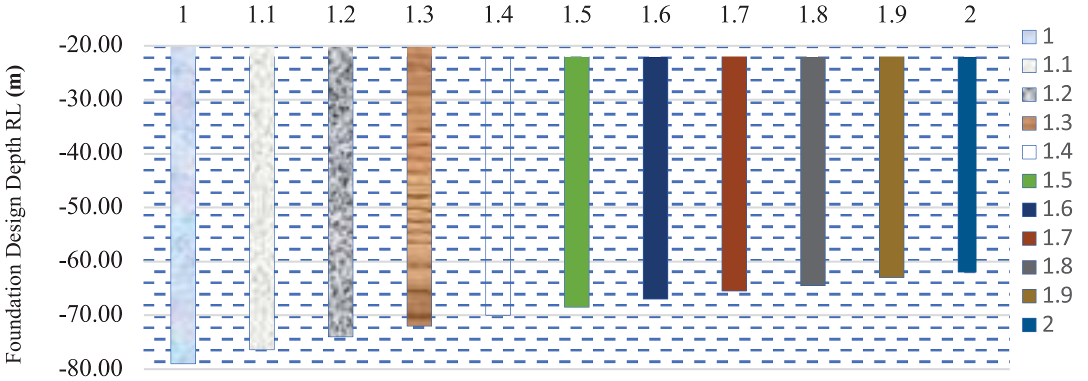

Figure 2. Impact of variation in UCS profile on design performance - Foundation design depth, for 40MN load, 1.5m dia pile versus percentage variation in design UCS profile at La Maison tower

Figure 2 demonstrates that, since the foundation design depth is dependent on a single variable, it is important to select the design profile in a reliable and safe manner, using a sufficient amount of the data set across the site and within the considered depth zone.

In weak carbonate rock formations, where obtaining enough good quality samples for testing is difficult, and where there may be great uncertainty in the ground profile (for example, when there is risk of underground anomalies like cavities), the reliability of the adopted design profile can be improved by including the geophysical data into the design profile, as discussed in the following section. Insitu shear wave velocity measurements from cross hole and down hole seismic tests and multichannel analysis of surface waves (MASW) are frequently available. It is important to use site and location specific data such as rock and soil density at the same sample depth, while processing the geophysical investigation data, to arrive at accurate values of shear wave velocities, representative of the layer considered. In Section 4 below, the shear wave velocity from a downhole seismic test conducted at the La Maison tower location is used to estimate the rock UCS properties using a correlation factor of 3.75 (Poulos 2022) which was validated for the Burj Khalifa site, very close to the La Maison Tower location and has a similar geological profile. The unit frictional resistances obtained from three load tests conducted at this site, are then compared against the unit friction calculated from the shear wave velocity correlation, to test the correlation.

4 Use of Geophysical Investigation Data for Estimation of Design Profile

There are direct methods available, such as laboratory measurements, and indirect methods, such as destructive or nondestructive seismic techniques, to determine rock properties. In rock formations, commonly weathered and fractured, and in geological conditions such as carbonate rocks and IGM materials, it is difficult to recover samples for UCS testing. In such ground conditions, the indirect methods, mainly the seismic techniques measuring P and S waves, are useful in reducing the risk involved in selecting a design profile with insufficient data, in ground conditions with large spatial variability. Several studies have been conducted in recent years to develop methods and correlations to use shear wave velocities in rock engineering, and it is noteworthy that the available shear wave velocity-based equations for determining strength and stiffness parameters of rock require further validation, which are site-specific or local geology-specific.

Shear wave velocity (V_s) in rock, obtained from cross-hole seismic tests, or downhole seismic tests, is a very useful measurement in determining elastic properties of rock, especially the small strain stiffness and UCS values of rock (Poulos 2017, Manoj et al. 2020). Rezaei and Davoodi (2021) presented empirical correlations for rock properties including UCS and E, based on shear wave velocity and on a database from laboratory and field tests, using statistical analysis. Cheenikal et al. (2007) and Altindag (2012) presented several relationships correlating V_s to UCS for various rock types. V_s, being a field measurement (especially when measured in a cross hole seismic test), potentially reflects the ground uncertainty between two boreholes, thus allowing improved reliability of the adopted design profile. The down-hole seismic tests also capture the vertical ground variability, including the jointing, degree of weathering and effects of faults, on the strength of rock. It is therefore advantageous to use correlations of V_s to E and UCS values, to try and validate the design profiles obtained from traditional laboratory tests, and hence to reduce the risk of ground uncertainty and ground variability.

Poulos (2022) presented an approach to estimate load settlement behaviour of shallow and deep foundations using small strain Modulus of Elasticity E estimated from insitu shear wave velocity measurements. The paper also presented using data from the Burj Khalifa site in Dubai, a rough correlation for weak carbonate rocks, by equating UCS in MPa to $3.75V_s$ where V_s is measured in km/s for shear wave velocities up to about 1.3km/s. The design UCS profile from La Maison tower, and the design profile derived from shear wave velocities, are shown in the Figure 3 below.

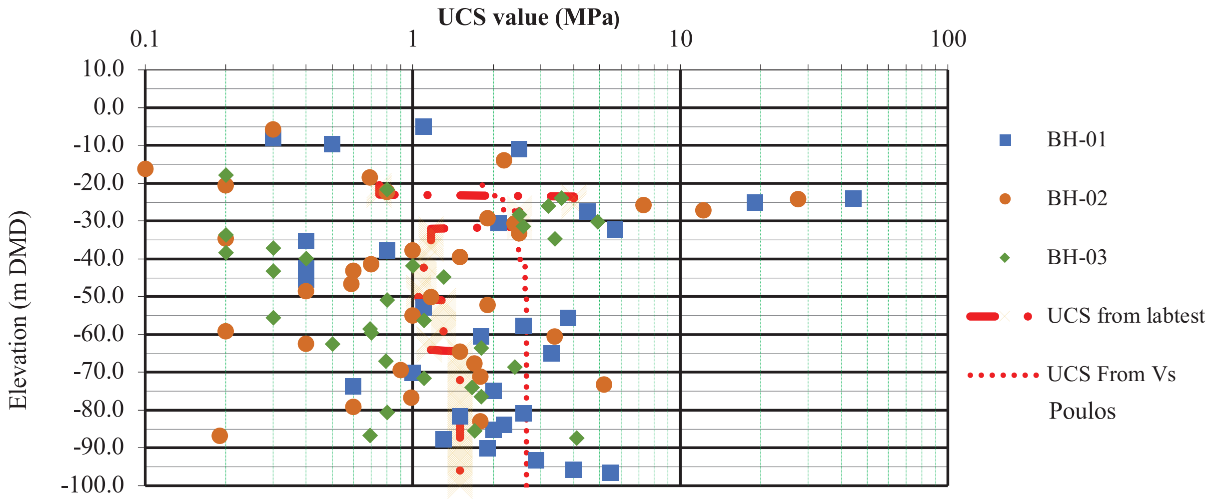

Figure 3. The design UCS profile and the UCS profile determined from shear wave velocity Vs - La Maison tower

The Barrette Osterberg load test data from La Maison tower site, is used to examine this correlation factor, against the UCS profile derived from the average V_s profile from the same location, and results are presented in Figure 4.

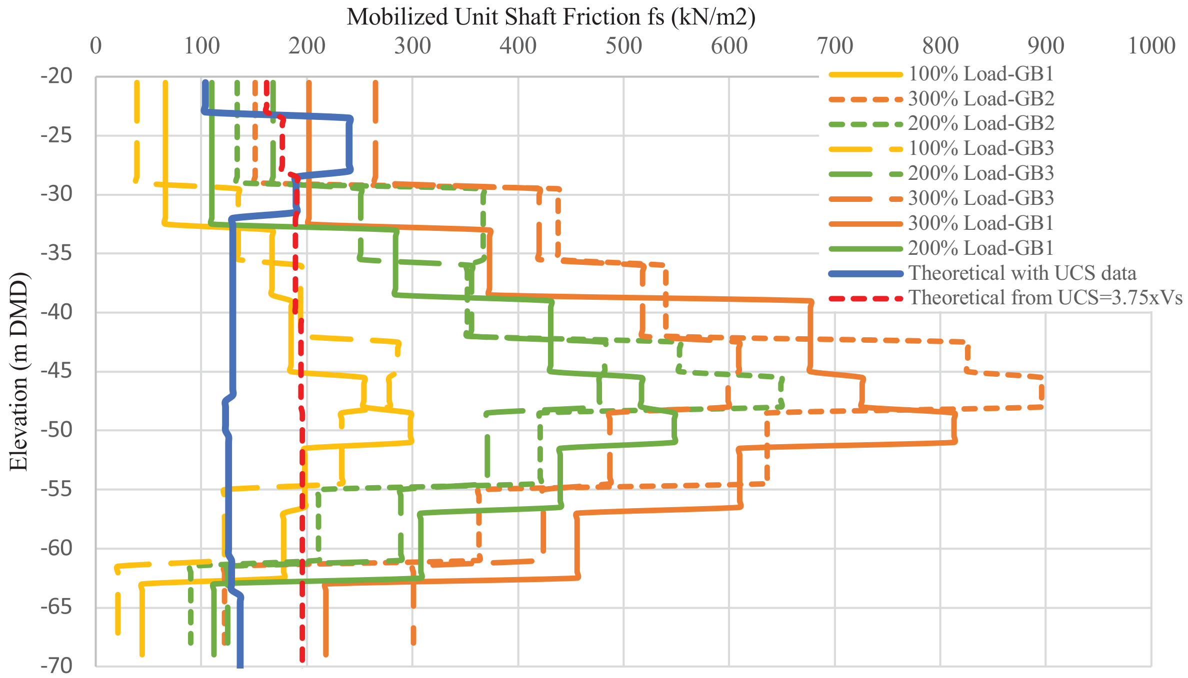

Figure 4. Estimated unit skin friction, from UCS =3.75V_s and original UCS profile, in comparison with three load test results from La Maison Tower

Figure 4 shows the unit skin friction measured in three load tests, at 100%, 200% and 300% of the test loads, which is then compared with the theoretical unit friction values, estimated using average UCS profile from the direct measurements, and using the UCS estimated using the relationship UCS= 3.75 V_s MPa developed by Poulos (2022) for the Burj Khalifa site. In order to develop the original design profile, the ground profile was divided into sublayers based on the rock type and geological profile, and average UCS and E values for each layer were assigned based on all available direct test data. The ultimate skin friction resistance was then estimated based on the Horvath and Kenny (1979), method which was the method used to estimate the test loads. The correlation factor derived for the Burj Khalifa site, when applied on average Vs profile measured at the La Maison Tower site, results in unit skin friction values which are in reasonable agreement with the load test data. It is however cautioned that these correlations are to be used carefully, as they are highly dependent on the rock type and its geological origin.

It must be noted that the intention of this demonstration is to show that V_s can be correlated to UCS for a particular geology and can be used as additional supporting information to validate the design profile developed using laboratory tests alone. It is not to be considered as an alternative to the more accurate direct measurements, but should be considered to support and increase the reliability of the design profile. The correlation factors must be tested for similar or same geological conditions, before applying them in an effort to improve the accuracy of the adopted design profile.

5 Recommendations and Conclusions

The importance of site characterisation in heterogeneous natural ground conditions, giving the ground variability and uncertainty, is highlighted in this paper using examples of few tall tower foundation sites in Dubai. Proper consideration of such ground variability and uncertainty in geotechnical design, can lead to more rational, sustainable, and economic design. Use of insitu shear wave velocity measurements to estimate the UCS profile from site specific correlations, can increase the reliability of the design profile used in the design of deep foundations. This is more important in ground conditions where there is limited amount of laboratory test information due to the difficulty in collecting good samples for UCS testing, and where average values are then taken conservatively from the available data.

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References

Altindag R (2012) "Correlation between P-wave velocity and some mechanical properties for sedimentary rocks". *International South African Inst Min Metal* 112:229–237

BS 5930:2015+A1:2020 "Code of practice for ground investigations"; *BSI, London, UK*.

Cheenikal L, Poulos H, Whiteley R (2007) Geophysical testing for rock assessment and pile design. *Proc. 10th Australia - New Zealand Conf. Geomechanics, Brisbane*, 442–447

Carter JP and Kulhawy FH (1987) Analysis and Design of Foundations Socketed Into Rock. *Geotechnical Engineering Group, Cornell University, Ithaca, NY, USA, Res. Rep*. 1493-4.

CIRIA Report 181, Piled foundations in weak rock, London 1999, ISBN 0 86017 494 8

FHWA-NHI-16-064 (2016) GEC 012 "Design and Construction of Driven Pile Foundations – Comprehensive Design Examples", *NHI Courses* No. 132021 and 132022

Horvath RG (1978) Field Load Test Data on Concrete-to-Rock Bond Strength for Drilled Pier Foundations. *University of Toronto,Toronto, ON, Canada*, Publication 78-07.

Horvath RG and Kenney TC (1979) Shaft resistance of rock-socketed drilled piers. *In Proceedings of Symposium on Deep Foundations. ASCE, Reston, VA, USA*, pp. 182–214.

Hovarth RG, Kenney TC and Kozicki P (1983) Methods of improving the performance of drilled piers in weak rock. *Canadian Geotechnical Journal* 20: 758–772.

ICE (2016) ICE Specification for Piling and Embedded Retaining Walls, *3rd edition. ICE Publishing, London, UK*.

Latapie B, Rhea A, Michelle A, Marwan A and Joyshwin S (2018) A review of piling industry practices in Dubai, UAE: proposed UCS-based correlations. *Geotechnical Research* 6(2): 103–129, https://doi.org/10.1680/jgere.18.00021.

Manoj S, Choudhary D, Alzaylaie M (2020) Value engineering using load-cell test data of barrette foundations – La Maison, Dubai. *Proc. Instn. Civil Engrs.– Geotechnical Engineering*, https://doi.org/10.1680/geen.19.00246

Poulos HG (2022). Use of Shear Wave Velocity for Foundation Design, *Geotechnical and Geological Engineering* 40(2)

Poulos HG (2017) Tall building foundation design. *CRC Press, Boca Raton, USA*

Rezaei M and Davoodi PK (2021) Determining the relationship between shear wave velocity and physico-mechanical properties of rock*s*, *International Journal of Mining and Geo Engineering*, Volume 55, Issue 1,Pages 65-72

Rosenberg P and Journeaux NL (1976) Friction and end bearing tests on bedrock for high-capacity socket design. *Can. Geotech. J., Ottawa* 13, 324–333.

Rowe RK and Armitage HH (1987) Theoretical solution for axial deformation of drilled shaft. *Can. Geotech. J.* 114–125

Williams AF and Pells PJN (1981) Side resistance rock sockets in sandstone, mudstone, and shale. *Canadian Geotechnical Journal* 18(4): 502–513.

Williams AF, Donald IB and Chiu HK (1980) Stress distributions in rock socketed piles. Proceedings of International Conference on Structural. *Foundations on Rock, Sydney, Australia*, vol. 1, pp. 317–326.