Value Engineering of Barrette Foundations For Tall Buildings in the Middle East

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Abstract

Large-diameter piles and barrettes are the two most common foundation types for tall buildings in the Middle East region, where ground conditions are challenging due to the presence of weak carbonate rocks. Barrettes are a better alternative when heavy foundation loads need to be transferred through limited base areas, as they offer greater contact area, generating increased friction for the same volume of concrete thus, giving significant savings. The advent of Osterberg Cell (O-Cell) testing made it possible to fully test high-capacity barrettes. In this paper, the design of barrette foundations are compared to piles, with settlement predictions using geophysics data compared to O-Cell observations. Based on foundation design and value engineering using O-Cell test results of a tall building project in Business Bay where a saving of 11 percent barrette length resulted in reducing carbon emissions by about 4770 MT, foundation designs of several tall buildings in Dubai are reviewed, and recommendations are provided for optimized design and realistic settlement predictions for future tall buildings, which will help save construction-related resources and reduce carbon footprint.

Keywords: Barrettes, Geotechnical Engineering, O-Cell Tests, Piles

Introduction

Rapid urbanization in recent decades resulted in a tremendous increase in the rate at which supertall towers (with a height of 300 meters or greater) are being constructed around the world (CTBUH 2020). Globally, the embodied carbon of a buildings account for about 11 percent of emissions. There is also an ever-increasing need for resource optimization, ensuring minimum carbon footprint with environmentally friendly and sustainable design and construction methods, which challenges civil engineers to go beyond the traditional and typical conservative design and testing methods, pushing them to evolve and adopt more innovative and optimized design solutions.

Value engineering and design optimization of tall and supertall tower foundations in weak rock formations and recommendations for future designs are discussed in this paper. Dubai ranks number 4 in the world as of 2020 in terms of the number of buildings of more than 150 meters' height (CTBUH 2020); therefore, a discussion focusing on the United Arab Emirates' (UAE's) geology is considered relevant. Figure 1 presents La Maison, a 320-meter residential building under construction in Dubai, the subject property in this research.

The supertall towers constructed in the Middle East region are typically supported by deep piles or barrettes, socketed in to weak and weathered carbonate rocks, whose strength and stiffness do not necessarily improve with depth (Poulos 2009, 2010, 2017; Poulos and Badelow 2015; Katzenbach, Leppla & Choudhury 2016). In this paper, foundation design for a tower using barrette foundations is compared with equivalent-diameter piles, to demonstrate that barrettes are an efficient alternative to bored cast-in-situ deep foundations, which efficiently transfer the heavy foundation loads of supertall towers to the ground. Value engineering using Osterberg cell (O-Cell) test results on barrettes and settlement prediction derived from cross-hole seismic tests are discussed in the context of a supertall tower in Business Bay. An improved design method is recommended for the future tall buildings in the region, which can result in about 20 to 30 percent savings in terms of foundation volume of concrete, resulting in time and cost savings, which in turn will have a huge impact on carbon footprint generated by each of these future constructions. A comparison is also made with some of the tall building foundation designs using conventional methods in the region.

Local Geology of the Middle East Region

The regional geology in the Middle East, and specifically the UAE, is highly variable and complex, due to the depositional history and climatic conditions which is hot and arid. Local geology shows a horizontally stratified, complex profile of weak and weathered carbonate rocks, in which the strength and stiffness vary with depth. The surficial loose-to-medium-density silty sand layer is mostly Aeolian, with the occasional presence of Sabha sand, and extends to approximately 17 to 20 meters below natural ground level, which is followed by weak intermediate geo-materials (IGM).

Figure 2 shows core samples from Business Bay, Dubai, where majority of the tall towers in the UAE are planned, which demonstrates the geotechnical uncertainty of typical local geology.

Barrettes as Tall Building Foundations

Barrettes are a superior alternative to piles, for the purpose of transferring heavy loads of high-rise structures in weak rock formations in a limited-footprint area. The approach to constructing barrettes depends on the depth requirement, ground conditions and equipment availability. Barrettes are installed using diaphragm wall cutters and grab-bucket or hydro-fraise-type drilling tools, the size of which determines the size of the foundations. Barrettes can be installed to greater depths (over 125 meters), and can undertake much heavier working loads compared to piles. The verticality of the barrettes can be controlled, and experienced contractors claim that a tolerance of up to 0.3 percent can be achieved.

Barrettes are more efficient in load transfer due to the larger surface area available to generate skin friction, in comparison to an equivalent-diameter pile. While grouping, if adjusted and aligned with column loads, a single barrette is sometimes sufficient as a bearing unit under each column. Raft thickness can also be reduced when placing the barrettes concentrically below the superstructure columns. A comparison of bearing capacity of barrettes and equivalent piles using design data from a supertall tower project site in Business Bay is presented below, to demonstrate the efficiency of barrettes in similar situations.

Figure 1. La Maison, a 320-meter residential building under construction in Dubai. © HDS

Figure 2. Core samples from three geological layers beneath Business Bay, Dubai: a) Core samples from shallow-depth zones (17 to 20 meters below ground) showing almost 100 percent recovery; b) from deep zones (63 to 67 meters below ground) showing no recovery in some runs; and c) from deeper zones (183 to 186 meters below ground), showing no recovery. © Manoj et al.

Design Example: Supertall Tower in Business Bay—Barrettes Chosen over Piles

Design data and site characterization from a supertall tower site located to the southeast of Burj Khalifa is presented below. Due to limited land availability, the structure has to be constructed in an area of 90 by 60 meters, requiring a transfer of 45 to 55 meganewtons per foundation to the weak carbonate rocks.

Site characterization and parameters for design

The subsurface profile at the site was selected, and design parameters chosen based on seven bore holes of 75 to 100 meters deep, and 30 pressure meter tests (PMTs). Table 1 presents the site characterization and the average design parameters.

Design comparison of barrettes and piles

The barrette's ultimate capacity was calculated using the Horvath and Kenney (1979) method as given below. This is the commonly adopted design method in the UAE for calculating ultimate skin friction in the rock-socketed piles.

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$$f_s = \alpha \text{ x } (UCS^{0.5}) \text{ .... Equation 1}$$

UCS = unconfined compression strength

f_s = ultimate skin friction resistance

α = correlation coefficient between ultimate skin friction and UCS

The value α in the equation is the coefficient, and a value of 0.20 for smooth and 0.30 for rough sides are typically adopted. In the below calculations, a value of $\alpha = 0.3$ is considered for calculation of ultimate unit side friction. It is to be noted that for many tall towers in the UAE, the same equation with a more conservative $\alpha = 0.2$ to 0.25 has been used in the design.

Strata Description	Thickness of Layer (m)	Unit Weight (kN/m³)	RQD (%)	UCS (MPa)	Φ′ (degree)	c′ (MPa)	E (MPa)
Gravelly Sand II	12.88	18	–	–	32	–	16
Calcarenite I	4.20	20	95	2.20	39	0.20	185
Sandstone I	8.80	20	95	0.75	41	0.07	110
Conglomerate I	5.00	22	100	4.00	44	0.39	1100
Conglomerate II	3.00	22	100	2.50	44	0.24	1100
Calcisiltite I	16.00	20	70	1.17	37	0.08	150
Conglomerate III	3.00	20	100	1.05	44	0.10	250
Calcisiltite II	10.50	22	70	1.10	37	0.08	330
Conglomerate IV	3.30	20	100	1.15	43	0.11	700
Calcisiltite III	26.20	22	70	1.30	37	0.08	350
Calcisiltite IV	10.00	20	70	1.50	37	0.10	200

Table 1. Geotechnical design parameters for a supertall building under construction in Business Bay, Dubai. © Manoj et al.

Barrette Size			Equivalent Pile Dimensions			Increase in Perimeter (%)
L x B (m)	Area (m²)	Perimeter (m)	Diameter (m)	Area (m²)	Perimeter (m)	
2.8 x 0.80	1.76	6.00	1.50	1.76	4.70	28
2.8 x 1.20	3.36	8.00	2.07	3.36	6.50	23
2.8 x 2.40	6.72	10.40	2.93	6.73	9.20	13

Table 2. Barrette size and equivalent pile diameters, alongside increase in perimeter. © Manoj et al.

The equivalent pile sizes for various barrette sizes are calculated by comparing the per meter equal volume of concrete. It is evident from Table 2 that the unit length of barrette offers significantly more contact area compared to same length of piles of equivalent area. This will mean that, for the same volume of concrete pumped into the ground, the barrettes transfer a significantly larger percentage of load to the ground by friction, as compared to equivalent-diameter piles.

Allowable capacities are calculated using the above Equation 1 and presented in Figure 3 for piles and barrettes of equivalent size for the typical ground conditions at the tower location. The barrette calculations are repeated to include the effect of end bearing (EB); however, it is not taken into account in the final design.

For the design load of 54 meganewtons, 2.07-meter-diameter piles will have to extend to about 81 meters below grade, whereas the same load can be carried by equivalently-sized barrettes resting at 70 meters deep. A saving of 11 meters of pile length per location (37 cubic meters of concrete per location) is achieved solely due to the change in geometry of the piles and barrettes. Based on this, barrettes are selected as the foundation system under the tower core at this project location. Preliminary O-Cell tests conducted on three test barrettes of 45 to 47 meters' length below cutoff level (22 meters), and redesigned by back analysis, is discussed below. The test load was three times design load.

O-Cell Testing of High-Capacity Barrettes.

Barrette foundations can be designed to transfer very heavy loads, which need better testing methods to test and verify such high capacity. Traditional static load tests use Kentledge or reaction piles, which limits maximum test capacity to 35 to 40 meganewtons. The drawbacks of traditional methods, combined with the high risk and high costs of the test set-up for heavy loads,

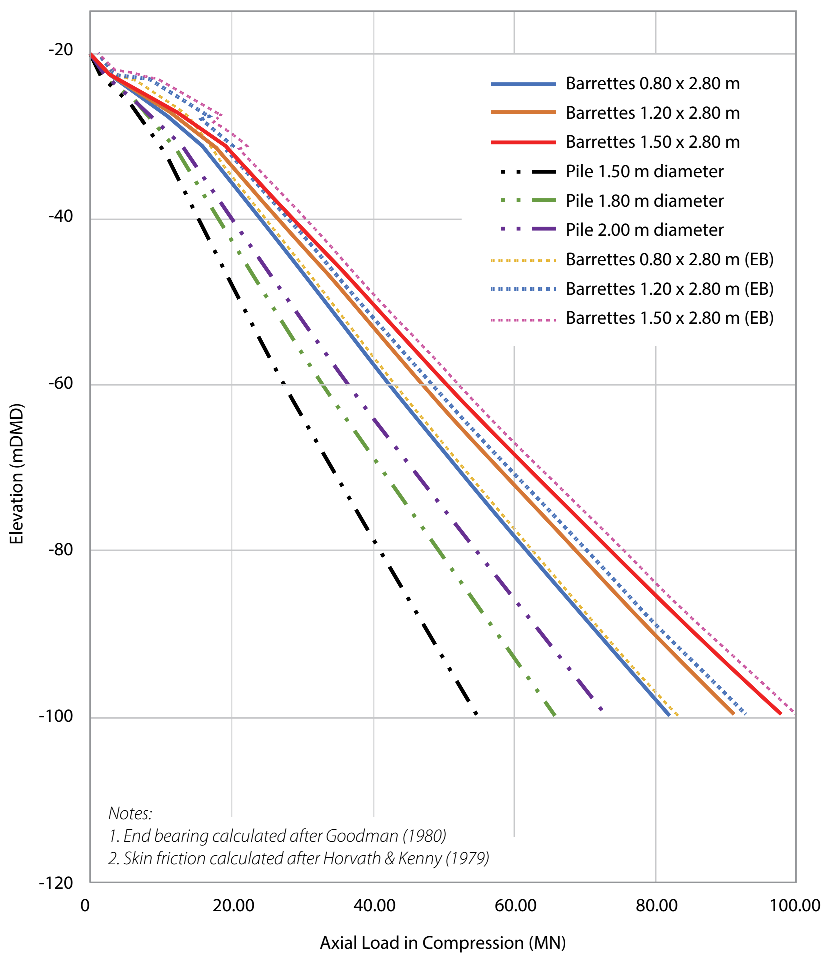

Figure 3. Comparison of the axial capacity of barrettes and pile foundations at La Maison. © Manoj et al.

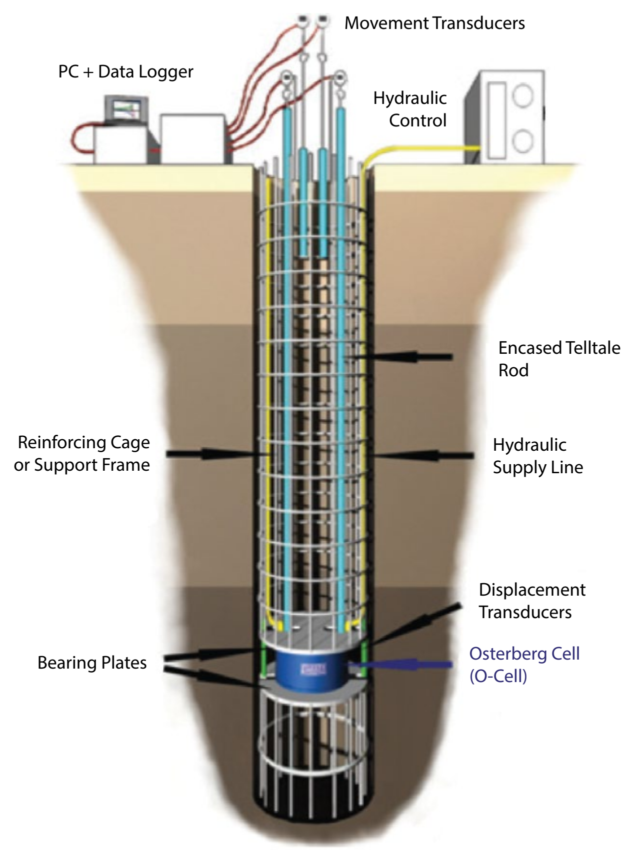

Figure 4. Typical cross-section elevation of an O-Cell installation. © Fugro LoadTest 2017

makes it a poor choice for tall buildings. Bidirectional static O-Cell testing overcomes these difficulties; the maximum test load is limited only by the capacity of the barrettes (England 2003) as evident from successful testing of barrettes to 363 meganewtons, as in case of a proposed 1,000-meter-tall tower in Dubai. The typical test set up is shown in Figure 4.

> “For the design load of 54 meganewtons, 2.07-meter-diameter piles will have to extend to about 81 meters below grade, whereas the same load can be carried by equivalently-sized barrettes resting at 70 meters deep.”

Value Engineering Using O-Cell Test Results

Barrettes in weak rocks the Middle East region are typically designed using the same methods as pile foundations. There are a wide range of design methods currently in practice. Many of them are based on the theory of applied mechanics and use

Barrette No.	Size (m x m)	Barrette Length from Cut Off Level (m)	Hydraulic Jacks		Working Load (MN)	Elastic Settlement at Working Load (mm)	Test Load (MN)	Elastic Settlement at Test Load (mm)	Achieved Load (MN)	Elastic Settlement at Achieved Load (mm)
			Depth (m)	No.						
B1	2.80 x 1.20	43.52	21.82	9	54.00	6.40	162.00	19.20	180.32	24.40
B2	2.80 x 1.20	46.22	23.13	9	54.00	6.20	162.00	20.80	183.11	25.60
B3	2.80 x 1.20	47.00	23.43	9	54.00	6.10	162.00	20.30	183.12	25.70

Table 3. Summary data from load tests conducted on barrette foundations for a supertall building under construction at Business Bay, Dubai. © Manoj et al.

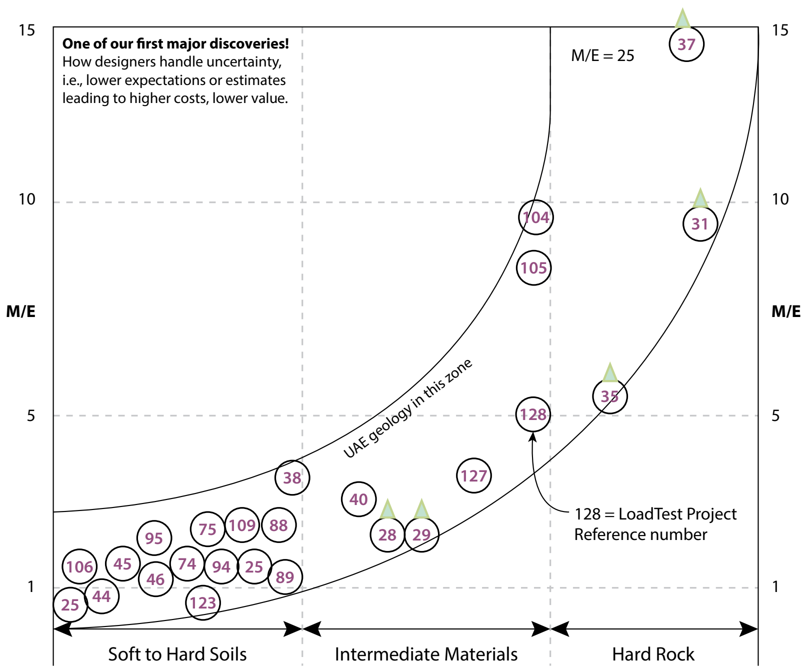

Figure 5. Measured vs. estimated ultimate loads for common soil types found in the Middle East. Source: Osterberg 1999

properties of the rock socket (Williams and Pells 1981; Williams, Donald & Chiu 1980; Katzenbach & Choudhury 2013) predicting ultimate frictional resistance from unconfined compression strength (UCS) of intact rock (Williams, Donald & Chiu 1980; Carter & Kulhawy 1987; Zhang & Einstein 1998; Poulos & Davids 2005; Poulos & Bunce 2008; Zhang, Salgado, Dai & Gong 2013). These methods are mostly developed based on load tests in different geological settings, and for smaller lengths of piles, with small capacities. The capacities estimated using these methods typically deviate from results of field load tests (Alrifai 2007; Ibrahim, Bunce & Murrells 2009; Poulos 2009, 2010, 2017; Poulos & Badelow 2015; Katzenbach, Leppla & Choudhury 2016). Developing a more acceptable and economical, yet still safe design method, applicable to both barrettes and large-diameter piles is the need of the hour. O-Cell testing and back analysis can help to achieve this (Latapie et al. 2018; Enriquez & Motara 2019; Manoj, Choudhury & Alzaylaie 2020).

This is further substantiated by Osterberg (1999), who analyzed several load test cases and presented evidence that underestimation of load capacity is correlated to the rated strength of materials (see Figure 5). The typical geology in UAE is of IGMs, as marked in the graph.

For the supertall tower in Business Bay, three static bidirectional load tests were carried out on barrettes of size 2.80 by 1.20 meters at their weakest locations; the results are summarized in Table 3.

These results were used to back analyze and predict ultimate available bearing capacity of the barrettes (Manoj et al. 2020). The barrette lengths are then based considering actual mobilized skin friction, based on the three test results at 100, 200, and 300 percent of the working load. The capacity is revisited and revised to match the results of 100-percent loading conditions. The initial design capacity and for a 2.80 by 1.20 meter barrette, and the modified capacity after revision, are presented in Figure 6, based on which the barrette length was revised.

The actual values obtained from load test of the three barrettes were back-analyzed, to study the correlation of ultimate friction with the UCS of rock obtained from site investigation data, as presented in Figure 7. The lower boundary of all the results was found to be above the values represented by the following equation 2:

$$f_s = 0.52\ UCS^{0.5} \text{ .... Equation 2}$$

UCS = unconfined compression strength
f_s = ultimate skin friction resistance

However, in order to keep estimates conservative, the load capacity and barrette lengths were revised using the below equation:

$$f_s = 0.4\ UCS^{0.5} \text{ .... Equation 3}$$

UCS = unconfined compression strength
f_s = ultimate skin friction resistance

Even though the results demonstrate that a minimum factor of 0.52 is available, for the actual design, a conservative factor of 0.40 was adopted, as reported by Manoj et al. (2020). Even the factor of 0.40 is a significant improvement over the typical 0.20 or 0.30 that was adopted in the design of many of the existing towers in the UAE. Considering the factor of 0.40, to transfer the design load of 54 meganewtons, the 42-meter length of the 1.20-by-2.80-meter barrette below the cutoff at 20 meters below ground level was found to be sufficient. The initial design length was 48 meters, based on a factor of 0.30. A total length reduction of six meters per location was achieved by using barrettes with this design. Comparing with initial pile design, the total savings is about 17 meters in length, which is 29 percent of the initial design length, resulting in 57 cubic meters of concrete per location, and a total of 11,436 cubic meters of concrete saved, comprising 200 barrettes under the tower core. Approximate reduction in carbon emissions due to this saving was about 4,680 metric tons based on an

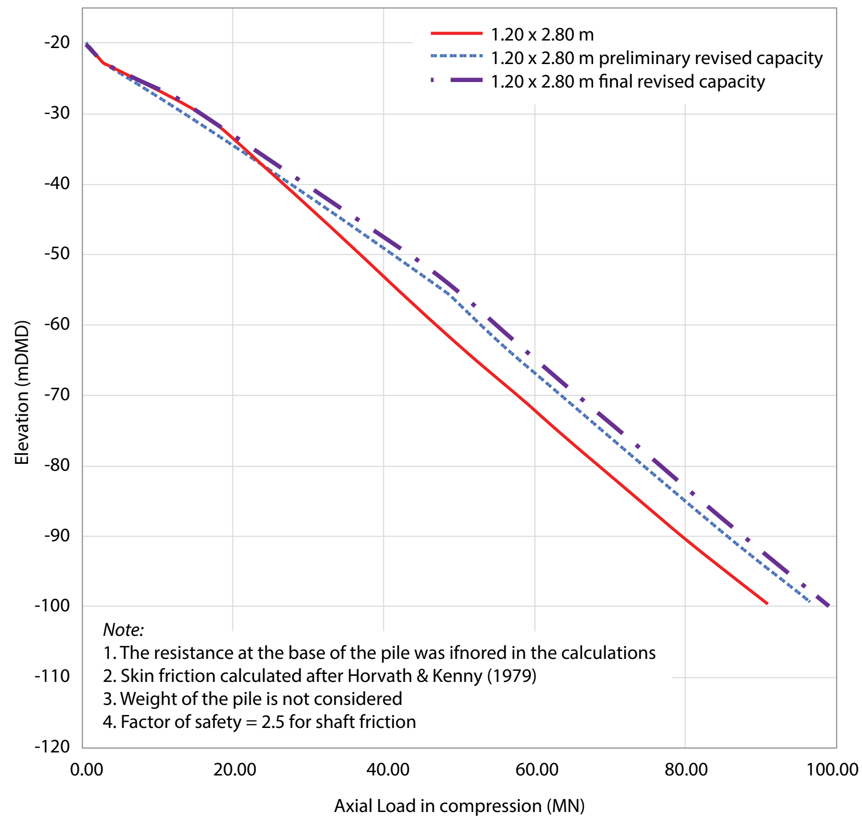

Figure 6. Initial barrette capacity vs. revised capacity, using O-Cell test data. © Manoj et al.

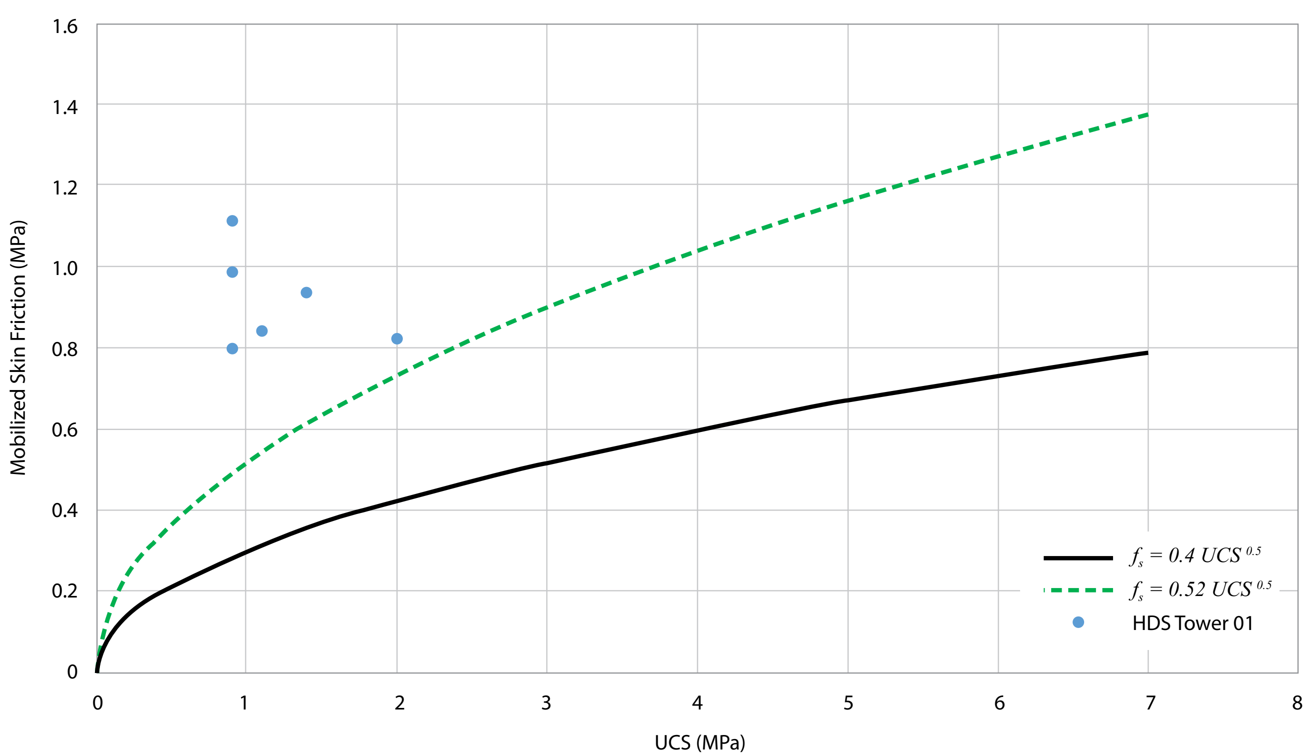

Figure 7. Uncompressed strength (UCS)-to-skin-friction correlation from load test data of three barrettes. © Manoj et al.

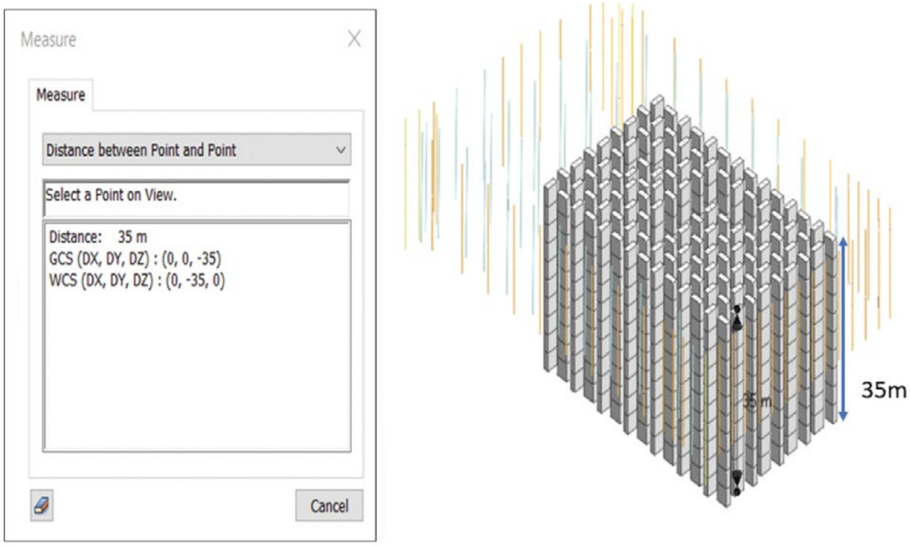

Figure 8. Finite element model showing the revised barrette length of 35 meters. © Manoj et al.

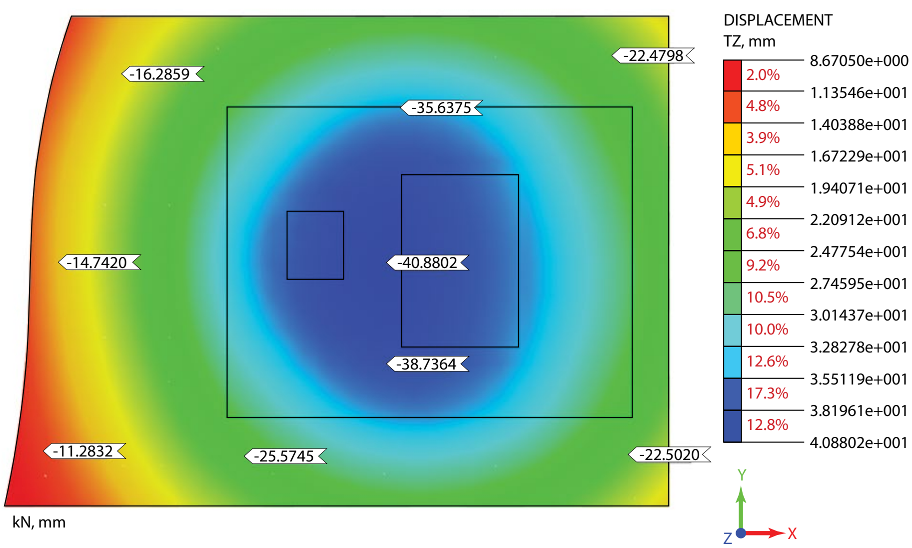

Figure 9. Settlement response, showing total displacements in tower core area under dead- and live-loading conditions with 35-meter barrettes. © Manoj et al.

estimate by World Business Council for Sustainable Development (WBCSD) of CO_2 produced for the manufacture of structural concrete at 410 kg/m^3. It is also noted that the design based on the lowest-bound equation from the load test results would have resulted in further reduction of barrette length to 35 meters; serviceability conditions are checked for this length in the following sections.

Settlement Prediction and Comparison With O-Cell Results

The foundation settlements of tall buildings are typically overestimated by orders of magnitude, despite sophisticated finite element group modeling of the groups of piles and barrettes. The predictions rarely match the actual measurements of site monitoring, or the results of load tests. This overestimation of settlement can be mainly attributed to the overly conservative stiffness parameters used in design (Poulos 2017; Latapie et al. 2018; Alzaylaie 2018). It is important to use appropriate stiffness parameters at appropriate strain levels to predict realistic barrette group settlements under the tower.

The results from down-hole or cross-hole seismic tests can be used to obtain the stiffness parameter (E_d), and settlement predictions can be made more realistically using $0.2E_d$ (Poulos 2017). Calibrated load test results on single barrettes in the above case are compared with the settlement prediction using E_d, and the results were found to be in agreement. The E_d values are then used in the group barrette model to check for total expected settlements for the revised barrette length of 35 meters, calculated using a factor of 0.52 (Equation 2). Results are presented in figures 8 and 9.

It is observed that the settlements are well within acceptable limits for the barrette group even when a reduced length of 35 meters (from Equation 2) is considered in design.

> "Implementing these recommendations can result in savings of 20 to 30 percent in foundation design, resulting in savings of the amount of concrete, operational costs, and plant equipment."

Review of Some Tall Tower Designs in United Arab Emirates

The design methods and foundation details along with ground conditions at some of the prominent tall towers in Dubai are listed in Table 4. It is noted that at the time of construction of some of these towers, there was limited experience of construction of tall towers in the region. The design methods available were developed for much lower foundation depths and loading zones, hence the design approaches were conservative. However, at present, there is sufficient experience in the region, and several published case studies are available for reference, based on which the design methods can be modified, saving a significant amount of resources.

Recommendations and Conclusions

Barrettes are a superior alternative to large-diameter piles for heavy structures such as high-rise buildings with limited base area, especially in weak and weathered rock formations, as they transmit much higher loads to the ground for the same volume of concrete. Current design methods are conservative, and a significant quantity of concrete can be saved by applying value engineering derived from O-Cell test data of barrettes.

It is recommended that initial design of barrettes in such weak rock formations, as is present in Dubai, be done by estimating ultimate skin friction for barrettes from the

Name and Details of Tower/Reference	Site Characterization	Foundation Design	Remarks
Emirates Twin Tower, Dubai *Triangular in plan with a face dimension approximately 50 to 54 meters, 8th tallest in the world at the time of its completion (355 meters) (Poulos 2009).*	23 boreholes, depth 80 meters. E_d from seismic data after using a reduction factor 0.2 used in design.	Piled raft system. 1.20 meters diameter piles 40–45 meters below base of 1.50 meter thick raft. Ultimate unit shaft resistance $f_s = 0.25\ (qu)^{0.5}$	This is one of the initial tall tower projects in Dubai and some conservatism in design is understood. However, a factor of 0.40 instead of 0.25 in estimating friction could have resulted in saving in pile length by about 25–30 percent. Noteworthy that consideration of pile raft system was not followed in many tall towers designed later.
Burj Khalifa, Dubai *The world's current tallest tower, 160 story with final height over 828 meters (Poulos & Bunce 2008).*	Boreholes 140 meters below ground level. UCS value ranging from 1 to 20 MPa.	Consideration of pile raft system. 3.7 meters thick raft supported on 1.50 meters diameter bored piles, 50 meters below the base of the raft. The maximum load 35 MN, minimum loads 12 MN. Ultimate unit shaft resistance $f_s = 0.25\ (qu)^{0.5}$	Design based on Emirates Tower design. Some conservativeness in design is understood as this is the tallest manmade structure ever built. However, a factor of 0.40 instead of 0.25 in estimating friction would have resulted in saving of pile length by about 30 percent. Measured settlements of 43 millimeters were much less than predicted settlements of 70–100 millimeters. Use of E_d for prediction would've given results closer to measured values.
The Pentominium Tower, Dubai *Would have been the tallest residential building in the world at over 100 stories tall if completed (Ibrahim et al. 2009).*	Eight boreholes 80–125 meters. In situ and laboratory testing.	Pile raft foundation ultimate unit shaft resistance $f_s = 0.25\ (qu)^{0.5}$	When the tower construction commences, the foundation design could be revised based on a factor of 0.40 instead of 0.25 after conducting load testing to validate design. The layout can be modified considering higher pile capacity resulting in significant savings.
The Nakheel Tower, Dubai *Planned to be taller than Burj Khalifa, at more than 1,000 meters. Barrettes completed and tested Project on hold (Haberfield et al. 2008).*	10 boreholes to 150–300 meters below ground. Water testing to 200 meters. Cross hole and down hole seismic testing to 200 meters. Pressuremeter testing up to 200 meters.	Barrettes with toe level -55 to -79 meters below ground level. The barrette sizes varied from 1.50 x 2.80 meter to 1.20 x 2.80 meter. The raft thickness varied from 2.5–4 meters and 6–8 meters.	O-Cell testing was done to 327 MN but not close to failure. When the tower will be reconstructed the design can be revisited to perform value engineering, increase load capacity of each barrette by about 20–30 percent and redo the layout.
Entisar Tower, Dubai *Foundation completed. Project on hold (Pereira et al. 2017).*	12 boreholes 20–160 meters deep. Seismic crosshole tests. Downhole seismic test. Multichannel analysis of surface waves (MASW) survey.	1.50 x 2.80 meter size Barrettes 57 to 68 meters long were installed in the ground to carry 55 to 58 MN load. Ultimate unit shaft resistance $f_s = 0.25\ (qu)^{0.5}$	The saving in Barrette depth could be 30–40 percent if optimization by back analysis is done conservatively and settlement predictions use E_d for group modelling. When the tower will be reconstructed higher capacities can be adopted by back analysis and redesign can result in significant savings.

Table 4. Foundation design details of some of the major tall and supertall towers proposed or constructed in Dubai. © Manoj et al.

relation $f_s = 0.5 \times (UCS)^{0.5}$ when UCS is in the range of 0.6 to 2.5 megapascals, instead of the commonly adopted method Hovarth and Kenny equation $f_s = (0.2 \text{ to } 0.3) \times (UCS)^{0.5}$. O-Cell tests can then be designed to validate this estimated capacity, with a sufficient margin of safety of at least three. The foundation group settlement analysis should be performed to check settlement limits using stiffness parameters $0.2E_d$, as is already used in some tall building designs.

The above recommendations can result in savings of 20 to 30 percent in foundation design, resulting in savings of the amount of concrete, operational costs, and plant equipment. Cement is the source of about eight percent of the world's CO_2 emissions. Such a huge saving in concrete volume in construction can also result in a significant reduction in carbon footprint. ■

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